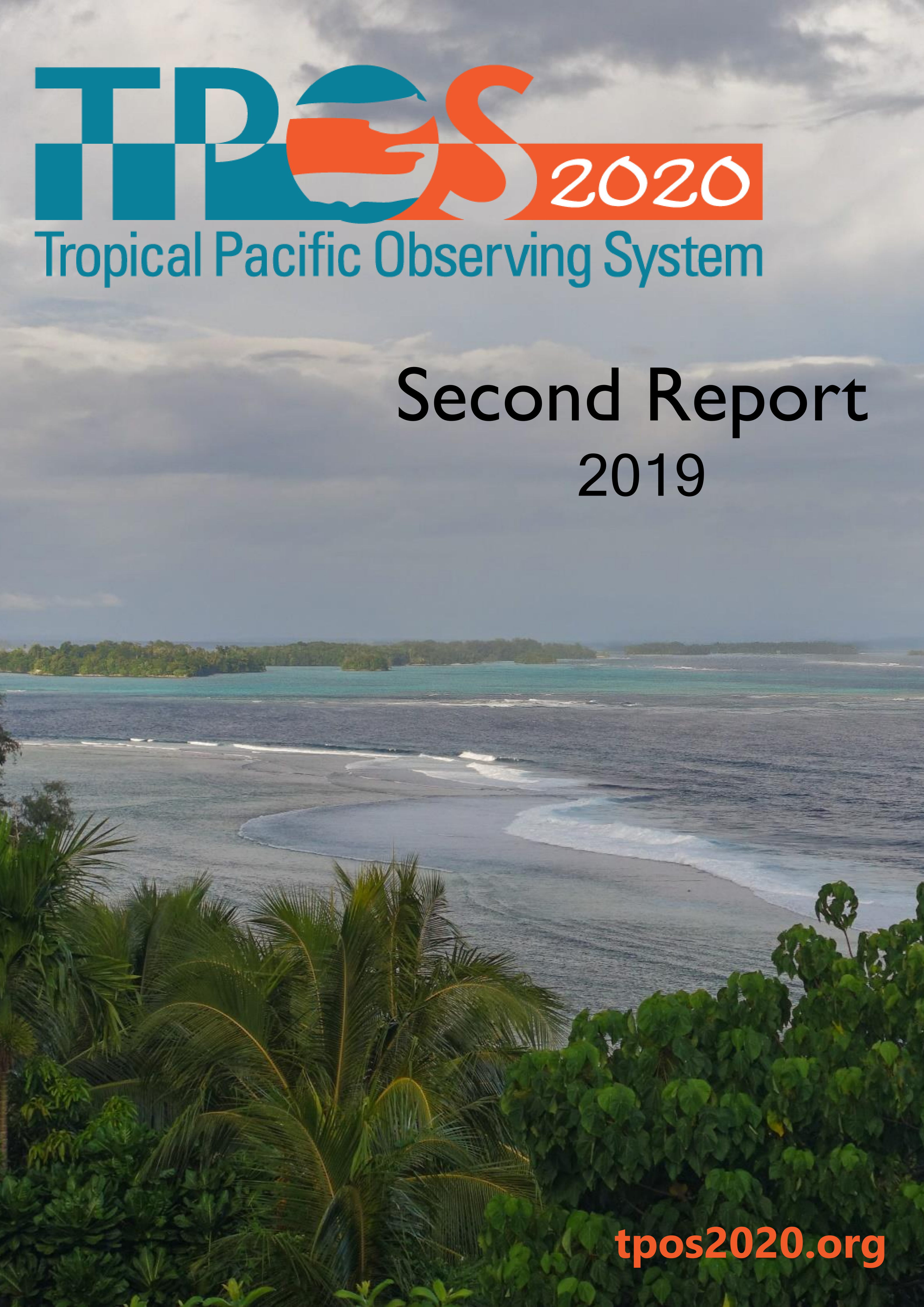

TPOS 2020
Tropical Pacific Observing System

Second Report
2019

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Second Report of TPOS 2020

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Contents

Executive Summary

This Second Report of the Tropical Pacific Observing System 2020 Project (TPOS 2020[1]) builds on the analysis and conclusions of the First Report, informed by new evidence and/or fresh perspectives on priorities. The report provides further elaboration and refinement of the recommendations and updated or new actions where appropriate, together with additional detail and recommendations in areas not covered in the initial report. Recommendations for a redesigned moored array, that remained fuzzy in the First Report, are now detailed.

This Second Report provides a major revision and more comprehensive update for two of the major foci of TPOS 2020, biogeochemical and ecosystem Backbone observations and the eastern Pacific. The western Pacific was revisited in the TPOS OceanObs'19 community white paper and this report includes an analysis of requirements arising from the complex scale interactions from weather to climate over the western Pacific Ocean. Additional consideration of air-sea fluxes and the planetary boundary layers in the tropical Pacific are also included in this report.

TPOS 2020 sponsors specifically requested further consideration of requirements arising from monsoon and subseasonal timescales; severe storms and any special ocean observing requirements; observations related to Indo-Pacific exchanges; and any requirements emerging from the new class of coupled numerical weather prediction models. This report, supported by the Community White Paper on the TPOS published for OceanObs'19 (Smith et al., 2019; hereafter TPOS OceanObs'19), represents a substantial, but not yet complete, response to this charge.

New Areas of Review

Three new topics are reviewed in this Second Report:

- coupled models for subseasonal to interannual predictions;
- observational requirements for coupled weather and subseasonal timescales; and
- TPOS data flow and access (see later in this Summary).

All three areas were touched on in the First Report but here we provide a deeper review and associated recommendations and actions.

Coupled models for subseasonal to interannual predictions

The review is based on a survey of operational seasonal-to-interannual prediction centers; a US CLIVAR workshop aimed at bridging the knowledge gap between sustained observations and data assimilation for TPOS 2020, including consideration of the models that underlie that process; and the published literature. The First Report noted there is an urgent need to improve the skill, effectiveness and efficacy of the modeling systems that are critical to realizing the impact of an improved TPOS. This report provides further analysis of the main systematic

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[1] "TPOS" alone refers to the observing system; "TPOS 2020" refers to the project.

errors but finds that translating that information into model developments to reduce biases has proven difficult and that systematic approaches are not in place. [2.3, 2.4, 2.5][2]

We propose building from the experiences of the numerical weather prediction community and the Coupled Model Intercomparison Project (CMIP) to establish such a systematic approach, with a regular cycle of three parallel lines of development: (a) an agreed community-planned set of experiments; (b) studies based on a set of common diagnostics and metrics; and (c) a series of process studies to bridge the observations and modeling communities. [***Action 2.1***; 2.7]

The community survey indicated a cycle of around five years might be workable, with a timetable for planning, commitment, execution and publication, and concluded by an independent assessment of progress. This report concludes that without such a commitment to a systematic process, the seasonal-to-interannual prediction community may never realize its full potential, nor that of TPOS observations. [2.7]

Recommendation 2.1. Establish a systematic and planned cycle of work among the participants in seasonal prediction, including (i) a planned and systematic cycle of experimentation; (ii) a coordinated set of process and/or case studies, and (iii) routine and regular real-time and offline system evaluation. An independent assessment should occur across all elements every five years. [2.7]

We provide two additional recommendations to promote innovative observing system sensitivity experiments and reanalyses to guide the evolution of the observing system.

Recommendation 2.2. Increase support for observing system sensitivity and simulation experiments to identify observations that constrain models most effectively and have high impact on forecasts. Correspondingly, development of infrastructure for exchanging information about data utilization and analysis increments should be supported. [First Report; 3.3.3.2, 6.1.6]

Recommendation 2.3. Increase support for the validation and reprocessing of ocean and atmospheric reanalyses; conduct TPOS regional reanalyses and data reprocessing to guide observing system refinement and to enhance the value of TPOS data records. [2.7]

Observational requirements of coupled weather and subseasonal prediction

The science around coupled weather and subseasonal prediction is advancing rapidly and several recent publications have reviewed progress and considered ocean observation needs in a general way. Key processes include heat and water fluxes in and between the atmospheric and oceanic boundary layers. At a general level, the First Report included a trend toward requirements with enhanced spatial resolution and finer temporal resolution, specifically to capture features such as fronts and the diurnal cycle and to avoid aliasing in air-sea flux estimates [First Report; Chapter 3]. The conclusion drawn in this report is that further research is required before we can be more

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[2] Unless indicated otherwise, the [] references are to sections in the Second Report.

specific or detailed in terms of essential variable spatiotemporal requirements; such research is underway. [***Recommendation 3.3***]

Two process studies are supported, one focused on the eastern edge of the west Pacific warm pool, and the other on equatorial upwelling and mixing.

Observations of sea surface temperature and salinity must be complemented by observations of near-surface winds, ocean surface waves, surface currents and vertical structure in the ocean mixed layer if we are to constrain/initialize processes in models on monthly and shorter timescales. The high temporal resolution of the Tropical Moored Buoy Array (TMA) and the move toward measuring more complete flux variables aligns with such needs and we conclude will almost certainly benefit coupled data assimilation and coupled model development.

The following recommendations would advance these goals:

Recommendation 3.1. Where feasible and practical, promote observing approaches that jointly measure the ocean and marine boundary layers, and air-sea flux variables, principally to support model development, as well as testing and validation of data assimilation methods and systems. [3.3.3.1, 3.3.3.2, 7.2.1.1]

Recommendation 3.2. Encourage and promote process studies that will improve the representation of key processes and allow further testing of the ability for observations to constrain the coupled system; to address biases in observations and models; and to improve CDA observation error estimates. [3.2, 3.3.1, 3.3.2].

The international Subseasonal-to-Seasonal project hindcast and real-time database is supporting research and model development. Studies on initialization of an intraseasonally-varying ocean are being supported, including sensitivity to ocean observation, and provide insight on common errors that need to be addressed. One subproject aims to provide ocean outputs from the forecast models for analysis.

Recommendation 3.3. Promote and engage with the Working Group on Numerical Experimentation-WCRP Subseasonal-to-Seasonal subproject on Ocean Initialization and Configuration. [3.4]

Requirements: The First Report Reprised and Extended

Biogeochemical and ecosystem Backbone observations

We report on further refinement of biogeochemical (BGC) and ecosystem observational requirements, including estimates of critical time and space scales, and the implications for the Backbone. Key processes that drive variability in biogeochemistry and ecosystem and thus determine biogeochemical requirements are: (i) the response to long-term climate change; (ii) seasonal to decadal variability of the tropical Pacific biological pump; (iii) seasonal to decadal variability of the tropical Pacific CO_2 flux and implications for the global carbon cycle ; (iv) the upper ocean carbon budget, including carbon export below the mixed layer and sources of anthropogenic carbon for upwelled water; and (v) volume and nutrient fluxes into the Equatorial Undercurrent.

This phenomenological basis permits an analysis of relevant biogeochemical Essential Ocean Variable (EOV) measurements, including for oxygen, nutrients (e.g., nitrate, phosphate and silicate), inorganic carbon, particles, chlorophyll and transient tracers. We considered new analyses of space and time decorrelation scales of some of these variables which may allow characterization of seasonal to interannual variability, including for oxygen minimum zones.

These advances, along with TPOS 2020 pilot projects (Saildrone® and BGC-Argo) and further input from the community have led to refinement and extension of the conclusions from the First Report. The main points are:

- Maintain and extend the $p\mathrm{CO}_2$ climate record [4.3.1; First Report, Rec. 12; ***Action 7.6***]
- Address the broader goals of the Biogeochemical Argo community through 31 BGC-Argo float deployments per year in the 10°N to 10°S band.

Recommendation 4.1. TPOS 2020 recommends a target of 124 BGC-Argo floats with biogeochemical sensors (specifically nitrate, dissolved oxygen, pH, chlorophyll fluorescence, particulate backscatter and downwelling irradiance) for the 10°N-10°S band. [4.3, 4.4]

- Re-institute CTD and bottle sampling on mooring servicing cruises - CTDs should be performed to 1000 m along each TMA line.

Recommendation 4.2. TPOS 2020 recommends CTDs with dissolved oxygen and optical sensors (chlorophyll fluorescence, particulate backscatter, transmissometer) and water samples (at a minimum for chlorophyll and nutrients) should be performed to 1000 m along each TMA line by servicing cruises, at every degree of latitude between 8°N and 8°S and every 0.5° between 2°N and 2°S at a frequency of at least once per year. Twice per year sampling is optimal and could be augmented by GO-SHIP and other ships of opportunity. [4.3.2, 4.4; ***Recommendation 7.3***]

- Continued coverage of satellite ocean color and CO_2 observations [4.2.5, 4.3.1, First Report, Rec. 13]
- Develop a coordinated and long-term observation strategy for the low-latitude western boundary current region [4.4, 7.4.5.1; TPOS OceanObs'19]
- Continue pilot studies for technology development to expand autonomous capabilities – especially for Oxygen Minimum Zones [4.3, 9.2.5, 9.2.3]
- Promote process studies to understand the impact of El Niño and long-term change on carbon export and ecosystems [4.1.1, 4.3, 4.4]

Eastern Pacific observing system

The eastern Pacific region has high societal impact and is among the most problematic for climate modeling, as oceanic processes, low-cloud physics, and tropical deep convection have complex interactions in this region. The sharp property gradients of the eastern Pacific form a key distinction from the rest of the basin and a major challenge to both observing and modeling. The Second Report revisits the phenomenological basis and requirements of the region, including the coastal waveguide, and extends the discussion of atmospheric processes and observations to the extent they are relevant for an integrated approach to the TPOS. We map a course for addressing outstanding science questions through both engagement with regional efforts, as well as pilot and process studies.

The following provide the overarching scientific motivation for an eastern Pacific observing system:

- Monitoring and predicting the El Niño-Southern Oscillation, including the evolution in understanding of tropical instability waves, the influence of tropical Atlantic SST, and the nature and spread of convection in the region;
- Understanding and addressing ocean model biases, including Kelvin wave dissipation processes, systematic errors in the vicinity of upwelling and the equatorial thermocline, and modelling of interaction with coastal upwelling dynamics;
- Understanding atmospheric and coupled model biases through a focused effort to better observe cold tongue and Inter-tropical Convergence Zone dynamics and associated cloud feedbacks, including the atmospheric thermodynamic and dynamic vertical structure; and
- Oxygen minimum zone dynamics and equatorial and coastal upwelling that brings cold nutrient-rich waters toward the surface resulting in phytoplanktonic blooms (see also the biogeochemistry discussion above).

Recommendation 5.1. The existing TMA line along 95°W should be maintained and updated to full-flux sites. [7.3.1]

Recommendation 5.2. Increase Argo density for the eastern Pacific as soon as possible. A coordination of South American countries to execute the doubling of Argo will be required. [***Recommendation 4.1*** and ***Action 7.9***].

TPOS 2020 reaffirms its support for pilot projects to evolve and strengthen observing capability in the region. The equatorial-coastal waveguide and upwelling system (***Action 5.2***) and Inter-tropical Convergence Zone/cold tongue/stratus system (***Action 5.3***) pilot studies are reaffirmed as high priority. A third pilot on atmospheric monitoring from eastern Pacific islands is recommended to test our ability to monitor: (a) vertical profiles of atmospheric winds, temperature and moisture variability; (b) surface conditions in the near-offshore region; and (c) atmospheric vertical structure and cloud radiative forcing in the core stratus deck region (***Action 5.4***).

One of the motivations for revisiting the eastern Pacific in this report was to enable and generate greater regional activity. Several opportunities are identified, including (a) enhanced data sharing and cooperation, to include improved transmission and quality of data, using regional mechanisms where appropriate, (b) direct participation in profiling float enhancements, (c) participation in a regional reanalysis project that would better resolve processes and fields relevant to Eastern Pacific stakeholders, and (d) assistance to establish collaborative frameworks so that greater regional value could be obtained from their observing efforts (***Action 5.1***). [5.2]

Recommendation 5.3. A pilot study along 95°W installing dissolved oxygen sensors to 200 m and an ADCP is recommended at the equator, with additional dissolved oxygen and current sensors on 2°N and 2°S if at all possible. [5.1.4]

Recommendation 5.4. TPOS 2020 recommends planning and execution of a reanalysis project for the eastern Pacific, making use of past and current data sets, as well as hydrographic sections between the Galapagos Islands and the coast. This reanalysis effort should include high-resolution regional atmospheric products that resolve important coastal winds, and ensembles for estimating uncertainty. [5.2]

TPOS 2020 strongly encourages stakeholders to advocate for and support an eastern Pacific focus for the United Nations Decade of Ocean Science for Sustainable Development (2021-2030), given the benefits will be relatively large for this region (***Action 5.5***).

Tropical Pacific decadal variability and long-term trends

Consultations after the publication of the First Report strongly encouraged TPOS 2020 to revisit the requirements arising from decadal variability, long-term climate trends and the climate record. This eport provides a comprehensive update, including a review of historical studies of decadal variability; implications from global climate change and other external-forcing for tropical Pacific climate; and an analysis of modeled and observed past changes in the El Niño-Southern Oscillation and potential future changes. [6.1.2-6.1.5]

Key findings include the need for better observational constraints for estimates of surface heat fluxes, and for improved understanding of the subsurface circulation, thermal structure, and heat budget of the upper ocean along the equator; and the need for sustained reliable observations and reanalyses of both the on- and off-equatorial winds and air-sea fluxes. Long-term sustained monitoring and high-quality reanalyses are highlighted as priorities. [6.1.6] We also discuss the potential role of TPOS for better calibrating and understanding paleo-proxy data records, a topic that should be considered for the coming years.

We stress the challenge of detecting multi-decade signals and the importance of maintaining a reference set of longstanding, continuous climate records, with quantified uncertainties, that can bridge any future changes in the observing system and confirm or refute any shifts that may coincide with the introduction of observing system or data processing changes. Such references must have enough coverage and sufficient quality and reliability to (1) detect and identify small dec-cen signals, (2) enable cross-checks for consistency, and (3) be able mitigate risks from unexpected failures of individual elements. [6.1.6]

The Northwestern Pacific Ocean

The TPOS OceanObs'19 Community White Paper provided recommendations for a low-latitude western Pacific boundary current monitoring system, including consideration of the Indonesian Throughflow. This report supplements that work with an analysis of complex interactions over a range of timescales in the northwestern Pacific Ocean, including stochastic forcing of El Niño and involvement in the delayed-action oscillator and discharge-recharge mechanisms.

The boreal summer intraseasonal oscillation, an elemental part of the Asian summer monsoon system, provides one example of potentially predictable signals on subseasonal to seasonal timescales in the northwestern Pacific Ocean, with likely far-reaching impacts (e.g., extreme rainfalls and droughts) of significant societal relevance for the region. The region also hosts the most intensive typhoon/cyclone hot spot according to observations over the last fifty years. Improved understanding may allow typhoon prediction to be extended beyond seven days.

An enhanced observing capability is needed to meet requirements in the northwestern Pacific Ocean arising from these complex scale interactions and their associated links between the tropics and subtropics. These enhancements are proposed as part of the evolution of the Backbone.

Air-sea fluxes and the planetary boundary layers

One purpose of the Backbone is to provide in situ time series for comparisons with satellite-based measurements and validating gridded synthesis products, including for those of wind stress and air-sea heat and water fluxes. The Second Report discusses how the TPOS might better support these goals.

Wind stress

The First Report design takes advantage of the revolution in broadscale wind estimation over the ocean enabled by space-based scatterometers, but combined with and complemented by in situ measurements, particularly from moorings. If space-based vector wind sampling could be increased and better spread across the diurnal cycle, the outlook is for greatly improved wind estimation. However, some questions remained about the differences between wind estimates from moorings and satellites, about errors in blended gridded wind products, and about the best approach to monitoring decadal-scale variability and detecting climate change. An Annex to the Second Report is devoted to these issues and to errors arising from sampling (space and time). Further research is needed to better understand these errors in gridded wind products and the impacts of sampling differences between satellite and buoy winds (***Action 6.1***). There are also outstanding issues around directional dependence of buoy and scatterometer wind differences (***Action 6.3***).

The First Report noted the many different approaches to producing gridded wind products (including uncertainty estimates), ranging from reanalysis products to specialized blended products using wind observations from different scatterometers and in situ data. The effect of surface currents remains an issue. Dedicated analyses have been started (as discussed in Annex A of the Second Report) to better document error sources from both moorings and satellites, to understand their differences, and distinguish the issues of measurement versus sampling errors (***Action 6.2***).

Heat and moisture fluxes

In the First Report, it was noted that the satellite-based estimates of heat and moisture flux variables were either non-existent or subject to large uncertainties. The Second Report revisits this assessment based on recent progress in these efforts.

For radiative fluxes, the report analyses studies that have looked at the bias and standard deviation of satellite derived downwelling shortwave and longwave products with encouraging results. There remain uncertainties that need to be better quantified and understood. The pathways for progress include more in situ radiation data, together with the development of standards that ensure their measurements and processing led to the highest possible quality. They also include the deployment of some highly instrumented Super Sites (section 7.4.7) in selected regions.

Satellite products of turbulent fluxes relying on surface state variables and bulk algorithms have also been continuously improved, even if satellite retrievals of near-surface temperature and humidity need further refinement. Documented errors in these variables have regional and regime dependencies, for example in the vicinity of large-scale atmospheric convergence/ divergence fields and associated cloud properties. In situ data sites within each of these regimes (with meridional extensions) will help improve near-surface temperature and humidity estimates. Additional measurements at “Super Sites” such as in situ directly measured fluxes using direct correlation flux observations and atmospheric boundary layer temperature and humidity profiles would also provide guidance for improving satellite retrievals.

Freshwater fluxes

As in Recommendation 9 from the First Report, increasing the number of in situ rain gauges would provide better statistics for satellite comparisons. The TPOS community should continue discussion with the satellite and in situ precipitation experts to examine to what extent and in what regions increased rain gauge density would be of value, and whether additional measurements (for instance a Super Site with radar) could be incorporated (***Action 6.4***).

Other considerations

The Second Report reaffirms the importance of surface currents for improving surface fluxes; the evaporation rate, and latent and sensible heat fluxes depend on the wind speed relative to the ocean current.

The Second Report confirms the priority placed on the requirement for more extensive measurements of the full suite of flux variables which are currently only made at a few sites on the equator. It also confirms the priority to extend surface sampling across the tropical convergence zones and into the subtropical trade wind regime and other key regimes. [6.5]

The Second Report also reaffirms the increased requirements for mean sea level pressure measurements based on recent sensitivity experiments. Near the equator, where rapid divergence can hinder effective sampling from drifters, sensors on the TMA (5°S – 5°N) could help meet the requirement.

The Backbone Observing System

The Second Report updates, and as necessary modifies, the Backbone observing system recommendations provided in the First Report, taking advantage of recent consultation and feedback, new dedicated studies and technical progress, and results from recent pilot studies. We recap the design and multiple functions of the Backbone and more fully explain some of the reasoning behind the Backbone recommendations where the First Report left uncertainty, or where issues have been raised subsequent to the publication of the initial Report.

In general, the recommendations of the First Report remain valid, with the underlying logic and evidence strengthened by the review. The major changes remain renewal and reconfiguration of the mooring array, and a doubling of Argo sampling in the tropical zone (10°N – 10°S), now including BGC-Argo sensors on 1/6th of the floats.

The reconfiguration of the tropical moored buoy array is now described in greater detail, including tiered parameter suites (7.3.1.1), and a refocused spatial configuration that maintains and enhances the focus on the equator while retaining a grid-like structure for detecting and validating basin-wide decadal and longer-term flux changes (7.3.2; Figure 7.4). The 3 tiers include a widely deployed and enhanced base level (Tier 1), with some that will include rainfall, pressure and mixed layer salinity (***Action 7.1***); a velocity-enhanced mooring that will be deployed at select sites/lines (Tier 2) (***Action 7.2***); and a small number of very highly instrumented "Super Sites" (Tier 3).

Consistent with identified requirements and priorities, the new moored array design focuses on [7.3.1]:

1) expanding the sampled surface meteorological regimes through poleward extension of some meridional spines;
2) markedly expanding the spatial coverage of variables for heat and water flux estimates, adding short and longwave radiation to Tier 1, and rainfall (***Action 6.4***);
3) complementing (2), resolving near surface and mixed layer diurnal variability across the domain (denser vertical resolution of temperature in the upper 50m);
4) systematically measuring near surface currents;
5) expanding surface barometric pressure measurements;
6) better resolving the near equatorial flow field in the central Pacific; and
7) sustaining and enhancing $p\mathrm{CO}_2$ measurements.

> ***Recommendation 7.1.*** TPOS 2020 recommends the adoption of and support for a refocused design for the tropical moored buoy array, with a three-tiered approach to instrumentation. These comprise the Tier 1 baseline with enhanced surface and upper ocean measurements over the existing array; Tier 2 with added velocity observations in the mixed layer; and Tier 3, an intensive Super Site that might be used in a campaign mode. [7.3.1].

The exact location of the moorings poleward of 8°S under the South Pacific Convergence Zone needs to be further explored, in consultation with community experts and regional partners (***Action 7.3***).

Tier 2 sites, in consultation with community experts to specify the priority sites (***Action 7.2***), will include an upward looking near-surface ADCP, measuring velocity in the upper 50m. The “Super Site” concept is still in development but will include additional instruments to provide more detailed or specialized information to refine the observing strategy and take advantage of technological advances. [7.4.7]

Full implementation of the TPOS design will deliver many gains, but also raises the potential for losses; such is inevitable in a process of redesign and reprioritization but is nevertheless regrettable, particularly with respect to some historical off-equatorial mooring sites. This is already the case in the western Pacific, although the new design aims to redress and minimize the loss. The gains and losses are described in detail [7.3.2, 10], including mooring coverage (Figure 7.5), rainfall sampling (Figure 7.6), decadal and longer-term wind (Figure 7.7) and latent heat flux (Figure 7.8) changes, and radiation and evaporation regimes (Figure 7.9). Subsurface impacts from changes to Argo and mooring sampling are also presented (Figures 7.10-15). A full summary is included. [7.3.3]

Progress with Implementation

Progress with implementation since the First Report has been very encouraging and TPOS 2020 has achieved significant buy in. We provide a schematic update of the status of the main Backbone Essential Ocean Variables which shows around half are in a satisfactory state (requirements met adequately or better), but for the remainder there is considerable work to do. For wind, and building on Recommendation 1 from the First Report, TPOS 2020 must drive further dialogue with agencies to explore ways to improve data availability and the diurnal spread of sampling by vector wind measuring satellite missions if the TPOS requirements are to be met (***Action 7.4***, 7.4.1, First Report, Rec. 1). For sea surface salinity, the community must continue to highlight the ongoing need and benefits of follow-on satellite missions (***Action 7.5,*** First Report Rec. 10). Underway measurements of $p\mathrm{CO}_2$ fall short of requirements and TPOS 2020 must act to establish measurements on all mooring servicing vessels and promote pilots of $p\mathrm{CO}_2$ measurements from autonomous underway vehicles (***Action 7.6***; 4.3.1; First Report, Rec. 12).

The First Report included recommendations and actions to enhance Argo coverage in the TPOS region; the Second Report reaffirms this strategy and priority. Around 20% of that enhancement is in place currently. This report provides further analysis of deployment strategies and stresses the need for greater international participation.

To address requirements in the western and northwest Pacific Ocean, the TPOS 2020 project has convened discussions with key stakeholders. China has outlined plans to contribute moorings and other capability to address these needs, including to track monsoon and typhoon development over the northwestern Pacific Ocean [the so-called Ding "丁" array; 6.2.2, 7.2.1.3]. In-principle support for maintaining the TAO part and the remaining 3 TRITON moorings has been provided by the National Oeanic and Atmospheric Administration (NOAA) and the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), respectively. We reprise and update the incomplete action from the First Report:

- *The TMA sites in the western Pacific within 2°S to 2°N should be maintained or reoccupied.*

These are core sites, and all should be supported.

The Second Report outlines a staged implementation approach [7.4.4; Figure 7.19; TPOS OceanObs'19], with ongoing assessment through to full maturity. Many elements will evolve with global implementation, but with recognition of and advocacy from the TPOS community. Others will require specific actions from the TPOS community, and these are discussed in more detail in the report. The actions, including reconfiguration of the moored array, will need to be carefully coordinated since no single player is able to respond to all requirements. Resource limitations are inevitable but through a cooperative implementation strategy and plan, the TPOS community can jointly meet most requirements and together enjoy the benefits of the whole TPOS.

Several specific actions are highlighted:

- In preparation for TMA-wide usage, Tier 1 ‘full flux’ moorings from all contributing operators should be piloted, intercompared and assessed, and agreement reached on where salinity, rainfall, and barometric pressure are most needed in addition to the core measurements. Instrument calibration and quality control procedures should be further developed, agreed and documented. [***Action 7.7***]
- A pilot of enhanced thermocline velocity measurements at established sites at 140 °W, 2 °N/S should be planned, and if successful, extended to include the new sites at 1°N/S. [***Action 7.8***]
- Argo float deployments should be doubled over the entire tropical region 10°S-10°N, starting immediately in the western Pacific, followed by the eastern Pacific and extending to the entire region, building to a total annual deployment rate of 170/year.

Of these, 31 should be equipped with biogeochemical sensors. [***Action 7.9***; ***Recommendation 4.1***]

- TPOS 2020 should develop and detail whole-of-system assessment activities, describing them in the final TPOS report (or earlier). Part of the assessment should include examining the tradeoffs between the number of sites versus the ability to maintain continuous records. [***Action 7.10***]
- For each specialized data stream or platform, ensure the creation of an engaged team of experts to oversee sensor management, develop quality control (QC) procedures and guide the delayed-mode QC for the TPOS data streams. [***Action 7.11***; ***Recommendation 8.3***]

The draft schedule attempts to synchronise actions and harmonise actions and assessments, but this will need to be revisited regularly.

TPOS needs to be proactive to ensure the climate record and our ability to detect change is at least maintained, if not enhanced.

Recommendation 7.2. To ensure that the TPOS observing platforms collect the accurate and interoperable measurements required to detect small [climate or "dec-cen"] signals, a series of actions should be taken, beginning before the rollout and continuing during implementation, to assess the performance and impact of the proposed platform/sensor changes. [7.2.1.2, 7.4.4]

Updates are provided for all Pilot Studies and Process Studies proposed in the First Report [7.4.5, 7.4.6; Figure 7.20].

The concept of a Super Site is to provide multi-year specialized and more comprehensive data sets, using a larger and/or more complex suite of measurements than the Backbone observing system offers. TPOS 2020 should further develop and articulate the concept, including possible approaches to determination of appropriate times, locations, and measurements. [***Action 7.12***]

Several additional actions and recommendations flow from the review of the First Report.

For sea surface temperature, Recommendation 3 from the First Report remains valid but additional emphasis is needed on the mix of observations and processing needed to properly resolve the diurnal cycle, incorporating remote microwave measurements, visible–near infrared sensing data, and in situ data at various depths near the surface. [First Report Rec. 3; ***Action 7.13***; 7.5.1]

The First Report recommendation for sea surface salinity might be misleading, and so has been updated:

Updated First Report Recommendation 10*: Continuity of complementary satellite and in situ SSS measurement networks, with a focus on improved satellite accuracy to augment the spatial and temporal sampling of SSS.*

Further progress has been made in relation to the First Report recommendation on surface currents (Recommendation 11). Two missions are now in the planning phase which are, in the view of TPOS 2020, potential game-changers with direct measurements of total surface currents, a requirement that has been highlighted with respect to surface wind stress and surface fluxes. [7.5, 9.3.1]

The importance of other in situ capabilities, while recognized in the First Report (Recommendation 21), was not sufficiently highlighted. Thus, a new recommendation from TPOS 2020 is:

> ***Recommendation 7.3.*** Improvement of dedicated capacities on servicing ships to allow repeated ancillary measurements. Underway measurements such as Shipboard Acoustic Doppler Current Profiler measurements, *p*CO2 and sea surface salinity should be systematically acquired. [7.5; ***Recommendation 4.2***]

TPOS 2020 continues to advocate for Pilot and Process Studies that will contribute to the refinement and evolution of the TPOS Backbone. [First Report, Action 14]

Additional Areas of Review

TPOS data flow and access

The Second Report proposes that data management should be considered alongside observations in the requirement determination process and that the architecture of our data systems requires greater clarity. We continue to advocate for the necessary investment:

> ***Recommendation 8.1.*** As an underlying principle, around 10% of the investment in the TPOS should be directed towards data and information management, including for emerging and prototype technologies. [First Report, 8.1, 8.2]

This report concludes a distributed approach to data systems promotes agility and efficiency, particularly if the distributed services are built upon commonly used standards and conventions. This report outlines a generalized system that takes advantage of other developments in this area. An important benefit is that the scientists and/or data providers are abstracted from the need to understand the formats required for real-time distribution. The ultimate aim is to have a virtual one-stop set of web services for all TPOS data, suitable for research, production, services, public and privately funded activities or other ad hoc use. [8.3]

This report identifies two other areas where TPOS should be proactive. First, the likely introduction of new partners, particularly for the tropical moored buoys, and new technologies, argues for a TPOS data management plan, initially spanning all TMA contributions and data modes. The second area is around delayed-mode data, data archeology, re-processing and re-analysis. Re-processing for reanalysis is now mainstreamed, to take advantage of knowledge that was not available in real-time, and/or to exploit improved techniques. One foci for TPOS 2020 is the western Pacific where there is a large cache of data that is for now "lost" to the wider scientific community, and likely to be "found" only through a major international collaborative effort (***Action 8.1***) aimed at retrieving and re-processing such data into a form that is FAIR (findable, accessible, interoperable, reusable).

> ***Recommendation 8.2.*** Data stewardship and the engagement of all TPOS 2020 stakeholders in data management must be a central platform in the sustainability of the TPOS. The FAIR Principles should be adopted as a basis for TPOS engagement. [8.4]

> ***Recommendation 8.3.*** TPOS 2020 should develop a project around the management of all TMA data including, to the extent possible, recovery and re-processing of other relevant mooring data. [8.4]

TPOS 2020 supports the global community in its endeavor to establish global information and management systems that will provide cost-effective ways to increase and improve accessibility, interoperability, visibility, utility and reliability; endeavors that will benefit TPOS data, for current TPOS stakeholders and beyond.

> ***Recommendation 8.4.*** TPOS 2020 should develop a pilot project, in conjunction with the WMO Information System effort, to explore the global distribution of TPOS data in near-real time. [8.5]

Emerging technologies

This report discusses the current state of a selection of emerging technologies that are of potential future relevance to TPOS and introduces an evaluation mechanism to assess readiness and guide integration of new observation techniques/platforms into the Backbone. The discussion includes:

1. NOAA Saildrone®[3] experiments;
2. Wave Glider® experiments;
3. PRAWLER profiler;
4. Ocean gliders;
5. Biogeochemistry, biology, and ecosystems technology;
6. Water isotope observations - applications and technology;
7. Remote sensing of ocean surface currents;
8. Global Navigation Satellite System radio occultations;
9. Microwave and infrared-laser occultations; and
10. Global Navigation Satellite System scatterometry.

Technological innovations were also discussed in the First Report and elsewhere in this report.

The proposed evaluation framework is an adaptation of that given in the Framework for Ocean Observing, simplified and adjusted for application to potential Backbone contributions (a Backbone readiness level). Preliminary assessments are provided for the emerging technologies discussed in the report, together with an assessment of the Technical Readiness Level.

The report acknowledges that further work is required to ensure the framework can be applied in a consistent manner (e.g., improved documentation) and to determine whether it will meet stakeholder/TPOS sponsor needs. The assessments also need to be extended to cover other potential technologies (***Action 9.1***).

The report emphasizes that such a framework only provides guidance, and decisions on adoption of new techniques and technology will need to consider other factors, such as roadblocks to/assistance for user uptake, availability of suitable data management facilities, and of course cost and effectiveness. Likewise, the relative impact of potential technologies must factor in actual and prospective model and assimilation sensitivity.

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[3] Saildrone and Wave Glider are trademark names; hereafter referred to without ®

Recommendation 9.1. That the Backbone Readiness Level framework be further developed and refined by TPOS 2020 before adoption. [9.4]

Next Steps

The work of implementing the new observing system for the next decades is just gaining momentum. Although the TPOS 2020 project will finish at the end of that year with a final report, much of the implementation of the changes proposed here will just be getting under way. We note the need for additional investment in order to move from where TPOS is today toward the full implementation of this plan [10]. Results of piloting new technology discussed in Chapter 9, and the process studies in Chapters 2 and 3 and in 7.4.6, will become clear over the next few years; these will need evaluation to determine their lessons and readiness for the Backbone.

The actions and recommendations of this report already point to substantive issues that will need to be included in the Final Report. More will emerge as TPOS 2020 stakeholders and the TPOS 2020 Resource Forum consider the implications from this report.

As the system evolves, maintenance of the climate record will be an essential consideration. Coordination of the interlocking networks will require regular consultation among the implementing partners.

For all these reasons, the need for appropriate governance, and for scientific advice, will continue past this project's sunset; the mechanisms for these are under discussion with our sponsors (TPOS OceanObs'19) and among the international organizations that set the framework for observing systems such as the TPOS (***Action 10.1***).

Chapter 1 Introduction and Background

Authors: Neville Smith, Billy Kessler

This Second Report of the Tropical Pacific Observing System 2020 Project (TPOS 2020) builds on the analysis and conclusions of the First Report (Cravatte et al., 2016; hereafter referred to as the First Report) and provides further elaboration of the recommendations and actions contained within the First Report. Additional detail and recommendations in areas not covered in the initial report are provided, while at the same time reappraising the initial recommendations and actions, informed by new evidence and/or fresh perspectives on priorities.

The Second Report does not cover all aspects of interest to TPOS 2020, most of which have been covered adequately in the First Report; rather, it is an update of the evolving design, drawing on new research and evidence as appropriate and responding to gaps identified by the sponsors of the Project. The topics were guided by the priorities of the TPOS 2020 sponsors rather than a desire for a comprehensive and complete account of the TPOS[4] and it relies heavily on the First Report and on white papers produced in the initial TPOS 2020 review (Global Climate Observing System (GCOS), 2014a, b). This report also benefits from the community white paper process initiated for OceanObs'19 and several of those papers are cited through this report.

The overarching rationale for a TPOS remains the societal and economic benefit engendered by the data flowing from the system. As highlighted in Chapter 2 of the First Report, the benefits of the TPOS manifest over multiple sectors for nations of the tropical Pacific Ocean and for regions remote from the tropical Pacific, primarily in the form of increasingly sophisticated and detailed climate outlooks and forecasts. Detection of climate change, and its consequences, also remains an important motivator.

Sustained, systematic coordinated observation of the tropical Pacific Ocean has been an international priority since the 1980s, driven by the global climate effects of the El Niño/Southern Oscillation (ENSO), and by the promised, and now demonstrated prediction skill in forecasting ENSO derived from ocean and air-sea interface observations (Chapter 2). TPOS has served the community well, in part because of a strong design, initially set down in the early 1980s (McPhaden et al., 1998) and continues to deliver measurements that advance our capability to describe, understand and predict ENSO and climate variability more generally (McPhaden et al., 2010).

The TPOS suffered several setbacks during the period 2012–2014 when support for the Pacific tropical moored buoy array (TMA) was reduced, leading to inferior data returns from the Tropical Ocean-Atmosphere (TAO) array (around 40% compared with the usual 80–90%; see Figure 1-1 in the First Report) and, in the western Pacific, a phased decommissioning of around thirteen sites of the TRITON (Triangle Trans-Ocean Buoy Network) moorings. The central and

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[4] As in the First Report, we use “TPOS” alone when we are referring to the observing system and “TPOS 2020” when we are referring to the Project and its recommendations and actions.

eastern Pacific data returns were back to normal by 2015, but there are now only two of the original TRITON sites west of 165°E. The TPOS 2020 Project was initiated to address these issues and to provide an updated design, taking account of science and technological developments since the initial design, as well as the more complex and demanding user requirements of today.

The First Report of the Tropical Pacific Observing System 2020 Project provided an enhanced redesign of the international tropical Pacific Ocean observing system (see tpos2020.org) for further background and detail on the Project). The Report included background on the social and economic drivers for TPOS and on key scientific considerations. The revised design takes advantage of developments in both satellite and in situ technologies, including multiple remote sensing options for wind, sea surface elevation, sea surface temperature (SST), salinity (SSS) and ocean color, the global array of profiling floats (Argo; temperature, salinity and biogeochemical properties) and advances in mooring, autonomous, and other in situ technology. The First Report embraced new strategies and priorities in a user-driven design, using the essential variable focus of the Framework for Ocean Observing (FOO; Lindstrom et al., 2012; Tanhua et al., 2019a). It also advocates for an integrated, multi-faceted approach in which in situ systems and remote sensing are mutually supportive, exploiting the individual strengths of observing system options.

TPOS OceanObs'19 reviews the approach and underlying rationale of the First Report and discusses the status and future plans for TPOS. This Second Report, first, provides additional background and elaboration of requirements for aspects of the TPOS that were not covered previously. The topics include the state of modeling and data assimilation for seasonal-to-interannual prediction systems (Chapter 2); potential implications from coupled weather and subseasonal applications (Chapter 3); and a chapter on TPOS data flow and access (Chapter 8). Next, in response to priorities identified by TPOS 2020 sponsors, the Second Report provides further discussion of requirements for biogeochemical and ecosystem observations (Chapter 4) and for the eastern Pacific (Chapter 5). Unlike the western Pacific where the potential for strengthening and enhancing the observing system is strong, progress in the eastern Pacific has been more challenging (TPOS OceanObs'19). Chapter 5 discusses options to overcome some of these challenges and develop a brighter future.

Chapter 6 provides further scientific analysis of the rationale and requirements for the TPOS 2020 Backbone (the fundamental, core, routine and sustained observing system), in part in response to feedback on the First Report, and updates the scientific basis. Chapter 7 provides further detail and elaboration of the Backbone for 2020 and beyond in the light of recent progress and new evidence provided in the preceding chapters and, as appropriate provides revised and/or new recommendations and actions. As with the First Report, we generally do not provide detailed costings for recommendations and actions, but we do factor-in feasibility and practicality, which include cost implicitly. Such detail is important for TPOS stakeholders and will be developed, as appropriate, during implementation, noting that there are significant regional and agency dependencies; the Report's focus is on scientifically based requirements and prioritized observing strategies.

Finally, again in response to urging from TPOS 2020 sponsors, Chapter 9 discusses the current state of emerging technologies and provides an evaluation mechanism to guide integration of new observation platforms into the TPOS.

Chapter 2 The Current State of Coupled Models for Subseasonal to Interannual Predictions

Authors: Arun Kumar, Neville Smith, Yosuke Fujii, William Large

2.1 Background

In establishing the TPOS 2020 Project, ENSO prediction was set as one of the three primary goals, yet the models and data assimilation (DA) systems that underpin most subseasonal to seasonal and interannual prediction (S2IP) systems have biases and systematic errors (see section 2.5 and references therein) that compromise their ability to fully utilize the TPOS. In response, the TPOS 2020 project focuses attention toward addressing the following three questions that were raised during the discussion in the 4th TPOS 2020 Steering Committee (SC-4):

1. How well do coupled S2IP models simulate reality?
2. How well do model and data assimilation systems integrate observations?
3. How well do coupled S2IP systems perform, and what is the respective contribution of observations in that performance?

Though these questions are not independent and their scope may overlap, they did provide the initial impetus for investing effort in this chapter and provided a convenient backdrop for framing the discussion (see section 2.8).This chapter summarizes the current state of the operational infrastructure for S2IP predictions (for example, the typical model resolutions that are currently used; data assimilation systems for atmosphere and ocean). A summary of the general performance of SST predictions in the tropical Pacific (particularly in the context of ENSO) is also given (sections 2.2 and 2.3).

To understand (a) the development process of S2IP prediction models and (b) observational needs of the S2IP community to initialize predictions, to verify forecasts and to identify model biases, a questionnaire was sent to S2IP operational prediction centers. Responses to the questionnaire helped quantify the current landscape of model development practices (section 2.4). The questionnaire also helped formulate recommendations in the context of model development for better utilization of TPOS.

To reduce model biases and show how TPOS 2020 can contribute to that effort (leading to enhanced utilization of TPOS observations), it was also important to survey current techniques that are used for assessing model biases. The information about the current practices for diagnosing model biases can provide a basis for how TPOS 2020 recommendations can accelerate existing model diagnostic and development efforts. For example, if process level model diagnostics is a robust technique then TPOS 2020 can recommend connecting such efforts with suitable process studies (section 2.5). The questionnaire sent to operational S2IP centers also gathered input about community requirements for observational data to further support model development and evaluation (section 2.6).

Based on sections 2.2 through 2.6, we provide a list of outstanding issues and potential impediments for improving models for S2IP predictions (section 2.7). Recommendations for

TPOS 2020 to further support current practices on model development are then put forward (section 2.8). The reader is also referred to Chapter 3, which examines observational requirements for coupled weather and subseasonal prediction and thus has some overlap with the discussion presented here.

2.2 A review of models for S2IP, their characteristics and supporting structures

The current operational infrastructure for S2IP is a robust landscape and currently is made of two independent streams—one for interannual predictions and one for subseasonal predictions. Historically, spurred by the Tropical Ocean-Global Atmosphere programme (TOGA) and development of the ocean observing system in the equatorial tropical Pacific, the operational systems for interannual prediction systems emerged first. The earliest examples of operational interannual prediction systems based on dynamical coupled ocean-atmosphere models were established in 1994 (Ji et al., 1994; Stockdale et al., 1998). These efforts were based on initialized predictions, and the prediction infrastructure also included ocean DA systems utilizing real-time data streams from TPOS. Since their advent 20 years ago, the landscape of interannual prediction systems evolved quickly and has now been formalized under the World Meteorological Organization (WMO) Global Data-Processing and Forecasting Systems (GDPFS) and includes Global Producing Centers for Long-Range Forecast (GPCs-LRF) and a Lead Center for Long-Range Forecasts Multi-Model Ensembles (LC-LRFMME) (Graham et al., 2011). At present there are 13 WMO recognized GPCs-LRF and 11 of them provide interannual predictions on a monthly basis using dynamical coupled prediction systems (see https://www.wmolc.org/).

The typical resolution of the current generation of operational interannual prediction systems is about 100 km for the atmosphere and 50 km for the ocean, with highest resolution of 35 km for the atmosphere and 25 km for the ocean at the European Centre for Medium-Range Weather Forecasts (ECMWF). The coupled forecast system infrastructure also includes ocean data assimilation systems that are generally uncoupled stand-alone systems. Research and developmental efforts are currently underway toward coupled data assimilation systems (World Meteorological Organization World Weather Research Program, 2017). The ocean data assimilation systems rely critically on TPOS (in situ and remote) to provide an estimate of the current state of the ocean in the equatorial Pacific, which is essential for making skillful initialized predictions of SST variability associated with ENSO.

The advent of operational subseasonal prediction systems followed the development of operational interannual predictions. Although not yet formalized under the WMO's GDPFS, the operational infrastructure for the subseasonal prediction effort is also robust, with more than 10 centers providing routine predictions on sub-monthly frequency. The development of subseasonal prediction systems is currently under the purview of the research component of the WMO, for example, the joint World Weather Research Program (WWRP) and World Climate Research Program (WCRP) Subseasonal-to-Seasonal (S2S) Prediction Project (http://s2sprediction.net/).

The number of coupled prediction systems participating in the S2S Project outnumber the atmosphere-only prediction systems, and the typical resolution of atmospheric and ocean prediction systems is similar to their interannual counterparts. Given the shorter lead-time for S2S predictions, and the fact that the sources of predictability also reside in the atmosphere and land initial conditions, additional focus, beyond oceans, is devoted to initializing these components of the prediction system. (For a discussion of the requirements of observations for subseasonal prediction refer to Chapter 3.)

2.3 Model performance for prediction and applications

The operational S2IP systems go through comprehensive assessments of their forecast quality. Such skill assessments are based both on reforecasts (that are available for each S2IP system) and real-time predictions. For oceanic variability, because of the influence of slowly evolving oceanic conditions on atmospheric and terrestrial climate, most skill assessments are for interannual prediction systems and focus is on the assessment of skill in predicting monthly or seasonal mean SSTs. The skill in predicting SSTs generally has a large spatial and seasonal variability. The skill is highest in the equatorial tropical Pacific and during the months of boreal winter, for example, December-January-February (Figure 2.1). This variability in skill is a feature associated with the spatial and temporal variability of ENSO. Results from skill assessment indicate that since their advent 20 years ago, dynamical coupled prediction systems have shown considerable improvements and have demonstrable high skill during the mature phase of ENSO. Levels of skill for SST prediction at higher latitudes and in other ocean basins is generally lower.

Despite high skill levels when assessed over a long period in predicting ENSO SSTs, the performance of interannual prediction models has sometimes been deficient even during the last decade. One example was the confident predictions for a 2012/2013 El Niño issued as late as September 2012, when in fact cooler than normal equatorial Pacific temperatures (not quite reaching the threshold for La Niña) were realized in December-January-February 2012/2013. It has also been documented that ENSO prediction became more challenging in the first decade or so of the twentieth century during which ENSO variability was weaker (Wang et al., 2010; Barnston et al., 2012) compared to its historical level. This may be due to low-frequency variability in the characteristics of ENSO with some ENSO regimes having higher predictability than others. A change in the characteristics of ENSO in the recent period has been noted with an increase in interannual SST variability in the central Pacific (associated with the so-called Central Pacific El Niño) (Lee and McPhaden, 2010; Capotondi et al. 2015b). Further, it has also been noted that the lead-lag relationship between warm water volume and SST variability in NINO3.4 region weakened in the recent period (McPhaden, 2012).

With ongoing efforts in improving models and reducing model errors and biases, an outstanding question persists: how much improvement in skill of SSTs remains to be realized? Model biases can influence prediction skill in multiple ways. SSTs are the primary forcing influence on atmospheric and terrestrial variability leading to skillful seasonal predictions for the benefit of society, and it is important that biases in SST predictions are reduced. As numerical ocean models are a core component of ocean data assimilation systems, initial model drift at the early stages of a forecast can reduce the efficacy of the use of TPOS during the assimilation cycle. Although observations can be employed to correct for such developing model biases (including shocks caused by imperfect initialization), systematic errors may remain if, for example, the biases are state dependent and thus not corrected by removing the mean drift (Hermanson et al., 2018).

In the presence of large model bias (resulting in drift during the early stages of the forecast), the primary contribution of observations is correcting for biases in the initial guess. Further, even if the initial analysis is constrained to follow observations, at the start of the forecast, the assimilated information can be easily lost because of initial shock, a phenomenon whereby the model forecast moves rapidly toward its preferred mean state and does not retain the influence of observations in the initial analysis. For this reason, along with developing recommendations for the future design of the TPOS, it is also essential to complement it by efforts to reduce model biases. TPOS 2020 needs better understanding of the model development process currently in place to facilitate model development efforts, particularly for S2IP systems.

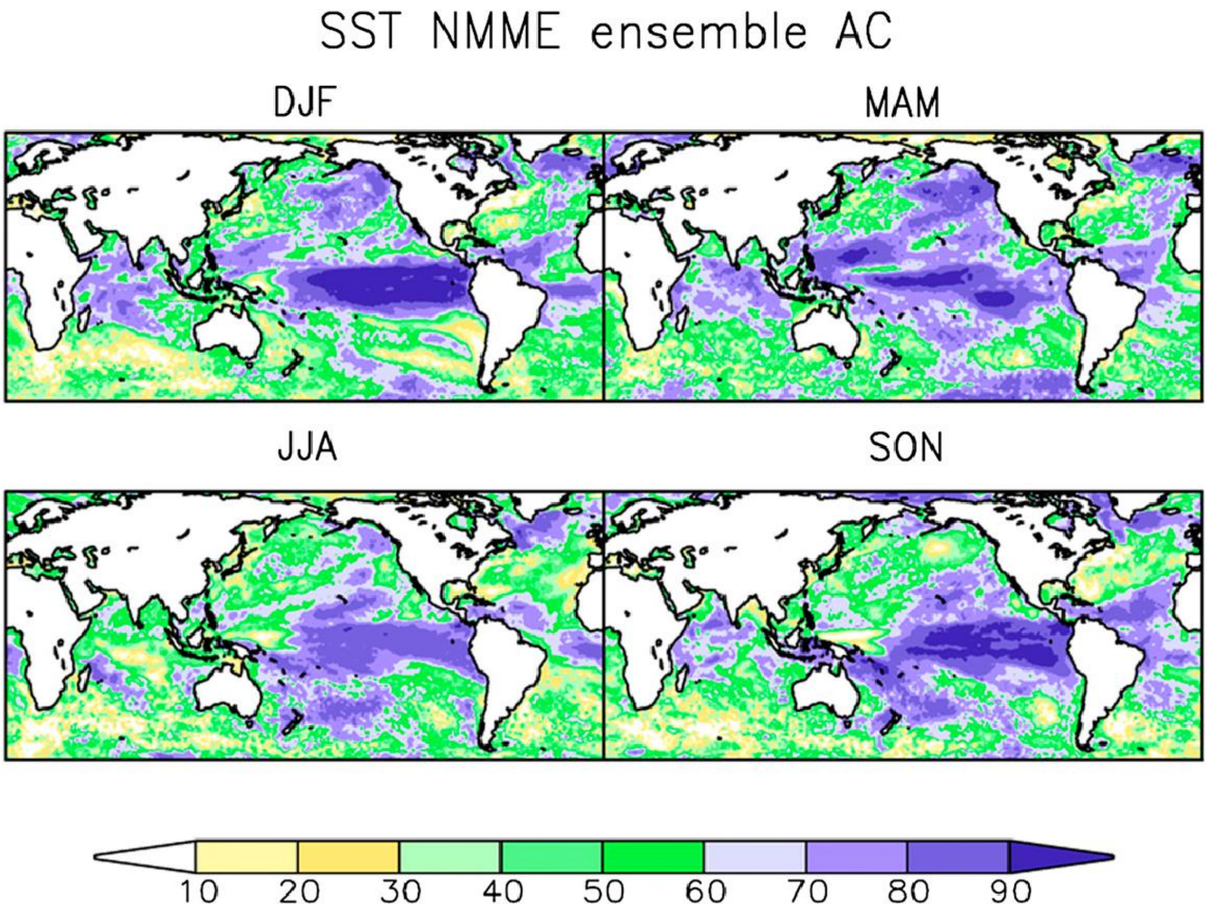

Figure 2.1: Forecast skill measured by the anomaly correlation (in %) for NMME (North American Multi-Model Ensemble) 7-model ensemble prediction of 2 m temperature (Becker et al., 2014). Four seasons are shown at 1-month lead: DJF, MAM, JJA, and SON. Autocorrelations are multiplied by 100.

2.4 A survey of the current state of model development process and tuning

How TPOS 2020, and its recommendations, can fit into efforts to reduce errors and biases on S2IP systems will depend on which model development practices are currently followed at operational centers. To better understand the model development process, a questionnaire was sent to the operational S2IP centers. The primary focus of the questionnaire was to gather information about:

- What is the origin of the component models in the S2IP systems?
- What observational data are used for S2IP model validation and evaluation?
- What are the S2IP specific model developments efforts, including model tuning?
- Are there specific observational data that S2IP centers wished they had?

At most of operational centers engaged in S2IP, the atmospheric component of the S2IP system was the weather prediction model used at the center. For the ocean component, the tendency was to rely on community ocean model development efforts, for example, NEMO (Nucleus for European Modelling of the Ocean) or MOM (Modular Ocean Model). The development of S2IP systems thus is a heavily leveraged effort and relies on ongoing model development efforts that may focus on other timescales.

Once the S2IP systems were put together, tuning efforts are made to reduce biases in prediction of SSTs and to improve the simulations of modes of variability that render predictability on this timescale—ENSO, Madden Julian Oscillation (MJO), etc. It is noted that the tuning process is specific to a particular bias metric and may not improve the overall performance of the prediction system.

As the operational implementation of S2IP systems requires an extensive set of reforecasts to accompany real-time predictions, the update cycle of S2IP systems is about once in five years. In summary, the responses to the questionnaire provided the messaging that model development effort focusing on S2IP timescales is not a norm and leverages efforts that focus either on improving weather predictions or climate change simulations.

For purposes of model validation and forecast evaluations, ocean and atmospheric reanalysis products are preferred. Their ease of use for the purposes of model evaluation is the primary contributing factor for their uptake over the raw observations. It was also noted that model biases tend to be large scale in nature and can be readily discerned when compared against reanalysis products. The current practice of using reanalysis data for model validation and evaluation makes validating the reanalyses for consistency with high quality direct observations a critical function of the observing system. Use of in situ observational data was judged to be more suitable for a process-oriented approach for model evaluation, however, because of the extensive requirements this approach places on model data, it has not been adapted widely in the understanding of model biases and tuning (Maloney et al., 2019). It is also noted that based on the responses to the questionnaire, specific requirements for observational data in support of the development of S2IP prediction systems were hard to discern.

2.5 Techniques for assessing model biases and performance

Systematic errors in coupled models are an endemic problem and have been the subject of many papers and fora (e.g., Bellenger et al., 2014; Richter, 2015; Flato et al., 2013; Zadra et al., 2018). A majority of these studies draw on the Coupled Model Intercomparison Project (CMIP, e.g., Taylor et al., 2012). While several of the seasonal prediction systems are from coupled models from the CMIP family, many have significant differences in configuration so that the bias and consequent impacts on performance can be different.

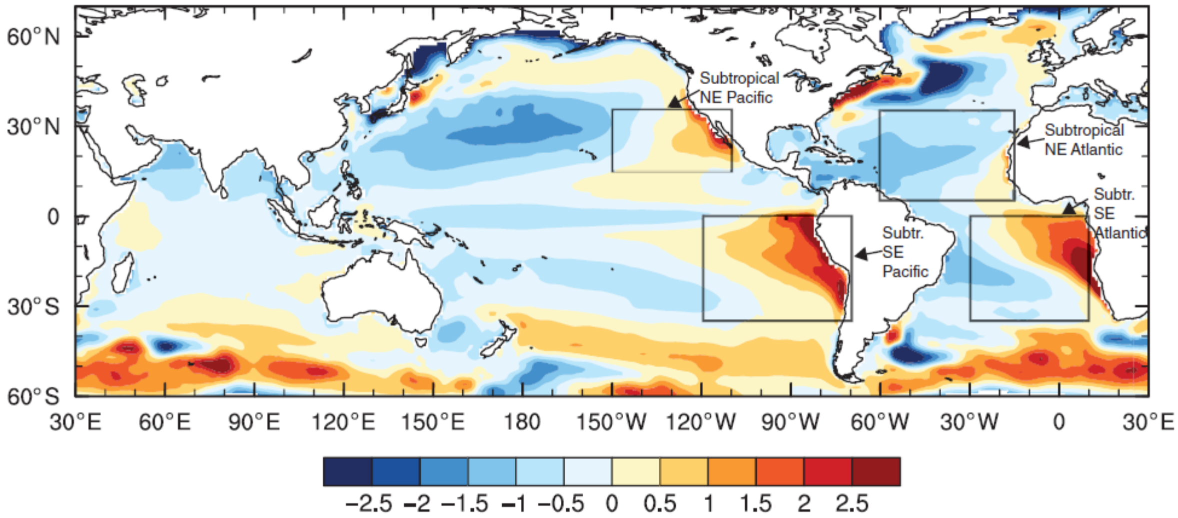

Figure 2.2: Annual mean SST bias of a CMIP5 ensemble relative to observations (from Richter, 2015).

Figure 2.2 shows the SST in CMIP5 models compared to observations; the bias in the southeast and northeast Pacific is large (due to an underestimation of stratocumulus) and there is a cool equatorial bias in the central and western Pacific. Figure 2.3 (from Bellenger et al., 2014) shows that the cold bias in the western equatorial Pacific is reduced by roughly one third in CMIP5 compared with CMIP3, but the envelope of the simulations remains outside the observed temperature. The SST bias in the east did not improve although its zonal gradient improved. Improvements in zonal wind stress are also noted.

Bellenger et al. (2014) also devised a normalized "score" for each CMIP5 model in terms of characteristics of ENSO variability (Figure 2.4, top) and against their representation of key processes (Figure 2.4, bottom). The models score reasonably well on ENSO variability but poorly with respect to key basic processes, suggesting the 'stretch' to represent ENSO came at the cost of realism and compensating errors may be at play. No such comprehensive studies are available that provide an overview for the current generation of seasonal prediction models.

Noting that the equatorial Pacific adjusts on relatively rapid timescales (1–3 months), one can easily appreciate that a biased model initialized with observations will generate significant perturbations once it is free to evolve toward its natural state, a feature often referred to as initial shock. It is also noted that due to initial shock the transition to model biases (inferred from climate simulations, e.g., CMIP) may not follow a quasi-linear pathway, and therefore, it is also important to analyze the evolution of biases in initialized predictions.

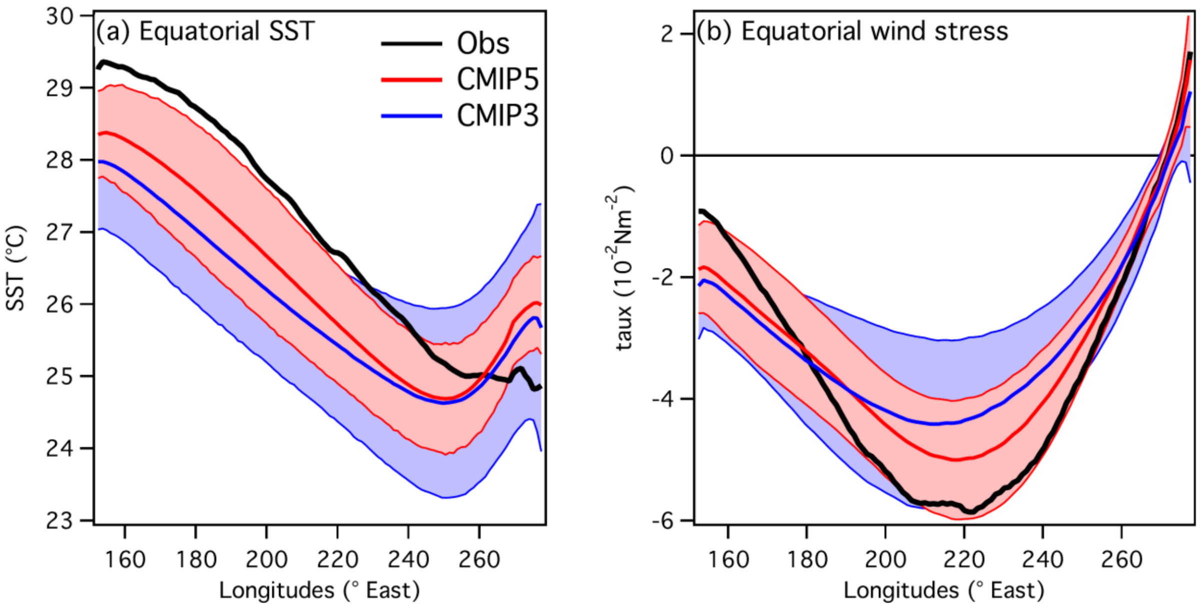

Figure 2.3: Average SST and zonal surface wind stress at the equator from CMIP3 and CMIP5 models compared with observations (from Bellenger et al., 2014).

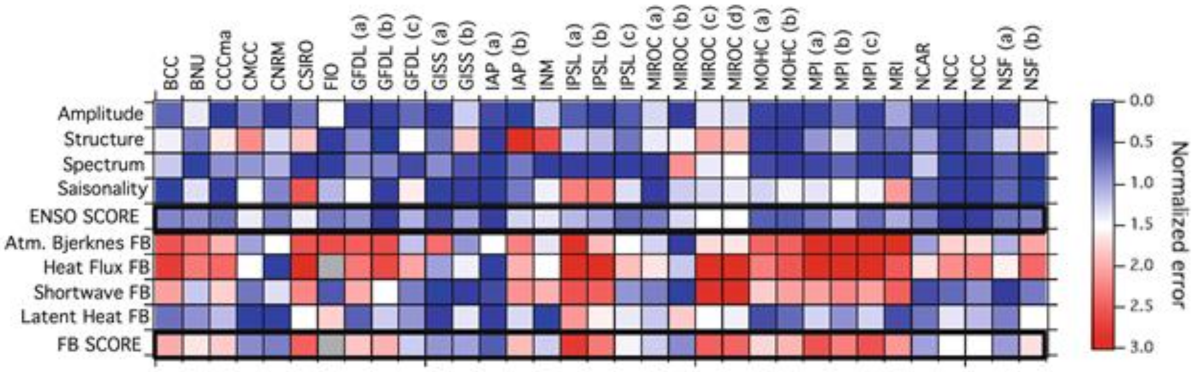

Figure 2.4: Bellenger et al. (2014) devised a normalize "score" for each CMIP 5 model based on the ability to capture key characteristics of ENSO (top half of figure). The bottom half represents scores against key processes.

These same biases and errors are present in seasonal prediction models but CMIP5-style protocols for systematic comparisons (including an agreed upon set of validation metrics and analysis procedures, e.g., Goddard et al. (2013) for decadal predictions) are not in place for their documentation. Individually, most centers do generate statistics around the mean drift in short-range forecasts. Figure 2.5 shows the one-month lead-time drift for two of the operational seasonal prediction systems. The spatial structure for SST biases are quite different, but significant, in both cases. For the actual forecast these systems subtract out such drift.

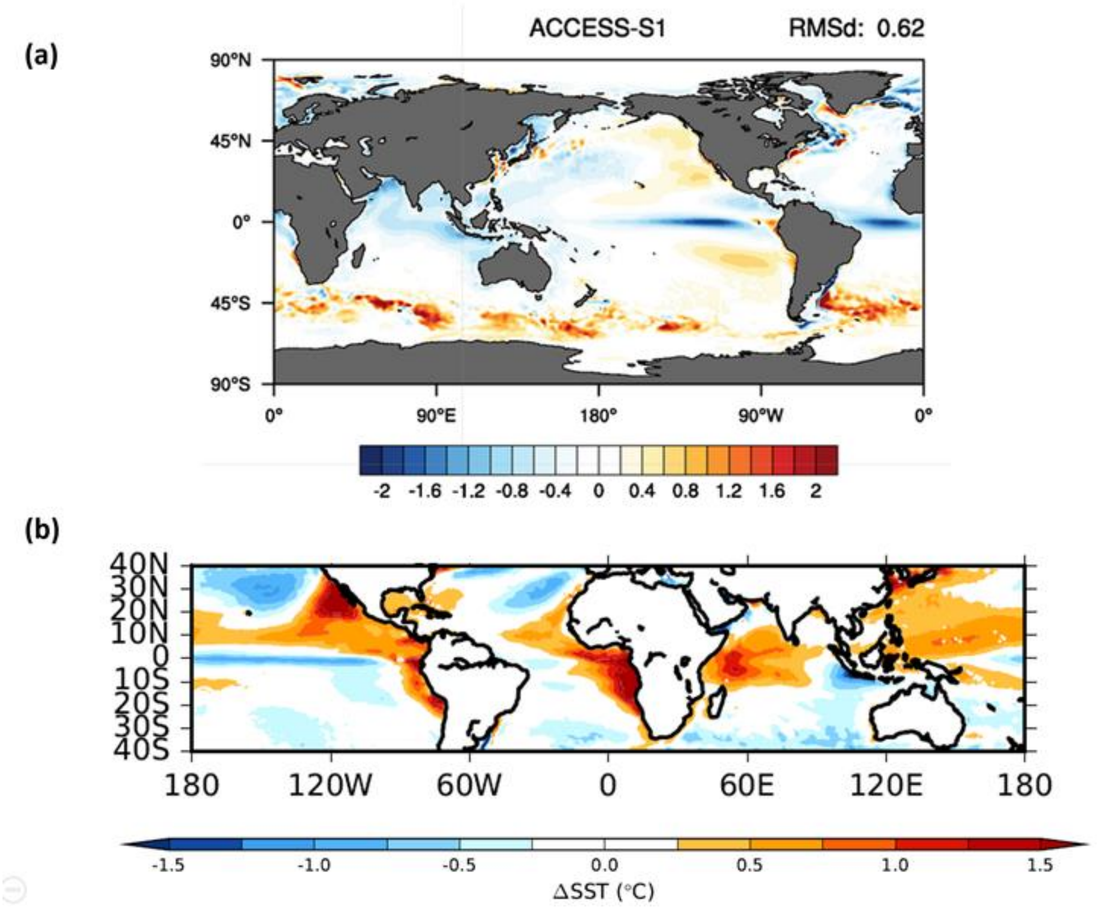

Figure 2.5: (a) Bias in the ensemble 3-month mean SST climatology (°C) of the new Bureau of Meteorology ACCESS-S1 model (Hudson et al., 2017), and (b) for June-July-August in the new ECMWF SEAS5 model (Johnson et al., 2019). Biases are at 1-month lead time forecast. For ACCESS-S1 SST bias is computed relative to the Reynolds OI v2 SST analysis; for SEAS5 the bias is relative to the latest generation of the ECMWF ocean analysis–ORAS5.

Seasonal prediction systems have developed techniques to post-process (or bias-correct) real-time predictions in the presence of systematic errors. The demonstrably significant and useful prediction skill forms the basis of successful implementation of operational infrastructure. However, unlike for the CMIP5 analysis, there are no standard diagnostics for a systematic comparison of models, and no agreed set of experiments to inform improving models. It is not uncommon for a model upgrade to be benchmarked against its predecessor rather than a more universal standard. It is generally assumed that systematic differences in prediction systems represent errors in the representation of physical processes, but internal variability (e.g., decadal changes in the character of ENSO; Wittenberg, 2009; Jeong et al., 2014; Wittenberg et al., 2014) and observational uncertainty may also play a role in quantifying their states. A systematic documentation of biases across operational seasonal prediction systems performed periodically would be an important aspect in documenting their evolution and benchmarking their performance.

Several groups are examining frameworks that would yield more systematic methods of diagnostics for the onset and evolution of model biases. For example, the Model Diagnostics Task Force[5] is leading an effort to develop a framework for process-oriented evaluation of climate and weather forecasting models (Maloney et al., 2019). US CLIVAR[6] convened a workshop "Bridging Sustained Observations & Data Assimilation for TPOS 2020" (Karnauskas and Kessler, 2019), which examined these issues, among others. The workshop noted that the direction for diagnosing reasons for model biases remains unclear and an extremely difficult endeavor, clouded by coupling of biases across different processes and across spatial and temporal timescales. The reasons for biases are often non-local and lack appropriate methodologies for their understanding. Others have also examined reasons for low prediction skill and have posited that it may be due to model errors inhibiting the realization of inherent predictability. Figure 2.6 (I. Richter, personal communication) shows this schematically with model error (bias) shown as the most significant factor contributing to lost skill. Richter also conjectured that in some regions (e.g., the tropical Atlantic) the unpredictable noise may be a more significant factor compared to the influence of model biases (Kumar et al., 2015; Richter et al., 2018).

There is also significant diversity in the data assimilation systems used by the operational seasonal prediction systems, and in theory, they too may be a source of error in the realization of predictability. At this time, no group is using high-end 4D-variational data assimilation (4D-Var) for global ocean data assimilation in operations, due primarily to the high computational cost. The National Oceanic and Atmospheric Adminstration’s (NOAA’s) National Centers for Environmental Prediction (NCEP) is currently transitioning to a hybrid ensemble Kalman filter (EnKF) / 3D-Var method. The US Navy uses 4D-Var for regional applications. The Japan Meteorological Agency (JMA) plans to introduce a 4D-Var global ocean data assimilation system for operational seasonal forecasts from 2021. Some groups are exploring coupled data assimilation for all prediction timescales. TPOS 2020 contends that until there are significant improvements in the model-based first-guess, i.e., reduction in biases present in the forecast model, improvements in the quality of analyses and initial conditions will remain problematic.

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[5] NOAA’s Model Diagnostic Task Force https://cpo.noaa.gov/Meet-the-Divisions/Earth-System-Science-and-Modeling/MAPP/MAPP-Task-Forces/Model-Diagnostics-Task-Force

[6] United States Climate Variability and Predicability Program, https://usclivar.org/

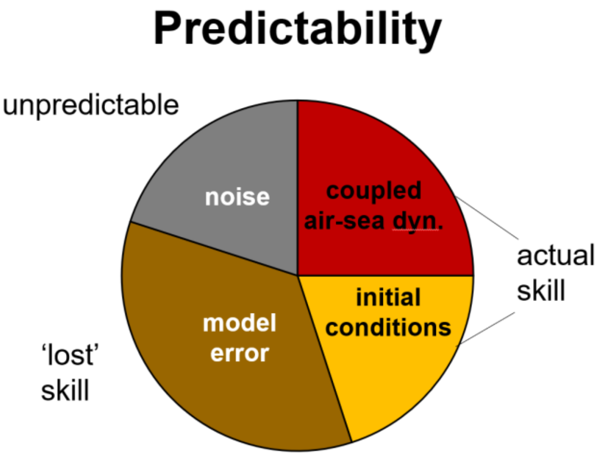

Figure 2.6: Schematic from I. Richter (personal communication) depicting factors that influence predictability and prediction skills. Observed variability (the entire pie) is comprised of an unpredictable component (noise; gray) and a predictable component that is related to the skillful prediction of coupled modes (red) and memory of initial conditions (yellow). Some of the predictability in the observed system is not realized due to model errors (brown).

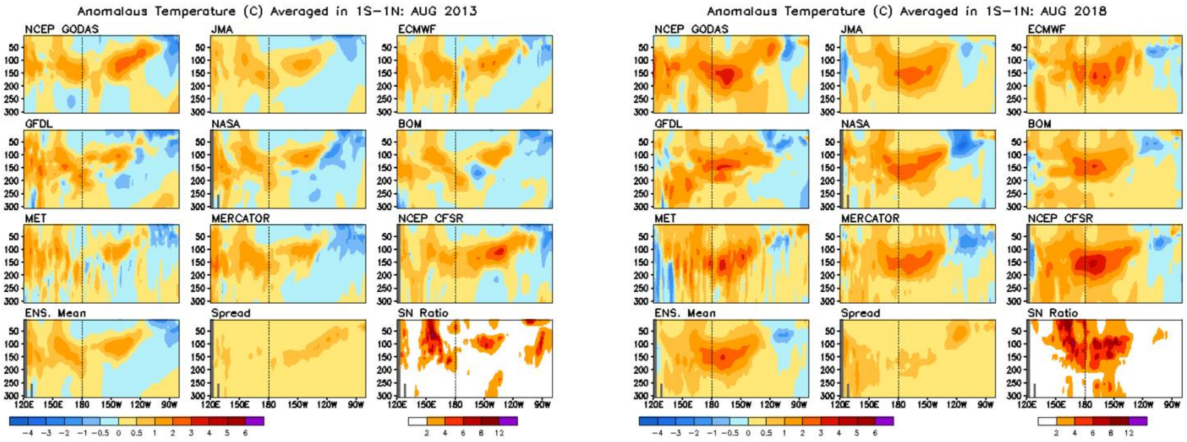

Figure 2.7: Anomalies of upper ocean temperature across the tropical Pacific from nine different analysis systems (from http://www.cpc.ncep.noaa.gov/products/GODAS/multiora93_body.html; see Xue et al., 2017a). The left panels are from August 2013, at the height of the TAO crisis, and the right panels are from August 2018. The anomaly for each analysis is with respect to its own 1993–2013 climatology.

Figure 2.7 shows some results from the Real Time Multiple Ocean Reanalysis Intercomparison project, a project that was instigated in the wake of the TPOS 2020 Workshop in 2014 (Xue et al., 2017a) with goals to provide routine comparison of ocean temperature analyses from different operational seasonal prediction systems. The input observational data to operational assimilation systems include TAO/TRITON, Argo, and (for the systems where sea surface height anomalies are assimilated) altimetry. In principle, given the level of observations currently available, analyses at the equator should be well constrained, however, at times significant differences are found. For the two examples illustrated in Figure 2.7, there is significant spread in the ocean temperature analyses for both months. The signal-to-noise was better in August 2018 than in 2013, except for some parts of the eastern Pacific.

It is not clear how much of the diversity among ocean analyses is due to model errors and how much is due to misrepresentation of errors in the data assimilation systems. Within the models, some errors originate from uncertainty in the specification of wind. Within the data assimilation systems, the specification of covariance models for temperature, salinity and ocean currents need improvement and will benefit from understanding of coupled covariances at the ocean/atmosphere boundary. From the experience gained from such projects it is clear that intercomparison projects are important and should be continued, however, by themselves they do not reveal much about the causes for discrepancies among analyses, and therefore, existing efforts are in critical need of enhancements, for example, as discussed in the Pilot 6.1.7 “Comparison of analyses and utilization of TPOS observations” (the First Report).

2.6 Ocean observations in support of model development and evaluation

As one of the respondents in the survey of the operational centers noted "Coupled model errors are large enough that errors in re-analyses don’t matter"; that is, for the type of model diagnoses and evaluations discussed above, the reference observational data set does not have to be of highest quality and resolution, implying that the existing observing system information is mostly adequate. However, for model development we often assume that more detailed and sophisticated data sets are needed, and it may be the case for more in-depth analysis of deficiencies in models. The TOGA and World Ocean Circulation Experiment (WOCE) experiments included several process studies that were used to improve understanding of processes and to develop models. For weather prediction, the complexity and capability of the present generation of models stretch the ability of data to test them (Zadra et al., 2018).

The TPOS design described in the First Report considered key processes (First Report, 3.3) and, to the extent possible, recommended a Backbone observational network that would support improved understanding of relevant process. The Report also outlined several process studies that would assist in guiding the evolution of the observing system and contribute to the improved understanding of processes and their representation in models.

The survey itself did not provide any clear direction in terms of additional observational data requirements for S2IP model development. Profiles through the ocean-atmosphere boundary layers and surface flux estimates were identified by several respondents. The "Bridging Sustained Observations & Data Assimilation for TPOS 2020" Workshop also considered this need but without clear conclusions. The Workshop did support two process studies, one focused on the eastern edge of the Pacific warm pool (section 7.4.6.3), and the other on Pacific upwelling and mixing (section 7.4.6.1; see the First Report for background information). The biases discussed in the previous section also drew attention to the eastern Pacific.

2.7 Outstanding issues

The TPOS 2020 Term of Reference to "observe and predict the state of ENSO and advance scientific understanding of its causes" continually brings back the issue of the skill, effectiveness and efficacy of the modeling systems that are the pathways to realize the impact of an improved TPOS. As discussed in section 2.5, it is not difficult to identify systematic errors, but taking the next step—translating that information into model developments that reduce biases—is extremely difficult and systematic approaches to find solutions are not in place.

The "Bridging Sustained Observations & Data Assimilation for TPOS 2020" Workshop (Karnauskas and Kessler, 2019) focused on the ocean aspects of the challenge of reducing model biases and included several relevant recommendations. There was strong support for process studies, particularly for the equatorial upwelling system in the central-eastern cold tongue (see section 7.4.6.1) and the complex of processes at the eastern edge of the warm pool (section 7.4.6.3). The first addresses a known deficiency in the way models represent coupling between the atmosphere and the ocean mixed layer and thermocline. The second addresses the difficulty of modeling the eastern front of the warm pool and the associated fresh pool. Salinity variability is an important factor in this region and presents a challenge for both modeling and data assimilation.

At this workshop, and subsequently in a break-out session on TPOS 2020 organized at the Subseasonal to Decadal Conference held in Boulder in September 2018 (https://www.wcrp-climate.org/s2s-s2d-2018-home), it was recognized that reducing model bias is an extremely hard problem. The CMIP process has certainly been effective for the climate change class of models but, as shown in Figure 2.3, some errors are proving hard to reduce. A promising avenue is being provided through the growth in coupled weather prediction (out to four weeks and longer; WMO World Weather Research Program, 2017) and associated coupled data assimilation systems (for discussion, see Penny et al., 2019 and section 7.2.1.1). There are indications that coupled data assimilation can improve the representation of surface fluxes. The numerical weather prediction (NWP) community has an outstanding record in model and data assimilation improvement (Bauer et al., 2015), with a discipline based on daily continuous testing by its user communities – the intolerance of forecast failure sharpens and focuses attention toward the key issues. It is likely the S2IP community will also benefit from the export of this discipline into subseasonal and seasonal timescales (many of the models covered by the survey already rely on developments in NWP), which in turn, may also benefit advancing NWP systems.

In Figure 2.8 TPOS 2020 outlines systematic and planned cycles of work, supported by regular assessment. The survey (section 2.4) suggested a cycle of five years might be appropriate, though there is neither an expectation nor a constraint that all operational centers be in sync with this cycle when updating their S2IP systems. The concept of periodic 5-year assessment of S2IP predictions systems will involve the following steps:

- PLAN: Develop a set of planned simulations, e.g., a protocol that include a coupled run and an ensemble of Atmospheric Model Intercomparison Project simulations;
- COMMIT: Operational centers commit to making simulations as part of their update cycle (that already includes an extensive set of hindcasts);
- EXECUTE: A period for centers to execute the work;
- PUBLISH: Data from model simulations are freely available to the community either via a repository or a cloud based platform; and
- ASSESS: On a periodic basis, e.g., five years, an assessment of the model biases and errors, and prediction skill is done.

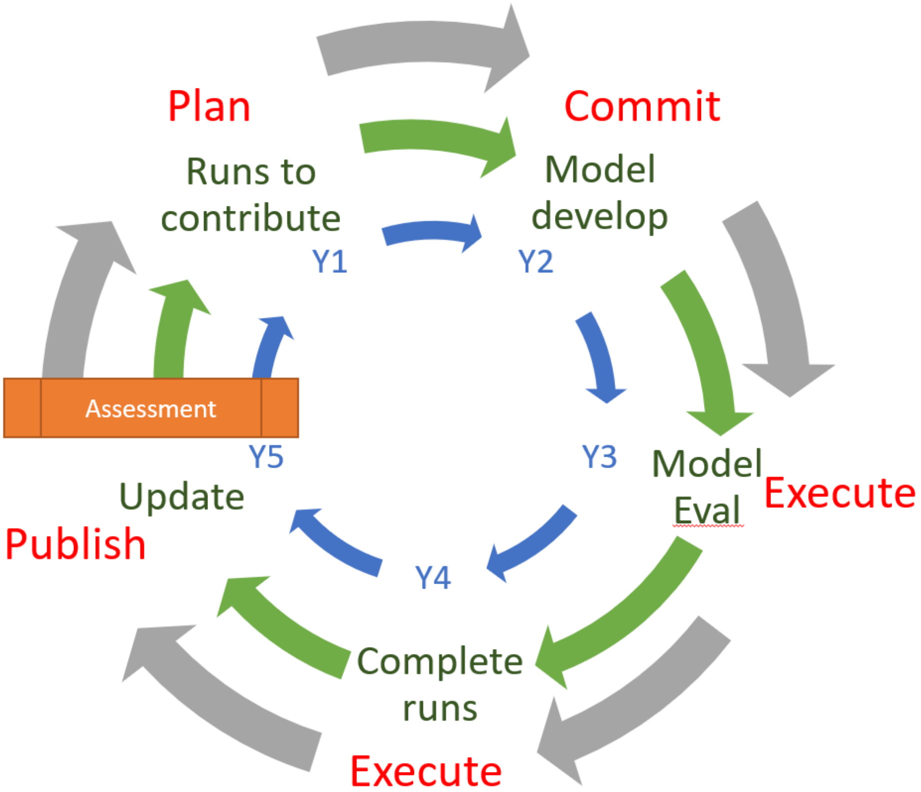

Figure 2.8: A schematic showing the three parallel cycles of activity needed for model and data assimilation improvement. The outer circle is a planned and systematic cycle of experimentation with an agreed protocol; the first 1-2 years are devoted to planning and commitment, while years 3 and 4 are devoted to execution. The middle circle is a more NWP-like cycle of process and/or case studies. The inner circle is the regular system evaluation, which is continuous through the cycle. An independent assessment would occur across all elements every five years.

The planned set of agreed experiments (three lines, in parallel) and the assessment cycle follows the example of CMIP; the planned experiments would be decided for their feasibility and impact and would seek commitment from centers to an agreed protocol to conduct the experiments (in addition to model hindcast and real-time forecast as part of the S2IP infrastructure). In parallel, there would be a series of process studies whereby observations and modeling would work together to yield improved understanding and flow-on benefits for model development (e.g., model and data assimilation parameterisations). Finally, there would be an agreed set of standard diagnostics (e.g., Bellenger et al., 2014; Xue et al., 2017a) and metrics that would highlight bias and systematic errors.

2.8 Recommendations and actions

In framing our goals for this 2nd report, we posed three questions:

1) How well do coupled S2IP models simulate reality (i.e., how close is their mean state to nature)?

- Results were outlined in section 2.3 with skill in predicting SSTs in the core region of El Niño variability generally high, although some notable failures in the prediction of some of the events also occurred in recent years.

2) How well do data assimilation systems integrate observations into the forecast models?

- This question has not been addressed explicitly. Section 2.5 (and Figure 2.7) showed analyses generally track observations closely but it is not clear whether this has a positive effect for forecasts. Given model biases in the equatorial Pacific, the efficacy of assimilation systems and the data's influence and impact on the subsequent forecast is likely to be reduced (Figure 2.6).
- A rapid onset of biases at 1-month lead-time points to imbalances in the initial conditions together with the contribution of model errors (e.g., errors in air-sea interaction and coupling or in the fast-physics components of the model).

3) How well do coupled S2IP systems perform, and what is the respective contribution of observations in that performance? To what extent do systematic errors mitigate against exploiting the potential predictability of the system?

- Section 2.3 suggests prediction systems have steadily improved and provide useful products.
- Operational predictions are a routine contribution to climate services and are being adopted for planning and decision-making purposes.
- Although systematic errors do impact performance and prediction skill, in some cases this impact may not be the dominating factor in realizing predictability which might be inherently limited by effects of unpredictable noise.

To advance the ongoing efforts in model diagnostics and assessment, and to promote the development process that would improve the utilization of TPOS observations, we provide the following recommendations and actions:

Recommendation 2.1. Establish a systematic and planned cycle of work among the participants in seasonal prediction, including (i) a planned and systematic cycle of experimentation; (ii) a coordinated set of process and/or case studies, and (iii) routine and regular real-time and offline system evaluation. An independent assessment should occur across all elements every five years.

- While seasonal prediction has made good progress over recent decades, the preceding sections highlighted the lack of a systematic approach to model improvement. A consequence for TPOS 2020 and beyond is the inefficient use of TPOS data and the consequent lost opportunities for prediction.
- Along with the routine hindcast and forecast operations of the operational S2IP systems, each center will be encouraged to do an agreed upon set of model simulations to facilitate a periodic assessment of the state of S2IP models using a standard set of validation metrics. This exercise will not require the operational centers to freeze their operational systems on a fixed schedule (as CMIP does).

Action 2.1. Further increase support for process studies to improve parameterization of specific processes that have larger than local impacts and whose representation in models is suspect. Although sustained observations are essential to support operational services, TPOS 2020 recognizes that investments in process studies will be critical for reducing model biases to enhance the efficacy of sustained observations.

The First Report highlighted several studies/projects that would contribute to improved modeling and data assimilation. Karnauskas and Kessler (2019) also drew similar conclusions. The NOAA Climate Variability Programme support of Pre-Field Modeling Studies in Support of TPOS Process Studies in 2018 is an excellent example of such support, but such work needs to be extended to other partners of TPOS 2020 (also see section 7.4.6).

Recommendation 2.2. Increase support for observing system sensitivity and simulation experiments to identify observations that constrain models most effectively and have high impact on forecasts. Correspondingly, development of infrastructure for exchanging information about data utilization and analysis increments should be supported.

- Both the First Report and Karnauskas and Kessler (2019) highlighted the need for such work, but also noted the challenges.
- Operational prediction centers, in addition to providing gridded analysis, should be encouraged to provide model based operational analysis output at selected *in situ* locations to facilitate direct routine comparison with observations.

Recommendation 2.3. Increase support for the validation and reprocessing of ocean and atmospheric reanalyses; conduct TPOS regional reanalyses and data reprocessing to guide observing system refinement and to enhance the value of TPOS data records.

- Such efforts are required, first to provide more credible and accurate data sets for model validations and diagnostics and, second, to improve models and data assimilation used for reanalysis.

Chapter 3 Coupled Weather and Subseasonal[7] Predictions

Authors: Yuhei Takaya, Harry Hendon, Yosuke Fujii, Neville Smith, Arun Kumar, Steve Penny, William Large

3.1 Introduction

The First Report alluded to the growing importance of coupled data assimilation and coupled models for weather, subseasonal and seasonal-to-interannual prediction, and to the potential for that to impact observing system requirements. While reference was made to subseasonal considerations in the First Report background of Chapters 2 and 3 that analysed requirements at the level of essential ocean variables (EOVs), there was no direct consideration of coupled weather and subseasonal prediction applications. Recommendations and Actions did capture more frequent sampling and improved spatial resolution but, again, without direct reference to these applications.

The key underlying assumption of this chapter is that the tropical Pacific Ocean is a source of both local and remote atmospheric predictability on weather timescales, and even more so on subseasonal timescales (National Research Council, 2010). In particular, the atmosphere responds to SST, so it is a prime prognostic field that depends on the evolving structure of the ocean below and the coupling with the atmosphere above. Therefore, greater understanding of ocean and atmosphere boundary layer processes across weather and subseasonal timescales and their coupling, and incorporation of this knowledge into operational coupled prediction systems through improved models and coupled data assimilation will lead to improved predictions.

In this chapter we consider observational needs for coupled weather and subseasonal prediction application in more detail, at the level of essential ocean variables that are relevant to air-sea interactions that drive SST variability, and where possible provide some guidance on how the Backbone may evolve in the future. The reader is referred to Chapter 2 for a discussion of coupled models used for operational prediction, some of which also covers subseasonal timescales.

The science around coupled weather and subseasonal prediction is advancing rapidly (Penny et al., 2017; National Academies of Sciences, Engineering, and Medicine, 2016; Subramanian et al., 2019; Penny et al., 2019) and this chapter refers to these publications extensively. The use of global coupled models in seamless systems that span short-range weather prediction to subseasonal and longer lead times is just now becoming standard (e.g., adopted by ECMWF in June 2018). Although improvement in some predicted fields has been conclusively demonstrated using coupled models for NWP (e.g., prediction of air temperature in the tropics, prediction of tropical cyclone intensity, prediction of the MJO; Buizza et al., 2018; Mogensen et al., 2018), the benefit of using a coupled model from day one for other metrics such as temperatures outside of

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[7] Usually defined as timescales from two weeks to a few months (a season).

the tropics, atmospheric winds and ocean surface waves is mixed. This may point to deficiencies in model physics or initial conditions that need to be diagnosed and rectified.

To set the scene, we first survey current operational modeling approaches, especially focusing on subseasonal to seasonal (S2S) systems as this is the perceived lead time for which coupled processes in the tropical Pacific will have the greatest impact on predictive skill. We also reference some of the findings of a Survey conducted by TPOS 2020 to support Chapter 2. We then review the key ocean and atmosphere processes of the tropical Pacific that underlie predictability, especially on the subseasonal timescale.

3.2 Survey of operational centers

A questionnaire was sent to operational centers engaged in subseasonal and interannual predictions to understand their model development strategies, their use of observational data for model diagnostics, their approach to model validation, and to identify any specific requirements for observational data (if gaps exist).

The current operational infrastructure for subseasonal predictions, although not fully established and defined in the standardized technical regulation of a WMO GDPFS manual (e.g., there are no standard performance metrics, forecasts are initialized on a variety of start days and use both lagged and burst ensembles), is well developed and 11 centers provide real-time predictions as part of the WWRP/WCRP S2S Prediction Project (http://s2sprediction.net/). The lack of coordination presents difficulties in the intercomparison of results, which is a key technique to gauge and promote forecast improvement. A US-led research project, SubX (http://cola.gmu.edu/kpegion/subx/) provides a resource for subseasonal prediction research in a more harmonized way in terms of experimental specifications including initial dates. The majority of S2S prediction systems for the subseasonal timescale (8 out of 11; https://confluence.ecmwf.int//display/S2S/Models) are based on coupled models. Some of the coupled prediction systems are derivatives of seasonal predictions systems (Chapter 2) while the uncoupled prediction systems are extensions of weather prediction systems. In general, the atmospheric component of the subseasonal prediction systems is the weather prediction model at the operational centers while the ocean component is based on community ocean model development efforts (e.g., four of the ocean models are NEMO based while three are based on MOM). Because of this dependence of component systems, in general, the model development efforts leverage the efforts devoted to improving weather prediction systems or improving the community ocean models and explicit model development strategies targeting subseasonal timescales are not apparent. This represents a challenge for developing TPOS 2020 specific recommendations for reducing model biases.

The horizontal resolution is typically not high enough to resolve the ocean eddies in the extratropics, however, there is a general tendency toward upgrading the ocean resolution of global S2S prediction models for better representation of sharp ocean fronts (e.g., in the Kuroshio and Gulf Stream regions). In addition, there is ongoing research and development of coupled regional weather prediction models, which may have higher ocean resolution (< 5 km). As for vertical resolution, a near-surface layer (~several meters) exhibits strong diurnal variability with a sharp vertical gradient. To represent the diurnal variability in the model, at least 1-m resolution near the surface is required, and some of the latest subseasonal prediction models have the required vertical resolution (Salisbury et al., 2018).

Regarding the use of observational data for model diagnostics and validation, the responses from the questionnaire indicated that identification of model biases generally relies on gridded reanalysis products (and primarily for the atmospheric component). MJOs being the dominant source of predictability on subseasonal timescales, efforts for process-oriented diagnostics also have been developed in conjunction with international groups such as the MJO Task Force[8] (Kim et al., 2014; Maloney et al., 2019). One unique aspect along the process-oriented diagnostics route has been the major community effort in field studies to improve understanding and simulation/prediction of the MJO (e.g., DYNAMO—Dynamics of Madden-Julian Observations[9]; YMC—Years of the Maritime Continent[10]; PISTON Field Campaign[11]). Such efforts provide an opportunity for TPOS 2020 to either link with future planned field studies or draw on the good practices developed as part of the earlier MJO studies to provide linkages between observationalists, modelers and diagnosticians during the planning phase of pilot studies proposed as part of TPOS 2020 (see 7.4.5 and 7.4.6).

In the context of specific observational data to fill gaps to improve the estimate of the initial state for predictions, diagnostics of model biases or particular phenomena (e.g., MJO), specific recommendations from the questionnaire were hard to identify (for further details, see Chapter 2), and may need to be developed through a broader community survey.

3.3 Model development, initialization and validation activities

The requirements on essential ocean and climate variables are discussed generally, in the context of improving our understanding of processes, model development and improving predictions. This is a first step toward determining which of these requirements should be considered in the context of the Backbone (Chapters 6 and 7) and whether there are any implications for the recommended responses.

3.3.1 Background on processes

The First Report provided some background on relevant processes in section 2.6 (for example, section 2.6.3 discussed the MJO). Several of the process studies in the First Report Chapter 6 also provided background on relevant processes (e.g., the low-latitude western boundary current study, section 6.1.1; air-sea flux estimation, section 6.1.4; intraseasonal variability and the northern edge of the warm pool).

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[8] MJO Task Force: http://www.wmo.int/pages/prog/arep/wwrp/new/MJO_Task_Force_index.html

[9] DYNAMO: https://www.eol.ucar.edu/field_projects/dynamo

[10] YMC – Years of Maritime Continent: https://www.pmel.noaa.gov/ymc/

[11] PISTON: https://onrpiston.colostate.edu/

A very important source of predictability for the S2S timescale is the MJO, in particular in the tropics, and some regions in the extratropics where the climate is affected by teleconnections modulated by the MJO. The MJO strongly interacts with the upper ocean across the warm pool, driving variations in mixed layer depth and temperature and forcing near surface current variations (Drushka et al., 2012). The air-sea interaction associated with the MJO results in SST anomalies of magnitude ~0.5 °C that have the same spatial scale as the MJO convective anomalies (~thousands of kilometers). These SST anomalies are of sufficient amplitude to impact the air-sea fluxes, and so feedback to the atmosphere (e.g., DeMott et al., 2015, 2016; Gao et al., 2019). The induced equatorial Kelvin wave current anomalies are also of sufficient amplitude to impact the evolution of the SST anomalies in the central Pacific during El Niño development (e.g., Kessler et al., 1995). The nature of intraseasonal air-sea interaction varies geographically. Vertical processes in the ocean, driven by both variations in surface heat flux and wind forcing, dominate most regions of the warm pool. However, horizontal processes driven by induced currents can be important such as at the edges of the warm pool. The vertical mixing processes are dominant in the western tropical Pacific and influence MJO variability (DeMott et al., 2015).

The MJO also acts to modulate the diurnal cycle of the ocean mixed layer/atmospheric boundary layer, with large amplitude diurnal variations developing during the suppressed phase of the MJO (Weller and Anderson, 1996). These variations are large enough to modulate surface fluxes, so affecting the atmosphere (Clayson and Bogdanoff, 2013) and are thought to play a role in the recharge of atmospheric moisture during the life cycle of the MJO (e.g., DeMott et al., 2015; Ruppert and Johnson, 2015). Daytime heating forms a diurnal thermocline and the accumulated heat is further mixed down to a deeper layer. These diurnal variations of SST place a strong demand on models because not only is high vertical resolution in the ocean model required (vertical grid spacing less than 1 m), but good boundary layer simulation is also required (Bernie et al., 2005). Although accurate representation of the diurnal mixing process remains a challenge for ocean modeling, increasing vertical resolution is gradually enabling models to reproduce these complex vertical mixing processes better (Salisbury et al., 2018; Bernie et al., 2005). Near-surface salinity also plays a key role in the evolution of the upper ocean over the lifecycle of MJO, with freshwater input acting to stabilize the near surface, thus inhibiting mixing of colder subsurface waters during the windy phases (Cronin and McPhaden, 2002).

3.3.2 Model development

Observations support development of S2S prediction models by enabling evaluation and validation across a hierarchy of models. Although it is not unique to the S2S challenge, model development usually undergoes a staged process using model hierarchies. Here we take ocean vertical mixing processes as an example to illustrate this approach. The staged development processes are divided into (1) one-dimensional or limited area modeling, which may employ Large Eddy Simulations or other high vertical resolution models, (2) ordinary resolution models with parameterizations to represent unresolved processes, and (3) regional and global modeling with and without atmosphere-ocean coupling. Observational data are used across several stages as a reference to evaluate model performance, but requirements can differ for each stage.

In the first development stage, evaluation of one-dimensional and limited area modeling requires frequent measurements (ten-minute sampling or better) with fine vertical resolution (better than 1 m near the surface) of essential variables (currents, temperature, salinity) and collocated heat, moisture, and momentum fluxes to force one-dimensional ocean mixed layer models. Other parameters like ocean surface wave and biogeochemical/ocean color measurements are also needed if these processes are considered. Previous process studies suggested that diurnal variability is a key aspect in air-sea interaction.

In the second development stage, regional and global models are used to test parameterization schemes developed in the first stage, or other processes (e.g., isopycnal eddy diffusion) that work in three-dimensional model simulations. In this stage, time series of essential and specific variables over days, at least in a certain region, are needed to perform model evaluations. Horizontal resolution required to simulate and evaluate ocean eddy variability is determined by ocean dynamics (Hallberg, 2013).

In the final stage, regional and global models represent three dimensional eddies to some extent, but fully resolving the ocean eddies is not achievable with operational computational resources currently available. Current global prediction models are partly capable of replicating ocean eddies and tropical instability waves (TIWs) with an increase of horizontal resolution to so-called *eddy permitting* resolution (~25 km; e.g., ECMWF SEAS5, Johnson et al., 2019; Met Office GloSea5, MacLachlan et al., 2015; Bureau of Meteorology ACCESS-S1, Hudson et al., 2017). This means these models are starting to represent, at least partially rather than just statistically, eddy-induced transports, which were formerly parameterized entirely with the Gent and McWilliams scheme (Gent and McWilliams, 1990) and its variants in lower resolution models. Tropical instability waves are reasonably represented in current global and regional models (Holmes and Thomas, 2015), and expected to alleviate a cold tongue bias and improve ENSO representation. To evaluate the simulation of eddy-induced transports (fluxes), ocean eddies should be sampled at high time frequency and high spatial resolution (approximately 10 km). As mentioned earlier, the evaluation usually relies on a gridded reanalysis provided by ocean analyses. Ideally, the resolution and frequency of sampling should be sufficient to constrain ocean states including mesoscale eddies in ocean data assimilation products.

3.3.3 Prediction

3.3.3.1 S2S prediction systems

As noted previously, many operational centers now have operational subseasonal prediction suites using atmosphere-ocean coupled models. Establishment of GPCs and multi-model ensemble lead centers for subseasonal prediction, which are a counterpart of those for seasonal (GPC-LRF) and annual to decadal predictions (GPC-ADCP), is under discussion. This means that the operational subseasonal prediction is now becoming mainstream.

Numerous studies have provided scientific rationales for the use of coupled models for S2S prediction (Subramanian et al., 2019 and references therein). Ocean coupling has positive impacts on the representation of the modes of the tropical variability. The MJO)Madden and Julian, 1971, 1972) and Boreal Summer Intraseasonal Oscillation (BSISO; Kikuchi and Wang, 2010; Kemball-Cook and Wang, 2001) are noteworthy examples. There is a growing consensus that ocean coupling enhances the predictive capability for MJO (DeMott et al., 2015; Vitart et al., 2007). The positive impacts of the ocean coupling on the MJO were reported by several operational coupled models (Woolnough et al., 2007; Shelly et al., 2014). The impacts on the BSISO was also investigated with a coupled model indicating non-negligible role of the ocean for the BSISO representation (Fu and Wang, 2004). Moreover, these Intraseasonal Oscillations (ISOs) have remote influence on the global climate through teleconnections and provide subseasonal predictability in the tropics as well as extra-tropics (Hendon et al., 2000). The ISOs also modulate extreme weather such as tropical cyclones (TCs) and extreme precipitation and temperature in the globe, indicating their relevance to global high-impact weather (Vitart et al., 2014b; Jones et al., 2004; Matsueda and Takaya, 2015). In weather prediction, ocean coupling has notable impacts on TCs, in particular, their intensity due to ocean cooling and ocean feedbacks to TCs (Mogensen et al., 2017). It is noted, however, that the current generation of models tend to under-represent the TC intensity because of their insufficient resolution, therefore, the current weather prediction models are not ready to draw full benefits of the ocean coupling by incorporating air-sea interaction processes associated with TCs (Mogensen et al., 2017).

Looking forward, many modeling centers have a strategy toward the seamless use of coupled prediction systems across all timescales (Met Office, 2015; ECMWF, 2016; National Centers for Environmental Prediction, 2015). Atmosphere-ocean coupled data assimilation is an emerging technology that has been under active research and development (e.g., Penny et al., 2019; section 7.2.1.1). These evolutions promise to advance the predictive capability on all timescales, and enhancements in the ocean observation will become more essential for operational weather and climate prediction in the near future.

3.3.3.2 Sensitivity to initial conditions

The potential of oceanic initial conditions to affect the forecast skill in coupled prediction systems is discussed in OceanObs’19 community white papers (Penny et al., 2019; Fujii et al., 2019). It is generally considered that the coupled weather and subseasonal predictions have some sensitivity to oceanic conditions through the processes discussed earlier, although it is not as large as for seasonal predictions. Marshall et al. (2016) showed that the record strength MJO event that developed in March 2015 was promoted by the unusual SST anomaly at the edge of the western Pacific warm pool, and without this anomaly in the initial condition the amplitude of the MJO was underpredicted by ~25%. Hence, accurate initialization of the upper ocean at the edge of the warm pool was critical for accurate prediction of the record amplifying MJO during March 2015. Upper ocean heat content is widely acknowledged to limit tropical cyclone intensity (e.g., Mogensen et al., 2017). Near-surface salinity anomalies in the western equatorial Pacific may also change the barrier layer (Lukas and Lindstrom, 1991), which affects the sensitivity of surface ocean currents to surface winds and may modulate the equatorial air-sea coupling (e.g., relationship between westerly wind bursts and migration of the warm water pool) and onset of El Niños (e.g., Maes et al., 2002; Ballabrera-Poy et al., 2002; Hackert et al., 2011, 2014; Druskha et al., 2015).

Ocean observations are undoubtedly required to initialize coupled models. However, little work has been done to quantify the sensitivity of S2S forecasts to the subsequent intraseasonally varying upper ocean. Thus, the S2S subproject on the ocean aims to identify the value of oceanic observations in the initialization of coupled predictions as a focus activity in the next few years (World Meteorological Organization, 2018) and to diagnose the current capability to predict the ocean state on S2S timescales, in order to reveal the primary ocean-atmosphere processes that are providing predictability on S2S timescales and to diagnose the capability of the S2S models to depict these processes. A key focus will be on the MJO, especially its signature in SST and the role of the SST variations for promoting the MJO. Studies for evaluating the impacts of oceanic data in coupled predictions are ongoing in a few operational/research centers (e.g., Subramanian et al., 2019). Further research using more S2S prediction systems is anticipated to make a reliable consensus on the impact of ocean observations. In addition, it is recommended to examine how well the key intra-seasonal variations such as oceanic Kelvin waves are depicted in the forecast models and if forecast skill is related to the quality of initialization of intra-seasonal variations. Examining the forecast of ocean intra-seasonal variations is the possible route to understand the initial shock and benefits of improved ocean initializations on the S2S forecast.

It should be also noted that the most current coupled prediction systems rely on uncoupled ocean data assimilation systems for the oceanic initialization. Atmospheric forcing of those systems is mostly calculated from analysis fields by atmospheric data assimilation systems. Thus, availability of near-surface atmospheric data ingested in the data assimilation system can also affect the quality of the oceanic initial condition. In particular, the near-surface wind, sea level pressure and ocean surface wave measurements seem to be highly important considering the fact that the sea-surface wind stress field dynamically affects the oceanic thermocline structure, particularly in the equatorial regions. In this sense, the satellite surface wind data are essential and in situ observations are also indispensable to calibrate the satellite data.

Coupled atmosphere-ocean data assimilation (CDA) may increase the value of near-sea-surface observation data by allowing assimilation of those data in a more physically consistent manner during the next 10 years. For example, physical representation of air-sea fluxes allows assimilation of satellite skin SST data including the diurnal cycle (e.g., Akella et al., 2017). Sea surface wind information can be estimated from satellite scatterometer retrievals more accurately by employing model information on the mixed layer temperature, near-surface velocity, and sea surface states in CDA reanalyses (e.g., Laloyaux et al., 2018); support of in situ observations is required for the efficient use of satellite data in a CDA system. The importance of in situ and satellite observation data around the sea surface is expected to increase with the progress of CDA development. See section 7.2.1.1 for further discussion.

3.3.3.3 Observations for testing and calibrating models

As noted in the previous section, observational requirements for testing and calibration tend to be general (for example, reanalyses) rather than specific data sets. Some centers use a broad range of data (e.g., the ECMWF) while others saw value in process-oriented diagnostics (e.g., National Center for Atmsopheric Research or NCAR). Subramanian et al. (2019) discuss these needs in more detail. It should be noted that the assessment of ocean observation impacts in Observing System Experiments (OSEs) are often affected by model errors and error compensation, mitigating against consistent and meaningful results.

WWRP engaged many of these same centers and other researchers to examine goals and challenges for coupled data assimilation for integrated earth system analysis and prediction

(Penny et al., 2017). They included the following insights relevant to observational requirements:

- Increase the observing effort of the cross-domain interfaces. This includes measurements of air-sea fluxes, air-land fluxes, etc.
- Identify dedicated field campaigns that can improve the skill of earth-system prediction through better formulation of either forecast, observation, or CDA methods due to the insights derived from those campaigns. Examples of successful field campaigns in the past include studies of coupling in tropical cyclones and MJO.
- Establish a mechanism to contribute observations from temporary and/or experimental observing systems that focus on taking measurements across domains, or that complement an existing observing system in a different domain to be used for CDA studies.

Penny et al. (2019) discuss the need for improving ocean and coupled reanalysis and S2S prediction, including the advantages of CDA and the specific requirements of such systems for testing and validation (see also sections 3.3.3.2, 7.2.1.1). In this context they note that there are advantages to directly assimilating satellite radiances to constrain SST (Balmaseda et al., 2018) since CDA treats the air-sea interface in a self-consistent manner. They also note the importance of salinity. Many prediction systems do not assimilate salinity data (Maes et al., 2014) despite some indications of potential benefits for S2S prediction. However, satellite SSS observations are useful for evaluating moisture exchange between the atmosphere and the ocean, for example. Statistical information on the relationship between atmospheric and oceanic variables should also be useful to validate an error covariance matrix generated by a strongly-coupled data assimilation system. Although, most centers currently use or test weakly-coupled systems in which error covariances between atmospheric and ocean variables are ignored, the statistical information based on observation data may support transition to strongly coupled systems in which the covariances are incorporated directly.

Penny et al. (2019) also note the potential value of observations through the ocean-atmosphere boundary layer (see also Penny et al., 2017; Karnauskas and Kessler, 2019). The sparse global coverage of air-sea flux variable measurements (First Report) means it is near impossible to directly constrain the atmosphere-ocean exchanges, but they have great value for validating any climate simulation and can be useful in constraining data assimilation analyses. Penny et al. (2019) further note the potential impact of emerging observing technologies for the subsurface layer and at the air-sea interfaces to better understand coupled interactions critical for prediction on S2S timescales (TPOS OceanObs'19; Chapter 9).

3.4 Discussion and recommendations

Penny et al. (2017), Penny et al. (2019), the National Academies of Sciences, Engineering, and Medicine (2016) and Subramanian et al. (2019) have considered ocean observation needs for S2S in a general way, but we recognize at this time further research is required before we can be specific in terms of essential variable requirements or potential enhancements/variations to the Backbone observing system.

Chapter 3 of the First Report focused on EOV requirements. At a general level, there was a trend toward requirements with enhanced spatial resolution and finer temporal resolution, specifically to capture features such as fronts and the diurnal cycle and to avoid aliasing in air-sea flux estimates. The high temporal resolution of the TMA was highlighted as a strength in relation to such requirements, and the move toward measuring all flux variables was also driven by such needs. Such requirements and responses will almost certainly benefit S2S and CDA. The First Report also set a goal for better tracking of mixed layer properties, under the assumption this would be needed for subseasonal forecasts.

We have noted the central importance of SST measurements and prediction at short timescales and the value of CDA in properly accounting for the coupled processes that determine SST. These processes include air-sea heat and moisture flux and the stability and mixing of the atmospheric and oceanic boundary layers. However, observations of SST (and SSS) must be complemented by observations of near-surface winds, ocean surface waves, surface currents and vertical structure in the ocean mixed-layer if we are to constrain/initialize such processes in models.

The Workshop "Bridging Sustained Observations & Data Assimilation for TPOS 2020" (Karnauskas and Kessler, 2019) also considered some of these issues but without clear conclusions. The Workshop did support two process studies, one focused on the eastern edge of the Pacific warm pool, and the other on Pacific upwelling and mixing.

We make the following recommendations:

> ***Recommendation 3.1.*** Where feasible and practical, promote observing approaches that jointly measure the ocean and marine boundary layers, and air-sea flux variables, principally to support model development, as well as testing and validation of data assimilation methods and systems [refer to sections 3.3.3.1 and 3.3.3.2; also 7.2.1.1]

> ***Recommendation 3.2.*** Encourage and promote process studies that will improve the representation of key processes and allow further testing of the ability for observations to constrain the coupled system, to address biases in observations and models, and to improve CDA observation error estimates. [refer to sections 3.2, 3.3.1 and 3.3.2]

The potential of the S2S Prediction Project hindcast and real-time database is enormous (Vitart et al., 2017), but little has yet been done to provide access to the ocean outputs from the participating coupled models. Questions to be addressed include how well are intraseasonal variations of the ocean represented in the initial conditions, how well are key intraseasonal air-sea interactions depicted in the forecast models and can forecast skill be related to initial condition quality. These studies can reveal what is the state of the art for initialization of an intraseasonally-varying ocean, what is the state of the art for predicting the intraseasonally-varying air-sea interactions, and what are common errors that need to be addressed. The Working Group on Numerical Experimentation (WGNE) has recently launched a new intercomparison project focussing on fluxes to address the above-mentioned questions.

> ***Recommendation 3.3.*** Promote and engage with the WGNE-WCRP Subseasonal-to-Seasonal subproject on Ocean Initialization and Configuration.

This project aims to provide ocean outputs from the S2S forecast models and to analyze them.

Chapter 4 Biogeochemical and Ecosystem Backbone Observations

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Biogeochemical processes and observing recommendations in the First Report focused on historical, long-term observations of ocean CO_2 flux and satellite ocean color. These included:

> (*Recommendation 12*) Continuation of high-frequency, moored time series and broad spatial scale underway surface ocean pCO$_2$ observations across the Pacific from 10°S to 10°N.
>
> (*Recommendation 13*) Continuation of advocacy for ocean color satellite missions with appropriate overlap to facilitate intercalibration for measurement consistency. In situ measurements of chlorophyll-a and optical properties for the validation of satellite ocean color measurements are required.
>
> (*Recommendation 14*) From 10°S to 10°N, observations of subsurface biogeochemical properties are required including chlorophyll concentration, particulate backscatter, oxygen and nutrients. Enhanced focus is needed for the eastern edge of the warm pool and the east Pacific cold tongue.

The First Report also identified the need to further determine the critical time and space scales for biogeochemistry (BGC) in the TPOS, which led to a JAMSTEC[12]-led data synthesis project (Yasunaka et al., 2019; S. Kouketsu, personal communication). This, along with TPOS 2020 pilot projects and emerging technology (e.g., Saildrone®, Wave Glidere®[13] and BGC-Argo; see Chapter 9) and further input from the community (Biogeochemical-Argo Planning Group, 2016) have allowed for further refinement of biogeochemical and ecosystem Backbone observational requirements in TPOS.

Further research is required to define a future sustained observing system for some biogeochemical variables, to better understand both their climate impacts and connections to higher trophic levels. The key measurements to support this must be provided by the Backbone observations and platforms (Chapter 7). The biogeochemical and ecosystem processes driving this design are:

- tropical Pacific biogeochemical and ecosystem response to climate change, including consequences of oxygen minimum zone (OMZ) variability and change to higher trophic level habitat (section 4.1.1);
- seasonal to decadal variability of the tropical Pacific biological pump. These observations would allow biogeochemical model/forecast development and assessment of ecosystem impact (section 4.1.2);

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[12] Japan Agency for Marine-Earth Science and Technology (JAMSTEC)

[13] Saildrone and Wave Glider are trademark names; hereafter referred to without ®

- seasonal to decadal variability of tropical Pacific CO_2 flux and implications for the global carbon cycle (section 4.1.3);
- upper ocean carbon budget including carbon export below the mixed layer and sources of anthropogenic carbon to equatorial Pacific upwelled water (section 4.1.4); and
- volume and nutrient fluxes into the equatorial undercurrent (EUC) to understand how this variability modulates biological variability in the central and eastern Pacific (section 4.1.5).

Constraining these processes drives TPOS 2020 biogeochemical requirements (section 4.3) to maintain a climate record of CO_2 flux and to resolve seasonal to interannual water column variability of EOVs: inorganic carbon, oxygen, chlorophyll, particles, and nutrients (section 4.2). This chapter concludes with required actions for incorporating biogeochemistry and ecosystem observations and research into the TPOS 2020 network (section 4.4).

4.1 Biogeochemical and ecosystem processes of the tropical Pacific

4.1.1 Tropical Pacific biogeochemical and ecosystem response to climate change

The tropical Pacific is a biologically productive and highly-dynamic region where ENSO, decadal-driven variability, and anthropogenic drivers all converge. One ecosystem-level vulnerability in tropical ocean regions is whether marine organisms will move to cooler waters as the ocean warms, and if so, will other organisms move in to fill missing ecological (and economical) niches? Are warm, El Niño conditions analogs for future mean state in ocean temperature, and if so, what can be learned from the ecosystem response to recent marine heat waves, such as the 2016 and 2017 events in tropical Pacific reefs? How does ocean heat, when combined with other stressors such as ocean acidification and overfishing, impact tropical Pacific ecosystems?

Climate-change-driven ocean warming and stratification are causing a global decline in dissolved oxygen. Climate models exhibit significant deficiencies in their simulation of OMZs (Stramma et al., 2012; Cabré et al., 2015; Oschlies et al., 2017). Nonetheless, most models suggest that tropical OMZs (see Figure 5.5) have expanded both horizontally and vertically, reducing habitat for organisms not adapted to live in low oxygen environments (Stramma et al., 2008). The OMZ in the eastern tropical Pacific already extends from 100 to 900 m. Further reduction of habitat could also cause shifts in the distribution of marine species and change ecosystem structure (Stramma et al., 2008). In addition to long-term change, the OMZ in this region is highly variable. The EUC and, to a lesser extent, the primary and secondary Tsuchiya Jets control the variability of the OMZ off the coast of Peru at seasonal to interannual timescales (Montes et al., 2014). The EUC brings oxygenated waters east, modulating OMZ volume in the eastern Pacific (see also section 5.1.4).

Although the eastern and central tropical Pacific is considered a high nutrient-low chlorophyll region where the supply of nutrients exceeds the rate of biological removal, there are still relatively high rates of photosynthetic primary productivity that fuel both higher trophic levels in the upper ocean above the OMZ and carbon sequestration to the deep sea (Mathis et al., 2014; Chavez et al., 2014). However, it is not fully understood how the coupling between physics and biogeochemistry drive changes at higher trophic levels or how sensitive biological carbon drawdown is to variability and change.

One tool for tracking changes at the base of the food web is net community production (NCP), which is primary production minus community respiration or, in other words, the upper limit on biological carbon export from the upper ocean to the deep sea. Existing estimates of NCP and the transfer of carbon to higher trophic levels and the deep sea are primarily based on a very limited number of ship-based process studies (Mathis et al., 2014), but these observations have not been sustained over time to address long-term change. Understanding how tropical Pacific ecosystems will respond to climate change requires establishing biogeochemical climate records and using observing system data to inform ecosystem process studies and model development.

Currently, the only sustained, long-term climate record for biogeochemistry in the tropical Pacific is the record of surface ocean $p\mathrm{CO}_2$ observations (Figure 4.1a). This three and a half decade long $p\mathrm{CO}_2$ record has begun to allow distinguishing natural variability from long-term change, however, the processes controlling these drivers is less understood. CO_2 outgassing from this region includes (1) CO_2 produced during the breakdown of organic matter during the ~10-year transit of subthermocline waters from the subtropics to the EUC and (2) anthropogenic CO_2 absorbed when these waters were last in contact with the atmosphere, also called pre-formed dissolved inorganic carbon (which includes CO_2). Once those waters reenter the mixed layer, biological production changes CO_2 concentrations further. A better understanding of how variability and change in circulation impacts delivery of these source waters to the tropical Pacific is critical to detecting and tracking the anthropogenic CO_2 signal and determining the progression of ocean acidification. This illustrates the interconnected nature of biogeochemistry and the physical measurements from the sustained Backbone.

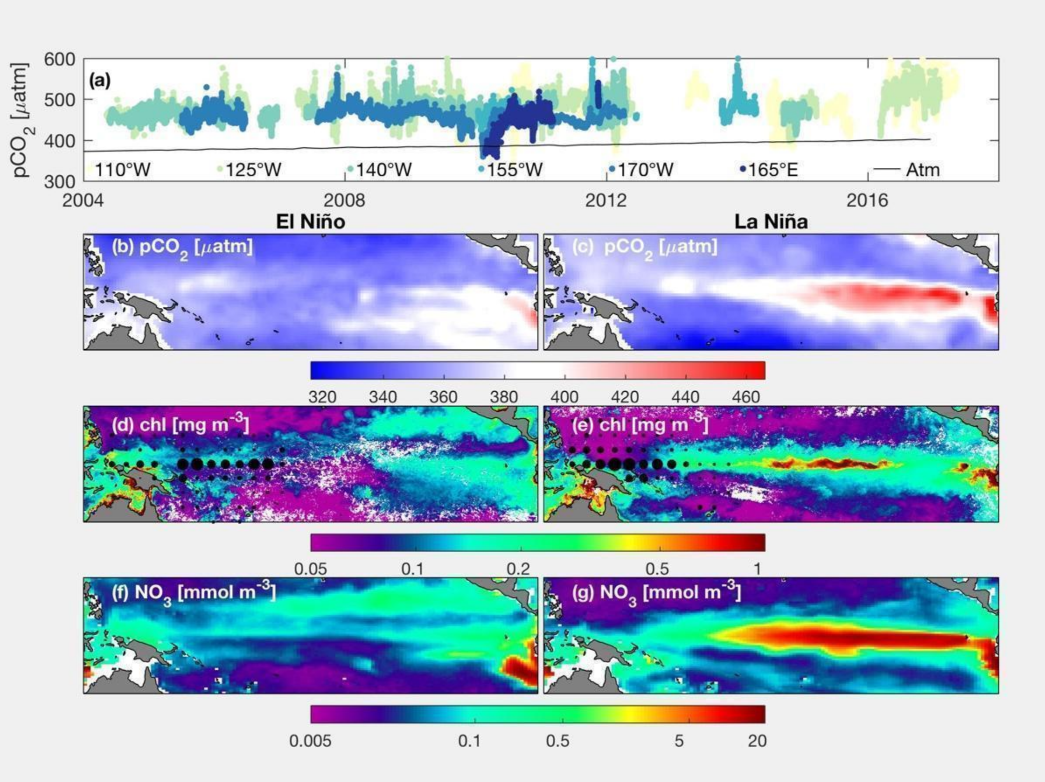

Figure 4.1. Summary of long-term trends and illustrative El Niño (January 1998) vs La Niña (July 1998) conditions for important biogeochemical parameters. **(a)** The long-term trends in surface ocean $p\mathrm{CO}_2$ and atmospheric $x\mathrm{CO}_2$. The colors indicate $p\mathrm{CO}_2$ from tropical Pacific moorings, all at 0°, from east (yellow) to west (blue). The solid line is atmospheric $x\mathrm{CO}_2$ (ppm) from a station on Easter Island (Dlugokencky et al., 2017). **(b)** and **(c)** Gridded surface ocean $p\mathrm{CO}_2$ from Landschützer et al. (2017). **(d)** and **(e)** SeaWiFS satellite monthly mean surface chlorophyll concentration. The filled circles represent the magnitude of the skipjack tuna catch for El Niño (panel (d), Jan-Jun 1992) and La Niña (panel (e), Jan-Jun 1989), adapted from Lehodey et al. (1997). **(f)** and **(g)** Surface nitrate concentrations from the NASA Ocean Biogeochemical Model (NOBM; Gregg and Rousseaux, 2014; https://giovanni.gsfc.nasa.gov/giovanni/).

4.1.2 Seasonal to decadal variability of the tropical Pacific biological pump to allow biogeochemical model/forecast development and assessment of ecosystem impact

As covered in the First Report and Chavez et al. (2014), the tropical Pacific supports economically and ecologically important fish populations, including the Peruvian anchoveta and several tuna, as well as protected sea turtles and cetaceans, and coral reef ecosystems. Physical fluctuations, especially ENSO, influence the extent and duration of ocean temperatures capable of coral bleaching and the abundance and distribution of fish populations. Satellite SST data can identify areas at risk for coral bleaching (https://coralreefwatch.noaa.gov), and the TMA data are currently used to inform a number of fishery management decisions. Yet, how coupled physical-biogeochemical processes in the region support such large tuna populations (Figures 4.1d and 4.1e), and drive changes at higher trophic levels is not well understood. This understanding is critical to provide robust predictions for fisheries management decisions and for assessing impacts on protected marine life and ecosystems (Lehodey et al., 2003).

Biogeochemical model development relies on credible circulation models and accurate parameterizations of biogeochemistry. Process studies such as the Joint Global Ocean Flux Study

(JGOFS) and the Southwest Pacific Ocean Circulation and Climate Experiment program (SPICE) have provided parameterizations for some biogeochemical pathways but there is still much room for improvement in this field. For this reason, TPOS 2020 will continue to support and advocate for process studies. Recently, biogeochemical and ecological modeling has begun to move into the realm of forecasts. Potential applications include prediction of fish abundance and distribution, OMZ magnitude, and the occurrence and extent of harmful algal blooms. From a physics-only perspective, predictions of temperature and currents alone have been used for monitoring fish catch, fish migration and larval transport (Johnson et al., 2005; Hobday and Hartmann, 2006; Bonhommeau et al., 2009). Temperature, salinity, altimetry and currents have also been successfully used as covariates to explain fish catch (Herron et al., 1989; Cole, 1999; Zagaglia et al., 2004; Bigelow and Maunder, 2007; Lumban-Gaol et al., 2015; Kaplan et al., 2016).

The only present data set to address seasonal variability in the tropical Pacific biological pump is satellite ocean color, which is used here as a catch-all term for satellite estimates of chlorophyll, biogenic particles, and derived products such as net primary productivity. Continuous satellite ocean color measurements have been made since the launch of SeaWiFS in 1997. In the late 1990s and into the early 2000s, the National Aeronautics and Space Adminstration (NASA) funded in situ bio-optical deployments on TMA moorings for the validation of SeaWiFS. These data were able to quantify chlorophyll variability at timescales of days to years, but only at two locations (0° 155°W and 2°S 170°W; Chavez et al., 1999).

For certain periods and locations in the tropical Pacific, observations of chlorophyll, nutrients and dissolved oxygen have been made with sufficient coverage and resolution to quantify interannual to decadal variability. Examples include the Japan Meteorological Agency (JMA; 1967 to present) and JAMSTEC (1994 to 2009) programs in the western Pacific (Yasunaka et al., 2019), the Monterey Bay Aquarium Research Institute observations, mostly on the NOAA ship *Ka'imimoana*, from 1997 to about 2005 in the central and eastern Pacific (Strutton et al., 2008) and long-term monitoring of coastal Peru since 1961 (Graco et al., 2017). Observations like these can document the influence of El Niño (Figure 4.1) and if sustained long enough, secular trends due to longer timescale modes of climate variability, including anthropogenic change. Unlike satellite ocean color, conductivity, temperature, depth (CTD)-based observations also capture the subsurface chlorophyll maximum, which is a persistent feature of the tropical Pacific. Biogeochemical-Argo floats would also quantify the depth and magnitude of the subsurface chlorophyll maximum. While Figure 4.1 shows the impact of ENSO on chlorophyll (Figures 4.1d and 4.1e) and nitrate (Figures 4.1f and 4.1g), these are not derived from in situ observations but satellite and model output, respectively.

Because of the complex arrangement of island exclusive ecomonomic zones (EEZs) and the importance of fishing rights, prediction of fish distributions has wide-ranging economic, management and ecological impacts. The skill of fisheries-related forecasts relies not just on the physical and biogeochemical parameterizations as mentioned above, but also on the uncertainties in the forcing and assimilation data used (Rousseaux and Gregg, 2017). Improved accuracy of satellite chlorophyll algorithms and expanded coverage of nutrient and oxygen measurements could significantly improve the data sets available to model developers, which could ultimately inform marine resource management and protection.

4.1.3 Seasonal to decadal variability of the tropical Pacific CO_2 flux and implications for the global carbon cycle

The ocean plays a large role in the climate system by absorbing 2–2.5 petagrams of anthropogenic carbon (PgC) per year globally. One approach for determining annual changes in global carbon is through annual carbon budgeting of anthropogenic CO_2 emissions and their redistribution among the atmosphere, ocean, and terrestrial biosphere. This top-down budgeting could provide independent verification of reported CO_2 emissions, however, reductions in the uncertainties in the budget terms are necessary to support this aim. In the budget from 2007–2016, for example, emissions exceed sinks by 0.6 PgC (equivalent to about half of US emissions), which is due to an overestimation of CO_2 sources or underestimation of sinks, or a combination of both (Le Quéré et al., 2018).

Tropical ocean CO_2 outgassing is a significant component of the global carbon budget. For perspective, the interannual variability of carbon outgassing in the tropical Pacific is 0.3–1.0 PgC yr^{-1} with La Niña conditions increasing CO_2 outgassing (Figure 4.1c) and El Niño reducing outgassing (Figure 4.1b). This variability rivals the entire global carbon budget uncertainty. In addition to the ENSO-driven interannual signal, the 30-year observational record of surface ocean pCO_2 also shows a change of up to 27% in tropical Pacific outgassing over decadal timescales associated with the Pacific Decadal Oscillation (PDO; Mathis et al., 2014; Feely et al., 2006). Poor constraint of these large natural variability signals could lead to increasing global carbon budget uncertainty.

Both observations and models are necessary to understand the present-day global carbon cycle and predict future climate. However, observations and models diverge in estimates of CO_2 flux from this region (Figure 4.2). Reconciling these differences to inform global carbon cycle budgeting and predictions will require sustained tracking of CO_2 flux across the tropical Pacific and a better understanding of how circulation and biological productivity control CO_2 outgassing in this region.

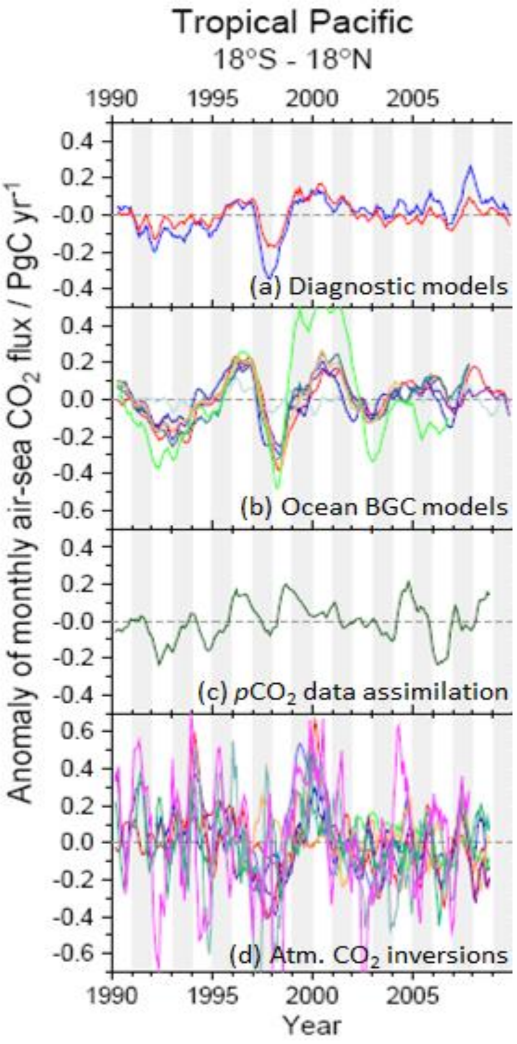

Figure 4.2. Time series of monthly CO_2 flux anomalies in the tropical Pacific from four different methods as indicated on the figure (after Ishii et al., 2014).

4.1.4 Upper ocean carbon budget, including carbon export below the mixed layer and sources of anthropogenic carbon to equatorial Pacific upwelled water

Long time series of chemical and biological measurements have shown that the central and eastern tropical Pacific are major sources of CO_2 to the atmosphere during non-El Niño and La Niña periods, in equilibrium with the atmosphere during strong El Niño periods, and a weak source during weak El Niño periods (section 4.1.3, Mathis et al., 2014). The flux to the atmosphere occurs because deep waters contain high concentrations of dissolved inorganic carbon and upwelling brings these waters into contact with the atmosphere. Because tropical Pacific phytoplankton are growth-limited by the availability of dissolved iron, ocean productivity is not sufficient to draw down the surface ocean partial pressure of CO_2 to below atmospheric levels. Interannual to decadal scale variations in trade wind forcing control the strength of upwelling in this region, and the depth of the thermocline, resulting in modification to air-sea CO_2 flux, nutrient supply, and ultimately biological productivity in the region (e.g., Figure 4.1).

Similarly, the ENSO-controlled trade wind variability has been shown to be the major factor controlling the variability in biological carbon export and nutrient fluxes in the region (Mathis et al., 2014). The fraction of organic matter production that escapes the upper ocean contributes to biological carbon sequestration. This carbon export to the deep ocean has been estimated to range from 0.7–2.5 PgC yr^{-1} (Chavez and Barber, 1987; Behrenfeld et al., 2006). Several processes have been identified as controlling phytoplankton consumption of macronutrients in the upper ocean, which limit carbon export. In the tropical Pacific these include trophodynamic processes such as grazing control of phytoplankton biomass and nutrient supply and availability, most notably the supply of iron (Mathis et al., 2014).

On longer timescales, the Pacific Ocean has undergone major regime shifts commonly associated with the PDO (McPhaden and Zhang, 2002, 2004). These shifts have been documented to be correlated with large-scale changes in the physics, chemistry (including CO_2 outgassing) and biology (Mathis et al., 2014). Only a few long-term studies of the effect of these regime shifts on CO_2 flux, primary productivity, and nutrient supply in the tropical Pacific have been conducted (Takahashi et al., 2003; Feely et al., 2006; Chavez et al., 2003, 2011; Ishii et al., 2014; Sutton et al., 2014a; Landschützer et al., 2014). Such studies demonstrate that the changes in primary production, the growth rate of CO_2 in surface waters, and the long-term decline in pH (section 4.2.3) are driven by both the decadal-scale changes in the physical environment as well as the secular changes in heat and CO_2 uptake.

Understanding the sensitivity of biological carbon drawdown in this region to changes in the ocean-climate system will require time-resolving (seasonal or better) measurements of air-sea interactions, vertical and aeolian nutrient supply, primary production, and phytoplankton biomass. While global biogeochemical models and atmospheric model inversions applied to the tropical Pacific region can roughly simulate the timing of chemical and biological changes, they have a difficult time reproducing the magnitude and duration of the processes involved (Mathis et al., 2014). This is partially due to a lack of highly resolved chemical and biological data available to validate the individual processes represented in the models. More detailed simultaneous temporal and spatial sampling of physical, chemical, and biological properties is required to delineate the long-term trends and validate underlying processes in the models.

4.1.5 Volume and nutrient fluxes into the EUC to understand how this variability modulates biological variability in the central and eastern Pacific

The equatorial undercurrent (EUC) flows from west to east at speeds more than 1 m s^{-1}, and shoals from about 200 m in the west to about 50 m in the east. It is found between about 2°N and 2°S (Johnson et al., 2002) and fed by equatorward undercurrents from the north and south in the western Pacific (section 7.4.5.1). The EUC and its western inflows are important to tropical Pacific biogeochemistry for at least two reasons: (1) the western inflows entrain iron from the shelves, becoming a source of low to moderate levels of the limiting nutrient iron to the upwelling tongue, thus regulating productivity (Ryan et al., 2006), and (2) further upstream, these feeder currents derive pre-formed inorganic carbon from the surface of the north and south Pacific. They also gain dissolved inorganic carbon due to remineralization as they transit toward the EUC. Both processes contribute to the upwelling and degassing of CO_2 in the central and eastern Pacific, as discussed in section 4.1.2. There is also substantial mid-basin geostrophic flow toward the equator at about the depth of the thermocline (Johnson and McPhaden, 1999; Grenier et al., 2011). This would contribute remineralized inorganic carbon to the EUC, but very little iron.

The volume and heat fluxes of the western boundary currents into the equatorial current system are central to understanding the heat and freshwater budget of the tropical Pacific, as discussed in section 3.3.4.1 of the First Report. The corresponding biogeochemical fluxes into the EUC are important for understanding the relative importance of local versus remote forcing to the observed variability in biological productivity, air-sea CO_2 fluxes and dissolved oxygen, including OMZs. Even occasional quantification of these fluxes would help to identify, for example, anthropogenic signals in the dissolved inorganic carbon content of the EUC and its source waters.

The biogeochemical measurements required include elemental concentrations and isotopes in both the EUC and its feeder western boundary currents. These measurements have only been made during short-term process studies or one-off ship transects. A comprehensive example is SPICE (Ganachaud et al., 2014, 2017), which spanned a broad range of physical and biogeochemical observations across the southern feeder currents of the EUC. The key objectives of SPICE were to understand the southwest Pacific Ocean circulation and South Pacific Convergence Zone (SPCZ) dynamics, and their influence on regional and basin-scale climate patterns. From a detailed biogeochemical perspective, Lehmann et al. (2018) used isotopic measurements of carbon, nitrogen and oxygen to determine important characteristics of the northern and southern source waters. They were able to conclude that the Southern Hemisphere is the dominant source to the EUC, and that remineralization rather than preformed sources dominate in the waters from the Northern Hemisphere. Sustained volume flux measurements with occasional biogeochemical transects have great potential for addressing science questions around biogeochemical variability across the upwelling system.

4.2 Biogeochemical EOVs for the tropical Pacific

The Global Ocean Observing System (GOOS, www.goosocean.org) defines a set of essential ocean variables (EOVs) grouped under physics, biogeochemistry, and biology and ecosystems. Most of these EOVs have specification sheets associated with them. These sheets provide background, drivers and applications of the measurement, products that can be derived, important time and space scales and platforms that can accommodate the observations. This section summarizes the potential implementation of BGC EOV measurements in the tropical Pacific. The EOV specification sheets describe the global implementation in more detail.

4.2.1 Dissolved oxygen

Dissolved oxygen concentration increases due to production via photosynthesis and exchange with the atmosphere and decreases due to consumption via remineralization (breakdown of organic material into inorganic forms). Like CO_2, the solubility of oxygen decreases with increasing temperature. Dissolved oxygen is typically high at the ocean surface where photosynthesis and air-sea gas exchange take place and lower at depth where remineralization occurs. Oxygen levels are important for defining habitat for higher trophic levels such as fish, and the eastern tropical Pacific is home to large subsurface OMZs (see section 5.1.4. and Figure 5.5). Changes in the spatial extent of OMZs and the depth of the oxygen minimum, will define the habitat of commercially and ecologically important fisheries such as skipjack and yellowfin tuna.

After temperature and salinity, dissolved oxygen is probably the most widespread ocean measurement. Global data compilations have shown large scale (mostly) decreasing oxygen concentrations, thought to be due to reduced solubility and ventilation in a warmer ocean (Schmidtko et al., 2017). In the tropical Pacific the trend is consistent with the global trend and proportional to the volume of the region. Greater data density is essential for improving our understanding of the evolving trend, and for validating the next generation of high-resolution models, as they become better able to simulate the complex equatorial currents. Dissolved oxygen has traditionally been measured in discrete samples from CTDs or from sensors incorporated into CTD packages that are calibrated with discrete samples. The last decade has seen an expansion of oxygen sensor deployments on other platforms such as Argo floats, particularly in the Southern Ocean. Tropical Pacific deployments remain sparse. NOAA recently funded a TPOS 2020 pilot study to deploy Argo floats with dissolved oxygen, bio-optics and acoustic rain and wind sensors (section 10.2.1 of the First Report).

Oxygen is an essential variable because it quantifies important processes by itself but also enhances the power of other measurements. Large-scale implementation of ocean dissolved oxygen observations would help to constrain the atmospheric O_2/N_2 ratio, which is used to determine the partitioning of anthropogenic CO_2 between land and ocean sinks. Mixed layer oxygen measurements, especially when made in conjunction with nutrient measurements, can quantify NCP. Because oxygen is consumed during remineralization, O_2 measurements below the mixed layer are a proxy for carbon export and variability in time (seasonal to interannual) and space (across basins).

Well-resolved dissolved oxygen observations also present a unique and powerful perspective to understand coupling between BGC and physics from a few days and months at the mesoscale to several decades and centuries on global scales. This perspective remains poorly explored, due to a lack of well-resolved observations on these temporal and spatial scales but also incomplete understanding of the coupling between dissolved oxygen and ocean physics. As we improve our process understanding of oxygen coupling to ocean circulation and heat, dissolved oxygen measurements can in turn address physical questions regarding mixing, upwelling, heat content and source waters.

High accuracy is not essential to define the large-scale boundaries of the OMZs, but at low concentrations accuracy becomes important to determine which processes in the nitrogen cycle are likely or even possible. Dissolved oxygen and its derived parameter—apparent oxygen utilization—help to deduce water mass ventilation, age and provenance, which is linked to the question of pathways into the EUC discussed in section 4.1.2. Improved measurements of dissolved oxygen distributions will also provide important initialization and validation data for models. Dissolved oxygen observations on a subset of the enhanced Argo array proposed for TPOS would resolve seasonal variability in the distribution of oxygen and make great progress toward addressing the science drivers listed in section 4.1. Strategic implementation of oxygen sensors on moorings in the eastern Pacific would also track higher-variability processes in the OMZ (see section 5.4, ***Recommendation 5.3***).

Analysis of existing dissolved oxygen measurements in the World Ocean Database (https://www.nodc.noaa.gov/OC5/WOD/pr_wod.html) enable estimate of its decorrelation length scales in the tropical Pacific, which help to inform the spatial resolution at which the measurements must be made. Figure 4.3 shows that these scales are approximately 15° in longitude and 9° to 20° in latitude, depending on depth. The meridional scale for subsurface oxygen (Figure 4.3) is larger than that of surface CO_2 (see section 4.3.1) because the former is controlled by particle sinking and remineralization, which are slower compared to surface productivity and air-sea exchange, which dominate the latter.

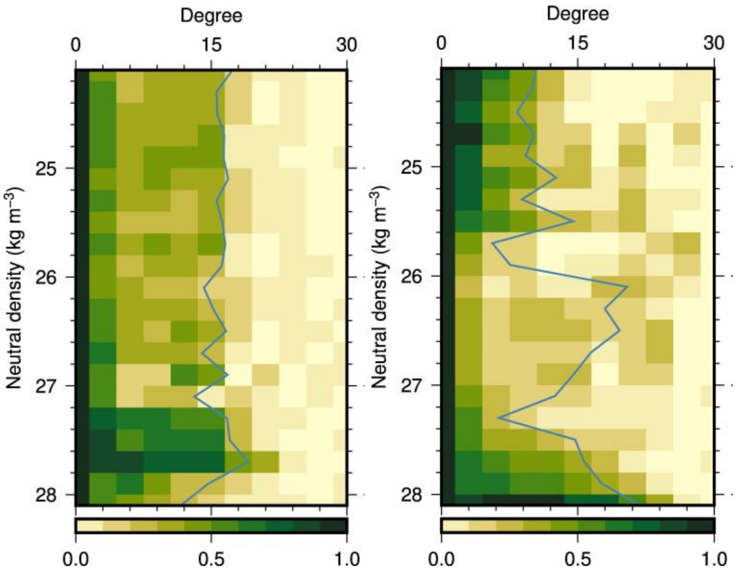

Figure 4.3. Lag autocorrelation distributions of oxygen anomalies on isopycnal surfaces from the long-term mean based on interpolation with a variational auto-encoder for the longitudinal (left) and latitudinal (right) directions. Blue lines show the decorrelation lengths, which are estimated by fitting Gaussian functions. Correlations were calculated with raw measurements of oxygen in 3° bins. In depth space the y-axis in each panel spans about 100 m to 800 m. Figure courtesy of Shinya Kouketsu, JAMSTEC.

4.2.2 Nutrients

The tropical Pacific is one of three large iron limited or high nutrient, low chlorophyll ocean provinces. Iron limitation means that moderate to high concentrations of CO_2 and dissolved nutrients persist at the surface, so measurements of dissolved nitrate, phosphate and silicate do not necessarily diagnose which macronutrient is limiting productivity, as can be done elsewhere. However, macronutrient concentrations and their ratios are important proxies for primary productivity, carbon export, water mass origin and ocean biomes, especially when combined with CO_2 observations. Derived products include measures of nutrient excess or deficiency such as N* (see Gruber and Sarmiento, 1997, for a definition), which identify areas of denitrification and nitrogen fixation. Without a reliable time series of nutrient measurements, we cannot detect large-scale and long-term changes in the uptake and remineralization of important elements such as C, N, P, Si and Fe.

Dissolved nitrate (and ammonium), phosphate and silicate have been measured in the tropical Pacific for decades, as briefly described in section 4.1.5. Except for a few coordinated programs, the data coverage is very patchy in space and time (Figure 4.4). Nonetheless, the data currently available have been used to document the impact of specific El Niño events (Chavez et al., 1999; Strutton and Chavez, 2000) and longer-term interannual variability (S. Kouketsu, personal communication; Strutton et al., 2008).

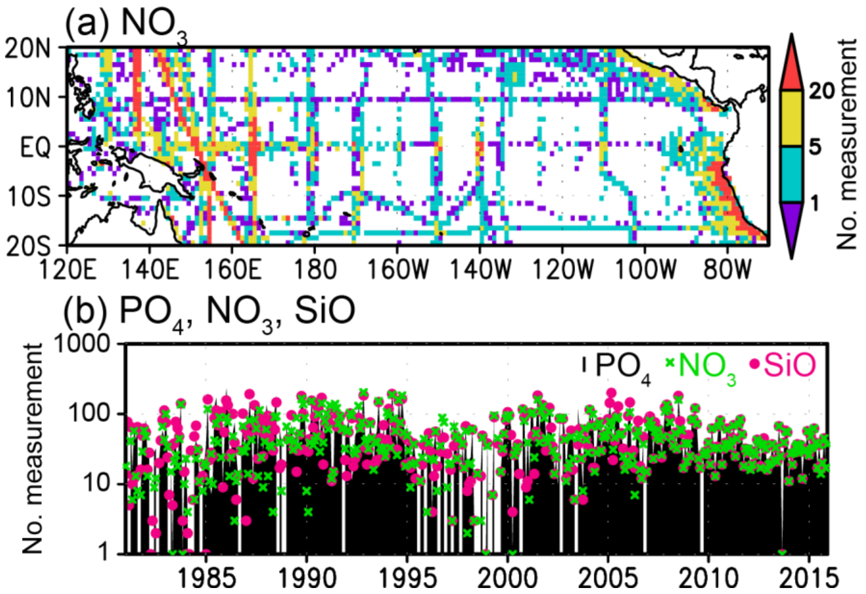

Figure 4.4. (a) Spatial distribution of number of surface nitrate measurements and (b) temporal distribution of number of nutrient measurements in GLODAPv2, WOD2013, and NIES VOS program. Panel (a) shows the total number of surface measurements in each 1° grid cell between 1981 and 2015. Panel (b) shows the total number of measurements each month in the tropical Pacific (20°S–20°N, 120°E–70°W). Figure from Yasunaka et al. (2019).

Similar to dissolved oxygen the addition of nitrate sensors to autonomous platforms (Argo is the most obvious because biofouling is less of a problem compared to moorings and autonomous surface vehicles (ASVs)), would dramatically increase the spatial and temporal coverage of observations in the tropical Pacific. This would make it possible to link the drawdown of nitrate at synoptic to interannual timescales with corresponding variability in NCP, oxygen and pCO_2. Sustained nitrate observations could document changes in the nutrient content of waters entering the western Pacific through the low-latitude boundary currents. Likewise, sustained ship-based observations on mooring cruises would quantify changes in the ratio of N, P and Si in tropical Pacific waters, which links these observations to phytoplankton community structure and carbon export. Deployment of nutrient sensors on select moorings, perhaps co-located with pCO_2 sensors, would improve our understanding of short-term variability associated with processes such as Kelvin waves and tropical instability waves.

Routine measurements of dissolved iron are logistically difficult because they are only currently possible with specialised ship-board expertise and equipment. Through the GEOTRACES[14] program, four cruises to date have sampled parts of the tropical Pacific, and occasional iron-

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[14] International Study of Marine Biogeochemical Cycles of Trace Elements and their Isotopes, http://www.geotraces.org/

focussed process studies also visit the area. TPOS 2020 supports and will continue to advocate for these efforts, but specific recommendations for iron measurements are not part of this report.

4.2.3 Inorganic carbon

The history and significance of pCO_2 measurements in the tropical Pacific have been discussed in section 4.1 and the First Report. It is important that high-quality mooring and surface underway pCO_2 observations continue to be made, because they are fundamental to understanding global carbon budgets. Opportunities exist for the observation of other carbon parameters. The four main measurements of interest are pCO_2, pH, dissolved inorganic carbon (DIC) and total alkalinity (TA). Measuring any two of these makes it possible to calculate the remaining two. Using pH sensors on floats or other platforms and estimating TA from salinity, it is possible to calculate DIC and pCO_2 (e.g., Sutton et al., 2014a; Williams et al., 2017).

As for O_2 and nutrients above, the addition of pH sensors to Argo floats would vastly expand observations of DIC and pCO_2. This would make it possible to address questions for carbon as outlined above for nutrients, namely changes in the supply to and consumption in the tropical Pacific. These changes could be linked to their physical drivers and natural variability could be constrained. In addition, pH measurements may be able to quantify ocean acidification in the future, yet autonomous pH sensors are not accurate enough for this purpose. High quality ship-based measurements of dissolved carbon species need to continue in order to detect small changes driven by climate.

4.2.4 Particulate matter

Particulate matter includes both biogenic material and other particles such as sediments, but for almost all the tropical Pacific the biogenic fraction is of most interest. The biogenic fraction includes living and dead matter; the major components in the currency of carbon are particulate organic carbon (POC) and particulate inorganic carbon (PIC). Measurements of PIC may show changes in the phytoplankton and zooplankton composition in response to ocean acidification, so they are particularly useful in conjunction with direct measurements of acidification. It is essential that we observe biogenic particles because of their role in the carbon cycle. Without these observations we would fail to understand the role of the biological pump in the changing carbon cycle.

POC can be measured in water samples at sea, by optical sensors (transmissometer and backscatter sensors) on CTD rosettes, autonomous platforms, and by ocean color satellites. The in situ and satellite optical measurements need to be validated, probably on a regional basis. In surface waters, measurements of POC document changes to the productivity of the system. Below the euphotic zone the same data show how fluxes of organic material to depth are changing.

Most current biogeochemical Argo deployments include the measurement of particles from a combined chlorophyll fluorescence and backscatter instrument (FLBB sensor). Incorporating this sensor into BGC-Argo deployments for the tropical Pacific should be the default. This would map the time and space variability of POC but the temporal resolution of Argo profiles may not be sufficient to estimate POC flux to depth. Strategic addition of FLBB sensors at multiple depths on moorings could achieve this (Briggs et al., 2011). In situ samples from mooring maintenance voyages and GO-SHIP[15] lines would permit validation of satellite-based products.

4.2.5 Chlorophyll, including satellite ocean color

Chlorophyll is a proxy for phytoplankton abundance and the core input variable for most satellite-based primary productivity models. Accurate measurements of chlorophyll are essential for tracking change at the base of the ecosystem. The coverage of in situ chlorophyll measurements in the tropical Pacific is similar to that of nutrients; they are patchy in space and time but have the potential to document long term changes. Since 1997 there have been continuous observations of satellite chlorophyll, or more generally, ocean color, from which other parameters such as POC and euphotic zone depth can be derived. Satellites offer basin-scale coverage but only of the upper ~20 m in the tropical Pacific. In situ measurements, specifically extracted chlorophyll from water samples, can validate the ocean color algorithms and provide resolution of variability with depth. These samples also help improve continuity in satellite ocean color between missions.

Satellite observations are central to quantifying basin-wide temporal change, but they must be complemented with in situ measurements. Fluorometers and irradiance sensors on Argo can both quantify chlorophyll while the latter also directly measures euphotic zone depth, another important input for most productivity models. The community will continue to advocate for continuous satellite ocean color observations where appropriate. Starting to resolve subsurface chlorophyll would require GO-SHIP and mooring maintenance voyages making depth-resolved chlorophyll measurements and where possible pigment or preserved samples to determine phytoplankton community structure. A broader spatial array of BGC-Argo in the TPOS region with FLBB and irradiance sensors would also contribute to this.

4.2.6 Transient tracers, N_2O, C isotopes, DOC

Nitrous oxide (N_2O) is an important trace gas in the atmosphere. It depletes ozone and acts as a greenhouse gas. Its significance will likely increase in the 21st century. It is produced by several reactions in the nitrogen cycle and ocean outgassing accounts for about 30% of atmospheric N_2O. OMZs and equatorial upwelling regions are important sites of N_2O production.

Carbon isotopes (specifically the ratio of ^{13}C to ^{12}C, denoted $\delta^{13}C$) document the changes in ocean DIC due to uptake of fossil fuel CO_2 that is enriched in ^{12}C. The measurement is really only amenable to ship campaigns with dedicated sampling equipment (GO-SHIP) although underway measurements may be possible with recent improvements in instrumentation. In the tropical Pacific, even sparse $\delta^{13}C$ observations would complement other measurements discussed above that document the contribution of anthropogenic carbon to the CO_2 degassed along the equator. Similarly, measurements of oxygen and hydrogen isotopes of water would

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[15] The Global Ocean Ship-based Hydrographic Investigations Program

be useful for understanding of atmospheric convective processes as well as hydrological influences in the marine environment and for paleoclimate-relevant applications.

Transient tracers include chlorofluorocarbons (CFCs), sulfur hexafluoride (SF_6), ^{14}C and tritium (which decays to ^{3}He). All these tracers are either conservative or have known decay functions and known atmospheric sources. Therefore, they can be used to determine ocean ventilation and the transit of water parcels through the ocean. These observations can be used to constrain source waters to the tropical Pacific, for example through the low latitude western boundary current, and complement the carbon observations aimed at partitioning natural and anthropogenic sources.

Dissolved organic carbon (DOC) accounts for about 662 ±32 PgC in the ocean, which is about 200 times greater than POC and 50 times smaller than DIC. It is a sink for photosynthetically fixed C and a food source for heterotrophic microbes. Its export to the deep ocean accounts for about 20% of the biological carbon pump. A large fraction of DOC seems to be unreactive, but the size of the pool makes it significant for climate.

All these parameters described in this section are only amenable to observations from ships, during process studies or GO-SHIP lines. Mooring maintenance cruises could support the collection of some samples given the involvement of an appropriate investigator.

4.2.7 GOOS EOVs not yet included here

Phytoplankton biomass (or its proxies, chlorophyll and POC) have been included here because they are amenable to measurement by satellites and in situ optical sensors. However, the related GOOS EOVs of *phytoplankton diversity, zooplankton biomass and diversity, and microbe biomass and diversity* have not been specifically addressed because they are not yet at the readiness level for inclusion in TPOS. They are at the level of measurements that have been included on an opportunistic basis in GO-SHIP voyages.

Fish abundance and distribution are parameters of intense interest to tropical Pacific nations. TPOS 2020 welcomes input on technologies, such as moored or underway acoustics, that could monitor fish, but at least thus far the focus of the observing system design has been on making the observations that could be used to predict fish habitat. Fish (and coral, see next paragraph) data are already being collected as core requirements for other observing programs. TPOS should ensure access to those data and advocate for their continued collection.

Coral cover and distribution are likewise very important to understand both ecologically and economically. Tourism industries and pelagic ecosystems depend on these habitats, which are likely under threat from warming and acidification. However, the historical open ocean/deep water focus of TPOS has not been amenable to collection of relevant data for coral health, with the exception of satellite SST and the Chuuk Lagoon mooring (7.5°N, 152°E; https://www.pmel.noaa.gov/co2/story/Chuuk+K1), which specifically collects data relevant to ocean acidification. Expanded pH measurements, on Argo for example, could better map conditions relevant to coral health across the tropical Pacific.

4.3 Biogeochemical requirements of the Backbone observing system

4.3.1 CO_2 flux and ocean color

In the First Report, initial recommendations for integrating biogeochemistry into the TPOS Backbone design focused on sustaining and expanding established air-sea CO_2 flux and ocean color observations in the tropical Pacific.

Surface ocean pCO_2 observations from the TMA mooring servicing vessels and on seven TMA buoys are the only sustained, long-term climate records for biogeochemistry in the tropical Pacific. Constraining the full spatial signal of tropical Pacific CO_2 flux requires air-seawater pCO_2 and wind speed observations spanning the 10°S–6°N, 165°E–85°W region (Mathis et al., 2014; Feely et al., 2006). The basin-scale understanding of CO_2 flux in the tropical Pacific is primarily derived from very high-quality surface pCO_2 measurements coupled with algorithms derived from satellite measurements of SST and satellite-based wind speed products. Given the biases in these wind speed products (Chiodi et al., 2019), there is a need for improving wind speed observations from ships and estimates from satellite-based products.

Fully characterizing the temporal signal and its drivers, such as variability due to TIWs, requires high-quality fixed time series observations. Existing air-seawater pCO_2 and wind speed observations on TMA buoys are located along the equator and at 8°S 165°E. However, new pCO_2 time series buoys are required in the western Pacific to better understand variability and change of CO_2 flux and ocean acidification in that region. Analysis of historical data suggests pCO_2 observations should be targeted in or near the western edge of the warm pool, and at its northern edge. These new sites should also build off climate records already established by ship-based time series (e.g., Oka et al., 2018). For these reasons the best new potential sites within the TMA are 0° 147°E and 13°N 137°E, respectively.

Existing surface pCO_2 assets in the tropical Pacific are of high quality with in situ calibration using standard reference gases. They provide validation measurements for any future expansion of the climate record to new and emerging surface pCO_2 platforms and sensors. Risks to the meridional sampling in parts of the TMA noted in the First Report led to the development and testing of new technology for collecting pCO_2 observations (based on moored pCO_2 technology described by Sutton et al., 2014b) from Saildrones, long duration autonomous surface vehicles (see section 9.2.1). These new technologies show promise for filling in observing gaps and conducting adaptive sampling as ENSO conditions develop.

The ideal spatial coverage of these assets in TPOS is informed by recent data syntheses of surface ocean pCO_2 observations in the tropical Pacific, which suggest a decorrelation scale of ±6° in latitude, ±13° in longitude, and ±2 months (Yasunaka et al., 2019). Note that these scales are different from those for O_2 (Figure 4.3) because the O_2 data are subsurface and controlled by different processes (remineralization) than surface pCO_2 (mostly degassing). This analysis shows that the combination of equatorial moorings and surface underway measurements can characterize the interannual variability in surface ocean pCO_2. This is confirmed in Figure 4.5a, which shows a significant regression between pCO_2 and the NINO3.4 index close to the equator from about 150°E to the coast of South America.

The $p\mathrm{CO}_2$ observations on TMA buoys were also used to validate CO_2 measurements made by NASA's Orbiting Carbon Observatory-2 (OCO-2) satellite (Chatterjee et al., 2017). Both observing systems showed that in the early months of the 2015–2016 El Niño, CO_2 outgassing from the tropical Pacific Ocean declined approximately 25–50%. OCO-2 provided the first set of broad-scale observations confirming the hypothesis that the tropical Pacific Ocean shows an early response to El Niño conditions, which are then followed by the terrestrial carbon response. In situ CO_2 flux observations will continue to be required to confirm results from evolving satellite and in situ technology.

For chlorophyll and particulate matter, the satellite record captures variability at spatial scales from pixels (kilometers) to the basin, and temporal scales from days to decades, but only for the upper few tens of meters. Bio-optical sensors on Argo (see below) can address subsurface variability. Future ocean color missions will deliver hyperspectral (NASA's PACE: Plankton, Aerosol, Cloud, ocean Ecosystem) and geostationary (Korea's Geostationary Ocean Color Imager II) data.

4.3.2 Water column biogeochemistry

Observations that constrain seasonal to decadal water column variability of inorganic carbon, oxygen, chlorophyll, particles, and nutrients are key to understanding the biogeochemical and ecosystem processes discussed in section 4.1. To date, water column biogeochemical measurements are sparse. Figure 4.4 is an example for nitrate showing that most of the tropical Pacific has fewer than 10 (likely surface only) samples since the 1980s, mostly from the repeat hydrographic surveys of GO-SHIP and predecessor programs. Using these data, Yasunaka et al. (2019) found similar decorrelation scales compared to surface $p\mathrm{CO}_2$ (4.3.1). Although this analysis is based on limited data, it does provide some confidence that BGC-Argo observations in the tropical Pacific have the potential to characterize seasonal to interannual variability of O_2 and the OMZ, inorganic carbon, chlorophyll, and nitrate, as well as many of the mechanisms driving the biological pump (4.1.5). The analysis conducted so far (Figure 4.5c-e) shows a patchy relationship between nutrients and the NINO3.4 index. Significant regressions are mostly in areas of little variability poleward of about 10° because of the lack of data around the equator where the largest signals are expected. The signals on the equator are most coherent for nitrate.

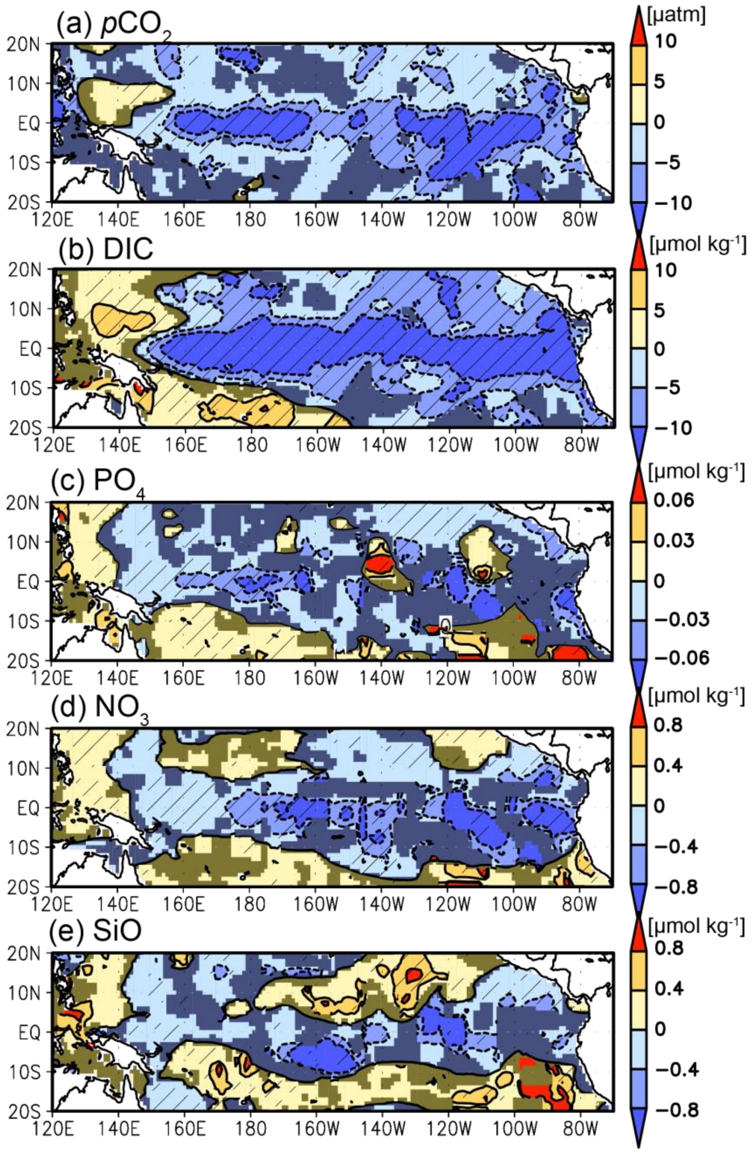

Figure 4.5. (a) pCO_2, (b) DIC, (c) Phosphate, (d) nitrate, and (e) silicate regression maps onto the NINO3.4 index. Diagonal shading indicates regression coefficients significant at $p<0.05$. Figure from Yasunaka et al. (2019).

Some parts of the ocean, for example as part of the Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) project, are becoming sufficiently dense with BGC-Argo floats to quantify seasonal signals in chlorophyll, biogenic particles, nitrate, dissolved oxygen and pH. But there have been few BGC-Argo float deployments in the tropical Pacific (Figure 4.6). BGC-Argo data combined with ship-based validation data and surface ocean CO_2 flux measurements could also be used to estimate vertical gradients in carbon chemistry that are necessary to developing upper ocean carbon budgets and export (4.1.3).

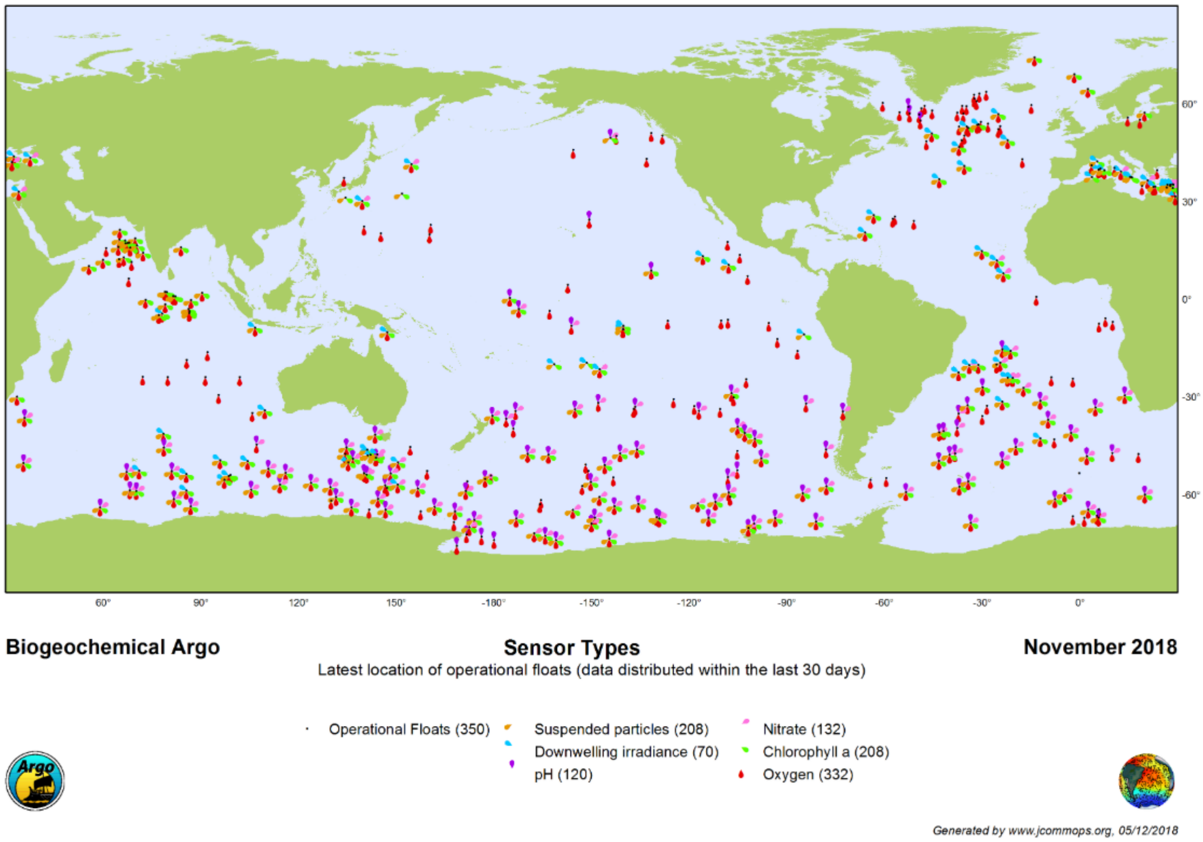

Figure 4.6. Global map showing the location and sensor suite of BGC-Argo floats. The map was extracted from http://biogeochemical-argo.org/float-map-network-status-maps.php on 20 Dec 2018.

BGC-Argo floats require ships for deployment and collecting water samples to calibrate the sensor data. New hydrographic surveys along existing TMA lines with upper ocean water column physical and biogeochemical observations proposed in the First Report would address this need. In addition, there are biogeochemical phenomena that cannot currently be measured autonomously (sections 4.2.6 and 4.2.7). These include the volume and nutrient fluxes, especially iron, into the EUC; how the variability of these fluxes modulates biological production in the central and eastern Pacific (section 4.1.5); identifying the sources and concentrations of anthropogenic carbon to equatorial Pacific upwelled water (section 4.1.4). Capturing these phenomena will require repeat ship-based observations in conjunction with modeling efforts. Model development will also be required to apply new knowledge gained by TPOS biogeochemical observations to questions about future ecosystem impact (section 4.1.2). Finally, repeat hydrographic surveys of biogeochemical observations over several decades will also provide a climate-quality time series to validate decadal to long-term changes observed by autonomous sensors with larger measurement uncertainties. The ship visits envisaged here include mooring maintenance cruises roughly twice per year, GO-SHIP voyages roughly once per decade, as well as process study cruises.

4.4 Required actions

The TPOS 2020 Biogeochemistry Task Team, in consultation with the broader community, makes the following recommendations for required actions:

4.4.1 Maintain the pCO$_2$ climate record

Moored observations of surface ocean and atmospheric pCO$_2$ should continue at 0° 110°W, 0° 125°W, 0° 140°W, 0° 155°W, 0° 170°W, 0° 165°E and 8°S 165°E. Additional moored systems in the western Pacific should be considered: 0° 147°E (in the planned Ding array; see sections 6.2.2, 7.2.1.3; Figure 7.4) and 13°N 137°E (JAMSTEC's TRITON array; see section 7.3). Sensors adopted should meet the measurement uncertainty necessary to serve the climate record (4.3.1).

Surface underway measurements of surface ocean and atmospheric pCO$_2$ should continue on ships of opportunity, research vessels, and mooring maintenance ships. That is, the organizations responsible for maintaining the TMA should equip mooring maintenance vessels with underway pCO$_2$ systems. Regardless of the distribution of moorings in the final TMA design, the primary goal for surface underway pCO$_2$ data distribution should be 10°N to 10°S at least once per year and ideally twice per year.

Since 2017, trials of an autonomous surface vehicle (Saildrone; see also section 9.2.1) have demonstrated the potential for this platform to complement or augment underway ship measurements to maintain the pCO$_2$ climate record. The vehicle's payload included atmospheric sensors, Doppler currents, temperature, salinity, bio-optics, pCO$_2$, pH, and dissolved oxygen. Trials are still in their early stages and testing of these platforms should continue in the tropical Pacific.

See the First Report, Recommendation 12, and Chapter 7 (***Recommendation 7.3; Action 7.6***).

4.4.2 Augment Argo with biogeochemical sensors

Current TPOS 2020 plans call for a doubling of the density of Argo floats, equatorward of 10°, relative to the current global density target of one operational float every 3°×3° (section 7.1.1.2, and the First Report). Refer to section 7.4.4 and Figure 7.19 for further details.

Section 4.3.2 made the case for augmenting regular Argo floats with biogeochemical parameters. The international BGC-Argo program recommends nitrate, dissolved oxygen, pH, chlorophyll fluorescence, particulate backscatter and downwelling irradiance as the optimal suite of parameters (BGC-Argo Planning Group, 2016). The standard configuration for SOCCOM is 5 of these parameters (irradiance is excluded). Observing system simulation experiments (OSSEs) indicate that the optimum global array is 1000 floats with at least 5 of the 6 parameters. The BGC-Argo implementation plan (BGC-Argo Planning Group, 2016, updated 2019) suggests that these 1000 floats should be distributed uniformly throughout the global ocean, although the implementation plan also suggests that higher density could be considered in areas of particular interest or importance, such as western boundary currents, upwelling systems and OMZs. The need for oxygen data in eastern Pacific OMZs could be addressed by some core Argo floats carrying dissolved oxygen sensors. A large proportion currently do. The broader goals of the BGC-Argo community would be addressed with 31 deployments per year of BGC-Argo floats in the 10°N to 10°S band. After 4 years this would sustain a tropical Pacific float array of 124 floats. This number is based on the globally uniform 1000 float target, the size of the tropical Pacific relative to the global ocean (>2000 m deep) and an average float lifetime of 4 years or 150 profiles at 10 days. The performance of the floats with respect to their longevity and sensor performance, as well as how many remain in the tropical band, should be monitored and the deployments per year adjusted as necessary (see Figure 7.19 and section 7.4.4).

> ***Recommendation 4.1.*** TPOS 2020 recommends a target of 124 BGC-Argo floats with biogeochemical sensors (specifically nitrate, dissolved oxygen, pH, chlorophyll fluorescence, particulate backscatter and downwelling irradiance) for the 10°N-10°S band.

4.4.3 CTD and bottle sampling on mooring servicing cruises

In the 1990s and 2000s when the *Ka'imimoana* was servicing TAO moorings from 95°W to 165°E, CTDs to 1000 m were performed on those lines at every degree of latitude between 8°N and 8°S, and every 0.5° between 2°N and 2°S. Each TAO line was visited roughly twice per year which equates to about 300 CTDs per year. The temperature, salinity and underway acoustic Doppler current profiler (ADCP) data from these cruises formed an important data set (Johnson et al., 2002) that was augmented with chlorophyll and nutrient samples on a routine basis for about a decade (Strutton et al., 2008), and other process studies for parameters such as primary productivity (Strutton and Chavez, 2000), oxygen isotopes (Hendricks et al., 2005), and phytoplankton physiology (Behrenfeld et al., 2006).

The TPOS 2020 Biogeochemistry Task Team recommends that, regardless of the latitudinal extent of mooring lines in the redesigned TMA, CTDs should be performed to 1000 m along each TMA line at the same spatial sampling as just described, with priority assigned to the 8°S to 8°N band. The CTD package should be equipped with dissolved oxygen and optical sensors (chlorophyll fluorescence, particulate backscatter, transmissometer), while water samples for chlorophyll and nutrients should be routine. Other parameters such as dissolved trace elements, inorganic carbon, particulate organic carbon, transient tracers, N_2O, C isotopes, hydrogen and oxygen isotopes of water, dissolved oxygen isotopes and DOC should be accommodated where possible, probably through the involvement of a motivated and funded investigator.

> ***Recommendation 4.2.*** TPOS 2020 recommends CTDs with dissolved oxygen and optical sensors (chlorophyll fluorescence, particulate backscatter, transmissometer) and water samples (at a minimum for chlorophyll and nutrients) should be performed to 1000 m along each TMA line by servicing cruises, at every degree of latitude between 8°N and 8°S and every 0.5° between 2°N and 2°S at a frequency of at least once per year. Twice per year sampling is optimal and could be augmented by GO-SHIP and other ships of opportunity.

Also refer to ***Recommendation 7.3***.

4.4.4 Continued coverage of satellite ocean color and CO_2 observations

Satellite ocean color (mostly surface chlorophyll concentration) is the best observational platform available for documenting the variability in surface ocean productivity across spatial scales from kilometers to basins and temporal scales from days to decades. Satellite data also provide important context for observations made from ships, moorings, Argo floats and other autonomous platforms. Similarly, observations from the OCO-2 (atmospheric carbon) satellite, when combined with moored pCO_2 data from the tropical Pacific, have improved our understanding of the timing of global changes in atmospheric CO_2 linked to El Niño events (Chatterjee et al., 2017). As for SST, winds and altimetry, observations from other components of the observing system contribute important validation data for satellite ocean color and atmospheric CO_2. TPOS 2020 should continue to advocate for future ocean color and CO_2 satellite missions, and the observing system design should facilitate satellite validation efforts (see First Report, Recommendation 13).

4.4.5 Strategy for the low latitude western boundary currents

As described above (section 4.1.5), the low latitude western boundary currents (LLWBCs) that feed the equatorial undercurrent are important for determining the upwelling and degassing of CO_2 in the central and eastern Pacific, and for delivering nutrients (including iron) to these same areas. The SPICE program (Ganachaud et al., 2014, 2017) and other smaller process studies (Lehmann et al., 2018) have provided important information on the relative importance of the currents that contribute to the EUC, but further work needs to be done to develop a coordinated and long term observation strategy for the LLWBCs (TPOS OceanObs'19), including the possibility of defining requirements for BGC sampling in these inflows. TPOS 2020 should continue to support process studies that further our understanding of how to quantify the volume and elemental fluxes from the western South and North Pacific into the equatorial band.

4.4.6 Pilot studies: Continue technology development to expand autonomous capabilities

TPOS 2020 should continue to provide advocacy and other support for continued development of biogeochemical observations on autonomous platforms, including but not limited to Saildrone as discussed in 4.4.1 (also see section 9.2). The biogeochemical measurements that will be routinely made by TPOS, or accommodated by process studies, provide an excellent opportunity for testing new sensors that might be incorporated into autonomous surface vehicles, profiling floats and other autonomous platforms.

Given the interest in measuring dissolved oxygen in the OMZ at the timescale necessary to develop seasonal predictions, a pilot study to test the autonomous sampling strategy is warranted. Characterizing how EUC and subthermocline zonal jet variability modulate OMZ volume in the eastern Pacific (4.1.1) will likely require oxygen sensors from at least 50 to 200 m on 95°W TMA moorings between 8°N and 8°S (see also ***Recommendation 5.3***). Further evaluation of moored profilers, such as the wave energy powered PRAWLER (section 9.2.3), as a tool for high-resolution sampling of T, S, oxygen, and chlorophyll from the surface to 500 m should also be considered (Osse et al., 2015). Pilot studies using the PRAWLER in other regions (e.g., SPURS 1&2) have already been completed, and an assessment is needed to determine whether this technology shows promise for deployment in the TMA. Incorporating this technology into the TPOS Backbone would require new processing tools at NDBC and other mooring maintenance groups, and a pilot study would be necessary as part of the transition from multiple fixed depth CTDs to one profiling sensor package.

4.4.7 Process studies to understand the impact of ENSO and long term change on carbon export and ecosystems

The TAO-TRITON array, combined with the satellite ocean color record, has a history of providing the contextual observations for interpreting biogeochemical process studies (Brzezinski et al., 2011; Dandonneau, 1999; Ishii et al., 2009; Matsumoto et al., 2004; Murray et al., 1997; Strutton et al., 2011). These contextual data have mostly been physical, such as ENSO phase, thermocline perturbations, status of tropical instability waves or passage of Kelvin waves. But with enhancements to Argo, both in spatial resolution and sensor packages, there is potential for a far richer data set of use to process studies. Evaluation of potential sampling changes, in particular for the TMA, should consider the impact on physical and biogeochemical processes. TPOS 2020 should continue to advocate for and support pilot and process studies that can assess the impacts of modifications to the observing system, particularly those that affect sampling or interpretation of biogeochemical signals.

Process studies could build off existing BGC-Argo demonstration projects as the full capacity BGC-Argo (4.4.2) is being developed. For example, in order to better understand variability of the biological pump (4.1.2), a process study could build off planned China-led BGC-Argo deployments and focus on the influence of ENSO variability on primary production in the western Pacific. This effort could also make use of existing satellite ocean color, modeling, and leveraged ship-based surveys. BGC-Argo deployments in the eastern and central Pacific could begin to address questions about variability in the upper ocean carbon budget (4.1.4). This also leverages off existing (i.e., moored and underway) and pilot (i.e., Saildrone and Wave Glider) seawater $p\mathrm{CO}_2$ observations that constrain surface ocean CO_2 flux.

Chapter 5 Developing an Eastern Pacific Observing System

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5.1 Background

The eastern Pacific (EPAC) region is arguably among the most problematic in the world for climate modeling, as oceanic processes, low-cloud physics, and tropical deep convection have complex interactions in this region that have eluded adequate representation for decades, contributing to severe biases in even state-of-the-art climate models (see Chapter 2, Figure 2.2). As discussed in Chapter 2, these biases have limited our ability to predict ENSO on seasonal to climate timescales (Barnston et al., 2015), and to evaluate its regional impacts. They also limit the use of these models for climate projections and subseasonal to seasonal predictions (Li and Xie, 2014; Xie et al., 2015).

The sharp property gradients of the eastern Pacific—vertical, meridional and zonal—form a key distinction from the rest of the basin and a major challenge to both observing and modeling, as we describe below. They demand high resolution of both measurements and models and imply that small-scale processes can be crucial.

The presence of the coast on the eastern edge of the Pacific basin, and the sub-tropical anticyclonic circulation together with the Andes ridge that forces winds to be alongshore, means that intense coastal upwelling in a boundary layer only tens of kilometers wide introduces strong cross-shore property gradients. This is difficult to model because its characteristics depend on the penetration depth of upwelling, which appears to extend through the thermocline (Kessler, 2006); the dynamics controlling this depth are not well understood and their effects are sensitive to model formulation. Beyond the property gradients it produces, the strong vertical transports due to Peru coastal upwelling act as an unusual window through the thermocline that connects the region to the basin-scale subthermocline circulation (Kessler and McCreary, 1993; Vergara et al., 2017). The coastal upwelling also serves as a link in the basin-scale transport pathways for nutrients, oxygen and heat into and out of the EPAC region.

The net surface heat flux into the ocean along the Peru-Chile coast is substantial (Colbo and Weller, 2007; de Szoeke et al., 2010), despite the cool SSTs and overlying stratus clouds in the region. Along the Chilean coast this net surface heat flux is primarily balanced by cooling from alongshore equatorward currents and offshore advection of upwelled coastal waters (Colas et al., 2012). However, closer to the equator off the coast of Peru, offshore and alongshore mean advection do not close the surface budget (Colbo and Weller, 2007; Colas et al., 2012), which has been attributed to the role of eddies transporting heat from the coastal region where they are produced. However, their effect on the mean heat budget remain unclear owing to limitations in the atmospheric forcing of the regional oceanic model (e.g., the blind zone of scatterometers, cf. Astudillo et al., 2017). Coastal processes on intraseasonal timescales have the potential to rectify onto interannual or longer-term heat budgets (Gruber et al., 2011; Renault et al., 2016) and influence ENSO development (Toniazzo et al., 2010; Dewitte and Takahashi, 2017), and are thus important to accurately represent in models.

The cold tongue of SST that extends from the South American coastal upwelling region across the equatorial east and central Pacific is a defining feature of the EPAC. The zonal SST gradient along the equator from the cold tongue to the warm waters of the western Pacific sustains the trade winds that then reinforce the zonal SST gradient. This positive feedback between the surface winds and the SST gradient across the Pacific is known as the Bjerknes feedback (section 2.6.1 of the First Report). The strength of this coupling in models has large impacts on their ability to simulate the tropical seasonal climate and ENSO (Lin, 2007; Back and Bretherton 2009a, b; Takahashi and Dewitte, 2016; Bayr et al., 2018). In addition to the zonal SST gradient, the northern edge of the cold tongue is defined by a sharp meridional front near 2°–5°N, where strong shear between the zonal currents generates instabilities known as tropical instability waves (Philander et al., 1986). The TIWs are known to be important in the surface-layer heat budget, producing an equatorward heat flux comparable in magnitude to equatorial upwelling (Bryden and Brady, 1985). TIW amplitude tends to decrease during El Niños and increase during La Niñas, contributing substantially to cold tongue heat balance variability, but the mix of processes involved remains poorly understood (e.g., Graham, 2014; Holmes et al., 2018). Below the surface, the equatorial thermocline is sharper and shallower in the east than in the central and western equatorial Pacific. Coupled models have difficulty simulating the cold tongue region, with persistent cold biases in SST, weak TIW amplitudes, excessive upwelling strength, and erroneous subsurface temperature structure evident in the majority of even the most recent models (e.g., Zheng et al., 2010; Figure 5.1).

The atmosphere in the EPAC is characterized by a set of regime transitions: from the intertropical convergence zone (ITCZ) north of the cold tongue front, to the cold tongue itself, to the stratus region across a vast region to the south (Raymond et al., 2004; de Szoeke et al., 2005; Cronin et al., 2006). Precipitation and SST are strongly coupled with wind (e.g., Mitchell and Wallace, 1992; Xie and Philander, 1994; Takahashi and Battisti, 2007a, b) seasonally driven by insolation. The Southern Hemisphere is dry for most of the year, yet a Southern Hemisphere ITCZ typically appears during boreal spring when the equatorial EPAC SST is warmest (Xie et al., 2018). Coupled models, as well as some atmosphere-only models (Zhang and Wang, 2006), have a persistent "double ITCZ" bias, referring to a spurious year-round Southern Hemisphere ITCZ over erroneously warm SSTs (e.g., Lin, 2007; Hirota et al., 2011; Li and Xie, 2014). Complex coupled processes in the EPAC link model cold tongue biases with the double ITCZ bias (Lin, 2007; Li and Xie, 2014), making it difficult to disentangle cause from effect.

The First Report (section 6.2.4) raised several high-priority science questions related to the atmosphere-ocean system in the EPAC. Here, we review those questions and map a course for addressing them through both engagement with regional efforts, as well as pilot and process studies. The engagement activities seek to take advantage of the diverse observations that stakeholders in the EPAC region have collected independently over many years; a deliberate effort on the part of those stakeholders will be required to organize these into centralized, quality-controlled data sets to meet research and operational needs throughout the region. TPOS 2020, along with other global programs, is an opportunity for stakeholders to engage in particular activities with clear scientific objectives and outcomes meeting the goals of the larger programs as well as those of the individual stakeholders.

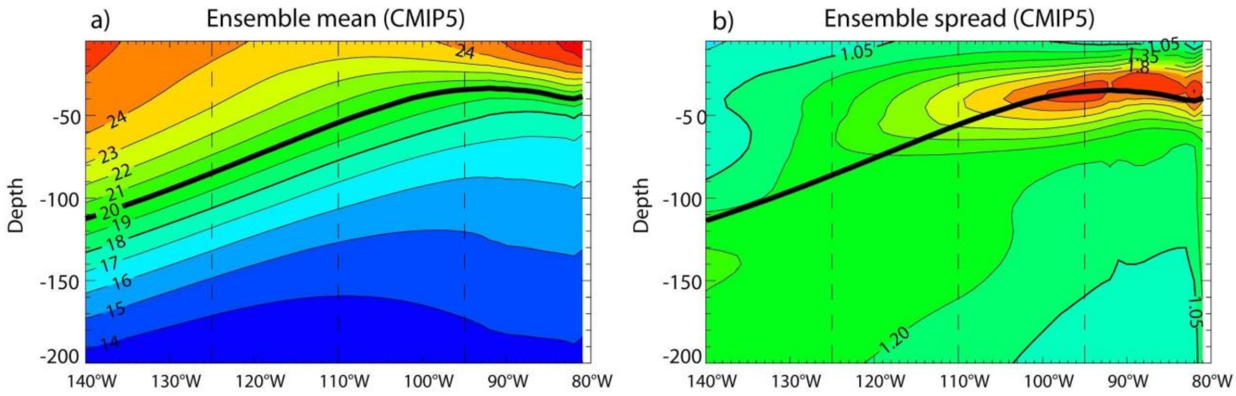

Figure 5.1: (a) Ensemble mean of temperature and (b) Ensemble spread of mean temperature among CMIP5 models. The ensemble mean thermocline depth is overplotted (black thick line). The ensemble models consist of the 19 models that have a realistic ENSO diversity compared to observations (see Cai et al., 2018). The vertical dashed lines indicate the longitudes of the TAO/TRITON buoys.

The proposed EPAC pilot and process studies described here seek both to improve understanding of the distinct regional processes that would advance model representation of the EPAC, and to define the sustained observations that would most effectively constrain state estimates and model solutions in this complex region. In addition, the pilot and process studies are a means of engaging stakeholders in the region around specific objectives that may then lead to further long-term cooperation on research and operational needs, while addressing shared near-term goals. This chapter is organized as follows. First, we provide a background on the scientific questions that were evaluated as highest priority in the First Report. Second, we suggest specific engagement activities that could lead to successful pilot and process studies. These more in-depth discussions are followed by a list of recommendations.

5.1.1 Monitoring and predicting ENSO

Because of the societal impacts of SST anomalies in the EPAC, the TMA was initially designed with El Niño events that have maximum anomalies in the EPAC in mind. However, recent literature reveals a diversity in the longitude of ENSO events (Capotondi et al., 2015b) and suggests that extreme El Niño events involve processes rooted in the far EPAC, i.e. east of 95°W (Takahashi and Dewitte, 2016). This diversity can generally be divided into two ENSO regimes (Takahashi et al., 2011), one associated with maximum SST anomalies in the EPAC (hereafter EP El Niño), and the other with maximum SST anomalies centered in the central Pacific (also called Modoki or warm pool El Niño events, hereafter CP El Niño). Extreme El Niño events are of eastern Pacific type, while strong or moderate El Niño events can be found in either the central or eastern Pacific, at least during the recent few decades of observation. La Niña events tend to exhibit less diversity in both longitude and amplitude (Timmermann et al., 2018).

As the occurrence of CP El Niños has increased since the 1990s, the inherent predictability of ENSO-related fluctuations appears to have declined despite improvements in models (Wang et al., 2010; Barnston et al., 2012). This is thought to be related to weaker recharge-discharge (meridional mass exchange with off-equatorial regions; Jin, 1997) during CP El Niños compared to EP events. As a consequence, the predictive value of the equatorial warm water volume increase that preceded El Niños prior to 2000 has been reduced in recent decades (McPhaden, 2012; Neske and McGregor, 2018). The relative cooling of SST east of the dateline while the Indo-Pacific to the west warms (Figure 6.2c) may also make it harder for deep convection to migrate to the EPAC, suggested by the lack of atmospheric response to the 2012 and 2014 warm events (McPhaden, 2015). Climate models indicate that a gradual surface warming trend in the Pacific and associated increased vertical stratification will further destabilize ENSO and yield an increased variance of SST anomalies in the EPAC (Cai et al., 2018).

ENSO diversity also appears to involve nonlinear processes localized to the EPAC that can be activated concurrently during strong to extreme El Niño event (Jin et al., 2003; Dommenget, 2010; Frauen and Dommenget, 2010; Takahashi and Dewitte, 2016). Recent studies indicate that large equatorial heat content anomalies (i.e., recharge) are neither a necessary nor sufficient condition for strong El Niños to develop (Menkes et al., 2014; Takahashi and Dewitte, 2016) and that stochastic forcing by easterly wind bursts in the EPAC have the potential to stall the development of EP El Niño (Hu and Fedorov, 2016) or damp its peak amplitude, as during the 2015/16 El Niño (Dewitte and Takahashi, 2017). We note that uncertainties in wind products continue to be a barrier to quantifying the relative importance of westerly wind bursts and easterly wind bursts in the development of SST anomalies (Chiodi and Harrison, 2017a; see also Action 6.2). In addition, the zonal wind response to SST is nonlinear in the EPAC, being strongly enhanced above a certain SST threshold, likely contributing to the sensitivity to stochastic wind forcing in this region (Takahashi and Dewitte, 2016). This evolution in our understanding of El Niño dynamics in recent years (Timmermann et al., 2018) suggests the need to revisit paradigms established during the early period of TOGA (Neelin et al., 1998) that have served as the pillars of ENSO research to date.

Despite the importance of the EPAC in ENSO dynamics, this region has been relatively undersampled by the in situ observing system (see Figure 5.2a). Even the SST-thermocline connection, key to the Bjerknes feedback, is poorly constrained in both reanalysis products (Figure 5.2) and coupled models (Figure 5.1). ENSO nonlinear processes, like those referred to above, are diversely simulated in climate models and reanalysis products (Su et al., 2010; Bayr et al., 2018; Cai et al., 2018). In addition, reanalysis wind stress products show significant biases affecting their ability to provide adequate forcing to ocean models for predicting SST anomalies (Chiodi and Harrison, 2017b). Thus, an important role for the TPOS is to enable improvements in data products and model parameterizations and physics for this region.

Better constraining the mean thermal structure in the shallow far eastern Pacific in reanalysis products is essential for ENSO forecasting. The mean thermal structure influences a number of diabatic processes including diapycnal mixing, eddy-induced transport, and short-wave penetration which are important to ENSO (Lengaigne et al., 2012), and can in turn rectify onto the mean state. The sharp and strongly tilted thermocline also influences the way wind fluctuations in the central-western Pacific (i.e., westerly wind bursts) transmit their energy to the east through the propagation of equatorial waves. Equatorial Kelvin waves change character (amplitude, vertical structure) near 120°W, where the thermocline slope is maximum and the thermocline itself shallows (Busalacchi and Cane, 1988; Dewitte et al., 1999; Cravatte et al., 2003; Mosquera-Vásquez et al., 2014). These waves can also interact with TIWs in a two-way feedback (Qiao and Weisberg, 1998; Holmes and Thomas, 2016), which influences the heat and momentum budgets of the large-scale flow, and thus potentially the development of ENSO (Holmes et al., 2018). Clarifying the mixed-layer oceanic heat budget in the far EPAC and its relationship with equatorial wave activity is essential for improving our predictive capabilities of strong to extreme El Niño events and make progress in the mechanistic understanding of the growth of SST anomalies in the EPAC during these events (section 5.1.3).

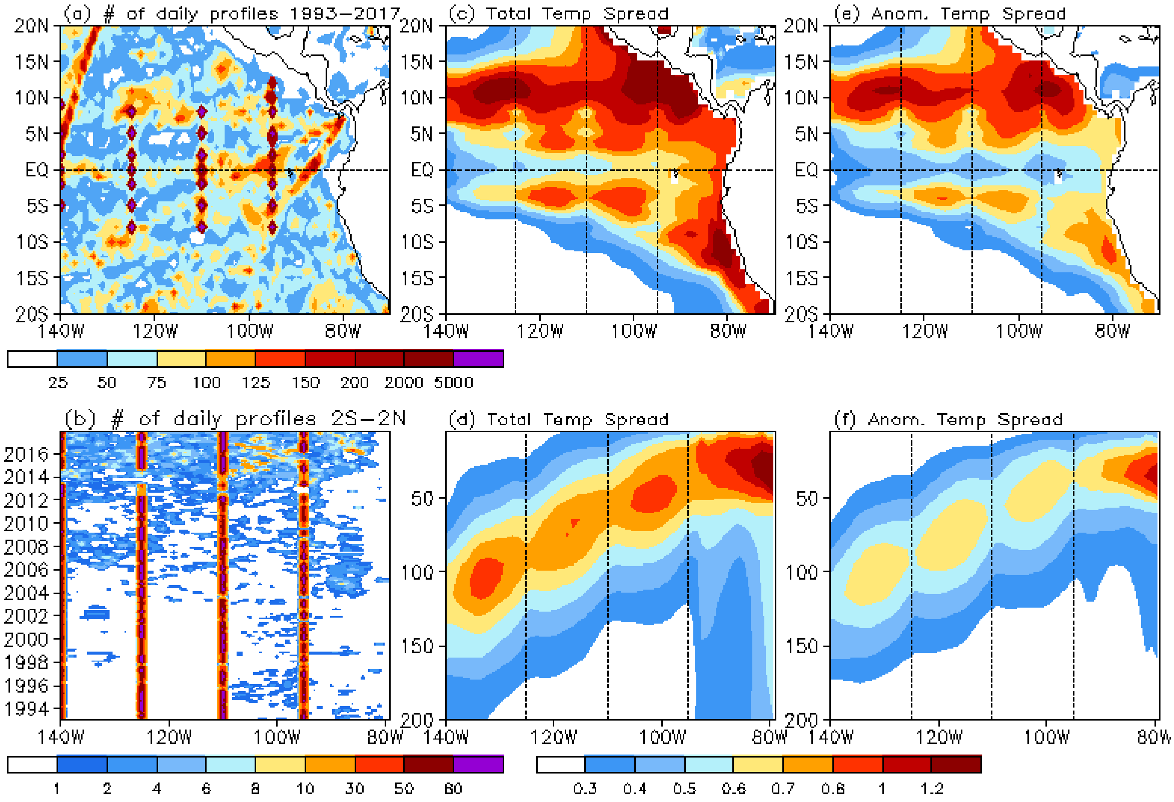

Figure 5.2: (left) The data counts (number of daily temperature profiles per month in each one degree box), the ensemble spread of (middle) total temperature and (right) anomalies for the period 1993–2017 among seven reanalysis products (See Figure 10 in Xue et al., 2017a for details) averaged over (top) the upper 200 m and (bottom) the equatorial band (2°S–2°N). (a) shows the total data counts in 1993–2017 and (b) shows the temporal evolution of the data counts in the equatorial band (2°S–2°N) each averaged over the upper 200 m. Note that the relatively high data density east of 95°W during 1994–2008 is mostly from XBT profiles, while from 2014 it mostly corresponds to data from Argo floats. The vertical lines in (c)-(f) indicate where the TAO/TRITON buoys are located.

Recent research has also highlighted regional coupled modes in the far eastern equatorial Pacific that could either act as an external forcing to ENSO and counteract the development of EPAC El Niño events (Dewitte and Takahashi, 2017), or yield coastal events off Peru and Chile (Takahashi and Martinez, 2017; Takahashi et al. 2018). The South Pacific meridional mode (SPMM), linking Southern Hemisphere extratropical atmospheric forcing to SST anomalies in the EPAC through wind-evaporation-SST feedbacks (Zhang et al., 2014), also appears to have a role on the development of EPAC El Niños (Zhang et al., 2014; Larson et al., 2018).

Overall, these studies indicate that the perceived role the EPAC plays in ENSO has evolved since the era when the TMA was first implemented. The EPAC is not only important for the deterministic ENSO processes, but also hosts and/or modulates potentially important sources of external forcing for ENSO (e.g., TIWs, Holmes et al., 2018; northern tropical Atlantic SST, Ham et al., 2013). Convection reaching the EPAC has been a signature of the El Niño events that have predominantly contributed to the El Niño composite seasonal weather anomaly over North America and global precipitation anomaly over the time for which convective activity information has been available from satellite-based measurements of outgoing longwave radiation (OLR; Chiodi and Harrison 2013, 2015). Better understanding what pushes or limits this spread of convection would likely have direct benefit to our ability to forecast ENSO-associated influences on seasonal weather. The recommendations for the EPAC observing system must reflect this evolution in thinking.

5.1.2 Addressing model biases: Waves and dissipation processes

The TPOS needs to provide measurements at fine spatial scales (vertical and horizontal) in order to improve the simulation of frontal zones, like the equatorial thermocline, the northern edge of the cold tongue and the coastal upwelling off Peru, where mixing and diffusive processes are important. Current reanalysis products have clear biases and deficiencies in these regions. Comparison of ocean reanalysis products highlights the dependence of the ocean models on the TMA and Argo observing system for reducing model errors, particularly above 300 m depth (Xue et al., 2017a). In the EPAC, such errors are most pronounced in the surface layer in the ITCZ and Peru upwelling regions, and in the subsurface in the vicinity of the equatorial thermocline (Figure 5.2). Uncertainty in atmospheric forcing (Taboada et al., 2018) and vertical propagation of these fluxes in the ocean are also known issues contributing to spread in ocean reanalysis SST under the ITCZ and SPCZ (Martin et al., 2015). Uncertainty in upper ocean temperatures to 100 m depth is particularly large in the far eastern Pacific (Figure 5.2), motivating a focused effort on improving observations, models and data assimilation systems (Chapter 2) in this region. Additional uncertainty in the ocean climatology of the far eastern Pacific and its potential to shift with new measurements in the region also impacts estimates of ensemble spread in ocean reanalysis products (Xue et al., 2017a) and further highlights the need for long term stability of observations across the basin.

While improvement in the realism of ocean reanalysis products is a high priority for TPOS, enhanced Argo profiling (section 7.3.2) offers the potential for improving our understanding of dissipation processes associated with planetary ocean waves, the conduit by which energy is transported rapidly from the surface to the deep ocean and zonally. Historically, the TMA has been invaluable for documenting oceanic equatorial wave activity during ENSO, although it is only with the emergence of altimetry in the late 90s that the first paradigms of ENSO could be tested. Altimetry provides a synoptic view of equatorial waves (Perigaud and Dewitte, 1996; Boulanger and Fu, 1996; Boulanger and Menkes, 1999) assuming the one-baroclinic mode approximation (i.e., considering that the sea level anomaly measured from altimetry is proportional to thermocline fluctuations). The additional information on the vertical structure of the waves provided by Argo combined with altimetry should allow better estimates of wave coefficients from which we can infer dissipation (i.e., scattering of energy associated with the zonally varying thermocline). Observations of upper ocean state variables collected by regional stakeholders would allow validation of the methods to derive this dissipation process from Argo and satellite data, and investigation of its impact on SST anomalies along the equator and along the coasts of Peru and Ecuador.

Improving our understanding of the dissipation process of the equatorial Kelvin wave is a prerequisite for addressing the oceanic teleconnection along the coast of Peru and the interaction with coastal upwelling dynamics, which has urgent societal implications including impacts on sustainable management of marine resources and biodiversity. A detailed plan to observe the coastal upwelling system was not part of the original TPOS design, although it is a source of variability (circulation and biogeochemistry) for the broader South East Pacific through cross-shore eddy fluxes (Toniazzo et al., 2010; Vergara et al., 2016) and its coupling with the overlying atmosphere (Toniazzio, 2010; Chelton and Xie, 2010; Dewitte and Takahashi, 2017). Investigation of Peru upwelling dynamics is thus viewed as a requirement for improving understanding of processes in the whole EPAC. Although some progress could be made from modeling, there is also an observational need that will have to be met through collaborations with institutions in Peru and Ecuador, considering in particular limitations of satellite winds (scatterometers) and reanalysis products in the coastal zone (Figure 5.2).

5.1.3 Cold tongue/ITCZ dynamics and cloud feedback

In the EPAC the ITCZ constitutes the regional component of the upward branch of the Hadley circulation (Figure 5.3). On interannual timescales, variability of precipitation in this region is dominated by ENSO SST anomalies that lead to the meridional displacement of the ITCZ (Cai et al., 2014). The southern branch of the ITCZ that appears seasonally in boreal spring, can be intensified in some years and may contribute to ENSO development in the EPAC (Xie et al., 2018) and to coastal El Niño events off Peru and Chile (Takahashi and Martinez, 2017; Xie et al., 2018; Takahashi et al., 2018). The coupling between the ITCZ and SST provides nonlinear feedbacks into the ENSO system (Lloyd et al., 2012; Dommenget et al., 2012; Takahashi and Dewitte, 2016) including those described in sections 5.1.1 and 5.1.2.

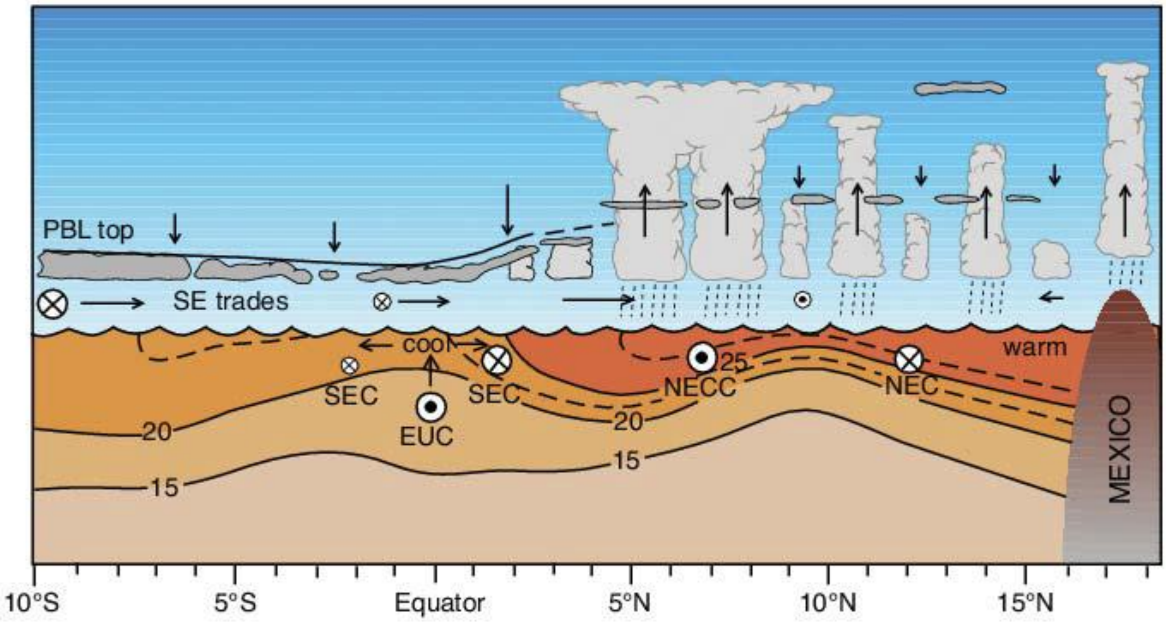

Figure 5.3: Idealized cross section through the ITCZ–cold tongue complex in the east Pacific showing the atmospheric meridional circulation, atmospheric boundary layer depth, and the oceanic thermal structure. SEC refers to the South Equatorial Current, NECC to the North Equatorial Countercurrent, NEC to the North Equatorial Current, and EUC to the Equatorial Undercurrent. The heavy cloud denotes the position of the ITCZ. Encircled x's (dots) denote westward (eastward) flowing winds or currents. Adopted with permission from Raymond et al. (2004).

The cold tongue bias in models is thought to be primarily associated with the representation of the Bjerknes feedback (Lin, 2007; Li and Xie, 2014; Bayr et al., 2018). It is enhanced by the unrealistic meridional alternation of the ITCZ between the hemispheres on seasonal timescales (de Szoeke and Xie, 2008). Uncertainties in cloud physics and planetary boundary layer (PBL) parameterizations are primary contributors to errors in models (e.g., Figure 5.4) and limit our ability to pinpoint the main source of the SST and double ITCZ biases.

In addition to the double ITCZ/cold tongue bias, south of the equator and along the eastern boundary in the vast stratus region, coupled models and reanalyses consistently underestimate the frequency of low cloud, resulting in overestimation of the net surface heat flux in the region (e.g., Cronin et al., 2006; de Szoeke et al., 2012). These errors likely contribute to the warm SST bias there (Figure 2.2), along with model deficiencies in ocean processes discussed in section 5.1.2., and errors in cloud microphysical properties (Bretherton et al., 2010; IPCC, 2013; Figure 5.4). Disentangling microphysical and dynamical processes in stratus clouds poses a challenge for the current observing system (Rosenfeld et al., 2014; Grosvenor et al., 2018). More in situ observations of clouds and the boundary layer in stratus regions continue to be needed for validating both high-resolution model microphysical parameterizations and satellite retrieval algorithms. Use of islands in the region is one way to provide such observations on diurnal to seasonal timescales.

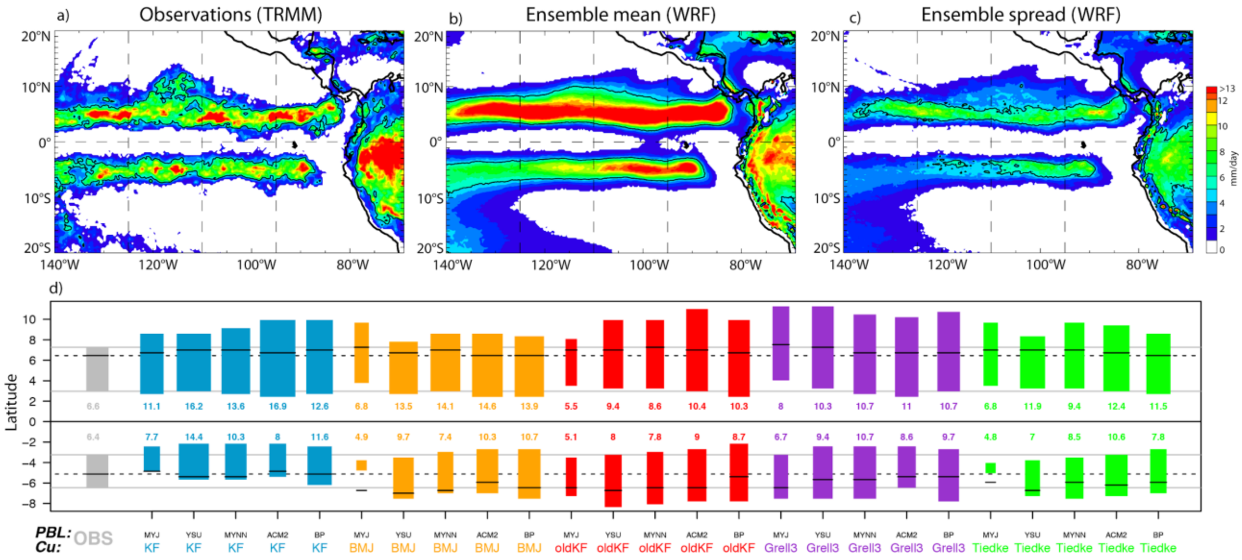

Figure 5.4: Sensitivity of precipitation within the ITCZ in the EPAC to cumulus (CU) and PBL parameterizations in WRF (horizontal resolution = 30 km): (a) mean precipitation for March 2007 from TRMM, (b) ensemble mean and (c) standard deviation for precipitation in 25 simulations of March 2007 using different combinations of 5 CU and 5 PBL parametrizations, and (d) characteristics of the ITCZ over the two regions regions (0°-15°N,130°W-100°W) and (0°-15°S,130°W-100°W) in observations (gray bars) and the 25 simulations (color bars): Bars indicate the latitudinal extension of the branches of the ITCZ. The thick black line indicates the latitude of the relative maximum precipitation during this month. The number near each bar provides the value of total precipitation and the bar thickness is proportional to this value. The vertical lines indicate where the TAO/TRITON buoys are located. Modified from Tapiador et al. (2018).

The inability of the current observing system to constrain models and satellite retrievals of important atmospheric parameters, including lower tropospheric water vapor and air temperature (sections 6.3.2 and 9.3.2), precipitation and evaporation (Tapiador et al., 2018), cloud properties (Rosenfeld et al., 2014; Grosvenor et al., 2018), and convective heating profiles, inhibits progress in improving model representation of the EPAC and has broader consequences for the tropics as a whole. For example, satellite based retrievals indicate that the vertical structure of convective heating is maximum in the mid-upper troposphere (Schumacher et al., 2004; Huaman and Schumacher 2018), but reanalysis products indicate that ascent is shallow (Back and Bretherton, 2006, 2009a,b), consistent with the direct observations of a strong and variable shallow overturning circulation in this region (Zhang et al., 2004; de Szoeke and Bretherton, 2005). The vertical structure of the latent heating is of particular importance to ENSO, since it has substantial influence on the surface wind response that is key for the Bjerknes feedback (Nigam et al., 2000; Nigam and Chung, 2000; Wu, 2003). Knowledge of these profiles is also crucial for understanding the overall atmospheric energy budget (e.g., Peters et al., 2008). A shallower profile would require strong horizontal moisture and temperature advection into the ITCZ to close the energy budget, which also has implications for climate change. More generally, the latent heating profile in the tropics has direct impacts on the tropical circulation (Schumacher et al., 2004; Yuan and Hartmann, 2008) and teleconnections with midlatitudes. Observations of the EPAC from the ITCZ to the stratus region on subseasonal to interannual timescales are important for resolving such long-standing issues.

5.1.4 Oxygen Minimum Zone (OMZ) dynamics

In the EPAC, the equatorial and coastal upwelling brings to the surface cold nutrient-rich waters resulting in phytoplanktonic blooms that have large-scale consequences. The far EPAC contains the most productive oceanic ecosystems in the world, and many livelihoods depend on a variety of marine products that contribute significantly to local and international economies and local cultures. Owing to the relatively sluggish subthermocline circulation combined with the export of particulate organic carbon from the coastal region, the EPAC is also the site of the most extended OMZ (Figure 5.5 and sections 4.1.1 and 4.2.1) in the world, involving complex biogeochemical processes (Paulmier and Ruiz-Pino, 2009).

The OMZ in the EPAC is the largest oceanic area where oxygen concentrations are reported to fall below the detection limit of the most sensitive oxygen sensors (STOX sensors, ~10-100 nM; Kalvelage et al., 2013). The EPAC connects tropical climate variability to the pathways extending from the equatorial subsurface currents (EUC, primary and secondary South Subsurface Countercurrents) to the coastal current systems (Montes et al., 2011), that also contribute to OMZ variability. OMZ variability is tied to local mesoscale processes and oxygen transport by the equatorial subsurface currents (Montes et al., 2014), but physical control of EPAC OMZ variability remains unclear at interannual (Graco et al., 2017) and longer timescales (Stramma et al., 2008). Model results suggest that remote equatorial variability is a main driver at a variety of timescales (Montes et al., 2014; Duteil et al., 2018). However, there is no consensus on the long-term trend of the tropical OMZ between models and observations (Stramma et al., 2012; Cabré et al., 2015), emphasizing a need for clearer observational description of fundamental aspects of the OMZ from dedicated observational experiments and long-term monitoring. Considering the scarcity of oxygen data and the global model deficiencies (Breitburg et al., 2018), the use of BGC-Argo floats in the EPAC (section 4.4.2) along with a pilot program to instrument moorings along 95°W with oxygen sensors (4.4.6) will allow a quantitative step in our understanding of the OMZ dynamics on the climate system on both subseasonal and longer timescales (see also sections 4.1.1 and 4.2.1).

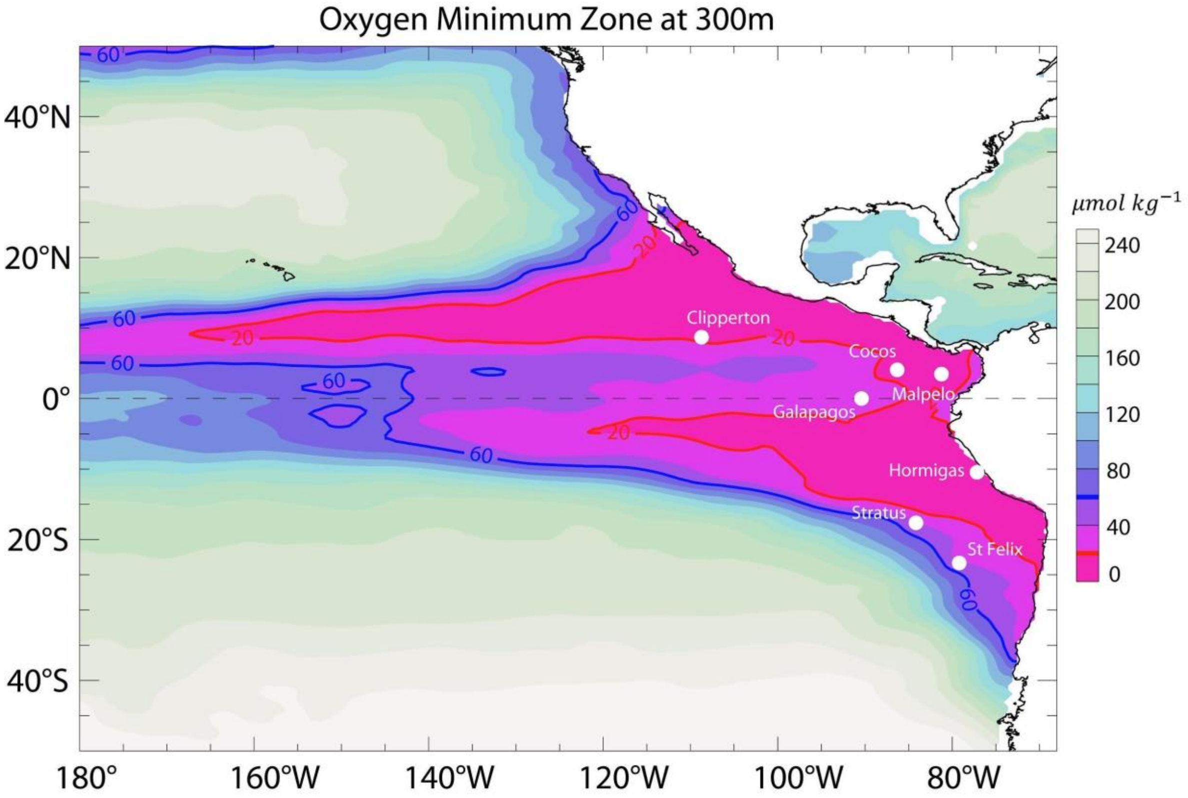

Figure 5.5: Horizontal distribution of annual mean oxygen concentration at 300 m depth extracted from CARS (CSIRO Atlas Regional Seas). Contours of 20 (red) and 60 (blue) µmol kg^{-1} represent the suboxic (OMZ core) and hypoxic waters, respectively. The location of the islands mentioned in section 5.3.3 are indicated, along with the location of the Stratus mooring.

5.2 Enabling regional activities

Oceanic and biological conditions in the coastal regions of the EPAC are monitored by the countries along the west coast of South America for ecosystem management. While there is currently no regional coordination in the framework of TPOS 2020, the Permanent Commission for the South Pacific coordinated several annual cruises for El Niño monitoring and the GOOS Regional Alliance for the Southeast Pacific (GRASP) provides a framework for data sharing and standardizing protocols for making measurements. At the most recent World Meteorological Organization (WMO) Regional Association III (South America) meeting, 21–23 November 2018, regional members of the WMO were urged to share operational meteorological and oceanographic measurements with the WMO Information System (WIS, including a modernised and more capable Global Transmission System or GTS). This resolution is a first step in organizing a data sharing effort in the region and may provide the necessary framework for further resolutions on data quality control and measurement standards. The Argo network is another key component of the observing system in this region. The objective of doubling the density of coverage for the TPOS region (see First Report and sections 7.1.1.2 and 7.3.2) combined with the BGC requirements (section 4.2) would amount to roughly 8–9 additional deployments per year just for the EPAC (east of 95°W; section 7.4.4) and would require participation by regional partners. TPOS 2020 advocacy will be needed to encourage the coordination of South American countries in meeting the observational needs of the far eastern Pacific region.

It is important that TPOS 2020 also provide a framework for regional coordination going forward, for TPOS 2020 recommendations for the EPAC to most closely align with regional needs. One activity that TPOS 2020 could facilitate is the construction of an ocean reanalysis product for the region, making use of past and current data sets including those from the World Ocean Database (WOD), satellites and Argo floats, as well as new hydrographic sections between the Galapagos Islands and the coast. Recent results suggest assimilating satellite SST and sea surface height (SSH) data improves representation of upwelling fields off the coast of Chile (Aiken, 2017). Developing a regional configuration of the Mercator Ocean system (already available over the global oceans at 1/12°) at 1/36° would take advantage of expertise within the TPOS 2020 Project. Use of additional regional models, such as the Regional Ocean Modelling System (ROMS; Shchepetkin and McWilliams, 2005) used by Aiken (2017), as well as an ensemble approach to the hindcast simulations, would permit evaluation of the uncertainty in the gridded ocean products produced from this activity.

The rationale for a regional oceanic reanalysis product is required because global reanalyses still have significant biases off the coasts of Peru and Chile (sections 5.1.2 and 5.1.3). For instance, atmospheric reanalysis products overestimate upwelling favorable winds (Astudillo et al., 2017), while present generation scatterometer retrievals are less reliable near the coast, providing no data within 25 km of the coast. These limitations degrade simulations of upwelling and confuse its dynamical interpretation, with regional ocean models yielding a significant cool bias and an overestimation of the turbulent flow (Combes et al., 2015; Cambon et al., 2013). Evaluating the sensitivity of regional ocean models to errors in the assimilation products, particularly atmospheric products, is required to design an optimal observing system in the region. Such an evaluation would also offer the opportunity to better define the sensitivity to elements of the observing system near the coast, by providing an OSE framework to learn how individual sites affect ocean analyses that would ultimately be used for ENSO forecasting (see ***Recommendation 5.4***).

In addition, TPOS 2020 could provide a collaborative framework so Peruvian institutions work with outside agencies to assess the impact of their in situ SST observations on data products such as NOAA's optimum interpolation (OI) SST (Banzon et al., 2016; Reynolds et al., 2007) and extended reconstructed SST (ERSST; Smith and Reynolds, 2004), which would provide evidence for the importance of sharing such data in real time as part of the Backbone observing system for improving the products for monitoring in Peru and potentially other nearby partners. Furthermore, since SST products are an important input to forecast model assimilation, this could potentially also improve ENSO predictions near the coast. OSEs could later be carried out to assess the impact of these data on analyses and forecasts. The implementation of real-time surface data sharing via the WIS (see section 8.3; Figure 8.2), with the help of the Peruvian weather service (SENAMHI) and JCOMMOPS[16], could eventually lead to sharing of subsurface data. Through GRASP, this could be extended to the other countries in the southeast Pacific and is in line with the recommendations of the WMO Regional Association III's latest

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[16] The Joint Technical Commission for Marine Meteorology (JCOMM) in situ Observations Programme Support Centre http://www.wmo.int/pages/prog/amp/mmop/jcommops.html

report. For this reason, the TPOS 2020 Eastern Pacific Task Team places a high priority on this exercise.

South American countries such as Peru rely heavily on meteorological and oceanographic data collected by private companies for their operational needs, but the data availability and quality from these sources is not standardized or well documented. TPOS 2020 should recommend that a database be created for past and current data collected in the region so that data quality and long-term trends in meteorological and oceanographic parameters can be estimated, providing valuable information to both the private sector and the people of the region. Companies collecting these data have indicated their willingness to cooperate, making this an opportune time to organize such an activity.

Through exercises of this nature, TPOS 2020 has the potential to both advance scientific knowledge of ocean processes near the coast of South America and their connection to the equatorial EPAC, as well as provide a framework for cooperation among the government and academic communities in the region to build an observing system specific to their real time forecasting needs. TPOS 2020 must take advantage of current efforts in the region to share meteorological and oceanographic data collection and distribution, through planned activities that address 1) data sharing, 2) data quality and measurement practices, and 3) outage tolerance of each data set. Planned activities that address and solve these issues will bring the most benefit to the region and are of the highest priority for the TPOS 2020 Eastern Pacific Task Team (also see the discussion in Chapter 8).

5.3 Toward an enhanced and sustainable EPAC Backbone

Further progress in our understanding of the mechanisms governing climate variability and predictability in the EPAC and of its impacts, in particular for ENSO, requires enhanced observing capabilities in this region, through a combination of existing remote and in situ technologies and appropriate TMA network design (e.g., First Report). More specifically, an East Pacific observing system design will need to consider the coastal transition zone (coastal upwelling system), equatorial upper ocean nonlinear processes, the dynamic and thermodynamic structure of the atmosphere across the region, air-sea fluxes including surface radiative fluxes, the OMZ, and external ENSO forcing such as the SPMM. The First Report (section 6.2.4) recommended a pilot study of surface winds, ocean currents and other ocean properties east of the Galapagos Islands, to assess observational needs and the best strategy for obtaining observations within the coastal upwelling zone and transition zone between the coast and the equatorial cold tongue region.

In addition, the First Report (section 6.1.5) recommended exploring a pilot study using island measurements to obtain atmospheric vertical structure in the ITCZ and a process study to gather information on the atmosphere and ocean across the ITCZ/cold tongue/stratus region. This section develops these recommendations further to more specifically address the scientific issues discussed in section 5.1. The intended outcome of these pilot and process studies is not only a better understanding of the dominant processes in the region, but also the needed observations required for monitoring these processes in real time to better inform society on weather to climate timescales.

5.3.1 Eastern Pacific equatorial-coastal waveguide and upwelling system

Regional agencies already collect observations of the ocean and biogeochemistry within the far eastern region, especially within their EEZs. Organizing and coordinating these could lead to defining a pilot study that might point to further sampling, as well as model evaluations. The goal would be better understanding of the necessary sustained observations for the benefit of the region and global downstream impacts, including:

- the development and evaluation of methods for deriving equatorial and coastal wave amplitudes based on altimetry and Argo data;
- evaluation of the oceanic teleconnection from the central equatorial Pacific to the coasts of Peru and Ecuador;
- improved understanding of diabatic processes in the momentum and heat budgets, and the observations needed to better constrain those processes in models; and
- testing strategies for monitoring oxygen and transport of water mass properties by the subthermocline zonal jets to the Peru-Chile undercurrent, the conduit by which the OMZ is influenced by equatorial variability (see sections 4.1.5, 4.2.1).

Recently, Peru has developed plans for a glider program off the Peruvian coast starting in 2020, which would provide important information on the subsurface (to 200 m) ocean structure and biogeochemistry of the near-shore region and help to evaluate the oceanic teleconnection between the equatorial waveguide and the coast. Together with existing near-shore programs for monitoring coastal upwelling conditions including temperature, salinity, current and oxygen profiles at historical sections, and regional engagement activities such as the ocean reanalysis project and OSEs (section 5.2), a regional sustained observing system could extend beyond the pilot program and contribute to the TPOS Backbone observing system.

5.3.2 East Pacific ITCZ/cold tongue/stratus system

With the persistent uncertainties in reanalysis and remote sensing in the EPAC ITCZ, SST biases in the cold tongue and stratus regions, and the perpetual double ITCZ south of the equator in coupled models, better observations of the atmosphere and upper ocean across the region are required. To guide what these observations should be we looked to the East Pacific Investigation of Climate 2001 (EPIC 2001; Raymond et al., 2004) study, which provided invaluable in situ information on the vertical structure of the ITCZ (Zhang et al., 2004; de Szoeke et al., 2005) and stratus clouds (Bretherton et al., 2010). While much was learned from this study, it was limited to October when the double ITCZ is not present in nature and could not provide information about the variability of the ITCZ and related atmospheric circulations and thermodynamic structure on interannual timescales associated with ENSO. To address these issues the TPOS 2020 Eastern Pacific Task Team, with input from the broader scientific community interested in this region, proposes a twofold approach: 1) A process study to capture a cross section of the atmosphere, clouds and upper ocean when the double ITCZ is present in nature; 2) A longer term island monitoring pilot study to place the process study observations in the context of seasonal to interannual variability in the atmosphere across the region. A pilot program to monitor atmospheric profiles from islands is discussed in section 5.3.3. Here, we discuss an outline for a process study of the ITCZ/cold tongue/stratus system that would focus on the South Pacific ITCZ (SPCZ) where models have the most difficulty.

Leveraging the EPIC 2001 observations collected throughout October 2001, a weak La Niña year, a process study similar to EPIC 2001 but in March of ideally an ENSO neutral year could be done. EPIC 2001 instrumented the TAO 95°W mooring line with radiation and rainfall sensors, providing bulk air-sea fluxes and cloud radiative forcing across the cold tongue/SPCZ/stratus region. A similar approach is suggested for the follow-on process study, making use of the recommended enhanced full-flux capability (Tier 1-type mooring; see section 7.3.1.1) for the Backbone along 95°W (section 7.3.1.2, Figure 7.4b). The process study would supplement the Backbone observations with a north-south transect along 95°W, from the cold tongue (at its seasonal warmest) south across the SPCZ, into the stratus region, of atmospheric winds, temperature and humidity profiles, surface heat fluxes, precipitation, cloud properties, latent heating profiles from Doppler radar observations (e.g., Mapes and Houze, 1995), and upper ocean measurements. Autonomous surface platforms such as Saildrones or Wave Gliders (Chapter 9) could additionally be used to observe the upper ocean and surface heat fluxes across the SPCZ and within the stratus region. The main objectives of this study are to:

- Capture equatorward meridional circulations in the free troposphere, including heat and moisture fluxes between wet and dry zones when the cold tongue is at a minimum and the SPCZ is active;
- Capture latent heating profiles for individual storms along a north-south transect for use in estimating the vertical structure of this parameter with latitude across the region;
- Characterize the surface branch of the meridional circulation across the cold tongue and into the Southern Hemisphere and co-located ocean-atmosphere coupling when the cold tongue is at a minimum and the SPCZ is active;
- Compare the processes controlling stratus cloud thickness and extent for the opposite season background state in the southeast Pacific from that observed during EPIC 2001;
- Characterize the effect of ocean mesoscale eddies on the upper ocean heat budget in the southeast Pacific based on the combined use of modeling and data from autonomous platforms and compare with results from EPIC 2001; and
- Provide in situ data sets for coupled model validation during the opposite season as EPIC 2001 in the cold tongue/SPCZ and stratus regions.

It is strongly encouraged that this process study be considered in conjunction with TPOS 2020 pilot programs testing new technology such as Saildrones and Wave Gliders. Together with shipboard measurements, these platforms could be used to provide spatial information on the upper ocean and air-sea fluxes across the cold tongue/SPCZ/stratus regime, contributing to a more robust classification of the processes dominating these regimes and the ability of remote platforms to capture those processes. The outcome of this process study, particularly if additional spatial information from autonomous platforms is collected, would be a unique look at the tropical Southern Hemisphere ITCZ, including associated atmospheric circulations, upper ocean structure, atmospheric boundary layer, and air-sea coupling. These observations will contribute to our understanding of the double ITCZ in nature, as well as provide invaluable in situ information for validating surface forcing and ocean and atmospheric structure in coupled model SPCZ and stratus regions.

5.3.3 Pilot atmospheric monitoring from islands

The First Report (section 6.1.5) discussed the possibility of France and Mexico establishing a climate station at Clipperton Island (10°N 109°W, area 6 km^2). However, the logistics of establishing a long-term station at Clipperton have since been found to be difficult given the remoteness of the island; more time is needed to study the possibility. Several other islands have since been identified in the region that are regularly visited, offering easier shorter-term targets for atmospheric monitoring in the EPAC. The primary goal of the island sites is to observe the vertical structure in winds, temperature and humidity in situ over longer timescales than afforded by the 1-month process study described in the previous section. Such observations remain either unavailable in the case of winds, or too imprecise in the case of moisture and temperature (section 9.3.2) from current satellite instruments. Planned increases in Global Navigation Satellite System (GNSS) radio occultation satellites along with further development of other remote sensing technology from space targeting the lower troposphere (section 9.3.2) would help address issues of moisture and temperature profiling in the tropics in the future. In addition, emerging techniques for automated discrete water isotope analyses would support and improve analysis of water budgets across the ocean-atmosphere interface, as well as the properties of clouds and convective events in this unique region (section 9.2.6). Until a better understanding and ultimate resolution of the longstanding model biases in the region regarding the seasonality of the ITCZ in the Southern Hemisphere and the vertical structure of the heating in the EPAC ITCZ north of the equator is at hand, profiles of atmospheric vertical structure and, if possible, water isotope analyses are recommended. While these observations alone cannot provide estimates of vertical heating profiles, they can constrain model estimates, shed light on properties of convective clouds, including providing estimates of convective-stratiform ratios (e.g., Aggarwal et al., 2016), which has implications for latent heating estimates (e.g., Schumacher et al., 2008), and provide a backbone array of atmospheric profiles for use in future field programs. A minimum radiosonde frequency of once per day is preferred to constrain forecasts and reanalysis products. A frequency of several times per week launches providing a stable monthly mean background state could also be useful for comparison with state-of-the-art models.

While islands have known effects on atmospheric convection (Sobel et al., 2011; Hirose et al., 2017), this effect is also known to be a function of island topography and size (Sobel et al., 2011), as well as the prevailing winds (Yanase et al., 2017). The islands being considered for this pilot are all less than 100 km^2 and lack topography with the exception of the Galapagos Islands, which exceed 1000 km^2. Thus, the islands are expected to have minimal impact on the atmospheric measurements collected at these sites. In the case of the Galapagos, radiosondes have been launched there since 1969, with a current frequency of about every other day. This long-term data set could be helpful in assessing the influence of island diurnal forcing on atmospheric circulation over the region in comparison to other small island and ship-based observations.

The islands targeted for this pilot study (see locations in Figure 5.5), the scientific objectives specific to those islands and associated targeted observations are summarized below. One or more of these island sites could also be selected as a part of a Super Site to provide long term monitoring with a larger suite of measurements than the Backbone observing system offers. This would be useful for improving error characterization or product biases (gridded products, including satellite and reanalyses) and/or model physics (section 7.4.7).

Goal 1: Monitoring vertical profiles of atmospheric winds, temperature and moisture variability associated with the seasonal migration of the ITCZ and associated convective heating structure.

> *Clipperton Island (10°N 109°W, area 6 km^2), the Galapagos Islands (0° 91°W, total area 7,880 km^2), Cocos Island (5°N 87°W, total area 24 km^2) and Malpelo Island (4°N 82°W, total area 4 km^2)*: As Clipperton Island is not habitable (but is annually visited by the French Navy), remote profiling of the atmosphere and water isotope sampling is suggested for this site if the French decide to establish a climate observatory here. The Galapagos Islands are inhabited regularly by park officials and have a history of launching radiosondes. Thus, the pilot project at this location could consist of 1–2 radiosondes daily as well as regular isotope sampling for the period of the project. Two other small islands, Malpelo and Cocos, both over 500 km from the coast, offer additional opportunities to observe ITCZ convection from very small surface "platforms" minimizing surface land influences while providing well situated measurements for better understanding ITCZ convection. Cocos Island already has a continuously operating global positioning system (GPS)-Met station and is designated a World Heritage Site. As such, it has regular visitors and some infrastructure. In addition, Costa Rican park rangers are allowed to live there and already oversee the GPS site. Malpelo Island has permanent personnel from the National Natural Parks of Colombia, who could launch the radiosonde monthly with the support of the General Maritime Directorate of the Ministry of National Defense of Colombia (DIMAR) and the Colombian Navy. Additionally, DIMAR has had a GOES (Geostationary Operational Environmental Satellite Program) satellite meteorological and weather station on the island since 2010. Surface disdrometer measurements could additionally provide in situ information at any one of these sites for satellite-based radar reflectivity-rainfall relationships and aid in the classification of the rainfall as convective or stratiform to complement water isotope measurements (see 9.2.6).

Goal 2: Monitor surface conditions in the near-offshore region to validate atmospheric reanalyses and satellite products.

> *Hormigas Island (12°S 78°W, < 1 km^2)*: This small island is located 62 km off the coast of Peru within the narrow zone near the coast where atmospheric forcing errors tend to be large in satellite and reanalysis products (Astudillo et al., 2017). Instrumenting Hormigas offers the possibility to monitor at the same location both oceanic and atmospheric conditions. The island is now being used to monitor seismic events using surface GPS and there is a lighthouse where surface meteorological measurements can be collected. Observations of surface meteorology including pressure, winds, temperature and humidity, as well as shortwave and longwave radiation, would allow monitoring of changes in surface winds along the coast of Peru and could provide information for comparison with satellite and reanalysis surface radiative forcing products. This, in turn, will allow better understanding of coastal upwelling dynamics through estimate of the near-shore decrease of the winds (i.e., wind curl) and air-sea

interactions along the coast of Peru. IMARPE[17] is maintaining a station nearby off Callao (12°S) on a monthly to bimonthly basis since 1992 (Gutiérrez et al., 2008; Graco et al., 2017) and a fixed deep mooring line was deployed in 2013 providing more than one year of high-frequency data (T, S, oxygen) (Bretagnon et al., 2018).

Goal 3: Monitor atmospheric vertical structure and cloud radiative forcing in the core stratus deck region.

St Felix Islands of the Desventuradas Archipelago (26°S 80°W, 5.36 km^2) and the existing OceanSITES Stratus mooring (20°S 85°W): Both of these sites are off the coast of Chile and are ideally located for monitoring the stratocumulus cloud deck, important for moderating local SST and surface buoyancy forcing, as well as being a key region for understanding the interhemispheric surface energy balance important to the seasonal double ITCZ in the EPAC (Kang et al., 2008; Li and Xie, 2014; Zhang et al., 2015). Despite their remote location (approximately 1000 km off the coast of Chile), St Felix Island has a Chilean military base with inhabitants year-round and has been recently selected as a site of interest for multidisciplinary oceanographic studies within top-tier national programs (Millennium Nucleus for Ecology and Sustainable Management of Oceanic Islands (ESMOI), Millennium Institute of Oceanography (IMO)). As this location is within the stratus region south of the equator, a pilot radiosonde observing campaign including a surface meteorological station with pressure, winds, temperature, humidity, rainfall and longwave and shortwave radiation would be useful for better understanding the atmospheric circulations and cloud radiative forcing in this region on monthly to seasonal timescales, with a longer pilot campaign permitting evaluation of any interannual to decadal variability in the circulation of this region corresponding to the center of action of the SPMM.

5.4 Recommendations and actions

The breakdown of the TMA in 2012–2014 resulted in greatly decreased data returns (First Report). Xue et al. (2017a) showed that such poor data returns throughout the array, including 95°W, were unacceptable (section 7.3.3.2). Due to high vandalism along 95°W, data returns are often in the 50–80% range or lower, especially for the wind data. Given the high value of this line, such data outages are considered tolerable. However, longer periods of below 75% returns would threaten the operational and research applications of these data.

Recommendation 5.1. The existing TMA line along 95°W should be maintained and updated to full-flux sites (see section 7.3.1).

Recommendation 5.2. Increase Argo density for the EPAC as soon as possible (see section 7.4.4 and Figure 7.19 for initial implementation guidance). A coordination of South

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[17] Instituto del Mar del Peru - http://www.imarpe.gob.pe/

American countries to execute the doubling of Argo will be required. (Also see ***Recommendation 4.1*** and ***Action 7.9***).

Because the EPAC is home to one of the largest OMZs, we support particular attention to the EPAC region for BGC-Argo deployments (section 7.4.4).

Recommendation 5.3. A pilot study along 95°W installing dissolved oxygen sensors to 200 m and an ADCP is recommended at the equator, with additional dissolved oxygen and current sensors on 2°N and 2°S if at all possible (section 5.1.4).

Recommendation 5.4. TPOS 2020 recommends planning and execution of a reanalysis project for the eastern Pacific, making use of past and current data sets, as well as hydrographic sections between the Galapagos Islands and the coast. This reanalysis effort should include high-resolution regional atmospheric products that resolve important coastal winds, and ensembles for estimating uncertainty (section 5.2).

Action 5.1. Focus regional coordination efforts on engaging Peruvian institutes to implement real-time sharing of surface oceanographic data (e.g., SST) as part of the Backbone through the WMO Information System, with the support of SENAMHI and JCOMMOPS. This effort could then be a model implemented by other countries in the region (e.g., in GRASP) and, eventually, evolve into subsurface data sharing. An ocean reanalysis project or OSE experiments are two activities that TPOS 2020 could use to motivate these efforts. The pilot study in Action 5.2 and discussed in section 5.3.1 would also help motivate coordination in the region.

Action 5.2. Coordinate a pilot program with Peru, Ecuador and Chile focused on the equatorial and coastal waveguide and upwelling system (section 5.3.1). It is recommended that this pilot study be in conjunction with ocean reanalysis and OSE activities to best utilize existing and new data sets in products for research and operational applications. Develop a reanalysis product from this pilot (and the glider program being started by Peru) to understand how new observations affect ocean reanalysis and forecast products before any additional new sustained measurements in the eastern Pacific are recommended.

Action 5.3. Initiate a process study to investigate the atmosphere and upper ocean in the cold tongue/SPCZ/stratus regions in austral summer when the double ITCZ is observed in nature (section 5.3.2). The process study should observe spatial structure of the surface fluxes; e.g., from Saildrone or similar platforms (sections 9.2.1 and 9.2.2). A coordinated regional coupled modeling study making use of these observations is also strongly recommended to help advance issues with the long-standing coupled model biases in the region.

Action 5.4. Initiate a pilot island observing system at select islands in the EPAC to address the goals discussed in section 5.3.3. It is recommended that this pilot be initiated in the same year as the pilot and process studies discussed in Actions 5.2 and 5.3.

Action 5.5. Work with the Intergovernmental Oceanographic Commission (IOC) to include the eastern Pacific in the Roadmap for the United Nations Decade of Ocean Science for Sustainable Development (2021–2030), as the benefits of capacity development are disproportionately large for this region compared to other regions in the tropical Pacific.

Chapter 6 Considerations Guiding the New Backbone

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Since formulating initial recommendations for the Backbone for the First Report, we explored several application areas in more detail, including decadal and longer-term trends, scale interactions in the Western North Pacific, flux estimation from space-based observations, new planetary boundary layer issues and the concerns expressed by some in the climate dynamics research community. Below, we discuss each of these areas and what they might mean for modifying recommendations for the TPOS design.

6.1 Tropical Pacific decadal variability and long-term trends

6.1.1 Observing challenges at decadal-to centennial scales

Decadal-to-centennial (dec-cen) variations and trends pose unique challenges for the tropical Pacific observing system. Compared to their seasonal-to-interannual counterparts, dec-cen signals are typically weaker in the tropics, and have produced many fewer realizations in the climate record. ENSO also serves as a noisemaker at dec-cen scales, particularly near the equatorial cold tongue (Figure 6.1), and undersampling of ENSO in short or gappy observational records can give rise to apparent dec-cen changes that would not have appeared in longer or more complete records. Temporal changes in observing strategies can also impart spurious trends and jumps in the dec-cen climate record, posing problems for monitoring long-timescale variations (Smith and Reynolds, 2004; Wittenberg, 2004; Willis et al., 2009; Gouretski and Reseghetti, 2010; Barker et al., 2011; Xue et al., 2013; Huang et al., 2015). While these shifts are typically associated with increasingly accurate monitoring of the real world, they also require reinterpretation or adjustment of *prior* observations, to remove spurious trends and correctly represent the evolution of tropical Pacific climate.

The brevity of the instrumental record, which is an acute challenge for dec-cen research, has strongly motivated the development of paleoclimate records based on physical and chemical measurements obtained from living and fossil corals, tree rings, ocean and lake sediments, alpine ice cores, cave deposits, and other proxy recorders of tropical Pacific climate. The number, density, quality, calibration, diversity, and understanding of these proxy records have all improved greatly over the past two decades, as have efforts to assimilate these records into gridded, multi-millennial, multi-proxy reanalyses for tropical Pacific climate and ENSO (Emile-Geay et al., 2013a,b; Tierney et al., 2015; Hakim et al., 2016). Paleo records provide an essential observational constraint for the level of dec-cen variability (including interdecadal ENSO modulation) that existed prior to the industrial era, and have been crucial for assessing the significance of recent apparent changes in tropical Pacific climate and variability (Cobb et al., 2003, 2013; Conroy et al., 2009; Li et al., 2013; McGregor et al., 2013; Carré et al., 2014;

Newman et al., 2016). Efforts are underway to better calibrate paleo proxies to improve their reliability, e.g., by better understanding the drivers of variations in seawater properties (temperature, salinity, and isotopic composition) and the biological uptake of those properties. A possible role for TPOS in those activities is described in section 9.2.6.

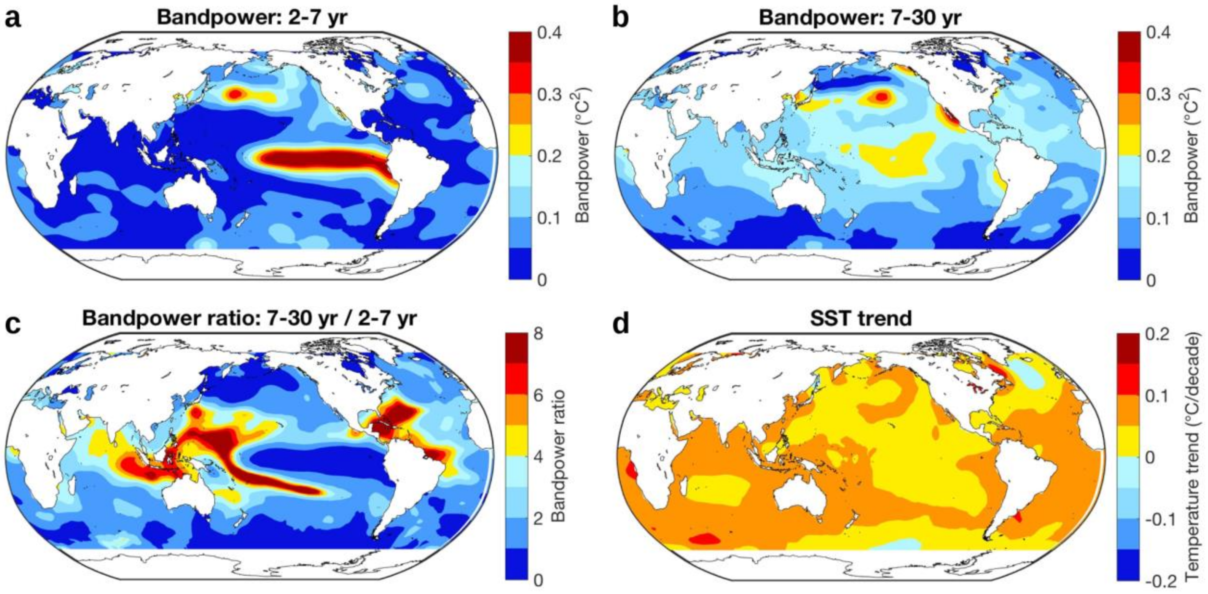

Figure 6.1: Global sea surface temperature variance and trends during 1900–2016, based on the ERSST.v4 data set of Huang et al. (2015). (a) Variance in the interannual (2–7 year) band. (b) Variance in the decadal (7–30 year) band. (c) Ratio of decadal to interannual variance. (d) Linear trend in SST. Figure adapted from Henley (2017).

Dec-cen research also relies heavily on model-based reanalyses to integrate and interpret the diverse and evolving observations. This poses additional challenges due to model biases and drifts, which emerge prominently on dec-cen scales. Reanalysis biases disproportionately affect under-sampled, and thus less-constrained, regions and epochs, which can lead to spurious shifts and trends in reanalysis estimates as observing densities and methods evolve (Trenberth et al., 2001; Wittenberg, 2004; Tokinaga et al., 2012; Xue et al., 2012; McGregor et al., 2016; Chiodi and Harrison, 2017a; Chiodi et al., 2019).

An additional challenge at dec-cen scales is the importance of characterizing both the net heat flux through the ocean surface and the vertical and lateral flows of heat within the atmosphere and upper ocean. Small errors in these heat budgets, when accumulated over many decades, can lead to large accumulated errors in temperatures and sea level in ocean simulations (Anderson et al., 2009; Delworth et al., 2012; Kuhlbrodt and Gregory, 2012; Sen Gupta et al., 2013; Hobbs et al., 2016; Mayer et al., 2017). Variations in the oceanic and atmospheric energy transports within the tropical Pacific region, and in the energy exchanged with the extratropics and the other ocean basins, also play key roles in tropical Pacific decadal variability as well as ENSO (Mayer et al., 2013, 2014), and these roles are often poorly simulated in models (Mayer et al., 2016; Graham et al., 2017; Wittenberg et al., 2018; Ray et al., 2018a,b). Thus, to improve models and their future projections, it is important to both accurately monitor the heat fluxes and transports across the tropical Pacific basin to evaluate the simulations and to support observational process studies that can improve simulations of the upper-ocean heat budget and atmospheric energy budget in models.

6.1.2 Historical decadal-scale variability

Figure 6.2 illustrates a particularly large tropical Pacific decadal trend observed during 1992–2011, associated with a transition to a negative phase of the Interdecadal Pacific Oscillation (IPO). The strengthening trade winds, enhanced zonal tilt of the thermocline, and intensified cold tongue in the equatorial Pacific during this period have been linked to a temporary lull in global warming (Kosaka and Xie, 2013; England et al., 2014), a global widening of the Hadley circulation (Allen and Kovilakam, 2017; Amaya et al., 2018), and prolonged drought over North America (Delworth et al., 2015).

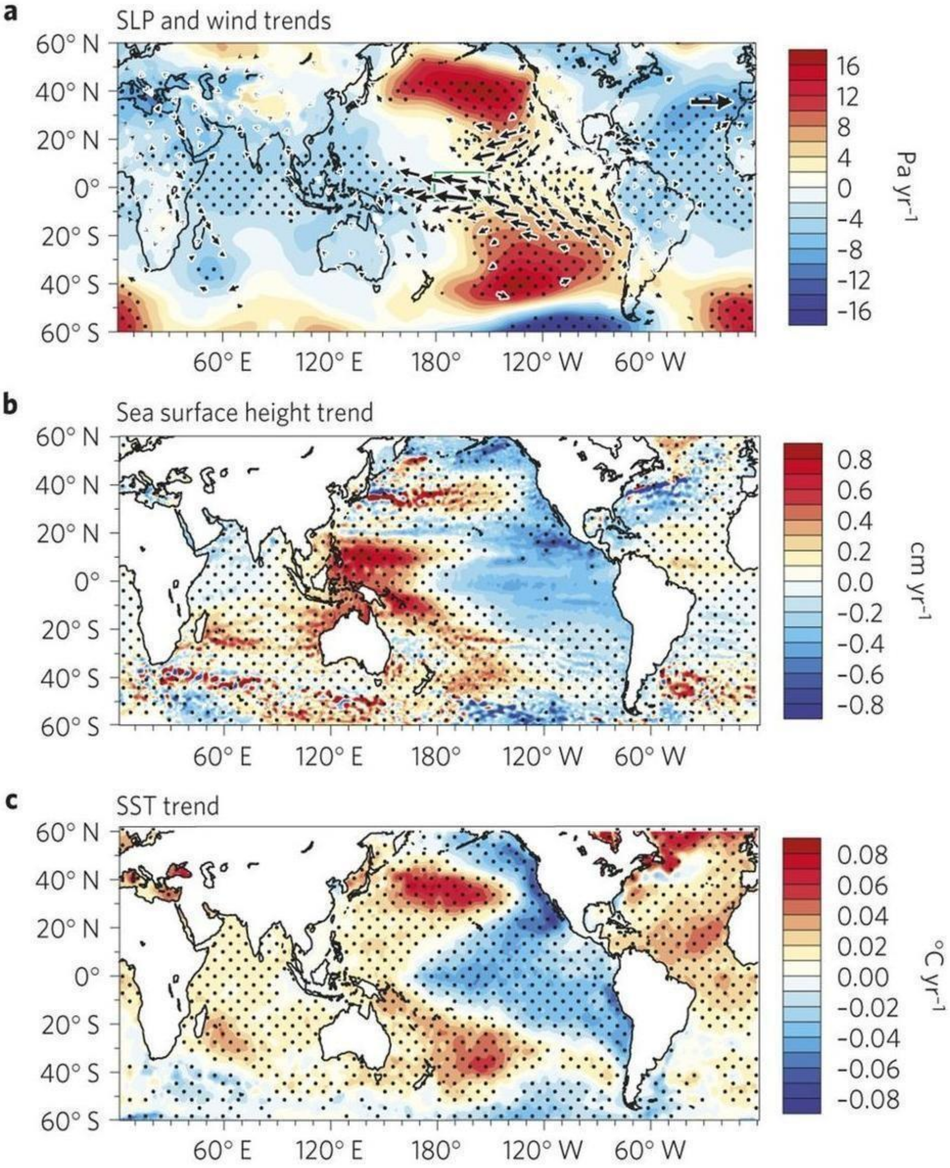

Figure 6.2: Observed linear trends in surface variables during 1992–2011. (a) Sea level pressure (Pa/yr, shaded) and surface wind stress on the ocean (Pa/yr, vectors; scale at top right is 3 mPa/yr) trends from the ERA-Interim reanalysis. (b) Sea surface height (cm/yr) trend from AVISO. (c) SST (°C/yr) trend from HadISST. Stippling indicates where trends are significant at the 95% confidence level. Adapted from England et al. (2014).

England et al. (2014) suggested, based on the ERA-Interim reanalysis that the time-mean surface easterly trade wind stress strengthened by about 50% over the central equatorial Pacific during 1992–2011, with substantial zonal and meridional structure in the wind stress changes off-equator. However, Chiodi and Harrison (2017a) found that the change in equatorial Pacific wind stress between 1992–2001 and 2002–2011 was only half as strong in the mooring observations as in ERA-Interim. This is consistent with de Boisséson et al. (2014), who found that the tropical-Pacific-averaged change in zonal wind speed (not stress) from the 1990s to the 2000s was 22% weaker in the mooring data than in the ERA-Interim and satellite (scatterometer and altimeter) estimates. Desbiolles et al. (2017) likewise found that during 1999–2009 the trends in equatorial Pacific trade wind speeds were weaker in their blended scatterometer product than in ERA-Interim. De Boisséson et al. (2014) further identified systematic biases among the various wind products, for the time-mean zonal wind speeds averaged over the tropical Pacific; in particular the tropical Pacific time-mean easterly winds were stronger in the satellite estimates than in the mooring data and in ERA-Interim. Such discrepancies in the wind climatologies and trends diagnosed from different platforms and products highlights the continuing need for ***long-term, multi-platform observations and improved assimilation products***, to enable observational estimates to be cross-checked among the various data sets.

The decadal changes illustrated in Figure 6.2 are just one recent example of the dec-cen variability that is prominent in both instrumental and proxy records of tropical Pacific climate (Henley, 2017). This variability stems from several sources, including natural and anthropogenic radiative forcings (section 6.1.3), reddening of the ENSO signal and its interdecadal modulation (section 6.1.4), and interbasin interactions (Cai et al., 2019). As reviewed by Di Lorenzo et al. (2013) and Newman et al. (2016), there are also interactions of the tropical Pacific climate system with higher-latitude Pacific modes, including: the North and South Pacific Decadal Oscillations (NPDO and SPDO); the North Pacific Oscillation and its oceanic expression the North Pacific Gyre Oscillation (NPGO); and the North and South Pacific meridional modes (NPMM and SPMM).

These many sources of dec-cen variability can interact. In particular, recent research has highlighted mechanisms by which the subtropics and extratropics interact with the various spatial flavors of ENSO and give rise to decadal variability (Di Lorenzo et al., 2015; Min et al., 2017). The NPDO and NPMM interact most strongly with the central Pacific flavor of El Niño, while the SPDO and SPMM interact more with the east Pacific El Niño.

For SST, the ratio of decadal (7–30 year) to interannual (2–7 year) variance is greatest in the western tropical Pacific and off-equator (Figure 6.1; Henley, 2017), highlighting the importance of long-term observations outside the equatorial zone. Lyu et al. (2017) found that at 7–30 year timescales, tropical Pacific sea level variability exhibits a dipole between the western and central tropical Pacific, linked to the NPGO (EOF2 of North Pacific sea level); at longer timescales the variability exhibits more of a dipole between the western and eastern tropical Pacific, linked to the NPDO (EOF1 of North Pacific sea level).

Compared to instrumental and proxy observations, climate models tend to underestimate the amplitude of tropical Pacific SST variability on multidecadal scales (Parsons et al., 2017; Kajtar et al., 2019). Models have also had difficulty reproducing the observed IPO patterns of wind stress, wind stress curl, and sea level anomalies, in part due to equatorial Pacific cold SST biases, which displace the simulated atmospheric convergence zones and alter the convective response to SST variations (Lyu et al., 2015). Climate models also failed to capture the intensity of the observed tropical Pacific trends between 1992 and 2014 (England et al., 2014; Power et al., 2017; Coats and Karnauskas, 2017; Peyser and Yin, 2017), a deficiency that may be related to a weaker than observed persistence of interannual variability in Walker circulation strength

(Kociuba and Power, 2015) and possibly the underrepresentation of interbasin connectivity (Kajtar et al., 2017; McGregor et al., 2018).

The mismatch in multidecadal variance between simulations and observations contributes to the uncertain projections from models, and calls for improved and extended observations and reanalyses of tropical Pacific SST, wind stress, surface heat fluxes, sea surface height, and heat content (***Recommendations 2.3, 3.1-3.2, 5.1-5.2, 7.2***, and ***Actions 2.1, 6.1-6.3, 7.1-7.2, 7.4, 7.9-7.10, 7.12-7.13***) to monitor future decadal changes and support improvements in the models used to reanalyze, forecast, and project the climate of the tropical Pacific. The long timescales of dec-cen variability also motivate using paleo proxy methods to extend the climate record (Section 9.2.6).

6.1.3 Externally-forced changes in tropical Pacific climate

Figure 6.3 illustrates projected future changes in tropical Pacific climate based on the CMIP5 models. These changes include: increased SST, especially in the equatorial cold tongue; enhanced tropical Pacific rainfall, with an eastward and equatorward shift of the atmospheric convective zones; weaker equatorial trade winds; weaker wind-driven currents and meridional overturning; stronger cyclonic wind stress curl and poleward Sverdrup transport in the upper ocean; a stronger equatorial undercurrent; and an intensified tropical thermocline (Vecchi et al., 2006; Collins et al., 2010; Vecchi and Wittenberg, 2010; Xie et al., 2010; Sen Gupta et al., 2012; Yeh et al., 2012; Cai et al., 2015). Not all models produce these changes – in particular there is disagreement about the change in SST contrast between the cold tongue and warm pool (Kohyama et al., 2017). So far, only the warming of the western equatorial Pacific SST has been unambiguously detected in observations and attributed to anthropogenic forcing based on model simulations (Knutson et al., 2013; Kam et al., 2016; L'Heureux et al., 2017; Newman et al., 2018).

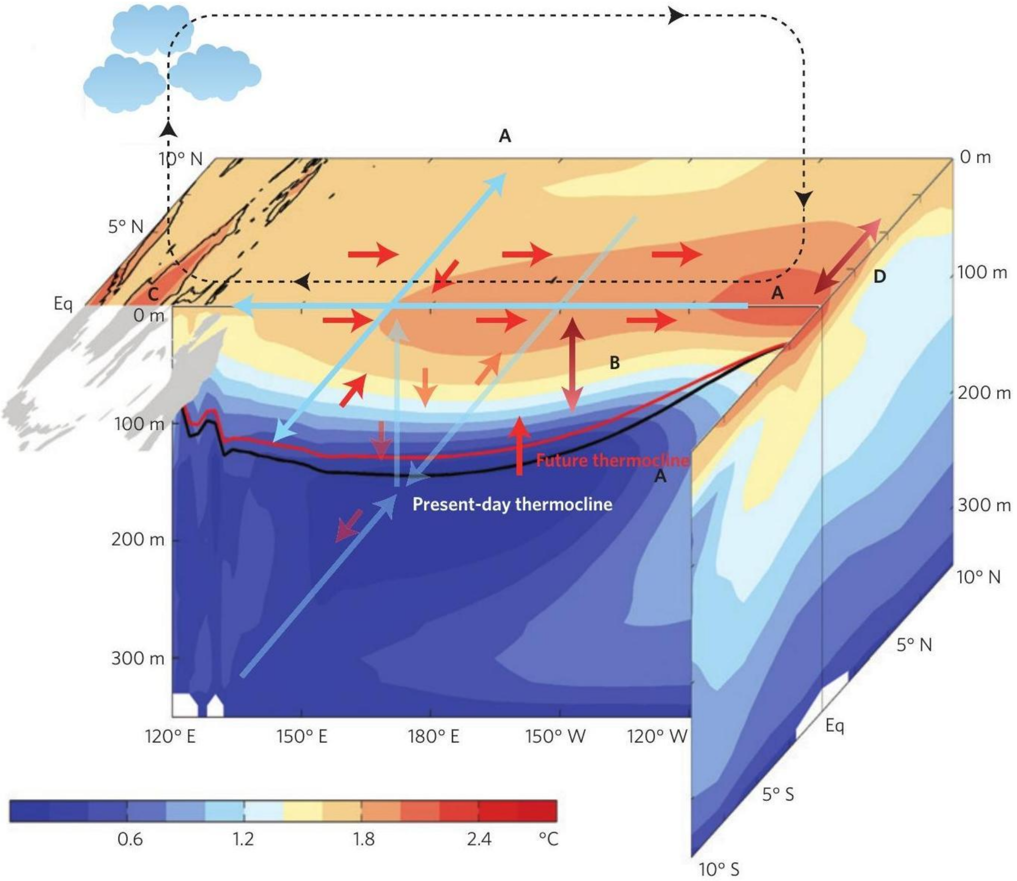

Figure 6.3: Schematic of expected future anthropogenic changes in the tropical Pacific troposphere and upper ocean, based on the ensemble-mean projection from the CMIP5 models. The surface of the tropical Pacific (red and orange shading) warms faster than the deeper layers (blue shading), leading to an intensification and shoaling of the equatorial Pacific thermocline (black and red curves, upward red arrow). In the troposphere, increased static stability acts to weaken the climatological Walker cell (dashed black loop), leading to weaker trade winds. The weaker trade winds in turn cause the mean ocean circulation (cyan arrows) to weaken (red/orange arrows), reducing the upwelling of cold subsurface water into the equatorial cold tongue. This enhances the warming of the cold tongue SST relative to the off-equator and west Pacific warm pool, which reinforces the weakening of the equatorial trade winds. From Cai et al. (2015).

Projections of future tropical Pacific climate are sensitive to model biases. For example, most models underestimate the cloud shading response to warm SST anomalies in the central equatorial Pacific and overestimate the upwelling of cold water within the equatorial cold tongue, biases which may lead the projections to warm too much in the west relative to the east (Ying and Huang, 2016a, b). Adjusting for these biases appears to offer more robust model projections of reduced SST contrasts between the equatorial cold tongue and warm pool in the future (Huang and Ying, 2015). However, it remains essential to assess and improve those models and projections, through better observational constraints for the ***surface heat fluxes, and improved understanding of the subsurface circulation, thermal structure, and heat budget of the upper ocean along the equator*** (***Recommendations 2.3, 3.1–3.2, 5.1–5.4, 7.2*** and ***Actions 2.1, 5.3, 6.1–6.4, 7.1–7.4, 7.8-7.13, 9.1***). It is also important to improve reconstructions of past climate variations and trends, through enhanced data rescue, synthesis, and reanalysis efforts applied to both instrumental and paleo proxy observations (sections 7.4.5.7, 8.4, and 9.2.6; Recommendation 2.3; and Recommendation 22 from the First Report).

6.1.4 Past variations in ENSO behavior

Recent decades have seen gradual changes in the spatial structure of observed El Niño events (Lübbecke and McPhaden, 2014; Figure 6.4). During 1980–1999 there was a preponderance of "eastern Pacific" events, with strong warm SST anomalies in the equatorial cold tongue, equatorial westerly wind anomalies spanning the western and central Pacific, and substantial flattening of the equatorial thermocline. In contrast, the period since 2000 has seen mostly weaker-amplitude "central Pacific" events, with warm SST anomalies near the dateline, weaker westerly wind anomalies in the west Pacific, stronger easterly wind anomalies in the eastern Pacific, and less flattening of the equatorial thermocline. Because of the wide disparities among trend estimates from atmosphere/ocean reanalyses (see references in section 6.1.1), sustained in situ observations have been essential in some cases for confirming inferred multidecadal changes in reanalyses – in particular the TMA for confirming changes in El Niño wind stress response (Harrison and Chiodi, 2009).

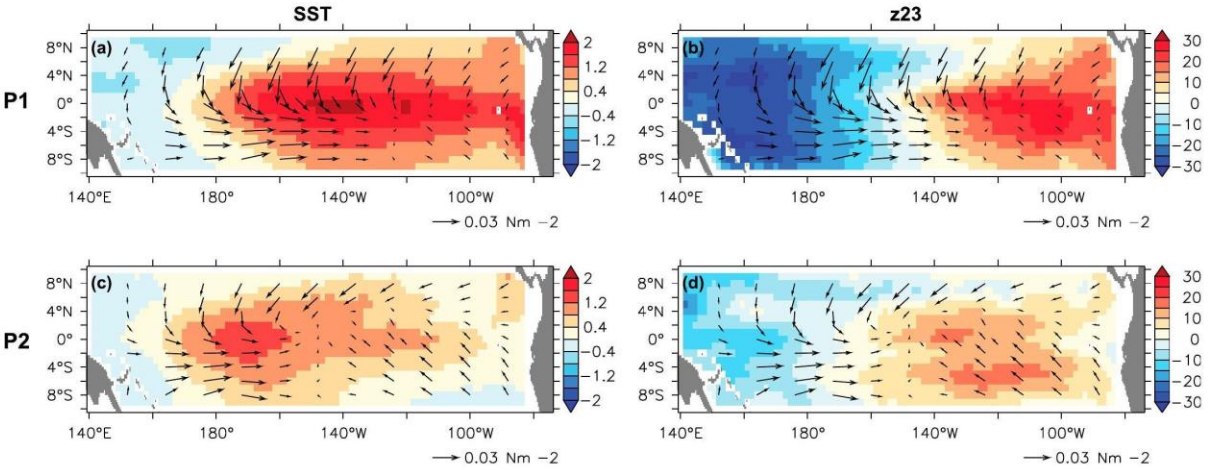

Figure 6.4: Multidecadal variations in ENSO structure. Composite DJF El Niño anomalies of (a,c) SST (°C) and (b,d) depth of the 23°C isotherm (m), with wind stress anomalies (Pa) overlaid, during (a,b) 1980-1999 and (c,d) 2000–2010. The composites represent an ensemble mean of eight different ocean reanalysis products (SODA.v2.0.2-4, SODA.v2.2.4, GODAS, ORA-S3, ORA-S4, GFDL-ECDA.v3.1, INGV.vOI5, GECCO2). From Lübbecke and McPhaden (2014).

The changes illustrated in Figure 6.4 are only a recent example of dec-cen variations in ENSO behavior that are prominent in historical and paleo records (Gergis and Fowler, 2009; Vecchi and Wittenberg, 2010; Cobb et al., 2013; Li et al., 2013; McGregor et al., 2013; Y. Liu et al., 2017; Lu et al., 2018). Yet the sources of past ENSO modulation remain unclear, due in part to confounding influences of varying sampling density, changing ENSO teleconnections, uncertain calibrations of proxies to local physical variables, imperfectly-known past radiative forcings, and uncertain dynamical relationships between ENSO and the background climate state. The past two decades have seen major research efforts to address these difficulties, and TPOS 2020 aims to contribute to these efforts in the future (e.g., section 9.2.6). Understanding these past variations could contribute to improved future projections of ENSO behavior, by clarifying the relative roles of intrinsic modulation versus external forcings in dec-cen changes in ENSO, and by subjecting models to more diverse tests of their behavior under a broader range of climate forcings than those observed over the past century.

Coupled global climate models and statistical models suggest that ENSO behavior can undergo strong and decadally unpredictable "intrinsic" modulation, even without any changes in external forcings (Wittenberg, 2009; Newman et al., 2011; Wittenberg et al., 2014). This intrinsic modulation applies to both ENSO's patterns and mechanisms (Kug et al., 2010; Capotondi et al., 2015b; Chen et al., 2017) and its seasonal-to-interannual predictability (Karamperidou et al., 2014; Ding et al., 2018, 2019).

Intrinsic ENSO modulation can in turn affect the multidecadal-mean state of the tropical Pacific, via El Niño/La Niña asymmetries (Rodgers et al., 2004; Okumura et al., 2017), asymmetries between central and eastern Pacific ENSO events (McPhaden et al., 2011; Choi et al., 2012; Nidheesh et al., 2017), and temporal blurring of climatological features like the equatorial cold tongue, atmospheric convergence zones, and equatorial thermocline (Watanabe and Wittenberg, 2012; Watanabe et al., 2012; Ogata et al., 2013; Atwood et al., 2017). Thus, ENSO can impart dec-cen signals, which are then further reddened by interactions with the extratropics (Di Lorenzo et al., 2013; Newman et al., 2016; Liguori and Di Lorenzo, 2018).

These two-way interactions between ENSO flavors and the IPO are mediated, in part, by wind-evaporation-SST feedbacks associated with the Pacific Meridional Mode (PMM) off-equator (Vimont et al., 2014). The PMM is not only an ENSO precursor, but it can also energize tropical Pacific decadal variability (Di Lorenzo et al., 2015), either via oceanic mixed layer integration of atmospheric forcing, or via changes in the ocean circulation forced by the PMM-related winds. While the pattern of the PMM is reasonably well-simulated by climate models, the SST-wind coupling shows much less persistence than observed (Lin et al., 2015), pointing to deficiencies in the model representation of tropical air-sea interactions that need to be understood and resolved. It is also possible that decadal ENSO changes arise as a response to decadal changes in the background conditions, mediated, for instance, by changes in the strength of the subtropical-tropical cells (STCs). While the STCs are clearly connected with Tropical Pacific decadal variability (McPhaden and Zhang, 2002), the latitudinal location of the winds that most effectively force the STCs at decadal timescales is not well understood, although tropical winds seem to play an important role (Capotondi et al., 2005, Figure 18). These IPO/ENSO connections differ greatly among climate models (J. Choi et al., 2013), and appear to be too weak in most models (Lin et al., 2018). ***Sustained reliable observations and reanalyses of both the on- and off-equatorial winds and air-sea fluxes*** may therefore be crucial for understanding and improving model simulations of the interactions between ENSO and Pacific decadal variability (***Recommendations 2.3, 3.1-3.2, 5.1, 7.2*** and ***Actions 5.3, 6.1-6.3, 7.1-7.4, 7.10-7.13, 9.1***).

6.1.5 Externally-forced changes in ENSO

SST reconstructions from historical and paleo proxy observations seem to suggest a strengthening of interannual SST and rainfall variance in the equatorial Pacific in recent decades, relative to the past few centuries (Vecchi and Wittenberg, 2010; McGregor et al., 2013). Yet the interpretation of these historical and paleo reconstructions is still debated, and it remains unclear whether this apparent change was the result of intrinsic variability, natural forcings, or anthropogenic forcings. It is also unclear how the amplitude, frequency, or spatial patterns of ENSO may change in the future. Detecting decadal changes in *extreme* ENSO events is particularly challenging, since such extremes are rare, and even a single such event can modify the interpretation of interdecadal changes—making long-term, continuous monitoring essential.

CMIP5 models project a wide range of possible ENSO responses to future climate change (Chen et al., 2017; Newman et al., 2018). This is due partly to *internal variability* which can produce different ENSO behaviors in different century-long realizations from a single model (Wittenberg, 2009; Stevenson et al., 2012; Wittenberg et al., 2014). However, even when considering the ensemble-mean, long-term response to radiative forcings, the models show differing *sensitivities* of the various ENSO feedback loops (DiNezio et al., 2012; Watanabe et al., 2012; Chen et al., 2017). These differing sensitivities stem from biases in ENSO's dynamical feedbacks and stochastic forcing processes (Gebbie et al., 2007; Kim et al., 2008; Bellenger et al., 2014), and also from the downstream impacts of biases in the simulated background climate of the tropical Pacific (Anderson et al., 2009; Capotondi et al., 2015a,b; K.-Y. Choi et al., 2013, 2015; Guilyardi et al., 2009, 2012, 2016; Graham et al., 2017; Timmermann et al., 2018). As a result, ENSO SST anomalies weaken in some models and strengthen in others, and there is no clear consensus on whether SST anomaly patterns will shift significantly toward the western or eastern equatorial Pacific.

However, model projections do suggest a strengthening of the future rainfall sensitivity to east Pacific El Niño events (Cai et al., 2018). Figure 6.5 shows the ensemble-mean of the CMIP5 projections for future changes in El Niño SST and rainfall anomalies. Most projections show enhancement of central equatorial Pacific warm SST anomalies relative to the far eastern and western equatorial Pacific, and an intensification and eastward/equatorward shift of the central Pacific rainfall anomalies.

Given these projections and their remaining uncertainties, it is important to sustain monitoring and reanalyses of these regions in order to assess future changes in ENSO and to evaluate and improve the model projections (Recommendations 2.3, 5.2, 5.4, 7.2 and Actions 6.1-6.4, 7.1-7.5, 7.7-7.12, 9.1). The enhanced observing system would not only extend climate records of SST and rainfall variability across the tropical Pacific, but also further constrain model representations of the dynamical feedbacks involved in ENSO and its sensitivities to external forcings. Key observational foci should include: (1) the responses of shortwave, longwave, latent, and sensible surface heat flux components to SST anomalies, and the mediation of those responses via changes in clouds, evaporation, wind speed, and air temperature; (2) the impacts of thermocline depth and upwelling variations on SST, especially in the equatorial cold tongue region (the so-called "thermocline feedback" and "Ekman feedback" involved in ENSO); (3) the impacts of upper-ocean zonal current variations on SST, especially in the central equatorial Pacific (the "zonal advective feedback"), and the modulation of those effects by the shallow barrier layers that often arise in the central equatorial Pacific during strong El Niño rain events; and (4) the impacts of tropical instability waves on equatorial cold tongue SST anomalies through meridional stirring and vertical mixing of upper-ocean heat. TPOS could also advance modeling and projections by helping to improve paleo-constraints for simulated ENSO variability, and its sensitivities to climate—e.g., by expanding observations of isotopes in seawater and rainfall (section 9.2.6) in order to improve the physical interpretations of proxy records.

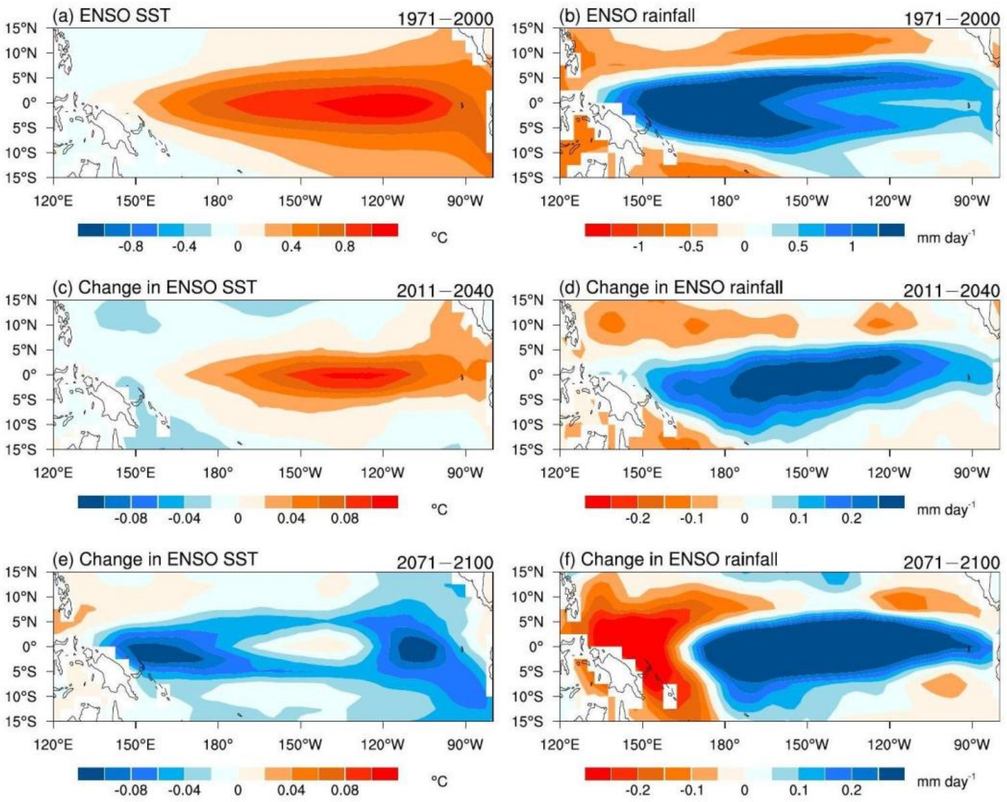

Figure 6.5: Projected future changes in ENSO patterns, based on 32 CMIP5 simulations. (a) Multimodel ensemble-mean standardized first PID of simulated historical ENSO SST anomalies during 1971–2000. (b) Multimodel ensemble-mean regression of rainfall onto the standardized first principal component of historical SST anomalies in (a). Also shown are the changes relative to 1971–2000 in the CMIP5 RCP8.5 projections during (c,d) 2011–2040 and (e,f) 2071–2100, for the simulated anomalies of (c,e) SST and (d,f) rainfall. From Huang (2016).

6.1.6 Requirements for the observing system

The numerous challenges for observing dec-cen variations in tropical Pacific climate and ENSO characteristics require observations that can accurately monitor multidecadal trends. The small magnitude of these signals demands accuracy and precision that are difficult to achieve, especially for surface fluxes where many 50-year changes in the heat flux components are less than 10 W m^{-2} (Coats and Karnauskas, 2017; Lyu et al., 2017). Observations are also needed to constrain model representations of the processes that govern tropical Pacific climate and ENSO, and to guide their advancement. Two CLIVAR panels have offered several recommendations for TPOS (Guilyardi et al., 2009, 2016). These emphasize the importance of long-term continuity, and caution against disrupting long-standing records. There is also emphasis on continuing reanalyses and syntheses of past and future observations, including integration of proxy measurements (such as coral $\delta^{18}O$) during and prior to the early part of the instrumental record. To that end, long-term measurements of isotope ratios in rainfall and seawater (section 9.2.6) would help to better calibrate proxy reconstructions, enabling them to extend the early climate record of dec-cen variability and provide context for any future changes.

For dec-cen monitoring it is thus essential to maintain a reference set of ***longstanding, continuous climate records with quantified uncertainties*** that can bridge any future changes in the observing system and confirm or refute any shifts that are observed as new components are introduced. These reference records must be sufficiently dense and reliable to (1) ***detect***

and identify small dec-cen signals amid larger-amplitude higher-frequency variability, (2) ***cross-check*** each other for physical consistency (e.g., from the momentum balance along the equator, one would expect decadally-enhanced easterly wind stress to be associated with an enhanced eastward gradient of surface pressure, and a stronger zonal tilt of the sea surface and thermocline), and (3) provide ***resilient*** dec-cen monitoring that can withstand unexpected random failures of individual elements. Past studies of interdecadal trends have benefitted from the availability of long records of in situ measurements made at fixed locations with relatively stable technologies—such as those from the TMA. Thus, maintaining some stable records will remain important for confirming any future trends detected in merged satellite products and reanalyses, and these reference sites must be carefully selected and maintained (***Recommendations 4.2, 5.1, 7.1, 8.2–8.3*** and ***Actions 6.1–6.4***).

OSSEs should be used to help quantify the relative importance of individual observing components for monitoring dec-cen changes such as those illustrated in Figures 6.2–6.5, and to quantify the robustness and synergies resulting from all the components working together as a system (Chapter 2, ***Recommendations 2.2–2.3***, and ***Action 9.1***). These studies should be designed in collaboration with community experts, including the CLIVAR Global Synthesis and Observations Panel (GSOP). Meanwhile, a qualitative assessment of the potential gains and losses from the proposed TPOS redesign is offered in section 7.3.3.

As discussed in sections 6.1.4 and 6.1.5 of this report, and in section 3.2 of the First Report, model-projected dec-cen changes in tropical Pacific climate and variability suggest that past regimes might not be a reliable guide to future regimes. Model projections of future regimes remain uncertain, posing a challenge for using OSSEs to target future observations at specific regimes. Thus, the in situ observing system should retain some mapping capability to be robust to potential future spatial shifts in regimes. These reference records will be one component of an integrated observing system, broadened and extended by its other components including satellite and Argo sampling (see Chapter 7). We reemphasize that an integrated observing system is needed to meet the dec-cen trend detection challenge.

6.2 Resolving the complex scale interactions from weather to climate over the northwestern Pacific Ocean

The Northwestern Pacific Ocean (NWPO) is part of the Indo-Pacific Warm Pool, which hosts the warmest water over the global ocean and hence drives the global atmospheric circulation through the ascending branches of the Walker and Hadley circulations. ENSO is an outstanding example in which the NWPO plays an important role both in stochastic forcing, for example via westerly wind bursts, and deterministic processes, such as the delayed-action oscillator and discharge-recharge mechanisms. In addition to ENSO, the Asian continent, particularly the Tibetan Plateau, further shapes the unique regional climate by anchoring the continent-scale Asian Monsoon. The convergence of the monsoon circulation and trade winds over the Western Pacific Ocean forms the so-called monsoon trough, a feature conducive for typhoon genesis.

Beyond these specific processes, the Western Pacific Ocean is a key part of complex land-ocean-atmosphere interactions, including between the monsoon and ENSO, the Indo-Pacific interbasin linkage, and the full spectrum of interactions from weather to climate. Among many challenges, the scientific issues concerning the Asian summer monsoon (particularly its intraseasonal variability) and typhoon are emphasized below, considering their far-reaching impacts and significant societal relevance for the highly populated Asian region. The issues related to the NWPO circulation are well documented in the recent review paper by Hu et al. (2015) and will not be touched upon here.

6.2.1 NWPO as one target region of subseasonal to seasonal prediction

With increasing success in predictions of short-term weather and long-term climate, it is desirable to fill the timescale gap by exploring predictability at the intra-seasonal or subseasonal scale. This is consistent with the seamless prediction goal identified in the World Climate Research Program’s Strategic Framework 2005–2015 (World Meteorological Organization, 2005). The subseasonal to seasonal prediction project (S2S) began in 2013 to promote such a development under the sponsorship of WMO and WWRP (see Chapter 3).

At these timescales, the NWPO is mostly influenced by the BSISO, which is an elementary building block of the monsoon system (Webster et al., 1998; Wang, et al., 2006). The BSISO has two prominent periods: 10–20 days and 30–60 days (Yasunari, 1979, 1980; Kajikawa and Yasunari, 2005). The structure and evolution of BSISO is more complex than its boreal winter counterpart MJO. The BSISO plays a critical role in NWPO weather-to-climate prediction and hence receives intensive attention in East Asian countries. On one hand, it is known to affect summer monsoon onsets, the active/break phases and the extreme events like heat waves. On the other hand, it modulates western Pacific Ocean typhoon activities. The spatial structure and life cycle of the two leading BSISO components, i.e., BSISO1 and BSISO2, are displayed in Figures 6.6 and 6.7 following Lee et al. (2013). BSISO1 exhibits a northward/northeastward propagating variability that often occurs in conjunction with the eastward MJO with quasi-oscillating periods of 30–60 days. BSISO1 more directly represents the close connection between the South Asian monsoon over the Indian Ocean and East Asian monsoon over the North Pacific Ocean. BSISO2 shows northward/northwestward propagation with short periods of 10–30 days, which occurs mainly during the pre-monsoon and monsoon onset season. As shown in Lee et al. (2013), BSISO2 is more associated with the monsoon onset processes.

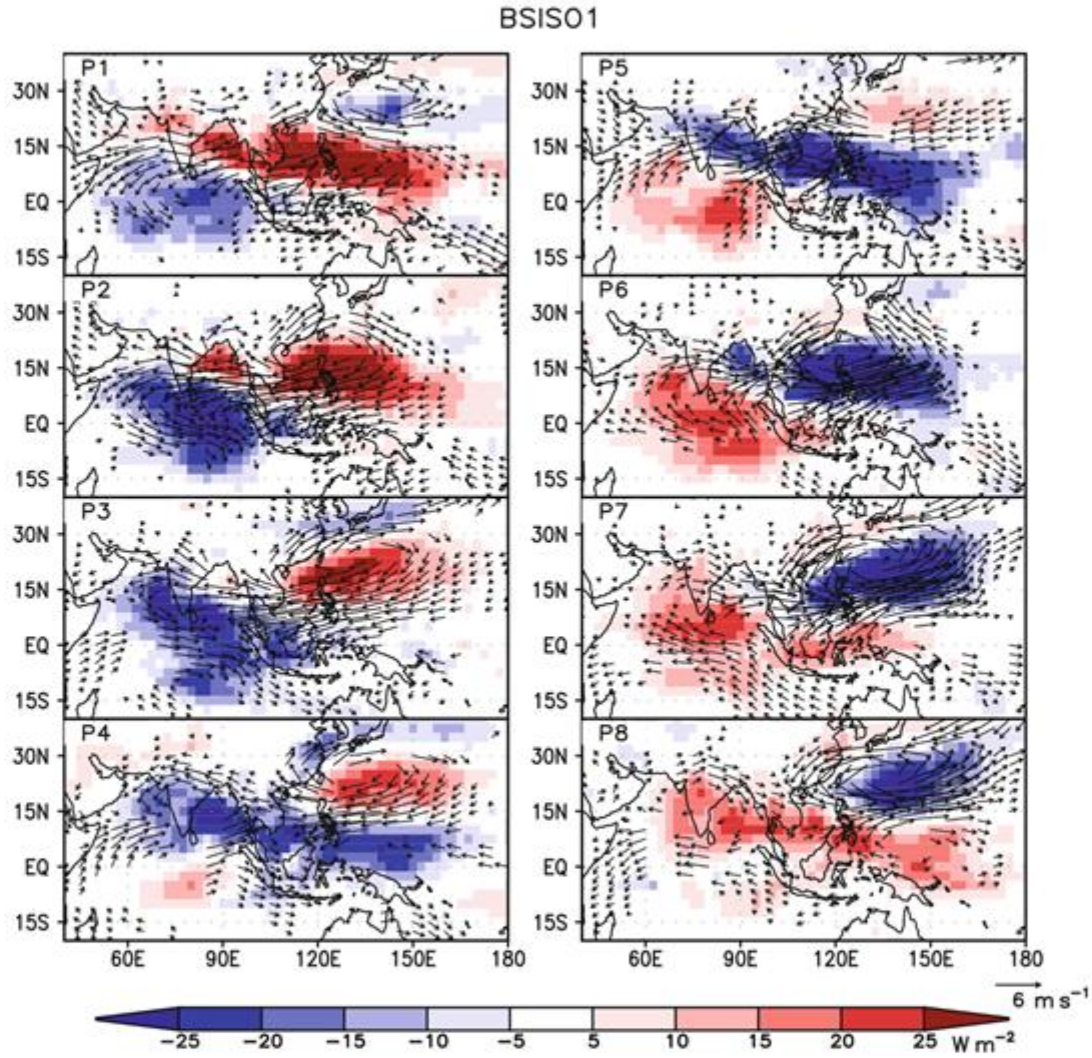

Figure 6.6: The life cycle composite of OLR (shading) and 850-hPa wind (vector) anomaly reconstructed based on BSISO1 in eight phases (from Lee et al., 2013).

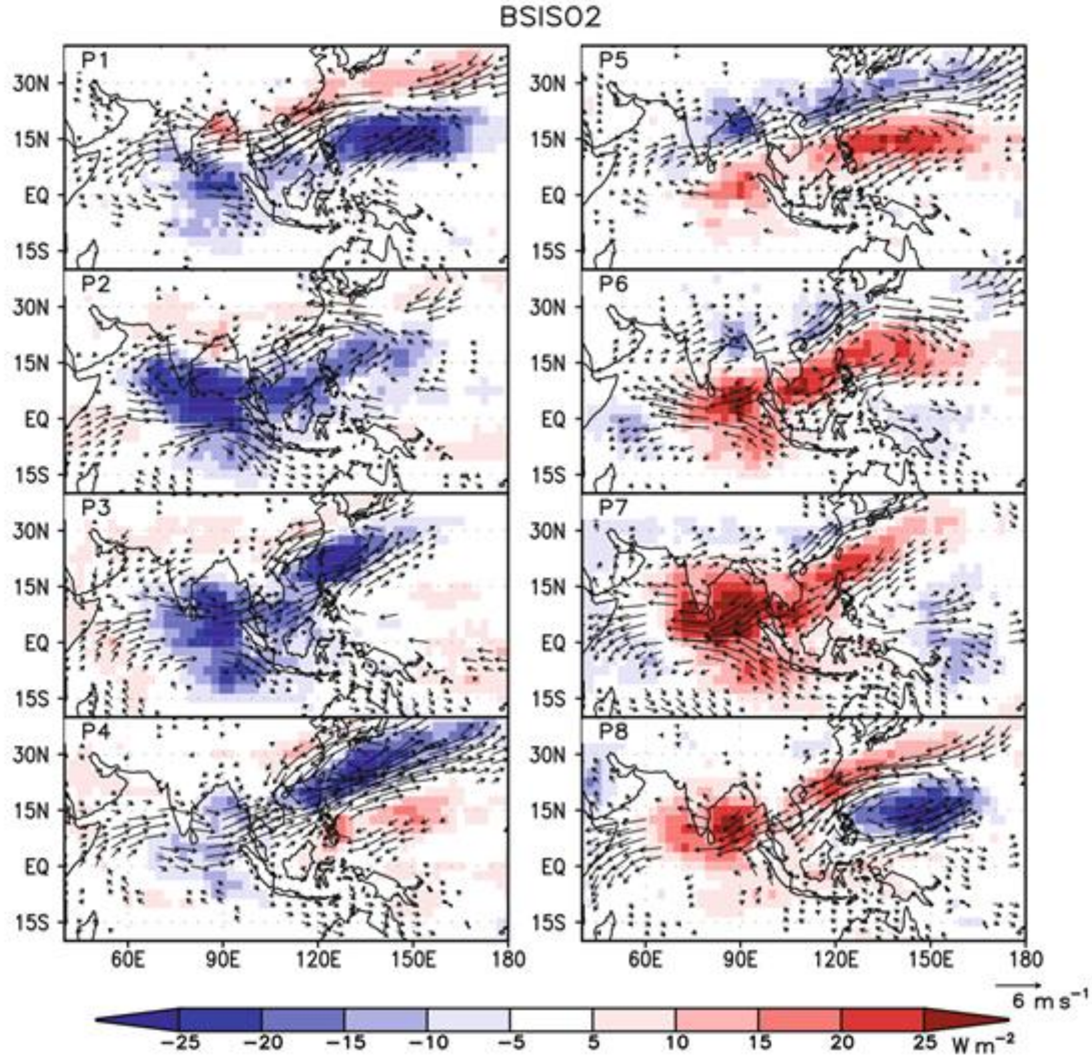

Figure 6.7: Same as in Figure 6.6 but for BSISO2.

The extreme heat wave disasters across the monsoonal Asian regions have been recently shown to be significantly modulated by the two BSISO modes, but with different contributions. For example, Hsu et al. (2017) found that BSISO1 (Figure 6.8) accounts for the heat wave over Southeast Asia in phases 8-1, over Pakistan to northwestern India in its phase 3-5 and over Northeastern Asia (Japan and Korea) in phases 7-8. The BSISO2 (Figure 6.9) leads to heat waves over southeastern China in phases 8-1, then over central India to Bangladesh and Myanmar in phases 2-4. Considering the fact that BSISO2 modulates the monsoon onset, the identified cases usually correspond to deadly pre-monsoon heat wave events spreading widely from South Asia to East Asia. These have a large societal impact and are highly visible to the public. Thus, understanding BSISO modulation on these extreme heat waves will help improve operational prediction and thus social preparedness.

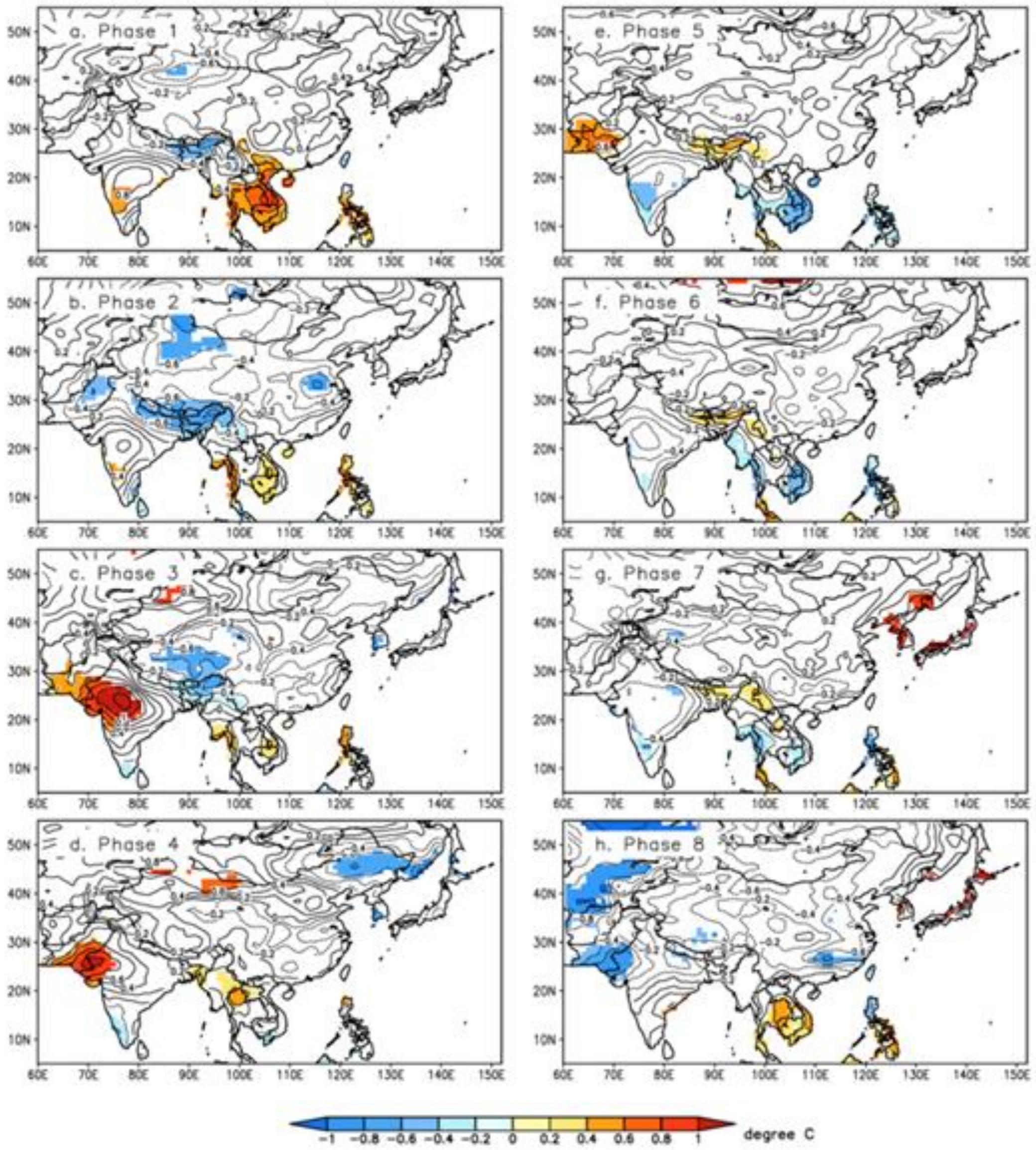

Figure 6.8: Composite surface air temperature anomaly (contour, unit: ºC) in eight phases of BSISO1. Only significant changes exceeding the 95% confidence level based on a Student's t-test and its effective degree of freedom are shaded in color.

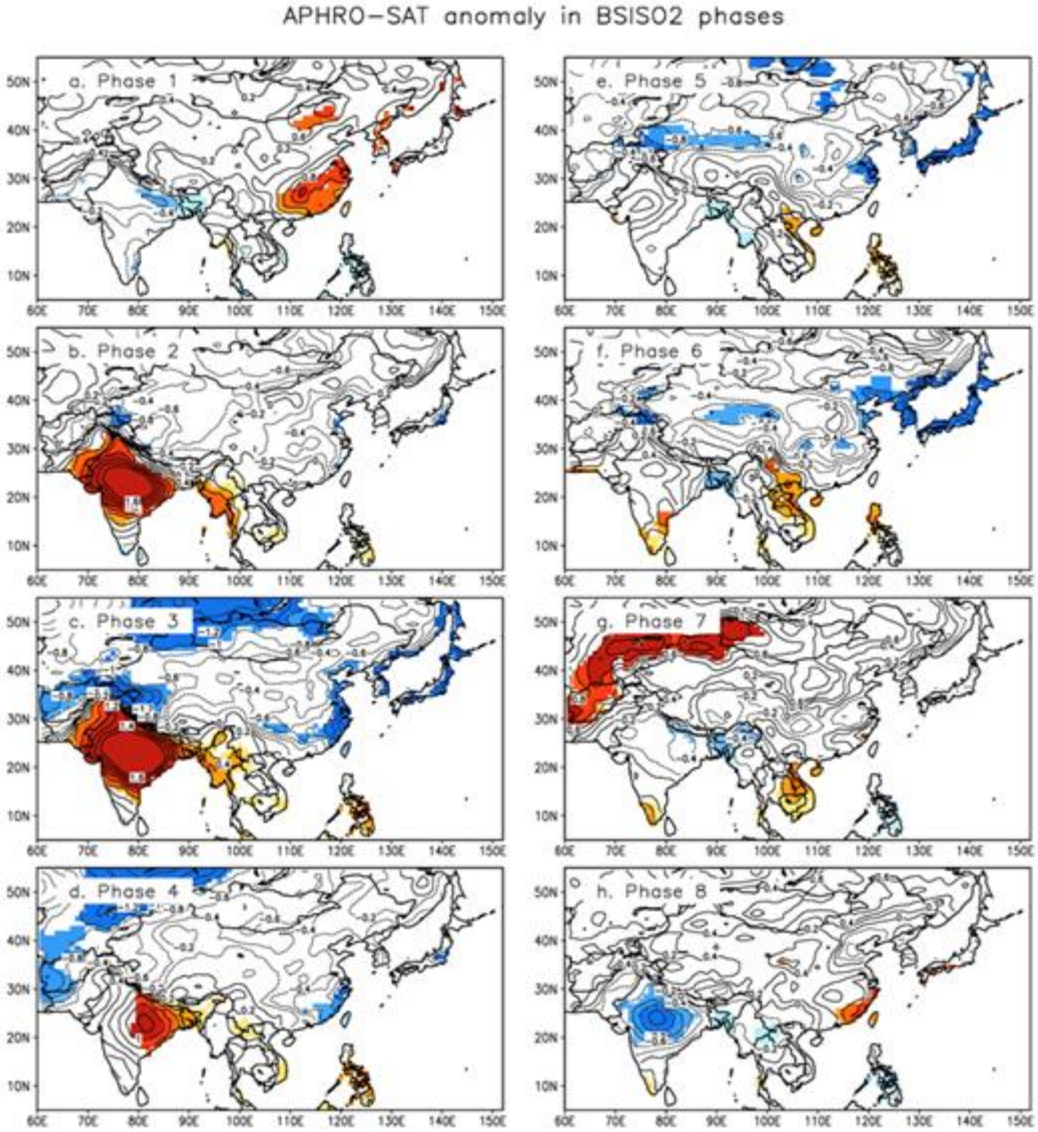

Figure 6.9: Same as in Figure 6.8 but for BSISO2.

Extreme rainfalls and droughts are also widely watched disasters occurring in conjunction with the summer monsoon’s active and break periods in Asia. In case of China, extreme rainfalls are a major reason for economic losses during the summer season. Hsu et al. (2016) identified the key extreme rainfall patterns associated with BSISO modes. As shown in Figure 6.10, the BSISO1 favors inland extreme rainfall along and north of the Yangtze River in phases 2–4, while the BSISO2 increases the risk of extreme rainfall from the southeastern coastal region to the Yangtze River during its phases 4–7.

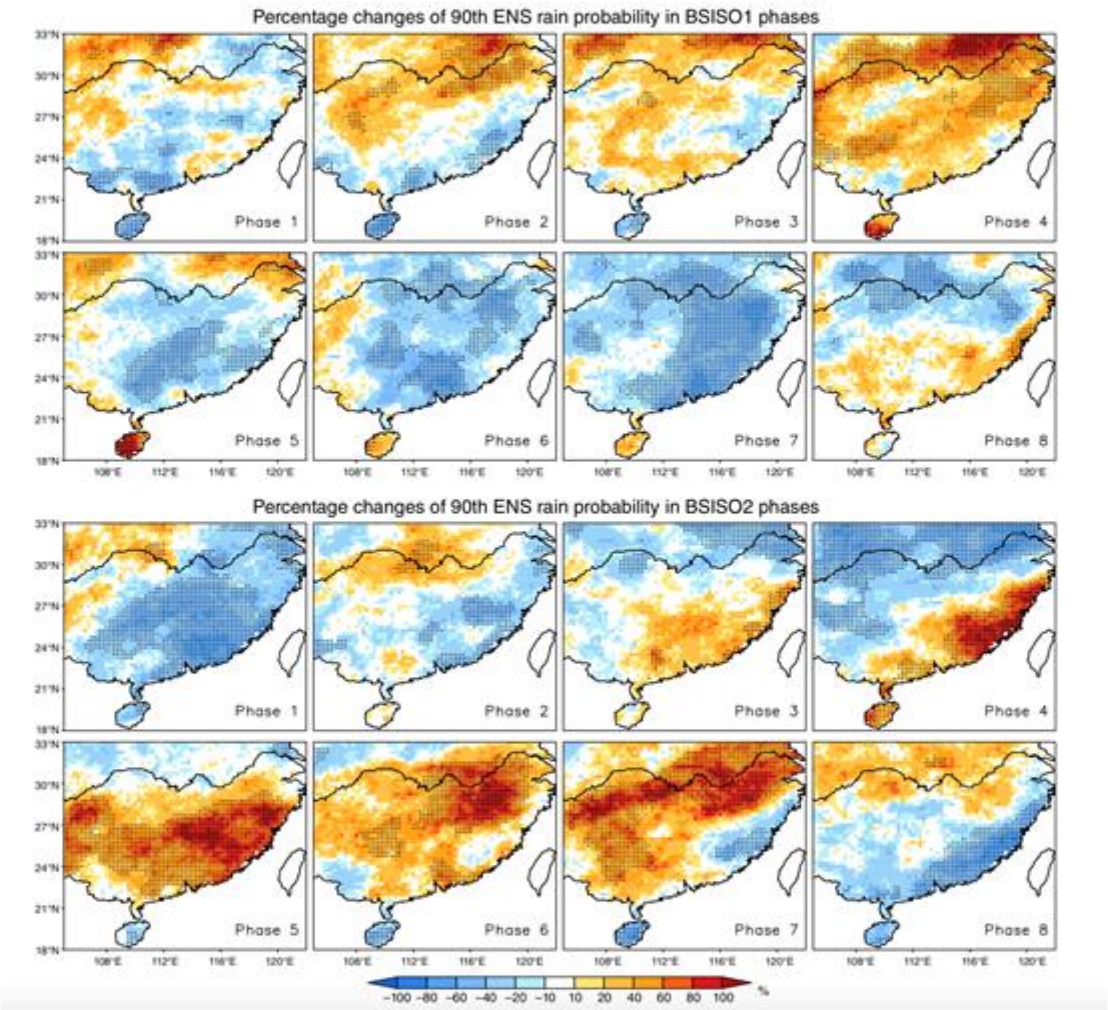

Figure 6.10: Percentage change (%) in the probability of extreme rainfall events (90th percentile) for each of the eight phases of BSISO1 (upper two rows) and BSISO2 (bottom two rows) with respect to the non-BSISO state. Changes exceeding the 95% confidence level are dotted. (From Hsu et al., 2016).

Even though it is widely recognized that intraseasonal variability holds the greatest potential to improve weekly to monthly weather and climate prediction, the performance of state-of-the-art Coupled General Circulation Models (CGCMs) in simulating and predicting the ISOs is far from satisfactory. Sperber et al. (2013) examined in detail the CMIP5 and CMIP3 models' capacity in reproducing the Asian summer monsoon and concluded that representation of boreal summer intraseasonal variability is still poor, though the multi-model ensemble significantly improves the performance. The S2S project is working intensively on understanding and improving the model performance for intraseasonal variability (Mariotti et al., 2018) over the global monsoon regions. The NWPO is one of the S2S priority regions given the high population density in the region and hence the urgent need to reduce monsoon related weather and climate disasters. The recent highlighting of the role of Western Pacific Subtropical High (WPSH) in modulating the Eastern Asian Summer Monsoon and NWPO typhoons further emphasizes the necessity of more scientific attention to the NWPO region (Wang et al., 2013).

6.2.2 The NWPO as a typhoon hot spot

The NWPO hosts the most intensive cyclone activity on Earth. According to the Climatological Atlas for Tropical Cyclones Affecting China (Shanghai Typhoon Institute, 2007), three mean cyclone tracks cross the NWPO, including the westward, northwestward and northward-marching tracks, with respective loadings toward southern China to Vietnam, southeastern China, and Korea and Japan. Typhoons have produced devastating economic and societal loss in coastal east Asia. Thus, the demand is very high to develop a more advanced typhoon prediction capability, not only for higher accuracy of the forecast track and intensity, but also by extending the forecast lead time (Figure 6.11).

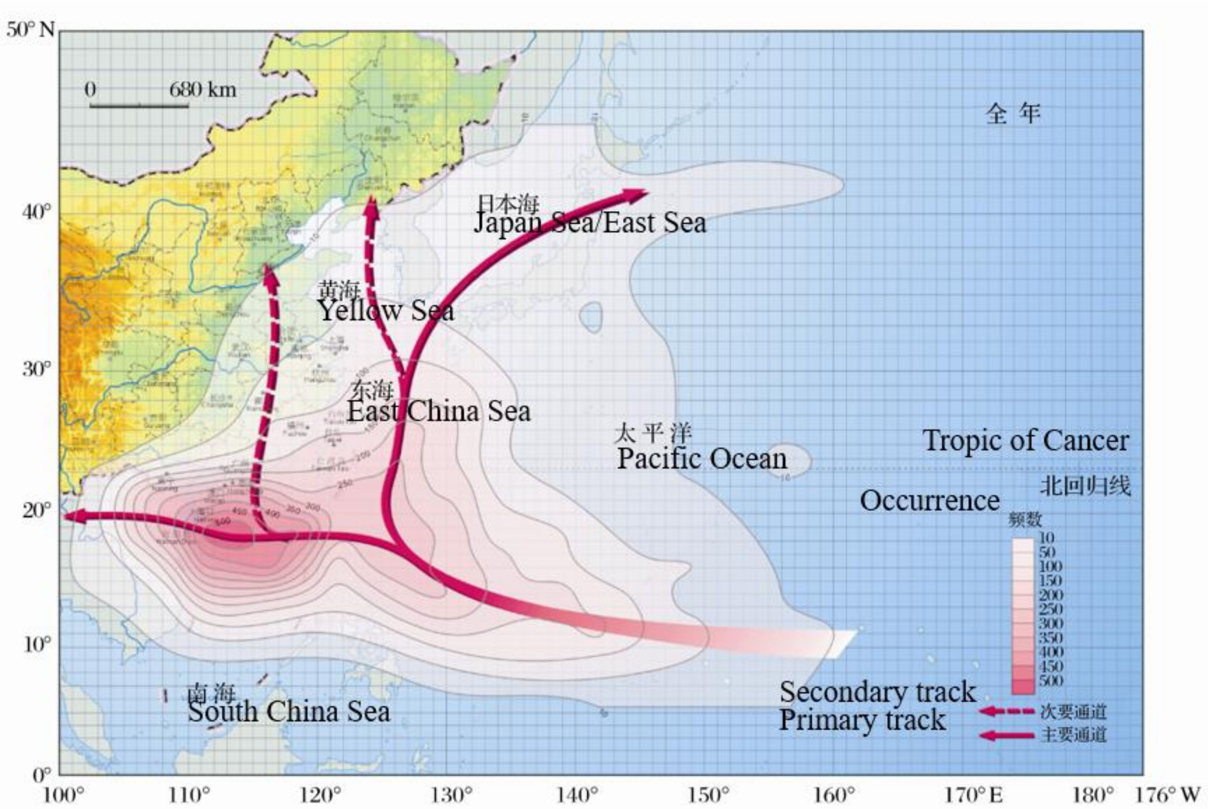

Figure 6.11: Statistics of tropical cyclones over the northwestern Pacific for the past 50 years. The color bar represents the typhoon occurrence and the solid (dashed) arrows represent primary (secondary) typhoon tracks. Adapted from Shanghai Typhoon Institute (2007).

From the point of view of seamless prediction, typhoon prediction could be potentially extended beyond weather times scales (~7 days) if the scale interactions are well understood and described in models. Xiang et al. (2015) gave such an example of predicting cyclone development 11 days in advance owing to improved model behavior on the intraseasonal scale. Recently Li and Zhou (2018) review the intraseasonal, interannual and interdecadal variability of NWPO typhoon behavior, where progress on modeling scale interactions are summarized. Beyond their modulation by the low frequency processes, the NWPO typhoons are also found to have upscale impact and be potentially important for El Niño prediction due to their significant contributions to westerly wind bursts (Lian et al., 2018).

It is widely understood that typhoon intensity prediction is still poor even though track prediction has been significantly improved during the past decades. The prediction error of typhoon genesis and development could be potentially attributed to the poor air-sea flux representation and parameterisation in the model. Atmospheric lower boundary layer moisture plays a critical role in supplying the energy for typhoon development. This moisture is mainly determined by essential variables including SST, sea surface relative humidity, and sea surface wind. The warm SST precondition for typhoon genesis; the SST drop during the typhoon passage due to the air-sea surface heat flux forcing; and oceanic mixing are the critical processes to be sampled by both in situ and satellite platforms. The data stream should be assimilated to improve the forecast products and used to validate the model performance. The Ding mooring array over the NWPO responds to these requirements by providing the full package of air-sea flux measurements (section 7.4.3).

6.2.3 Summary

The NWPO is a region of potential enhanced prediction capability, which would have immense societal benefit. An enhanced observing capability is needed to better capture the complex scale interactions and their associated links between the tropics and subtropics via the BSISOs. Thus, the present TPOS is designed to support this goal, as discussed below (7.2.1.3).

6.3 Improving surface flux estimation

Because air-sea fluxes are essential to understanding the coupled processes that dominate the variability in the tropical Pacific, it is vital that the TPOS observe accurate fluxes both in situ and remotely. The TPOS 2020 project must therefore include a framework for improving these flux estimates. One purpose of the Backbone is to provide in situ reference time series for validating model gridded products and satellite-based measurements, including for those of wind stress and air-sea heat and water fluxes. Here we discuss how the TPOS might better support these goals, starting with wind stress and then examining the challenges of estimating heat flux and its components.

6.3.1 Wind stress

The wind field is of central importance to understanding and predicting the evolution of the tropical Pacific, and wind estimation is thus a critical challenge that the observing system must carefully address. The new TPOS 2020 design takes advantage of the revolution in wind estimation over the ocean enabled by space-based scatterometers. Our First Report (sections 3.1.1.2 and 5.1) included detailed consideration of requirements for surface wind observations in light of scatterometry, and developed recommendations for synergistic use of satellite and in situ wind measurements.

Despite particular challenges (see Annex A), for many applications the existing space-based wind stress products are already effective in describing wind variability on weekly to interannual timescales (its ability for longer timescales is further discussed in section 7.3.2.1), delivering 25 km spatial resolution or better and thus resolving wind (and wind curl) features that previously were poorly resolved by in situ sampling. This is illustrated for two westerly wind bursts (Figure 6.12), for which the important spatial structure between the TMA lines is captured by scatterometer winds. However, the ability of the moored data to resolve faster events at daily and hourly timescales is clearly evident when the wind variations around these events is examined (Figure 6.12, bottom panel). This is one illustration of the synergies between these two wind observing techniques.

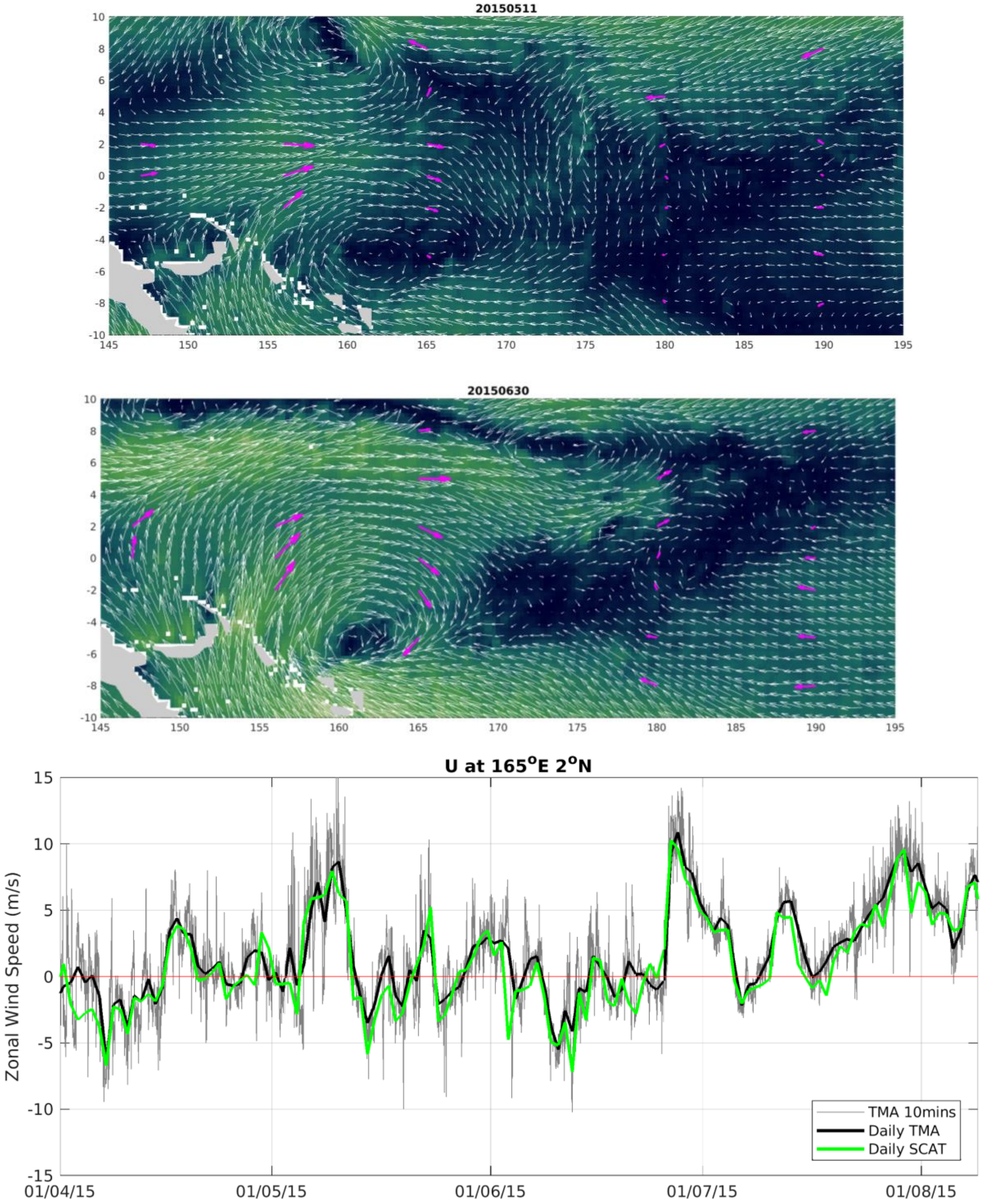

Figure 6.12: Two 5-day averages of surface winds in the western tropical Pacific. Speed is in color and the vector winds are shown in white (from an Advanced Scatterometer (ASCAT) product from Bentamy and Fillon, 2011—hereafter B11) (http://cersat.ifremer.fr/user-community/news/item/97-release-of-new-global-wind-fields-from-metop-scatterometer) and magenta (from the TMA). For the ASCAT product, only every 3rd point is plotted. Lower panel shows the daily and 10-minute averages from the TMA (gray and black, respectively) and daily ASCAT (green) averages for the zonal winds. Larger resolution image at http://tpos2020.org/2nd-report-draft/

For studies of seasonal through decadal timescales, the comparisons with the moored measurements show that the current scatterometer products already capture most of the variance measured at TMA sites (>80%) (Figure 6.13). Off-equatorial wind variance appears better captured by these satellite winds than that near the equator.

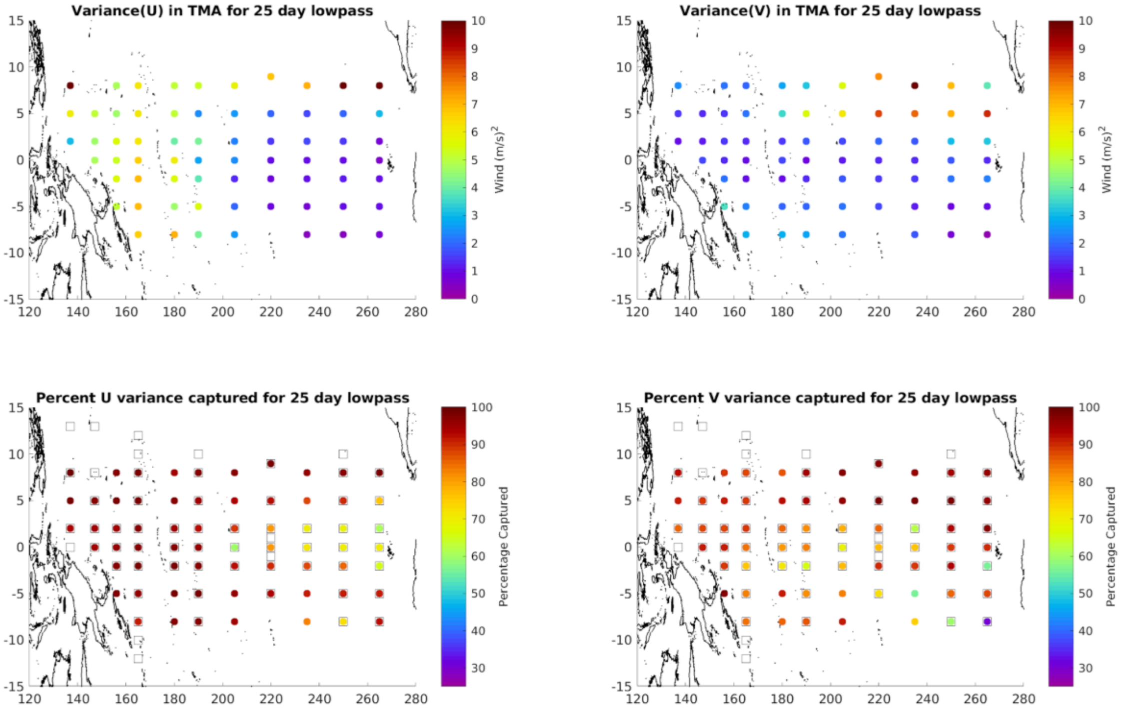

Figure 6.13: Comparison of the variance of TMA and ASCAT winds at monthly or longer time periods for January 2007–October 2018. Top panels: total variance of the zonal (left) and meridional (right) winds. Bottom panels: percent variance captured by the B11 product, October 2018.

As noted in the First Report (section 5.1), challenges remain to further improving wind estimation (detailed in Annex A): (1) current scatterometer coverage is inadequate to describe variability at timescales shorter than 3 days and is degraded in rainy regions for some frequency bands (e.g., Ku- band); this limitation also poses challenges for estimating air-sea fluxes that depend nonlinearly on the wind speed (see Cronin et al., 2014; First Report sections 3.1.1.3 and 5.8); (2) scatterometer sampling needs to be increased to avoid aliasing by the diurnal cycle and other fast changing processes (refer to the First Report, section 5.1.2 for details); and (3) a more rigorous approach to the stress/wind conversion is needed to better synthesize satellite and in situ winds. It is necessary to account for the effect of surface currents that can cause differences between satellite winds (relative to the moving ocean surface) and buoy winds (relative to a stationary frame). Dedicated analyses have been started (see Annex A) to better document error sources in surface wind estimation from both moorings and satellites, understand their differences, and separate the issues of measurement versus sampling errors. This work should continue, and we recommend the following actions:

Action 6.1. Studies should be undertaken to better understand sampling errors in scatterometer wind products and the impacts of sampling differences between satellite and buoy winds (Section A.2).

Action 6.2. Efforts to make, evaluate, and improve gridded wind products that synthesize data from multiple platforms should be prioritized (funded) (Section A.3).

Action 6.3. The directional dependence of buoy/scatterometer wind differences needs to be investigated and understood (Section A.4).

Observational needs for better retrievals are accurate estimates of surface currents, relative humidity, air and sea temperatures and, ideally, radiation measurements, some of which are currently only available at a limited number of buoy locations. Furthermore, directly-measured vector wind stress on buoys can be used for evaluating direct retrievals of wind stress from scatterometers that relate backscatter directly to vector wind stress (instead of relating backscatter to equivalent neutral winds then converting to wind stress). Such an approach is currently hampered by the scarcity of these direct stress measurements. The deployment of direct covariance flux packages which measure stress directly can help drive this approach forward (see sections 7.4.5.4, 7.4.7). In addition, new space-based wind observations are being developed, such as CYGNSS (see section 9.3.2.3), which should be assessed as another source of data for gridded wind products.

6.3.2 Heat and moisture fluxes

Surface fluxes are key to diagnosing coupled ocean-atmosphere interactions. The requirements and recommendations for sea surface air temperature, humidity, and radiation have been described in the First Report (sections 3.1.1.3 and 5.8). Historically, the instrumentation used on the TMA to collect the state variables required to estimate surface heat fluxes, delivers an accuracy of around 15 W m^{-2} in daily averages across the TPOS region, with higher error values likely in the western Pacific (Cronin et al., 2014). In the First Report, it was also noted that the satellite-based estimates of these variables were either non-existent or subject to large uncertainties. Here we revisit this assessment based on recent progress in these efforts.

6.3.2.1 Radiative fluxes

Derivation of satellite-based surface radiative fluxes depend on a number of factors. Generally surface irradiances are computed using satellite-derived observations of top of the atmosphere irradiance, cloud and aerosol properties and temperature, combined with specific humidity and temperature profiles derived from satellites or from reanalyses. Uncertainties in any of these inputs increases uncertainty in the final surface radiation fields (e.g., Kato et al., 2018). Of these properties, some near-surface measurements that would be of value for *improving* the satellite-derived surface radiation measurements would be cloud base and other cloud property information and improved profiles of temperature and humidity (extending throughout the atmospheric boundary layer, but including near-surface values, e.g., Rutan et al., 2015). In addition, in situ aerosol properties would be of value, particularly in regions with dust and/or significant sea salt production. Observations of the sea state, which influences surface albedo and emissivity, would additionally provide valuable information for reducing errors in satellite-derived radiative fluxes. To the extent that there are regionally and temporally coherent variabilities in lower-level clouds (and temperature and humidity), errors in these fields can translate to regional or temporally coherent errors in the final surface radiation fields. These additional measurements are not feasible to provide on the TPOS Backbone; however, select locations that have at least some of these measurements (as in the “Super Site” concept proposed in this Report, see section 7.4.7) would enable additional progress in improving the satellite radiation data.

At present, it is unclear to what extent, and in what locations, the satellite radiation data sets need to be improved. Recent analyses of differences between the TMA buoy downward surface radiation data sets and satellite-derived radiation fields on monthly averaged values of downwelling shortwave radiation show mean biases of under 5 W m^{-2}, depending on the product, with root mean square (RMS) differences between 12 and 16 W m^{-2} (Figure 6.14; Pinker et al., 2017), with little regional coherence (e.g., Figure 6.15; Kato et al., 2018). As seen in Figure 6.15, comparisons of the TMA and satellite downwelling longwave show mean differences of between 1 and 6 W m^{-2}. Given the lack of regional coherence, it is impossible to determine whether there are any regimes over the tropical Pacific in which the satellite radiation fluxes have lower accuracy. The standard deviations between satellite and buoy monthly mean diurnal cycles are higher (on the order of 20–30 W m^{-2}, although this is based on analyses over all available ocean buoy data, including WHOI UOP[18] buoys, PIRATA[19] buoys, RAMA[20] buoys, and TMA buoys; Rutan et al., 2015). Given that this comparison is not limited to the TMA buoys, it may not fully define the standard deviation of satellite radiative fluxes on these scales in the tropical Pacific.

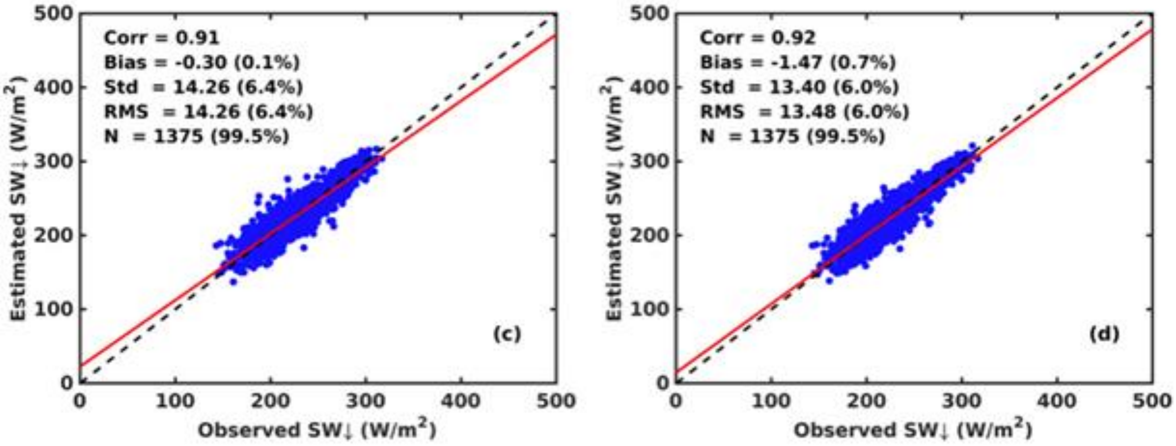

Figure 6.14. Surface downwelling shortwave radiation on monthly averages between radiation estimates based on the ISCCP DX data set (left panel, Rossow and Schiffer, 1991) and the MODIS data set (right panel, Wang and Pinker, 2009) and the TMA buoy data. From Pinker et al. (2017).

Careful comparisons of buoy and satellite surface radiation fields of annual cycles, interannual variability, and trends have been performed at sites other than the TMA buoys, for instance the Ocean Reference Station STRATUS (20°S, 85°W) (Pinker et al., 2018; Figure 6.16). At this location, no significant trends were detected in either the buoy or the satellite data in either downwelling shortwave or longwave radiation, and the satellite data sets reproduced the annual variability well. Similar analyses have not been undertaken by the satellite radiation community

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[18] Woods Hole Oceanographic Institution Upper Ocean Processes group

[19] Prediction and Research Moored Array in the Tropical Atlantic

[20] The Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction

for the TMA buoys most likely due to the uncertainty regarding the quality of the current radiative data set for long term analyses.

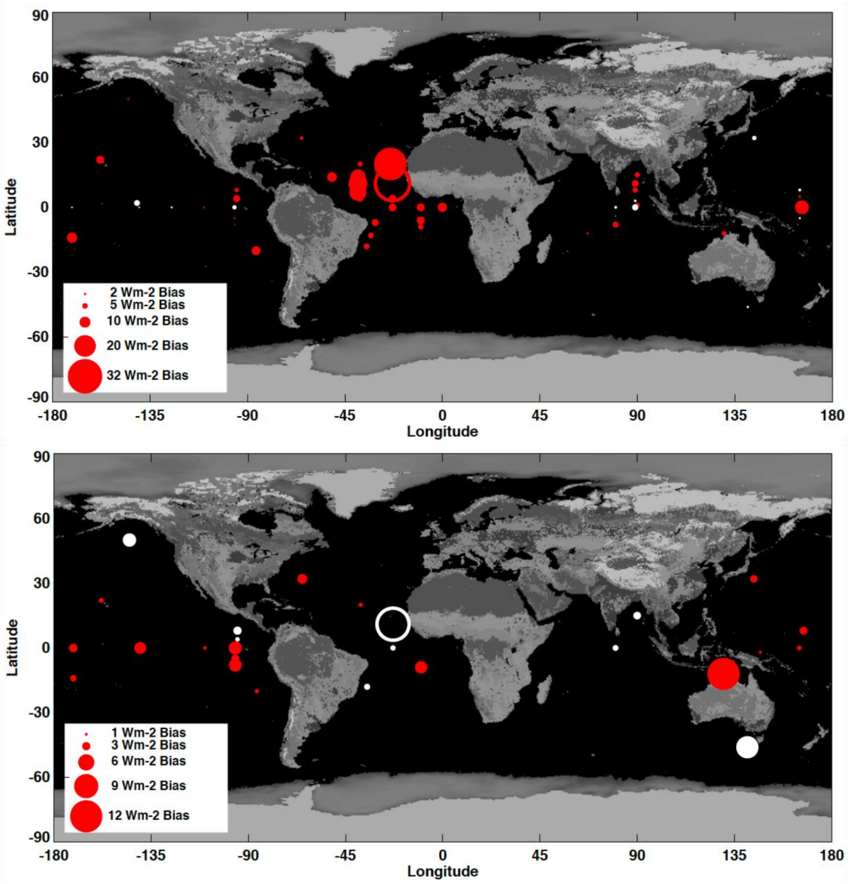

Figure 6.15. Difference of Energy Balanced and Filled (EBAF) shortwave (top) and longwave (bottom) downward irradiances from buoy measured values. The size of the circle is proportional to the difference, with red and white circles indicating positive and negative difference, respectively. From Kato et al. (2018).

Understanding the differences between the satellite and in situ data sets would be enhanced by ensuring that the in situ data be of the highest possible quality, with uncertainties that are quantified and minimized (Cronin et al., 2014). On land, the Baseline Surface Radiation Network (BSRN) has an established set of guidelines for methods of measurement, data management, and data uncertainty and stability information (e.g., Ohmura et al., 1998). While not all of their suggestions are practical for application to ocean sites, some have been used for radiation measurements on ocean buoys, such as those used at the Ocean Site STRATUS. This entails two independent measurement packages, pre- and post-calibration of the radiation sensors, and overlapping deployments of buoys (e.g., Colbo and Weller, 2009; Weller, 2015). A key feature is a careful and continuing analysis of potential sources of uncertainty in the radiation measurements, including sources associated with placement on the buoy relative to other instruments and sources associated with buoy motion, as well as changes to calibration during the deployment. It should be noted that even with the very careful traceability and data quality procedures used in BSRN, errors in longwave down irradiance are on the order of 10 W m^{-2}; errors in direct solar irradiance are closer to 2 W m^{-2}.

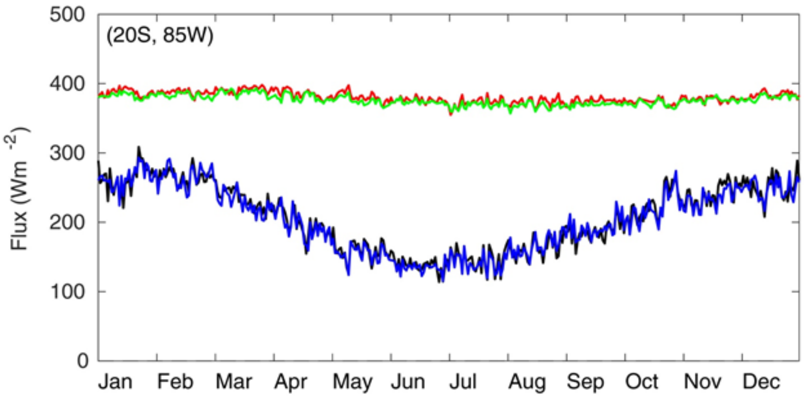

Figure 6.16. The annual cycle of downwelling shortwave (SW) radiation and longwave (LW) radiative fluxes averaged for the period of 2001–2012 as observed from the Ocean Reference Station STRATUS buoy (Colbo and Weller, 2009) and satellite. Black: Satellite-derived downwelling SW; blue: buoy-measured downwelling SW; red: Satellite-derived downwelling LW; green: buoy-measured downwelling LW (from Pinker et al., 2018).

Increasing the number of locations with well-characterized radiation flux measurements will:

- help refine estimates of actual satellite biases (e.g., Rutan et al., 2015).
- provide guidance on the realism of variability in the surface radiation fields that are evident on multiple timescales from the satellite observations. For instance, regional variability in the surface radiation fields over the ENSO cycle is shown by satellite data (Pinker et al., 2017) to be tied to SST and cloudiness. The enhanced TPOS array would allow for independent analyses of these regional variations for the first time.

6.3.2.2 Turbulent heat fluxes

With the sparseness of buoy measurements, in practice present-day derivations of turbulent fluxes relies on satellite values of near-surface (typically 10 m) wind speed, temperature, and humidity, and sea surface temperature, with the bulk fluxes themselves calculated from a bulk flux parameterization, most commonly a version of COARE (Coupled Ocean-Atmosphere Response Experiment) 3.0 (Fairall et al., 2003). In the satellite-based products, buoy data (from the TMA or other arrays) are not assimilated; though some products use a combination of research vessel and buoy data as inputs for algorithm training, and/or as a source of independent validation. If used for algorithm training, typically only a fraction of the available TMA data is used, as otherwise the tropical inputs would overwhelm the statistics from mid- and polar-latitudes. Improvements in the available fields of any of the derived values will improve the calculated fluxes. Several comparisons of satellite-based products with global ocean buoys have been performed, including Bentamy et al. (2017). Comparisons of data from the OceanSites buoys with products that are solely satellite-based demonstrate latent heat flux mean biases (over the ensemble of all buoy sites shown in Figure 6.17) that range from about −5 to 8 W m^{-2}, and sensible heat flux biases from −2 to 2 W m^{-2}, while noting that this is an ensemble mean bias and can be larger or smaller depending on which buoys are included in the comparison. Latent heat flux calculated from daily (averaged up from hourly or sub-hourly fluxes) buoy and co-located flux products show root-mean square (RMS) differences of up to 60 Wm^{-2} at some locations of the tropical Pacific (Figure 6.17). Four of the products shown (IFREMER, HOAPS, SeaFlux, J-OFURO) are solely satellite-based; the other products assimilate buoy data into their production stream.

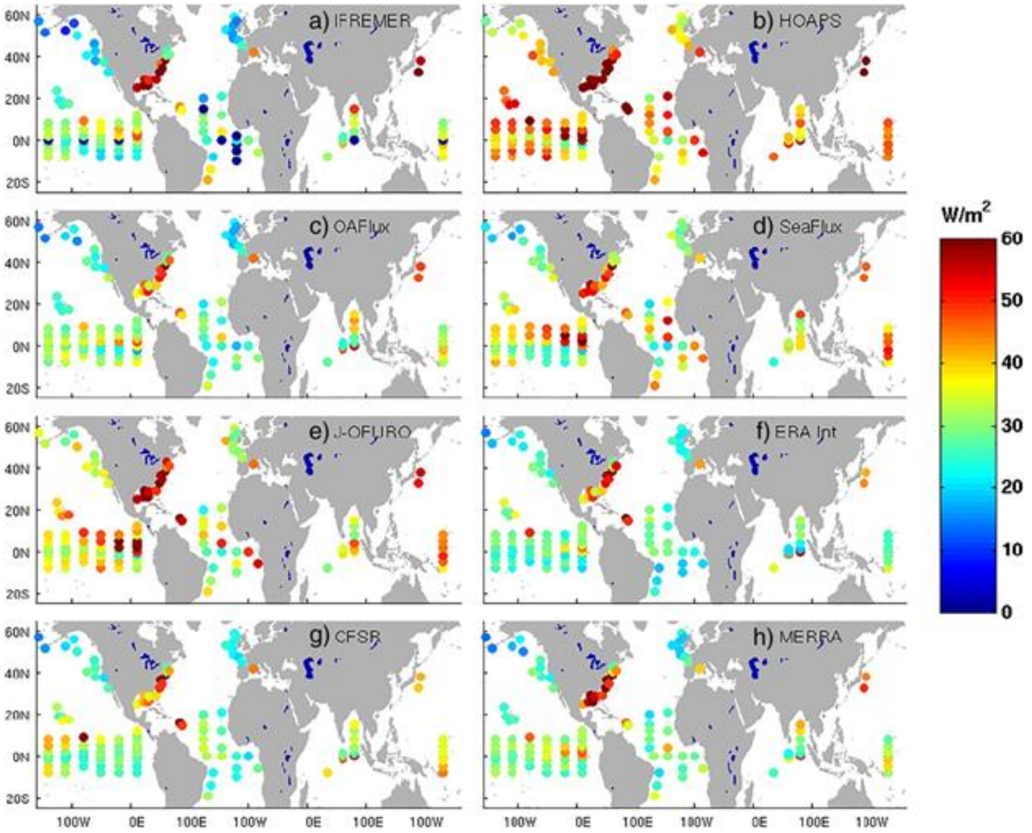

Figure 6.17. Root mean square difference between daily buoy and co-located latent heat flux products estimated for the period 2000–2007. From Bentamy et al. (2017).

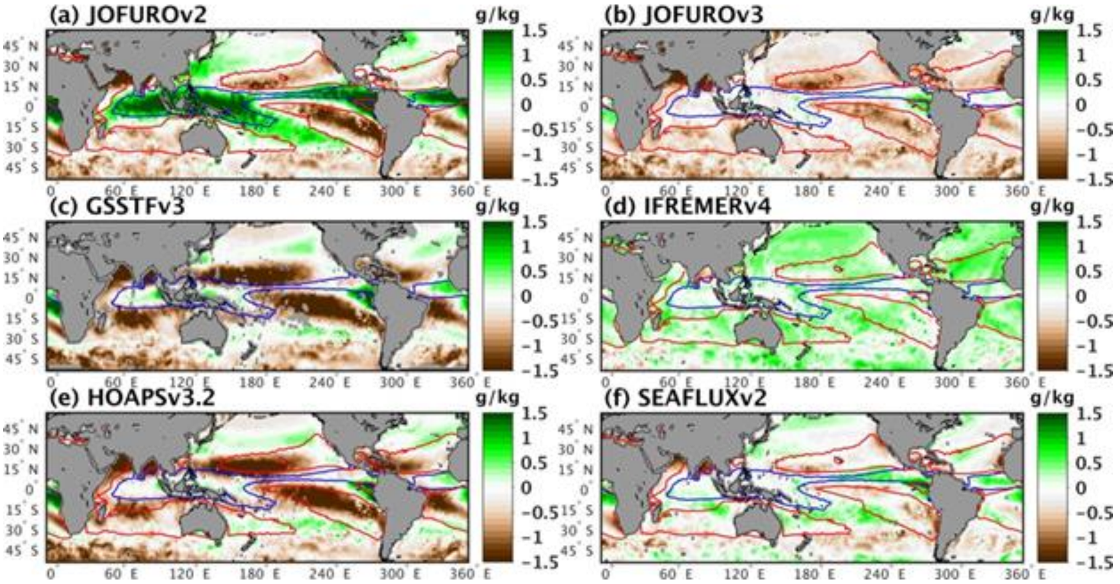

Figure 6.18. Mean near-surface humidity differences (product minus observations) are shown for (a) J-OFUROv2, (b) J-OFUROv3, (c) GSSTFv3, (d) IFREMERv4, (e) HOAPSv3.2, and (f) SeaFluxv2 over the common period 1992–2008. Observations are from NOCS v2, daily corrected fields. Red (blue) contours outline the 15% relative frequency of occurrence regions for the subtropical inversion layer (deep convective) dynamical regimes. From Roberts et al. (2019).

In an analysis of the regional variability in errors in the latent heat flux, Roberts et al. (2019) investigated the errors in the satellite near-surface humidity field by comparisons with ICOADS data. The errors were correlated with the large-scale atmospheric convergence/divergence fields and associated cloud properties (Figure 6.18). It should be noted that two of these products are updated versions of those used in Bentamy et al. (2017). Particularly among the more recent satellite products (right panels), errors are reduced, but the regional error variability is still associated with the background cloud/moisture properties. ***Retaining in situ data sites within each of these regimes will help improve near-surface temperature and humidity values, as well as (as noted above) radiation-needed inputs.*** This figure also clearly highlights the continued improvement in the satellite products; the newer versions or products on the right represent significant decreases in errors compared to, for instance, the older GSSTFv3 product (last updated in 2012) and the previous version of the J-OFURO[21] product.

Long-term trends in latent heat flux between several satellite products and the available data from the TMA are shown in Figure 6.19, as well as a mean of three reanalysis products. There is consistency in the patterns of trends: less latent heat cooling generally in the western Pacific and along the SPCZ and increased latent heat cooling in the eastern tropical Pacific, with some regions off of Central America reversing that trend. Data from the TMA are also shown for those buoys that have the input measurements needed for flux calculation for at least 50% of the months and decade. The mean of the reanalysis is slightly reduced compared to the satellite products, and the J-OFURO has a larger area of increased flux as well as stronger trends overall in the SPCZ. If these patterns are indeed real and continue into the future, ***a northward extension of the meridional line at 110°W (see sections 7.2.1.2 and 7.3.1) would just reach into the regional increase in latent heat flux. The additional extensions in the western Pacific would also help differentiate out the regionality of the increased evaporation in this region.*** To the extent possible, reducing data dropouts would improve understanding of the comparisons between the buoy and satellite data on long-term trends, to ensure that aliasing due to seasonal or interannual variability is not affecting the buoy results.

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[21] Japanese Ocean Flux Data Sets with Use of Remote Sensing Observations - //j-ofuro.scc.u-tokai.ac.jp/en/

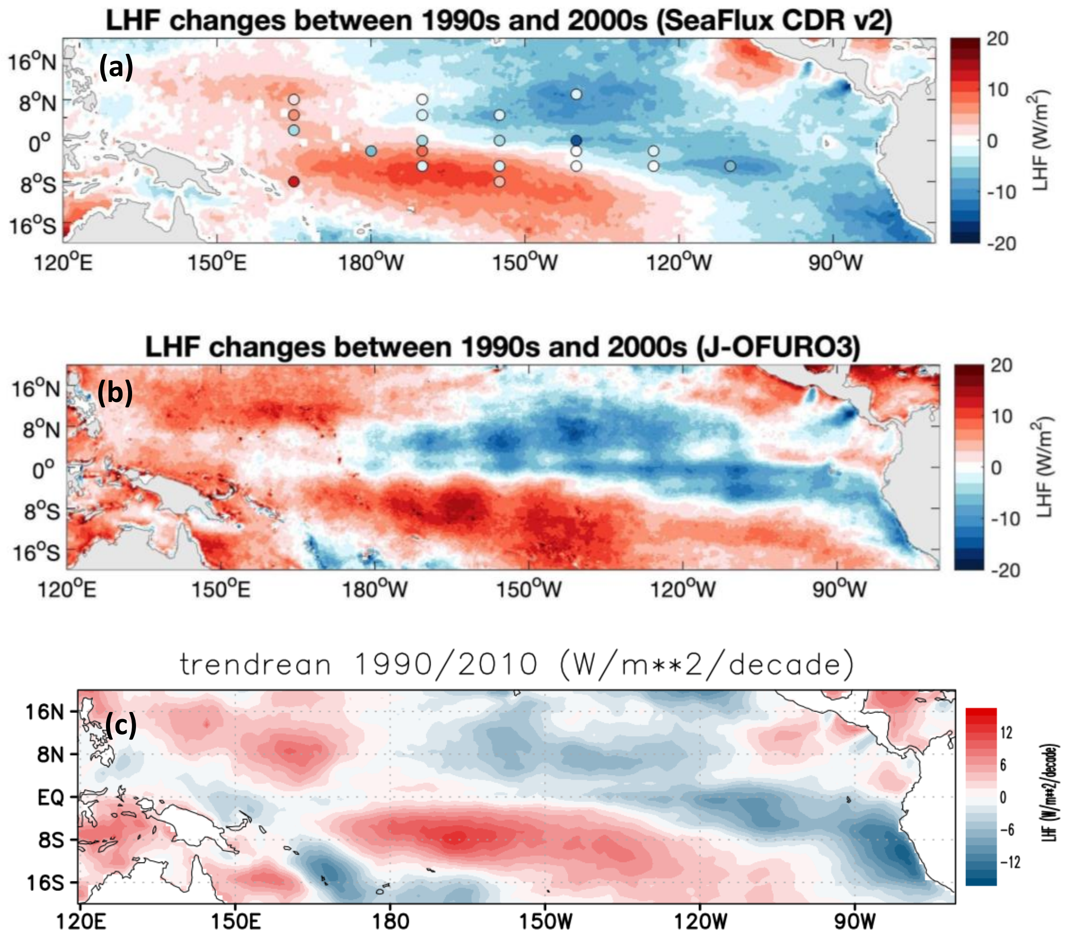

Figure 6.19. Latent heat flux trends from (a) SeaFlux v2.0, (b) J-OFURO3, and (c) a mean of three reanalysis products (CERA-20C, JRA-55C, and 20CRv2c). Trends are calculated from the methodology of de Boisséson et al. (2014). Also shown for comparison are the latent heat flux trends calculated similarly from the TMA buoys, with the caveat that at least 50% of the hourly data in each month must be available for flux calculation, and in turn at least 50% of the months in each time period (1990–1998 and 1999–2013) must also be available before a trend is computed. In all panels, blue and red indicate ocean cooling and warming, respectively.

The TMA surface measurements have a major role in characterizing errors in satellite fields. **The highest quality comparisons would be with in situ directly measured fluxes using direct correlation flux observations.** As the same algorithms are used to compute the fluxes from both the buoy bulk values and the satellite bulk values, any errors associated with the flux algorithm itself typically are not then evident in the comparisons with calculated buoy fluxes. Observations of the air specific humidity (or relative humidity) and air temperature, winds, and sea surface temperature are also necessary for helping provide information on the errors in the satellite-derived values. The particular needs for wind observations are highlighted in the previous section. If the in situ sea surface temperatures are measured below the very near surface (below a few tenths of a meter) then surface solar and longwave radiation measurements are needed as well to allow for modeling of the diurnal warming of the actual surface of the ocean. The importance of the diurnal warming on fluxes and atmosphere-ocean variability has been shown on a variety of scales, including the MJO (Zhang, 2005; Seo et al., 2014), ENSO (Bernie et al., 2008; Tian et al., 2018) and at both instantaneous and long-term means (Clayson and Bogdanoff, 2013), as compared with fluxes with daily averages (or without diurnal warming) (see also First Report, section 2.6.5). Hourly or sub-hourly measurements at accuracies that are within those required for various physical processes (see, for example, Cronin et al., 2019) that are nearly continuous are needed for determination of trend variability.

Additional measurements are needed for providing guidance for improving the retrievals of air temperature and humidity. As shown above, errors in these fields are in part correlated with regions of convergence/divergence and large-scale cloudiness. Measurements of atmospheric boundary layer temperature and humidity profiles and increased cloud observations would be needed to more fully unravel this issue. While not possible currently for the Backbone TMA surface measurements, these measurements would be a prime candidate for adding to a “Super Site” (see section 7.4.7). As discussed above, either direct measurements of stress or the full suite of measurements aimed at improving wind retrievals would also be of benefit to the turbulent flux products.

6.3.3 Freshwater fluxes

Satellite rainfall retrieval algorithms and cloud classification schemes have to be validated using colocated scanning radar and sounding networks based on small islands (Schumacher and Houze, 2003; Yuter et al., 2005; Schumacher et al., 2007, 2008). Rainfall retrieval algorithms can additionally be validated from island gauge networks and rain gauges on moorings (Morrissey and Wang, 1995; Serra and McPhaden, 2003; Bowman, 2005; DeMoss and Bowman, 2007; Huffman et al., 2007; Serra, 2018). Given the sporadic and intermittent nature of precipitation, the number of observations for a given regime needs to be relatively high in order to achieve stable statistics (e.g., Morrissey et al., 2012). While efforts have been made to estimate the error characteristics of the TMA capacitance rain gauges (Serra et al., 2001; Morrissey et al., 2012), updates to the TMA moorings as well as ongoing uncertainty in the gauge sampling errors and accuracy across a spectrum of rain rates will require longer and more complete rain records. As with the heat fluxes, improved understanding of the accuracy of the measurements and their sampling errors (e.g., Morrissey et al., 1995), as well as an increase in the number of observations would enhance the usefulness of the TMA surface measurements toward understanding satellite precipitation errors.

As in Recommendation 9 from the First Report, increasing the number of in situ rain gauges would provide better statistics for satellite comparisons. The TPOS community should work with satellite and in situ precipitation experts to examine to what extent and in what regions increased rain gauge density would be of value, and whether additional measurements (for instance a Super Site with radar, section 7.4.7) could be incorporated to greatly enhance the value of the rain gauges for satellite comparisons.

One estimate of the trends in the tropical Pacific from satellite is shown in Figure 6.20. Changes in this region are related to the narrowing of the ITCZ and resulting enhancement in precipitation intensity under the ITCZ, a topic of considerable current interest (see also Wodzicki and Rapp, 2016; Byrne and Schneider, 2016). The maximum trends in the tropical Pacific are on the order of 2% per decade in the Global Precipitation Climatology Project (GPCP) data set. Such small trends are quite sensitive to potential errors in satellite cross-calibration procedures (Adler et al., 2018), and would need cross-checking with complementary in situ observations. For this challenging purpose, data from moorings need to be properly quality controlled to meet the required accuracy, with complete enough coverage through either sufficiently dense spatial sampling to account for disruptions in temporal sampling at any one site, or more robust temporal sampling at each site to allow for removing the seasonal signal. Additional measurements would also help in understanding the signals: paleoclimate data paired with modern-day observations of water isotopes (see section 9.2.6) in rainfall, vapor and seawater can provide information about trends in tropical Pacific hydrology; sea surface salinity responding to evaporation and precipitation changes and integrating time and space scales could also provide complementary information.

Action 6.4. Continue discussion with the satellite and in situ precipitation experts to evolve the TPOS 2020 recommendations for in situ rain gauges and complementary measurements.

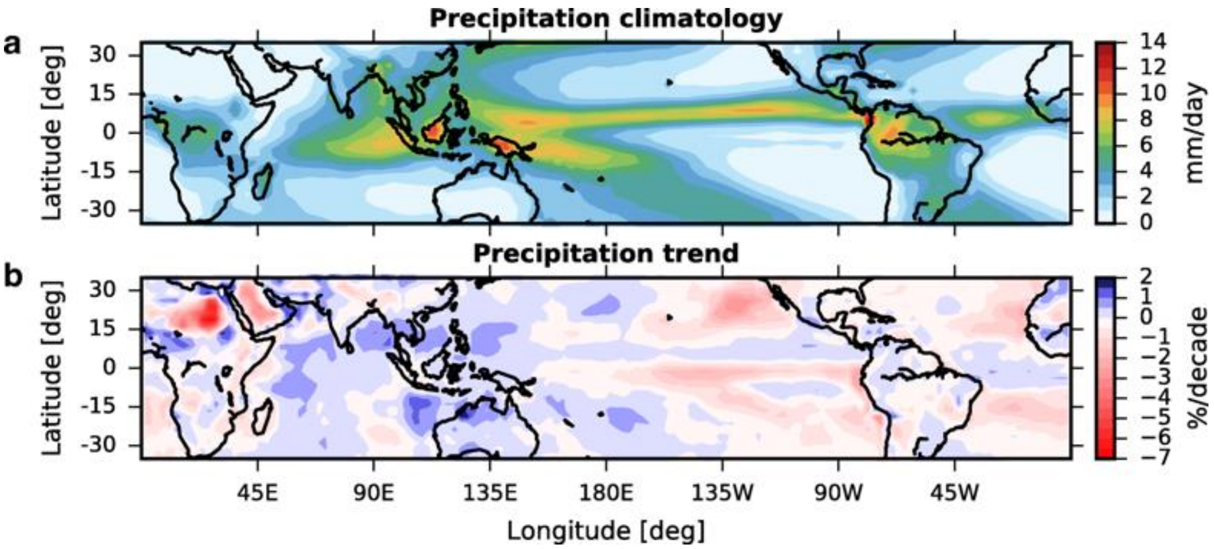

Figure 6.20. (a) Global Precipitation Climatology Project (GPCP; version 2.3) 2.5° × 2.5° annual-mean precipitation climatology from 1979 to 2017. (b) Trends in de-seasonalized GPCP monthly-mean precipitation over 1979–2017. From Byrne et al. (2018).

6.3.4 Importance of surface currents for improving surface fluxes

The wind stress, the evaporation rate, and latent and sensible heat fluxes depend on the wind speed relative to the ocean current. This “relative wind speed” is defined as the magnitude of the difference between the wind velocity and the surface ocean velocity. The latent and sensible heat fluxes and evaporation rate are linearly proportional to the relative wind speed, meaning that a 10% error in relative wind speed gives a 10% error in the latent and sensible heat fluxes. The wind stress is proportional to the square of the relative wind speed, meaning that a 10% error in relative wind speed will give about a 20% error in wind stress.

When measurements of ocean surface velocity are not available, the ocean current speed is often assumed to be zero when estimating the surface fluxes from in situ, satellite, or reanalysis data. Ocean current speeds are typically much smaller than wind speeds, but in some regions the contribution of ocean currents to the relative wind speed can be substantial. The tropical Pacific has strong mean and seasonal surface currents that can exceed 1 m s^{-1}; even away from strong currents, wind-driven near-inertial currents can exceed 0.5 m s^{-1} (e.g., Plueddemann and

Farrar, 2006). Between 10°S and 10°N, the mean and standard deviation of the surface currents are both on the order of 0.35 m s^{-1} (Lumpkin and Johnson, 2013). Assuming an ocean current value of 0.5 m s^{-1} and a wind speed of 6 m s^{-1}, the uncertainty in latent and sensible heat fluxes from neglecting the ocean current would be about +/-8%. The error in wind stress would be about +/-16%. However, the errors are likely to be systematic because the background currents have large-scale structure. The long zonal currents of the tropical Pacific imply relative-wind effects organized in latitude bands. This is especially significant for wind stress, since the long zonal currents will therefore result in systematic wind stress curl structure. It is also particularly important near the equator, where the winds are relatively weak and the zonal surface currents relatively strong, and where the zonal wind stress strongly affects the subsurface upwelling, zonal thermocline tilt, and intensity of the equatorial cold tongue.

In addition to helping avoid unacceptably large bias and random errors in estimates of ocean surface fluxes, having more in situ information on ocean near-surface currents would help improve our knowledge of the state of the upper ocean and surface atmosphere in a few other ways. More extensive in situ near-surface current measurements (co-located with winds and fluxes) would: (1) aid interpretation of satellite wind measurements; (2) allow evaluation and improvement of surface current products, which tend to have important errors in the near-equatorial regions where the geostrophic approximation is much less reliable, especially on short timescales; (3) allow evaluation and improvement of future satellite missions to measure ocean surface currents (Rodriguez et al., 2019; Ardhuin et al., 2018); and (4) allow progress in understanding the near-surface currents and shear and their role in transporting heat and salinity in the tropical Pacific climate system. See sections 7.5.1 (update on the First Report recommendation 11) and 9.3.1 for more details about these future missions.

6.4 Marine sea level pressure

The First Report supported efforts to increase the number of surface drifters and moorings measuring sea level pressure (sections 3.1.2.4 and 7.4.1) and recommended sea level pressure be included as "standard" on moorings.

Recent literature supports those conclusions. Ando et al. (2017) noted the positive impacts of TRITON pressure measurements. WMO (2016) reviewed the impact of various observations on numerical weather prediction, including the impact from surface pressure measurements from drifters (see also Horanyi et al., 2017; Centurioni et al., 2017; Ingleby and Isaksen, 2018). The message of these studies is that surface pressure measurements are important, including in the tropical region. Poli (2018) and the Tropical Atlantic Observing System review (P. Dandin, personal communication) have examined the impact for the tropical Atlantic and reaffirmed the conclusions above for the PIRATA buoys (Figure 6.21).

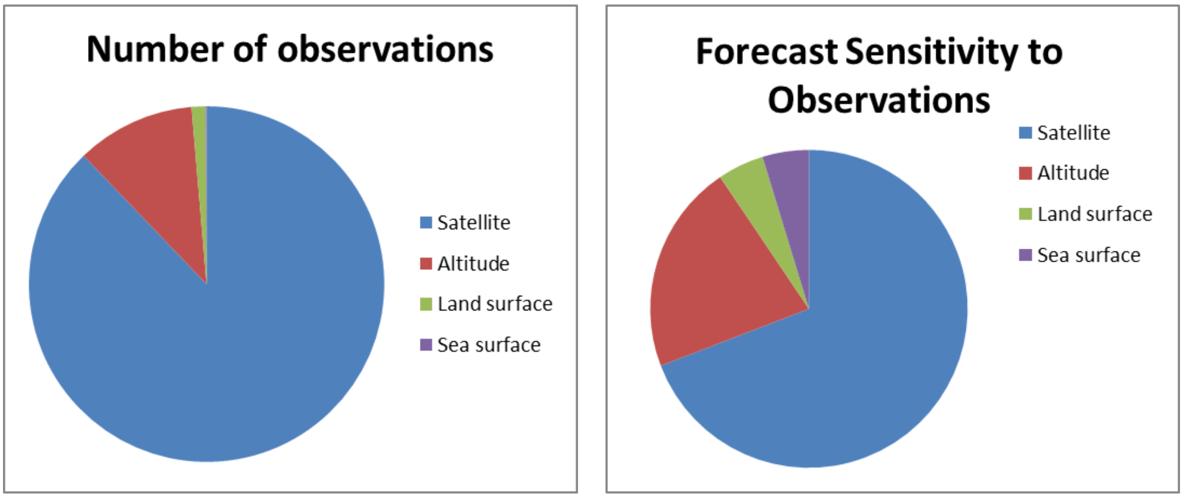

Figure 6.21: Number of atmospheric observations assimilated operationally by ECMWF (left) and the contribution of these observations to improving the forecasts (right) (from Poli, 2018).

The WMO requirement for sea level pressure (see http://www.wmo.int/pages/prog/www/OSY/GOS-RRR.html) is around 1500 globally (reporting multiple times per day) or, around 1 per 3 × 10 degree box in the tropics (sampling requirements for surface wind can be used as a good proxy). Drifters are least effective near the equator because of rapid divergence and could be complemented by sensors on the TMA (5°S–5°N). Genesis regions for severe storms may also be given priority if the TMA is sampling in regions where the drifting buoy program has sampling issues.

6.5 More measurements in more regimes

Accurate estimation of the air-sea exchange of heat, water, and momentum is essential to understanding and predicting the state of the tropical Pacific Ocean and its effects on the atmosphere. The First Report (see their section 3.1) discussed the importance of these fluxes and recommended a substantial increase in colocated in situ sampling of the state variables needed to estimate these fluxes. All of the TMA buoys currently measure SST, air temperature, humidity, and wind, but adding measurements of surface currents, precipitation, downwelling solar radiation, and downwelling longwave radiation is required to allow a more accurate estimation of the air-sea exchange of heat, water, and momentum. The present TMA makes this full suite of measurements at only a few sites on the equator, and the First Report recommended making these measurements at all surface mooring sites (see also section 7.3.2.1).

The existing TMA spans nearly the full zonal extent of the basin between 8°S and 8°N, but its sampling does not extend across the tropical convergence zones and into the subtropical trade wind regime, and only a few sites along the equator allow sustained estimation of the full air-sea heat and moisture fluxes. These present capabilities limit the utility of the existing TMA surface measurements for constraining reanalyses or for characterizing and improving satellite flux estimates and models, because many of the existing TMA sites are in similar atmospheric regimes. Thus, in addition to increasing the number of sites where the complete suite of surface variables are simultaneously measured, the strategy discussed in the First Report also included a focus on increasing the diversity of weather/climate regimes in which these measurements are made. This would lead directly to improvements in our understanding of the exchanges between the atmosphere and ocean across the broader range of regimes of the tropical Pacific; more importantly, it would enable evaluation and guide improvement of coupled models, atmospheric and coupled reanalysis systems and satellite-based measurements of flux and weather variables. These reanalysis and remote-sensing data products are increasingly relied upon for research and operations (Chapters 2 and 3), thus improving them would greatly expand the reach and utility of the TMA.

Some of the key regimes we refer to are illustrated by the following non-exhaustive list:

- equatorial cold tongue where net downward heat fluxes are largest, diurnal SST variability is large, surface currents are strong, and upwelling is a large influence;
- western equatorial warm pool where westerly wind bursts are prevalent, barrier layers are common, and diurnal SST variability large;
- deep convection zones found in the off-equatorial warm pool and under the ITCZ and SPCZ where the highest rainfall and lowest radiative heating occurs and where winds are particularly gusty;
- dry and sunny inflows to the convergence zones, both north and south of the equator where winds are strong and evaporation rates are high;
- far eastern tropical Pacific where stratus clouds can form and the mean winds are northward across the equator. In this region the thermocline is sharp and shallow, so its fluctuations can quickly modify SST;
- frontal regions, occurring both at the eastern edge of the warm pool and the northern edge of the cold tongue. Both are regions where strong air-sea interaction affects the larger-scale system.

Continued advancement in our ability to observe and estimate air-sea fluxes and surface properties using in situ and satellite techniques will also require some measurements that are more difficult and intensive, but that could be carried out at fewer sites. These “Super Sites” (section 7.4.7) would have a broader and more detailed set of information that could be used to gain better understanding of air-sea interaction, of physical processes represented in models, and of remote sensing data. For example, estimation of wind stress will benefit from improvements in the bulk formula used to estimate wind stress, which in turn requires direct measurements of the near-surface momentum flux in the atmospheric boundary layer (known as the direct-covariance or eddy-covariance technique) together with measurements of bulk variables (like wind speed, current speed, air temperature, humidity, sea temperature, and surface waves) (e.g., Edson et al., 2013). Estimates of wind stress from satellite scatterometers, which respond primarily to variations in wind stress (see Annex A), could be made ‘directly’ by developing retrieval algorithms that relate the measured radar backscatter to the same in situ measurements; this would presumably yield more accurate estimates of the wind stress than the current practice of estimating wind speed from the radar backscatter before using that wind in a bulk formula.

6.6 Concerns expressed since publication of the First Report

The design principles, variable requirements and associated recommendations for the observing system were discussed in detail in the First Report. The writing process for the TPOS 2020 First Report was intended to get as much stakeholder input as possible, engaging the international climate research community and many other interested groups through town-halls and workshops. The review process comprised an invited expert review followed by an open review through a broadly disseminated call for input and generated more than 1000 specific comments that were tracked and taken into consideration when revising the First Report. This level of community input and feedback is vital to ensuring that the TPOS Backbone design is fully reflective of the requirements of users, sponsors and stakeholders. The communities were generally supportive of the TPOS 2020 approach and enthusiastic about the recommendations to enhance the TPOS capability.

Nonetheless, some readers of our First Report, including the International CLIVAR Pacific Regional Panel (PRP), while supportive of many TPOS 2020 recommendations that would enhance the TMA, raised objections about the proposed TMA reconfiguration. These were largely focused on preserving the climate record. In particular, the PRP concerns pointed to the reliability, accuracy and continuity of the surface meteorological records that might be at risk from the proposed greater reliance on satellite sampling. While the PRP recognizes the accuracy and spatial information that satellite scatterometers provide, their concerns with the TPOS reconfiguration focus on: i) the unresolved nature of the differences between wind measurements from scatterometers and moorings; ii) the relatively low temporal resolution of satellite scatterometer sampling; and iii) the relatively short duration of satellite missions, which means that the climatological record relies on piecing together measurements from multiple scatterometers. In addition, they expressed concern about the adequacy of Argo to replace the subsurface temperature observations at any TMA sites that might be decommissioned. They considered that “the highest priority of the TPOS 2020 project should be to maintain the existing TMA as a component of the broader observing system, until there is clear and convincing evidence that off-equatorial moorings that have been producing unique and valuable data for 25 years can be adequately and satisfactorily replaced by other technology” (CLIVAR Pacific Region Panel, personal communication). They “believe that the ability to diagnose future ENSO variability in a changing climate in all its dynamical, spatial, and temporal complexity will be seriously compromised by any reduction in the existing array.”

TPOS 2020 agrees that TMA surface measurements have great value, and indeed recommends retaining most sites, and expanding both the parameters and regimes sampled by the TMA. However, we have attempted to evaluate the priority of TMA sites in the context of the full suite of available platforms, and assessed each measurement based on its ability to address all five functions of the Backbone (listed at the start of Chapter 7). Following in-depth discussion, we conclude that maintaining all point time series does not necessarily rise above all other considerations in a multiplatform system. Our judgment is that the recommended TPOS as a whole is the most effective and realistic balance between gains and losses (see section 7.3.3). In part, this judgment reflects our different perception of the relative strengths and weaknesses of moored and satellite sampling of atmospheric surface variables. It also reflects the broad set of applications the TPOS must serve; in addition to the ENSO and dec-cen interests of the PRP, this includes weather forecasting and subseasonal to seasonal prediction (Chapter 3), biogeochemistry (Chapter 4), and the suite of observations directed at model and data assimilation advancement (Chapter 2).

In response, TPOS 2020, through its Backbone-Task Team has continued to engage the PRP to reconcile these concerns through direct discussions and the initiation of a “Surface Wind Team” to better understand and document the differences between wind estimates by satellites and moorings (see section 6.3.1 and Annex A), and continues to carefully re-examine the recommendations and actions within the First Report. We have also adapted the TMA mooring configuration proposed in the First Report to include an extra meridional spine to provide more confidence in the ability of the TPOS to monitor longer term wind changes. We will work with the PRP through the life of the project, as well as again invite additional input from the broader community of research and operational stakeholders, to obtain an appropriate balance between gains and risks for prioritization of the TMA between now and the Final report of the TPOS Backbone.

Chapter 7 The TPOS 2020 Backbone Observing System

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In this chapter, we update, and as necessary modify, the requirements and recommendations provided in the First Report. We take advantage of new dedicated studies, feedback from readers of the First Report, as well as technical progress, in particular the results of recent pilot studies. We also highlight some aspects and more fully explain some of the reasoning behind the First Report. Finally, we provide updates on the status of the actions and process/pilot studies that were recommended.

Based on all these revisited requirements, this chapter replaces the less specific ("fuzzy") aspects of the First Report which provided a conceptual sketch of the new Backbone (see Figure 7.1) with more detailed recommendations for the eventual Backbone in 2020 and beyond.

7.1 Meeting the multiple functions of the Backbone Observing System: A recap from the First Report

As laid out in the First Report, the new Backbone TPOS design aims to deliver to five key functions:

1. Provide data in support of, and to evaluate, validate and initialize, ENSO prediction and other forecasting systems and to foster their advancement;
2. Provide observations to quantify the evolving state of the surface and subsurface ocean;
3. Support integration of satellite and in situ approaches including calibration and validation;
4. Advance understanding and modeling of the climate system in the tropical Pacific, including through the provision of observing system infrastructure for process studies; and
5. Maintain and extend the tropical Pacific climate record.

We revisit the Backbone in an environment quite different from that of thirty years ago, when the TAO array was envisaged as the primary means of meeting the above needs. Today, we take advantage of the remarkable developments in both the in situ and satellite components of the observing system, including multiple scatterometers, multiple altimeters, passive microwave and other advanced space-based radiometers, global Argo, and advances in mooring and other in situ technology. Present and future elements can be assessed against their ability to meet the key TPOS functions, with high priority given to those that contribute to multiple functions.

The new capabilities, which have complementary strengths that multiply their usefulness, led to a reassessment of the role of the TMA. Moorings' unique capabilities provide excellent temporal resolution of many different oceanographic, meteorological, and biogeochemical variables, enabling diagnosis of co-variability and of spectral characteristics of phenomena, and allowing specification of the errors inherent in less frequent sampling. Moorings are presently the only technology that provides long-term collocated ocean and atmosphere observations, sampling the full suite of variables to estimate air-sea fluxes, including direct velocity measurements.

While the collocated measurements of the TMA remain crucial to the observing system, they are no longer the only means of tracking the state of the tropical Pacific as they were when originally deployed in the early 1990s. Today Argo greatly improves the vertical resolution of subsurface features, and samples between the TMA lines, while satellites provide unprecedented spatial coverage and resolution for many essential surface variables.

Thus, in the new TPOS Backbone, we have sought to exploit the complementarities among observational platforms to drive forward a major advance in our capability to monitor the tropical Pacific Ocean and surface atmosphere. The new design sees a partial shift in the focus of the TMA from a grid-like configuration to regime measurements where its unique strengths are brought to bear. The TMA will be complemented by the enhancement in subsurface vertical and temporal resolution (particularly for salinity) from Argo, and the much-improved spatial coverage of surface winds by satellite scatterometry. While the priorities expressed here might lead agencies to discontinue occupation of some TMA sites (which would need careful transition planning and assessment), the design expands the TMA to cover a broader range of latitudes and oceanic and atmospheric regimes.

The proposed new TMA will still retain a grid-like configuration, capable of state tracking at the large scales associated with decadal and longer timescale changes, and the expansion of some of the TMA lines away from the equator will improve the latitudinal range of this capability. The preserved mapping capability will still provide independent validation of long-term changes diagnosed from other parts of the observing system. In this sense, the tropical Pacific climate record, particularly for surface meteorology and subsurface temperature, will be extended into the future at most existing TMA locations and extended spatially via the other newer networks, with independent validation built into the design, a situation found in few other ocean regions. In addition, the TPOS 2020 design will expand measurements of biogeochemical parameters, required for both critical research questions and nascent operational services (see Chapter 4). The new TMA design is further detailed below (section 7.3.1). For those readers not familiar with the key recommendations for the Backbone from the First Report, we present these below, as they provide a critical context for what follows.

7.1.1 Recommendations for an integrated Backbone

As discussed in detail in the First Report, Chapter 3, the integrated Backbone must enable better forecasts and track the state of the coupled system, preserve and improve the climate record and increase our understanding of critical phenomena. These include near-surface physics on sub-daily timescales, frontal air-sea interaction and near-equatorial ocean physics.

The major recommendations from the First Report are briefly restated below (also see TPOS OceanObs'19), with focus on those that represent a specific TPOS response (refer to the First Report http://tpos2020.org/first-report/ for details and Appendix B; the First Report recommendations are referenced in [brackets]).

7.1.1.1 Air-sea interface surface variables

- Improve coverage and reduce diurnal cycle aliasing of vector winds and wind stress with a constellation of multi-frequency scatterometer missions and complementary satellite wind speed measurements to enable all-weather wind retrievals over 90% of the area of the tropical Pacific Ocean every 6 hours [Recommendations 1, 2]. The in situ winds play a vital role for validation and to construct the climate record, and associated surface currents are needed to aid interpretation of satellite wind measurements (see section 6.3.4)
- Continue and enhance space-based precipitation measurements complemented by expansion of the open-ocean in situ network covering diverse rainfall climate regimes [Recommendations 8, 9].
- Enhance in situ observations of the state variables needed to estimate the full surface heat and freshwater fluxes, for monitoring the subseasonal-to-decadal coupled ocean-atmosphere interactions, with emphasis given to diverse regions (e.g., moist vs. dry zones, stable vs. unstable zones, etc.), and for evaluating and improving remotely sensed fields and atmospheric reanalyses. This will be accompanied by pilot studies of new platforms and technologies and process studies to improve gridded products and understanding of the sensitivity and impact of observed air-sea flux variables in forecast and reanalysis systems [Recommendation 15 and Actions 6–11].
- Continuation of high-frequency moored time series and broad spatial scale underway surface ocean $p\mathrm{CO}_2$ observations across the Pacific from 10°S to 10°N [Recommendation 12].
- Continuity of complementary satellite and in situ sea surface salinity (SSS) measurement networks, with a focus on improved satellite accuracy [Recommendation 10]. Recent results (e.g., Boutin et al., 2018; Hasson et al., 2018) show improvements in the quality of SSS retrievals, encouraging TPOS 2020 to reiterate this recommendation.
- Our recommendations for other satellite-sampled surface variables (SST, sea surface height, ocean color) follow those of other global observing system plans (for example, Global Climate Observing System, 2016) [Recommendations 3–7, 13]; the importance of passive microwave SST measurements is highlighted.
- Existing technologies cannot meet surface velocity requirements. The First Report encourages efforts to measure surface velocity from space, and to develop techniques to validate this approach [Recommendation 11] (see sections 7.5.1, 9.3.1)

7.1.1.2 Subsurface variables

Broad-scale sampling of subsurface temperature and salinity is required, with enhanced vertical resolution and better meridional spacing. Additional targets are to resolve near-surface stratification and to improve sampling of equatorial currents [Recommendations 16–20]. Specifically:

- Target the fast, coupled upper ocean physics across key regimes: enhance mooring resolution in the upper layer and expand the moored array poleward to give broader coverage and better temporal resolution of faster processes and the parameters needed to estimate total surface fluxes and mixed layer response;

- Double Argo profile returns between 10°N and 10°S, starting in the western Pacific;
- Restore the equatorial moored array in the west;
- Target the circulation and physics on the equator: maintain and expand direct measurements of velocity across the basin; and
- Expand direct velocity sampling, initially at 140°W, to better resolve the meridional structure of the EUC and the advection and mixing processes where the EUC interacts with the mixed layer.

These recommendations resulted in a design that would reconfigure the TMA to have fewer meridional spines but more poleward sampling, and to double Argo in the tropical band (Figure 7.1; was Figure 7.2 of the First Report).

As detailed in the previous chapters, since these recommendations were formed, new communities have been consulted and further feedback (section 6.6) has resulted in some new insights, as summarised below.

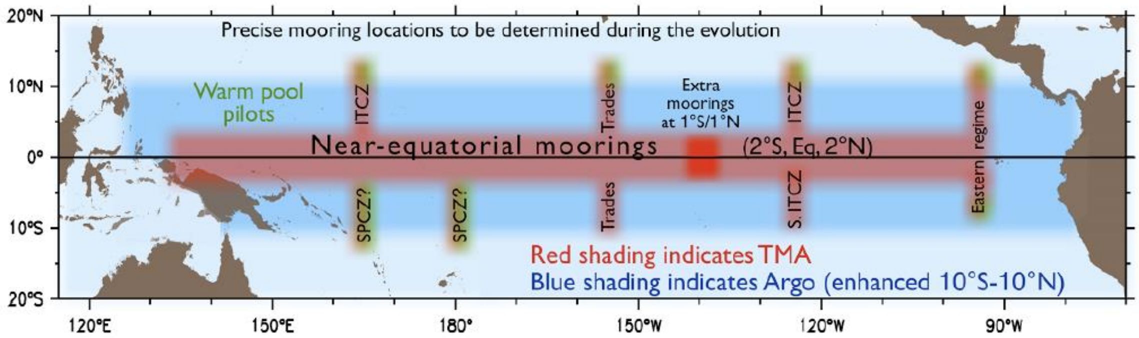

Figure 7.1: Schematic of recommended sustained moored and Argo networks from the First report. Red shading indicates TMA moorings, blue indicates Argo, enhanced within 10°S-10°N (darker blue shading; First Report section 7.4.3). The reconfigured TMA consists of near equatorial sites (broad red stripe centered on the equator) plus several extensions to cross the ITCZ and SPCZ. Precise sites are "fuzzy" (green shading) in some details, for example, how far north and south the extensions will go and whether the SPCZ line will be along 165°E or along 180°. Two extra moorings at 1°S and 1°N will increase the equator spanning meridional resolution at 140°W (bright red square). Possible future western augmentation is here labeled “Warm pool pilots.”

7.2 New requirements and better addressing key challenges

7.2.1 Summary of requirements for Backbone from previous chapters and sections

Based on the new considerations in the chapters above, we summarize below the implications for the Backbone.

7.2.1.1 Coupled prediction and data assimilation

Coupled data assimilation systems are rapidly developing and are expected to play an essential role for the future of NWP and S2S forecasting systems (Penny et al., 2017; Penny et al., 2019;

see Chapters 2 and 3). Although we considered some of these needs in the First Report, we wish to update and provide more explicit requirements here (see Chapter 3).

Coupled data assimilation refers to the assimilation of observational data using a coupled forecast model. For example, ECMWF transitioned to a coupled model with interactive ocean and sea-ice components for all forecast timescales on 5 June 2018. This upgrade improved forecasts and produced consistent gains in the extended range. However, there are many approaches to applying coupled data assimilation, which are generally classified in a spectrum between "weakly coupled" and "strongly coupled."

Weakly coupled data assimilation (WCDA) is commonly used today for assimilating observational data in conjunction with coupled Earth system forecast models. The WCDA approach assimilates observations from each domain, generates an updated state estimate for the corresponding domain, and then uses each of these state estimates to independently initialize each component of the Earth system model. This follows historically from data assimilation being independently applied to weather forecast models, ocean models, and other Earth system modeling components, using uncoupled models that are supplied with external forcing fields.

Operational centers are now transitioning toward strongly coupled data assimilation, with ECMWF leading in this transition (e.g., Laloyaux et al., 2018; Schepers et al., 2018), which allows observations from one domain to influence the state estimation and model initialization in another. For example, high-frequency measurements of the thermocline depth along the equator might be used to make corrections to the estimated atmospheric surface winds via known correlations in forecast errors.

Coupled Earth system models are undergoing continuous development and are relatively new for use in weather and S2S prediction. Early investigations have indicated that "using interactive ocean and sea ice components in ECMWF's Integrated Forecasting System (IFS) can significantly improve sea-surface temperature predictions in Europe and, as a result, predictions of near-surface air temperature" (Mogensen et al., 2018). A number of physical mechanisms have been identified as providing this benefit, relating to their impact on in situ SST estimates: (1) advection of seawater, (2) cooling via upward sensible and latent heat fluxes (dependent on surface air temperature, humidity, and winds), (3) heating via insolation (enhanced with light winds and reduced mechanical mixing), and (4) cooling by mechanical mixing (e.g., with shallow warm water sitting atop a cold layer).

Coupled data assimilation and coupled modeling focus on the many interactions between individual components of Earth system models that have traditionally been analyzed in isolation. This includes coastal interactions in estuaries and extended zones of influence between land and sea. It includes interactions between sea ice and the adjoining atmosphere and ocean boundary layers. Perhaps most importantly to TPOS 2020 is the air-sea interaction, of which some review of the state of modeling in regional and global models has been discussed by Schrum (2017).

There is a clear need to improve modeling of the air-sea interface, which today exists as a remnant of methods used in lower resolution models of the past.

- For model development, moorings with an increased suite of sensors capable of measuring flux quantities relevant to conserving total heat, momentum, and mass (including freshwater and geochemical constituents) in the coupled system will be useful (see Recommendation 3.1).
- As future forecasting systems also aim to better resolve the diurnal cycle in the boundary layers, the high temporal resolution provided by moorings combined with satellite measurements of surface and boundary layer quantities will become even more important (see sections 6.3.1 and 6.3.2).
- For ocean state estimation, initialization and prediction, dynamic observing platforms such as Argo floats and autonomous vehicles may be more useful to constrain the broader ocean circulation by providing spatial information at the timescales of the ocean dynamics of interest.
- Further research is required before we can be specific in terms of essential variable requirements or potential enhancements/variations to the Backbone observing system over and above those already provided through the First Report (Recommendation 3.3, section 3.4).

7.2.1.2 Decadal-centennial dynamics

As discussed in section 6.1, tracking and further understanding the mechanisms of decadal and longer-term changes in the tropical Pacific represents one of the most challenging targets for the observing system, largely due to the relatively small magnitude of the signals. The signal to noise in the subsurface is likely higher than for surface fluxes, where many 50-year changes in the heat flux components are less than 10 W m^{-2} (Coats and Karnauskas, 2017; Lyu et al., 2017). This represents a formidable accuracy requirement and highlights the need to independently cross-check signals detected across platforms. In the ideal system, derived fluxes from state variables observed by the TMA can be used to validate estimates from satellite products and atmospheric or coupled reanalysis. Similarly, the subsurface estimates of change detected by Argo and altimetry could be validated by the observations of the TMA. This ‘validation role’ of the TMA requires that it has the right spatial structure to capture these signals and that the instrumentation and data practices deliver the required accuracy. In addition, the high temporal resolution of TMA data can reveal sampling weaknesses and the uncertainty structure of sparser-in-time sampling such as obtained from Argo or the satellite constellation, one example being the diurnal cycle and its potential to bias or alias the lower frequency variability in satellite products.

Associated with this challenge is temporal completeness (percentage of measurement days in a record). Historically, no TMA sites have delivered a complete record in winds and other state variables required to calculate fluxes such as the latent heat flux. Typically, wind record completeness is around 80%, while for latent heat fluxes it is lower at 60% or less (Figure 7.2; noting that this includes significant system-wide gaps of both TAO and TRITON). For radiative fluxes, only a few moorings were sustainably equipped (Cronin et al., 2014). Given the large interannual variability in the tropical Pacific, this low level of coverage could compromise the TMA’s use in accurately detecting decadal and longer term trends.

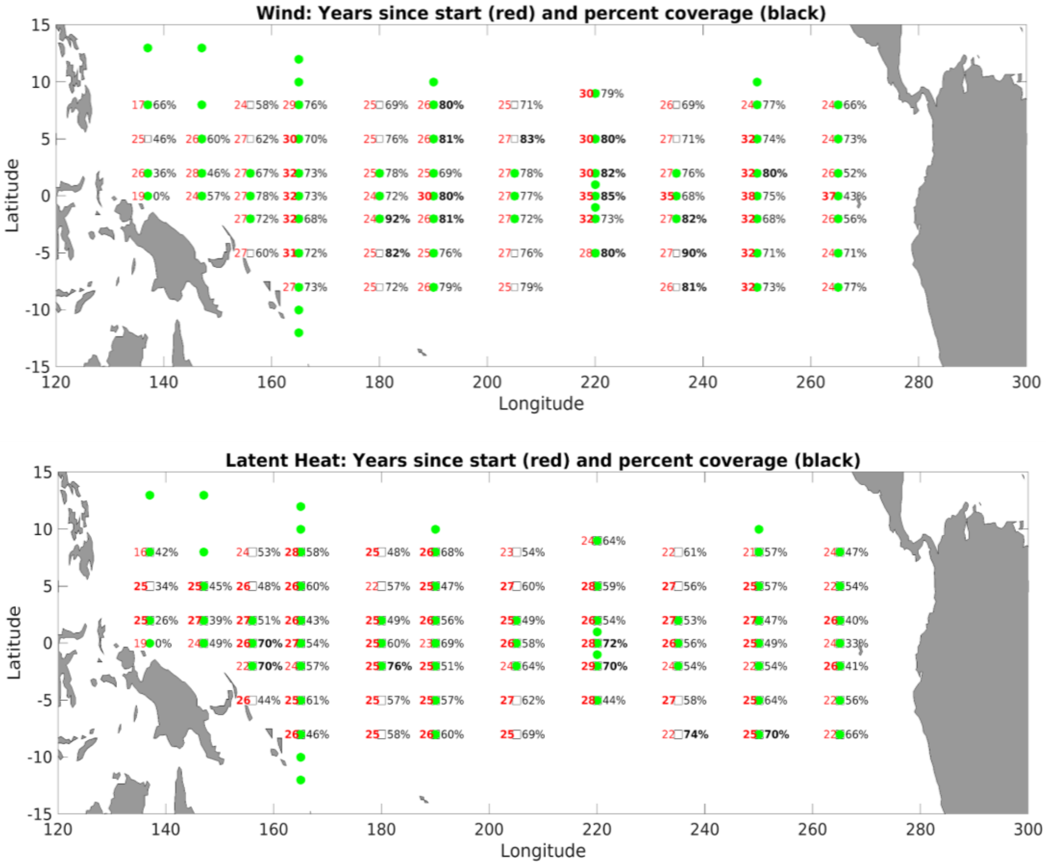

Figure 7.2: Historical observation coverage from the TMA. Top is for winds and bottom is for latent heat. Red numbers indicate years since the record start and black number the percentage of days with an observation. Source: https://www.pmel.noaa.gov/tao/drupal/flux/index.html. Larger resolution image at: http://tpos2020.org/2nd-report-draft/

Single platform approaches can thus be limited, and we argue that both satellite and in situ data streams (surface and subsurface) are needed to meet the dec-cen trend detection challenge, with all data types supporting each other (as discussed in the First Report). Even in combination, monitoring decadal and longer-term changes in surface fluxes remains a major challenge to the TPOS, and will require attention to both sampling completeness and accuracy. Our response to this challenge is:

- to sustain TMA long-time series and retain a capability with the potential to be able to detect expected dec-cen change and future changes in ENSO spatiotemporal patterns;
- to sample across more regimes for satellite intercalibration and validation, to better cross-validate spatial patterns of trends in heat and freshwater fluxes (see sections 6.3.2 and 6.3.3)
- to develop the capability of enhanced sites that might more directly drive retrieval and flux algorithm improvements ("Super Sites", see section 7.4.7);
- to continue working toward improving the measurement accuracy by improving instrumentation and data practices.

A multi-parameter view is also useful, where changes in winds should be reflected in surface pressure and sea level changes.

7.2.1.3 Western Pacific climate and weather applications

It is urgent that observations, research and services address societal demands for more sustainable management, better emergency preparedness and disaster reduction. This is even more urgent in the heavily populated NWPO region. The international community needs the 'optimal' NWPO observation system to better understand the monsoon and typhoons in general (see section 6.2), and intraseasonal variability considering its critical role in bridging weather and climate. Monsoon prediction is a long-standing issue with slow progress over more than one century. Typhoon prediction is still struggling to reduce intensity error and to extend lead times. Without appropriate data streams from the observing system, the community has no way to understand the key processes bearing on the predictability of typhoons in the next generation of weather and climate models.

Thus, a new moored array is required that will optimally measure the north/northwestward propagating BSISO, the west-east displacement of the WPSH, the typhoon genesis region and the NWPO current system including the equatorial undercurrent, North Equatorial Counter Current and North Equatorial Current. The buoys should be equipped with the standard marine meteorological package to enable the net air-sea heat and water fluxes to be estimated, and to improve the quality of the global heat flux data set and reduce the biases and uncertainties (Yu et al., 2013).

7.2.1.4 Biogeochemical requirements

Chapter 4 details the justification for enhancing BGC sampling as part of the TPOS. The resulting sampling requirements are as follows:

- maintain a BGC-Argo float array consistent with the globally recommended density (Biogeochemical-Argo Planning Group, 2016), resulting in a requirement of 124 BGC-Argo floats in the 10°N–10°S tropical band (Recommendation 4.1);
- maintain pCO_2 time series at the existing equatorial sites at 110°W, 125°W, 140°W, 155°W, 170°W, 165°E and 8°S 165°E. In addition, new pCO_2 records should be established at 0°, 147°E and 13°N, 137°E;
- during TMA servicing voyages, hydrographic casts to 1000 m every 1 degree of latitude between 8°N and 8°S, and every 0.5° between 2°N and 2°S on each meridional line, including major nutrients and optical parameters;
- regardless of the distribution of moorings in the final TMA design, the goal for surface pCO_2 data coverage should be 10°N to 10°S, at least once per year and ideally twice per year**.** Continue to test the collection of surface pCO_2 measurements from Saildrone as alternatives to ship-based measurements.

7.2.1.5 Eastern Pacific requirements

Chapter 5 details the requirements for the eastern Pacific region. Concerning the Backbone in situ Observing System, the major recommendations are:

- the existing TMA line along 95°W should be maintained, and updated to full-flux sites;
- increase Argo density for the EPAC as soon as possible. A coordination of South American countries to execute the doubling of Argo will be required. Because the EPAC

is home to one of the largest OMZs, biogeochemical Argo floats are recommended for this region (see also Recommendation 4.1).

7.3 The new TPOS 2020 Backbone

In general, we found that most of our First Report recommendations for the Backbone, as summarized in Appendix B and in section 7.1.1, remain valid and indeed are strengthened by considering the above issues. Only minor changes are needed with respect to recommendations on satellite sampling, as discussed below. In response to the recommendations for the TPOS, two major changes are recommended for the in situ Backbone: a doubling of Argo sampling in the tropical zone (10°N–10°S), including 1/6th as BGC-Argo floats; and a reconfiguration of the TMA. At the conclusion of the First Report the latter was not delineated in detail (see section 7.1.1.2). We do so below, and present a refocused, multi-tiered TMA with greatly enhanced capabilities. In addition, we present more evidence on the impacts on subsurface state estimates comparing the present TPOS with the new Backbone.

7.3.1 The new Tropical Moored Array

In response to the requirements and challenges discussed above and in the First Report, we recommend an evolution of the TMA in order to focus resources on:

1) expanding the surface meteorological regimes sampled through poleward extensions of some meridional spines to capture higher rainfall, dry inflow and cyclone genesis regions
2) markedly expanding the spatial coverage of variables for heat and water flux estimates, including rainfall
3) resolving near surface and mixed layer diurnal variability across the domain
4) systematically measuring near surface current
5) expanding surface barometric pressure measurements
6) better resolving the near equatorial flow field in the central Pacific
7) sustaining and enhancing $p\mathrm{CO}_2$ measurements

This new TMA will thus comprise more highly instrumented and capable moored systems than used at present and will return hourly or better data of a larger and more complete parameter set. Despite the potential loss of a small number of off-equatorial moorings the reconfigured TMA retains the ability to detect and map large-scale decadal and long-term changes.

7.3.1.1 Tiered parameter suites

To span the full range of needs from state tracking, insight into physics across regimes and the development of new parameterisations and/or satellite retrievals, we envisage 3 tiers of moored sites (Figure 7.3)—a widely deployed enhanced base level (Tier 1) that will include more measurement capability than the present standard mooring configuration, a velocity-enhanced mooring that will be less widely deployed (Tier 2) and very highly instrumented "Super Sites" (Tier 3). The latter concept is still under development and may, for instance, be deployed on a campaign basis as a moveable capability rather than a sustained site (see section 7.4.7).

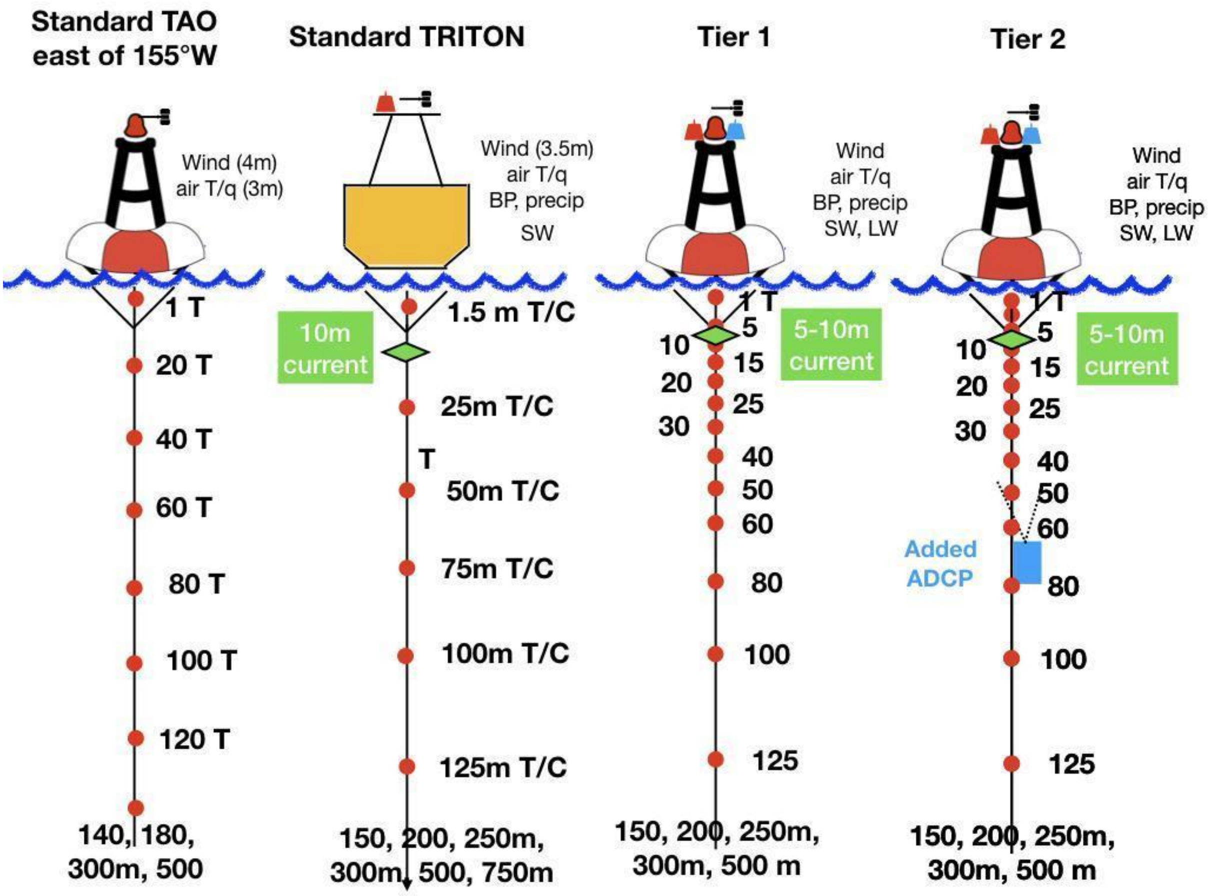

Figure 7.3: Schematics comparing the instrumentation of the current TAO and TRITON moorings- on the left, with those of the new enhanced TMA Tier 1 and Tier 2 on the right. In the subsurface, red dots and black text indicate the depths of temperature and salinity measurements, and green diamonds velocity measurements. Tier 2 moorings will have an upward looking current profiler (blue rectangle). Above the surface, parameters are noted as: Wind = wind speed, air T/q = air temperature and specific humidity, BP = barometric pressure, precip = rainfall, SW and LW = downwelling shortwave and longwave radiation, respectively.

Tier 1: These will become the base mooring configuration of the new TMA. They will include the full suite of surface meteorological variables needed for bulk heat and water flux estimation. Note that most present TAO sites only measure variables for latent and sensible fluxes, and few measure downwelling radiation or rainfall (First Report, Figure 3.4). In addition, this type of mooring will have the ability to adequately describe the rapidly varying near-surface layer of the ocean through enhanced vertical resolution in the mixed layer. Temporal resolution of hourly or better will allow sub-daily processes to be captured such as the interacting diurnal variability in the near surface ocean and atmosphere.

Specifically, ***all*** Tier 1 moorings will measure:

- ocean temperature in the upper 50 m (typically with 5–10 m vertical resolution);
- ocean temperature from 50 to 500 m, with vertical resolution similar to present TAO/TRITON;
- sea surface temperature;
- air temperature, relative humidity, downwelling short and longwave radiation;
- surface winds;
- near-surface velocity (typically a point measurement of vector current above 10 m depth).

This instrumentation augments present TAO/TRITON sampling in three ways:

1. denser vertical resolution of temperature in the upper 50 m
2. short and longwave radiation as a standard measurement
3. near-surface velocity

Measurements that are key for some sites, but are ***not necessary on all*** Tier 1 moorings, are:

- mixed layer salinity—needed where high-frequency variability is significant and important for air-sea interaction, mainly under the rainy regions; Sensors should be installed on all moorings in the western Pacific warm pool, and under the ITCZ and SPCZ;
- rainfall—the required density needs to be further examined;
- barometric pressure on all sites if possible; otherwise, favor locations where impact on numerical weather forecasts is the most important, where drifters are lacking and where SST fronts might induce convergences. These include the convective regions.

More work is needed to specify where this extra capability is best deployed.

Action 7.1. TPOS 2020 Task Teams should work with community experts to specify the Tier 1 sites where salinity, rainfall, and barometric pressure are most needed in addition to the core measurements.

Tier 2: These moorings will be based on Tier 1 capabilities, but in addition will include an upward looking near-surface ADCP, measuring velocity in the upper 50 m, corresponding to the temperature enhancement in Tier 1. Such moorings are still currently being piloted with encouraging results (see section 7.3.2.2). However, more work is needed to test this technology and to determine where and how many of these mooring types should be part of the Backbone.

A pilot Tier 2 has been funded by NOAA's Ocean Observation and Monitoring Division and began deployments in 2017. Instrumentation similar to the Tier 2 recommendation (Figure 7.3) has been installed on six operational TAO moorings spread across several regimes, with three more to be deployed in 2019. Several arrangements of instrument depths and configurations are being tested to determine the most effective sampling. The goal is to establish a firm basis for the instrumentation, sampling, realtime transmission and data procedures on the Tier 2 moorings. Some early results are shown later in Figure 7.12.

Action 7.2. TPOS 2020 Task Teams to work with community experts to specify the priority sites for Tier 2 deployments, based on the results of the pilot currently underway and analysis of where ocean velocity measurements are most needed.

Tier 3: The third type of mooring is a "Super Site"—a concept still in development. These sites would include additional instruments to provide more detailed or specialized information. For example, the Super Sites might include direct correlation flux measurements (to gather long-term measurements for improving bulk formulae), measurements of surface waves, upper-ocean turbulence measurements, and more detailed measurements of temperature, salinity, and velocity. See section 7.4.7 for more details.

Subsurface velocity enhancements: In addition to the above general tiers, which focus on surface and near surface enhancements, we recommend the continuation of velocity measurements from ADCPs from near the surface to 300 m at the long-established equatorial sites at 110°W, 140°W, 170°W, 165°E and 156°E. We also recommend the installation of additional Tier 2 and ADCP-equipped moorings at 140°W at 1°N and 1°S, and ADCPs installed at 2°N/2°S. This will provide, for the first time, a transport resolving array for the Equatorial Undercurrent. See First Report, section 3.3.3 for a deeper discussion.

Surface carbon fluxes: *p*CO_2 sensors should be maintained at the equatorial sites at 110°W, 125°W, 140°W, 155°W, 170°W, 165°E and at 8°S, 165°E. New *p*CO_2 observation sites need to be established in the western Pacific at 0°, 147°E and 13°N, 137°E.

7.3.1.2 Spatial configuration

The new TMA is modestly reconfigured to sample more poleward, maintain and enhance a focus on the equator and yet still maintain a grid structure capable of detecting and validating basin-wide decadal and longer-term flux changes (Figure 7.4).

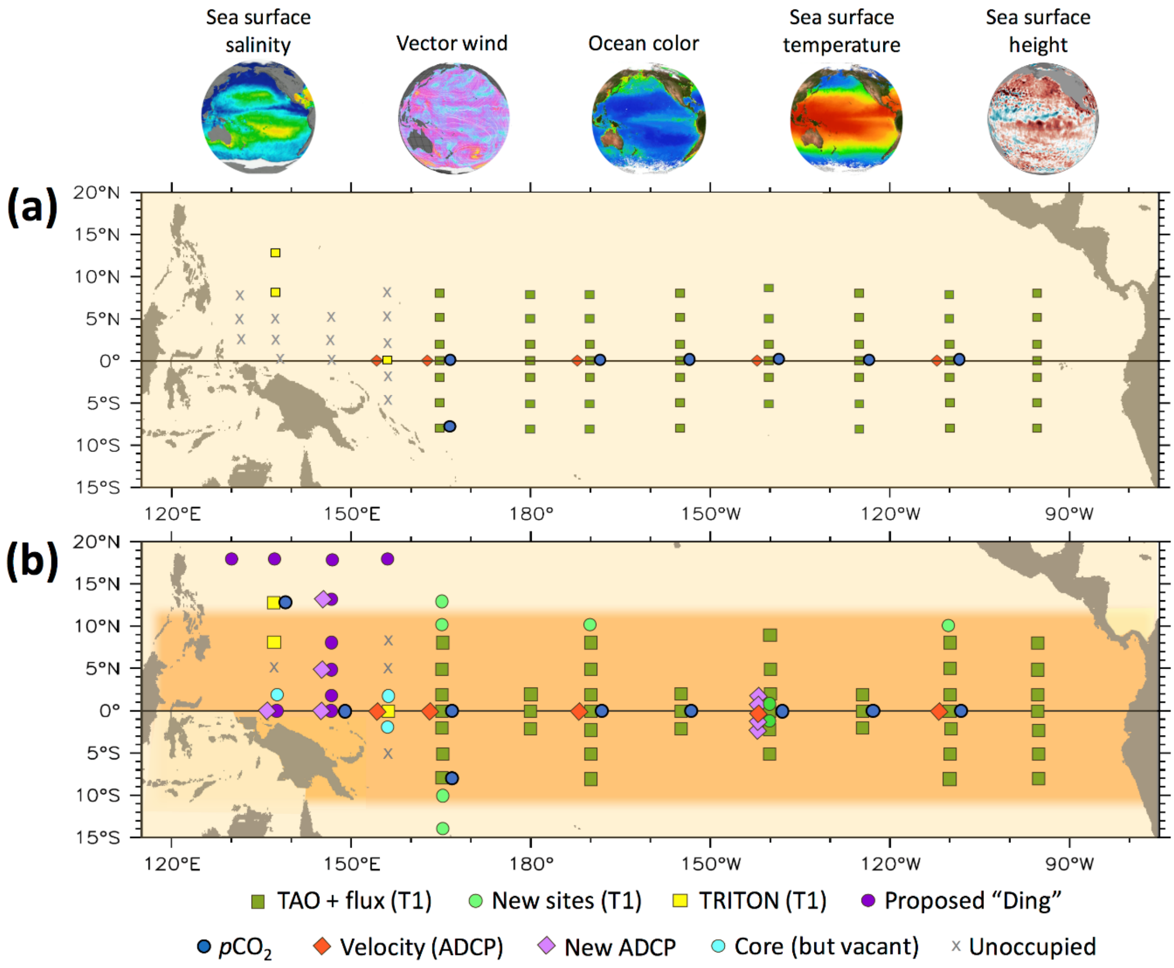

Figure 7.4: Locations and tiers (see Figure 7.3) of the current (a) and future (b) TMA. "Core and vacant" means that these sites are high-priority but not maintained. TAO sites that are not discussed in this plan are left blank. The exact locations of some of the "new sites (T1)" poleward extensions are nominal and may be moved slightly due to implementation challenges.

Key features of this design are that:

1) all historical sites between 2°N and 2°S are to be sustained, and we strongly recommend that the vacant western Pacific sites within this band be supported as soon as possible;

2) poleward extensions (spines) along meridians were chosen for the longevity and completeness of their historical records (see Figure 7.2), the likelihood of future data return (considering vandalism rates) and the regime coverage they provide;
3) enough spines are retained to capture basin-wide changes (see section 7.3.6.1 below);
4) establish new sites poleward of 8°N/S to better capture the convective rainy conditions in the ITCZ/SPCZ;
5) new sites at 1°S and 1°N, 140°W will better resolve the fine meridional scales near the equator, including the surface fluxes and the structure of the equatorial undercurrent (see section 7.3.3.2 and First Report section 3.3.3);
6) the northern west Pacific warm pool and the cyclogenesis region to its north are more densely instrumented.

Recommendation 7.1. TPOS 2020 recommends the adoption of and support for a refocused design for the tropical moored buoy array, with a three-tiered approach to instrumentation. These comprise the Tier 1 baseline with enhanced surface and upper ocean measurements over the existing array; Tier 2 with added velocity observations in the mixed layer; and Tier 3, intensive Super Sites that might be used in a campaign mode.

Action 7.3. The exact location of the moorings poleward of 8°S under the SPCZ needs to be further explored, in consultation with community experts and regional partners.

7.3.2 Improved capabilities of the new Backbone

The new Backbone will deliver many gains, but also losses associated with the possible decommissioning of some historical off-equatorial TMA sites. These are described below.

7.3.2.1 Surface variables

A view of the changes in coverage of some key surface variables is illustrated in Figure 7.5.

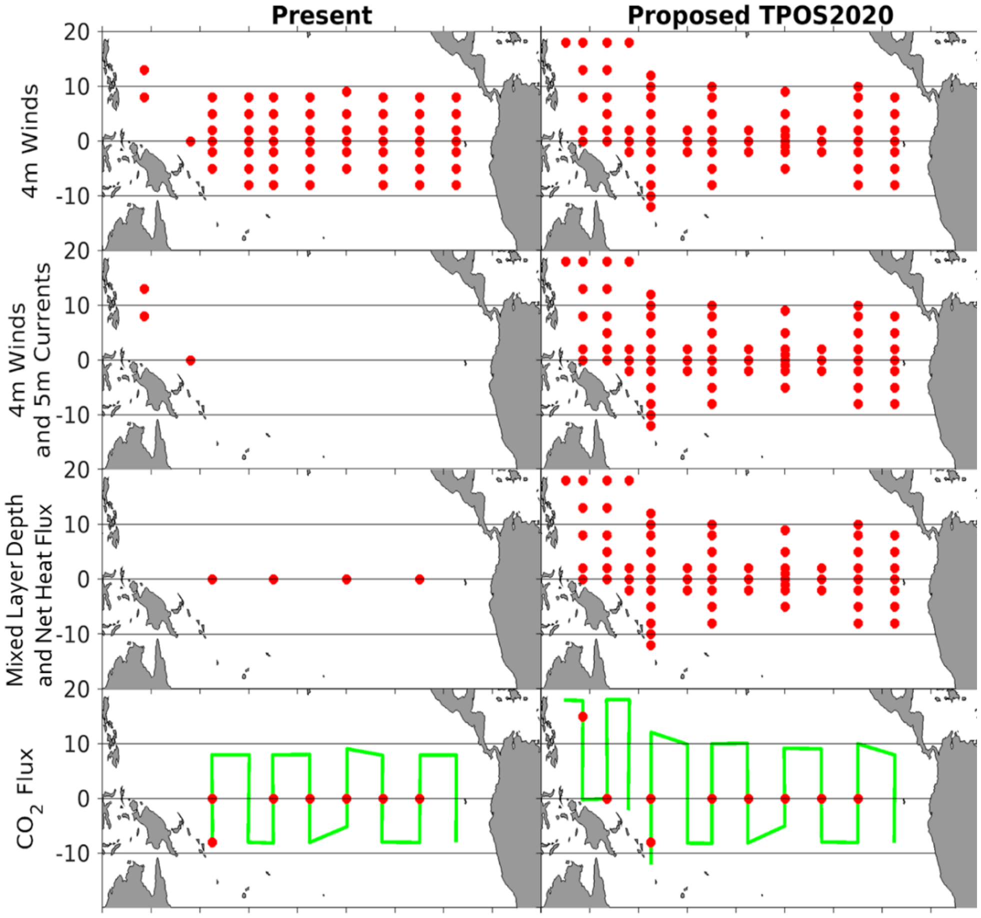

Figure 7.5: Coverage changes for near-surface variables from the present observing system (left) to the TPOS 2020 proposed system (right). Red marks moored measurements, green lines are indicative of annual (or better) ship-based measurements, perhaps supported by ASV in the future. Note that mixed layer depth is marginally resolved at the existing flux sites.

For winds (and latent heat flux), a transition to the new TPOS may result in a longitudinal thinning of some sites in the central Pacific, but an increase in meridional sampling near the equator and poleward in the SPCZ and ITCZ. This reconfiguration will provide observations in regions of high rainfall (see July and October in Figure 7.6) to support the understanding of rain impacts on space-based vector wind estimates (First Report, section 5.1 and Annex A) and hopefully improve wind-estimation techniques in these regions. By recommending a near surface current measurement at all sites, TPOS 2020 will also deliver a step change in our understanding of the near surface circulation and how currents might impact flux and wind stress estimates (First Report, section 5.6 and Recommendation 11, Annex A.2).

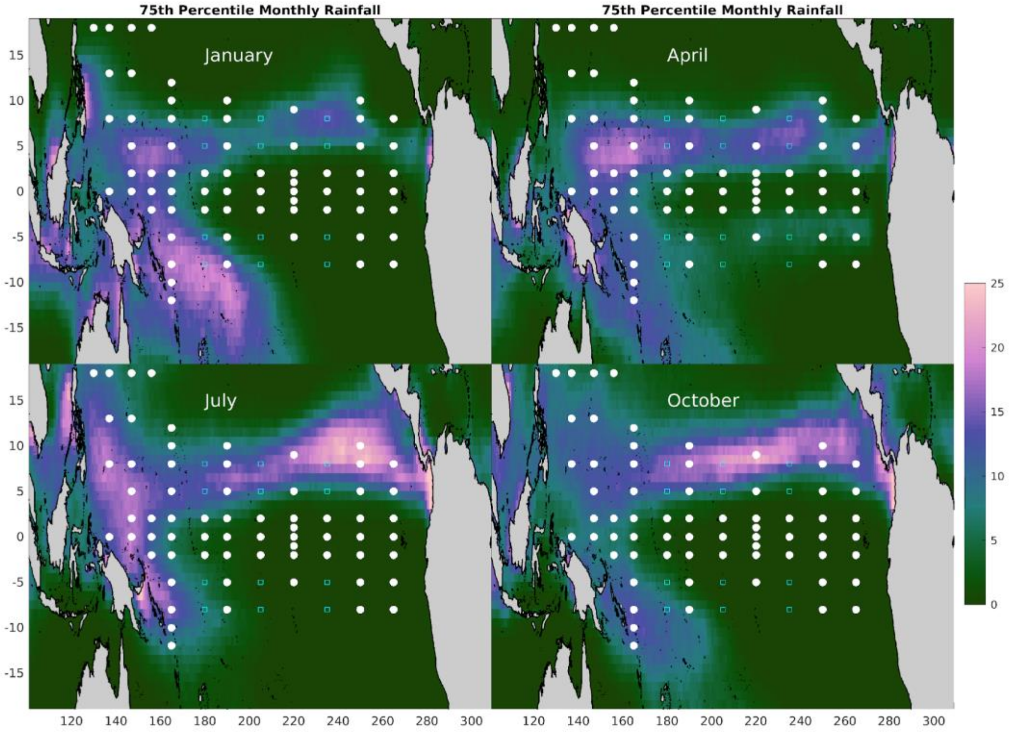

Figure 7.6: Typical high daily rainfall values (75th percentile) by month. Units are mm/day. Values are based on GPCPV2.3[22] estimates from 1996 to June 2018.

A key goal of the new TPOS 2020 is to retain the ability to independently track decadal and longer wind changes from both the TMA and satellite/atmospheric reanalysis products. De Boisséson et al. (2014) have illustrated that three independent space-based sensors can indeed capture the decadal wind changes seen in the TMA. To determine how the new TMA perform in validating these changes we use the de Boisséson et al. (2014) diagnosed decadal wind change field compared to the current system. Using simple spatial linear interpolation of the de Boisséson et al. (2014) decadal wind changes between the mooring sites, we find that the new TMA grid performs as well as the existing one, but with better northern and westward resolution (Figure 7.7). A similar result is found for estimated decadal latent heat flux changes (Figure 7.8). These results are due to the very large zonal scales in these long-term wind and flux changes. Notwithstanding that this result is for a particular period and longer-term trend, and may or may not be representative, we argue that the new TMA retains the capability to validate the spatial pattern of such changes detected from space or via atmospheric reanalyses, in addition to its ability to track changes in regimes.

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[22] Global Precipitation Climatology Project precipitation data set, version V2.3. https://www.esrl.noaa.gov/psd/data/gridded

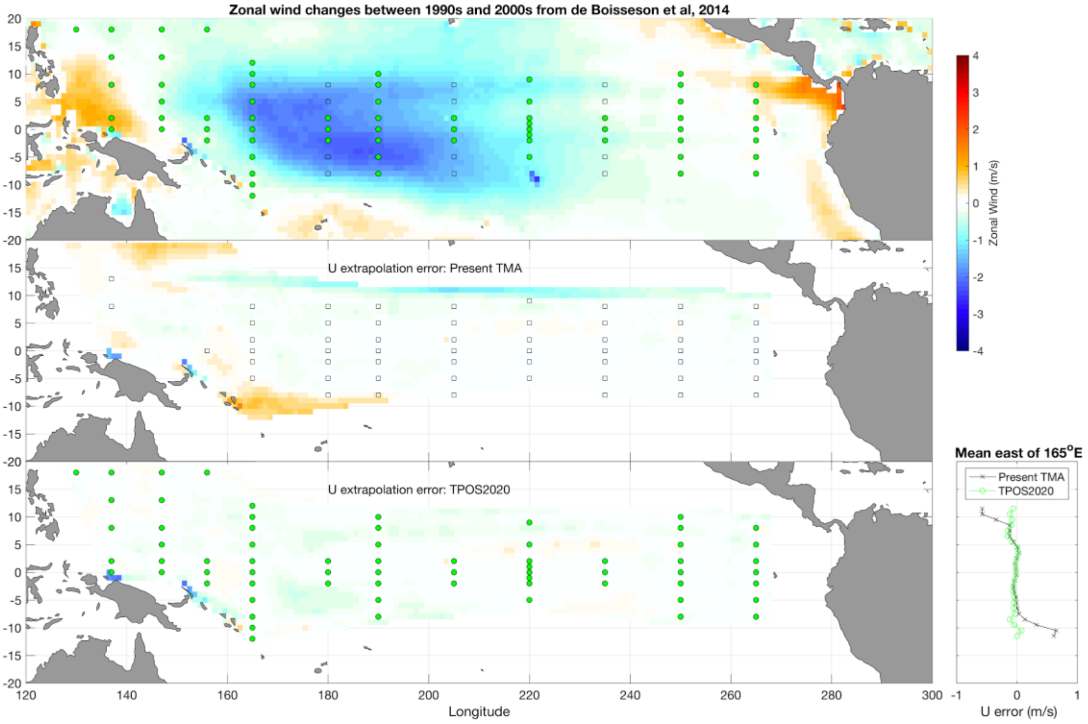


Figure 7.7: Top panel: decadal wind changes derived from satellite wind measurements. Errors in a reconstruction of this field based on subsampling this field at the current TMA sites (middle panel) and proposed TPOS 2020 TMA sites (bottom panel). Existing TMA sites are indicated by black squares, and the TPOS 2020 sites as green circles. Panel on the right shows the zonal average error east of 165°E.

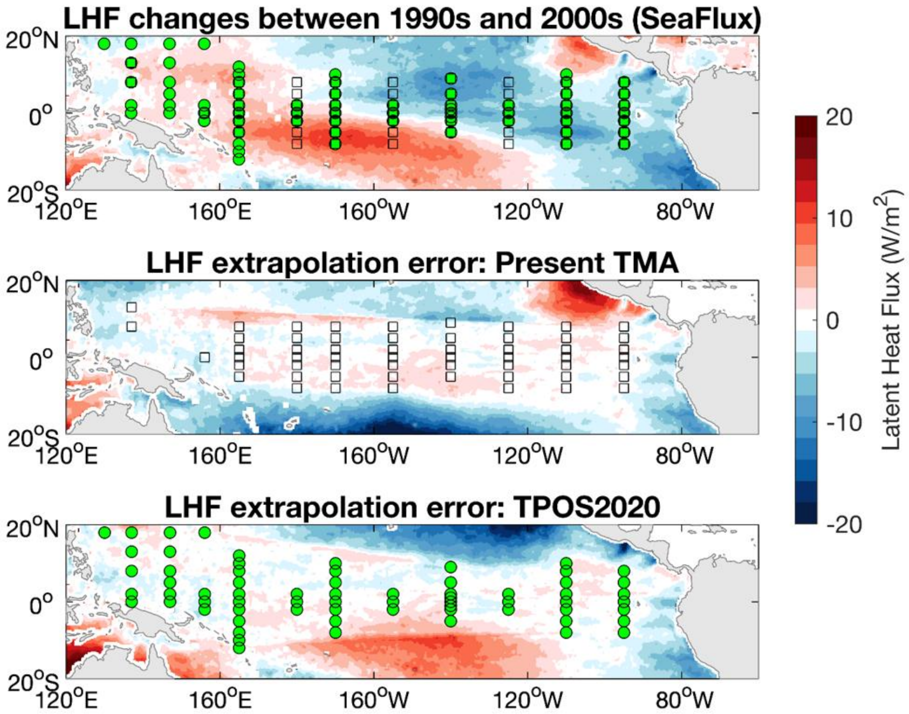


Figure 7.8 As for Figure 7.7, but for latent heat flux changes derived from satellite measurements (SeaFlux; http://seaflux.org/).

Through extending both downwelling longwave and shortwave to all sites, our ability to calculate net heat fluxes increases from 4 sites to 67. By establishing new sites poleward of 8°N, the highly evaporative dry inflow in the Northern Hemisphere will be sampled for the first time (Figure 7.9, bottom panel). We also greatly expand sampling of cloudy regimes in both the ITCZ and the SPCZ (Figure 7.9, top panel).

Carbon flux observations will also improve (Figure 7.5, bottom panel) by extending moored sampling in the western Pacific warm pool. Most spatial information will derive from ship-based estimates (particularly mooring servicing voyages), and thus be dependent on mooring servicing voyage tracks unless new autonomous platforms measuring winds and $p\mathrm{CO}_2$ become more widely used.

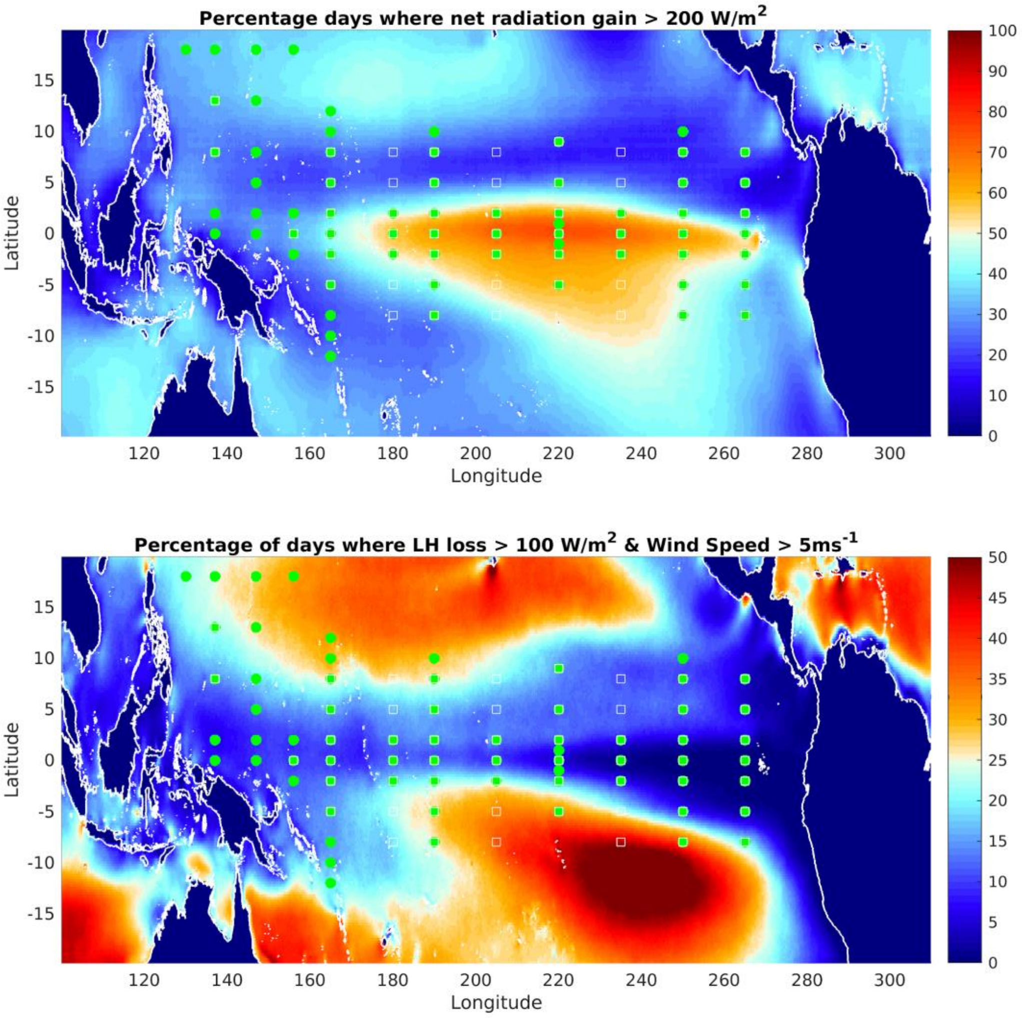


Figure 7.9: Contrasting radiation (cloudy) and evaporation regimes across the region. Top: Percentage of days of high net radiation gain; bottom: Percentage of where high evaporation and windy conditions occur in the region (from JOFURO-3, 1988–2013). Existing (white squares) and proposed (green circle) TMA sites are marked.

7.3.2.2 Subsurface variables

Coverage changes for subsurface parameters are shown in Figure 7.10.

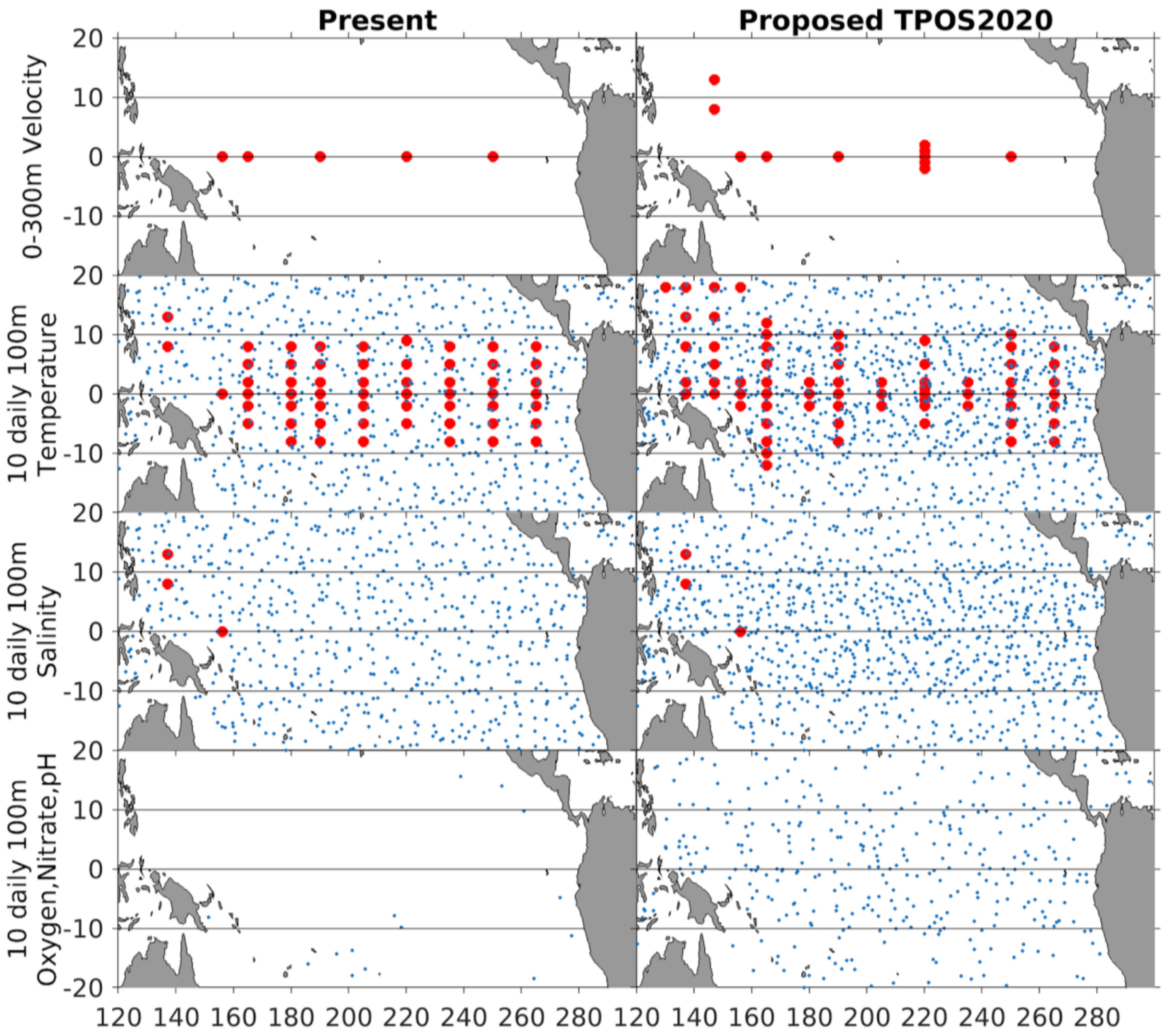


Figure 7.10: Schematic view of coverage changes for subsurface variables from the present observing system (left) to the TPOS 2020 proposed system (right). Red marks moored measurements, blue Argo float based observations. Note that near surface salinity will be measured by some subset of the TMA, likely those in convective regimes. However, the exact locations of these sites is still being considered (***Action 7.1***).

Besides maintaining the highly valued long records of equatorial velocity, subsurface velocity measurements (top panel, Figure 7.10) will be augmented by new sites measuring the flow in the far western North Equatorial Current and by establishing a transport resolving array spanning the equator at 140°W. Based on past synoptic underway velocity survey data (Cravatte et al., 2017), it is clear from Figure 7.11 that a 2°N–1°N–0°–1°S–2°S velocity mooring line will largely capture the Equatorial Undercurrent transport and its variability, a metric in high demand for model testing, climate dynamics and biogeochemical research. In addition, this array will resolve the fine meridional scales near the equator, the meridional shear, and provide a description of the time-varying equatorial meridional cell.

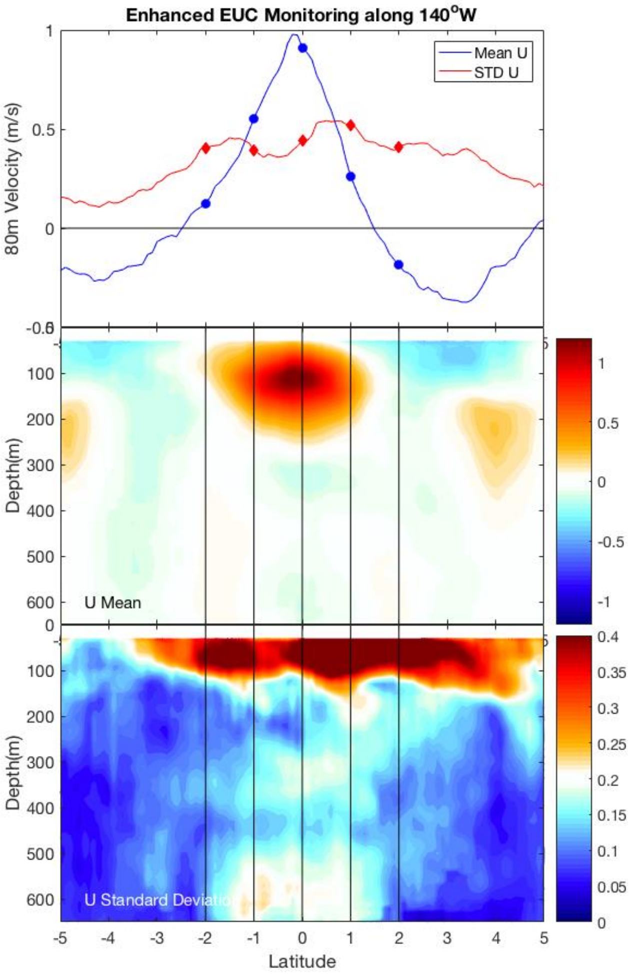


Figure 7.11: Top: Mean (blue) and standard deviation (red) of zonal velocity at 80 m (m/s). Middle: Zonal velocity as a function of latitude and depth. Bottom: Standard deviation of zonal velocity. In all panels, the proposed sites of the 140°W transport-resolving array (2°S, 1°S, Eq, 1°N, 2°N) are marked. Based on the ship-based velocity profiles analyzed by Cravatte, et al. (2017).

Conversion of a subset (to be determined) of Tier 1 moorings to include near surface velocity profiles has the potential to illuminate a great deal about the physics of the mixed layer and the mixing of heat and freshwater into the upper ocean. Early results from pilots underway suggest a single ADCP installed on existing moorings can be effective (Figure 7.12) and could efficiently capture these dynamics across regimes and ENSO cycles. These moorings with an added ADCP would be known as Tier 2.

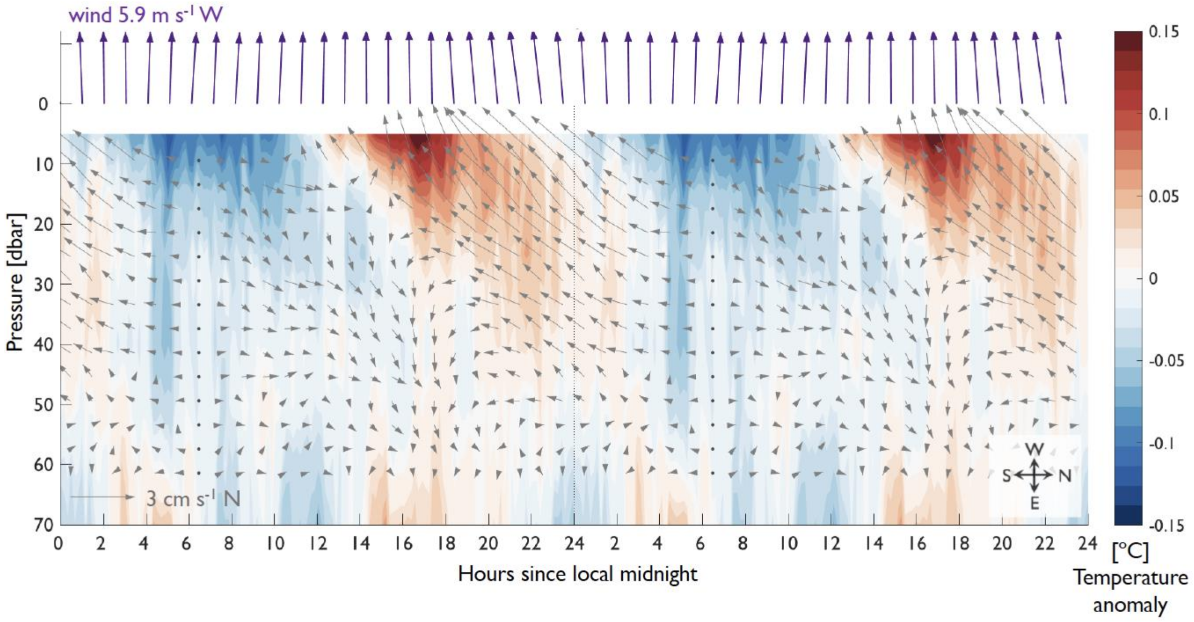


Figure 7.12 Mean diurnal composite (Sep 2017 to Jan 2018) of wind (purple arrows), current shear relative to 68 m (gray arrows), and temperature anomaly (color fill) in the central equatorial Pacific from the NDBC TAO mooring at 0°, 155°W. Two cycles of the same 24-hour composite are shown; upward-facing arrows indicate the westward direction. Current shears are shown with respect to the mean shear profile at 6:28 am. Westward wind momentum that enters the surface ocean starting at noon appears to penetrate as deep as 50 m by the following midnight. Courtesy of J. Masich.

Equipping Argo floats with biogeochemical subsurface sensors will result in a revolutionary increase of the available data (Figure 7.10, bottom panel), enabling routine mapping of these variables at monthly and longer timescales for the first time.

Figure 7.10 illustrates our response to the First Report recommendation of enhanced broad-scale sampling of subsurface temperature and salinity throughout the tropics and better meridional spacing and increased vertical resolution in the equatorial region. A particular target was to resolve near-surface salinity stratification, especially under the atmospheric convergence zones (First Report, Recommendations 17 and 18). It was recognized that meeting these requirements would need a mix of platforms, and improved synthesizing tools such as statistical or dynamical models and data assimilation.

Here we further examine the strengths and weaknesses of this mix of platforms, describing the spatial and temporal scales they will and will not be able to resolve and on the impact of those observations in oceanic reanalyses products (see Fujii et al., 2019, 2015a for a thorough discussion of this issue). We mostly focus on recent results from dedicated studies, which better illustrate the tradeoffs expected with the TMA reconfiguration and enhanced Argo sampling. We re-emphasize that while no single platform is able to fully meet the subsurface temperature and salinity measuring requirements, we can design a mix that most closely accomplishes the goals.

Argo floats now deliver 2 dbar vertical sampling, thus providing much better vertical resolution and closer zonal spacing than the current TMA, and a more homogeneous coverage continuous with the global array (particularly suited for data assimilation). These are necessary to meet the subsurface temperature and salinity requirements (see sections 3.1.3.1 and 3.4.1 of the First Report) especially away from the equator where zonal scales shorten. We also expect that enhanced Argo coverage will better resolve the frontal areas and will systematically improve salinity estimation across the domain.

Performance of the current TPOS for subsurface temperature and salinity

While Argo floats will not resolve high-frequency variability, the presently-implemented Argo array is able, at some equatorial mooring sites, to describe 70–80% of the variance at intraseasonal timescales (periods of 20–100 days) and more than 90% of the variance for the seasonal to longer-term variability (Gasparin et al., 2015, see their Figure 4). Off-equator, where zonal scales shrink, the ability of core Argo alone to measure subsurface temperature variability is lower. At seasonal and longer timescales, the current array is typically able to measure around 60–80% of the variance, but less than 20% of the variance at intraseasonal timescales (Figure 7.13).

When combined with altimetry, through statistical tools (Gasparin et al., 2015, their Figure 7) or data assimilation (Verdy et al., 2017), the comparison with moored observations is improved. Assimilating these observations using a dynamical oceanic model and 4D-Var data assimilation (including SSH, Argo and other data sets but no moorings) further reduces the error, more effectively for periods shorter than 100 days, and resolves a larger part of the off-equatorial variance (Verdy et al., 2017; Figure 7.14). However, for periods shorter than 20 days, the moorings continue to provide unique information.

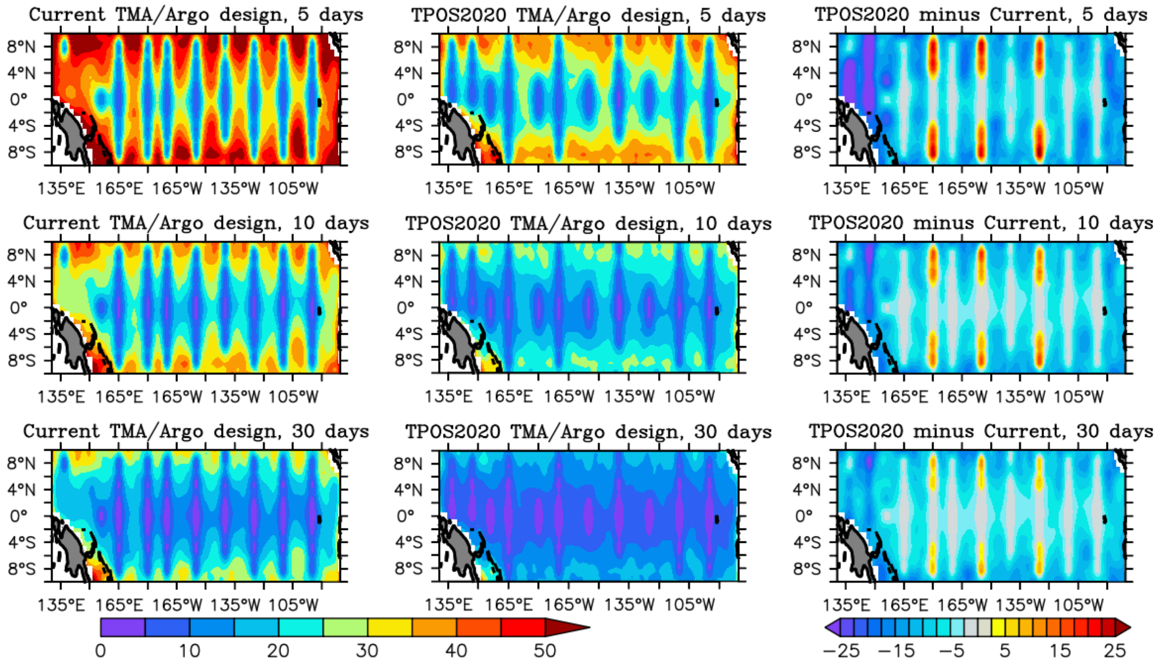


Figure 7.13: Estimated errors, given as a percentage of the temperature variance signal, for different configurations of the in situ TPOS and different timescales (upper panels: 5 days, middle panels: 10 days, lower panels: 30 days). Left: for the current moored array/core Argo distribution. Middle: for the recommended moored array/double Argo sampling. Right: difference between both observing systems.

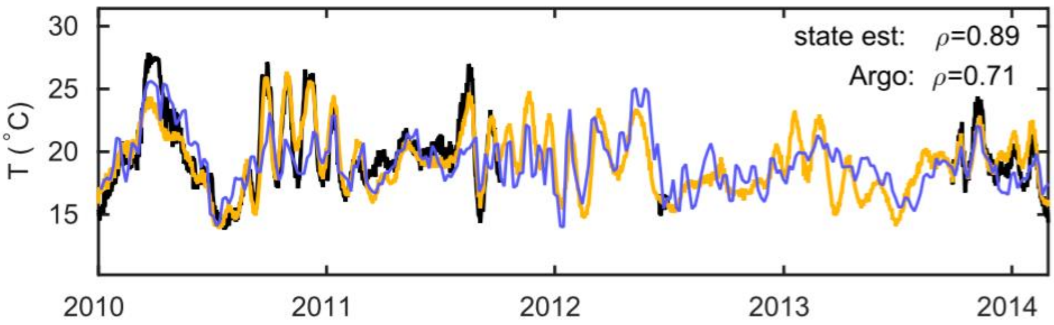


Figure 7.14: Time series of temperature at 100 m from TAO observations at 155°W, 8°N (black), state estimate from Verdy et al. (2017) (orange), and Argo mapped product (blue). Correlation between moored observations and each of the products is indicated top right. Note that the large gaps in the moored data resulted from the 'TAO crisis' associated with a lack of serving shiptime. Figure from Verdy et al. (2017).

Oceanic reanalysis intercomparisons, OSEs and OSSEs have also been performed to estimate the impact of the TPOS on ocean reanalyses (Fujii et al., 2015b; Xue et al., 2017a; 2017b; Gasparin et al., 2019; see Chapter 2, section 2.5 for discussion). All these studies, from various points of view, conclude that Argo and TMA both have positive impacts and are complementary.

The Real-Time Ocean Reanalysis Intercomparison project, started in 2014, provides real-time information about the divergence between reanalyses, allowing forecasters to share information about the quality/deficiencies of ocean reanalyses, and to monitor the impacts TPOS have on these reanalyses. These efforts are led by NCEP for temperature (https://www.cpc.ncep.noaa.gov/products/GODAS/multiora_body.html) and the Bureau of Meteorology (BOM) for salinity (http://poama.bom.gov.au/project/salt_19812010). Within this effort, Xue et al. (2017a) compared an ensemble of nine operational reanalyses and studied the evolution of the ensemble spread (potentially a measure of data impact) in the 0–300 m averaged temperatures. They showed that the reduction of TAO moorings in 2012–2014 increased the ensemble spread among the reanalyses, at the equator and off equator. Follow-on studies also showed that the loss of TRITON moorings in the western Pacific after 2014 slightly increased the spread among temperature reanalyses, suggesting that the current Argo coverage alone is not sufficient to constrain the temperature fields (Fujii et al., 2019). This study also highlighted deficiencies in the way current model and data assimilation systems use the observations. Some ocean data assimilation systems overfit the fixed mooring observations either by underestimating the errors associated with these observations or improperly specifying the error structure functions that determine non-local influence of the observations on the analysis. The result is a state estimate that fits too strongly and too locally to the mooring data, generating a dynamically inconsistent solution and spurious variability at larger scales (Xue et al., 2017a; Sivareddy et al., 2017). This, again, points to the need for better communication during the design of the TPOS with experts in ocean and coupled data assimilation, if these systems are to better utilize the data provided by TPOS in order to provide more accurate gridded fields to the community (see Chapter 2).

Expected gains with doubled Argo

Here we examine the expected accuracy of subsurface temperature estimation based on the combination of moorings and doubled Argo float densities recommended in this Report (section 7.3). We first exploit the improved subsurface covariance functions from Gasparin et al. (2015), used here to model the expected error in subsurface temperature signals for different timescales

(5–30 days) and for different combinations of moorings (current configuration or TPOS 2020) and different Argo coverage—original or doubled (Figure 7.13).

The recommended TPOS would typically reduce the error by 15% at 5-day timescales, and by 5–10% at monthly timescales. However, some degradation in accuracy would be felt very locally if moored sites are decommissioned, up to 25% at 5-day timescales, to 5–10% at monthly timescales. We would thus lose high-frequency subsurface temperature information.

OSEs have also been performed to assess TPOS data impact in the JMA's seasonal forecasting system (Fujii et al., 2015b). Results suggest that the increase of anomaly correlation coefficients for both temperature and salinity is proportional to the number of assimilated Argo profiles in the NINO3 and NINO4 regions, confirming a strong positive impact of increasing Argo density (Fujii et al., 2015b). Results also suggest that the impacts of moorings in the western region are larger than that of Argo, confirming that reinstalling moorings in this region is of crucial importance for initializing seasonal forecasts. Positive impacts of moorings and Argo on the skill of ENSO predictions with this system are also shown in Fujii et al. (2015a, 2019). Efforts toward evaluating TPOS impacts on subseasonal forecasts have started (see Chapter 3 and ***Recommendation 3.3***).

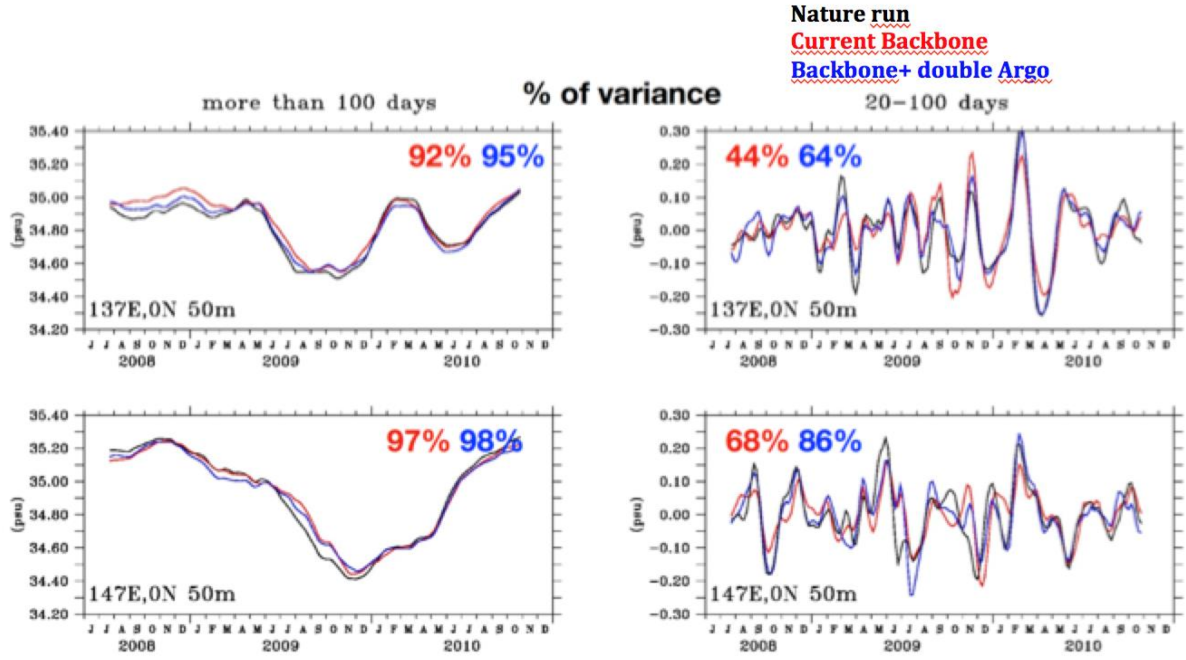


Figure 7.15: (Courtesy of F. Gasparin). Salinity at 0°N, 137°E (upper panels) and 0°, 147°E (lower panels) at 50 m depth from the nature run (black), from the simulation with the current Backbone data synthetic observations assimilated (red) and from the simulation with current moorings and double Argo synthetic observations assimilated (left panels) at seasonal-to-longer-term, and (right panels) intraseasonal timescales (20-100 days). Numbers give the percentage of the nature run variability captured by the two simulations.

Impact studies in reanalyses have also started at Mercator Ocean. OSSEs analyzing the impact of altimetry alone, then altimetry plus the current Backbone, and then of doubling Argo coverage in the 3°S–3°N band in the Mercator reanalysis system have been initiated (see Gasparin et al., 2019, for details on the method). Preliminary results show that in this system, altimetry strongly constrains the subsurface temperature variability, even at intraseasonal timescales. The addition of the current TMA and Argo system better constrain the subsurface temperature variability, and more importantly the salinity mean fields and variability representation. Further doubling Argo significantly improves the representation of salinity at intraseasonal timescales (Figure 7.15) and of the intraseasonal displacement of the salinity front at the eastern edge of the warm pool. In this system, enhancing Argo only slightly improves estimates of barrier layer thickness. Dedicated OSSEs within different systems should continue to be performed to evaluate the TPOS 2020 recommendations, and internationally coordinated efforts should be enhanced (see section 2.8). There continues to be an urgent need to improve the oceanic model and data assimilation systems so they can make better use of the observations.

7.3.3 Summary of gains and losses

Expected gains for atmospheric and near surface variables from TMA:

Additional sensors on all moorings will

- provide a much more complete description of air-sea interaction across the regimes of the tropical Pacific, and permit better reference and calibration sites for comparison with satellite derived air-sea flux variables;
- enable the computation of the net air-sea heat flux exchanges (turbulent and radiative components). Only four sites in the present TMA have this full capability; most others are missing radiative components;
- describe the evolution of the mixed layer at timescales from hourly to interannual, including the important diurnal cycle, with a denser vertical resolution in the mixed layer;
- reference near-surface currents to improve satellite wind retrievals and help validate models and upcoming surface current measuring missions;
- provide a basin-wide view of near surface velocity variability at hourly timescales;
- improve NWP forecasts, especially of developing cyclones, via increased barometric pressure observations; and
- resolve mixed layer salinity, velocity and shear under rainy/convective regions through the deployment of Tier 2 moorings.

Meridional extensions of the TMA across the ITCZ and SPCZ at several longitudes will

- provide an improved reference and calibrate satellite scatterometer vector winds under heavy and patchy rainfall, and in convective conditions;
- extend sampling of surface meteorology, including short and longwave radiation on all sites, through the convergence zones and into some dry regions, extending the regime coverage of surface flux reference stations;
- enable better prediction of weather and extreme events such as typhoons in the northwest Pacific;
- provide in situ sampling of multi-decadal signals over a broader domain, both at the surface and at depth (see below).

Expected gains for subsurface variables:

Increased Argo density will

- improve the vertical resolution and horizontal spacing of temperature and salinity profiles throughout the equatorial region and the near-tropics;
- improve the monitoring of T/S variability at intraseasonal and longer timescales;

- reduce analysis errors in model data assimilation systems;
- enhance resolution of salinity stratification in the west, and improve understanding of barrier layer formation and maintenance;
- come closer to resolving the off-equatorial mesoscale eddies, and in conjunction with satellite altimetry allowing a clearer description of their meridional heat fluxes;
- potentially improve forecasts of NINO3 and NINO4 temperature (Fujii et al., 2015b, 2019);
- through greatly increasing the number of BGC-Argo floats in the tropical Pacific, enable a major gain in biogeochemical sampling, providing routine mapping of dissolved oxygen, nitrate, pH, chlorophyll fluorescence, particulate backscatter and downwelling irradiance at monthly and longer timescales.

New TMA sites at 1°N and 1°S, 140°W, including adding thermocline velocity profiles to existing 2° mooring spacing, will

- better resolve the fine meridional scales near the equator;
- produce the first velocity section across the equatorial undercurrent since early short-term experiments almost 30 years ago;
- provide an ongoing description of the ageostrophic equatorial limb of the meridional cells;
- illuminate the oscillations that have blurred EUC transport variations inferred from equator-only measures (Leslie and Karnauskas, 2014);
- describe the meridional shear on the EUC flanks that contribute to TIW generation and resolve the sharp shear and property gradients as the cold tongue front passes back and forth across the denser mooring line.

Potential losses:

If constrained by funding limitations given the substantial costs of the enhanced TPOS we recommend, agencies may decommission some lower priority off-equatorial moored sites in the central Pacific. This would induce losses. In that case we expect:

- breaking of long records at the decommissioned mooring sites. This may degrade the ability to detect and diagnose low frequency changes and trends. We argue (section 7.1) that in the context of alternate and overlapping measurement systems, these losses will be largely compensated for, especially since low-frequency changes have large spatial scales.
- localized loss of subsurface temperature information at high frequencies, especially for periods shorter than 20 days for which moorings provide unique information. This would degrade detection of changes to the high frequency variability. We note that zonal decorrelation scales are short at the off-equatorial sites, so their high-frequency information cannot be extrapolated to describe the signals at non-local scales.
- loss of long time-series of in situ surface wind, and of air temperature and relative humidity at any decommissioned moorings, with a potential for missing smaller-scale or localized signals that may occur as a result of climate change.
- that given current deficiencies in atmospheric model and data assimilation systems, there may be some localized degradation in the accuracy of atmospheric reanalyses. Strategies for mitigating these losses should continue to be explored (see section 7.4 of the First Report)

- the wider spacing of the TMA spines make its gridding capability more vulnerable to mooring failures along one spine.

We accept the possibility of these losses as more than mitigated by the multiplying gains of the rethought system and consider the particular measurements to be of lower priority than the many enhancements described above.

The most tangible gain, already amply demonstrated, is the reinvigoration of support for new observations, research and model development in the tropical Pacific. In response to the First Report, agencies are funding technology pilot studies (for example, section 9.2), enhancing existing platforms (section 7.3.1.1), planning new sustained observations (section 7.4.3), and developing model infrastructure for process studies (section 7.4.6) and observing system assessment (sections 2.5, 2.6 and 3.3.3.2). The observing system as a whole has been rejuvenated through new programs in agencies across the Pacific. Indeed, the climate record in the tropical Pacific is much more secure than it had been 5 years ago.

The TAO/TRITON crisis of 2013–2014 demonstrated the risk to not acting as the agencies supporting the array lost enthusiasm. In the absence of compelling evidence of the impact of ocean observations on seasonal forecasts, decreasing agency support for the arrays had concrete results: TAO data returns dropped below 50%, and much of the TRITON array was decommissioned, with measurable consequences on data products (Tollefson, 2014; Fujii et al., 2015a,b; Xue et al., 2017b; Ando et al., 2017). Both moored arrays were on a steep downhill slide; their rejuvenation was largely a result of TPOS 2020. The credibility of the project depended crucially on its willingness to state priorities among the measurements, and on its open-minded assessment of the possible ways to meet the sampling needs. The climate record in the tropical Pacific is far stronger than it was when the project was started.

Potential losses of some lower-priority (though still useful) observations must be balanced against the gains described above. Maintaining point time series is of great value but not the only consideration in assessing the need and utility of a particular observation, evaluated and compared among many important considerations.

A climate record is a “set of measurements of sufficient extent, resolution, consistency, and/or continuity to detect climate variability and change” (First Report). When regimes are adequately sampled and characterized by several measurements, the climate record value of each individual point sample decreases. It may be smaller than the value of introducing new climate records that can guide the interpretations, referencing and modeling of the next decades.

7.4 Progress with implementation, including pilots and process studies

The First Report provided a list of key actions for near-term implementation. Not all of these actions have been taken, in part because garnering agency support in many nations takes time, pilot activities are still underway and because some recommendations lacked final detail, such as the configuration of the TMA. Below we assess the status of the TPOS and consider some issues around implementation and transition, and update the actions needed.

7.4.1 Update on the status of future evolution of Backbone EOVs

An assessment of the present status and projected evolution of Backbone EOV measurements over the coming years is illustrated in Figure 7.16.

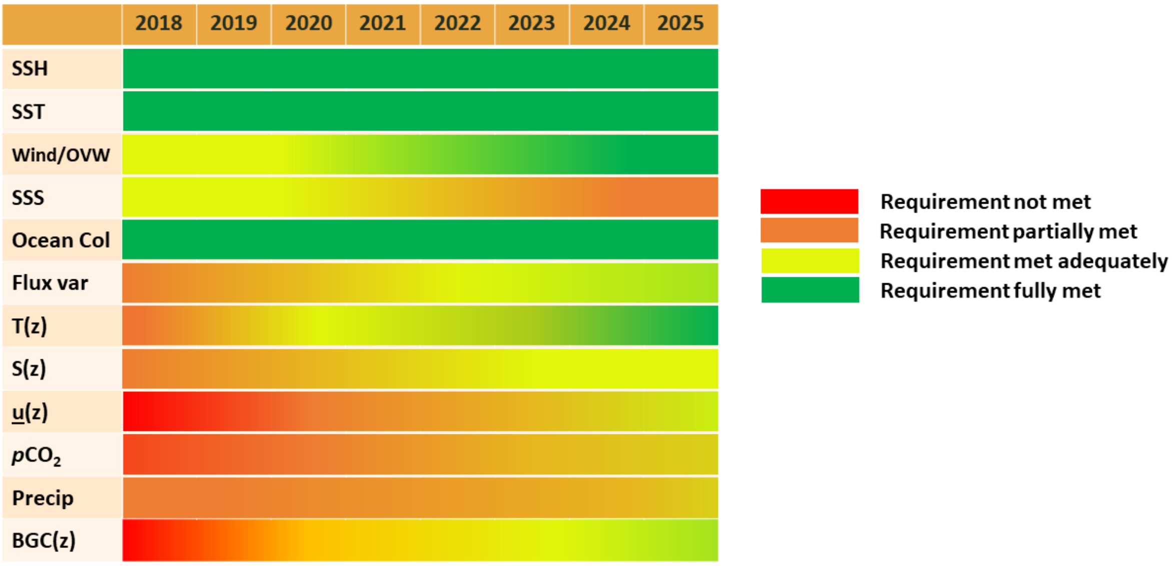


Figure 7.16: Status and prospects for EOV observations in the TPOS 2020 region (adapted from: TPOS OceanObs'19, Figure 8). This is an overview of the whole observing system, including both the in situ and satellite elements. The EOVs are: sea surface height (SSH), sea surface temperature (SST), ocean vector winds (OVW), sea surface salinity (SSS), Ocean colour (Ocean Col), variables needed to estimate total heat flux (Flux var), subsurface temperature (T(z)), subsurface salinity (S(z)), ocean velocity profiles (u(z)), the partial pressure of carbon dioxide (pCO_2), rainfall (Precip) and biogeochemical parameter profile (BGC(z)).

TPOS requirements for satellite-based systems measuring SSH, SST and ocean color are being fully met and are projected to remain so. Greater certainty would be reassuring with regard to future space-based passive microwave measurements of SST, and future in situ SST observations.

The constellation of wind measuring satellites (imaging radiometers and scatterometers) continues to grow over time (Figure 7.17), improving coverage across the day which helps drive down noise due to sub-daily variability and reduce aliasing by the diurnal cycle. Even with four working scatterometers, wind measurements are assessed as adequate (Figure 7.16) but do not yet meet the TPOS requirement. Currently while every 6 hours ~80% of TPOS area is sampled for wind speed, only 45% is sampled for vector winds (Annex A, Figure A.2). Thus, an additional scatterometer is required to further improve the spatial/temporal coverage to fully meet TPOS requirements, provided its equatorial crossing time is chosen correctly (see Annex A).

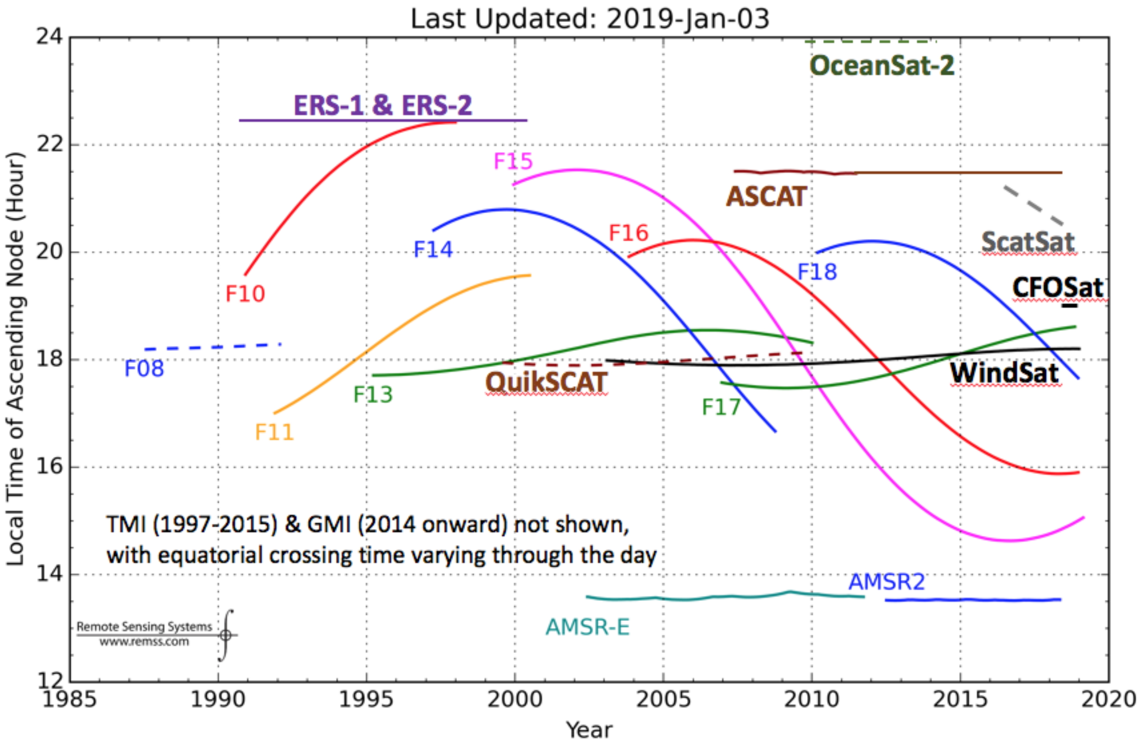


Figure 7.17: Growth of the constellation of space-based wind sensors as illustrated by the diurnal distribution of their equatorial crossing time by year. Missions that measure vector winds (scatterometers and polarimetric microwave radiometers) are bolded, while speed measuring missions are not. Solid lines show ascending and dashed lines descending crossing times (Adapted from: http://www.remss.com/support/crossing-times/).

Action 7.4. Drive further dialogue with agencies in the Committee of Earth Observation Satellites (CEOS) to explore, where feasible, improving data availability, the diurnal spread of sampling by vector wind measuring satellite missions, and ensuring missions meet the TPOS requirements of coverage (Recommendation 1, First Report).

Based on experimental satellite missions and in situ observations, sea surface salinity has improved recently in quality (Boutin et al., 2018). These experimental missions will end in the coming years but the quality of SSS and the demonstrated impacts now justifies follow-on missions (First Report Recommendation 10). The projection (Figure 7.15) illustrates that SSS degradation will occur unless new missions are launched.

Action 7.5. Continue to highlight the ongoing need and benefits of follow-on satellite SSS missions as a key component of the TPOS.

Prospects for improvements of surface heat flux estimates are good providing the TMA can be upgraded and satellite-based flux estimates continue to improve (section 6.3.2). Rainfall measurements remain at threshold for satellite data but should improve somewhat for in situ if TPOS 2020 recommendations are adopted.

Ocean color requirements are being fully met and will be of increasing utility through synergies with BGC-Argo. Underway measurements of *p*CO_2 are made primarily from mooring servicing cruises, limiting the coverage and falling short of requirements because of lack of coverage in the western Pacific. These requirements will be met if TPOS 2020 recommendations are adopted.

Action 7.6. Underway $p\text{CO}_2$ observations should be continued or established on all mooring servicing vessels. Pilots of $p\text{CO}_2$ measurements from AUVs (e.g., Saildrone or Wave Glider) should continue as a potential means to drive up spatial and temporal sampling.

With regard to in situ systems for EOVs, the present sampling of subsurface temperature by the TMA and Argo is useful for limited requirements including current-generation ENSO forecast systems. The sampling does not adequately sample shorter scales (e.g., in the mixed layer, in high-gradient regions, and near the equator) that have significant impacts on the large scale and are required for both accurate analyses and model advancements.This should improve to “fully met”, especially in the western Pacific, with Argo doubling and implementation of the reconfigured TMA. Subsurface salinity is highly dependent on Argo, and not presently adequate in high gradient regions. Gradual improvement is anticipated through Argo doubling.

Subsurface velocity is dependent on moored current meters plus the Argo trajectory estimates at 1000 m. Implementation of the reconfigured TMA will improve velocity estimation in the equatorial band and at the surface. Moorings and glider transects that are being piloted in the low latitude western (and recommended for the eastern) boundary currents and Indonesian throughflow could partially satisfy u(z) requirements there. Subsurface BGC refers primarily to dissolved oxygen, nitrate and pH on BGC-Argo floats, but would ideally also include targeted moored sensors in areas such as OMZs, providing pilots are carried out and are successful.

7.4.2 Status and prospects for implementation of enhancing Argo

The First Report emphasized the need to immediately start the enhancement of Argo in the western Pacific, to restore and maintain subsurface temperature and salinity sampling in this region where the TMA has been much reduced, and then target the eastern Pacific. However, strong zonal dispersion will likely occur, particularly along the equator. Further work is needed for optimizing estimates of intraseasonal variability off the equator.

At present (April 2019) there are 382 operational Argo floats between 10°S and 10°N in the Pacific, approximately 1.2 times the original Argo requirement and with some concentration of floats near the equator. In addition, the transition to the Iridium transmission system has greatly helped to reduce the floats' divergence from the equator by reducing surface time. This now allows even better near-equatorial temperature and salinity sampling.

An action was also to further explore how to optimize float deployments and missions to better deliver to TPOS recommendations of doubled sampling from 10°N to 10°S. We find that floats deployed in the TPOS region with short surface time (such as those using Iridium communications) largely remain there compared to older models that suffered strong divergence (Figure 7.18). This suggests that maintaining density in the TPOS region is feasible, though rapid zonal displacements suggest an even east-west density will be difficult to sustain.

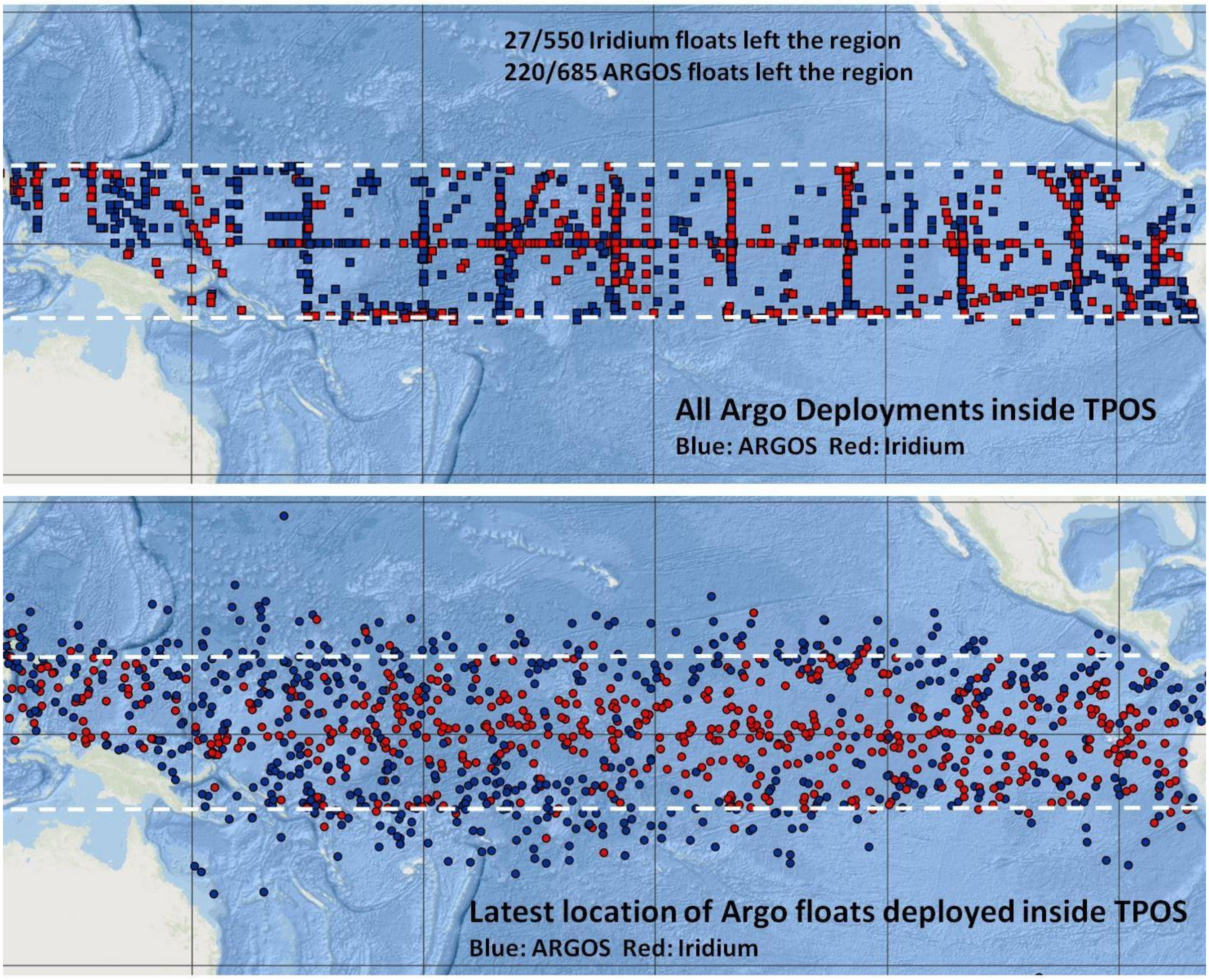


Figure 7.18 A comparison of long-term float deplacements in the TPOS region. Blue marks locations of floats using Service Argos which have 12-18 hour surface times, while red marks floats using Iridium. Top: Deployment locations of Argo floats in the TPOS region. Bottom: Final (as of December 2018) locations of the same floats.

There is strong interest by Argo national programs in enhancing coverage in the western Pacific and along the equatorial wave-guide, consistent with TPOS 2020 priorities. To date opportunities for deployments in the region have been limited but should increase with the presence of servicing ships to maintain the future TMA. There are not yet firm commitments for additional floats, but commitments are expected and some gains in coverage will be realized through increased float and sensor lifetimes in the coming years. Multi-national participation is needed to mitigate the preponderance of US Argo floats in the TPOS 2020 region (90% of present operational floats).

7.4.3 Status and prospects for implementation of enhanced TMA

To address the recent decay of the TRITON buoy array and new needs in the northwest Pacific Ocean, the TPOS 2020 project conducted a Western Pacific Workshop on 4–7 September 2017 in Qingdao, China, hosted by the First Institute of Oceanography, Ministry of Natural Resources, China. The brainstorming discussion led to plans by the Ministry of Natural Resources, China, to contribute buoys and moorings to address observational needs to track monsoon and typhoon development over the northwestern Pacific Ocean (see section 6.2.2).

After debate and consideration, the final array has the shape of the Chinese character "丁", which is pronounced [Ding]. Its literal meaning is "the fourth". This happens to represent the Chinese fourth ocean observation program, following programs for the coastal ocean, the polar ocean and the Indian Ocean. Therefore, the Ding name has been chosen, to include 10 moorings including surface buoys and 4 subsurface-only (upward-looking ADCP) moorings (Song et al., 2019; Figure 7.4). The present Ding array proposal has four components, including a far northern line along 18°N that extends the meridional scope of the previous mooring array, a meridional line along 147°E, and a buoy and subsurface mooring pair on the equator at 138°E. The detailed coordination information is listed in Table 1.

Due to the engagement of both JMA and JAMSTEC in the TPOS 2020 project, three TRITON moorings will be maintained by Japan as part of TPOS 2020. These will be at 0°, 156°E and 8°N, 137°E, which are historical TRITON sites. In addition, a new site at 13°N, 137°E has been established, which will possibly be developed into a Tier 3 Super Site.

While TPOS 2020 continues to refine its recommendations, the USA's NOAA will continue to maintain the TAO array. In addition, it is supporting technology pilots and process studies (sections 7.4.5.4 and 7.4.6). As the TPOS 2020 design is being firmed up, implementation timelines and logistics in coordination with international partners is starting to be discussed through the TPOS 2020 Transition and Implementation Task Team (see section 10.3). One major concern in this outlook is that three of the six high priority sites in the western equatorial region have no agency commitment to date (Figure 7.4, cyan circles). These sites monitor the formation region of the EUC, the passage of MJO windbursts and sample a critical convective regime over the warm pool. Their re-instrumentation remains an urgent task. Thus, we reprise and update the incomplete Action 1 from the First Report:

First Report, updated Action 1 The TMA sites in the western Pacific within 2°S to 2°N should be maintained or reoccupied.

These are core sites, and all should be supported.

Table 1: The list of the buoys and moorings in the proposed Ding array in the northwestern Pacific

Station No.	Longitude	Latitude	Configuration
1	130°E	18°N	Mooring with surface buoy
2	138°E	18°N	Mooring with surface buoy
3	147°E	18°N	Mooring with surface buoy
4	156°E	18°N	Mooring with surface buoy
5	147°E	13.3°N	Mooring with surface buoy and additional subsurface ADCP mooring
6	147°E	8°N	Mooring with surface buoy
7	147°E	5°N	Mooring with surface buoy and additional subsurface ADCP mooring
8	147°E	2°N	Mooring with surface buoy
9	147°E	0°	Mooring with surface buoy and subsurface ADCP mooring
10	138°E	0°	Mooring with surface buoy and subsurface ADCP mooring

7.4.4 Recommendations for a staged implementation

A staged implementation of the new Backbone is recommended, with ongoing assessment through to full maturity. Many elements relate to global systems and will evolve accordingly, but with recognition of and advocacy from the TPOS community (users, sponsors, research). Others will require specific actions from the TPOS community, and these are discussed in more detail below.

A possible transition timing is shown in Figure 7.19 with most activities beginning in 2019–2020, and serious implementation and change spread over 2020–2024. Note that this schedule is only indicative since there are many variables in the implementation that are currently unresolved. In this schema, full implementation would not be achieved until 2024. The transition rate is resource dependent, but a steady and slower implementation allows assessment of the changes to occur, the buildup of international expert peer groups and allows learnings on the use of new platforms and sensors.

The schedule for enhancing the western Pacific part of the TMA is initially dependent on Chinese plans for the so-called “Ding” array (“丁”) (see above). Here we assume a pilot will be deployed in 2019 (for cross-calibration and testing) and that the full array will follow over the next 3–4 years. We also assume JAMSTEC will continue to occupy three sites, including a potential Super Site (see below). This ‘TMA west’ schedule will deliver partial restoration of the core historical equatorial TMA (4 out of 7).

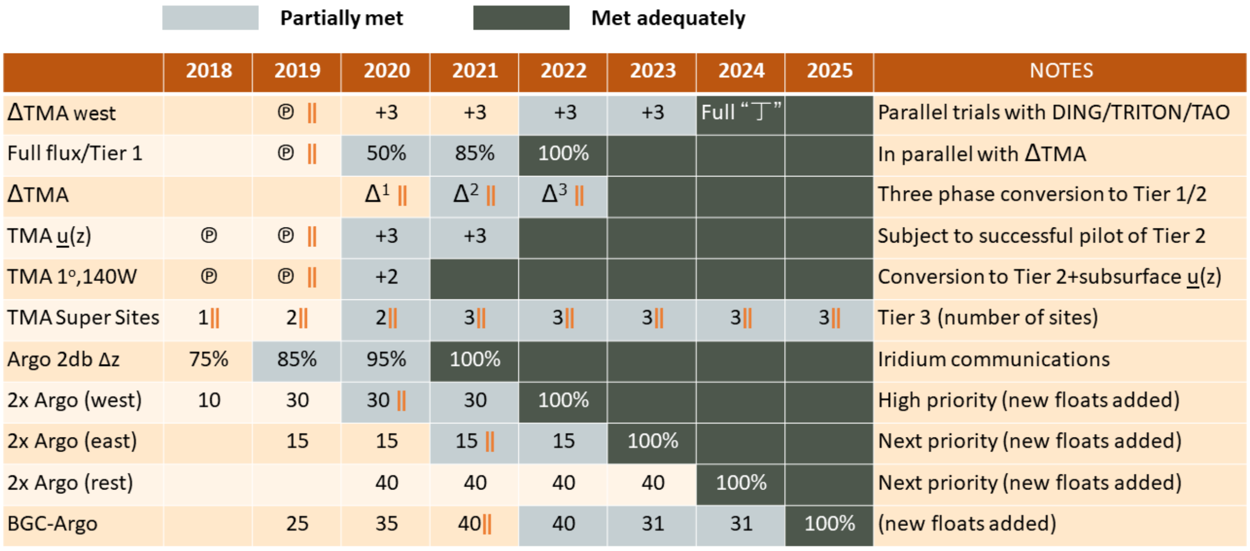
Several sensor and platform configurations required for the TPOS 2020 Backbone are currently being trialed (pilot experiments), including improved vertical sampling of mixed layer (or upper) currents (TMA Δz); subject to positive evaluation these will be implemented at the equatorial mooring sites. The proposed 1°N/S enhancements to the TMA at 140°W (see section 7.3) also fall into this category, but long-term implementation has some dependency on the eastern TMA reconfiguration (ΔTAO). The full flux Tier 1 configuration (see section 7.3 and Figure 7.3) involves a largely proven approach but it will be prudent to phase this change in so that assessment and evaluation can take place. The scale of this change will require careful planning and coordination, including for instrument calibration and data management needs. The roll-out should begin with the established TMA sites before any new sites are instrumented.

Action 7.7. In preparation for TMA-wide usage, Tier 1 ‘full flux’ moorings from all contributing operators should be piloted, intercompared and assessed. Building on past work on the TMA, instrument calibration and quality control procedures should be further developed.

Action 7.8. A pilot of enhanced thermocline velocity measurements at established sites at 140°W, 2°N/S should be planned, and if successful, extended to include the new sites at 1°N/S. Similar pilots should be carried out at the new sites in the northwest Pacific Ocean.

The transformation of the TMA is assumed to be in three phases Δ^1, Δ^2 and Δ^3 and will undoubtedly pose the greatest challenge since it will be undertaken in an environment where resources are a strong consideration and full implementation requires coordination and cooperation between three or more nations and agencies. The changes should be staged, and an assessment should accompany each stage (denoted in the figure by ‖). Sensitivity studies should be conducted to test the assumptions behind the design and to evaluate any anticipated impact. However, it should be noted that any such study will not be decisive since the studies themselves are impacted by assumptions and parameterizations, and sensitivity experiments often must be interpreted in the presence of significant systematic errors (see Fujii et al., 2019 for a fuller discussion).

The planned timing of Argo enhancements is also illustrated in Figure 7.19. Around 170 floats have to be deployed per year to maintain double density. This begins with about 10 “additional” floats deployed in the Western Pacific in 2018—“2× Argo (west)”—increasing to 30 per year in subsequent years. If the float average lifetime is 4.5 years, then 30 deployments per year will increase the Western Pacific array by 135 floats. Second, “Argo Δz” in Figure 7.19 represents high vertical resolution sampling (typically 2 dbar spacing) achieved through the use of bi-directional high-bandwidth satellite communications, such as Iridium. The transition to Iridium has progressed rapidly and at present 86% operational floats in the TPOS 2020 region already use Iridium.



░ Partially met ■ Met adequately

	2018	2019	2020	2021	2022	2023	2024	2025	NOTES
ΔTMA west		℗ ‖	+3	+3	░ +3	░ +3	■ Full “丅”	■	Parallel trials with DING/TRITON/TAO
Full flux/Tier 1		℗ ‖	░ 50%	░ 85%	■ 100%	■	■	■	In parallel with ΔTMA
ΔTMA			Δ^1 ‖	Δ^2 ‖	Δ^3 ‖	■	■	■	Three phase conversion to Tier 1/2
TMA u(z)	℗	℗ ‖	░ +3	░ +3	■	■	■	■	Subject to successful pilot of Tier 2
TMA 1°,140W	℗	℗ ‖	░ +2	■	■	■	■	■	Conversion to Tier 2+subsurface u(z)
TMA Super Sites	1‖	2‖	░ 2‖	░ 3‖	░ 3‖	░ 3‖	░ 3‖	░ 3‖	Tier 3 (number of sites)
Argo 2db Δz	75%	░ 85%	░ 95%	■ 100%	■	■	■	■	Iridium communications
2x Argo (west)	10	30	░ 30 ‖	░ 30	■ 100%	■	■	■	High priority (new floats added)
2x Argo (east)		15	15	░ 15 ‖	░ 15	■ 100%	■	■	Next priority (new floats added)
2x Argo (rest)			40	40	░ 40	░ 40	■ 100%	■	Next priority (new floats added)
BGC-Argo		25	35	40‖	░ 40	░ 31	░ 31	■ 100%	(new floats added)

Figure 7.19: Schematic providing detail of the schedule for change in the Backbone involving Argo, the TMA, and so-called “Super Sites”. The symbol ℗ denotes a pilot mode. The symbol ‖ refers to review/evaluate points. For Argo the numbers show the annual seeding rate of ‘additional floats’ to double the array density. For the TMA the numbers usually refer to enhancement levels. In anticipation of changes to the TMA (denoted by ΔTMA), we assume three phases Δ1, Δ2 and Δ3. The shading indicates the degree to which requirements will be met through this schedule (approximate) except for the Super Sites. “TMA west” currently consists of the TAO line at 165°E and 3 JAMSTEC sites. The former State Oceanic Administration has outlined plans to develop the so called “ding” array (denoted by “丅”), which extends the TMA to the northwest while at the same time supporting some of the key equatorial sites of the TMA (Chen et al., 2018). (Adapted from: TPOS OceanObs’19, Figure 9).

Third, “2× Argo (east)” consists of 15 additional near-equatorial floats deployed each year east of about 120°W. This level of deployment will enhance along-equatorial coverage by about 67 floats. “2× Argo (rest)” represents 40 “additional” off-equatorial floats per year, doubling Argo coverage over the remainder of the TPOS 2020 region. The sum of additional Argo floats in 2020 and beyond is 85 per year (170 in total), sufficient for doubling the entire array. Finally, for BGC-Argo, we have taken account of the requirements articulated in Chapter 4 and anticipated a shorter life time for BGC-Argo floats, at least through the early stages of development and deployment out to 2022–2023 (Figure 7.19). We recommend a review of progress around that time. Figure 7.19 shows a ramping up to 40 TPOS BGC-Argo deployments per year and then settling to approximately 31 per year as the technology matures and stabilizes.

The orange vertical bars in Figure 7.19 indicate planned dates for assessments of the impact of enhancements. It should be kept in mind that 5 years of “additional” deployments are needed for the full Argo coverage to reflect the added deployment rate. If resources were available, an alternative approach is to rapidly seed the region to full doubling to enable longer overlap with the existing TMA sites and possible acceleration of its reconfiguration.

Action 7.9. Argo float deployments should be doubled over the entire tropical region 10°S-10°N, starting immediately in the western Pacific, followed by the eastern Pacific and extending to the entire region, building to a total annual deployment rate of 170/year. Of these, 31 should be equipped with biogeochemical sensors (BGC-Argo).

The major enhancements to the TMA and Argo sampling will present challenges of scaling, logistics, and data quality and management. Each enhancement should be preceded by a pilot beginning as soon as possible and lasting at least a year, followed by assessment of costs, demonstrated technical capabilities, data flow, and product impact. Results from assessment of the pilot deployments should be widely and rapidly disseminated. Progression to full implementation can occur once any substantial issues raised by the pilot deployments are identified and resolved. It is essential to demonstrate the ability to deploy complete arrays and to sustain a high-quality data stream.

Assessments carried out during implementation should include:

1. intercomparisons to ensure equivalence of observations of buoy/sensor combinations via side-by-side tests e.g., DING vs TAO vs TRITON for the Tier 1 level suite;
2. analysis of effectiveness of capturing subsurface temperature variability from enhanced Argo or Argo/Altimetry gridded products at the TMA sites. Many products are automatically generated, and this analysis could also be automated to track and capture any impact in spread among presently operating state estimates (see discussion in Chapter 2 and section 7.3.6.2), and prediction systems (Recommendation 2.2);
3. deployment of error analyses and post-calibration assessments, particularly for sensors used to measure parameters used for bulk fluxes, given the 10°W/m^2 target for the combined net heat flux;
4. rapid analyses of new velocity measurements—both for instrument accuracy and data return;
5. systematic use of near surface velocities with wind measurements to probe impacts on stress comparisons with space-based estimates.

Details of other needed assessments will be developed over the last years of the TPOS 2020 project as implementation plans start to materialise. However, it will be crucial to entrain user community experts in this effort.

Recommendation 7.2. To ensure that the TPOS observing platforms collect the accurate and interoperable measurements required to detect small [climate or “dec-cen”] signals, a series of actions should be taken, beginning before the rollout and continuing during implementation, to assess the performance and impact of the proposed platform/sensor changes.

Action 7.10. TPOS 2020 Task Teams, implementation groups and community experts should develop and detail whole of system assessment activities, describing them in the final TPOS 2020 report (or earlier). Part of the assessment should include the tradeoffs between the number of sites versus the ability to maintain continuous records.

Action 7.11. For each specialized data stream or platform (e.g., buoys), ensure the creation of an engaged team of experts to oversee sensor management, develop quality control (QC) procedures and guide the delayed-mode QC for the TPOS data streams. (Also see ***Recommendation 8.3***)

7.4.5 Updates on pilot studies for the Backbone

Chapter 6 in the TPOS 2020 First Report outlined several Pilot and Process Studies that were determined necessary to guide sampling strategies for the evolution of the sustained network as part of the TPOS Backbone (Figure 7.20). This section provides a brief update on the progress and status of those studies.

A Pilot Study is defined as a small-scale preliminary activity or study that is conducted in order to evaluate feasibility, cost, risks and sampling strategy before commitment and implementation as part of the sustained network. Seven Pilot Studies were put forward as part of the TPOS First Report.

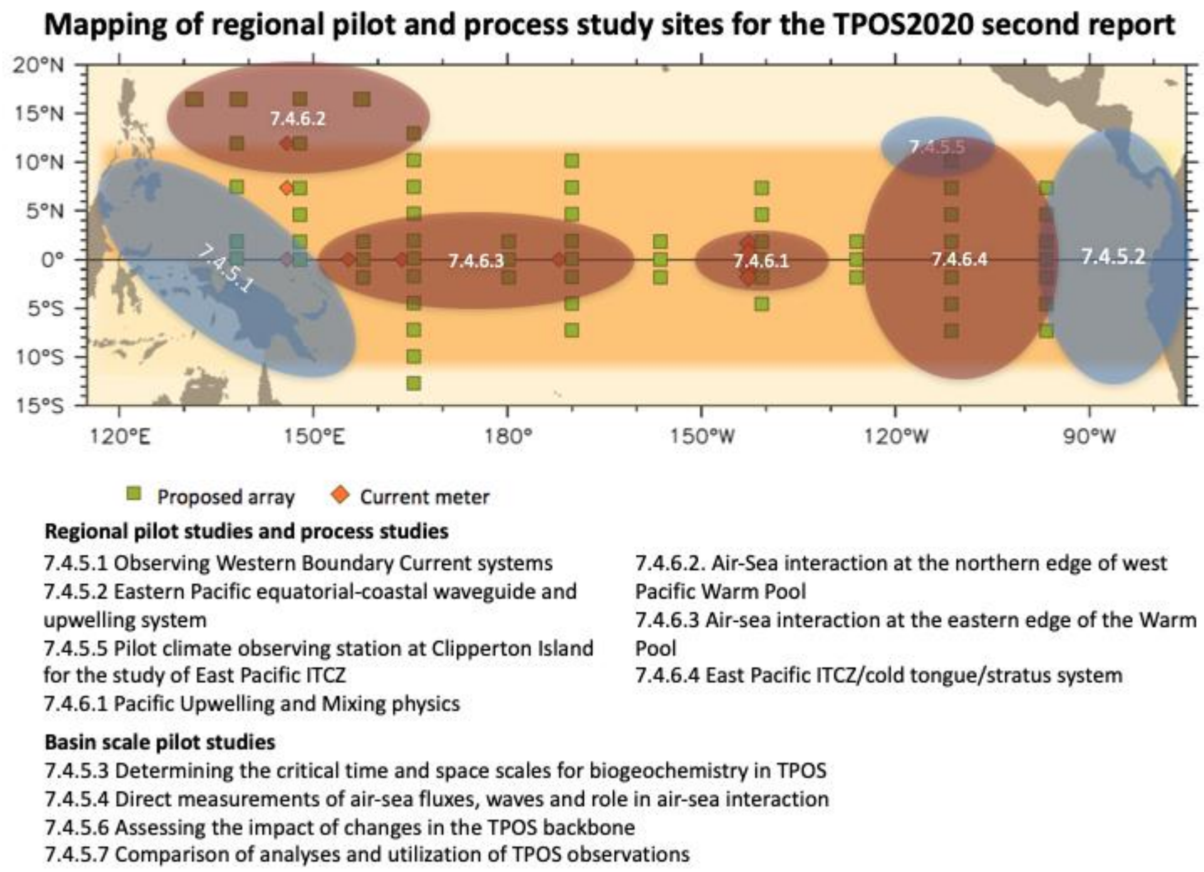


Figure 7.20: Mapping of regional pilot (shaded in blue) and process (shaded in red) study sites.

7.4.5.1 *Observing western boundary current systems: A pilot study*

The goal of this Pilot Study is to determine the time and space scales, and the key sites and variables needed to develop a sustained boundary observing system in the LLWBC of both the North and South Pacific Ocean and the leaky western boundary via the Indonesian seas. The planning for this Pilot Study found synergy with existing efforts as part of international large-scale projects such as SPICE, ITF (Indonesian Throughflow) and NPOCE, and also with the many OceanObs'19 community white papers that helped in developing sampling strategies of relevance to LLWBCs (Todd et al., 2019; Sprintall et al., 2019; TPOS OceanObs'19). In particular, TPOS OceanObs'19 recommended a multi-platform approach consisting of a combination of line-mode transects (gliders, moorings, expendable bathythermographs (XBTs), etc.) with broad-scale sampling (Argo, drifters, remotely-sensed). Specifically, the target was to monitor the LLWBCs heat transport to 500 m at monthly/seasonal timescales including simultaneous heat transport measurements in the northern and southern LLWBCs and the ITF. Also recognized was the need for monitoring and better understanding of the locations and processes of the LLWBCs micronutrient content variations (see also Chapter 4).

Thus, while progress has been made in this Pilot Study in developing an abstract understanding of what might be needed for an LLWBC monitoring strategy, there remains a need for a more solid internationally coordinated effort to better assess the existing and historical observing systems of these LLWBC so as to help guide future Backbone implementation needs and coordinated data sharing, among other things. As with many Pilot Studies, this progress has been somewhat hampered because of strains on funding availability and dedicated personnel availability to more actively pursue this mission. Nonetheless, in conjunction with the TPOS 2020 Western Pacific Task Team, there is an ongoing effort to create an inventory documenting past and present observing activities within each LLWBC system, as a first concrete step toward a more thorough assessment of what combination of components might work best for a synchronous sustained measurement system in each boundary current regime.

7.4.5.2 Eastern Pacific equatorial-coastal waveguide and upwelling system

This Pilot Study is to use historical and ongoing observations to help guide the sampling strategy needed to develop a pilot array to observe the equatorial coastal wave guide and the coastal upwelling zone off Peru. Progress is reported in section 5.3.1.

7.4.5.3 Determining the critical time and space scales for biogeochemistry in TPOS

The goal of this Pilot Study is to better inform the temporal and spatial scales of surface and subsurface biogeochemical observations (such as nutrients, oxygen, carbon, etc.) needed for the Backbone. Planned work has been done, and results are reported in Chapter 4.

7.4.5.4 Direct measurements of air-sea fluxes, waves and role in air-sea interaction

This Pilot Study aims to determine the best strategy for measuring direct covariance fluxes (DCF) and waves as part of the TPOS Backbone. Since the First Report, two projects have received funding to explore the development and testing of new platforms and technology as part of this Pilot Study: development of low power DCF systems for use on TMA buoys and the use of autonomous surface vehicles (e.g., “Saildrone”) to measure air-sea flux parameters, reported in section 9.2.1.

7.4.5.5 Pilot climate observing station at Clipperton Island for the study of East Pacific ITCZ

This study aimed to establish a Pilot Climate Observatory at the uninhabited Clipperton Island (French territory) to better understand the processes controlling the east Pacific ITCZ convection. The establishment of a station at Clipperton has proven challenging from a diplomatic and logistical perspective. In response, alternative islands have been proposed as sites for enhanced atmospheric profiling as part of a larger pilot study to include islands within the eastern Pacific observing system (section 5.3.3).

7.4.5.6 Assessing the impact of changes in the TPOS Backbone

The goal of this Pilot Study is to develop a well-defined framework through which specific TPOS Backbone observing system recommendations might be evaluated in terms of ocean state estimation and near-term predictions. Specific considerations in the First Report included the impact of doubling Argo and the reconfiguration of the TMA, while maintaining remotely sensed SST and SSH measurements. Participation from multiple models (and modeling centers) and multiple approaches is considered essential for drawing robust conclusions. There has been some ongoing activity on the assessment of the Backbone system based on a combination of OSEs, OSSEs and alternative techniques (e.g., DFS—Degree of Freedom of Signal, FSOI—Forecast System Observation Impact, etc.) to assess the changes in the TMA configuration and other recommendations in the TPOS 2020 First Report. Some further details are given in Chapter 2.

7.4.5.7 Comparison of analyses and utilization of TPOS observations

This Pilot Study aims to quantify how (and what) observations are being used for routine ocean monitoring and predictions, and what their influence is. The ongoing Real Time Multiple Ocean Reanalysis Intercomparison project[23], hosted by the Climate Prediction Center (CPC), compares ocean reanalysis output from various operational seasonal prediction systems. Additional activities include the exchange of information on observational data that are ingested in data assimilation systems, particularly for ENSO class prediction systems; exchange of analysis increments from operational centers; and delayed-mode intercomparisons of ocean reanalyses. Outcomes of these activities is expected to provide an ongoing assessment of use and efficacy of TPOS in monitoring and prediction. A rudimentary prototype effort is currently underway at CPC and BOM. Further details are provided in Chapter 2 and section 7.3.2.2.

Similar to other pilots, implementation of these two model assessments will require both external and in-kind resources. Without specific identification of funding, moving things beyond concept and ideas is a hard task and it is not yet clear where the support for implementing the two pilot studies would come from.

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[23] https://www.cpc.ncep.noaa.gov/products/GODAS/multiora93_body.html

7.4.6 Updates on the Process Studies

Process studies are aimed toward understanding phenomena that are central to Pacific basin climate, but where there is currently too little known about the phenomena to design a sampling strategy. Whereas the outcomes of Process Studies are typically scientific, the tangible outputs for the TPOS 2020 Backbone might include improved knowledge, model parameterizations, and the demonstrated need and development of instrumentation and techniques for sustained monitoring of the phenomena. In turn, this may increase the ability of models to infer the process from sparser data sampling strategies that then lead to refinements of the sustained sampling array.

Stakeholders in TPOS, such as NOAA and JAMSTEC, have funded a number of new initiatives that promote new technology and modeling studies in support of these Process Studies.

7.4.6.1 Pacific upwelling and mixing physics

This Process Study aims to better understand the spatio-temporal variability and the physical processes responsible for the interaction between upwelling and mixing in the eastern equatorial Pacific with a goal to improve model parameterizations (First Report, section 6.2.1). Two modeling studies in support of this Process Study were funded by the Climate Variability and Predictability Program of NOAA. These include: “A Pre-Field Modeling Study of Scales, Variability and Processes in the Near Surface Eastern Equatorial Pacific Ocean in Support of TPOS” (PIs Bryan, Kessler and Thompson) and “Simulations and analysis of mesoscale to turbulence scale process models to facilitate observational process deployments in the Equatorial Pacific Cold Tongue” (PIs Whitt, Bachman, Holmes, Large and Lien).

7.4.6.2 Air-sea interaction at the northern edge of west Pacific warm pool

The purpose of this process study is to capture the multi-scale structure of the BSISO through high-resolution in situ observations in both the atmosphere and ocean (section 6.2.2 in the First Report).

In cooperation with the international efforts of YMC led by BMKG[24] in Indonesia, PMEL[25]/NOAA in US and JAMSTEC in Japan, several observational efforts have been undertaken in 2018. In August-October 2018, the PISTON project by U.S. groups conducted a special field campaign from a research vessel deployed around 12°–17°N, 135°E. Very high-resolution time series of the atmosphere and oceanic mixed layer were captured from shipboard measurements, as well as two heavily-instrumented moorings were deployed to retrieve ocean-atmosphere time series. Within the same region, Japan’s JAMSTEC also deployed their research vessel in August 2018, conducting special ocean-atmosphere observations during TRITON buoy

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[24] Badan Meteorologi, Klimatologi, dan Geofisika, Indonesia

[25] Pacific Marine Environmental Laboratory

maintenance cruises. These observations captured detailed variations such as the diurnal cycle, impact of typhoons, etc. These two vessels also used dual-Doppler radar observations from shipboard polarimetric radars that successfully captured the fine three-dimensional structure of the precipitation systems. Finally, Korea's Institute of Ocean Science and Technology (KIOST) conducted special observations from their research vessel nearby in November to December 2018. They also continue observation by several underwater instruments nearby since 2017.

The ongoing effort will focus on determining what aspects of this process study might be suitable for longer term observations to contribute to the Backbone array of TPOS. In particular, together with promised efforts of the "Ding" array by the State Oceanic Administration (SOA) of China (section 7.4.3), the group will make continuous efforts to maintain a better observing system in the north western Pacific focusing on the strong impacts to eastern and south-eastern Asia of typhoons and the generation of typhoons in association with ENSO variations in the entire tropical Pacific.

7.4.6.3 Air-sea interaction at the eastern edge of the warm pool

The purpose of this process study is to understand the primary mechanisms maintaining the frontal structure at the eastern edge of the west Pacific warm/fresh pool. The basic strategy for this process study will be to use the TPOS Backbone to provide context, with additional measurements from autonomous vehicles and shipboard systems to allow a better mechanistic understanding of processes.

A small working group was established during the 5th Steering Committee meeting to coordinate observations and a modeling effort to better understand the variabilities and physical processes of the eastern edge of the warm pool. Saildrones have recently been deployed from Hawaii (section 9.2.1) to measure the coupled ocean-atmosphere response to the zonal variations of the eastern edge of the warm pool for several months. In addition, four pre-field modeling studies that employed diverse approaches and models in support of this Process Study were funded by the Climate Variability and Predictability Program of NOAA in 2018. JAMSTEC has also proposed to conduct a short-term cruise to measure the vertical structure of the upper ocean to the lower atmosphere in the eastern warm pool region from December 2019 to January 2020. The ongoing goal is for the working group to recommend the additional observation or revision to the current Backbone designs to provide better long-term monitoring of the eastern edge of the warm pool.

7.4.6.4 East Pacific ITCZ/cold tongue/stratus system

This Process Study aims to explore the coupled air-sea processes that potentially contribute to the double ITCZ bias in climate models that can lead to significant overestimation of the rainfall in the tropical southeastern Pacific (section 6.2.4 in the First Report). An international process-oriented field campaign has been proposed to provide guidance as to the needed sustained observations as part of the TPOS to improve the representation of processes controlling the location of the ITCZ in nature and its seasonality, particularly of the Southern Hemisphere ITCZ. Details are provided in section 5.3.2.

7.4.7 New pilots/process studies for the Backbone

Super Sites (Tier 3)

The concept of a Super Site is to provide a multi-year, larger suite of measurements than the Backbone observing system offers that would be useful for improving error characterization or product biases (gridded products, including satellite and reanalyses) and/or model physics. This would be a different focus than a targeted process study which is aimed at answering specific scientific questions regarding a phenomenon or process. The Super Site would consist of a to-be-determined combination of buoys (one or more), mobile platforms (drifting or autonomous underway vehicles (AUVs)), frequent ship visits for augmented measurements and/or refurbishment of existing sensors, and possibly an island station.

There are a number of rationales for the existence of a Super Site. The enhanced observations would be of benefit for improvement of satellite retrievals and the synthesis of in situ and satellite observations (see section 6.3.2). Improvement of retrievals of surface radiative fluxes, for instance, will come from not only more measurements of the surface radiation flux, which can provide information on errors, but perhaps more importantly auxiliary measurements which provide context and additional information for constraining the physics of the system. In the case of the surface radiation fluxes, this could include aerosol information, planetary boundary layer profiles of winds, temperature, and humidity, sea state information, and cloud base information. These data would also be of value for increasing the atmospheric boundary layer measurements needed for understanding the coupled mixed layer system, driving coupled model improvements, and increasing understanding of heat, mass, momentum, and gas exchange within the environment.

In addition, a site with an enhanced set of measurements that has a relatively frequent revisit rate by ship would allow for a superior set of biogeochemical and physical measurements, as many of these sensors can have biofouling or other issues after a matter of a few months, rendering them less useful for a long-term site with infrequent (yearly) revisits. As these sites are not part of the Backbone observing system, new and emerging technologies could be tested at no risk to the current system. In that sense, a prototype Super Site is currently being developed, with the NOAA Ocean Observing and Monitoring Division funded test mooring, which consists of testing a series of daisy-chained ADCPs to get real-time current profiles, in addition to a buoy measuring direct covariance momentum and buoyancy flux, next to a TAO mooring. At a Super Site, additional buoys could be placed that require a separate type of measurement that would be too difficult to accommodate on a single buoy, such as a LIDAR (light detection and ranging) buoy, a wave buoy and even a radiation buoy where radiometers would not have to compete with other sensors for unshaded vertical locations. In addition, measurement of key processes such as very near surface currents and ocean mixing that are difficult and expensive for operational sites would be tractable at a Super Site.

A further advantage of such a site that is collecting a relatively complete look at both the ocean and atmospheric boundary layers for a multi-year time period would be in its benefits to high-resolution modelers. Cloud-resolving and large eddy simulation models require comparisons with statistically robust samples of data, which is simply not possible with a campaign which lasts on the order of a few months.

Some sample measurements that would enhance the TPOS capabilities include, but are not limited to: atmospheric temperature, humidity, wind profiles; direct momentum, latent heat, and sensible heat flux measurements; infrared radiometers for skin sea surface temperature; downward looking pyranometers for albedo; very high resolution temperature, salinity, and current profiles in the uppermost ocean; wave information; bio-optical profiles, dissolved oxygen, nitrate, and $p\mathrm{CO}_2$; upper ocean dissipation/mixing measurements; aerosol measurements; rain radars, and cloud base and other cloud properties.

There are multiple considerations that would need to be taken into account for the development of a Super Site, including identifying a budget and oversight entity for maintenance. It should be noted that there could appropriately be multiple sponsors of a Super Site, depending on the suite of measurements that are proposed and the location of the site. In addition, the existence of a longer-term suite of a variety of measurements may be enhanced by scientific proposals of individual PIs to focus on specific science or instrument objectives. Appropriate sites, the life time of the infrastructure/facilities/instruments, and the appropriate grouping of measurements would also need to be identified.

In order to make progress at improving measurements (both in situ and satellite), additional multi-year time campaigns with enhanced measurement capabilities and ship support should be developed.

Action 7.12. TPOS 2020 Task Teams should develop and articulate the Tier 3 concept, including possible approaches to determination of appropriate times, locations, and measurements.

7.5 Summary and new/changed recommendations

We have described a new design for the TPOS which responds to the high-level recommendations in the First Report, as well as new concerns outlined in this Report. This new design represents a major upgrade to the TPOS, serving a broader number of applications, supporting emerging research and services, and strengthening the climate record. We also note actions that will further test the design and lay the groundwork for implementation.

7.5.1 Revised recommendations from First Report

Of the 22 recommendations for the TPOS from the First Report, most remain valid. However, some updates and slight changes are needed to reflect the evolution in the requirements.

☐ First Report Recommendation 3*:*

<u>Preamble</u>

- *Unbiased and accurate high-resolution long-term sea surface temperature (SST) sampling is required, with particular focus on persistently cloudy and rainy regions and sharp horizontal gradients in the cold tongue region. Ideally, for improved understanding of processes near the surface, sampling should resolve the diurnal cycle and thus be able to characterize near-surface temperature profiles in regions where diurnal variability is large. [3.1.1.1, 3.3.1, 3.3.2, 5.2] TPOS 2020 recommends:*

Recommendation 3: *Sustaining satellite measurements of SST, using infrared sensors for higher spatiotemporal sampling; passive microwave sensors filling gaps under clouds; and the diversity of satellite and in situ platforms contributing to inter-calibration*

This recommendation and its preamble are still valid, and resolving the diurnal cycle is a key requirement for an accurate estimation of the air-sea fluxes. It is important to highlight the needs for an adequate SST sampling, and a correct processing of the data. In the tropical Pacific, the Himawari-8 Advanced Himawari Imager and GOES-17 Advanced Baseline Imager (not yet operational) provide high spatiotemporal (10–15 minutes), sampling of cloud-free regions with diurnally-varying skin retrievals. Improvements to these retrievals should continue. In addition, clearer analysis of the depth used for non-skin surface temperature retrievals should be provided, for comparison with the microwave sensor products and in situ platforms. Passive microwave sensors products providing data under cloudy conditions should be sustained, and both skin and near-surface in situ data are still important for continued calibration of the products.

Action 7.13. Continue efforts toward estimating SST diurnal cycle of skin temperature, by better incorporating remote microwave, vis/infrared, and in situ data at various depths.

☐ First Report Recommendation 10:

Preamble

- *Broadscale sea surface salinity (SSS) sampling is required, with sufficient resolution to characterize sharp salinity fronts in the equatorial zone [3.1.1.6]. For understanding key processes and phenomena, higher resolution salinity sampling is particularly important in the west Pacific warm pool and in frontal regions [3.3.1, 3.3.2, 5.5]. In situ and satellite measurements together provide complementary observations of SSS to meet TPOS needs. In situ measurements provide accurate near-surface salinity measurements. Argo provides coverage on larger space scales; tropical moorings provide high frequency measurements, Voluntary Observing Ships (VOS) provide high spatial resolution measurements along tracks and a long climate data record. Satellites provide SSS with near-uniform sampling that resolves gradients, as well as better coverage in coastal oceans and marginal seas. TPOS 2020 recommends:*

Recommendation 10: *Continuity of complementary satellite and in situ SSS measurement networks, with a focus on improved satellite accuracy.*

This recommendation might be misleading, as the goal is not only to improve satellite accuracy, but to improve SSS sampling for the reasons mentioned above. The updated recommendation is now:

Updated Recommendation 10*: Continuity of complementary satellite and in situ SSS measurement networks, with a focus on improved satellite accuracy to augment the spatial and temporal sampling of SSS*

☐ First Report Recommendation 11:

Preamble:

- *Surface current (speed and direction) is required with a high spatial and temporal resolution, especially in the equatorial band, to facilitate the assimilation and synthesis of satellite and in situ wind measurements [3.1.1.2]. Time series of equatorial subsurface currents are widely used in model validation and development and will continue to be needed for future data assimilation [3.1.3.2]. For improved understanding of processes and phenomena, TPOS 2020 identifies requirements for enhanced vertical resolution of current measurements to resolve near-surface shear; meridional sampling near the equator to resolve the circulation; and improved monitoring of other key circulation elements such as low-latitude western boundary currents and intermediate depth currents [3.3.1, 3.3.3, 3.3.4.1, 3.3.4.2, 5.6]. TPOS 2020 recommends:*

Recommendation 11: *Continuation of technological developments to measure ocean surface currents remotely, and improved in situ measurements of surface and near-surface currents, particularly near the equator, and to collect collocated measurements of wind and surface currents;*

Update: Since the publication of the First Report, three concept missions have been proposed to space agencies to measure ocean surface currents from space using Doppler radar technology (section 9.3.1). SKIM (Sea surface KInematics Multiscale monitoring), which should measure surface currents and waves, is under development for European Satellite Agency (ESA) Earth Explorer-9 selection; WaCM (Wind and Current Mission), which should measure winds and currents, is recommended by the US Decadal Survey for competition in the Explorer-class category. If these missions are accepted, they will be game-changers with direct measurements of total surface currents, especially in the equatorial band where satellite-derived indirect estimates are subject to large errors (First Report). If flying, they will modify the requirements in terms of ground-truth in situ observations. Measurements of near-surface currents (as close as possible to the surface) and of near-surface velocity shear will be needed, but process studies are needed first to better understand the near-surface shear, and the depths and locations at which in situ data will be needed.

☐ First Report Recommendation 21:

Preamble:

Other existing in situ components should continue to be supported. These include the surface drifter network; underway data collected from VOSs and Ships of Opportunity (including ancillary measurements on service vessels); high-resolution expendable bathythermograph transects; deep, long regular hydrographic transects (known as GO-SHIP); fixed point reference sites under OceanSITES; and tide gauges for calibration and monitoring sea level change [3.1.1.1, 3.1.1.3, 3.1.1.4, 3.1.1.6, 3.1.2.4, 3.1.3]. TPOS 2020 recommends:

Recommendation 21: *Continued support for in situ observations from drifters, ships, tide gauges and reference mooring sites.*

The dedicated capacities offered by a servicing ship should be considered as an integral component of the observing system. A dedicated ship permits to acquire ancillary data such as temperature, salinity, and pressure (CTD) profiles, dissolved oxygen, nutrients, through water samples, $p\mathrm{CO_2}$, and velocity (shipboard ADCP). Such data acquired during maintenance cruises of previous TAO/TRITON array have proven invaluable for describing the current velocities and water mass properties climatology and variability (see Roemmich et al., 2014; Mathis et al., 2014), and should be reinvigorated. CTDs should be performed to 1000 m along each TMA line, with priority assigned to the 8°S-8°N band. The CTD package should be equipped with dissolved oxygen and optical sensors (chlorophyll fluorescence, particulate backscatter, transmissometer) and water samples for chlorophyll and nutrients should be routine. Other GO-SHIP parameters such as dissolved trace elements, inorganic carbon, particulate organic carbon, transient tracers, N_2O, C isotopes and dissolved organic carbon should be accommodated where possible, probably through the involvement of a motivated and funded investigator.

The importance of these capacities, while recognized in the First Report, was not sufficiently highlighted. Thus, a new recommendation from TPOS 2020 is:

> ***Recommendation 7.3.*** Improvement of dedicated capacities on servicing ships to allow repeated ancillary measurements. Underway measurements such as Shipboard Acoustic Doppler Current Profilers, $p\mathrm{CO_2}$ and sea surface salinity should be systematically acquired.

7.5.2 Reprised actions

There is continuing support for Action 14 from the First Report:

First Report Action 14 Through the TPOS 2020 Resources Forum, the TPOS 2020 Transition and Implementation Group, and links to research programs and funders, support should be advocated for ***Pilot and Process Studies*** that will ***contribute to the refinement and evolution of the TPOS Backbone.***

Indeed, as outlined above, many of the Process Studies proposed as part of the First Report have attracted financial support and are being implemented. Additional funding opportunities are needed in support of the Pilot Studies.

Chapter 8 TPOS Data Flow and Access

Authors: Neville Smith, Kevin O’Brien, David Legler

8.1 Background

In the 2014 Tropical Pacific Observing System 2020 Workshop (Global Climate Observing System, 2014a, b), Smith and Hankin (2014) evaluated requirements for delivery of data and derived products and information, in real time and delayed mode, and the fitness for purpose of then existing TPOS data systems. One of the recommendations emerging from that workshop was that:

- As an underlying principle, a minimum of 10% of the total observing system effect should be directed toward data and information management, particularly for emerging and prototype technologies and a data and information management plan should be part of the TPOS 2020 implementation plan, to take account of opportunities to pilot new approaches.

This recommendation was discussed at the first meeting of the TPOS 2020 SC[26]. The SC recognized the potential for consolidation of data streams, moving away from platform specific data management systems to integrated approaches, but decided it was premature to define a TPOS data and information activity/implementation plan (but supported the idea of a TPOS data integration pilot project).

Consequently, the First Report did not have a dedicated section on data management, data flow and access. Subsequent discussions (for example, Steering Committee meeting #4[27]) noted the many activities within the global community, but at the same time concluded there were specific issues that TPOS 2020 might address that would add value to TPOS and the global effort. The TPOS 2020 Resource Forum[28] endorsed a proposal for a chapter on data information flow and access in the 2nd Report.

Subsequently, the TPOS 2020 community participated in several community white papers on data management for the OceanObs'19 conference, some of which highlighted specific needs relevant to TPOS 2020 (Tanhua et al., 2019b; Pinardi et al., 2019; Snowden et al., 2019; Vance et al., 2019; Pearlman et al., 2019). This chapter develops some of those ideas further within the specific context of TPOS 2020 and makes recommendations around requirements and needed action.

This chapter intentionally focuses and addresses only a narrow set of the topics and challenges, compared with the broad scope of the global data management community. The global actions

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[26] http://tpos2020.org/project-reports/steering-committee-reports/steering-committee-meeting-1/

[27] http://tpos2020.org/project-reports/steering-committee-reports/steering-committee-meeting-4/

[28] http://tpos2020.org/project-reports/resource-forum-reports/resource-forum-meeting-2/

are important for TPOS and the absence of any attention here should not be interpreted as lack of support.

This paper attempts to identify a small number of areas where we think TPOS 2020 might add value and/or where bespoke data management activities could be productive for TPOS, and for the future data and information system. We take the view that we should not open TPOS-specific lines of activity unless there is a clear user-driven demand for doing so.

8.2 Essential elements and requirements

Figure 8.1 (adapted from TPOS OceanObs'19) depicts the observing system requirement setting process (cf. Lindstrom et al., 2012), only now applied to data management. The data management requirements will emanate from several levels; (a) from the data users who are specifying needed accuracy (quality) and sampling (how often; timeliness; discretization) at the level of variables, (b) from operators of observing elements/networks who will want effective and efficient transmission of observational data, and (c) from the perspective of the ocean observing system design where delivering timely, fit-for purpose data and products is paramount. The FAIR Principles (Tanhua et al., 2019b), metadata models and standards, Data Object Identifiers (DOIs), persistent identifiers for data and products (PIDs), Global and other Data Assembly Centers (GDACs, DACs), Thematic Acquisitions Centers and many other characteristics and attributes usually appear as requirements. To the extent possible such requirements should be common across EOVs and across platforms, but this is not yet practical.

“We want it now” is a common refrain among users which impacts consideration of timeliness, efficiency and simplicity. Systems that deliver services through multiple channels, and with different offerings in terms of integration and quality, are likely to receive priority as solutions to such requirements (Snowden et al., 2019).

One of the experiences from TPOS 2020 (and from the parallel review of the Tropical Atlantic Observing System) is that the architecture of our data systems is opaque to many users (both on the input and output sides) and probably needs review (Snowden et al., 2019; Tanhua et al., 2019b). For TPOS 2020, many users prioritize quality (climate change, research), some of which is only possible with off-line scientific interventions (e.g., Argo; see Tanhua et al., 2019b). The climate record depends critically on the quality control provided by such processes. Moreover, the integrity of climate data records is often secured and enhanced through such delayed-mode processing.

TPOS 2020 has also highlighted fundamental issues around data exchange, noting that in certain areas and regions open accessibility is problematic (Snowden et al., 2019). In the Eastern Pacific (Chapter 5) this is a major barrier to progress. Elsewhere, the issue is more to do with the lack of priority given to data management. As Tanhua et al. (2019b) noted "Data that are poorly documented can be considered lost and will have little or no value without access to the team that collected the data."

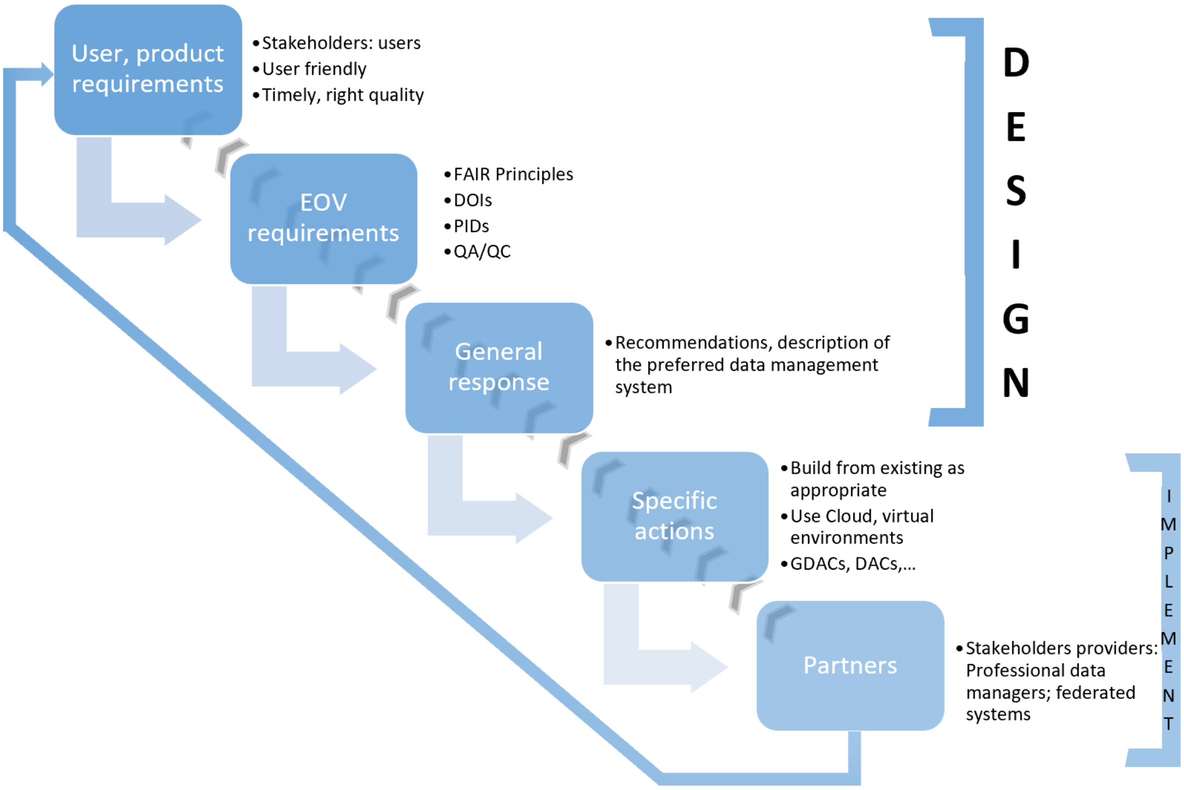

Figure 8.1: A schematic of the data management requirement setting process (adapted from TPOS OceanObs'19). See text for further explanation.

National and institutional data policy also remains an issue despite successive OceanObs conferences highlighting the value of a data sharing paradigm being adopted across all systems. In the tropical Pacific the lack of a cohesive data strategy is mainly an institutional/research issue, while for developing countries it has both technical capability and historical roots. Because of this, it will be important for TPOS 2020 to embrace a distributed data landscape. The advantage of a distributed approach is that data systems can be more agile and serve both niche and global communities with little or no additional effort. This is a particularly strong advantage if the distributed services are built upon commonly used standards and conventions.

For many aspects, TPOS 2020 has concluded it is more effective to provide advocacy and support for global actions and efforts rather than encourage further bespoke activities focused on platforms and the TPOS regional initiative (hence the contribution to the OceanObs'19 papers cited above). However, it may be very effective to embrace recommendations from such global efforts and initiate change initially through a bespoke development. In some cases, it may be opportune for TPOS 2020 to initiate action in the form of a Pilot, with the explicit support of global programs. Such examples are developed in the following sections.

8.3 Quick turn-around data requirements

From a whole of data lifecycle perspective, investing in automation of data workflows and effective and widely adopted standards will be crucial for the quick turn-around of data from the point of measurement to "consumption". As an example, and as discussed in Pinardi et al. (2019), the JCOMM pilot project “Open Access to GTS” showed it is possible to create a simplified workflow for data providers distributing their data to the real-time community (users, services, researchers and others who place a priority on timeliness). An important benefit was that the scientists and/or data providers were abstracted from the need to understand the formats required for distribution via the GTS and were only required to make their data available through the Environmental Research Division's Data Access Program (ERDDAP) distributed data service. This interoperable data platform allowed a National Data Center to simply harvest the data from the data providers before encoding and injecting the data onto the GTS for global distribution in near-real time.

In the context of TPOS, we note the potential to use such an approach as a virtual data management environment whereby distributed data providers can use a third-party managed and maintained environment to, first, get data and metadata into the system. Additionally, basic data management tools and facilities should be provided by the system to data providers, associated users, and other interested parties (Figure 8.2). With the appropriate back-end infrastructure the data would become findable, accessible and (to some extent) interoperable and reusable simply by the scientist/data provider properly documenting the data and making it available through an interoperable data platform. The *quid pro quo* in such an arrangement is that the scientist/data provider gets cost-effective (perhaps even free) access to a data management service (at the cost of some set-up work) while the community "common good" is served by including a broader set of inputs.

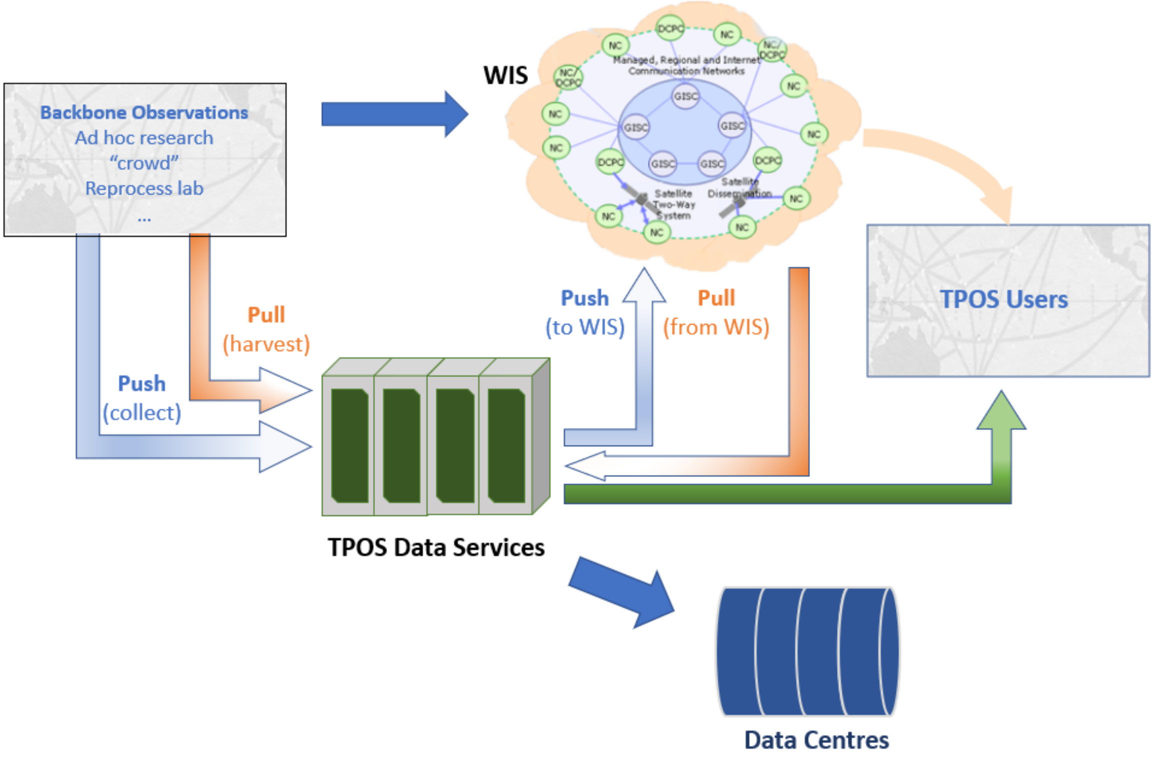

Figure 8.2: A schematic of a generalized data and information system that takes advantage of the new capabilities of WIS 2.0 but adds additional capability for harvesting additional data and for users to access data. Backbone observations would normally be submitted through WIS, but later re-processed or quality-controlled data may be pushed through TPOS Data Services. Re-processed and other research data that may not have entered the data system previously can be added through this route, as could community/crowd sourced data. TPOS Data Services may push some of these data into WIS or pull data from WIS for TPOS users and/or specialized data centers.

As discussed in Tanhua et al. (2019b), the Sensor Web Enablement initiative for marine profiles[29] and some data streaming services[30] have similar aims. The WMO Information Service also aspires along these lines, for example enabling broader community "crowd sourcing" of data. TPOS 2020 recognizes that we need to lower the barrier for scientists and others to contribute to the data system, both for data being collected now but not exchanged, but also for data that are essentially "lost" without such interventions. This can be done in a way that does not adversely affect goals around data stewardship or the very important goals around offline scientific quality control.

Section 5.2 provides an Eastern Pacific example of such a requirement. For historical and cultural reasons, many data are not exchanged in real-time or available in delayed mode. Recommendation 5.4 suggests a reanalysis project might provide enough motivation and incentivise regional engagement, and Actions 5.1 and 5.2 provide a stepwise pathway to improve regional capability and capacity in a way that delivers both greater regional and global value, in the manner depicted schematically in Figure 8.2.

Of the data streams touched by TPOS 2020 recommendations, BGC-Argo presents some of the most significant challenges. Chapter 4 discusses the requirements and recommends specific enhancements for the tropical Pacific (section 4.4.2 and Recommendation 4.1). The Biogeochemical Argo group provide guidance on data management (http://biogeochemical-argo.org/data-management.php) and best practice and TPOS 2020 will endeavour to follow and contribute to the implementation of those plans.

The ultimate aim for TPOS is to have a virtual one-stop set of web services for all TPOS data, suitable for research, production, services, public and privately funded activities or other ad hoc use. The basic idea is that such a system would become a system of choice, and for cloud and Virtual Research Environments (VREs) and their more general equivalents to become mainstream; see Vance et al. (2019) for a more detailed discussion.

Another reason for promoting such developments is that as new observing technologies are introduced, we need to find ways to facilitate the seamless integration of these new data streams into near-real time and delayed mode data management systems, a step that is critical for uptake of these new capabilities. One example of this was the use of the Open GTS Pilot to bring Saildrone data onto the GTS (also see Chapter 9).

Finally, we note that complexity does impact efficiency and, perhaps just as importantly, uptake on the provider side and utility on the user side. The complexity is necessary, as evidenced by the OceanObs'19 papers cited above, but it need not be a barrier to uptake and broader utilization. Data platforms, such as ERDDAP, can greatly reduce complexity for the user by providing uniform access to data streams and allowing users to leverage software clients of choice when working with data. For data providers, because ERDDAP can act as the middleman for a wide variety of different data formats, it also eases the requirements to make

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[29] https://odip.github.io/MarineProfilesForSWE/

[30] See, for example, https://aws.amazon.com/streaming-data/

data available through interoperable services. The advantage of this is that historic data collections often need not be completely reformatted, and current processes likely use formats supported by ERDDAP. These capabilities highlight intriguing possibilities for using ERDDAP to enable developing programs and/or nations to quickly and cheaply provide access to their data reservoirs.

The ocean community is gravitating toward principles and methods that enjoy use and recognition beyond our own needs. The FAIR principles are one such example. The challenges of such complexity, and the cost of maintaining and evolving such data systems is then shared among a broader community. This does not obviate the need for investment by the TPOS and broader ocean community, but it greatly reduces the risk of such investment being channeled into bespoke and other legacy methods/capabilities that are not designed or fit for the longer term.

8.4 Delayed and re-processed data streams

TPOS 2020 has identified two areas where specific (rather than general global) action may be useful.

As noted in TPOS OceanObs'19, the TPOS is welcoming new players and new technology to the system. In some cases, there is established data management infrastructure to call upon, in other cases little. For the TMA, the likely introduction of a new partner (the State Oceanic Administration) is universally welcomed but introduces some challenges to maintaining a seamless TMA data management system. Presently, the National Data Buoy Center, the Pacific Marine Environmental Lab and JAMSTEC collaborate to ensure data are available in real time but also quality controlled to ensure a strong TMA data record. However, in comparison to the Argo data management system, additional work is required on data flow and standards for delayed mode data, which currently is distributed among several players.

At a recent TPOS 2020 workshop, it was decided that a single data management plan, spanning all TMA contributions and data modes, would be developed. The starting point would be a description of a Core Tropical Moored Buoy Array configuration – that is, a common understanding of the instrumentation and sampling that contributes to the TMA (shown schematically in Figure 7.3). The next step will be a shared understanding and plan for quality assurance and quality control, for both the quick turnaround data (real-time) and higher-quality delayed-mode data. This plan will need to balance the desire for timely processing of data with the demand for recognized and certified (that is, published subject to peer review) data repositories. All the characteristics noted in the previous two sections will be in play.

To the extent possible, this data management plan will embrace distributed contributions and the possible evolution of technology and observing system design. For example, TPOS 2020 strongly supports the collection of data on the voyages that maintain the TMA (Recommendations 4.2 and 7.3), for calibration and quality assurance, and for contextual data for the fixed-point TMA; these data should be embraced in the data management plan. Similarly, the TPOS 2020 plan supports the introduction of new technology and the integration of the TMA data stream with complementary data from, for example, satellites and Argo. The data plan must embrace interoperability so that the strengths of complementary data can be brought to bear within a single integrated system.

The second area is around delayed-mode data, data archeology, re-processing and re-analysis. As noted in Snowden et al. (2019), the workflow for ocean data is open-ended. Re-processing for reanalysis is now mainstreamed, to take advantage of knowledge that was not available in real-time, and/or to exploit improved techniques. Such re-processing may occur multiple times; this does set challenges for following the identity and provenance of data, among other things, as noted in Tanhua et al. (2019b). The value-add of reprocessing can be compromised if the associated data processes do not provide clear detail on how the data were re-processed, or how it is improved (or different) from earlier versions, or if the re-processed data are not accompanied by adequate metadata/information to allow users to distinguish between differing versions.

One of the foci for TPOS 2020 is in the western Pacific. The TPOS 2020 Western Pacific Task Team has been endeavoring to document and follow the various experiments and oceanographic surveys that are being undertaken in the region. Many are led by researchers and there is often neither the incentive nor the will to ensure the data are properly documented and made findable and accessible for the broader ocean community. As discussed in section 8.2, this may be due to institutional and national data policies (e.g., proprietary periods, security), to lack of resources, or simply to the absence of access to enabling technologies that would enable such a step. Whatever the history or reasons for such short-comings, it is clear there is a large repository of western Pacific data that is for now "lost" to the wider scientific community, and likely to be "found" only through a major international collaborative effort aimed at retrieving and re-processing such data into a form that is FAIR.

Sydney Levitus is world-renowned for his championing of data archeology (the Global Oceanographic Data Archaeology and Rescue (GODAR) project; e.g., Levitus, 2012) and it is remarkable that after such efforts, the need for data rescue (and GODAR) remains acute. The Eastern Pacific section highlighted challenges in that region, some of which GODAR are addressing. Data are also being lost (i.e., not findable or accessible) in other regions of the tropical Pacific Ocean, for a variety of reasons, some of which were touched on above. Reanalysis and data reprocessing projects are one way of motivating and facilitating recovery. In the TPOS 2020 context, for the western Pacific, one goal is to enable data recovery, reprocessing and high-end reanalysis efforts using models and data-driven techniques, among other things, to improve our understanding of and ability to monitor low-latitude western boundary currents and to begin to close the mass and heat budgets that are so important for climate change and climate prediction.

8.5 Discussion, recommendations, actions

Tanhua et al. (2019b) and Snowden et al. (2019) reached similar conclusions with respect to investment in data management. They concluded that, with only a few exceptions, data management is poorly funded in the context of its critical role in the ocean observing system and, therefore, that ocean data are often not processed (or reprocessed) at a level that realizes the true potential and benefit, and in a form suitable for true interoperability and reusability. TPOS 2020 supports their conclusion.

This chapter focused on just a small set of issues that have emerged as the TPOS 2020 project has matured. For the most part, TPOS 2020 relies on global initiatives to advance and extend data management capacity and capability, particularly around data flow and access. TAO provided an early benchmark, and the Argo initiative and several satellite programs are setting the current benchmarks. The TPOS 2020 community will actively work with those initiatives to ensure requirements are being met.

We examined some aspects of the architecture of TPOS 2020 data management (section 8.2) and concluded that data management should be more fully embraced by the FOO (also see Tanhua et al., 2019a, b). We identified the need for better understanding of the architecture.

Based in the background provided by the OceanObs'19 papers and the discussion here, we wish to return to and reaffirm the guidance provided by the La Jolla TPOS 2020 workshop (Global Climate Observing System, 2014a):

Recommendation 8.1. As an underlying principle, around 10% of the investment in the TPOS should be directed towards data and information management, including for emerging and prototype technologies.

We see significant progress and success where investment has tracked near this level (e.g., Argo), but risks and challenges where data management investment lags behind or is not fully integrated (see below).

At this point we leave open the question of whether a data and information management plan should be part of the TPOS 2020 implementation plan, or whether we should work with, and advocate for the interests of TPOS within the global data management architecture. We do note that global coordination and facilitation mechanisms do not always maintain the regional stakeholder engagement and interest, nor maintain the strong partnerships with science that are so essential for maintaining high-quality data streams. This question should be addressed during the transition which will be covered by the Third Report.

The importance and fundamental role of the FAIR principles was discussed in sections 8.3 and 8.4 and covered in detail by Tanhua et al (2019b). We wish to reinforce the need for all stakeholders to engage with and support data management, and to do such in accordance with principles that maximise the value of data (e.g., the FAIR Principles).

Recommendation 8.2. Data stewardship and the engagement of all TPOS 2020 stakeholders in data management must be a central platform in the sustainability of the TPOS. The FAIR Principles should be adopted as a basis for TPOS engagement.

Noting (from the previously cited OceanObs'19 community white papers) that cross-platform services are being developed, particularly in Europe (e.g., Copernicus Marine Environmental Monitoring Service Thematic Assembly Centre; International Council for the Exploration of the Sea; European Marine Observation Data network) to meet the demands of a wider range of users, it is timely to ask how quickly cross-platform approaches should be championed in TPOS. Section 8.4 floated the idea that data quality control, assembly and management facilities established for Argo and the TMA might also be extended to new data streams that are targeted at similar user communities (e.g., Wave Glider and Saildrone data, or data from ancillary vessels). We recommend, as a first step, that a project be developed to deliver a fully integrated data system for TMA, engaging with new players, and ensuring consistent workflow from measurement, through real-time data exchange and delayed-mode quality control and reprocessing.

Recommendation 8.3. TPOS 2020 should develop a project around the management of all TMA data including, to the extent possible, recovery and re-processing of other relevant mooring data.

TPOS data should, to the extent possible, be shared, open for all to access, and stored in FAIR-aligned data repositories (Tanhua et al., 2019b). TPOS-aligned repositories should provide additional quality checks and develop data services and facilitate discovery and reuse of data and other research outputs. Ideally, TPOS-aligned repositories would share a common data management platform, such as ERDDAP, thereby providing uniformity in data and metadata access. Providing such uniformity of access will ease the process of integrating TPOS data and metadata with supporting EOV/ECV (Essential Climate Variable) products such as the IOC's Marine Climate Data System (MCDS). TPOS should also work closely with JCOMMOPS to ensure that complete platform metadata are available through the JCOMMOPS services. The JCOMM and WIS communities are endeavoring to establish global information and management systems that will provide a cost-effective way to increase and improve accessibility, interoperability, visibility, utility and reliability and TPOS 2020 and the TPOS community more generally should work with these efforts to maximize the benefits from TPOS data, for TPOS stakeholders and beyond.

Action 8.1. TPOS 2020 should develop data management projects in parallel with the development of a Low-Latitude Western Boundary Current Pilot Project (TPOS OceanObs'19; section 7.4.5.1) and Eastern Pacific regional activities (section 5.2, Action 5.1) to enhance the recognition and adoption of the FAIR principles and to re-process data that would otherwise be lost.

Recommendation 8.4. TPOS 2020 should develop a pilot project, in conjunction with the WMO Information System effort, to explore the global distribution of TPOS data in near-real time.

This pilot might also include establishing integrated automated workflows for applying level 1 quality control and making the data available through web services. Similar to the JCOMM Open Access to GTS project, these services would then be the basis from which the WIS 2.0 effort would distribute the data.

Chapter 9 Emerging Technologies: Assessing Potential for the Backbone

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This chapter discusses the current state of emerging technologies and provides an evaluation mechanism to guide integration of new observation platforms that may serve important roles in TPOS observational arrays of the future. The innovations can come in many forms, not just through new sensors. While in principle the term 'emerging technologies' embraces emerging modeling and data management techniques as well, such technological advances are not discussed in this chapter.

9.1 Introduction and background

Recent years have been a fruitful period for new ocean technology, both in situ and remote. At the start of the TPOS 2020 project, Rudnick et al. (2014) discussed and reviewed the capabilities, usefulness and readiness of new in situ technologies for the tropical Pacific observing system. The First Report (http://tpos2020.org/first-report/) reported emerging uses for several autonomous samplers, including the Saildrone, Wave Glider, and subsurface ocean gliders. Since the publication of the First Report, further testing and trials have provided new information about the potential uses of these and other instruments for meeting Backbone requirements, and new possibilities are emerging. With the rapid advancement of technology, and of the emerging requirements these might fulfill, the discussion here is necessarily incomplete and will evolve.

Here we provide an update for emerging platforms and sensor technologies (sections 9.2 and 9.3) and discuss a process that could be used to guide their transition into the existing and future observing system (9.4); as a potential framework for managing technological transitions more broadly.

Beyond the impressive technical progress, we emphasize that the emerging technologies discussed below will all require substantial development of new procedures and software to process and quality control the often highly irregular data, in order to disseminate a product that will be accessible and useful to the broader community. This is essential to raise the new instruments from experimental use (e.g., in a process study), to a mature element of the sustained TPOS. The effort required to accomplish this mandatory task should not be underestimated. Section 9.4 sets out a process for this transition through readiness level assessments and, specifically, suggests a framework in the context of Backbone readiness levels together with technical readiness levels (TRLs; see 9.4).

9.2 Emerging in situ technologies

9.2.1 NOAA Saildrone experiments

Saildrones have a hull 7 m long and vertical wing 4.6 m high, making them larger than other currently existing ASV. Saildrones use wind energy for propulsion and solar energy to power electronics. They are typically launched from convenient ports, traveling on their own to the observational region. Depending upon wind speed, their speed over ground (SOG) can be greater than 5 knots, although SOG of 1–3 knots are more typical.

More than 18 sensor packages covering a wide range of surface variables have been integrated into the platform through a Cooperative Research and Development Agreement with NOAA Pacific Marine Environmental Laboratory (PMEL); at present, Saildrone platforms can measure 22 EOVs and ECVs. Saildrone's tall wing allows the three-dimensional wind to be measured at 10 Hz at 5 m height, well above the surface roughness level, while its precise and accurate navigation sensors enable transforming each wind measurement into coordinates relative to the fixed Earth prior to averaging. Air temperature and humidity are measured at 2.4 m, as is solar radiation and an infrared sensor for measuring the skin temperature of the ocean. The solar radiation sensor measures both diffuse and total irradiance, so that the inferred direct component can be corrected for effective changes to the zenith angle associated with the platform motion. Other sensors measure longwave radiation, barometric pressure, SST, SSS, air- and sea- $p\mathrm{CO}_2$, dissolved oxygen, chlorophyll, and an ADCP for measuring current profiles to about 80 m depth. Together, these sensor suites allow computation of air-sea heat, momentum, and carbon fluxes. It is expected that the system can also measure wind stress and turbulent buoyancy flux as direct covariance fluxes, without the need of a bulk algorithm, although this still needs to be tested.

NOAA Ocean Observing and Monitoring Division has funded a TPOS 2020 pilot study to evaluate and learn how this new ASV could be used within the TPOS. The first mission was launched from California, USA on 1 September 2017 and returned to shore 7 months later, having traveled more than 13,000 kilometers. A 3-week intercomparison against the WHOI SPURS-2 flux mooring at 10°N, 125°W showed excellent agreement (Zhang et al., 2019). Notably, the Saildrone observed extremely abrupt fronts at each crossing of the cold tongue northern edge during winter 2017–2018, when the equatorial cold tongue was fully developed.

The low wind and high current conditions of the tropics are challenging for Saildrone. During the first mission, weak winds on the equator made it impossible to navigate eastward against the strong westward South Equatorial Current. Thus, for the second mission (launched from Hawaii, USA, 3 October 2018), the wing was enlarged. This, however, did not resolve the navigation control issue on the equator. Further engineering solutions (e.g., antifoulant) will be applied, depending upon the analysis of the mission 2 Saildrones when they return to port. These changes, both to the performance and sensor placement, will require further testing.

Overall, Saildrones appear to be a promising platform for monitoring air-sea interaction, fronts, and evolving surface features, including the upper ocean current response to wind forcing (Zhang et al., 2019; Voosen, 2018). Saildrones have demonstrated their ability to do repeat transects but transects through the low wind conditions of the equator remain a challenge.

Future possibilities include surveys along or across the equator, repeat sections across the cold tongue front, under the ITCZ, or along TMA lines to provide BGC data not included on Tier 1 moorings (section 7.3.1) and to add spatial context to the moorings' air-sea flux sampling. Adaptive sampling by controllable surface vehicles like Saildrone is also an important new capability with added value within TPOS 2020. Alternatively, Saildrones' main role may be in focused process experiments where their very fine spatial sampling could be valuable.

Readiness level summary[31]:Technical – 8-9
Backbone – 5

9.2.2 Wave Glider experiments

The Wave Glider is an autonomous surface vehicle produced by Liquid Robotics with capabilities for near-surface sampling. It propels itself by harnessing wave energy via a wing and rudder system at about 7 m depth, leveraging the weaker wave motion at that depth compared to the surface. In typical tropical conditions, the Wave Glider is capable of speeds of 0.5–1.5 m s^{-1}, and endurance of around 12 months (https://www.liquid-robotics.com/wave-glider/how-it-works/). Sensors deployed on the JAMSTEC Wave Glider are similar to those on the Saildrone (section 9.2.1) and are directed at long-term monitoring of surface fluxes in the west Pacific warm pool. The JAMSTEC Wave Glider also has a CTD for profiling.

JAMSTEC has conducted experiments near Okinawa and in the Indian Ocean and established an operating base at Palau Island (7.5°N, 134.5°E) in the heart of the warm pool. A month-long comparison against an m-TRITON mooring in the eastern Indian Ocean demonstrated good agreement between the two platforms. A 4-month mission showed that the Wave Glider could survive cyclone conditions.

The JAMSTEC Wave Gliders performed repeated transects between the TRITON sites at 8°N and 13°N, 137°E, adding spatial information and context to the buoy flux measurements. After several successful transects, a Wave Glider was lost due to internal component failure, which led JAMSTEC to suspend the program until the issue is resolved. However, most of the sensors were validated during the test programs.

Three Wave Gliders were also deployed together during the U.S. NASA SPURS-1 (subtropical Atlantic) and SPURS-2 (Pacific ITCZ) experiments, to make repeated surveys around and between the anchor moorings. Their ability to sample the very-near-surface (30 cm and 6.5 m depths) temperature and salinity with fine spatial resolution captured the shallow structure, including shallow "fresh puddles" after rain events.

The Wave Glider shows promise as a long-term sampling platform for surface and near-surface EOVs.

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[31] These assignments are preliminary. See section 9.4 for a full explanation.

Readiness level summary: Technical – 7-8
Backbone – 3

9.2.3 PRAWLER profiler

The PRAWLER (PRofiling crAWLER) is a moored device that uses wave energy to crawl a sensor package up and down the mooring line under a surface buoy (Osse et al., 2015). Near-real time command and control can be used to change the sampling modes from continuous sampling to station mode to "Park and Profile". The continuous sampling provides vertical profiles with high vertical resolution and sampled as frequently as the cycling permits. Although the crawler "truck" that carries the sensors can cycle over a 500 m range the number of profiles is dictated by local wave energy (that determines the time taken for the PRAWLER to complete one up and down cycle) and the battery capacity (determines the number of sampling profiles possible for the carried sensors in a given deployment period). For a 14-month deployment, about 8 profiles per day can be made; more frequent profiles would require a shorter deployment. The station mode keeps the PRAWLER at designated discrete depths for chosen time periods. This mode is useful for sensors with a slower response time that must equilibrate to sample accurately. The "Park and Profiling" mode enables the PRAWLER to park at depth out of the surface waters to minimize bio-fouling when not making measurements, to cycle repeatedly over a particular depth range, or to do hourly profiles for a limited time during an intensive observing period. The vertical resolution of the profile can be selected based on the response time of the sensor and the scientific needs and can also be changed from shore as required if 2-way communications are available.

The PRAWLER currently carries a pumped Seabird CTD with anti-foulant, an Aanderaa® Data Instruments Oxygen Optode, and a Wetlabs Flourometer for chlorophyll fluorescence. Experimental sensors are being developed for other variables; the surface buoy can also support meteorological measurements comparable to other TMA platforms. Between 2012 and 2018, NOAA-PMEL and partners deployed over 30 PRAWLER moorings in the Atlantic, Pacific, Gulf of Mexico, Bering and Chukchi Seas, experimenting with the technology and enabling a succession of improvements that increased the reliability, controllability, and capability of the platform. During the 14-month deployments at 9°N, 125°W and 11°N, 125°W as part of the SPURS-2 field program, the PRAWLER made 8 profiles per day measuring temperature, salinity and dissolved oxygen (DO) with 1–2 m vertical resolution in the upper 190 m, and 5–7 m between 190–460 m, taking 20–30 minutes per profile, with all data telemetered in near-real time via Iridium. PRAWLERs are now available commercially from McLane Labs. It is estimated that for temperature, salinity, dissolved oxygen and chlorophyll, the PRAWLER TRL level is 7–8.

The advantage of using a PRAWLER is that a high-resolution profile, co-located with surface sampling, is made from one package of sensors (and thus only one calibration), reducing costs, and potentially reducing bio-fouling. This advantage is also its inherent risk. If the crawler truck is damaged or the wire obstructed, perhaps by fishing vandalism, the entire profile is lost. For some purposes, the advantages will outweigh the risks; in particular, PRAWLERs are one of the best technologies for measuring mixed layer depth variability, incorporating the vertical resolution of an Argo profile with nearly the temporal resolution of a surface mooring's typical fixed-depth sensors.

Readiness level summary: Technical – 7-8
Backbone – 5

9.2.4 Ocean gliders

Ocean gliders move vertically by controlling buoyancy like Argo floats, but convert vertical motion to horizontal by gliding on fixed wings. The dive angle is controlled by moving the internal battery packs fore and aft, and steering is accomplished by rotating an off-center battery pack. Gliders typically dive to 1 km depth at shallow dive angles, giving forward motion about 25-30 cm/s (~1 km/hr) over surface-to-surface distances of a few km. Endurance is about 6 months, enabling mission lengths of several thousand km (Rudnick, 2016). Weighing about 50 kg and needing little ancillary equipment, gliders can be assembled and deployed in remote regions where infrastructure is limited, with all operations done near shore using local small boats, a key advantage that makes them cheap to operate.

Temperature and salinity sampling is comparable to Argo (but presently only to 1 km depth), usually with a Seabird pumped CTD. Their payload is 3-4 kg, so additional sensors can be added, including an ADCP for velocity profiles (Todd et al., 2017); fluorometers for plankton biomass are routinely carried (see section 3.2.5), and other biogeochemical samplers are possible. With a calibrated flight model that specifies horizontal motion as a function of orientation in the water and drag, absolute velocity during a dive can be usefully inferred by differencing the known start and end positions of each dive with that expected from the flight model (Davis et al., 2012). At each surfacing, science and engineering data are transmitted, giving near-real time capability, and new mission instructions can be sent. Several groups build and operate gliders, some of which are available commercially, and new glider models are under development at institutions around the world.

Gliders are suitable for several types of missions, the simplest being a controllable Argo-like profiler. They can also hold station in a small area as a “virtual mooring” or conduct repeat sections across a feature of interest. Their spatially dense (few km) sampling is appropriate for phenomena that the slow glider can sample quasi-synoptically, and whose scales require this high spatial resolution; boundary currents have therefore been a frequent target. However, boundary currents can have speeds as large as or larger than that of the glider itself, requiring careful strategy for navigation in these regions. Gliders require at least 100 m of water to operate and therefore can approach close to coasts, though narrow straits with fast currents are beyond present capabilities. In strong currents, gliders’ paths are irregular and often hard to repeat exactly, making it difficult to assemble their data into a product accessible to non-specialists.

In the tropical Pacific, gliders have successfully made repeat transects across both the LLWBCs; for 4 years across the Mindanao Current (Schonau and Rudnick, 2017) and for more than 10 years across the New Guinea Coastal Current system (Davis et al., 2012; Kessler et al., 2019). Their combination of temperature and salinity with absolute velocity and geostrophic shear at high spatial resolution has provided an excellent depiction of the structure and variability of these current systems, including the ability to estimate advection terms. Another set of missions sampled from 2°S to 2°N across the equatorial undercurrent just west of the Galapagos Islands, accomplishing 30 missions during 2013–2016. Although biofouling in the highly productive cold tongue affected the flight characteristics and degraded the inferred absolute velocity, an ADCP carried on these gliders enabled description of the equatorial undercurrent as it approached the blocking islands.

Recently, Peru has developed plans for a glider program off the Peruvian coast starting in 2020, which would provide important information on the subsurface (to 200 m) ocean structure and biogeochemistry of the near-shore region and help to evaluate the oceanic teleconnection between the equatorial wave guide and the coast (refer to Chapter 5 for relevant Backbone context).

The 47 Solomon Sea glider deployments over a decade are an example of what we can expect in real-world western boundary operations in remote regions (Davis et al., 2012; Kessler et al., 2019). Assessed by the gliders' ability to complete the coast-to-coast transects that are their mission, 40 of these (85%) were fully successful, while 7 partly or entirely failed.

The consistent occupation of these transects over multiple years has proven that gliders are mature enough to fill important roles in TPOS, especially where narrow currents near coasts carry major fractions of the mass and other property transports. For these objectives, gliders have a Backbone readiness level of 6 ("proven capability in an operational environment") to 7 ("fit for purpose"). Their ability to be deployed from remote regions with minimal facilities makes them attractive for the role of sampling the LLWBCs that is otherwise difficult to fill. However, operating in remote regions requires a dedicated team ready to deal with the many obstacles (weather, governmental and tribal relations, customs issues) such situations provide. Gliders have proven themselves in their near-shore niche; whether they have additional roles in open-ocean situations, e.g., long-term occupation of cross-equatorial transects, remains to be seen.

Readiness level summary: Technical – 9
Backbone – 6

9.2.5 Biogeochemistry, biology and ecosystems

Observing critical biogeochemical processes in the tropical Pacific (section 4.1) and other regions requires investment in new technologies. Of the biogeochemical EOVs (http://www.goosocean.org/), only a subset can be measured autonomously, and only a few technologies have been incorporated into sustained observing systems. These technologies/platforms are ocean surface color/chlorophyll (satellite and in situ), dissolved oxygen, dissolved nitrate and inorganic carbon (via $p\mathrm{CO}_2$ and pH). New technologies show promise for measuring additional parameters such as dissolved phosphate, silicate and iron, isotopes, and DOC, for example, but further development followed by feasibility pilots are needed. Over the last decade, significant reductions in size and power requirements of the sensors have allowed for deployment of biogeochemical sensors on smaller autonomous platforms such as floats, gliders, and ASVs.

Three emerging platforms with promise to improve sampling of biogeochemical EOVs include BGC-Argo, and, as discussed above, long-range ASVs such as Saildrone, and highly-resolved subsurface oxygen and chlorophyll profiles on the moored PRAWLER. Each platform is best suited to address different biogeochemical processes and TPOS requirements, so a mix of technologies will be needed to capture the high spatial and temporal variability of the tropical Pacific. For example, BGC-Argo is well suited to address variability in the biological pump (section 4.1.2) and combined with air-sea CO_2 flux measurements, can better constrain the upper ocean carbon budget (section 4.1.4). Whereas the PRAWLER technology may be best suited for higher-frequency observing of the changing shape and intensity of the OMZ in the eastern Pacific, where monitoring of habitat for marine resource forecasting and management is needed (section 4.1.1).

The outlook for automated observations of most marine biology and ecosystems parameters is less clear. Phytoplankton biomass can be measured by fluorometers or radiometers on moorings, Argo floats, gliders and ASVs. Effort continues to be directed to determining phytoplankton functional types from space[32] and this work will meet with greater success when hyperspectral satellites become a reality. Zooplankton and fish abundance can be inferred from acoustic data. This has mostly been done from moored acoustic Doppler current profiles (ADCPs) but it is feasible that these acoustic instruments could be deployed on ASVs or even Argo floats with supplementary batteries. Acoustic instruments can also detect fish but perhaps the best way forward at higher trophic levels is to use TPOS infrastructure to deploy passive acoustic sensors to detect already-tagged fish. Microbial biomass and diversity can be assessed using molecular techniques, and these could potentially be applied to preserved samples taken from autonomous platforms, but this approach requires further development.

While autonomous biogeochemistry, biology, and ecosystem technologies have come a long way, the current and near-term outlook of the emerging technologies is such that most biogeochemical technologies are in the pilot stage, and biology and ecosystem technologies are mostly at the concept or early pilot stages and not yet beyond Backbone readiness level of 4.

Readiness level summary: Technical – 6-9
Backbone – 2-5

9.2.6 Water isotope observations - applications and technology

Water isotope measurements of the near-surface atmosphere (vapor or precipitation) or ocean can be made either in situ or remotely, and contribute to several aspects of understanding tropical Pacific climate:

i) ***heat and moisture fluxes***—water isotopes provide another degree of freedom for the quantification of evaporation and condensation fluxes from complementary ocean-atmosphere observations, and provide for direct comparison to output from water isotope-equipped climate models (see Galewsky et al., 2016, and references therein)
ii) ***ocean and atmosphere mixing***—water vapor parcels and ocean water masses carry unique signatures in water isotope space, especially when combined with relative humidity (atmosphere; e.g., Worden et al., 2007) and salinity (ocean; e.g. Conroy et al., 2014), by analogy to T-S plots used in physical oceanography

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[32] See http://ioccg.org/wp-content/uploads/2018/09/ioccg_report_15_2014.pdf

iii) ***detection of changes in tropical Pacific climate***—water isotopes are a sensitive indicator of changes in the water budget, and when combined with complementary observations from the atmosphere and ocean, can aid in the detection of trends in physical processes of relevance to the broader climate community.
iv) ***extending the record of tropical Pacific climate***—water isotopes form the basis for most paleoclimate reconstructions of tropical Pacific climate. Most notably, hundreds of coral oxygen isotopic records extend back decades to centuries at monthly to seasonal resolution, and require modern-day observations of water isotopes for robust dynamically-relevant interpretations of their climate signals. A lack of ongoing water isotope measurements across the tropical Pacific leaves this potential virtually untapped.

The measurements are typically of isotope ratios in water vapor, or rainfall, or seawater ($^{18}O/^{16}O$ and $^{2}H/H$ of H_2O, referred to as d^{18}O and dD, respectively). Major networks of regional- to global-scale water isotope observations exist, reflecting 60 years of dedicated monitoring in some locations, and satellite platforms that provided global coverage, if currently only for several years (see review by Bowen et al., 2019, for a list of relevant data archives).

Observations of atmospheric water isotope variations were retrieved on 7 satellites in recent decades, yielding a rich trove of data used to probe the workings of the global water cycle (e.g., Worden et al., 2007). A full list of available satellite water isotope data sets is available at https://climatedataguide.ucar.edu/climate-data/water-isotopes-satellites. Ground-based measurements are a key complement to satellite isotope retrievals, because i) satellites only measure column-integrated water vapor, such that the rainwater and seawater reservoirs must be inferred indirectly, and ii) there is an ongoing need to ground-truth satellite-based water isotope observations with ground-based measurements.

As of this year, many of the major climate modeling centers (e.g. NCAR, NASA-GISS, Hadley, LMD) have incorporated water isotope tracers into their coupled modeling frameworks, in recognition of the potential for data-model comparisons of water isotope variations for continued improvement of key parameterizations (i.e. atmospheric convection, ocean mixing, boundary layer dynamics) in coupled climate models. Water isotopes provide another degree of freedom (in addition to, e.g., temperature, precipitation, and salinity) that can be used to constrain fluxes of heat and moisture through the earth system. As such, water isotope observations are an increasingly important diagnostic tool for assessing accuracy of i) ocean and atmospheric circulation patterns (Stevenson et al., 2015; Nusbaumer et al., 2017), ii) atmospheric convective and cloud physics (Field et al., 2014), iii) land surface hydrology (Risi et al., 2016; Wong et al., 2017), and iv) the global water budget in coupled climate models (see review by Galewsky et al., 2016).

Early analyses of water isotope ratios via mass spectrometry were costly and time-consuming, but the development of commercially available Cavity Ringdown Spectroscopy (CRDS) in the early 2000s has driven an exponential increase in the diversity and number of water isotope observations. The analyzer is of modest size and cost ($70K), and relies on measurement in the vapor phase, and thus is particularly well-suited to continuous measurement of water vapor isotopes. However, a variety of commercially available, integrated sample introduction systems allow for the analysis of liquid water such as rainfall and seawater either in discrete samples (<1 mL of volume required) or via continuous sample introduction (e.g., via a ship's seawater intake line, as demonstrated by Bass et al., 2014, and subsequent studies). The specific design of a water isotope observing system would depend on the scientific questions of interest, and the availability of well-tested platforms such as ships, island-based sites, and/or aircraft.

Long-term field deployments from the poles to the tropics (Wei et al., 2019) demonstrate the readiness of the CRDS technology for remote, continuous collection of water vapor isotopes. For such deployments, periodic calibrations (every 3–6 months) are required to correct for instrument drift, following well-established protocols that can be partly automated (Gupta et al., 2009).

The same instrumentation can be used for analysis of rainfall isotope samples collected at island sites or on ships, via either autonomous collection or with the help of an onsite technician. Sampling resolutions vary depending on the application, but the collection and analysis of daily cumulative rainfall samples and weekly seawater samples are most typical, and likely most relevant to the TPOS. Small sampling volumes and lack of preservation requirements make rainwater and seawater isotope sampling straightforward.

The addition of water isotopes to the TPOS would leverage long time series of water isotopes collected around the world. Water vapor and rainfall isotopes would directly complement observations of meteorological conditions, while seawater isotopes would complement salinity, temperature, and ocean current observations. Dedicated shipboard analyses of water vapor, rainfall, and seawater isotopes would be the most cost-effective and logistically feasible, and would likely involve calibrations during home ports of call. This would not provide continuous data streams, but when supplemented with remotely-sensed observations of water isotopes, and where possible, island-based stations [some of which already exist, e.g., at Christmas Island (2°N, 157°W)], would deliver data sufficient for most if not all potential applications. For island-based operations, samples could either be collected and analyzed on-site, or could be collected by local partners and analyzed off-site (as successfully implemented by many researchers). Buoy deployments (i.e., 'Tier 3 buoys', see sections 7.3.1.1, 7.4.7) are likely to represent a technical challenge but might offer unique advantages for sustained open-ocean deployments.

Readiness level summary:	Technical – 8
	Backbone – 4-6

9.3 Remote sensing/emerging satellite capabilities

Satellite technologies that provide information about the Earth's atmosphere and oceans continue to evolve, as do the algorithms used to interpret their signals and the methods by which these observations are assimilated into operational models. While in situ observations such as Argo and the TMA offer high temporal resolution and subsurface information unattainable by satellites, space-borne platforms offer unmatched coverage and horizontal resolution, of particular importance over the ocean, where in situ measurement platforms are inevitably sparse. TPOS 2020 emphasizes the important role of satellites in assembling a complete and effective observing system for the tropical Pacific (First Report). Here, we call additional attention to still emerging or developing satellite technologies that are already or could be capable of measuring essential ocean/climate variables for the ocean and atmosphere, including the thermodynamic and dynamic state and certain greenhouse gases (GHGs), with a precision and accuracy that meet the standards of a climate baseline and high-quality research data set. The newest satellite technologies additionally are working to look deep into the troposphere, offering a means of observing the atmospheric boundary layer over the ocean, which is critical for improving our understanding, forecasting and physical modeling of coupled processes such as ENSO and the MJO (see Chapters 2 and 3).

9.3.1 Ocean surface currents

Direct remote sensing of ocean surface velocity from satellites is technically feasible using Doppler radar techniques, and there are three satellite mission concepts being developed for ocean velocity measurements (Villas Boas et al., 2019, presents an overview). None of these concept missions are presently being implemented, but, given the technical readiness of the technique (Chapron et al., 2005; Rodriguez et al., 2018) and the importance of ocean currents in the climate system (Villas Boas et al., 2019) and for ocean prediction, it seems likely that at least one of the concept missions will be implemented in the next decade. The Sea surface KInematics Multiscale monitoring satellite mission (SKIM; Ardhuin et al., 2018) is in a final detailed design phase and is competing with one other prospective mission to be selected for implementation beginning in September 2019 with a potential launch in 2025. A potential US satellite mission, tentatively called the Winds and Currents Mission (WaCM; Rodriguez et al., 2019) would address high priority measurement needs highlighted by the U.S. National Academy of Sciences *2017–2027 Decadal Survey for Earth Science and Applications from Space* and requirements identified in the First Report (Recommendation 11) and this Second Report (Chapters 6 and 7) The SEASTAR mission concept (Gommenginger, 2019) was one of 21 missions proposed to the 2018 ESA Earth Explorer 10 call for mission ideas; it was not selected for implementation but the concept remains viable.

All three of these candidate missions for measuring ocean surface currents directly rely on Doppler radar techniques. SKIM and WaCM are Doppler scatterometers that are physically similar to existing scatterometers, but in addition to measuring the intensity of backscattered radar pulses like conventional scatterometers, they would also measure the phase (or frequency shift) of backscattered radar pulses to allow estimation of the surface current speed and direction (e.g., Rodriguez et al., 2018). The WaCM Doppler scatterometer could achieve an 1800 km swath and speed accuracies between 25 cm/s and 50 cm/s sampled at 5 km resolution (Rodriguez et al., 2019) – if averaged to 25-km resolution, these accuracies will be 1–2 cm/s, comparable to modern in situ current meters.

These surface current Doppler scatterometers would provide a wealth of new information on the dynamics and evolution of the equatorial Pacific. The measurements should allow new insights into equatorial currents, equatorial upwelling (horizontal divergence), and the surface part of the tropical shallow meridional overturning circulations. At the same time, the new surface current satellites will require measurements of near-surface currents to help with calibration, validation, and interpretation of the measurements.

Readiness level summary: Technical – 7
Backbone – 2

9.3.2 Profiling the atmospheric boundary layer remotely

Vertical profiles of temperature, pressure, moisture and winds are fundamental to studies of atmospheric processes, model development and improvement, constraining gridded reanalysis products, and initialization of operational forecasts. In the tropics water vapor plays an important role in the development of convection, actively determines the radiative and latent heating of the atmosphere and top of the atmosphere radiative balance, and drives global circulation (e.g., Sherwood et al., 2010; Mapes et al., 2017). Boundary layer moisture is of particular importance, being the source of moisture to convection, as well as contributing to the static stability of the atmospheric column through its effect on density. Clear-sky radiative effects of moisture are also concentrated in the boundary layer where most of the water vapor resides in the atmosphere. As mentioned in section 6.3.2.1, profiles of boundary layer moisture and temperature have the potential of significantly improving satellite-derived radiative fluxes as well.

Over the past few decades, remote sensing technologies have evolved to permit observation of moisture at different levels in the troposphere, greatly advancing our understanding of tropical convection and its coupling to dynamics (Mapes et al., 2006; Kuang, 2010; Sherwood et al., 2010). Of the radiance-based sounders, the hyperspectral infrared sounders offer the highest vertical (1–3 km) and horizontal resolution (15 km) (Milstein and Blackwell, 2016; Menzel et al., 2018. However, the infrared measurements are sensitive to clouds which strongly attenuates the signals.

Microwave sounders help address the issue of cloud effects on infrared sounder signals (e.g., Susskind et al., 2014; Milstein and Blackwell, 2016), as well as provide a measure of the column water vapor and liquid water.

While sounders have contributed to advancements in many areas of tropical research and operational needs, greater accuracy and resolution in moisture and temperature is needed, particularly in the lower troposphere, to further advance understanding of the hydrological cycle in the tropics and its feedbacks on the atmospheric circulation and climate sensitivity (Sherwood et al., 2010; Wulfmeyer et al., 2015; Pincus et al., 2017; Stevens et al., 2017). The following two subsections highlight a selection of emerging technologies at varying readiness levels, with a look ahead at possible capability by 2030 for observing the atmosphere over the TPOS region.

9.3.2.1 *Global Navigation Satellite System radio occultations*

GNSS radio occultation (GRO) observations provide information on atmospheric refractivity, in all-weather conditions, at very high (~200 m) vertical resolution but relatively coarse horizontal resolution (~200 km) (for further background information see Kursinski et al., 1997; Anthes et al., 2008). The newer GPS satellites offer improved technology not yet flown on a satellite, which will see deeper into the troposphere due to better signal to noise ratios, and thus potentially address TPOS requirements (launch scheduled for mid- to late 2019). At low latitudes and below 10 km, use of temperature information from NWP analyses enables profiling of humidity from the GRO measurements (Kursinski and Hajj, 2001; Kursinski and Gebhardt, 2014).

Strong inversions at the top of humid atmospheric boundary layers cause sharp vertical gradients in refractivity that affect GRO temperature and humidity retrievals at and below the boundary layer top (Xie et al., 2012). While this situation causes current GRO retrievals within these inversion-capped boundary layers to be unreliable, the strong effect of inversions on refractivity results in reliable estimates of boundary layer heights from GRO measurements (Xie et al., 2012). The very high vertical gradients that lead to non-unique profiling within the boundary layer (Xie et al., 2006) can be solved via a combination of very high signal to noise ratio GRO measurements that the newest GRO satellite mission will deliver (Sokolovskiy et al., 2014) and profiling the boundary layer via the method described in Xie et al. (2006). The higher quality GRO technology raises hopes for improved observations of the marine atmospheric boundary layer across the Tropical Pacific. Radiosonde observations like those from small islands in the East Pacific recommended in Chapter 5 (sections 5.3.3 and 5.4) could be used to validate boundary layer profiles derived from GRO using this technique.

The IROWG (International Radio Occultation Working Group) recommends a minimum of 20,000 occultations per day for NWP and research; at present about 2000 per day are collected. Harnisch et al. (2013) suggest that the current density of GRO observations is far below what is needed to significantly improve model wind, relative humidity, temperature, and geopotential height fields in the Tropics. The COSMIC[33]-2A / FormoSat-7 mission, a constellation of six low Earth orbit (LEO) satellites presently scheduled to launch in mid- to late 2019, will include the high-quality GRO technology and provide nearly 6000 occultation profiles within +35° of the equator each day. Higher quality GRO technology is also scheduled to be launched on CubeSats through private-public partnerships with NOAA beginning in spring-summer 2019. The newer COSMIC-2 observations are likely to have increased impacts on improving forecast errors, particularly with respect to their ability to better resolve super-refraction in the lower troposphere. In addition, COSMIC-2 will focus observations in low latitudes, increasing the sampling density of occultations in the tropical Pacific by approximately a factor of four.

GRO offers moisture profiles in the lower free troposphere to 0.4 g/kg (Kursinski and Gebhardt, 2014), with 200 m vertical resolution in all-weather conditions, exceeding the capability of all other mature space-based technology for observing water vapor (Nehrir et al., 2017). The high precision and unbiased nature of these observations additionally provides tight constraints on models, resulting in improved operational and reanalysis gridded fields and exposing model errors, making it an important emerging technology for TPOS 2020.

Readiness level summary:	Technical – 8-9
	Backbone – 5-6

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[33] Constellation Observing System for Meteorology, Ionosphere, and Climate

9.3.2.2 Microwave and infrared-laser occultations

New technologies that make use of the refraction and absorption of microwaves between LEO satellites (LEO-LEO microwave occultation, LMO) offer the opportunity to unambiguously separate temperature, pressure and moisture signals in both clear-sky and cloudy conditions without the need for additional independent temperature information (Kursinski et al., 2002; 2009; Schweitzer et al., 2011). LMO is a differential absorption system which enables it to see both through clouds as well as sense the clouds. Because this technique makes use of absorption as well as refraction of the emitted signal, it can also be used to profile ozone and line-of-sight winds in the upper stratosphere and lower mesosphere (Kursinski et al., 2016; C. Liu et al., 2017). Additional information is also provided on liquid water and ice cloud variables, as well as atmospheric turbulence (Kursinski et al., 2016; C. Liu et al., 2017).

Error estimation of LMO systems indicate thermodynamic variables (temperature, pressure and humidity) are more accurately retrieved than with GRO technology (Kursinski et al., 2002; Kirchengast and Schweitzer, 2011; Schweitzer et al., 2011; C. Liu et al., 2017). Estimated errors are on the order of <0.2% for pressure, <0.5 K for temperature, and <10% for humidity from 5 to 35 km with minimal biases in all three parameters. By sampling a wider range of frequencies than considered in Schweitzer et al. (2011), the Active Temperature, Ozone and Moisture Microwave Spectrometer (ATOMMS) concept (Kursinski et al., 2009, 2012) promises improved error estimates over a wider altitude range, particularly for humidity.

LMO can be combined with LEO-LEO infrared-laser (LIO) technology to provide not only thermodynamic profiles into the upper troposphere, but also greenhouse gases (GHGs) and line-of-sight winds, with profiles of cloud layers and aerosols as by-products (Proschek et al., 2014;C. Liu et al., 2017). The combined LMO and LIO technology (LMIO) would complement GRO observations, which together offer thermodynamic, dynamic and GHG profiles for atmospheric and climate monitoring and research (C. Liu et al., 2017). Nehrir et al. (2017) identifies LMO, LIO and LMIO as emerging satellite-based technologies for observing water vapor in the free troposphere (above the boundary layer).

The United States has built a prototype of an LMO instrument (ATOMMS: Kursinski et al., 2009, 2012) and used it on mountaintops to demonstrate retrieval of water vapor to better than 0.5%, in conditions ranging from clear to heavy convective rain (Ward et al., 2018). An additional system has been built by the National Space Science Center, Chinese Academy of Sciences and was tested in May 2016 between two mountain peaks, similar to the test of the ATOMMS instrument.

A key issue affecting the testing of this technology has been cost. As with GRO technology, the latest Microsat/Nanosat class satellites promise to be a solution to the cost issue if the LMO system can be miniaturized for these platforms (Kursinski et al., 2016; C. Liu et al., 2017; Nehrir et al., 2017). Based on the ATOMMS prototype and miniaturized design incorporating CubeSat technology, Kursinski et al. (2016) estimated the cost at approximately US$5M per satellite.

Ground-based tests of LEO to LEO infrared-laser occultation (LIO) have been carried out for greenhouse gases only because of the use of fixed points on the earth for testing the technology, which prevented profiling the atmosphere. The LMIO technique has not yet been field tested. Satellite missions have been proposed that would permit testing these techniques, but none have been selected for funding at this point. As with the LMO technique, costs are a significant factor in their implementation.

Readiness level summary: Technical – 6-7
Backbone – 2

9.3.2.3 Global Navigation Satellite System scatterometry

Another emerging technology is the use of GNSS signal scattering off the ocean surface for obtaining wind speed under all-weather conditions, an improvement over current satellite techniques whose signals attenuate under rainy conditions (section 3.1.1.2 of the First Report). At the end of 2015, NASA launched eight LEO micro-satellites into orbit as part of the Cyclone Global Navigation Satellite System (CYGNSS) mission (Ruf et al., 2016). While this technique has been directed at obtaining surface wind speeds below tropical cyclones (e.g., Cui et al., 2019), it also has important implications for obtaining ocean surface winds under the Pacific ITCZs/SPCZ, making it of interest to TPOS 2020.

Readiness level summary: Technical – 8-9
Backbone – 5-6

9.3.2.4 Summary

The use of radio occultations (GRO) for observing the atmosphere at high vertical resolution has provided highly accurate and precise measurements of atmospheric temperature and pressure in the upper troposphere and lowermost stratosphere and new higher quality technology to be flown in the coming years promise to see deeper into the troposphere. Microwave and infrared-laser occultation (LMO, LIO, LMIO) technologies have improved accuracy and vertical resolution over GRO but also are unable to resolve moisture and temperature below the free troposphere (Nehrir et al., 2017). The potential positive impacts of GRO, LMO, LIO, and LMIO for operational and research applications motivates continued development of these technologies. Nanosat class satellites may offer a cost-effective means of reaching these goals in the near future, with CYGNSS already making use of such technology for surface wind speed estimates.

While not discussed here, spaceborne DIAL (differential absorption lidar) has great potential for profiling lower troposphere temperature and moisture. NASA is currently developing the High Altitude Laser Observatory (HALO) DIAL system, which is smaller and uses less power than other existing DIAL systems. Further reduction in the size and power requirements of the instrument for deployment on satellites, while maintaining specifications needed for studies of lower tropospheric water vapor, clouds and climate has not yet been possible (Nehrir et al., 2017). If this technological hurdle can be overcome, DIAL would be an exciting new satellite instrument for observing the tropical lower troposphere.

9.4 Evaluation of readiness for the Backbone

9.4.1 A readiness framework for the Backbone

The TPOS Backbone consists of fundamental, core sustained contributions to the observing system. This definition of the Backbone sets the bar for evaluation of emerging technologies (Backbone readiness levels).

(E1) Requirement: Does the emerging technology produce measurements of EOVs that are relevant to user requirements? That is, are they addressing a fundamental need (such as discussed in the preceding sections)?

(E2) Sustainability: Is there a reasonable expectation the technology could be sustained in the field, taking account of investment needs, reliability and robustness?

(E3) Core: Does the data management infrastructure exist to satisfy quality and timeliness objectives and thus enable the technology to be considered suitable as a core contribution?

The FOO (Lindstrom et al., 2012) also used three overarching criteria, somewhat like the above, and described a set of readiness levels (concept, pilot and mature) through which technologies would transition (FOO Readiness Levels, FRLs). Such approaches were not new but did provide an improved GOOS framework for transitioning technology. They further divided each of these readiness levels into sublevels, creating nine sublevels in total going from the initial technical innovation ("idea") through to mature deployment in a sustained observing system. The nine sublevels draw some parallels with the widely-used engineering technical readiness levels (TRLs, e.g., Mankins, 1995; Eisman and Gonzales, 1997; Smith, 2004) but the two should not be confused; a technology will normally be at TRL 8 (system development completed) or 9 (has been used successfully in field operations) before entering the FRL framework at sublevel 1 (FOO ‘Level 1, “Idea”).

There are many different pathways to use and uptake by the Backbone that may be taken for promising techniques, instruments or sensors (e.g., parallel trials of a new sensor on mature platform; new signal processing methods; etc.) so whatever framework is used, it should simply be a guide and not seen as a top-down directive. The "gateways" between levels for emerging technology are soft rather than hard, to encourage participation and innovation, and consistent with TPOS being defined by requirements and standards, not a set of definitions and formal approval procedures (also see section 9.5).

When inviting contributions to this chapter, TPOS 2020 took a quite broad view on relevance and potential impact; that is authors made their own judgments as to the potential of the technology for TPOS 2020 and beyond. Here we wish to narrow that window using the Backbone evaluation categories above. For convenience, we use a scale of 1 to 9, but without any attempt to follow the detail accompanying the FRLs in Lindstrom et al. (2012). Rather, we qualitatively evaluate each approach against the following criteria:

(C1) **Effectiveness**: How effective is the technology for each Backbone category?

- Does it have advantages over existing approaches (its strengths), or important weaknesses?
- Fit for purpose?

(C2) **Efficiency**: Is the technology efficient compared with existing approaches?
  - Reduced cost per EOV measurement;
  - Greater potential within a sustained environment, e.g. reduced maintenance?
  - A more cost-effective route for quality and delivery?

(C3) **Extension:** Does the candidate technology address a gap in the response to the TPOS 2020 design?
  - Is this technique yielding a new EOV data stream?
  - Does it have the potential for sustainability and durability that hitherto was not achievable?
  - Does it introduce real-time capabilities that have hitherto been missing?

Similar criteria are used by the Integrated Marine Observing System[34]. Table 9.1 is an example of such a qualitative Backbone readiness level evaluation for gliders, based on the TPOS 2020 experience (see section 9.2.4 for background). In terms of effectiveness, glider sampling is relevant to EOV requirements filling a niche (e.g., for LLWBCs); it is potentially sustainable, but with challenges; the needed infrastructure is available, but still being developed. In terms of efficiency, it is at a medium level across all the Backbone primary criteria. Finally, gliders can potentially extend the observing system in terms of the needs it can meet, and offers distinct advantages in terms of sustainability. Glider networks remain in "pilot" mode (Backbone readiness level in the 4–6 range) but with significant potential.

Table 9.1. Example Backbone readiness evaluation: Gliders. L, M and H denote low (concept), medium (Pilot) and high (Mature) evaluations against Backbone values and the criteria of Effectiveness, Efficiency and Extension. The Backbone readiness is estimated based on these evaluations.

Criteria	**Backbone Fit**		
	Requirements	*Sustainability*	*Core data*
Effectiveness	M	L-M	M
Efficiency	M	M	M
Extension	H	M-H	M
Backbone Readiness	7	5	6

9.4.2 Assessment and transition

TPOS 2020 wishes to test this approach with the community before undertaking a more comprehensive assessment. Table 9.2 summarizes the preliminary assessments provided in sections 9.2 and 9.3.

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[34] http://imos.org.au/facilities/newtechnologyproving/

Table 9.2. Summary of TRL and preliminary Backbone readiness level assessments.

	TRL	Backbone readiness level
NOAA Saildrone experiments	8-9	5
Wave Glider experiments	7-8	4
Prawler profiler	7-8	5
Gliders	9	6
Biology/BGC	6-9	2-5
Water isotopes	8	4-6
Satellite currents	7	2
GNSS radio occultation	8-9	5-6
Microwave, laser occultations	7	2
GNSS scatterometry	8-9	5-6

Table 9.2 does not include some of the "pilot" enhancements discussed under the tiered approach of section 7.3.3.1, but it should. For example, the ADCP enhancements proposed for 140°W have been through a pilot phase but are now proposed to be picked up as Tier 2 enhancements. Other trials are proposed for the TMA, including BGC sensors, while most of the Tier 3 (Super Site) approaches lie in the lower ranges of the readiness levels introduced above.

9.5 Discussion and Recommendations

There is no intent in this chapter to pick winners among the emerging technology options; rather, the intent is to provide an assessment of whether the technology is ready to contribute to the sustained data stream (the Backbone). We recognize and acknowledge that further work is needed to either refine the present approach (section 9.4) so that it meets stakeholder needs, or perhaps to revert to the FOO approach and provide examples of how it might be applied in practice.

No matter how much potential these or other emerging technologies show, ultimately it is the uptake and use which will determine the impact as part of the Backbone. The evaluation presented here does try to take account of whether the technology is meeting a niche need or gap, but in the end, the assessment such as shown in Table 9.2 is simply guidance, not a prescription. We have not discussed user uptake in detail, whether that is for a service or for research, but note that readiness of the technology is just one part. There may be issues in assimilation (e.g., the availability of a forward model for taking measurements into the field of the model) or additional processing may be needed to make it useable. In other cases, the data may not be impactful directly, but may rely on other data to be more impactful (e.g., in situ and remotely sensed surface salinity). In theory, applications should not be concerned which technology the EOV measurement comes from so long as it provides a reliable estimate of the required field. In yet other cases, some models may simply be ill-equipped or not ready to use the data. For satellites, the agencies often invest heavily in model and assimilation development to ensure data are used, but for niche in situ streams such investment is mostly absent.

We also caution about using such assessments for intercomparing technologies. The potential value of a particular approach will have multiple dependencies, of which readiness of the technology will be just one. The implementer will take care and try to discriminate between platforms that deliver bang-for-buck, and those that do not, but this too will vary with use and platforms will usually have distinct advantages along with some disadvantages (the design in Chapter 7 discusses many such tradeoffs). In each of the examples presented here, we have identified a niche that might be addressed, but in most cases further testing and proving is needed.

Fujii et al. (2019) discuss at length some of the ways the relative impact of different platforms have been evaluated in the past (variations around OSEs, OSSEs), but even then, the outcome is simply guidance because of the sensitivity of the results to the model/assimilation system that is being used. Previous chapters of this Report have also discussed some aspects of this issue, including in some cases the potential of new technologies. Such approaches will be limited when the impact of the technology data is indirect (for example, flux variable data for validating models).

Recommendation 9.1. That the Backbone Readiness Level framework be further developed and refined by TPOS 2020 before adoption.

Action 9.1. TPOS 2020 to assess all candidate technologies, platforms and methods against the Backbone criteria for efficiency, effectiveness and extension.

Chapter 10 Concluding Remarks and Next Steps

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10.1 From the First Report to the Second

This Second Report of TPOS 2020 describes an ambitious evolution of the tropical Pacific observing system that would deliver better value for the multiple users of its data and data products. Building on our First Report, the proposed design is refined based on two years of extensive study, consultation, and consideration of many comments on the earlier version. Scientific colleagues around the world contributed ideas and analyses, operational prediction centers studied the implications of these proposals in their systems, and ongoing discussions with stakeholders and our sponsoring agencies identified weaknesses, opportunities and particular requirements. We emphasize that the new report evolves from and does not replace the First Report, which remains our foundation; topics that were adequately covered in the First are not repeated here, so the absence of a topic in this Report does not indicate lack of importance.

As with the First Report, the design recommendations proceed from specification of requirements that are derived from identified uses of the data. Defining these specifications is the major focus of both the First Report and this one. Several significant matters were raised but not sufficiently fleshed out on the First Report, and benefit from focused discussion here. These are the subjects of Chapters 2-5, 8, and subsections of Chapter 6.

In particular, this report gives more careful consideration to the models that are the conduit between the direct observations and many users, and also provide forecasts on timescales from weather to interannual that contribute to the societal value of the observing system. Integration in an assimilating model is essential to take advantage of the complementarity of in situ and remote sampling, with their multiple time and space scales. Thus, although the project's charge focuses on observations, we cannot ignore the essential role of models in developing products of broad applicability. Chapter 2 examines these questions, noting that persistent model biases degrade the benefit of the observations in the data products, requiring attention to model improvement to reach full value from the observing system. Several process studies, suggested in the First Report, gain additional justification and focus from this need. Chapter 3 considers the emerging topic of coupled weather and subseasonal prediction, examining potential additional requirements and model needs.

The First Report briefly discussed the need for biogeochemical observations, focusing primarily on ocean color and on the longterm measurements of $p\mathrm{CO}_2$ that had been developed on some TMA buoys and their service cruises. Here, Chapter 4 expands that limited view, broadening the recommended sampling to add more biogeochemical and ecosystem variables, including dissolved oxygen and nutrients, inorganic carbon and particulate matter. The possibility of BGC-Argo extending measurements throughout the upper ocean would enable connecting the BGC properties to the ocean circulation and estimating upper ocean carbon budgets. These recommendations build on dedicated studies since the First Report that informed TPOS 2020 about the space and time scales of biogeochemical variability in the

Tropical Pacific. Other variables like plankton biomass and diversity, fish abundance and distribution, are recognized as important, but are not considered in this report. However, a fuller picture of biogeochemical properties in the context of the physical circulation may make possible both observations and model studies for ecosystem evaluation and management that would be of crucial use to Pacific nations who depend on marine resources; it will also help to diagnose the mechanisms and impacts of climate change on these systems.

Similarly, the First Report sketched pilot studies for the eastern region, noting the multiple scales and phenomena including upwelling along the South American coast and the distinctive transitions from the stratus region in the south to the sharp cold tongue, the ITCZ and the east Pacific warm pool off Central America. Unlike most of the rest of the basin, winds in the east are strongly meridional, and both winds and radiative forcing are linked to effects of the nearby continent. As the region where the great zonal currents of mid-ocean interconnect and reorganize, and where much of the vertical motion of the general circulation takes place, processes in the east have basinwide impacts. It is also a region where fluctuations of the tropical climate – especially ENSO – have major socio-economic impacts. The initial suggestions of the First Report are considered in more detail in Chapter 5, focusing on specific actions and drawing attention to the need for regional coordination for data sharing.

Chapter 6 considers several issues that bear on the Backbone design. Observing requirements are formulated to ensure that a careful climate record able to detect and characterize decadal variations and trends (including climate change) will be maintained. The rationale for an expanded moored array in the northwest part of the region is explained, including its role in intraseasonal and typhoon forecasting for the east Asian coastal states. We examine the current state of surface flux sampling, including the complementary possibilities from in situ and remote sensing approaches. We consider the needs of coupled data assimilation for clearer representation of near-surface processes, and the potential for well-validated coupled models to resolve some of the persistent biases of present prediction systems. Near-surface observations, including of surface currents, complement and add value to flux estimates based on remotely-sensed properties. Uncertainty and lack of understanding of the differences between satellite and in situ estimates holds back progress; a strategy for getting the most value out of the different techniques is essential background for the configuration of the Backbone arrays considered in depth in Chapter 7.

The First Report did not consider data management issues in detail, but discussions since then have pointed to the need for a more deliberate approach. This both speaks to the vision of an integrated sampling strategy, and to the steps by which data requirements are proposed and value is realized. Chapter 8 raises these issues and proposes a series of actions to provide a pathway for the different agencies and nations that implement theTPOS to assure consistency, data quality, and access by all users.

Several important phenomena will not be adequately described by the proposed basin-scale Backbone measurements, often because they act on small spatial scales, yet cannot be ignored because they have impacts on the large scale. New observing techniques that might augment the Backbone sampling are being tested in pilot studies, and their capabilities are coming into focus. Chapter 9 begins a preliminary evaluation of some of these, attempting to define their roles in a future observing system. Prospective satellite capabilities have the potential to dramatically expand measurement of previously intractable phenomena, including surface currents, and profiles of the lower atmosphere. A framework for evaluating the readiness and applicability of these emerging technologies is sketched out.

10.2 A systematic approach to Backbone priorities

The heart of this report, and our principal charge, is to design a set of interlocking Backbone arrays that will deliver the sustained data for future progress. The multiple bases for meeting this charge were described in our First Report and remain valid, but much study and debate has honed previously fuzzy elements (e.g., Fig.7.1) and led to some modifications. Refinements from the First Report include a stronger focus on measurements of surface fluxes, and of variables describing the interaction of the ocean mixed layer with the lower atmosphere, discussed in Chapter 6. These considerations led to the definition of a tiered approach to moorings, with Tier 1 the base configuration of the new TMA (Fig.7.3).

The spatial structure of the recommended TMA remains much as described in the First Report (Fig.7.1), with focus on the near-equator, and several of the meridional spines extended poleward to expand the regimes sampled. Compared with the earlier recommendations, one more spine is supported, to retain the ability to capture basin-wide changes even as spatial patterns of climate may shift (Fig.7.4).

The First Report was vague about the required shape of the TMA in the Warm Pool north of the equator. Here, we propose an array that adequately samples this region of intense air-sea interaction, and additionally extends to the northwest to enable description of the multiple phenomena that produce seasonal variability and affect shorter-term weather across the coastal regions of east Asia (see 6.2.2).

The basis for our priorities for the Backbone was established by our sponsors at the start of the project in 2014, reaffirmed by the TPOS 2020 Steering Committee and our Resource Forum. Our mandate is to design a TPOS Backbone to fulfill five functions:

1. Provide data in support of, and to evaluate, validate and initialize ENSO prediction and other forecasting systems and to foster their advancement;
2. Provide observations to quantify the evolving state of the surface and subsurface ocean;
3. Support integration of satellite and in situ approaches including calibration and validation;
4. Advance understanding and modeling of the climate system in the tropical Pacific, including through the provision of observing system infrastructure for process studies;
5. Maintain and extend the tropical Pacific climate record.

All of these functions require sustained sampling across the climate regimes of the tropical Pacific (see 6.5). We have sought to understand the impact of an observation in context of the rest of the system. That context often adds value by sampling a dimension another technique does not. We have tried to maximise these complementarities, such as the fine temporal resolution of mooring temperatures with the fine vertical resolution of Argo profiles. In some cases, especially when remote and in situ sampling cover the same region and variable, this led us to value focused, more-capable platforms higher than a thin grid of simpler measurements. We considered the system as a whole, with a diverse set of overlapping requirements in overlapping regimes met with the diverse tools we are now fortunate to have. We believe that this integrated approach delivers resilience and robustness, while at the same time rising to the challenge of the five functions that are our mandate to realize.

Our recommended Backbone includes the elements we considered were the most important to advance understanding and to support present and future prediction systems. We do not find that any part of the present networks has no value – the tropical Pacific is and will remain undersampled – but do assess some new observations as having a larger impact than some existing ones, even taking into account their role in maintaining a climate record. Progress in coming decades will require long background time series of some different properties than are now measured and that were not foreseen when the present arrays were designed; as well, new model capabilities require constraints and verification that present networks are not able to provide. New in situ and remote technical capabilities make this sampling possible, and in some cases can supersede present methods. Surface gradients and fluxes are one example where the new recommendations would enlarge the scope of future climate records; we judged this gain more significant than the potential losses of some less-detailed records (see 7.3.2).

Not all of our conclusions have gained full consensus across the scientific community. The proposed reconfiguration of the moored array (7.3.1.2) has generated ongoing controversy, based on an understandable concern about the maintenance of a credible climate record (see 6.6). The project has identified and seriously probed this issue from its inception, and we continue to conclude that the multi-platform (space based and in situ) observing system we recommend will track decadal and longer term changes for traditional TMA measured quantities, but in addition expand that capability to new parameters (e.g., salinity, fluxes, broader biogeochemical measures, surface velocity) and also deliver more strongly to the other functions of the observing system.

Our recommendations are made in a realistic context. Although we are not working within a defined budget, we understand that resources are limited. If implemented in full, the recommendations here would represent a significant increase in resources devoted to the TPOS, and we are clear-eyed that there may need to be trade-offs. We can recommend, but the outcome depends on what our sponsors and stakeholders are able to fund.

A summary of all recommendations and actions is provided in Appendix B, along with those from the First Report.

10.3 Governance

The TPOS 2020 Project has effectively taken the design and support of the TPOS “offline” from global governance of the networks (by the IOC/WMO). The TPOS 2020 Steering Committee is responsible for scientific and technical aspects, while the Resource Forum provides representation for stakeholders (users, providers, beneficiaries). Prior to the creation of the TPOS 2020 Project, there was no dedicated governance arrangement and responsibility was distributed, principally within JCOMM.

The demonstrated seasonal-interannual prediction skill - extending worldwide through teleconnections - derived from observations in the Tropical Pacific necessitates continued engagement with Meteorological Services as we formulate our redesign. It has therefore been important to engage JCOMM, and WMO through the WMO Integrated Global Observing System (WIGOS), in discussions on future governance. An implementation team, now known as the TPOS/JCOMM Transition and Implementation Task Team (figure 10.1A), is an early manifestation of the type of coordination and cooperation that will be needed for maintenance of the TPOS in the future. WMO WIGOS recognizes the activities of the Transition and Implementation Task Team as a Regional Pilot and the joint sponsorship by JCOMM is an acknowledgement by JCOMM that such coordination might be needed in the post-TPOS 2020 era (see the decision in WMO, 2017).

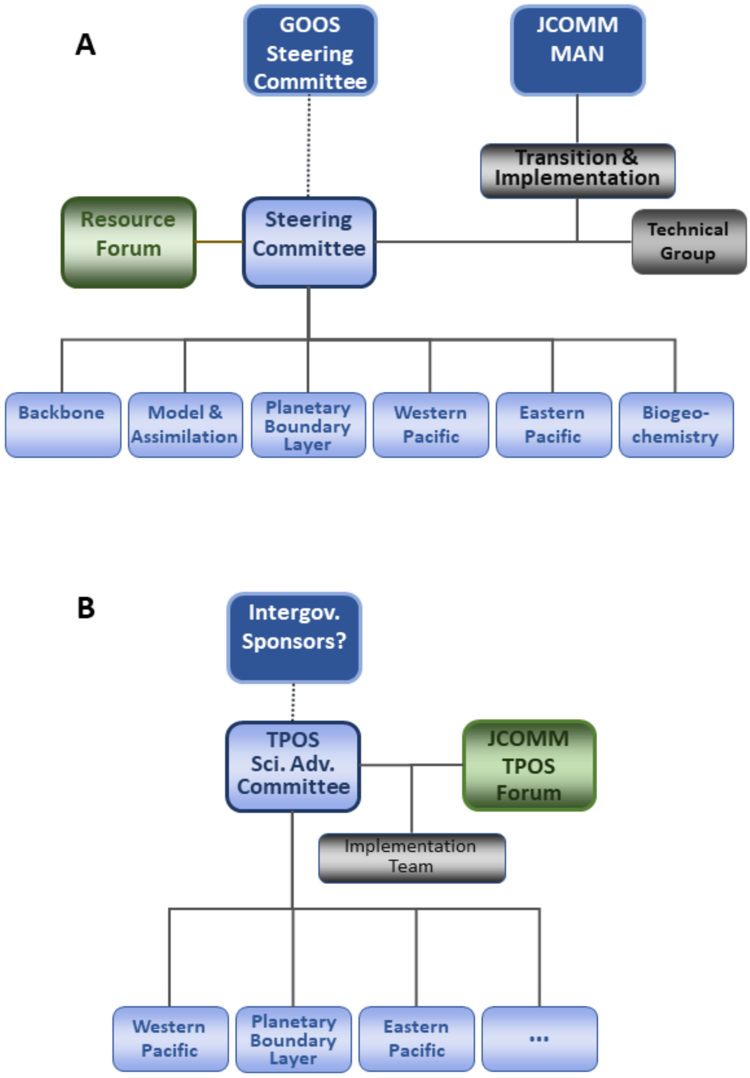

Figure 10.1 (A) TPOS 2020 Project governance arrangements. The TPOS 2020 Steering Committee has six Task Teams (as shown) and shares a seventh (the Transition and Implementation Task Team) with the JCOMM Management Group. The Resource Forum is a key element of the structure. Further details are available from tpos2020.org. (B) Possible post-2020 TPOS arrangements. It is likely a science/steering committee will continue and that at least some of the Task Teams will have renewed mandates. A regional TPOS Forum is proposed to facilitate coordination and cooperation between partners, and with users/beneficiaries.

Discussion of post-2020 TPOS governance arrangements have commenced (TPOS OceanObs'19) and must consider scientific and technical oversight and leadership (the legacy of the Steering Committee) as well as regional coordination following on from the regional pilot. Strengthened regional coordination approaches are also being considered in other basins (e.g., in Atlantos https://www.atlantos-h2020.eu/); and a number of approaches will probably be tested, to address particular scientific and geopolitical contexts. Tanhua et al. (2019a) developed some principles that are relevant to TPOS governance arrangements:

- Responsiveness. Respond to the needs of stakeholders and participants.
- Purposeful. Governance must be purposeful for, and on behalf of the community.
- Clear objectives. Clear and purposeful (relevant) objectives and strategy.
- Transparency. To ensure public access to and benefit from the system.
- Efficiency and Effectiveness. Maximize value; flexibility and nimbleness for timeliness.
- Authoritative. Appropriate capability, skills, and respect of the community.
- Performance and accountability. Monitoring and measures of success and performance.

We support a TPOS post-2020 governance arrangement in line with such principles.

A central theme in the TPOS governance discussions is that active and mutually supportive partnerships among TPOS stakeholders are vital for its robustness and sustainability. A TPOS Forum where partners (providers of observing capability) and users/beneficiaries can review the performance and guide the evolution of the TPOS (figure 10.1B) is proposed. It is further proposed that the TPOS 2020 (project) Steering Committee be succeeded by a TPOS Scientific Advisory Committee, advising the TPOS Forum and other sponsors (e.g., GOOS and/or the World Climate Research Program) of the evolving scientific requirements and assessing potential technical solutions. Further discussion with the scientific community will be needed to finalize the best and most effective arrangement.

Action 10.1. The TPOS 2020 Resource Forum and Steering Committee, in consultation with the broader TPOS community, further develop and seek agreement on post-2020 governance arrangements.

10.4 Next steps

The work of rebuilding the observing system for the next decades is just beginning. Although TPOS 2020 will finish at the end of that year with a final report, much of the implementation of the changes proposed here will just be getting under way (Figure 7.19). Results of new technology pilots discussed in Chapter 9, and the process studies in Chapters 2 and 3 and in 7.4.6, will become clear over the next few years; these will need evaluation to determine their lessons and readiness for the sustained observing network. As the system evolves, maintenance of the climate record will be an essential consideration, as well as the delivery, application and utility of the data streams to serve the other Backbone functions. Coordination of the interlocking networks will require regular consultation among the implementing partners. For all these reasons, the need for appropriate governance, and for scientific advice, will continue past this project’s sunset.

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Annex A – Winds

Authors: Larry O'Neill, Carol Ann Clayson, J. Tom Farrar, Tong Lee, Shayne McGregor

Introduction

Interactions between the surface winds and fluxes drive substantial coupled ocean-atmosphere processes in the tropical Pacific. The surface wind and wind stress drives the flux of momentum and energy between the two fluids. The resulting coupled processes occur over a broad range of spatial and temporal scales. Prominent processes and variability in the tropical Pacific include the El Niño-Southern Oscillation (ENSO), Madden Julian Oscillation (MJO), Pacific Decadal Oscillation (PDO), equatorial upwelling, tropical cyclones, westerly wind bursts, and tropical instability waves along the edges of the equatorial cold tongue. These processes are important components of broader scale teleconnection and bridging patterns coupling the tropics and extratropics. To continue research and monitoring these fundamental coupled processes, wind and wind stress measurements resolving these broad temporal and spatial scales is essential. This section briefly summarizes the current and near future state of the surface wind observing system in the tropical Pacific and highlights some current observational challenges.

A.1 Current state of the surface wind observing system in the tropical Pacific

The surface vector wind observing system in the tropical Pacific currently consists of in situ anemometers mounted on the TAO moorings, a small number of satellite scatterometers, and a series of satellite passive microwave radiometers. The state of the TAO in situ measurements has been discussed in detail earlier in this report (e.g., 7.3.2.1), so here we will mainly discuss the current and relevant past capabilities of operational satellite instruments.

The majority of satellite instruments currently in orbit measure the surface wind speed with passive microwave radiometry. In contrast, only a few active radar scatterometers in orbit measure the wind speed *and* wind direction. The directional information provided by scatterometers is crucial for understanding wind-driven variability in the upper ocean, for example, from fluctuations of the easterly trade winds. The scalar wind speed measurements provided by passive radiometers are useful for surface heat and freshwater flux estimation and for constructing gridded wind products with high temporal resolution. Thus, both of these satellite-derived observations are included in the following discussion.

In the First TPOS 2020 Report, the goal for surface wind measurement was set at 90% areal coverage every 6 hours. This level of coverage is necessary to resolve the diurnal cycle of surface winds and fluxes and tropical convection. To assess the current state of satellite surface wind coverage, Figure A.1 shows a time series of the percentage of areal coverage of the tropical Pacific from satellite surface wind measuring instruments since the year 2000. This figure is an updated and more TPOS-specific version of that shown in Figure 3 of Atlas et al. (2011). The blue time series indicates active scatterometer-only missions, red passive radiometer-only, and purple the combined active-passive coverage. The instrument inventory used in the construction of the time series and their duration of geophysical data records are listed in the top half of the panel. This blue scatterometer-only time series represents the coverage of surface vector winds, as opposed to just the scalar wind speed. Currently, only about 40% of the tropical Pacific is sampled at least once every 6 hours for vector winds. In contrast, the current coverage for wind speed is much more extensive from the active-passive combination (purple curve), with about 75% of the tropical Pacific region containing at least one satellite wind speed observation during 6-hourly periods.

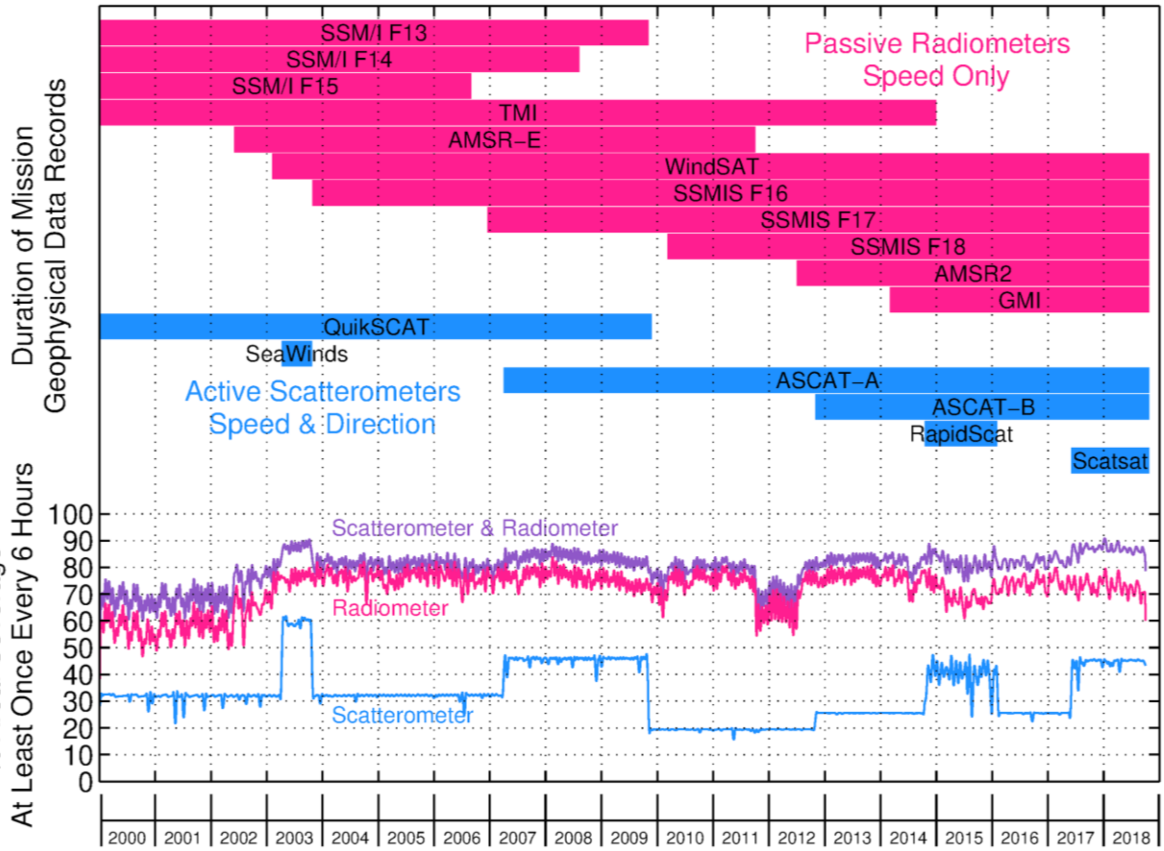


Figure A.1: Time series of 6-hour coverage from satellite surface wind datasets for the last 18+ years. The percentage areal coverage of the tropical Pacific Ocean observed by these missions in a 6-h period is shown in the bottom half of the graph. The blue curves represent the scatterometer-only missions with speed and directional measuring capabilities, red curve is the passive radiometer-only missions with speed-only capabilities, and the purple curve is the total active-passive combined coverage of wind speed. All time series are filtered using a 15-day running average. The geographic area considered is bounded by 160°E–100°W and 15°S–15°N. The top half of the figure lists the name and duration of the geophysical data records from all the passive and active satellites used. Note that the purple time series is not the sum of the red and blue curves because of redundant areal coverage within 6-hour windows by the passive and active instruments. This figure is an updated and enhanced version from Figure 3 in Atlas et al. (2011).

The satellite scatterometers instruments in orbit as of April 2019 are the Advanced Scatterometer (ASCAT) onboard the Metop series of polar-orbiting satellites, of which there are now three (ASCAT-A, ASCAT-B, and ASCAT-C). ASCAT-A is in its 13th year of operation, while ASCAT-B is beginning its 7th year. ASCAT-C was recently launched in November 2018, and is now producing preliminary developmental-grade wind observations with research-quality observations expected within the next year. EUMETSAT is committed to a second generation of polar-orbiting environmental satellites, named Metop-SG, split into an A and B series. The B series will carry a scatterometer similar in design to ASCAT, called SCA. The first METOP-SG-B satellite is planned for launch in 2022. SCA features increased surface coverage per pass via wider off-nadir swaths and a narrower nadir gap compared with the current ASCAT design, and a finer spatial resolution of about 25 km, compared with ASCAT's 50 km.

In addition to these instruments, there are currently four other scatterometers in orbit. Two are onboard the Chinese Hai-Yang 2A and 2B satellites (HY-2A and HY-2B); the third scatterometer is ScatSat-1 that was launched by the Indian Space Agency ISRO in 2016 and is designed to gap-fill the OSCAT-2 and OSCAT-3 missions; and the fourth is the CFOSCAT (China-France Oceanography Satellite (CFOSAT) Scatterometer), launched on 28 October 2018. It is anticipated that research quality datasets may be made available to the general scientific community from these instruments, which will contribute to the tropical Pacific observing system for surface vector winds. Finally, a Ku-band scatterometer is scheduled for launch on OSCAT-3 by the ISRO sometime during 2020.

Prior notable scatterometer missions consisted of QuikSCAT (1999-2009), SeaWinds on ADEOS-2 (2003), OSCAT on OceanSat-2 (2012-2014; referenced as OSCAT-1), and RapidScat on the International Space Station (2014–2017). QuikSCAT, ADEOS-2, and RapidScat utilized nearly identical SeaWinds scatterometers. Since the ISS has a lower inclination orbit, RapidScat observed the tropics somewhat more frequently than the polar-orbiting QuikSCAT. The purpose of showing the QuikSCAT and ADEOS-2 SeaWinds in Figure A.1 is to highlight the improved sampling capability of two wide-swath Ku-band scatterometers, whose combination nearly doubled the 6-hour coverage of the tropical Pacific.

In addition to these active radar scatterometers, the WindSat polarimetric passive radiometer has estimated the surface vector wind field over most of the global ocean since 2003 and is still in operation. While WindSat's wind measurements, particularly wind direction, are less accurate than those measured by scatterometers, it has nonetheless provided an important platform to intercalibrate the intervening constellations of scatterometer missions (e.g., Ricciardulli and Wentz, 2015; Wentz et al., 2017). An improved developmental radiometer, called COWVR, was due to launch in February 2018. In May 2018, the satellite mission was delayed indefinitely due to unspecified technical issues with the spacecraft's bus. The US Air Force Space Rapid Capabilities Office (RCO) is currently devising a new spacecraft bus for the COWVR instrument, and no date is yet planned for launch.

Since 2000, the coverage of the ocean by scatterometer measurements of surface vector winds is approximately 20% to 50% at the 6-hourly interval, while for measurements of the surface wind speed from the combined scatterometer and radiometer constellation, it is approximately 55% to 75% (Figure A.1). The TPOS 2020 goal of 90% coverage of surface wind is currently not met in either wind speed or direction, although wind speed coverage is fairly close. An enhancement of coverage to the proposed 90% level at the 6-hourly interval in both vector winds and wind speed will provide a more powerful constraint for NWP models and synthesized wind products than is currently available.

A.2 Consideration of measurement accuracy and sampling capabilities

A number of issues arise when evaluating the efficacy of observing and monitoring the surface winds over the tropical Pacific from the complete observing system combining satellite and buoy wind measurements. Among the issues are understanding measurement errors from each platform and understanding sampling errors due to each platform's unique measurement strategy and capabilities. The second issue arises from the use of satellite and in situ vector wind measurements to produce uniform gridded wind products without spatial and temporal gaps.

(a) *Measurement errors*

The uncertainty of wind speed measurements from anemometers on moored buoys is the greater of 0.3 m/s or 3% of the measured wind speed, while directional uncertainties for instruments deployed after 2000 is 5° (Freitag et al., 2001). However, there is evidence of systematic errors in the wind measurements due to flow distortion from the buoy structure (e.g., Edmond et al., 2012; Bigorre et al., 2013), although these studies are not in reference to the TAO Atlas moorings specifically. In light of these findings, further research is needed to fully characterize systematic flow distortion effects on reported wind directions and speeds from the instruments deployed in the TAO array.

Scatterometer backscatter measurements are used to retrieve the so-called stress-equivalent neutral wind (ENW) at 10-m height, which is the wind speed at 10 m consistent with the observed wind stress and air density in a neutrally-stable surface layer. In the tropical Pacific, where unstable (convective) conditions generally prevail, the mean difference between the 10 m ENW and the actual (stability-dependent) wind speed is about 0.25 m s^{-1} on average (O'Neill, 2012).

Scatterometer wind retrievals are typically compared with moored buoys to evaluate the relative accuracy of retrieved winds. Over the tropical Pacific, the RMS difference between the QuikSCAT and buoy 10-m ENW total wind speed is 0.9 m s^{-1}, while the mean difference (QuikSCAT minus buoy) is -0.4 m s^{-1} (Table 4 in O'Neill, 2012). The RMS difference is a combination of buoy and scatterometer uncertainties, sampling differences between satellites and buoys, atmospheric stability, and from ocean current impacts on scatterometer wind observations. Two main factors are thought to be important in this difference are: (1) the spatial and temporal scales of the measurements (i.e., with moorings point measurements averaged over some time, while scatterometers are snap shots with a large spatial footprint); and (2) the fact that both instruments measure winds from different frames of reference, with scatterometers measuring winds relative to the ocean surface, while mooring instrumentation measure the absolute wind (i.e., they must also measure surface ocean currents to compute surface relative winds).

The single RMS difference statistic incompletely characterizes the differences between the scatterometer and buoy winds collocated in time and space. Four other characterizations of the differences between scatterometers and buoys are shown here and discussed below. The RMS difference between scatterometers and buoys are known to be: (1) a function of location and rain frequency (Figure A.2); (2) a function of timescale (Figure A.3); (3) a function of the differing measurement techniques; and (4) the RMS difference in the zonal wind component as a function of the TAO zonal wind speed (Figure A.4).

Precipitation degrades the accuracy of the scatterometer wind retrievals, mainly by causing erroneous turning of the retrieved winds into the cross-track direction and erroneously increasing the retrieved wind speed (e.g., Weissman et al., 2012). Rain-induced uncertainties are greater for Ku-band scatterometers such as QuikSCAT, than it is for C-band scatterometers such as ASCAT. The RMS difference in scatterometer and TAO wind speed (the 10-m ENW) at each TAO buoy location is shown in Figure A.2. The red hues indicate the rain frequency from the TMPA 3-hourly rain climatology. QuikSCAT is shown in the right column and ASCAT-A is shown in the left column. The RMS differences are generally slightly lower in ASCAT-A than in QuikSCAT where rain is relatively infrequent over the equatorial cold tongue. In relatively rainy ITCZ and SPCZ regions, however, the QuikSCAT RMS wind speed and vector wind component differences are over a factor of 2 larger. ASCAT-A has only slightly larger differences in rainy regions. Enhanced processing of Ku-band scatterometer winds have systematically reduced, but not eliminated, rain-induced errors, for instance in

QuikSCAT and RapidScat (Fore et al., 2014). Regardless, rain-contamination of scatterometer winds remains an ongoing concern in regions of the tropical Pacific which experience relatively frequent rain.

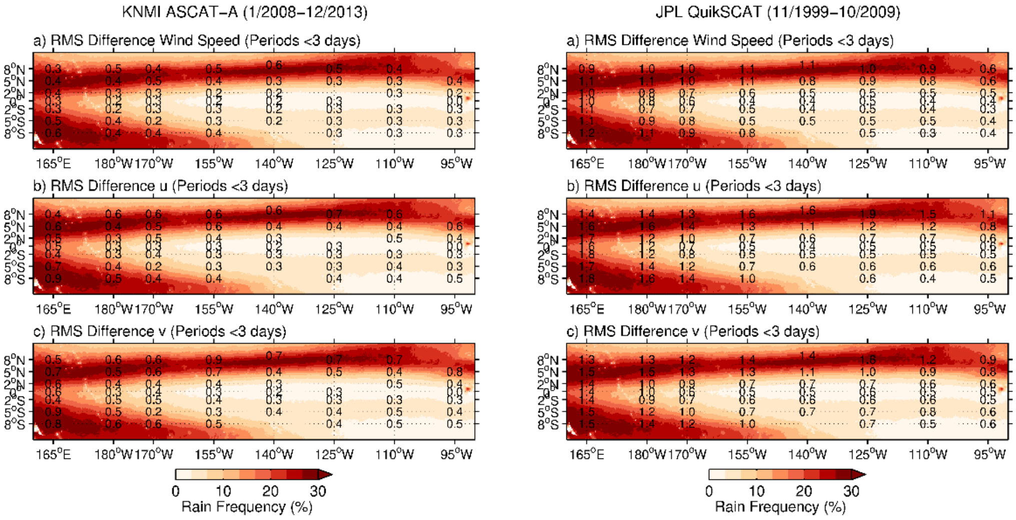


Figure A.2: RMS difference between scatterometer and buoy winds listed as numbers in units of m/s. The left column shows the ASCAT-A and the right QuikSCAT. The red shading indicates the frequency of rain. Each row shows the (top) wind speed, (middle) zonal wind component, and (bottom) meridional wind component.

Rain events of the tropical Pacific are typically convective in nature. Individual convective events have timescales of a few hours from onset to decay (e.g., Mapes, 1993; Ricciardulli and Sardeshmukh, 2002; Kilpatrick and Xie, 2015). However, envelopes of enhanced convective activity during, for instance, the wet phase of the MJO, have timescales of 10–20 days (e.g., Zhang, 2005). Thus, rain contamination can lead to enhanced uncertainties on synoptic timescale variability in Ku-band winds. This is demonstrated in Figure A.3, which shows the RMS wind differences between collocated scatterometer and TAO winds as a function of timescale. Each curve represents one of the 55 TAO buoys used in the analysis. Shown is ASCAT-A (left column) and QuikSCAT (right column). The RMS differences are strongly enhanced on timescales less than 5 days in the QuikSCAT winds compared with ASCAT-A. These differences are mainly due to increased uncertainty in the QuikSCAT winds in rain compared to ASCAT-A. Note that over intraseasonal and longer timescales, the RMS wind speed differences are below 0.25 m s^{-1} in both instruments. Rain thus affects the ability of Ku-band scatterometers to accurately resolve variability in the winds over the tropical Pacific on timescales less than 5 days.

Satellites and buoys view the winds associated with small-scale, transient convective rain cells differently. Sampling differences can thus also contribute to the larger RMS differences between the satellite and buoy winds in convective regions. The extent to which this sampling difference contributes to the RMS differences between satellite and buoy winds, however, is poorly understood. High-resolution regional and mesoscale models such as WRF provide a potential tool to assess this effect may provide information to help resolve this issue. It is also noted that such an assessment is subject to limitations of the models' horizontal and spatial resolutions and microphysical and convective parameterizations. Furthermore, processed-oriented in situ experiments with innovative sampling methods and technology can also be utilised to potentially resolve this issue.

Scatterometer radars inherently infer the surface wind stress which generates centimeter-scale gravity-capillary waves. The surface stress results from not only the local wind speed, but also the motion of the surface and the surface layer stability (e.g., Ross et al., 1985; Portabella and Stoffelen, 2009). That is, scatterometers measure the winds relative to the moving sea surface, while stationary buoys measure winds relative to a fixed point (e.g., Ross et al., 1985; Kelly et al., 2001, 2005). There are currently three known issues associated with measurement technique differences that can lead to differences between scatterometers and buoys wind measurements. The first is a known temperature dependence of surface ocean viscosity, which acts to modulate the scatterometer backscatter measurement independent of the local wind (e.g., Bentamy et al., 2012; Grodsky et al., 2012). The most recent QuikSCAT and ASCAT retrieval algorithms have implemented an SST-dependent correction for this effect (e.g., Ricciardulli and Wentz 2015; Stoffelen et al., 2017), which decreases some of the uncertainties associated with this process. A second source of uncertainty is converting in situ buoy winds to stress and 10-m neutral winds using bulk formula. A study by O’Neill (2012) shows that this potential source of uncertainty is secondary in the tropical Pacific, however, since the air-sea temperature differences are relatively small. While not an error per se, surface currents in the tropical Pacific create a third difference that contributes to apparent differences in satellite and buoy wind measurements (e.g., Kelly et al., 2001). Reconciliation of the differing frames of reference of scatterometers and buoys is required to correct these relatively large differences between these unique observational systems.

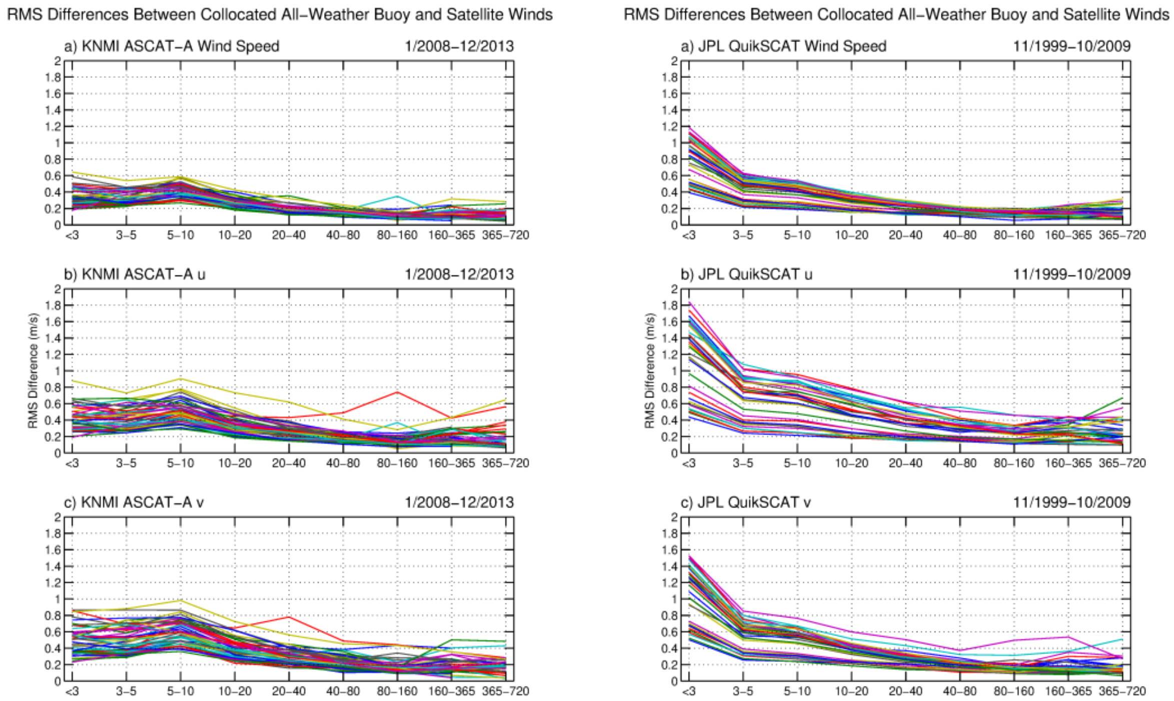


Figure A.3: RMS differences of 10-m equivalent neutral stability winds (ENW) between scatterometer and TAO buoy winds as a function of timescale. Each curve represents one of the 55 TAO moorings used in this comparison. The left column is the ASCAT-A comparison, and the right column is the QuikSCAT comparison. Each row shows one of the wind speed, zonal (u) wind component, and meridional (v) wind component. The x-axis shows the timescale of variability retained in the temporal band-pass filter, or more specifically, the half-power point of the loess quadratic filter used. The TAO winds have been adjusted to the 10-m ENW for this analysis using the COARE v3.5 bulk flux formulation.

(b) *Sampling errors*

It is important not to confuse the measurement error with the sampling error (e.g., from an inadequately-sampled diurnal cycle). Increasing satellite temporal and spatial coverage with a variety of orbits to capture diurnal variability can alleviate the sampling errors. Most satellites observing surface winds over the ocean are in sun-synchronous orbits and provide at most two observations at a point each day in the tropics. QuikSCAT, for example, averaged about 1.4 observations per day at the equator over its entire mission. ASCAT has less coverage due to its narrower swath and nadir gap, about 0.9 observations per day at the equator. A single satellite by itself thus will not completely resolve diurnal or sub-diurnal periodicities. Non-sun-synchronous satellites, such as TMI or RapidScat on the International Space Station, have lower inclination orbits and therefore sample the tropics somewhat more frequently but at the expense of mid and high-latitude coverage. Part of the rationale of showing 6-hour sampling coverage in Figure A.1 was to assess the capability of the satellite observing system at minimally resolving diurnal variability of surface winds in the tropics.

Satellite sampling characteristics can be estimated by comparing the highly-resolved TAO time series with a subsample at only the scatterometer observation times. Figure A.4 shows the fraction of wind variance captured by the scatterometer winds compared to the full TAO wind time series. The x-axis shows the timescale of variability, ranging from less than 3 days to greater than 180 days. Both QuikSCAT and ASCAT-A are assessed here based on the length of their geophysical data records. This analysis isolates and quantifies the timescale limitations of temporal sampling from a single scatterometer separate from measurement accuracy. This plot shows that the scatterometers underestimate the temporal variance on timescales less than 3 days by about 50% to 100%. Incidentally, the variance on timescales longer than 3 days is uniformly overestimated by scatterometers for unknown reasons. Since only TAO winds are used in this comparison, this overestimation cannot be from ocean currents or from scatterometer measurement errors; it is due entirely to the temporal sampling characteristics of the individual satellite, most likely temporal aliasing of diurnal and synoptic weather variability. Further investigation is needed to define specific requirements for wind sampling errors in satellite wind observations. This will allow an assessment of satellite orbit configurations which can minimize sampling errors. The results of such an investigation will likely inform the design of future satellite missions.

Currently, more research is needed to identify sampling needs in the tropical Pacific and to identify the configuration of the satellite constellation to sample these processes. A specific question of such an investigation is whether 90% coverage by satellites every 6 hours, as proposed in the First TPOS 2020 Report, is sufficient to reduce the temporal sampling issues uncovered in Figure A.4. A second question is whether simultaneous wind speed and direction measurements are necessary, or whether scalar wind speeds alone are sufficient. In either case, it is necessary to identify how the satellite sampling strategy affects knowledge of specific physical processes in the tropical Pacific.

(c) *Spatial representativeness of scatterometer and in situ measurements*

Satellites estimate the average vector winds over an area. Buoys, on the other hand, average in time, which can approximate a spatial average via the Taylor frozen turbulence hypothesis. Unresolved subfootprint variability in satellite measurements will thus contribute to differences between satellite and buoy wind measurements. The differing reference frames of each platform are not measurement errors per se but are more accurately termed as a sampling error.

The impact of such sampling differences on satellite-buoy wind consistency is likely particularly important in rainy regions (e.g., the ITCZ) where small-scale variability associated with convective rain cells (~10 km scale) are captured by satellites and buoys differently. This may contribute to the larger difference between satellite and buoy winds in rainy regions (e.g., Figure A.2). Ongoing effort is made to analyze WRF model output to shed light on the potential impact of such sampling difference on the consistency of winds measured by satellites (averaged over footprints) and by buoys (snapshots). Innovative ideas of field experiment and in situ technology (including shipboard radar) to estimate the effect of sampling difference on wind measurement consistency would be helpful.

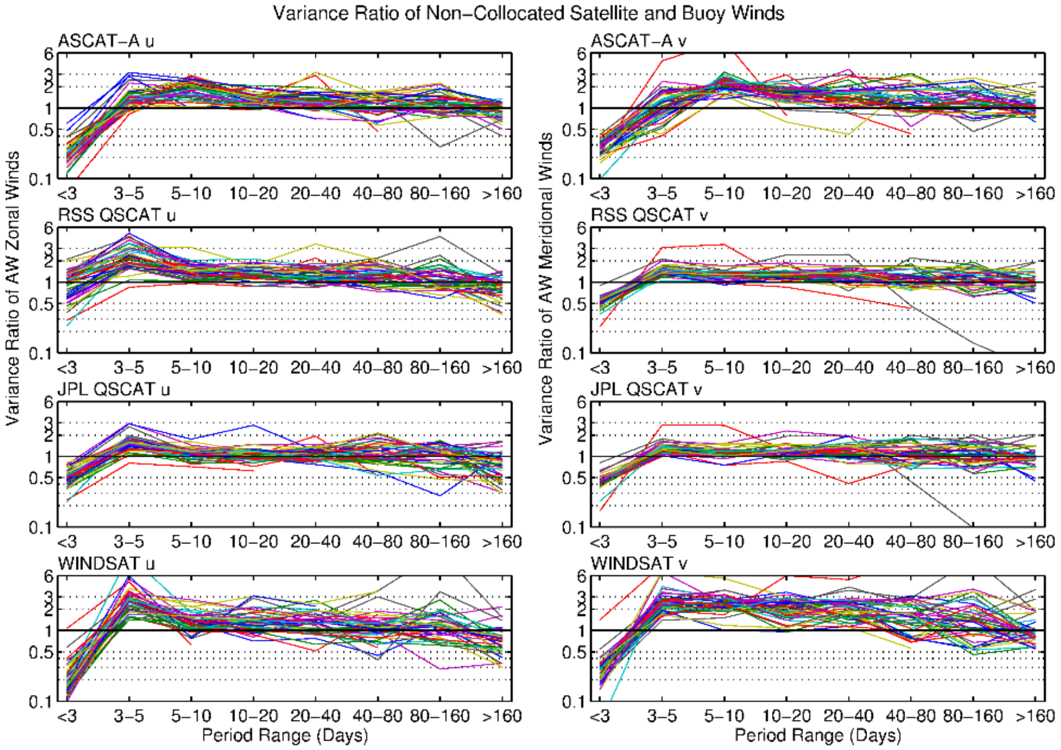


Figure A.4: Assessment of the capability of the scatterometer temporal sampling strategy at capturing the variance of the full-resolution TAO winds. Each curve represents the ratio of the temporal variance of the TAO-only vector wind components, where the variance ratio is the variance of the TAO winds subsampled at the scatterometer observation times divided by the variance of the full TAO data record. The x-axis is the ranges of timescale of variability.

A.3 Challenges in producing gridded wind products in the tropical Pacific

Gridded vector wind products have proven very valuable in advancing the understanding of physical processes operating in the tropical Pacific and elsewhere. Their specific advantages include: i) a format that allows easy integration in space and time to facilitate the development of climatologies and to study variability and trends of the winds themselves, the circulation of the upper ocean and regional sea level change; ii) easy collocation with observations of other gridded parameters; iii) consistent screening for data quality that incorporates state-of-the-art data and statistical techniques.

Despite all of the positives of these gridded vector wind products, several notable issues are apparent within these products. These issues are perhaps best highlighted by the significant differences identified between products (e.g., Wittenberg, 2004; McGregor et al., 2012, 2017). These are: i) The data/methods used to fill in regions where surface winds are not observed. In products like CCMP (Atlas et al., 2011), a NWP reanalysis wind product is selected as a “background” which is reverted to in the absence of observations. This choice has been shown to affect the mean and long-term trends, which has implications for simulations of ocean circulation, sea level, and SST (McGregor et al., 2017; Chiodi and Harrison 2017). Uncertainties in NWP reanalysis winds in the tropical Pacific (e.g., Chiodi and Harrison 2017) can affect satellite-derived gridded wind datasets since many use these fields as either background or first-guess fields in the objective analysis procedure to fill in spatial and temporal gaps in the satellite observations; and ii) The incorporation of differing measurements types and those with differing frames of reference (scatterometer and buoy), has led to spurious hotspots of wind stress curl and surface heat flux around buoy locations (e.g., Josey et al., 2014; McGregor et al., 2017).

It is recommended that these gridded wind products are evaluated in detail to determine their relative abilities to reconstruct required scales of variability within the tropical Pacific.

Below is a list and brief description of known currently-funded efforts to use statistical interpolation techniques to produce gridded surface wind analysis fields from satellite and in situ wind measurements. We note that is beyond the scope of the current report to discuss potential and planned improvements in reanalysis products here. Evaluation studies are needed to determine how these products approximate the surface wind field, including evaluation of resolved spatial and temporal scales of variability, as well as the depiction of long-term variability and change in the wind field.

Efforts underway:

(a) JPL-MEaSUREs. This work will develop a long-term scatterometer-only Earth Science Data Record (ESDR), including for vector winds, wind stresses, and their curls and divergences. A significant part of the effort is intercalibrating the various scatterometer datasets, which include both Ku- and C-band instruments. The goal is to produce updated Level 2 datasets for all scatterometer missions, gridded Level 3 swath-level data products, and Level 4 gridded wind analyses ESDR for ENWs, wind stresses, and their curl and divergence fields.

(b) CCMP Version 3 (JPL/Remote Sensing Systems): This is a joint effort by JPL and RSS to update and improve the CCMP analyses of Atlas et al. (2011) and Wentz et al. (2015). Improvements include using a more advanced variational analysis method that considers timescale dependent error covariance, in particular, limiting the influence of the mean and trend of reanalysis winds on the CCMP winds.

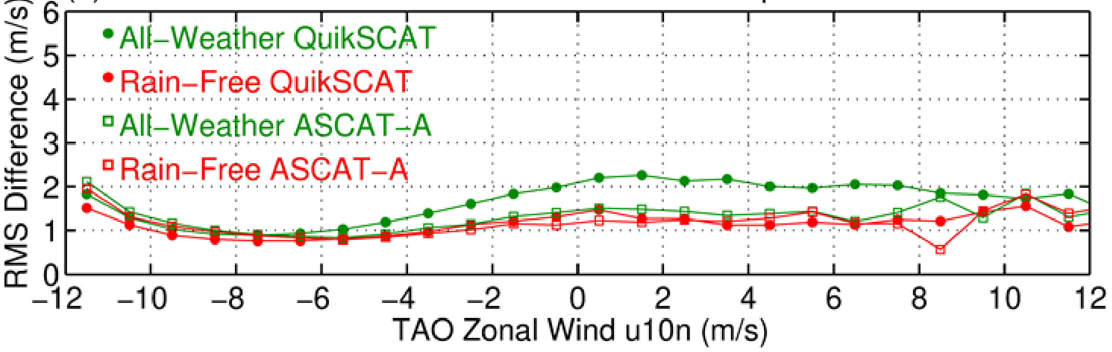
(c) OAFlux: Also, newly funded under the most recent NASA MEaSUREs announcement, OAFlux aims to produce an improved higher-resolution version of the current OAFLUX analysis that includes the daily wind analysis.

A.4 Concerns related to zonal wind disagreements between buoy and scatterometer data

One concern about a reduction of the number of TMA sites is related to the occurrence of zonal wind errors that vary as a function of zonal wind speed. These errors are illustrated in Figure A.5. We examined RMS disagreement of QuikSCAT and ASCAT-A scatterometer wind speeds versus 55 TAO sites (Figure A.5). The RMS total wind speed disagreements are plotted as a function of TAO zonal wind speed. There is a noticeable increase of RMS speed differences of the ‘all-weather' QuikSCAT wind speeds for eastward TAO winds, with about twice as much RMS disagreement from TAO for positive zonal winds. This increased disagreement between the scatterometer and buoy total wind speeds mostly diminishes when rain-flagged data points are excluded. ASCAT-A, which is less susceptible to rain contamination, shows a much smaller dependence of RMS total wind speed errors on zonal wind speed (Figure A.5, bottom panel).

However, the situation is not the same for the comparison of TAO and scatterometer zonal winds. A clear increase in magnitude of the RMS difference between scatterometer and buoy zonal wind measurements is observed with the transition to more positive zonal wind speeds (Figure A.5, bottom panel). Given the role of westerly wind events in the initiation and maintenance of El Niño events, this discrepancy has the potential to impact seasonal forecast skill. The exact causes of this discrepancy are yet to be understood, and understanding this disagreement is recommended to be a future research priority.

(a) RMSD Between Scatterometer and TAO Wind Speed vs. TAO Zonal Wind



(b) RMSD Between Scatterometer and TAO Zonal Wind vs. TAO Zonal Wind

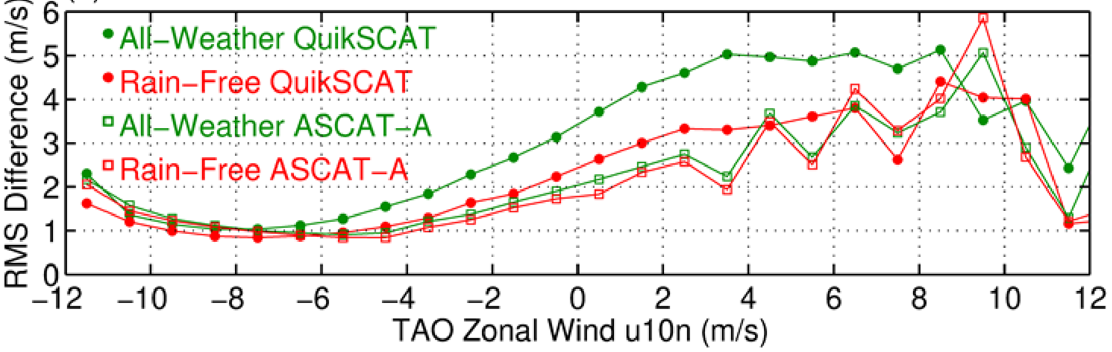


Figure A.5: Upper panel: RMS difference between wind speed from TAO and from QuikSCAT (green curves) and ASCAT-A (red curves) as a function of the TAO zonal wind. Lower panel: RMS difference between zonal wind component from TAO and from QuikSCAT (green curves) and ASCAT-A (red curves) as a function of the TAO zonal wind. There is a larger disagreement in the zonal wind component when the winds are eastward, but the RMS errors in speed do not have a pronounced dependence on zonal wind direction-- this suggests that there is a scatterometer wind direction error that occurs preferentially in conditions coinciding with westerlies. 55 TAO buoys were used for this analysis. The data record used for QuikSCAT spanned Nov 1999 to Oct 2009, and the ASCAT-A data record spanned Jan 2008 to Dec 2014. Precipitation data were from the 3-hourly TRMM 3B42 analysis.

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Appendix A – Acronym List

Table A.1: List of all acronyms from the Second Report text, including [information for reference or relatability] and (additional parts of the acronyms that are not part of the acronym proper).

4D-Var	Four dimensional variational data assimilation
ADCP	Acoustic Doppler Current Profiler
ASCAT	Advanced Scatterometer
ASV	Autonomous surface vehicle
ATOMMS	Active Temperature, Ozone and Moisture Microwave Spectrometer
AUV	Autonomous underway vehicle
BGC	Biogeochemistry/biogeochemical
BOM	Bureau of Meteorology [Australia]
BSISO	Boreal summer intra-seasonal oscillation
BSRN	Baseline Surface Radiation Network
CCMP	Cross-calibrated multi-platform
CDA	Coupled [ocean-atmosphere] data assimilation
CEOS	Committee on Earth Observation Satellites
CFOSAT	China-France Oceanography Satellite
CFOSCAT	China-France Oceanography Satellite Scatterometer
CGCMs	Coupled general circulation models
CLIVAR	Climate and Ocean: Variability, Predictability and Change
CMIP	Coupled Model Intercomparison Project
CO_2	Carbon dioxide
COARE	Coupled Ocean-Atmosphere Response Experiment
COSMIC	Constellation Observing System for Meteorology, Ionosphere, and Climate
CP	Central Pacific
CPC	Climate Prediction Center [NOAA]
CRDS	Cavity ringdown spectroscopy
CTD	Conductivity-temperature-depth/pressure [sensor]
CU	Cumulus
CYGNSS	Cyclone Global Navigation Satellite System
DA	Data assimilation
DAC	Data assembly center
DCF	Direct covariance fluxes
Dec-cen	Decadal to centennial
DIAL	Differential absorption lidar
DIC	Dissolved inorganic carbon
DIMAR	General Maritime Directorate the Ministry of Natural Defense of Colombia
DOC	Dissolved organic carbon

DOI	Digital object identifier
DYNAMO	Dynamics of Madden-Julian Observations
ECMWF	European Centre for Medium-Range Weather Forecasts
ECV	Essential Climate Variabile
EEZ	Exclusive economic zone
EnKF	Ensemble Kalman filter
ENSO	El Niño Southern Oscillation
ENW	Equivalent neutral wind
EOF	Empirical orthogonal function
EOVs	Essential Ocean Variables
EPAC/EP	Eastern Pacific
EPIC2001	East Pacific Investigation of Climate Processes in the Coupled Ocean-Atmosphere System 2001
ERA	ECMWF global atmospheric reanalysis product
ERDDAP	Environmental Research Division’s Data Access Program
ERSST	Extended reconstructed sea surface temperature
ESA	European Satellite Agency
ESDR	Earth Science Data Record
EUC	Equatorial Undercurrent
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FAIR	Findable, Accessible, Interoperable, Reusable
FOO	Framework for Ocean Observing
FRL	FOO Readiness Level
GCOS	Global Climate Observing System
GDAC	Global data assembly center
GDPFS	Global Data-processing and Forecasting Systems
GFDL	Geophysical Fluid Dynamics Laboratory
GHG	Greenhouse gas
GISS	Goddard Institute for Space Studies
GLODAP	Global Ocean Data Analysis Project for Carbon
GMF	Geophysical model functions
GNSS	Global Navigation Satellite System
GODAR	Global Oceanographic Data Archaeology and Rescue
GOES	Geostationary Operational Environmental Satellite Program
GOOS	Global Ocean Observing System

GO-SHIP	Global Ocean Ship-based Hydrographic Investigations Program
GPCs-ADCP	Global Producing Centres for annual to decadal climate prediction
GPCs-LRF	Global Producing Centres for long-range forecast
GPCP	Global Precipitation Climatology Project
GPS	Global Positioning System
GRASP	GOOS Regional Alliance for the Southeast Pacific
GRO	GNSS radio occultation
GTS	Global Telecommunication System
HOAPS	Hamburg Ocean Atmosphere Parameters and Fluxes from Satellite Data
ICOADS	International Comprehensive Ocean-Atmosphere Data Set
IFREMER	Institut Français de Recherché pour l'Exploitation de la Mer
IFS	Integrated Forecasting System [of ECMWF]
IMARPE	Instituto del Mar del Peru
IOC	Intergovernmental Oceanographic Commission (of UNESCO)
IPO	Interdecadal Pacific Oscillation
IROWG	International Radio Occultation Working Group
ISCCP	International Satellite Cloud Climatology Project [NASA]
ISOs	Intraseasonal oscillations
ITCZ	Intertropical Convergence Zone
ITF	Indonesian throughflow
JAMSTEC	Japan Agency for Marine-Earth Science and Technology
JCOMM	Joint Technical Commission for Oceanography and Marine Meteorology
JCOMMOPS	Joint Technical Commission for Oceanography and Marine Meteorology in situ Observations Programme Support
JGOFS	Joint Global Ocean Flux Study
JMA	Japan Meteorological Agency
JOFUROv3	Japanese Ocean Flux Data sets with Use of Remote Sensing Observations
JPL	Jet Propulsion Laboratory [NASA]
KIOST	Korea Institute of Ocean Science and Technology

LC-LRFMME	Lead Center for Long-range Forecasts Multi-Model Ensembles
LEO	Low Earth orbit (satellites)
LIDAR	Light detection and ranging
LIO	LEO-LEO infrared laser
LLWBC	Low latitude western boundary current
LMD	Laboratoire de Météorology Dynamique
LMIO	LMO and LIO combined technology
LMO	LEO microwave occultation
LW	Longwave
MJO	Madden Julian Oscillation
MODIS	Moderate resolution imaging spectroradiometer
MOM	Modular Ocean Model
N_2O	Nitrous oxide
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction [NOAA]
NCP	Net community production
NDBC	National Data Buoy Center [NOAA]
NEC	North Equatorial Current
NECC	North Equatorial Counter Current
NEMO	Nucleus for European Modelling of the Ocean
NIES	National Institute for Environmental Studies [Japan]
NINO3.4	A defined region that serves as a sea surface temperature index
NOAA	National Oceanic and Atmospheric Administration
NPDO	North Pacific Decadal Oscillation
NPGO	North Pacific Gyre Oscillation
NPMM	North Pacific meridional mode
NPOCE	Northwest Pacific Ocean Circulation and Climate Experiment
NWP	Numerical Weather Prediction
NWPO	Northwestern Pacific Ocean
O_2	Dissolved oxygen
OCO-2	Orbiting Carbon Observatory-2 [NASA Satellite]
OI	Optimum interpolation
OLR	Outgoing longwave radiation
OMZ	Oxygen minimum zone
OSE	Observing system experiment
OSSE	Observing system simulation experiments
PBL	Planetary Boundary Layer
$p\mathrm{CO}_2$	Partial pressure of carbon dioxide

PDO	Pacific Decadal Oscillation
PgC	Petagrams of carbon
PI	Principal investigator
PIC	Particulate inorganic carbon
PID	Persistent identifiers for data and products
PIRATA	Prediction and Research Moored Array in the Tropical Atlantic
PISTON	Propagation of Intra-Seasonal Tropical Oscillations
PMEL	Pacific Marine Environmental Laboratory [NOAA]
PMM	Pacific Meridional Mode
POC	Particulate organic carbon
PRAWLER	Profiling Crawler
PRP	Pacific Regional Panel (of CLIVAR)
QC	Quality control
RAMA	The Research Moored Array for African-Asian-Australian Monson Analysis and Prediction
RMS	Root-mean-square
S2IP	Subseasonal to seasonal and interannual prediction
S2S	Subseasonal to seasonal
SC	TPOS 2020 Steering Committee
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SENAMHI	Servicio Nacional de Meteorología e Hidrología
SKIM	Sea surface Kinematics Multiscale monitoring (satellite mission)
SOA	State Oceanic Administration
SOCCOM	Southern Ocean Carbon and Climate Observations and Modeling (Project)
SOG	Speed over ground
SPCZ	South Pacific Convergence Zone
SPDO	South Pacific Decadal Oscillation
SPICE	Southwest Pacific Ocean Circulation and Climate Experiment
SPMM	South Pacific Meridional Mode
SPURS	Salinity Processes in the Upper Ocean Regional Study
SSH	Sea surface height
SSS	Sea surface salinity
SST	Sea surface temperature
STCs	Subtropical-tropical cells
SW	Shortwave
TA	Total alkalinity
TAO	Tropical Atmosphere-Ocean [mooring array]
TCs	Tropical cyclones

TIWs	Tropical instability waves
TMA	Tropical Moored Array
TOGA	Tropical Ocean-Global Atmosphere (programme)
TPOS	Tropical Pacific Observing System [refers to the observing system]
TPOS 2020	Tropical Pacific Observing System 2020 Project [Refers to the Project]
TRITON	Triangle Trans-Ocean Buoy Network
TRMM	Tropical Rainfall Measuring Mission [NASA]
TRL	Technical Readiness Level
UOP	Upper Ocean Processes [WHOI Research group]
VOS	Voluntary Observing Ships
VRE	Virtual research environments
WaCM	Winds and Currents Mission
WCDA	weakly coupled data assimilation
WCRP	World Climate Research Programme
WGNE	Working Group on Numerical Experimentation
WHOI	Woods Hole Oceanographic Institution
WIGOS	WMO Integrated Global Observing System
WIS	WMO Information System
WMO	World Meteorological Organization
WOCE	World Ocean Circulation Experiment
WOD	World Ocean Database
WPSH	Western Pacific Subtropical High
WRF	Weather Research and Forecasting (Model)
WWRP	World Weather Research Programme
XBT	Expendable bathythermograph
xCO_2	Mole fraction of carbon dioxide in dry air
YMC	Years of the Maritime Continent

Appendix B – Summary of Recommendations and Actions

B.1 Second Report Recommendations

Recommendation 2.1. Establish a systematic and planned cycle of work among the participants in seasonal prediction, including (i) a planned and systematic cycle of experimentation; (ii) a coordinated set of process and/or case studies, and (iii) routine and regular real-time and offline system evaluation. An independent assessment should occur across all elements every five years.

Recommendation 2.2. Increase support for observing system sensitivity and simulation experiments to identify observations that constrain models most effectively and have high impact on forecasts. Correspondingly, development of infrastructure for exchanging information about data utilization and analysis increments should be supported.

Recommendation 2.3. Increase support for the validation and reprocessing of ocean and atmospheric reanalyses; conduct TPOS regional reanalyses and data reprocessing to guide observing system refinement and to enhance the value of TPOS data records.

Recommendation 3.1. Where feasible and practical, promote observing approaches that jointly measure the ocean and marine boundary layers, and air-sea flux variables, principally to support model development, as well as testing and validation of data assimilation methods and systems [refer to sections 3.3.3.1 and 3.3.3.2; also 7.2.1.1]

Recommendation 3.2. Encourage and promote process studies that will improve the representation of key processes and allow further testing of the ability for observations to constrain the coupled system, to address biases in observations and models, and to improve CDA observation error estimates. [refer to sections 3.2, 3.3.1 and 3.3.2]

Recommendation 3.3. Promote and engage with the WGNE-WCRP Subseasonal-to-Seasonal subproject on Ocean Initialization and Configuration.

Recommendation 4.1. TPOS 2020 recommends a target of 124 BGC-Argo floats with biogeochemical sensors (specifically nitrate, dissolved oxygen, pH, chlorophyll fluorescence, particulate backscatter and downwelling irradiance) for the 10°N-10°S band.

Recommendation 4.2. TPOS 2020 recommends CTDs with dissolved oxygen and optical sensors (chlorophyll fluorescence, particulate backscatter, transmissometer) and water samples (at a minimum for chlorophyll and nutrients) should be performed to 1000 m along each TMA line by servicing cruises, at every degree of latitude between 8°N and 8°S and every 0.5° between 2°N and 2°S at a frequency of at least once per year. Twice per year sampling is optimal and could be augmented by GO-SHIP and other ships of opportunity.

Recommendation 5.1. The existing TMA line along 95°W should be maintained and updated to full-flux sites (see section 7.3.1).

Recommendation 5.2. Increase Argo density for the EPAC as soon as possible (see section 7.4.4 and Figure 7.19 for initial implementation guidance). A coordination of South

American countries to execute the doubling of Argo will be required. (Also see ***Recommendation 4.1*** and ***Action 7.9***).

Recommendation 5.3. A pilot study along 95°W installing dissolved oxygen sensors to 200 m and an ADCP is recommended at the equator, with additional dissolved oxygen and current sensors on 2°N and 2°S if at all possible (section 5.1.4).

Recommendation 5.4. TPOS 2020 recommends planning and execution of a reanalysis project for the eastern Pacific, making use of past and current data sets, as well as hydrographic sections between the Galapagos Islands and the coast. This reanalysis effort should include high-resolution regional atmospheric products that resolve important coastal winds, and ensembles for estimating uncertainty (section 5.2).

Recommendation 7.1. TPOS 2020 recommends the adoption of and support for a refocused design for the tropical moored buoy array, with a three-tiered approach to instrumentation. These comprise the Tier 1 baseline with enhanced surface and upper ocean measurements over the existing array; Tier 2 with added velocity observations in the mixed layer; and Tier 3, intensive Super Sites that might be used in a campaign mode.

Recommendation 7.2. To ensure that the TPOS observing platforms collect the accurate and interoperable measurements required to detect small [climate or "dec-cen"] signals, a series of actions should be taken, beginning before the rollout and continuing during implementation, to assess the performance and impact of the proposed platform/sensor changes.

Updated Recommendation 10*: Continuity of complementary satellite and in situ SSS measurement networks, with a focus on improved satellite accuracy to augment the spatial and temporal sampling of SSS*

Recommendation 7.3.Improvement of dedicated capacities on servicing ships to allow repeated ancillary measurements. Underway measurements such as Shipboard Acoustic Doppler Current Profilers, $p\mathrm{CO}_2$ and sea surface salinity should be systematically acquired.

Recommendation 8.1. As an underlying principle, around 10% of the investment in the TPOS should be directed towards data and information management, including for emerging and prototype technologies.

Recommendation 8.2. Data stewardship and the engagement of all TPOS 2020 stakeholders in data management must be a central platform in the sustainability of the TPOS. The FAIR Principles should be adopted as a basis for TPOS engagement.

Recommendation 8.3. TPOS 2020 should develop a project around the management of all TMA data including, to the extent possible, recovery and re-processing of other relevant mooring data.

Recommendation 8.4. TPOS 2020 should develop a pilot project, in conjunction with the WMO Information System effort, to explore the global distribution of TPOS data in near-real time.

Recommendation 9.1. That the Backbone Readiness Level framework be further developed and refined by TPOS 2020 before adoption.

B.2 Second Report Actions

Action 2.1. Further increase support for process studies to improve parameterization of specific processes that have larger than local impacts and whose representation in models is suspect. Although sustained observations are essential to support operational services, TPOS 2020 recognizes that investments in process studies will be critical for reducing model biases to enhance the efficacy of sustained observations.

Action 5.1. Focus regional coordination efforts on engaging Peruvian institutes to implement real-time sharing of surface oceanographic data (e.g., SST) as part of the Backbone through the WMO Information System, with the support of SENAMHI and JCOMMOPS. This effort could then be a model implemented by other countries in the region (e.g., in GRASP) and, eventually, evolve into subsurface data sharing. An ocean reanalysis project or OSE experiments are two activities that TPOS 2020 could use to motivate these efforts. The pilot study in Action 5.2 and discussed in section 5.3.1 would also help motivate coordination in the region.

Action 5.2. Coordinate a pilot program with Peru, Ecuador and Chile focused on the equatorial and coastal waveguide and upwelling system (section 5.3.1). It is recommended that this pilot study be in conjunction with ocean reanalysis and OSE activities to best utilize existing and new data sets in products for research and operational applications. Develop a reanalysis product from this pilot (and the glider program being started by Peru) to understand how new observations affect ocean reanalysis and forecast products before any additional new sustained measurements in the eastern Pacific are recommended.

Action 5.3. Initiate a process study to investigate the atmosphere and upper ocean in the cold tongue/SPCZ/stratus regions in austral summer when the double ITCZ is observed in nature (section 5.3.2). The process study should observe spatial structure of the surface fluxes; e.g., from Saildrone or similar platforms (sections 9.2.1 and 9.2.2). A coordinated regional coupled modeling study making use of these observations is also strongly recommended to help advance issues with the long-standing coupled model biases in the region.

Action 5.4. Initiate a pilot island observing system at select islands in the EPAC to address the goals discussed in section 5.3.3. It is recommended that this pilot be initiated in the same year as the pilot and process studies discussed in Actions 5.2 and 5.3.

Action 5.5. Work with the Intergovernmental Oceanographic Commission to include the eastern Pacific in the Roadmap for the United Nations Decade of Ocean Science for Sustainable Development (2021–2030), as the benefits of capacity development are disproportionately large for this region compared to other regions in the tropical Pacific.

Action 6.1. Studies should be undertaken to better understand sampling errors in scatterometer wind products and the impacts of sampling differences between satellite and buoy winds (Section A.2).

Action 6.2. Efforts to make, evaluate, and improve gridded wind products that synthesize data from multiple platforms should be prioritized (funded) (Section A.3).

Action 6.3. The directional dependence of buoy/scatterometer wind differences needs to be investigated and understood (Section A.4).

Action 6.4. Continue discussion with the satellite and in situ precipitation experts to evolve the TPOS 2020 recommendations for in situ rain gauges and complementary measurements.

Action 7.1. TPOS 2020 Task Teams should work with community experts to specify the Tier 1 sites where salinity, rainfall, and barometric pressure are most needed in addition to the core measurements.

Action 7.2. TPOS 2020 Task Teams to work with community experts to specify the priority sites for Tier 2 deployments, based on the results of the pilot currently underway and analysis of where ocean velocity measurements are most needed.

Action 7.3. The exact location of the moorings poleward of 8°S under the SPCZ needs to be further explored, in consultation with community experts and regional partners.

Action 7.4. Drive further dialogue with agencies in the Committee of Earth Observation Satellites (CEOS) to explore, where feasible, improving data availability, the diurnal spread of sampling by vector wind measuring satellite missions, and ensuring missions meet the TPOS requirements of coverage (Recommendation 1, First Report).

Action 7.5. Continue to highlight the ongoing need and benefits of follow-on satellite SSS missions as a key component of the TPOS.

Action 7.6. Underway $p\mathrm{CO}_2$ observations should be continued or established on all mooring servicing vessels. Pilots of $p\mathrm{CO}_2$ measurements from AUVs (e.g., Saildrone or Wave Glider) should continue as a potential means to drive up spatial and temporal sampling.

First Report, updated Action 1 The TMA sites in the western Pacific within 2°S to 2°N should be maintained or reoccupied.

Action 7.7. In preparation for TMA-wide usage, Tier 1 ‘full flux’ moorings from all contributing operators should be piloted, intercompared and assessed. Building on past work on the TMA, instrument calibration and quality control procedures should be further developed.

Action 7.8. A pilot of enhanced thermocline velocity measurements at established sites at 140°W, 2°N/S should be planned, and if successful, extended to include the new sites at 1°N/S. Similar pilots should be carried out at the new sites in the northwest Pacific Ocean.

Action 7.9. Argo float deployments should be doubled over the entire tropical region 10°S-10°N, starting immediately in the western Pacific, followed by the eastern Pacific and extending to the entire region, building to a total annual deployment rate of 170/year. Of these, 31 should be equipped with biogeochemical sensors (BGC-Argo).

Action 7.10. TPOS 2020 Task Teams, implementation groups and community experts should develop and detail whole of system assessment activities, describing them in the final TPOS 2020 report (or earlier). Part of the assessment should include the tradeoffs between the number of sites versus the ability to maintain continuous records.

Action 7.11. For each specialized data stream or platform (e.g., buoys), ensure the creation of an engaged team of experts to oversee sensor management, develop QC procedures and guide the delayed-mode QC for the TPOS data streams. (Also see Recommendation 8.3)

Action 7.12. TPOS 2020 Task Teams should develop and articulate the Tier 3 concept, including possible approaches to determination of appropriate times, locations, and measurements.

Action 7.13. Continue efforts toward estimating SST diurnal cycle of skin temperature, by better incorporating remote microwave, vis/IR, and in situ data at various depths.

First Report Reprised Action 14 Through the TPOS 2020 Resources Forum, the TPOS 2020 Transition and Implementation Group, and links to research programs and funders, support should be advocated for *Pilot and Process Studies* that will *contribute to the refinement and evolution of the TPOS Backbone.*

Action 8.1. TPOS 2020 should develop data management projects in parallel with the development of a Low-Latitude Western Boundary Current Pilot Project (TPOS OceanObs'19; section 7.4.5.1) and Eastern Pacific regional activities (section 5.2, ***Action 5.1***) to enhance the recognition and adoption of the FAIR principles and to re-process data that would otherwise be lost.

Action 9.1. TPOS 2020 to assess all candidate technologies, platforms and methods against the Backbone criteria for efficiency, effectiveness and extension.

Action 10.1. The TPOS 2020 Resource Forum and Steering Committee, in consultation with the broader TPOS community, further develop and seek agreement on post-2020 governance arrangements.

B.3 First Report Recommendations

Recommendation 1 A constellation of multi-frequency scatterometer missions and complementary wind speed measurements from microwave sensors to ensure broad-scale, all-weather wind retrievals over 90% of the tropical Pacific Ocean every 6 hours for the next decade and beyond with different equatorial crossing times to capture the diurnal cycle.

Recommendation 2 In situ vector wind measurements, with particular emphasis on extending the in situ based climate data records, and intercalibrating different satellite wind sensors especially in the equatorial Pacific and in tropical rainy areas.

Recommendation 3 Sustaining satellite measurements of SST, using infrared sensors for higher spatiotemporal sampling; passive microwave sensors filling gaps under clouds; and the diversity of satellite and in situ platforms contributing to intercalibration.

Recommendation 4 Maintenance of the current level of in situ SST observations and improvement of drifter SST quality. Both will contribute to satellite SST calibration and validation, as well as providing an independent reference dataset for the SST climate record. Specifically target convective and rainy areas for SST ground truth, while keeping SST in situ measurements on moorings in the equatorial region.

Recommendation 5 Continuation of the high-precision SSH measurements via the Jason series of satellite altimeters for monitoring large-scale SSH, and the continuing development of wide-swath altimetry technology to measure meso- and submesoscale SSH variations that are particularly energetic in crucial regions including the western boundary.

Recommendation 6 Maintenance of in situ tide gauge measurements for the calibration and validation of satellite SSH, upgraded with global navigation satellite system referencing and complemented by sustained temperature and salinity profile measurements.

Recommendation 7 Continuation of ocean mass measurements to complement satellite SSH and Argo-derived steric height measurements, and in situ bottom pressure sensors to help calibrate and validate satellite-derived estimates.

Recommendation 8 Continuation and enhancement of international collaboration for precipitation-measuring satellite constellations to sustain the spatiotemporal sampling of precipitation measurements in the tropics.

Recommendation 9 Continuation and expansion of open-ocean in situ precipitation measurements for the evaluation and improvement of satellite-derived products, especially for providing a long-term climate record.

Recommendation 10 Continuity of complementary satellite and in situ SSS measurement networks, with a focus on improved satellite accuracy.

Recommendation 11 Continuation of technological developments to measure ocean surface currents remotely, and of in situ measurements of surface and near-surface currents, particularly near the equator. Provide collocated measurements of wind and surface currents.

Recommendation 12 Continuation of high-frequency, moored time series and broad spatial scale underway surface ocean pCO2 observations across the Pacific from 10°S to 10°N.

Recommendation 13 Continuation of advocacy for ocean color satellite missions with appropriate overlap to facilitate intercalibration for measurement consistency. In situ measurements of chlorophyll-a and optical properties for the validation of satellite ocean color measurements are required.

Recommendation 14 From 10°S to 10°N, observations of subsurface biogeochemical properties are required, including chlorophyll concentration, particulate backscatter, oxygen and nutrients. Enhanced focus is needed for the eastern edge of the Warm Pool and the east Pacific cold tongue.

Recommendation 15 Enhancing in situ observations of state variables needed to estimate surface heat and freshwater fluxes in the west Pacific warm pool, along the equator, and along meridional lines from the seasonal southern ITCZ across the equator, the frontal zone and Northern Hemisphere ITCZ in the western Pacific, the trade wind region of the central and eastern Pacific and the southerly regime of the eastern Pacific.

Recommendation 16 A combination of fixed-point moorings, profiling floats and lines/sections from ships to meet the sustained requirement for subsurface temperature and salinity observations. Integration through data assimilation and synthesis is needed to produce the required gridded fields.

Recommendation 17 Enhancing meridional resolution of temperature and salinity in the equatorial zone through a mix of (a) additional moorings near the equator and (b) targeted enhancement of Argo profiles in the equatorial zone (approximately doubling density).

Recommendation 18 Enhancing vertical temperature and salinity resolution from the TMA via additional upper ocean sensors on moorings from the top of the thermocline to the surface, and returning Argo profiles at 1 dbar resolution from 100 dbar to the surface (or as close as is practical).

Recommendation 19 Maintenance and, potentially, augmentation of the sampling depth range of current profiles on the existing equatorial moorings, and enhancement of the meridional resolution of velocity along targeted meridians by additional moorings near the equator.

Recommendation 20 Doubling the density of Argo temperature and salinity profile observations through the tropics (10°N–10°S), to deliver improved signal-to-noise ratios (better than 4:1) at weekly timescales, starting with the western Pacific and the equatorial zone.

Recommendation 21 Continued support for in situ observations from drifters, ships, tide gauges and reference mooring sites.

Recommendation 22 A coordinated program of (a) data assimilation studies to assess the effectiveness of the TPOS 2020 Backbone design; and (b) studies on the utilization and influence of observational data among an appropriate subset of ocean analysis systems.

B.4 First Report Actions

Action 1 Six TMA sites in the western Pacific within 2°S to 2°N should be maintained or reoccupied.

Action 2 Argo deployments should immediately be doubled equatorward of 10° in the west (especially outside the TMA-occupied region) to maintain subsurface temperature and salinity sampling and compensate for the declining TMA.

Action 3 Argo float deployments should be doubled over the entire tropical region 10°S-10°N, and return increased upper ocean vertical resolution.

Action 4 Through the TPOS 2020 Backbone Task Team and the Argo Steering Team, further explore how to optimize float deployments and missions to better deliver to TPOS goals.

Action 5 Moorings at 1°S and 1°N at selected longitudes should be added to enhance the resolution of near-equatorial dynamics. Enhancement of instrumentation on all moorings spanning 2°S and 2°N at these longitudes should be targeted, including velocity profiles as feasible.

Action 6 A staged reconfiguration of the TMA should emphasize enhancement in key regimes.

Action 7 Promote and support sensitivity and impact studies of wind and wind vector data inputs on operational analysis and reanalysis and specialized wind stress products, including their application to climate change detection. The effectiveness of rain metadata flags and various approaches to crosscalibration of scatterometers should also be considered.

Action 8 Renew and help coordinate efforts to understand the sensitivity and diagnose the impact of TMA air-sea flux variables in weather prediction, atmospheric reanalyses and coupled models, including through existing activities focused on the impact of observations.

Action 9 The Transition and Implementation Group (see section 7.7) should initiate discussion with TPOS stakeholders on sustainable solutions for the distinct implementation problems of the western and eastern Pacific regions, especially for the needed TMA contributions.

Action 10 All equatorial mooring sites should be upgraded to flux moorings.

Action 11 Meridional lines of flux sites should be extended from the equator to intersect both the SPCZ and ITCZ in the west, and across the ITCZ, the cold tongue and the seasonal southern ITCZ in the east.

Action 12 Underway pCO2 observations should be continued or reinstated on all mooring servicing vessels, and the present network of moored pCO2 measurements should be maintained and possibly extended. Measurements of dissolved oxygen from the surface to about 1500 m should be made on ships where practical, and oxygen sensors should be considered on each mooring.

Action 13 To mitigate risks in meeting surface flux requirements associated with changes in the TMA, TPOS 2020 seeks (a) enhanced sampling by VOSClim and other in situ systems for flux variables, (b) support for relevant new technology developments and (c) encourages efforts to improve the realism of reanalysis and possibly real-time NWP flux products through output correction/flux adjustment techniques.

Action 14 Through the TPOS 2020 Resources Forum, the TPOS 2020 Transition and Implementation Group and links to research programs and funders, support should be advocated for Pilot and Process Studies that will contribute to the refinement and evolution of the TPOS Backbone.

Action 15 In consultation with key stakeholders, including GOOS, JCOMM, WMO/WIGOS and GCOS, a transition process should be initiated, including the creation of a TPOS 2020 Transition and Implementation Group, for overseeing implementation of TPOS 2020 Recommendations and Actions

Appendix C – Acknowledgments

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