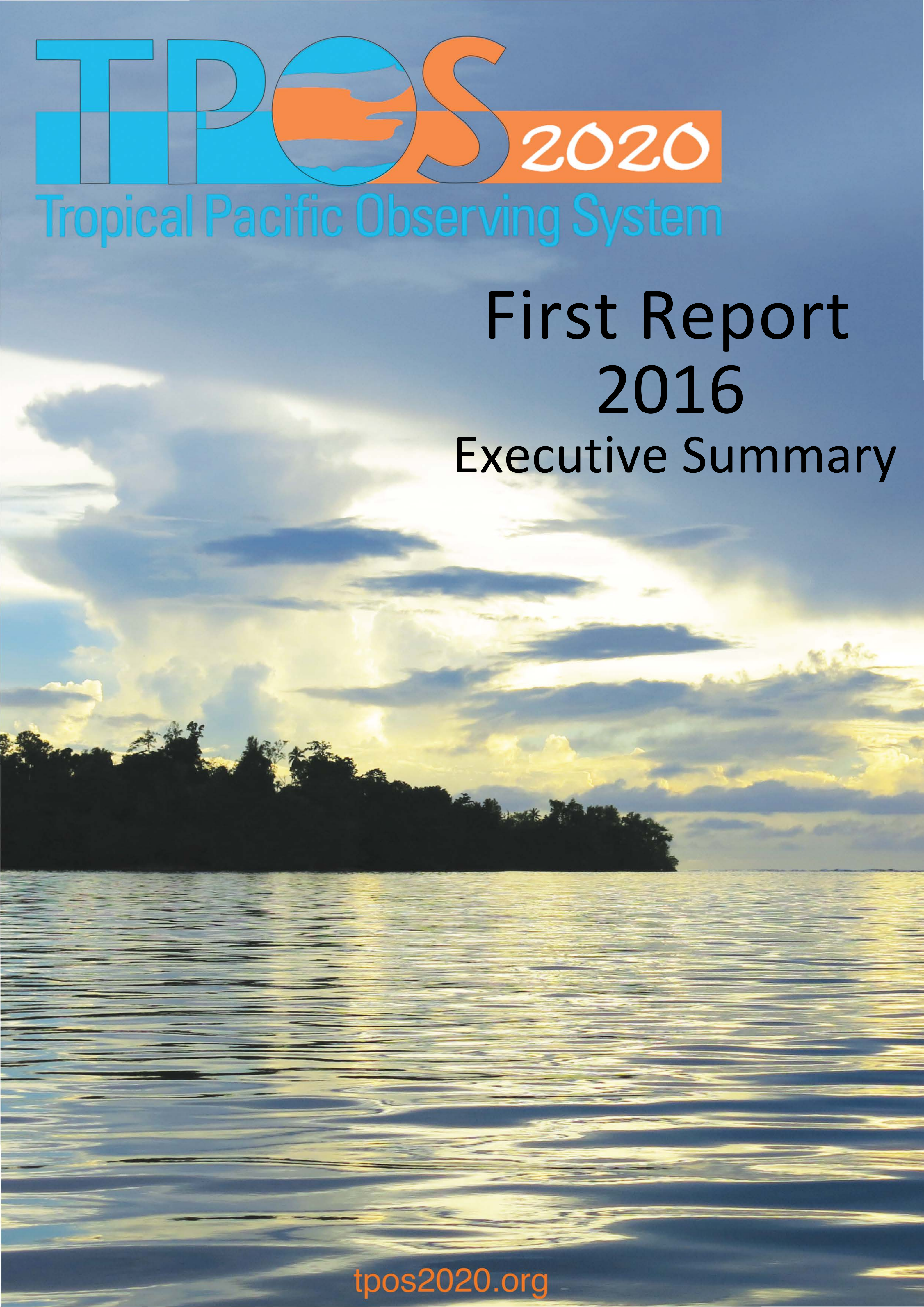
Tropical Pacific Observing System

First Report 2016

Executive Summary



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First Report of TPOS 2020

Executive Summary

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Coordinating Lead Authors: Sophie Cravatte, William Kessler, Neville Smith and Susan Wijffels

Contributing Authors: Lisan Yu, Kentaro Ando, Meghan Cronin, Tom Farrar, Eric Guilyardi, Arun Kumar, Tong Lee, Dean Roemmich, Yolande Serra, Janet Sprintall, Pete Strutton, Adrienne Sutton, Ken Takahashi, and Andrew Wittenberg

See Appendix C in the full report for the complete list of authors, contributors and reviewers.

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Executive Summary

TPOS 2020 (Tropical Pacific Observing System 2020 project) is a once in a generation opportunity to enhance and redesign international observations of the tropical Pacific. Variability of this strongly coupled atmosphere-ocean system reverberates across the global climate and provides a principal source of interannual climate predictability extending worldwide.

The main driver of the project is an identified significant risk to El Niño–Southern Oscillation (ENSO) predictions and associated services due to the deterioration of the tropical moored buoy array (TMA) in the Pacific in 2012-2014. The TPOS network aims to mitigate this risk as well as to accelerate advances in the understanding and prediction of tropical Pacific variability and its profound consequences to multiple sectors, ranging across agriculture, marine ecosystems, human health and disaster preparedness, around the globe. In response to other science drivers, especially climate, TPOS 2020 will continue key observational records, intensify monitoring of key upper ocean/surface atmosphere parameters and phenomena, include ocean biogeochemistry and expand to both the eastern and western boundary regions.

This report lays out the rationale and plans for the first step of the redesign and enhancement of the TPOS. It aims to provide sponsors with a means to justify and defend current and future investments in both sustained and experimental observations in the tropical Pacific. This report focuses on the fundamental and core contributions to the sustained observing system (herein referred to as the Backbone of the TPOS) and is organized around five key functions [1.3][1]:

(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.

The redesign builds on the foundations of the 1985-1994 Tropical Ocean – Global Atmosphere (TOGA) program and the many innovations and enhancements since that era [2.2, 2.3]. The many public benefits stemming from ENSO monitoring and prediction and its supporting scientific research remain a primary motivation for the TPOS. The network also provides a foundation for improved weather and ocean forecasts, as well as climate and marine environmental monitoring services. Such public good

[1] Section references from the main report are given in square brackets

services demand a reliable, effective sustained TPOS [2.1, 2.2, 2.4]. This report outlines both the initial recommendations and actions to meet the demands of 2020 and beyond [5, 7].

The TPOS has been highly successful in the 20 years since TOGA [2.5], providing a foundation for improved understanding and for developing the many services that have emerged over that period [2.4]. TPOS 2020 revisits requirements while taking account of science issues and new understanding that has come to the fore, and the greater sophistication of the analyses, modeling, and prediction systems as well as services that are now in place or being developed [3.1]. The TPOS design is reconsidered to take advantage of advances in new technology, both satellite and in situ, and to deliver increased efficiency, effectiveness and reliability, refocusing observations on the needs of the coming decades. The requirements are first developed for Essential Ocean and Climate Variables[2] and, to the extent possible, they are characterized in terms of spatial and temporal sampling, regime dependencies, accuracy, quality and the need for continuity, as appropriate [3.1.1, 3.1.2, 3.1.3]. The requirements are also driven by the need to sustain and improve the climate record [3.2].

New targets for improved understanding and model development include the ocean mixed layer and the surface fluxes that interact with it; the diurnal cycle; equatorial ocean-atmosphere coupled physics; the Pacific boundary regions; and biogeochemistry, especially the large air-sea carbon fluxes [3.3]. These requirements will be met by a combination of sustained and experimental networks.

The new TPOS 2020 approach lessens the reliance on any single platform and harvests some of the efficiencies available from recent technological developments [7.6]. Key regimes will be observed comprehensively for the first time, delivering benefits to coupled model development, better system-wide gridded products and understanding more generally. TPOS enhancements will enable much-needed improvements to operational modeling systems; improvements that have proved elusive.

Principles are developed to guide the design for the new Backbone and its implementation [4, 7.1]. These include a coherent joint consideration of satellite and in situ platforms, exploiting their capabilities to reduce uncertainty in the climate record of the tropical Pacific [5] and introducing Pilot and Process Studies [6] that will inform further refinement of TPOS during and after the conclusion of the Project in 2020.

The next section of this Summary outlines the ocean variable **requirements** and the associated **recommendations** for the observing system, while the following section, Implementation, focuses on key **actions**. The order in which recommendations and actions are stated here does not imply priority, and in some cases differs from their order in the main text of the report.

[2] The Essential Ocean and Climate Variables, appearing in the next section of the Summary, are shown in ***bold italics***

To the extent it is possible at this stage in TPOS 2020, the report includes estimates of the cost against significant items. The Recommendations and Actions are feasible and implementable, but proper costing will only be possible after deeper dialogue with those responsible for implementing the TPOS.

REQUIREMENTS AND RECOMMENDATIONS

Climate change monitoring and detection requires stringent accuracy, duration and continuity that flow through all the essential climate variables. Delivering such a climate record demands appropriate redundancy and resiliency against failures of the system components that might otherwise cause damage [3.2.1].

❑ TPOS requires unbiased accurate ***surface wind/wind stress*** with good spatial and temporal coverage, including in high rain regions and low- and high-wind regimes. It is important to maintain long time series of in situ winds for intercalibration and to underpin the climate record, especially in the equatorial Pacific and strong convection and precipitation areas [3.1.1.2, 3.2.1, 5.1]. Monitoring frontal and other small-scale processes requires that vector wind fields resolve gradients at scales no larger than 50 km [3.3.2]. Surface currents are also needed to reconcile differences between scatterometer and in situ winds [see Recommendation 11]. TPOS 2020 recommends:

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.

❑ 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 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.

❑ High-accuracy broad-scale ***sea surface height (SSH)*** sampling is required for climate as well as smaller scale (to submesoscale) for initialization of ocean prediction models. Ocean mass (gravity or bottom pressure) sampling should be maintained [3.1.2.1, 3.1.2.2, 3.3.4, 5.3]. TPOS 2020 recommends:

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 (see below).

Recommendation 7 Continuation of ocean mass measurements to complement satellite SSH and profile-derived steric height measurements, and in situ bottom pressure sensors to help calibrate and validate satellite-derived estimates.

❑ Satellite ***precipitation*** measurements, evaluated against in situ data across diverse climate regimes are required. Rain-rate and collocated wind speed and direction sampling is particularly important in the convective regions of the western equatorial Pacific and under the Intertropical and South Pacific Convergence Zones [3.1.1.2, 3.1.1.5, 5.4]. TPOS 2020 recommends:

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.

❑ Broad-scale ***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.

❑ ***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 model 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; and

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.

❑ Air-sea carbon dioxide (CO_2) flux requirements are partially addressed by the existing high-quality sea surface partial pressure of CO_2 (***p*CO_2**) sampling. These observations quantify the seasonal to interannual variability in CO_2 fluxes impacted by ENSO and advance understanding of natural variability in the context of human-induced change [3.1.1.4, 3.3.5]. TPOS 2020 recommends:

Recommendation 12 Continuation of high-frequency, moored time series and broad spatial scale underway surface ocean $p$$CO_2$ observations across the Pacific from 10°S to 10°N .

❑ Broad-scale surface ***ocean color*** measurements are required, with sufficient resolution to diagnose regime boundaries and with sufficient accuracy to diagnose seasonal changes. There is an additional requirement for in situ sampling for chlorophyll-a to validate remotely sensed ocean color measurements [3.1.1.4, 5.7]. TPOS 2020 recommends:

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.

❑ Understanding seasonal biogeochemical processes requires measurements at semi-annual timescales, spanning the tropical Pacific from 10°S to 10°N, augmented by high-frequency observations at selected sites [3.3.5]. In order to properly understand CO_2 dynamics, one needs to understand variations in ***oxygen***, which is consumed at depth during the recycling of organic matter (e.g., phytoplankton) produced at the surface. Expanding oxygen minimum zones have fundamental implications for marine life. TPOS 2020 recommends:

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.

❑ Comprehensive sampling both of the state variables needed to estimate turbulent ***heat fluxes*** (SST, air temperature, humidity, wind and surface currents), and of the ***radiative fluxes*** (downwelling solar radiation, downwelling longwave radiation and emissivity) is needed in the full range of climatic/weather regimes and key oceanic regimes [3.1.1.3, 5.8]. These are essential to evaluate and improve atmospheric reanalyses, satellite-based surface flux estimates and coupled data assimilation systems, and to improve our understanding of the exchanges between the atmosphere and ocean in these different regimes. TPOS 2020 recommends:

Recommendation 15 In situ observations of state variables needed to estimate surface heat and freshwater fluxes should be enhanced in key regions. These include the west Pacific warm pool, along the equator, and on several meridional lines extending from the SPCZ and seasonal southern ITCZ, across the equator through the northern hemisphere ITCZ.

❑ TPOS 2020 supports efforts to increase the number of surface drifters and moorings measuring ***sea level pressure*** [3.1.2.4, 7.4.1].

❑ Sea surface waves (***sea state***) change surface stress at low wind speeds and are important for coastal sea level and related impacts. A few permanent directional wave buoys in the tropical Pacific would complement and validate satellite wave data [3.1.2.3].

❑ Broad-scale sampling of ***subsurface temperature and salinity*** is required, with enhanced resolution through the tropics (approximately 2° x 2° resolution), and better meridional spacing (100 km) and increased vertical resolution (10 m or finer) in the equatorial region. Stable and accurate deep profiles are required. An additional target is to resolve near-surface salinity stratification, especially in the Warm Pool region, at its eastern edge and under persistent rain bands.

For improved understanding of phenomena and processes, finer vertical resolution is required above 100 m depth. Sampling within 2°S-2°N should be sufficient to resolve meridional gradients. Profiles in the west-central equatorial region should resolve phenomena at timescales no longer than 5 days [3.3.1, 3.3.2, 3.3.3, 3.3.4.1].

Better resolution of the physical fields will aid interpretation and modeling of biogeochemical processes. Most of the platforms used for enhanced temperature and salinity can accommodate in situ biogeochemical observations [3.3.5].

The diversity of ENSO and its future changes will require sampling of the tropical Pacific environment to follow ENSO's spatiotemporal patterns and underpin improved ENSO prediction and model forecast skills.

TPOS 2020 recommends [4, 5.9]:

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 practical); and

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.

❑ Other existing in situ components should continue to be supported. These include the surface drifter network; underway data collected from Voluntary Observing Ships 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.

❑ Modeling and data assimilation are fundamental elements of the TPOS design and critical for delivering integrated products of value to stakeholders, including predictions and synthesized gridded fields. We outline work to provide additional guidance for the TPOS 2020 design, identify the causes of coupled model biases and assess the influence of observational data on ocean analyses and other products [3, 4, 6.1.6, 6.1.7, 7.5]. TPOS 2020 recommends:

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.

IMPLEMENTATION

This report provides advice to sponsors on near-term implementation actions with respect to platforms and other technical aspects, consistent with the above requirements and recommendations. The focus on the near-term generally precludes specific actions related to satellites; the reader is referred to the recommendations for relevant guidance.

It is critical that all recommendations and actions from TPOS 2020 are subject to careful consideration prior to implementation, taking account of existing stakeholder commitments, capacity and capability. The transition from the TPOS as it exists now to its future configuration must be managed and coordinated effectively to maintain data streams for operational forecasting, to ensure continuous climate records and to take account of changes to sampling methods. [3.2, 7.1 and sections of 7.7]. Ongoing assessment of the transition is required so that risks are properly managed.

There are a number of existing mechanisms available to facilitate such a process, and TPOS 2020 partners can contribute advice and guidance. There are also opportunities to use regional mechanisms. [7.7.1, 7.7.2, 7.7.3]

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.

❑ The most pressing action is to address the decline of the TMA in the west; the response here focuses on restoring the most critical capabilities and on seeking sustained commitments [1.2, 7.2, 7.4.3].

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.

❑ Enhanced Argo profiling throughout the tropical region (10°S - 10°N) is recommended [Recommendations 17, 20]. The deployments would target a density of one profile every 5 days per 3x3 square or, equivalently, one profile per 2.1x2.1 degree square every 10 days. The increase would be staged, building on experience in the west. Near the equator the higher-frequency TMA sampling remains critical and complements the excellent vertical resolution provided by Argo [Recommendations 18, 19; 7.4.3].

Action 3 Argo float deployments should be doubled over the entire tropical region 10°S-10°N, and return increased upper ocean vertical resolution.

❑ The ocean scales of variability, background noise (e.g., eddies and synoptic weather effects) and different phenomena (tropical instability waves and barrier layers) vary across the tropical Pacific. Refinements of deploying and missioning a float array may deliver further benefits to the TPOS [3, 5.9].

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.

❑ TPOS 2020 concludes there is a strong case for beginning the transition of the TMA from its present grid structure between 8°S and 8°N, to one with more capable moorings that sample the varied regimes of the tropical Pacific [3.1.1.3] and captures the basin-scale variability in the surface and subsurface fields [3.1]. Any such change would be carefully implemented to maintain climate records and assessed according to the Global Climate Observing System (GCOS) Climate Monitoring Principles. Actions 5 and 6 would begin these changes.

Present sampling capability in the near-equatorial region does not meet scale requirements demanded by the sharp meridional gradients across the equator [3.1.3, 3.3.3, 3.4, 5.9.1; Recommendation 17]. Given the capabilities of available platforms, the most effective way to do this would be to increase the meridional resolution of enhanced fixed-point sampling spanning the equator at one or few selected longitudes.

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.

❑ Given the ability of Argo to deliver high-resolution profiles (Action 3), and of scatterometers and models to capture the trade winds [3.1.1.2, 5.1], there is now the possibility to refocus the TMA toward other priorities.

Action 6 A staged reconfiguration of the TMA should emphasize enhancement in key regimes.

❑ We recommend more complete surface flux measurements in particular regimes, with corresponding enhanced sampling in the mixed layer [3.1.1.3, 5.8; Recommendation 15]. Fixed-point (mooring) measurements are particularly well suited to these tasks because of their ability to target regimes and to sample the high frequencies (diurnal) of these processes.

Action 10 All equatorial mooring sites should be upgraded to flux moorings.

❑ The existing TMA, limited within 8° of the equator provides only partial coverage of key climatic regimes [3.1] and generally does not have adequate sampling to determine all key flux terms.

Action 11 Meridional lines of flux sites should be extended from the equator to intersect both the South Pacific and Intertropical Convergence Zones in the west, and across the Intertropical

Convergence Zone, the cold tongue and the seasonal southern Intertropical Convergence Zone in the east and central Pacific.

❑ Reduction of horizontal coverage away from these key regimes should be accompanied by assessments of impacts on subsurface fields, surface fluxes (including wind stress), and underway and ancillary data collection, especially for *p*CO_2 data [7.4.4.2, 7.4.6]. The earlier Actions 1 and 2 for the western Pacific will provide a valuable reference for the actions here.

We note significant differences in surface wind and flux products within the tropical region and a paucity of studies on the impact of TMA surface meteorological data in weather prediction and associated reanalysis products, and in coupled models [3.1, 4].

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 cross-calibration 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.

Also see Action 13 below.

❑ Vandalism of TMA buoys has been a recurrent problem, particularly for the 95°W TAO mooring line, which resulted in reduced measurements during the recent 2015-16 El Niño. Regional involvement would be valuable to sustain sampling of this important regime.

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.

❑ Risks arise from the refocusing of the TMA, particularly for surface flux variables, some of which have no present alternative to buoy measurements. To mitigate these risks, Voluntary Observing Ships and other in situ systems should be encouraged to enhance focus on these variables. New technology and improvements in the testing and calibration of reanalysis and weather products offer additional routes to meeting surface flux requirements [7.4.6].

Action 13 To mitigate risks in meeting surface flux requirements associated with changes in the TMA, TPOS 2020 seeks (a) enhanced sampling by the Voluntary Observing Ship Climate Fleet 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 Numerical Weather Prediction flux products through output correction/flux adjustment techniques.

❑ Biogeochemical and ecosystem requirements, recommendations and actions will be a major focus for TPOS 2020 in subsequent reports. In this report the societal relevance and utility of established sustained and experimental biogeochemical systems is emphasized [2.6.7, 3.3.5]. Opportunistic use of existing platforms, such as moorings, floats and research and servicing vessels is a key strategy. Maximizing the use of mooring servicing cruises in particular is a critical component for Backbone biogeochemical observations. Service ships should continue underway measurements for pCO_2 to ensure continuity in the record of CO_2 flux, to serve as validation for moored measurements and new technologies, and to provide context for spatial variability between moored observations. Mapping the extent of the eastern Pacific oxygen minimum zone is also an early action that can be taken by TPOS 2020 [3.3.5].

Action 12 Underway pCO_2 observations should be continued or reinstated on all mooring servicing vessels and the present network of moored pCO_2 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.

❑ Several Pilot and Process Studies, as well as ongoing work being led by TPOS 2020 Task Teams, are outlined in this report. Some of these studies are precursors needed to further guide sampling strategies, test and improve delivery, cost and suitability for sustained implementation. Others target improved understanding of phenomena and processes [3.3], some of which are partly or wholly addressed by the recommendations and actions above.

In addition to the project initiatives recommended below, several groups around the Pacific are already engaged in research projects exploiting recent technical developments that point to additional monitoring opportunities for TPOS 2020 [7.5.2].

New technology is also considered, because it provides opportunities for broader engagement in the development of TPOS and for introducing efficiencies and/or enhancing relevance and impact of the observing system.

Recommended projects and supported initiatives include [6.1, 6.2, 10]:

Pilot Studies/Programs for the Backbone

Observing Western Boundary Current systems: A Pilot Study [6.1.1]
Eastern Pacific equatorial-coastal waveguide and upwelling system [6.1.2]
Determining the critical time and space scales for biogeochemistry in TPOS [6.1.3]
Direct measurements of air-sea fluxes, waves and role in air-sea interaction [6.1.4]
Pilot climate observing station at Clipperton Island for the study of East Pacific ITCZ [6.1.5]
Assessing the impact of changes in the TPOS Backbone [6.1.6]
Comparison of analyses and utilization of TPOS observations [6.1.7]

Process studies

Pacific upwelling and mixing physics [6.2.1]
Air-sea interaction at the northern edge of west Pacific warm pool [6.2.2]
Air-sea interaction at the eastern edge of the Warm Pool [6.2.3]
East Pacific ITCZ/warm pool/cold tongue/stratus system [6.2.4]

Examples of funded new technology projects

- Profiling floats equipped with rainfall, wind speed and biogeochemical sensors (NOAA) [10.2.1]
- Autonomous surface vessels as low-cost TPOS platforms (NOAA) [10.2.2]
- Flux surface glider experiment (JAMSTEC) [10.2.3]
- Enhanced ocean boundary layer observations on NDBC TAO moorings (NOAA) [10.2.4]
- Development and testing of direct (eddy covariance) turbulent flux measurements for NDBC TAO buoys (NOAA) [10.2.5]

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.

This is the first in a sequence of reports by TPOS 2020. The initial recommendations and actions begin a process of transformation and change to an observing system that will be more capable, more resilient and more effective. The integrated design lessens the reliance on any single platform, and its implementation harvests some of the efficiencies available from recent technological developments. Broad-scale ocean and surface conditions will be more accurately tracked. Key regimes will be observed comprehensively, delivering a clearer ongoing description of the evolving tropical Pacific climate and guiding coupled model development. TPOS enhancements will enable much needed improvements to operational modeling systems, addressing the scientific challenges of coming decades.

Subsequent reports will include refinements arising from evolving technology and additional insights gained from Pilot and Process studies. Biogeochemistry and ecosystem observations, and their interpretation in the context of improved physical-system observations, will be a major focus. The value of all TPOS observations is increased by integration through assimilation and syntheses, so future designs will address needs from advanced model parameterizations and changes that increase the effectiveness of data assimilation systems.