TPOS 2020
Tropical Pacific Observing System

Final Report
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Final Report of TPOS 2020

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Contents

Executive Summary

The TPOS 2020 project is a once-in-a-generation opportunity to enhance and redesign the international Tropical Pacific Observing System (TPOS). Begun in response to the 2012-2014 crisis of the TAO and TRITON moored arrays, the effort included agencies, stakeholders and researchers worldwide, reflecting the global effects of tropical Pacific variability and the necessity of adequate observations to support research and prediction.

The TPOS 2020 redesign aims to take full advantage of the diverse remote and in situ techniques available today, fitting them together as an integrated system. We seek to accelerate advances in technology, and in understanding and predicting tropical Pacific variability, and thereby to broaden the stakeholder base by increasing the value of the TPOS to the supporting agencies and to other users of the data and its products. The plan recognizes that models and the wide utility of their assimilation products are an essential element in this integration.

Our First (Cravatte et al., 2016; hereafter R1) and Second (Kessler et al., 2019b; hereafter R2) Reports laid out detailed rationales and plans for this redesign and enhancement, and specified the ocean and atmosphere variable requirements for its success. This Third and Final Report (also referred to as R3) does not repeat results or analyses from the earlier reports (their summary recommendations are restated here in Appendix B). This shorter report is an update that resolves remaining issues where possible now, and defines questions for our successors. Instead of a full restatement here, we refer to relevant sections of our earlier reports. All three reports were subject to an extensive review process; as such they represent a broad community view that, together, form elements of a whole.

This Final Report updates progress since the earlier reports in biogeochemical observations (section 2.1), prediction modeling (2.2), data management and access (2.3), the backbone moored array (2.4) and the oceanic connection to the subtropics via western boundary currents (2.5).

Beyond the TPOS 2020 redesign and enhancement, ongoing scientific advice will be necessary for the future evolution of the arrays, within the WMO Integrated Global Observing System (WIGOS). As a "WIGOS Pre-operational Regional Pilot" the next incarnation of the project will continue to require clear connections to the intergovernmental entities. Chapter 3 proposes a post-2020 governance structure (3.4) to enable scientific evaluation of potential changes (3.2) and the needed intergovernmental connections (3.3). The conclusion section 4 provides some lessons learned.

Recommendations from our previous reports express the main conclusions of TPOS 2020. Those are restated in Appendix B. The following are additions and refinements explained in the indicated sections of this Final Report.

Biogeochemistry, biology and ecosystems

This Final Report clarifies previous recommendations for oxygen observations, describes future pilot studies for moored oxygen measurements in the eastern Pacific, and suggests a way forward for derived products and ecosystem observations.

R3/Recommendation 1 We reaffirm the complementarity between oxygen observations on moorings along 95°W (for high temporal resolution) and BGC-Argo (for broader sampling). [2.1.1][1]

R3/Recommendation 2 Annual CTD O_2 and biogeochemical sampling from instrumented TMA service vessels is needed. Twice per year sampling is encouraged, including additional inorganic carbon variables when achievable. [2.1.1]

R3/Recommendation 3 A BGC-Argo strategy for independent validation of sensors is needed, likely via discrete bottle samples on TMA service cruises. [2.1.1]

R3/Recommendation 4 Greater effort should be devoted to entraining ecological observations from moorings and ships (could include acoustic observations of zooplankton and fish, listening for tagged fish, environmental DNA). Consultation with relevant international panels on fisheries and ecosystems are recommended. [2.1.2]

R3/Recommendation 5 Encourage development of gridded biogeochemical products from expanded TPOS observations (chlorophyll, carbon, nitrate, O_2, pH, pCO_2). [2.1.3]

Modeling studies and progress

This Final Report responds to recent model and prediction center developments with specific recommendations to take fullest advantage of these opportunities.

R3/Recommendation 6 Encourage the evolving coordination between prediction centers to better document the model biases, and to monitor the efficacy of observations used in S2S forecast systems. These should include periodic assessments across the operational centers, and coordinated OSE or OSSE experiments with multiple forecast systems.[2.2]

R3/Recommendation 7 Encourage process studies leading to improved process parameterizations, towards reducing the model biases that degrade the efficacy of observational initializations. [2.2]

TPOS data flow and access

R3/Recommendation 8 Improve interoperability and integration of data, working through the GOOS Observations Coordination Group. [2.3]

[1] [] Bracketed numbers refer to sections of this Final Report/R3.

Backbone moorings

In R1 and R2, several recommendations for the tropical moored array (TMA) were imprecise; these are further clarified in this Final Report, with explicit priorities stated:

Northward and southward extensions had been recommended, but with approximate locations.

Salinity enhancements had been recommended, but their depths and locations were approximate.

Near-surface velocity measurements had been recommended at every site; priorities are now stated.

R3/Recommendation 9 New moorings are required at 10°N at 110°W, 170°W, 165°E. Moorings further poleward are also recommended, but research is required to specify the measurements needed and their specific locations (Figure 2). [2.4.1]

R3/Recommendation 10 Pilot moorings enabling research on the SPCZ are needed before specific sites can be recommended (Figures 2 and 4). [2.4.2]

R3/Recommendation 11 Highest priority for TMA salinity measurements are shown in Figure 5: In the warm pool and its eastern extension: at moorings along the western equator from 137°E to 170°W, and on the 165°E meridional line from the SPCZ at 5°S across the equator to 5°N. Also at two long-term historical sites (0°,140°W; 0°,110°W), and under the ITCZ at 8°N,110°W. [2.4.3]

R3/Recommendation 12 Second priority (highly desired) for TMA salinity measurements are most of the other Warm Pool sites (and near its eastern edge) at 2°N and 2°S from 137°E to 170°W. Also at the remaining equatorial sites, under the SPCZ further south (8°S,165°E), and at 140°W, 2°S and 2°N (Figure 5). [2.4.3]

R3/Recommendation 13 Salinity should be measured at dense vertical resolution (1m; every 5m to 30m, then every 10m to 80m, and at 100m). The complementary role of short-cycle Argo floats should also be considered. [2.4.3]

R3/Recommendation 14 Highest priority for near-surface point current meters are shown in red in the top panel of Figure 8: Equatorial sites where longterm subsurface ADCPs already exist; along 140°W from 2°S to 2°N where subsurface ADCPs will be added; and on all Tier 2 moorings (thus also at 5°S and 5°N,140°W). [2.4.4]

R3/Recommendation 15 Second priority for near-surface point current meters are shown in blue in Figure 8: at all other equatorial sites, and at 2°S-2°N at 110°W, 140°W, 170°W, 165°E. Also at 9°N,140°W under the ITCZ. [2.4.4]

R3/Recommendation 16 We recommend that Tier 2 sites (giving mixed layer ADCP velocity profiles above about 60m) be rotated among several locations during the next few years to gain more experience before providing final recommendations. Figure 8 (bottom panel) suggests likely locations for these pilot sites. [2.4.4]

LLWBC/ITF system

The low latitude western boundary currents (LLWBC) of the north and south Pacific Ocean, including the Indonesian Throughflow (ITF), play crucial roles in ocean dynamics and climate variability on both regional and global scales. In R1 and R2, we recommended a pilot study in this area. In this Final Report, we report on progress made on pilot work as well as unresolved and ongoing issues that require additional attention.

R3/Recommendation 17 Encourage community workshops (e.g., under the auspices of the CLIVAR PRP) to bring together the three regional-focus efforts (northern and southern WBCs, ITF) towards an organized combined sampling program. [2.5.3]

R3/Recommendation 18 Encourage engagement of modeling efforts towards solving the difficult problems of complex bathymetry, mixing and tides, and the strong narrow near-shore currents that characterize this system. [2.5.3]

Considerations for the future

R3/Recommendation 19 Develop a rolling evaluation of the overall and ongoing effectiveness of the TPOS for research and prediction system goals. [3.1]

R3/Recommendation 20 Develop an explicit, independent structure to assess the capabilities, role and readiness of possibilities for inclusion in the backbone.[3.2]

R3/Recommendation 21 Encourage GOOS to consider best practices for broad stakeholder engagement, including both research and operational drivers. [3.3]

R3/Recommendation 22 We recommend a three-part primary governance structure, centered on a Scientific Advisory Committee to provide scientific advice to sponsoring agencies and the intergovernmental bodies, and to integrate new knowledge from the research community. A Stakeholder group would work to align resources and assess success. An Implementation Coordination Group would provide a forum for sharing technical advice and considerations, and coordinate field operations, sampling specifications and testing (Figure 9). [3.4]

Chapter 1 Introduction

Report overview

This Third and Final report of the TPOS 2020[2,3] project is an update that resolves issues where that is possible now, and sets the stage for our successors. It does not repeat results or analyses from our earlier reports (their summary recommendations are restated here in Appendix B). Nor does it revisit the substance of the design. Instead, for this material we refer to sections of our First (Cravatte et al., 2016) and Second (Kessler et al., 2019b) Reports (here referred to as R1 and R2; if R1 or R2 are not indicated, section numbers refer to this final report); please follow those references for this background.

Subsections of the present Chapter 2 report progress since R1 and R2 in a few areas. These include biogeochemistry, biology and ecosystems (2.1), prediction modeling (2.2), data flow and access (2.3), the backbone moored array (2.4) and the oceanic connection to the subtropics via low latitude western boundary currents (2.5). Even where we cannot now provide specific recommendations for some important measurements with enough confidence to define their place in the sustained system, we are able to specify the needs and issues to help guide our successors.

Beyond the design, it is clear that ongoing scientific advice will be necessary for the future evolution of the arrays, and as a "WIGOS Pre-operational Regional Pilot" the project will continue to require clear connections to the intergovernmental entities. Chapter 3 proposes a post-2020 governance structure (3.4) to enable scientific evaluation of potential changes (3.2) and the needed intergovernmental connections (3.3). Section 3.1 assesses our success against our terms of reference, and Chapter 4 concludes with some lessons learned in this long journey.

Approach

The TPOS 2020 project was formed in response to the twin crises of the TAO and TRITON moored buoy arrays in 2012-2014 (R1/1.2). The breakdown was caused in large part by failure to fully appreciate the diverse needs of stakeholders who depend on mooring data across a wide range of applications and scales; the narrowing focus led to lack of use and agency disinterest. Our approach has tried to broaden the stakeholder and user base of TPOS observations by enabling the data to speak more comprehensively. The result of adopting these proposals would

(a) increase the value of the arrays to the agencies supporting these programs,

(b) build wider support to avert the risk of another crisis, and

(c) take better advantage of the diverse remote and in situ techniques available today.

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[2] As in previous reports, we use "TPOS" alone when we are referring to the tropical Pacific observing system and "TPOS 2020" when we are referring to the Project and its recommendations and actions.

[3] See Appendix A for all acronyms; in many cases, we have elected not to spell them out, to retain flow and brevity.

We argue throughout our reports that a qualitatively more complete picture of the role of the tropical Pacific in the climate system is now possible with a backbone built on the complementary capabilities of the satellite constellation, the moored arrays, and the revolution in in-situ sampling created by Argo.

While much of these reports concern the observations, we recognize that observations alone will not deliver the fuller picture we seek. The societal value of a modern observing system comes primarily as the output of a comprehensive model assimilation that is able to incorporate the strengths of multiple observing techniques with dissimilar sampling characteristics. Most users of TPOS data in fact get the information they need from these outputs, not the observations directly. Throughout the redesign, we saw the added value of the consistent combination of information provided by assimilation to be as important as the in-the-water observing components.

Perhaps our greatest success has been to reinvigorate interest in the tropical Pacific, stimulating energy, work and commitment among agencies, international partners and researchers across many specialties, reflected in the analyses in the three reports. This work and enthusiasm is ongoing. Significant agency investments supported pilot studies that clarified approaches to meet the needs of a modern observing system. They enabled exploring the potential roles of emerging technologies. Analyses considered the difficult questions involved in fitting together satellite and in situ sampling. The result is a system that is more robust, better able to deliver relevant products to its stakeholders, and advances more effective use of the data for prediction efforts at centers worldwide.

Chapter 2 Progress since Second Report and Remaining Issues

2.1 Biogeochemistry, Biology, and Ecosystem

This section resolves perceived differences in R1 and R2 regarding oxygen observations (see R1/6.1.3 and R2/4.2.1), describes future pilot studies for moored oxygen measurements and suggests a way forward during the implementation phase.

2.1.1. Dissolved oxygen observations

In R2, there were some differences in emphasis between chapters 4 (Biogeochemistry) and 5 (Eastern Pacific) regarding the best way to make observations of dissolved oxygen (O_2). R2/Chapter 4 favored biogeochemical Argo (BGC-Argo) floats at a density consistent with the recommendations of the international BGC-Argo steering committee (Biogeochemical-Argo Planning Group, 2016).

R2/Recommendation 4.1: TPOS 2020 recommends a target of 124 BGC-Argo floats (assuming 31 deployed per year) with biogeochemical sensors (specifically nitrate, dissolved oxygen, pH, chlorophyll fluorescence, particulate backscatter and downwelling irradiance) for the 10°N-10°S band.

It was also suggested that enhanced O_2 measurements in the east could be achieved by some core Argo floats (not full BGC-Argo) incorporating O_2 sensors. There are many such floats and some national programs are moving towards all floats carrying O_2 sensors. TPOS 2020 supports the latter idea and advocates prioritizing Argo-O_2 deployments for the eastern Pacific. R2/Chapter 4 also advocated for O_2 measurements on CTDs.

R2/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 1000m 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.

A different but complementary recommendation was presented in R2/5.4:

R2/Recommendation 5.3 A pilot study along 95°W installing dissolved oxygen sensors to 200m 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.

Similar O_2 observations could be achieved by PRAWLER moorings (Osse et al., 2015), as discussed but not specifically recommended in R2 Chapter 4. The purpose of these intensified O_2 observations on the eastern-most mooring line is to monitor the O_2 variability in the equatorial undercurrent (EUC) and study its connection with the eastern Pacific oxygen minimum zone (OMZ), benefitting established Peruvian and Chilean coastal observational programs (R2/5.1.4). Global and regional models indicate that the OMZ and oxygen variability of the eastern Pacific Ocean, in particular off the slope of Peru and Chile, is partly driven by changes in O_2 transport by the EUC (Busecke et al., 2019; Duteil et al., 2014, 2018; Espinoza-Morriberón et al., 2019; Montes et al., 2010, 2014; Pizarro-Koch et al., 2018). Moored measurements along 95°W, would quantify O_2 concentrations of the EUC and connect with long- or short-term moored O_2 observations on the shelves of Chile and Peru, such as those recently deployed by DIHIDRONAV (Dirección de Hidrografía y Navegación de la Marina de Guerra del Perú; Graco et al., 2017). Characterizing OMZ dynamics and developing seasonal prediction of OMZ volume in the eastern Pacific will require measurements at high temporal and vertical resolution, such as can be achieved by moored sensors.

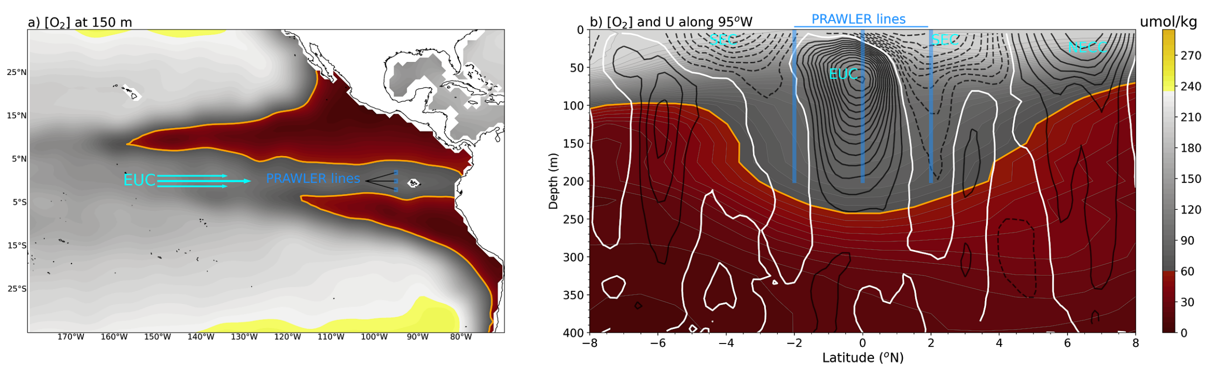

Figure 1: Climatological dissolved oxygen from the World Ocean Atlas (Garcia et al., 2018) at a) 150m depth, and b) along 95ºW with climatological zonal velocities from Johnson et al. (2002). Orange line denotes the boundary of hypoxic conditions ($[O_2]$<60µmol/kg). Zonal velocity is contoured at 5cm/s intervals in black (eastward flowing) and dashed (westward flowing) lines, separated by 0-contour line in white. Potential locations for O_2 measurements on moorings (PRAWLER or instruments at discrete depths) are shown in blue. The Equatorial Undercurrent (EUC), South Equatorial Current (SEC), and North Equatorial Countercurrent (NECC) are abbreviated in cyan.

The goal of the 95°W pilot study is to characterize the complex and variable nature of the EUC. Ideally, the moored O_2 sensors on this line would be near the mean depth of the EUC core, which would permit estimation of at least the variability in the eastward O_2 flux, if not its total magnitude, as well as potentially its recirculation by the South Equatorial Current (Montes et al., 2010). These data would be also valuable for validation of biogeochemical models, which have consistently showcased major deficiencies in simulating the equatorial oxygenated tongue set by the EUC (Figure 4 of Cabré et al., 2015). The use of mooring line profilers, such as the PRAWLER, should be considered to provide a time series of high-resolution profiles of O_2 (Figure 1b; R2/4.4.6 and 9.2.3). In addition to understanding the easternmost part of the OMZ, it is important to get the O_2 transports in the EUC and other currents right for understanding the expanse of the OMZ north and south of the equator (Stramma et al., 2010) and accurately representing the OMZ more broadly in climate models (Busecke et al., 2019). The deeper tropical circulation, below the EUC to 2000m, includes the equatorial intermediate current and deep jets (Cravatte et al., 2017; Ménesguen et al., 2019). A recent intercomparison modeling study (Duteil et al., in review) and compilation of observations (Delpech et al., 2020) shows that this deep circulation may play a major role in supplying oxygen to the east, but it is currently poorly reproduced by ocean models. This deeper circulation would have to be targeted by BGC-Argo floats (Margolskee et al., 2019), but moored sensors could be tested during the 95°W pilot study to sample O_2 deeper than 200m or gliders could potentially perform transects of the order of 500km in length, penetrating to 1000m (Jakoboski et al., 2020). Data on the dynamics at these depths, and the ability to validate and compare models, would be a novel contribution.

BGC-Argo O_2 measurements provide a lower temporal resolution picture of dissolved O_2, but a far superior broad spatial scale perspective. Climatological O_2 products as well as long term trends in O_2 in the tropical Pacific are based on sparse data. Thus, sustained and enhanced basin scale sampling through BGC-Argo is necessary to improve the quality of these products and improve confidence in observed long-term trends in this region. This is essential for monitoring and prediction of the eastern Pacific OMZ, which is crucial for understanding the habitat available to economically and ecologically important fisheries such as tuna (Gilly et al., 2012; Laffoley and Baxter, 2019). Oxygen data in the east will also help to understand the relations among equatorial upwelling, nutrient supply and primary production, and their changes under La Niña and Niño events. These observations would also be important validation and initialization data for models, and derived products such as apparent oxygen utilization (AOU) would serve as tracers of water provenance, to answer questions related to natural versus anthropogenic dissolved inorganic carbon concentrations, and estimates of net community production and carbon export (Yang et al., 2017; Bushinsky and Emerson, 2015). For this final report, TPOS 2020 emphasizes that moorings and BGC-Argo serve two important and separate but complementary purposes.

Two additional points of clarification are necessary on R2/Recommendation 4.2 for CTD and bottle sample collection on tropical moored array (TMA) mooring servicing cruises. First, once per year sampling is the recommendation, with twice per year sampling achievable in some cases where similar sampling is done through other programs, like GO-SHIP. Second, BGC-Argo should develop a strategy for making independent measurements for validating biogeochemical sensors. Measuring inorganic carbon parameters in addition to nutrients and chlorophyll via discrete bottle samples collected on the TMA mooring servicing cruises could be one way to address this, particularly if those cruises are used to deploy BGC-Argo floats.

R3/Recommendation 1 We reaffirm the complementarity between oxygen observations on moorings along 95°W (for high temporal resolution) and BGC-Argo (for broader sampling).

R3/Recommendation 2 Annual CTD O_2 and biogeochemical sampling from instrumented TMA service vessels is needed. Twice per year sampling is encouraged, including additional inorganic carbon variables when achievable.

R3/Recommendation 3 A BGC-Argo strategy for independent validation of sensors is needed, likely via discrete bottle samples on TMA service cruises.

2.1.2 Ecosystem observations

When read in the context of the Global Ocean Observing System (GOOS) essential ocean variables (EOVs), the biogeochemistry sections of R1 and R2 have clearly focused on lower trophic level observations. The base of the food chain has been covered through satellite ocean color, bio-optical measurements on BGC-Argo floats, and ship-based observations of phytoplankton. Moored and BGC-Argo measurements of dissolved oxygen will provide information on climate impacts and the habitat available to tuna and other large fish, but beyond that there has been little emphasis on ecological observations. As TPOS 2020 has developed, so have the recommendations and specifications for EOVs under the GOOS Biology and Ecosystem Panel.

Through the implementation phase, TPOS 2020 recommends greater effort be devoted to entraining ecological observations that could be accommodated on moorings and ships. These include acoustic observations of zooplankton and fish, passive acoustic sensors on moorings to listen for tagged fish (e.g., Ocean Tracking Network receivers), and environmental DNA sampling for a range of species (Liu et al., 2019). These data could be used to map the spatial and temporal variability of animals driven by El Niño-Southern Oscillation (ENSO), changes in the type of El Niño events, and climate change.

Groups that should be consulted in the implementation phase include the Western and Central Pacific Fisheries Commission, the Inter-American Tropical Tuna Commission and the GOOS Biology and Ecosystem Panel which has zooplankton, fish and turtle-bird-mammal as three of its functional groups.

R3/Recommendation 4 Greater effort should be devoted to entraining ecological observations from moorings and ships (could include acoustic observations of zooplankton and fish, listening for tagged fish, environmental DNA). Consultation with relevant international panels on fisheries and ecosystems are recommended.

2.1.3. Derived data products

Ocean biogeochemical and ecological models currently suffer from two significant and related impediments: (1) biogeochemical observations are sparse (R1/6.1.3; R2/7.4.5.3, R2/4.2.1 and R2/Figure 4.3), and (2) biogeochemical and ecological parameterizations in models are poorly constrained because of insufficient understanding of these processes (Fennel et al., 2019). The recommendations from R1 and R2 and the additional clarity provided here, will help address both of these issues for biogeochemistry. Further engagement with ecological stakeholders is required during implementation.

The primary biological data set used to validate biogeochemical models is satellite ocean color, which TPOS 2020 regards as essential for the observing system going forward (R1/Recommendation 13). The horizontal spatial coverage is of course excellent, but this data set provides no subsurface coverage and chlorophyll is a poor phytoplankton proxy because ocean BGC models do not carry chlorophyll as a variable. These deficiencies point to BGC-Argo floats as an essential validation platform, because they provide not only subsurface structure but also more useful parameters such as carbon biomass (from particulate backscatter), dissolved O_2 and dissolved nitrate.

In the Gulf of Mexico, Damien et al. (2018) validated a coupled circulation-biogeochemical model using chlorophyll profiles from BGC-Argo floats from 2011 to 2015. More recently, Wang et al. (2020) explored biogeochemical model optimization using BGC-Argo observations of chlorophyll and carbon in the same basin. They found improvements in model performance when adding BGC-Argo data, but chlorophyll profiles were not sufficient because they failed to constrain the ratio of chlorophyll to phytoplankton carbon. Incorporating phytoplankton biomass and particulate organic carbon from backscatter, improved estimates of primary productivity and carbon export.

R2/Recommendation 4.1 (124 BGC-Argo floats), when implemented, will provide profiles of chlorophyll and carbon (as well as nitrate, O_2 and pH) at the density specified in the International BGC-Argo implementation plan. We envisage these observations being developed into gridded products for uptake by modellers and other users. This includes the delivery of derived products, such as dissolved inorganic carbon and AOU, and will enable refinement of biogeochemistry scale estimates for the tropical Pacific. These derived products will require that inorganic carbon parameters, oxygen, nutrients, and chlorophyll be measured as part of the R2/Recommendation 4.2 for CTD and bottle sample collection on TMA mooring servicing cruises.

The current and future TPOS contributes to global $p\mathrm{CO}_2$ gridded products which typically have spatial and temporal resolutions of 1° and monthly, respectively (Landschützer et al., 2016). These products rely heavily on the moored $p\mathrm{CO}_2$ observations along the equator, but perhaps more crucial are the ship-based underway data along the mooring lines, because these provide broader spatial context at close to the temporal resolution of the product. Both the moored equatorial measurements and transects along mooring lines are considered essential for TPOS (R1/Recommendation 12).

Gridded products are extremely useful for tracking global trends in ocean CO_2 sources and sinks, including trends associated with ENSO, decadal climate variability such as the Pacific Decadal Oscillation, and climate change in the tropical Pacific. Data assimilation that incorporates the growing range of parameters and platforms emerging from TPOS—BGC-Argo, O_2 profiles from ships and moorings, moored surface $p\mathrm{CO}_2$ and satellite chlorophyll—will help derive dynamically consistent gridded climatological products, as well as biogeochemical state estimates spanning years to decades (Verdy and Mazloff, 2017), and continue help informing the observing network design.

R3/Recommendation 5 Develop gridded biogeochemical products from expanded TPOS observations (chlorophyll, carbon, nitrate, O_2, pH, $p\mathrm{CO}_2$).

2.2 Modeling Studies and Progress

Providing information for initializing models for weather and climate predictions is one of the foremost justifications for the global observing systems. The benefit of observations for this purpose, however, can depend on the quality of the model that is used for data assimilation and prediction. Although observational design recommendations by TPOS 2020 were formulated only after careful assessment, for optimal utilization of observations themselves it is also essential that corresponding requirements for model-based prediction systems (including for data assimilation) are adequately incorporated in the TPOS evolution. Thus, to benefit from the sustaining and improving TPOS, it is essential (a) to improve the modeling infrastructure, and (b) monitor the efficacy of observations that are being utilized in seasonal to interannual prediction (S2IP) systems. These requirements provided the basis for recommendations in the previous TPOS reports and are summarized below.

Modeling infrastructure is used for estimation of the states of the ocean and atmosphere via data assimilation, which synthesizes diverse types of observations into a gridded analysis. Such state estimates (also called "analyses") are widely used for initializing model predictions, and evaluating and validating models. In addition, models are also an essential tool in understanding and predicting climate variability on various time-scales. In the last decade, operational predictions based on atmosphere-ocean coupled models from days to decades have commenced; although continual advances are being made, biases in simulating critical processes, e.g., ocean mixing, air-sea interaction, persist.

The scope of space and time scales covered by current operational S2IP systems has vastly expanded beyond that possible when the existing TPOS was originally conceived. Prediction systems now represent the variability of the ocean and atmosphere boundary layers, depict the continuum of weather and intraseasonal convective variations, and capture broad decadal variations in the meridional flow, as well as depicting the fundamental air-sea interactions associated with ENSO that were the original focus of TPOS. The deficiencies in models currently used for the operational S2IP systems undermine the efficacy of the utilization of the observed data in two ways: during the assimilation, observations, instead of providing information about spatial and temporal anomalies, are used for correcting for model biases, and (2) information from the assimilated observations, without influencing forecast skill, is readily dispersed (effectively forgotten) during the initial stages of the forecast (Mulholland et al., 2015).

Recognizing the need to reduce model biases, a TPOS 2020 recommendation was for development of a community effort to document model biases and to quantify how S2IP prediction systems may be improving with time (R2/Recommendation 2.1). This recommendation, designed after the highly successful CMIP model intercomparison paradigm, calls for organizing an activity for periodic assessment of S2IP prediction systems across different operational centers.

TPOS 2020 recommendations also included enhanced international coordination for model development such as in the Subseasonal-to-Seasonal (S2S) Project, and for process studies aimed at improving the parameterization of physical processes that are poorly represented in climate models. In addition to large scale monitoring that is required to constrain basin scale interactions, observations from process studies are anticipated for further developing the parameterization schemes to better represent the interaction between the atmosphere and ocean boundary layer (R2/Recommendation 3.3). It is also expected that the development of improved physical parameterization in S2IP systems will reap further benefits from the bottom-up evaluation and modeling approach (and a hierarchical modeling strategy) by utilizing more in situ observational data (Jakob, 2010; R2/Chapter 3).

Based on an assessment of current gaps, the TPOS 2020 recommendations described observational requirements both for forecast initialization (the backbone observing system), and for addressing major gaps in the understanding of physical processes and their representation in models (via recommendations for process studies, Appendix C.2). In addition, TPOS 2020 recommendations also included monitoring the efficacy of observational data in assimilation systems (R1/6.1.7) and coordinating observing system simulation experiments (OSSEs) to test the adequacy of the future design of the TPOS (R1/6.1.6).

To understand the adequacy of observational changes for initializing the operational predictions, one needs to evaluate the impacts of potential changes through observing system experiments (OSEs), in which influence of the existing observing elements is evaluated by changing the mix of available observational data in assimilation. In addition, OSSEs, which are idealized simulations with candidate future observations, are also recommended to ensure that no degradation in current observational capabilities occurs (R1/Recommendation 22). Although OSEs and OSSEs have been widely used in the context of weather prediction, they are less common for subseasonal to longer predictions. Several modeling centers have performed limited OSEs for ocean analysis and demonstrated the gains in ocean analysis and seasonal prediction; however, much less is currently known for the subseasonal predictions. Further, to make inferences that are robust, such experiments need to involve multiple forecast systems. In response to TPOS 2020 recommendations, recently, OSEs of the subseasonal prediction have been carried out with European Centre for Medium-Range Weather Forecasts (ECMWF) and Japan Meteorological Agency (JMA) systems; initial analysis and forecast skill verification overall show a positive impact on the skill improvement for coupled subseasonal forecasts when subsurface in situ ocean observations were assimilated.

In response to TPOS 2020 reports, the ocean analysis and S2IP community are currently discussing possible coordinated efforts to advance TPOS 2020 modeling and data assimilation recommendations. In the ocean analysis community, there are two international groups that exchange knowledge and coordinate international activity: OceanPredict Observing System Evaluation Task Team (OS-Eval TT) and CLIVAR GSOP. OS-Eval TT is planning to exchange information associated with the needs of OSEs and OSSEs and developing a set of coordinated experiments. The S2S project has just commenced its Ocean Subproject, but the only operational centers providing ocean outputs currently are ECMWF, Environmental and Climate Change Canada, Météo-France, and China Meteorological Administration. Further participation by other centers in the Ocean Subproject can expedite quantification of forecast sensitivity and highlight common analysis errors. Efforts targeting reduction in the persistent model biases of the tropical Pacific will also have a positive influence on the usefulness of observational data during assimilation.

Regarding the need for documenting model biases and improvements, the WMO Expert Team on Operational Climate Prediction Systems (ET-OCPS) and WCRP Working Group on the Subseasonal to Interdecadal Predictions (WGSIP) initiated a discussion. To date, however, efforts to implement these recommendations are in their nascent stages.

To provide a balanced approach for observational needs and advancing S2IP systems as the legacy of TPOS 2020, we urge that concerted efforts be made to advance TPOS 2020 recommendations for modeling, as well as for the assessment of observational data.

R3/Recommendation 6 Encourage the evolving coordination between prediction centers to better document the model biases, and to monitor the efficacy of observations used in S2S forecast systems. These should include periodic assessments across the operational centers, and coordinated OSE or OSSE experiments with multiple forecast systems.

R3/Recommendation 7 Encourage process studies leading to improved process parameterizations, towards reducing the model biases that degrade the efficacy of observational initializations.

2.3 Update on TPOS Data Flow and Access

This section provides an update on the discussion of TPOS data flow and access (R2, Chapter 8) and, specifically, on progress against the four recommendations and action.

R2/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.

The recognition that increased funding is a key factor for improving data and information management continues to gain momentum, though it is hard to accurately gauge any tangible increase in actual spending. Indeed, one of the recommendations coming out of the OceanObs'19 meeting was that "Funding agencies of ocean observing systems need to align funding to meet the demands of data management …".

In fact, as the data management landscape evolves over the coming decade, improved interoperability and the requirement to reach users outside of the traditional ocean domains suggests that there will be, and already is, an increased demand to move beyond bespoke data practices and provide more integrated data services. These additional services include ensuring data and metadata are compliant with the FAIR (Findable, Accessible, Interoperable and Reusable) data principles (Wilkinson et al., 2016) and are fully documented, archived and easily discoverable. As noted in Tanhua et al. (2019), "it is imperative that new data management repositories or data assembly centers have sustainable, long-term funding".

Many in the data management community now believe 10% represents a minimum (S. Pouliquen, personal communication), and that in some cases the requirements (such as those noted in the previous paragraph) may warrant closer to 20%. Such guidance is inherently imprecise but is a useful starting point when considering budgets.

The TPOS community will have to keep pushing the value arguments for increased funding dedicated to data management to ensure program managers and agencies are aware of the requirements from higher-level data management and interoperability projects.

R2/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.

The GOOS Observations Coordination Group (OCG) is working on implementing a data management strategy to encompass the global ocean observing networks, many of which are active in the tropical regions and participate in the TPOS. The goal of the data strategy is to ensure that high quality data are: 1) available through accessible services, 2) are well documented, 3) are preserved for future generations and, 4) are citable. The OCG data strategy will be designed to be a living document, enabling the strategy to be agile in the face of technological and data management innovations. The strategy will be built around the FAIR data principles (Tanhua et al, 2019) and will leverage standards and best practices found within the community. The implementation of the OCG data strategy will ensure that TPOS data and TPOS data products are available in a variety of formats both for human and machine-to-machine access. The strategy will embrace a distributed data infrastructure that can, however, be federated to provide for the development of a virtual one-stop data and metadata access point. The OCG data strategy will also recommend that Digital Object Identifiers are created for TPOS data products to allow data users to cite the source of their data. This will provide a useful feedback mechanism to better understand the use of TPOS-generated data and data products. The development of a TPOS-blessed citation text could also provide more visibility for the data collected and used.

Improving interoperability and integration of data amongst the TPOS networks will be a primary implementation goal of the OCG data strategy. Additionally, it is a goal to ensure that data services implemented are also compatible with higher level data efforts, such as the UN Decade of the Ocean data strategies and IOC data strategies.

R2/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.

This recommendation is dependent on progress with implementation of changes in the observing system, and the TMA in particular. Some progress has been made with data quality, and standard data management practices will be developed and implemented as new players contribute to the TMA.

R2/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; R2/7.4.5.1) and Eastern Pacific regional activities (R2/5.2, R2/Action 5.1) to enhance the recognition and adoption of the FAIR principles and to re-process data that would otherwise be lost.

No progress as yet on the data aspects of a LLWBC project (see section 2.5 for an update). This data management project, which may be handled by another coordination body, remains however a primary step toward an integrated, international observational program for the region.

R2/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.

The GOOS OCG Open Access to the GTS (Open-GTS) project has been developed with the goal of reducing the barriers preventing data providers from distributing their data globally in near-real time and enabling compliance with the WMO Resolution 40 (http://www.umr-cnrm.fr/aladin/IMG/pdf/resolution40.pdf). The WMO's Global Telecommunication Service is the traditional vehicle by which global ocean and marine meteorological data are distributed. After a successful pilot project under the guidance of OCG and JCOMM, the Open-GTS project is moving towards operational status. It is currently being implemented by the US Integrated Ocean Observing System (IOOS), whose goal is to move all of the near-real time data distribution from their Regional Associations to the Open-GTS workflow. An OCG-led Open-GTS implementation strategy has been written, and revised, through the process of collaborating with US IOOS.

In addition, the Open-GTS has been selected as a WMO demonstrator project to help guide the evolution of the WIS, called WIS 2.0. As a result of the recent work, the Open-GTS project can be leveraged as a means to distribute data not currently getting to the GTS/WIS from the TPOS region. To develop a pilot project, we would need to identify the platforms/data that are not getting to the GTS, but should in fact be distributed globally in near-real time.

R3/Recommendation 8 Improve interoperability and integration of data, working through the GOOS Observations Coordination Group.

2.4 Backbone Moorings

In R2, some elements of the backbone moored array remained fuzzy (R2/7.3). It was recognized that the Tier 1 sites where salinity, rainfall, and barometric pressure were most needed in addition to the core measurements still need to be specified (R2/*Action 7.1*). It was also recognized that priority sites for Tier 2 deployments, and analysis of where ocean velocity measurements are most needed should be examined (R2/*Action 7.2*). Finally, the exact positions for the northern extensions of the moored array spanning the Intertropical Convergence Zone (ITCZ), and for the southern extension under the South Pacific Convergence Zone (SPCZ), were not determined. This section aims to clarify these with new recommendations where possible (e.g., the light-green squares in Figure 2 and the Tier 1 and 2 configurations in Figure 3), and by spelling out the multiple considerations to guide a future decision for our successors.

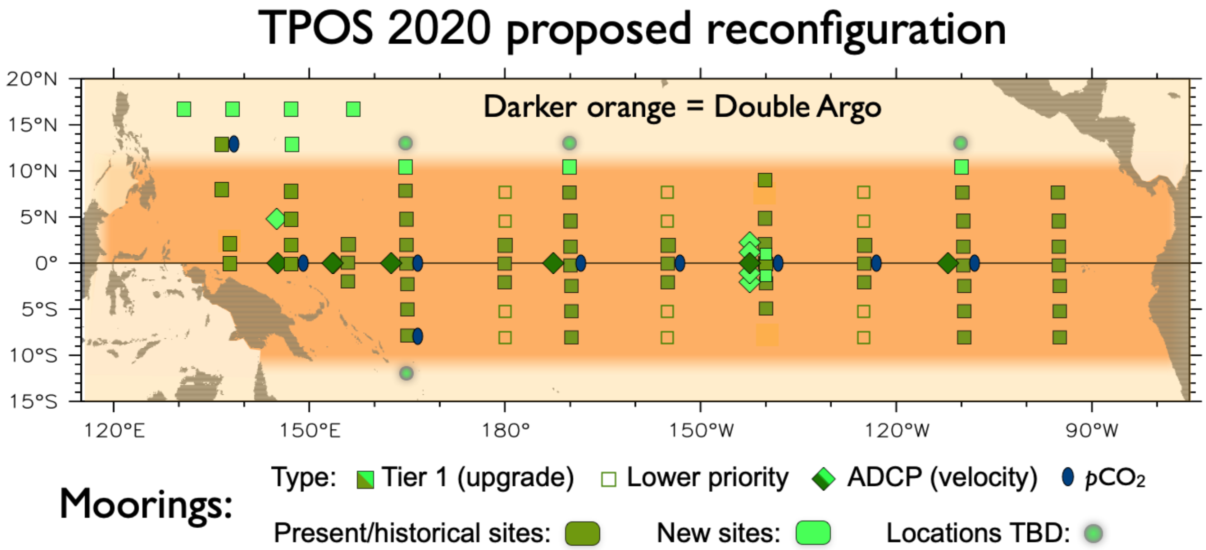

Figure 2: Recommended TMA and Argo backbone (compare R2/Figure 7.4). Darker orange shading shows the 10°S-10°N band where Argo doubling is recommended (R1/7.3; R2/7.3.2.2), including BGC-Argo (R2/4.1.5; R2/Rec. 4.1). Dark green squares show the retained present and historical TMA sites; empty squares mark lower-priority sites (R2/6.6; R2/7.3.3). Light-green squares show recommended additions (2.4.1; 2.4.2; R2/7.3.1.2; R1/3.3.3); "fuzzy" gray-green circles show regions where a new mooring is recommended but determining specific locations requires further research (2.4.1; 2.4.2). Diamonds show moorings including velocity profiles (dark are existing, light are new) (R1/3.1.3.2; R1/Rec.19). Dark-blue ovals show moored pCO_2 sites (R1/5.7; R1/Rec.13).

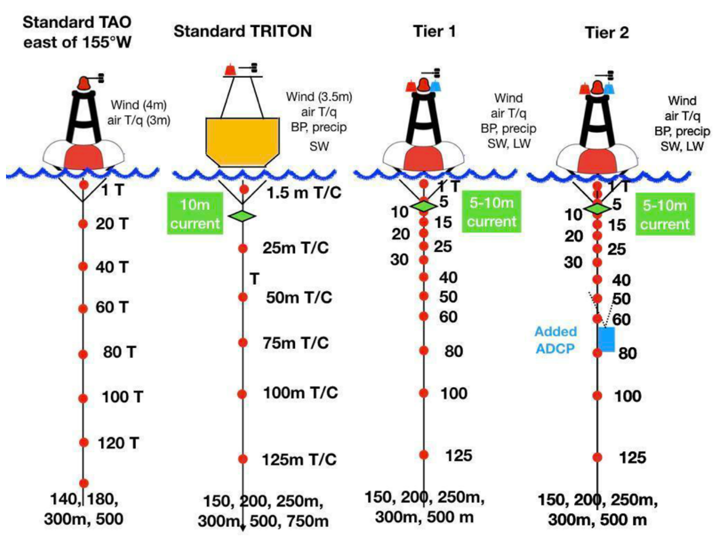

Figure 3: Configurations of existing TAO and TRITON moorings, and the proposed base mooring configuration for TPOS Tier 1 and Tier 2 moorings. In addition, Tier 2 sites (particularly in the western and central Pacific) should have enhanced salinity measurement capability (see also 2.4.3 of this report). In the subsurface, red dots and black text indicate the depths of temperature and salinity measurements (T and T/C mean Temperature and Temperature/Conductivity sensors, respectively), and green diamonds indicate point current-meter measurements. Tier 2 moorings will have an upward looking current profiler (blue rectangle). The red and blue shapes on the surface moorings indicate additional sensors (SW and LW, downwelling shortwave and longwave radiation). (Originally appeared in R2/Figure 7.3).

2.4.1 Latitudes of the northern extensions

In R1 and R2, northward extensions of the TMA (Tier 1 moorings) were recommended, with new moorings north of 8°N (R1/7.3; R2/7.3.1.2). In the central and eastern Pacific, the meridional spines 165°E, 170°W and 110°W were identified targets for the northern extensions although exact latitudes of the extension were not specified. In the western Pacific, new mooring sites in the north have also been proposed.

R2 explained four main rationales for these extensions:

1. provide improved sampling in the deep atmospheric convection zones where high rainfall and low radiative heating occurs, and where winds are often gusty. Both R1 and R2 emphasized the requirement for in situ observations to evaluate and intercalibrate scatterometer wind measurements under heavy ITCZ rain, in particular to estimate the contamination of rain-flagged scatterometer wind measurements (e.g., R1/5.1.1);
2. sample for the first time the highly evaporative dry inflow region in the northern hemisphere, where model-to-model comparisons show large differences in mean air-sea heat flux (Yu, 2019);
3. enable better prediction of shorter-scale temporal variability such as weather, extreme events such as hurricanes and typhoons, and the Boreal Summer Intraseasonal Oscillation (BSISO), by sampling their genesis regions in the eastern and western off-equatorial tropics;
4. provide in situ sampling of multi-decadal signals over a broader domain, in particular of heat and momentum fluxes (e.g., R2/7.2.1.2, 7.3.2.1);

The optimal latitudes of the northern moorings depend on each of these rationales, and community experts argued that 10°N, 11°N, 13°N and 14°N all had advantages as mooring sites.

Rationale (a) is fundamental to confidence in our wind products, which has a broad impact across many of our goals. Meeting this challenge requires moorings under the ITCZ; recognizing its differing characteristics across the basin, and the annual north-south movement of ITCZ convection, we recommend new moorings at 10°N at 110°W, 170°W and 165°E (R2/Figure 7.6).

Rationales (b), (c) and (d) all require sampling north of 10°N. The needed measurements to meet all of these requirements are focused on the near-surface ocean and lower atmosphere; pilot moorings north of 10°N with attention to air-sea flux sampling should be explored, but in some cases the technology to meet these needs might not be moorings. Several proposed and ongoing pilot and process experiments are exploring potential methods and approaches (3.2; R1/6.1.4, 6.1.5, R1.6.2.2 and 6.2.4; R2/6.2.1, 6.2.2, 7.2.1.3, 9.2.1 and 9.2.2).

The BSISO of rationale (c), is not yet well-enough understood to define a strategy for sustained observations. Questions remain about the mechanisms by which the warm pool expands northwestward in late boreal summer. However, given its importance to the onset and development of the monsoon, a process study (Appendix C.2.1) has been developed, anchored by a 13°N, 137°E flux mooring. This study would also provide a firmer basis for requirements that could be met by potential TMA extensions in the northwest.

Fundamentally, the northern region north of 10°N is less well understood and has not been instrumented as part of the historical TMA, leaving us without a firm basis to confidently balance the multiple requirements.

As a conclusion:

- we recommend new moorings at 10°N at 110°W, 170°W and 165°E (Figure 2)

- we recognize that research will be needed prior to the finalisation of the location of further northward extension latitudes. We leave this work and these decisions to our successors.

R3/Recommendation 9 New moorings are required at 10°N at 110°W, 170°W, 165°E. Moorings further poleward are also recommended, but research is required to specify the measurements needed and their specific locations (Figure 2).

2.4.2 Latitudes of the southern extension, under the SPCZ

R1 and R2 recommended establishing a new mooring site in the Southwest Pacific, south of 8°S, to better capture the deep convective, rainy regime of the SPCZ. Such a mooring would also be key to better understand and predict the MJO (Madden-Julian Oscillation), the dominant source of predictability on subseasonal timescales, with global teleconnections. Yet, the precise location of this southern extension was not specified, and it was recognized that its exact location under the SPCZ needs further exploration, in consultation with community experts and regional partners (R2/Action 7.3)

There is widespread interest in a meridional line of flux sites spanning both the ITCZ and SPCZ, and a southward extension along 165°E was first envisioned. However, feedback from the WGNE MJO Task Force questioned this choice of longitude. They noted that by 165°E, the MJO convection was either decaying or had already disappeared, at least during non-El Niño years. Mooring sites further west, along 150°E or 156°E, between 15°S to 10°S would be better suited for observing the air-sea coupled processes at high-frequency (hourly to sub-monthly timescales), contributing to the MJO maintenance and propagation. These coupled feedbacks are particularly critical during the suppressed phases of the MJO. A Tier 1 mooring, sampling both the oceanic mixed layer and the surface meteorological variables at high-frequency, is the only platform that would allow observing these coupled phenomena and their modulations at seasonal and interannual timescales.

With these unresolved physical and logistical complications, we leave the specific locations to our successors and sponsors (Figure 2), emphasizing that the moorings should be first deployed as a pilot experiment, under the supervision of a scientific PI, and that if the pilot was successful, the PI could then assist with the transition of the mooring to be a more permanent contributor to the TPOS. The numerous EEZs in the Southwest Pacific are also shown in Figure 4, above the Outgoing Longwave Radiation field, to help identify partners and help for logistics.

R3/Recommendation 10 Pilot moorings enabling research on the SPCZ are needed before specific sites can be recommended (Figures 2 and 4).

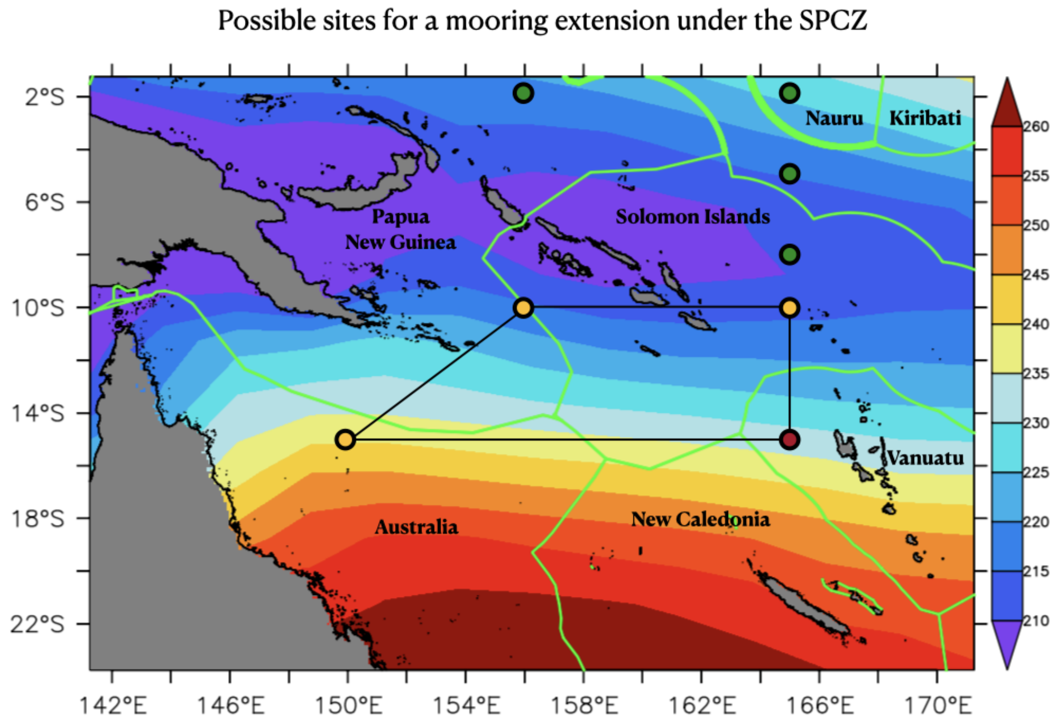

Figure 4: Map of the western tropical Pacific with the January-March climatological OLR (Outgoing Longwave radiation) values (W/m^2), (doi:10.7289/V5W37TKD). Green lines show EEZs, and dots show existing or possible sites for a mooring extension under the SPCZ. The green dots indicate the existing TAO/TRITON moorings; the red dot is at 15°S, 165°E, and the yellow dots mark the regions of interest for MJO coupled feedback observations (15°S, 150°E; 10°S, 156°E; 10°S, 165°E).

2.4.3 Salinity Sensors on the TMA

2.4.3.1 Introduction

Historically, at least until the advent of Argo, salinity measurements in the tropical Pacific have been much sparser than temperature observations and largely confined to TMA time series in the western tropical Pacific. TRITON moorings measured salinity at 25m vertical resolution (Ando et al., 2017). R1 recommended broad-scale salinity sampling with enhanced resolution, better meridional spacing and increased vertical resolution to better observe near-surface salinity stratification, especially in the Warm Pool and under rain bands (R1/3.1.1.6). R1 also specifically recommended continuity of satellite SSS measurements (R1/5.5) and a doubling of the Argo array in the tropical Pacific (R1/7.3).

While doubling Argo density will do a good job of providing broadscale, high-vertical resolution salinity profiles for the TPOS backbone on intraseasonal and longer time scales, studies of subseasonal variability require more frequent sampling. Near-surface salinity observations also provide important time series for validation and calibration of satellite observations and proxies (e.g., coral $\delta^{18}O$), as well as support long-standing climate records to detect climate change. For these reasons, R2 also identified the importance of maintaining a salinity time series in the near-surface region on specific moorings in the TMA. In particular, it was recognized that mixed layer salinity observations were not necessary on all Tier 1 moorings, but rather should be focused at key locations where high-frequency variability is significant and important for air-sea interaction, such as under the rainy regions in the western Pacific warm pool, and under the ITCZ and SPCZ (R2/7.3.3.1). Here we provide the rationale of where these sensors should be located on the TMA and recommend a strawman for their deployment.

2.4.3.2 Rationale for Location of Salinity Sensors on the TMA

The Climate Record

Historical salinity has been measured at the surface on all TMA moorings since roughly 2006, although at many sites, SSS measurements began in 2000 or earlier. All TRITON buoys in the Western Pacific had subsurface salinity sensors on the moorings along 156°E, 147°E, 137°E and 130°E. TAO moorings at the equator at 165°E, 170°W, 140°W and 110°W also included subsurface salinity measurements over various periods beginning mostly in the 1990s. Typically at these locations, the TAO salinity sensors were/are located near-surface, at 5m and 10m, while TRITON sampled salinity at all instrument depths (1m, then every 25m to 150m, then sparser to 750m; see Figure 3). Salinity data were reported hourly and transmitted on GTS with automatic quality control.

Salinity measurements can be challenging because they are subject to biofouling and other phenomena that can often slowly impact the accuracy of the measurements, resulting in long-term drift. In addition, salinity is calculated as a function of conductivity, temperature and pressure measurements, and each of these is measured by a different physical sensor within the instrument. Although for the most part the time series of each measurement can be combined fairly seamlessly, salinity spiking can occur in the thermocline or where there are large vertical property gradients. Some well established techniques allow quality control and correction of salinity spikes (e.g., Lueck and Picklo, 1990; Johnson et al., 2007) and, when possible, sensor drift can also be detected through calibration and comparisons with independent salinity profiles from CTD casts and Argo profiles (e.g., Ando et al., 2005).

For these and other reasons, the historical record of salinity measured on the TMA is incomplete, with many significant gaps in the time series when sensors failed and could not be quickly replaced. For example, salinity profiles at 0°, 140°W have missing or questionable data over about one-quarter of the time series from 2006 to 2020, partly reflecting the TAO crisis of 2012-2014 (R1/1.2). Despite the gappy records, the select few TMA locations that have maintained a relatively long term time series were originally selected because they were identified as where high-frequency salinity variability was important for understanding air-sea interaction. This criterion remains relevant.

Pacific regimes that need TMA upper-ocean salinity observations

As discussed in previous TPOS 2020 reports (e.g., R1/3.1.3.1), salinity sensors on the TMA that are capable of higher frequency measurements will be most valuable in certain regimes.

Subseasonal variability (a frequency not well captured by Argo) is strongest in the tropical Pacific warm/fresh pools, which straddle the equator in the Western Pacific and also exist in the northeastern tropical Pacific. In these regions, the vertical density gradient in the upper 50-100m is dominated by the salinity gradient primarily because of the presence of barrier layers (R1/2.6.6). In the west Pacific warm, fresh pool, thick barrier layers are found year-round, but their presence during March-May is critical for air-sea interactions caused by the passage of intraseasonal MJO and westerly wind events that can trigger El Niño events (Maes and Belamari, 2011). Understanding where and when salinity-dominated stratification occurs during these relatively short-period, episodic events will help to improve their representation in models and could lead to better ENSO forecasts (Hackert et al., 2020). Thick barrier layers are also often associated with the strong gradients at the edge of the fresh pool rather than the warm pool (Maes et al., 2006), and so the eastern extent of these pools should be monitored. Models often have a hard time capturing the freshwater pools, barrier layers, and their variability, because of the models' coarse vertical discretizations and inadequate simulated surface fluxes of freshwater, momentum, radiation, and solar penetration into the water column (Maes et al., 2002; Breugem et al., 2008; Zhang et al., 2010; Maes and Belamari, 2011; Zhi et al., 2015).

Salinity-stratified barrier layers can trap heat and momentum and so modify the SST, which in turn mediates the intensity of air-sea exchange through SST-wind coupling (Godfrey and Lindstrom, 1989). In addition, the shallower mixed layer responds more readily to winds, boosting the near-equatorial advective feedback through the formation of freshwater jets in the near-surface layer (Roemmich et al., 1994). Little is known at present about the longevity of these dynamically important surface currents although they are also thought to play a role in El Niño generation (Maes et al., 2002; Gasparin and Roemmich, 2016).

Barrier layers in the northeast tropical Pacific are found in the freshwater pool and salinity gradients west of the topographic gaps in the Panama isthmus, and are modulated by the seasonal march of the ITCZ and the Pan-American monsoon. The mixed layer and the isothermal layers are much shallower here (~20-40m) compared to the western tropical Pacific, and the corresponding barrier layers are thus thinner (Katsura and Sprintall, 2020) and so potentially more susceptible to air-sea exchange. In addition, the intense sporadic nature of the rainfall in the ITCZ – and the SPCZ – make the near-surface salinity highly variable on short time scales, and thus difficult to monitor via intermittent Argo profiles. Satellite wind and/or rain products in these regions are also challenged (see sections on satellite cal/val, e.g., R1/3.1.1.2 and 5.1; R2/Annex A) and not able to adequately capture the higher-frequency of these forcing fields.

We conclude that both surface and subsurface salinity measurements are needed in the warm-fresh pools of the tropical Western Pacific and Northeast Pacific, which are dominated by barrier layers, particularly in the near-equatorial band. Many sites in these regions also coincide with historical TMA salinity measurements, and hence would add some continuity to the historical record. The wet regimes of the atmospheric convergence zones could also benefit from higher-frequency upper-ocean salinity measurements where barrier layers are patchy, and these would additionally be useful for satellite cal/val. Real-time salinity measurements could also aid in data assimilation and initialization of subseasonal-to-seasonal forecasts, as important tropical Pacific variability (MJO, Westerly/Easterly Wind Events/Bursts, ENSO) depends on the near-surface salinity stratification in the west Pacific. Finally, co-location of high-frequency salinity measurements with current shear measurements, along with high-quality heat and freshwater flux observations, would better elucidate the role of the wind-induced acceleration of lateral currents in the near-surface freshwater warm pools, and the role of these shears and currents in oceanic mixing and air-sea coupling.

2.4.3.3 Salinity priorities

Selected high-frequency (hourly or better) measurements of salinity on TMA will improve our understanding of salinity-driven air-sea interaction processes, leading to model improvements and assisting with cal/val of satellite measurements.

Salinity measurements with higher vertical spacing are particularly needed above 100m for detecting barrier layers. Below 100m, the relationship between temperature and salinity should allow proxy estimates of salinity from temperature sensors. Tighter vertical spacing in the shallower region would also support “nearest neighbor” checks to help uncover instrument drift as well as allow for some redundancy in case of instrument failure.

Priorities are summarized below, and see Figure 5:

- **Highest priority** for TMA salinity measurements are in the **warm pool and its eastern extension on the equator** (137°E, 147°E; 156°E, 165°E, 180°, 170°W), **historical sites** (0°, 140°W; 0°, 110°W), off-equator along **165°E** at 2°S and 2°N, and 5°N, and in the wet regimes of the **SPCZ** (5°S, 165°E) and **ITCZ** (8°N, 110°W).
- **Second priority** (highly desired) for TMA salinity measurements are the other sites of the Warm Pool (and near its eastern edge) at 2°N and 2°S from 137°E to 170°W; on the

equator at 155°W, 125°W and 95°W; under the **SPCZ** further south (8°S, 165°E), and at 140°W, 2°S and 2°N.

- Salinity measurements at the priority sites should be obtained with **vertical resolution** in the mixed layer at depths of 1m; 5-30m every 5m; 30-80m every 10m; and at 100m.
- Salinity measurements on all designated **Tier 2 moorings** (see 2.4.4.2 and 2.4.4.3) to simultaneously measure the shear, stratification and high quality air-sea fluxes.

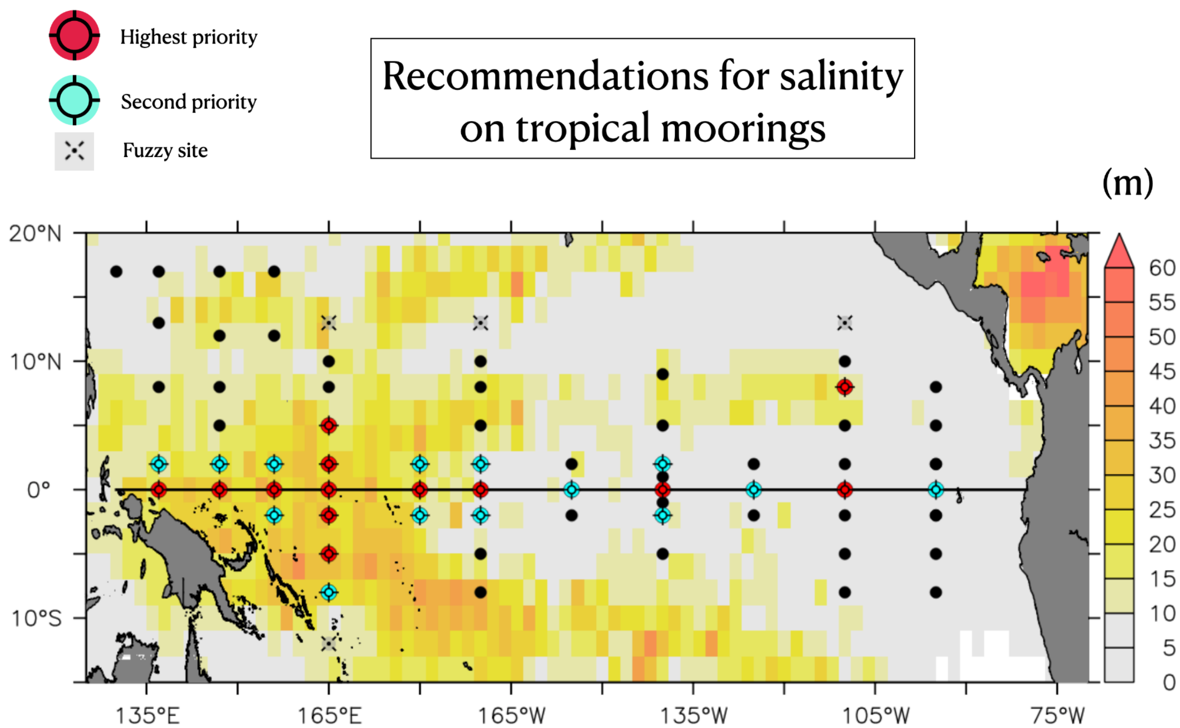

Figure 5: Recommendation for salinity sensors on tropical moorings: Red = Highest priority; Blue = Second priority. Grey and dotted crosses: fuzzy sites. Black dots are other recommended TMA sites with lower (unstated) salinity priority. Color shading indicates the barrier layer thickness maximum from monthly climatological values, in meters (produced from Mignot et al., 2007; colorbar at right). All mooring positions shown are nominal.

Salinity sensors would likely benefit from annual turn-arounds (recalibration or replacement) to help rectify expected long-term drift. It will be essential that pre- and post-deployment calibration of all sensors be implemented. A standard and consistent quality control technique should be adopted, along with sufficient resources for effective data dissemination and analysis, and higher-level data products (e.g., aggregated and gridded monthly means) to support model evaluation.

In addition, the possibility of deploying Argo floats with a shorter cycle time (i.e., 5 days instead of 10 days) to sample higher frequency salinity variability should be explored.

R3/Recommendation 11 Highest priority for TMA salinity measurements are shown in Figure 5: In the warm pool and its eastern extension: at moorings along the equator from 137°E to 170°W, and on the 165°E meridional line from the SPCZ at 5°S across the equator to 5°N. Also at two long-term historical sites (0°, 140°W; 0°, 110°W), and under the ITCZ at 8°N, 110°W.

R3/Recommendation 12 Second priority (highly desired) for TMA salinity measurements are most of the other Warm Pool sites (and near its eastern edge) at 2°N and 2°S from 137°E to 170°W. Also at the remaining equatorial sites, under the SPCZ further south (8°S, 165°E), and at 140°W, 2°S and 2°N (Figure 5).

R3/Recommendation 13 Salinity should be measured at dense vertical resolution (1m; every 5m to 30m, then every 10m to 80m, and at 100m). The complementary role of short-cycle Argo floats should also be considered.

2.4.4 Velocity measurements

2.4.4.1 Introduction: Summary of requirements

R1 and R2 recommended significantly enhancing TPOS sampling of near-surface velocity and vertical profiles of upper-ocean velocity.
As explained in R1/3.1.3.2 and 5.6, and R2/6.3.1 and 6.3.4, near-surface velocity measurements are needed to:

- Provide in situ referencing for satellite wind retrievals (i.e., the wind relative to the moving ocean surface), especially where winds are weak and currents strong;
- Allow evaluation and improvement of surface velocity products based on geostrophy and wind-response assumptions, which can have significant errors — especially in the near-equatorial regions where these approximations are less useful, and on short timescales;
- Increase the realism of bulk estimates of air-sea fluxes of momentum, heat, water vapor, CO_2 and trace species that depend on the difference between the surface wind and the surface ocean current. The ocean currents have major impacts on these fluxes in low wind/high current regimes, especially near the equator;
- Enable evaluation and improvement of future estimates of ocean surface currents from satellite-based radar;
- Advance understanding of the variability of near-surface currents, and their role in transporting heat, salt, and tracers within the tropical Pacific climate system.

In all these cases it would be desirable to sample as close to the surface as possible. However, waves interacting with the surface buoy complicate measurement of velocity shallower than about 7-8m (Farrar et al., 2007).

In addition, upper-ocean (~10-50m depth) vertical shear measurements (i.e., Tier 2) are required to describe the following target phenomena:

- The unique physics of the equatorial surface boundary layer, including its near-surface stratification, shear and divergence, from hourly to interannual timescales, including the diurnal cycle which mediates important air-sea interactions;
- Ocean/atmosphere coupling at fast timescales (subdaily) in convective and low wind regions — such as the West Pacific Warm Pool and the Eastern Pacific ITCZ — where thin fresh near-surface layers can develop after intense rain events;
- Processes that vertically distribute quantities (momentum, heat, CO_2 and trace species) that are fluxed across the sea surface into the water column;
- Responses of the tropical near-surface zonal current systems and shallow tropical cells to intraseasonal wind events and ENSO forcing;
- Impacts of tropical instability waves (TIWs) on tropical Pacific climate and ENSO, via their meridional stirring and shear-induced vertical mixing in the upper ocean;
- The structure, intensity, and time evolution of the oceanic upwelling circulation spanning the equator, which is an essential constraint on the heat budget, biogeochemistry, and ecology of the equatorial zone.

To fulfill these observational needs, two mooring enhancements were proposed:

1) Point current-meters on every mooring (at the shallowest possible depth, typically 7-8m), to measure what we refer to as "near-surface currents". Subsequent implementation discussions with stakeholders suggested that these instruments are costly; they recommended prioritizing which sites should be equipped with such current-meters.
2) "Tier 2" moorings that would additionally provide enhanced velocity profiles in the upper-ocean (sampling the 10-50m layer; see Figure 3), for example using upward-looking ADCPs to sample the upper 50m, extending as close to the surface as feasible. However, the number and locations of these Tier 2 moorings were not specified in R2. R2/Action 7.2 stated that "TPOS 2020 Task Teams should work with community experts to specify the priority sites for Tier 2 deployments, based on the results of the mooring pilot study currently underway (Appendix C.1.3; R2/7.3.2.1 and Masich et al., 2021) and analysis of where ocean velocity measurements are most needed."

2.4.4.2 Siting of near-surface velocity and shear measurements

Locations for shallow point current meters

We believe that near-surface (7-8m or as shallow as possible) point current meters on *every* mooring would advance many aspects of the TPOS. However, if this is not feasible then the highest priority locations include some coverage within the following regimes and conditions (in no particular order):

- Where ageostrophic velocities and their variance are largest (near the equator, and along the Cold Tongue Front, typically located around 2°N) (Figure 6; R1/3.3.2);
- To complement and extend the range of the existing long-term subsurface equatorial ADCPs (110°W, 140°W, 170°W, 165°E, 156°E);
- On all Tier 2 moorings, for independent validation of their ADCP profiles near the surface;
- Where the winds are weak and the surface currents are strong, to improve wind stress and heat flux bulk estimation (especially near the equator, Figure 7; also Renault et al., 2020);
- To sample the rapid (sub-daily) variation of surface currents that develop in response to thin fresh layers under the ITCZ;
- To provide full regime coverage for future satellite radar surface current estimates.

Locations for Tier 2 moorings

The TPOS 2020 Backbone Task Team has worked toward formulating recommendations for priority sites for Tier 2 deployments, using preliminary results from pilots and through dedicated analyses. However, despite much discussion, we are not ready to formulate a final recommendation for the backbone Tier 2 mooring locations, which should be based on substantial evidence that sustained measurements would be indeed impactful. To inform future discussions, our rationale and preliminary conclusions are given below. At this stage:
We recommend that the proposed Tier 2 sites discussed below be rotated during the next few years. Through these pilot studies of Tier 2 sites, the TPOS community can gain more experience before providing final recommendations.

Here we provide rationales for pilot studies that would further clarify priorities for Tier 2 locations:

Within the equatorial wave guide, results from the GOMO mooring pilot (Appendix C.1.3; Masich et al., 2021) show that systematic downward-propagating diurnal jets are present where the EUC is close to the surface in the central and eastern equatorial Pacific. To capture the unique physics of the EUC as it shoals and interacts with the mixed layer, TIWs, and atmospheric forcing (wind variations, diurnal fluxes), all the moored sites along the **140ºW transport array (2ºS, 1ºS, 0º, 1ºN, 2ºN)** should be Tier 2, where deeper subsurface ADCPs would be deployed

(R2/7.3.2.2). This will ensure that the near-surface meridional divergence is described, along with the impacts of the diurnal cycle and TIWs on shear, density, and mixing. Complementing the deep-reaching velocity measurements already planned or existing at these sites (which reach up to within 25m of the surface), the Tier 2 upper-ocean velocity measurements will extend velocity coverage to the near-surface, to capture the crucial directly wind-driven transport that would otherwise be missed.

In addition to the above, **moorings at 2ºS and 2ºN on alternating meridians** should be considered as possible upgrades to Tier 2 (at 170°W, 110°W, 165°E, see recommendations in 2.4.3.3). This will help monitor how the structure of the near-surface flow evolves across the changing velocity and wind regimes from west to east. These sites also span contrasting climate regimes. The western sites will capture high-intensity convective rain events over the warm pool, while the eastern sites will capture drier and windier regimes but with very thin and shallow thermoclines and strong mean velocities. Lastly, these sites will span several regimes where winds are often weak and currents are strong, and will sample the highest near-surface velocities captured by drifters.

High rainfall events in **extreme rainfall regimes** can result in thin, relatively fresh, “slippery” near-surface layers that can sustain high vertical shears, and concentrate the wind stress-induced accelerations of the currents very near to the surface (Shcherbina et al., 2019). To sample these shear/buoyancy/flux interactions in very high rainfall regimes, **some Tier 2 sites should be placed in the west Pacific and also under the ITCZ and SPCZ**. The 165ºE meridian extends into both convergence zones, while the 140ºW line extends into the ITCZ. One of the highest rainfall sites is at the northern extension at 110ºW. In addition, 156ºE also provides good sampling of high rainfall rates in the ITCZ and Warm Pool. **Pilots should be envisioned at these sites, to determine the necessity (or not) of sustained shallow velocity monitoring within the ITCZ and SPCZ.**

Full Tier 2 coverage across a range of latitudes would detect the spatial structure and inter-connections of near-surface velocity and shear evolution forced by the diverse forms of wind bursts (wet westerly bursts and dry easterly bursts) and over ENSO cycles, as both the climate and dynamical regimes change with latitude and time. Two meridians are attractive for full coverage with Tier 2 capability: (1) 165°E, as it spans the two major convergence zones and is situated near the variable edge of the warm pool, and (2) 140°W, which will already be more densely sampled in the equatorial belt, and extends northward into the ITCZ and southward into the windier and drier trade wind regime. While the vertical shear at 110°W is of interest, the shallow EUC leads to a large portion of the surface current shear being located within the very challenging near-surface region above 10m (Johnson et al., 2001). 110°W also suffers from frequent vandalism. Thus Tier 2 capabilities at the off-equator locations there should be considered through other emerging technological solutions, e.g. uncrewed surface vehicles.

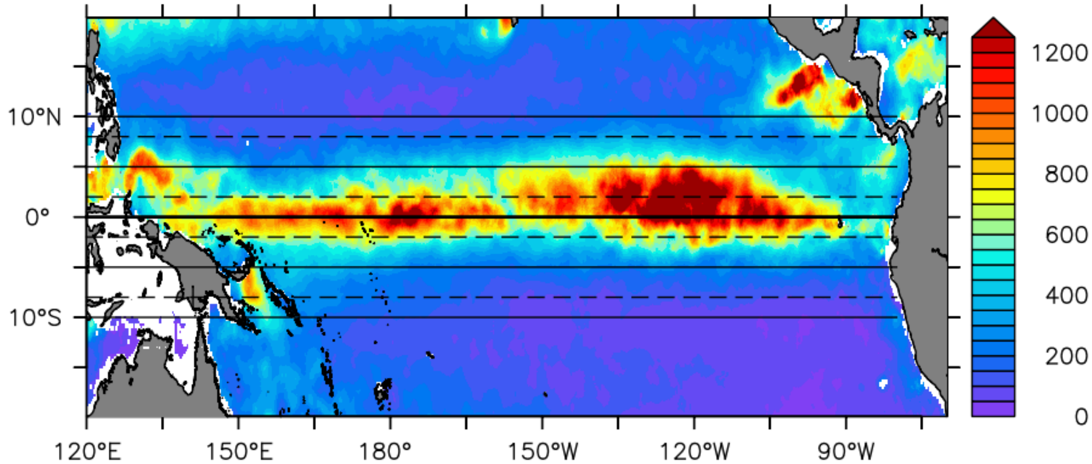

Figure 6: Mean surface EKE (Eddy Kinetic Energy; cm^2/s^2) determined from drifter velocity data, from Laurindo et al. (2017). The thick solid line is the equator, while the thin solid and dashed lines are at 2°, 5°, 8° and 10°, the nominal meridional locations of moorings.

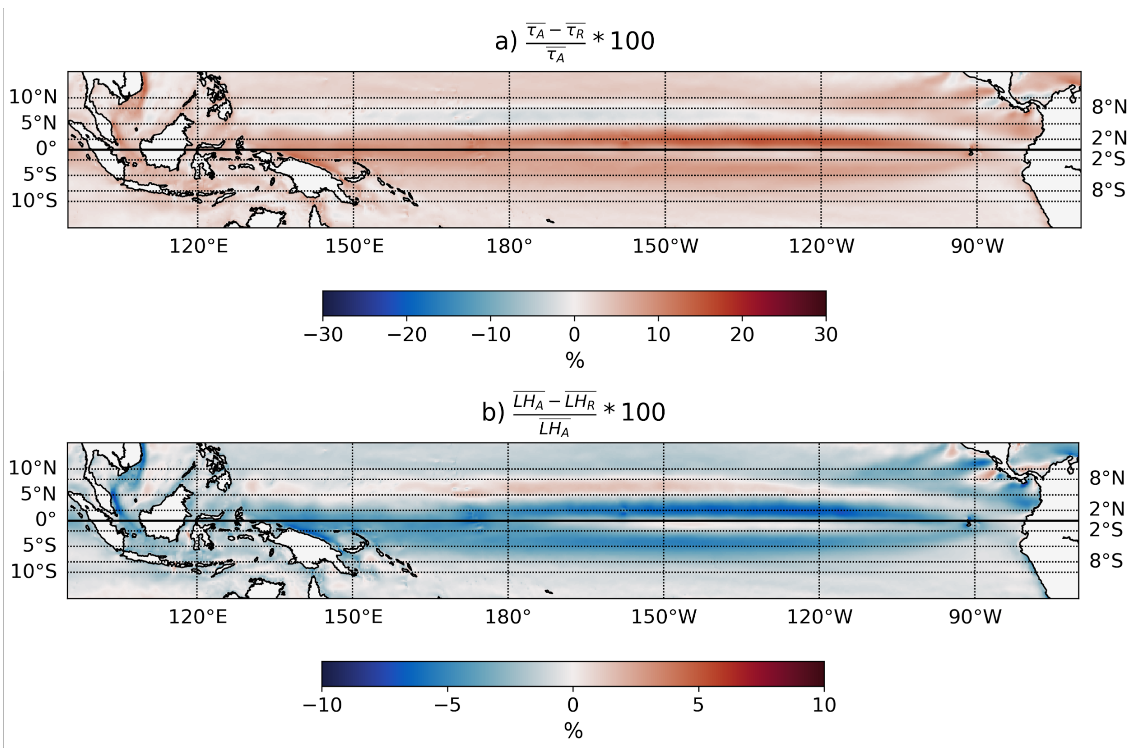

Figure 7: (a) Mean difference (%) between a surface stress (τ_a) estimated using only the absolute 10-m wind, and a stress (τ_r) estimated using the difference between the 10-m wind and the oceanic surface current . Both τ_a and τ_r are estimated using the same hourly 10-m wind from a 5-year coupled simulation (with thermal and current feedback, see e.g., Renault et al. (2020)). (b) As in (a), but for the latent heat flux using only daily fields. Courtesy of Lionel Renault and Sebastien Masson.

2.4.4.3 Summary of Priorities

Based on these target phenomena and rationales, we propose two levels of priority for near-surface currents and Tier 2 sites (noting that all Tier2 moorings should be equipped with a near-surface point current meter) (Figure 8):

a) Top priority for near-surface currents:

- Equatorial sites where subsurface ADCPs already exist: 110°W, 140°W, 170°W, 165°E, 156°E
- Along 140°W, at 2°S, 1°S, 1°N, 2°N, where subsurface ADCPs will be added
- On all Tier 2 moorings (thus also at 140°W, 5°S, 5°N)

Second priority:

- at all other equatorial sites, and at 2°S-2°N at 110°W, 140°W, 170°W, 165°E
- At 140°W, 9°N

b) Top priority for Tier 2 moorings:

- Along 140°W, at 5°S, 2°S, 1°S, 0°, 1°N, 2°N, 5°N

Recommended Tier 2 Pilots:

We recommend additional initial rotating locations for the following sites, to help determine where and if sustained monitoring is needed:

First priority:

- Along alternating meridians (170°W, 110°W), at 2°S, 0°, 2°N, and 147°E, 0° and 2°N
- Along 165°E, at 5°S, 2°S, 0°, 2°N

Second priority:

- At 165°E, 8°S and 5°N, and 110°W, 10°N, in intense rainfall regions
- Along 147°E or 156°E
- at all other equatorial sites 2°S-2°N

R3/Recommendation 14 Highest priority for near-surface point current meters are shown in red in the top panel of Figure 8: Equatorial sites where long-term subsurface ADCPs already exist; along 140°W from 2°S to 2°N where subsurface ADCPs will be added; and on all Tier 2 moorings (thus also at 5°S and 5°N,140°W).

R3/Recommendation 15 Second priority for near-surface point current meters are shown in blue in Figure 8: at all other equatorial sites, and at 2°S-2°N at 110°W, 140°W, 170°W, 165°E. Also at 9°N,140°W under the ITCZ.

R3/Recommendation 16 We recommend that Tier 2 sites (giving mixed layer ADCP velocity profiles above about 60m) be rotated among several locations during the next few years, to gain more experience before providing final recommendations. Figure 8 (bottom panel) suggests likely locations for these pilot sites.

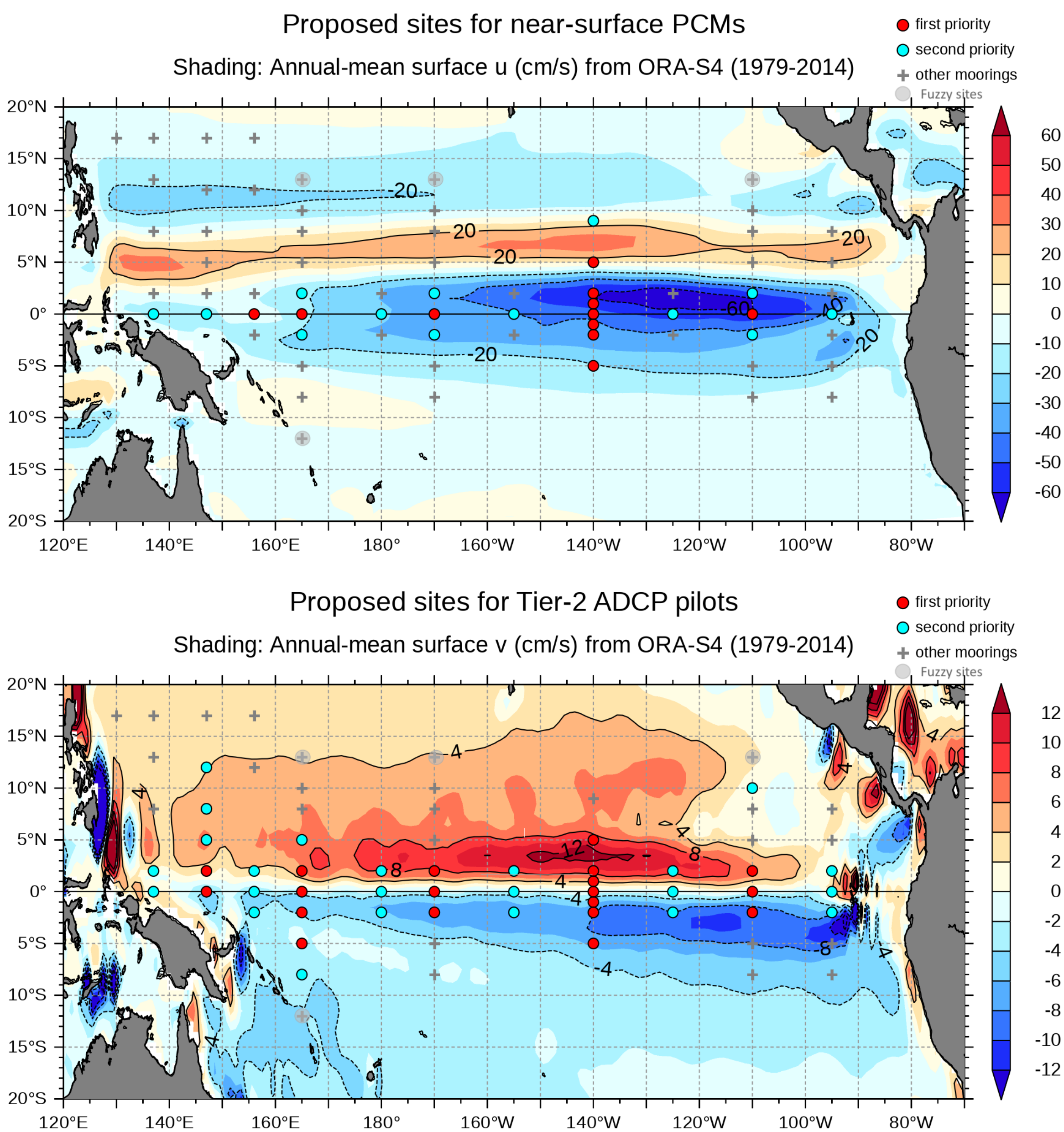

Figure 8: Preliminary recommendations for sites to include (a) shallow single-point current meters (PCMs), and (b) Tier 2 moorings with shallow upward-looking ADCPs. Colored dots indicate first priority (red) and second priority (light blue) sites. Shading indicates the (a) zonal and (b) meridional components of the climatological annual mean near-surface currents (cm s^{-1}), as simulated by the ORA-S4 ocean reanalysis during 1979-2014. All mooring locations are nominal; some may require EEZ clearances.

2.5 The LLWBC/ITF System

2.5.1 Introduction

The low latitude western boundary currents (LLWBC) of the north and south Pacific Ocean, including the Indonesian Throughflow (ITF), play crucial roles in ocean dynamics and climate variability on both regional and global scales (Smith et al., 2019; Todd et al., 2019; Sprintall et al., 2019). Work over several decades has established that the mass, heat and property transports through the LLWBC/ITF system influence the entire tropical strip at interannual and longer timescales (see discussion and references in R1/3.3.4.1 and R2/4.1.5 for BGC fluxes). Yet these fast, narrow and often highly-sheared currents, in many cases amid sharp topography and constricted straits, are difficult to resolve even in fine-resolution models and satellite products, thus in situ observations remain essential. A further challenge is that the effects on the tropical strip combine variability of all three flows; but the need here is for a synoptic description of the whole system. Monitoring the combined effects would be far more valuable than the present unorganized sampling of the individual currents. No observing array for the tropical Pacific can be complete without measuring this circulation, but sustained observations across the LLWBCs have proven difficult to implement.

Recognizing this challenge, a pilot study was proposed as part of TPOS 2020 to determine the key observational sites in the LLWBCs and ITF, and decide on the variables to be observed in context of their priority and the readiness of technology. Most importantly, the pilot would determine the time and space scales that must be resolved in order to develop a sustained boundary observing system (see R1/6.1.1).

Here we report on progress made to date on this pilot study as well as unresolved and ongoing issues that require additional attention.

2.5.2 Progress to date

The Ocean Obs ’19 (OO19) papers identified and provided details highlighting the broad array of measuring systems that have existed over the past decade in the LLWBCs (Smith et al., 2019; Todd et al., 2019) and the ITF (Sprintall et al., 2019). The diverse situations of these currents (often narrow and including a few confined straits), the frequently strong eddies that complicate a measuring strategy, and the varied requirements for heat and property fluxes as well as velocity mean that these systems cannot be sampled with any single technology.

For the LLWBCs, key recommendations targeted simultaneous monitoring of both the north and south LLWBC mass and heat transport above 500m at monthly/seasonal timescales. For the ITF, recommendations focused on velocity profiles in the inflow and outflow straits, with special attention for a few important finer-scale features as well as maintaining the long time series of the IX1 XBT transect.

The OO19 papers for the LLWBCs supported the need for the implementation of a more rationalized and coordinated sampling effort and recognized the need for a multi-platform approach, but stopped short of expressing the specific combination of platforms that would combine to build a successful monitoring system (Smith et al., 2019; Todd et al., 2019).

The TPOS 2020 pilot study (R1/6.1.1) takes advantage of the large collective experience to begin to formulate measurement possibilities.

In the Solomon Sea, a loose coalition of researchers under the SPICE program (Ganachaud et al., 2014) have endeavored to examine the various platforms measuring transport variability over the same time period in this Southern Hemisphere LLWBC. Initial comparisons of integrated transport over the upper 500m showed favorable agreement between the inflow and outflow measurements of the Solomon Sea over the common 19 month time period (Anutaliya, 2019).

Several measurement platforms produce useful estimates of the flow and variability, but each platform also has limitations in describing the LLWBC system:

- Subsurface ADCP moorings are uniquely able to measure velocity at high temporal scales in the narrow straits that are major features of the ITF and LLWBCs. However, only velocity measurements extend above 100m, so moored measurements in narrow dynamic channels typically omit the temperature and salinity information in the upper layer that are vital for heat and freshwater fluxes (Alberty et al., 2019).
- Gliders measure velocity and temperature/salinity simultaneously from 5-1000m, but cannot operate in the intense currents of the narrow straits, and their slow travel leaves them susceptible to eddy aliasing. They can be deployed by local small boats and provide near-real-time data (Kessler et al., 2019a; Schonau and Rudnick, 2017).
- Bottom-mounted PIES measure pressure (thus geostrophic transport) at high temporal resolution, but are endpoint measures that use proxies to infill detail about the flow and property structure within the channel (Anutaliya et al., 2019).

All of these techniques are strengthened by being embedded in the Argo network.

Clearly none of these techniques serves all the necessary requirements, but this exercise facilitates progress towards the ultimate goal of determining what combination of these measurements might be most cost-effective and lead to a logistically viable data product, as well as providing a useful product for testing the reliability of models for resolving this complex and remote LLWBC system.

First steps toward assessing what combination of platforms might work best for a sustained measurement system in each boundary current regime have also been undertaken by a number of global and western Pacific regional partnerships. The TPOS 2020 Western Pacific Task Team

(WP-TT) assembled an inventory of international cruises and projects of past and present observing activities within each LLWBC system. Updates to this spreadsheet are continuing, with the idea that this at least alerts the community of potential collaborative opportunities to determine ways to share costs such as through ship time, instrument input and logistical capabilities. The idea is that this record could then also help to foster dialogue on how the prospective intersection of the projects might produce components that mutually contribute to a synchronous sustained observing system in the boundary currents.

In addition the CLIVAR/WCRP-endorsed NPOCE program (npoce.qdio.ac.cn; Hu et al., 2020) has targeted moored arrays deployed within the northwest Pacific Mindanao LLWBC and the ITF, working toward a consistent quality-controlled atlas of the velocity time series in these systems. This task has been identified as a high priority in the new science plan currently being created as part of NPOCE-II in order to better understand exchanges between the two systems, as well as reduce model bias.

Finally the recently formed GOOS OOPC Boundary Systems Task Team (BS-TT), consisting of international experts in observations and models, also has a goal to develop a conceptual design for sustained observing activities in boundary currents and adjacent shelf seas globally. Initial goals of the BS-TT are much aligned with the TPOS 2020 Pilot Study in LLWBCs: to examine historically well-observed boundary current systems and mature integrated observing systems and identify knowledge gaps, observing system design, and experience in the synthesis of multi-platform observations. The idea is to build community consensus as a way forward to encourage reviews, pilot experiments, observing system evaluation experiments, and by being an advocate for new sustained observing activities. The ultimate goal is the establishment of a Boundary Systems Observing Implementation Plan, as recommended by the Framework for Ocean Observing (FOO), to sustain community commitment and contributions to coordinated efforts in boundary systems, and to sustain investment in them by increasing their linkages to other ocean observations and newly developed technology, and to advance the scientific and societal benefits that these systems provide

2.5.3 Pathways for Future Progress

Combined, the WP-TT, SPICE, NPOCE and BS-TT efforts provide a strong basis to assess measurement and sampling strategy for the Pacific LLWBCs. These research projects have gone a long way to define requirements and evaluate the technologies that can meet them. Yet, as noted in previous reports, progress has been difficult because this work inherently engages multiple nations, agencies and international programs, each with their own interests and constraints. Progress has been hindered by a lack of integration among these observational programs focusing on different pieces of the LLWBCs. Trying to coordinate these programs and funding introduces non-scientific (including geopolitical) factors that have proven to be a significant complication. This limits progress towards our goal of an overall strategy to monitor the system as a whole.

Headway might best be achieved by drawing key players from the international observational community, as well as the climate analysis and modeling communities, and agreeing on targeted and feasible terms of reference with realistic but firm timelines. Further fostering dialog among international partners would be a necessary step toward building an international integrated observational program, and facilitate operations in EEZ waters, where limited access remains an issue in some key locations. Support from high-level intergovernmental organizations would help: the international organizational umbrella provided by NPOCE in conjunction with the BS-TT might be tapped to continue this pilot study post TPOS 2020.

Ultimately, only partial and incomplete descriptions of the mass, heat and property flows through the LLWBC/ITF system will be possible from observations. The observational experience of recent decades has built the tools and background to monitor crucial chokepoints where land defines clear boundaries. However, some aspects are likely to resist adequate definition from observations alone; these include the upper layers of channels where intense shipping precludes shallow sampling and the extremely complex corner of the far western equator where multiple currents intermingle (Hu et al., 2015). The full picture of the LLWBC/ITF system in context of the tropical Pacific circulation will come from model solutions constrained and verified by carefully chosen in situ measurements. Such exercises will also enable deciphering the multiple influences of the LLWBCs/ITF on the Indo-Pacific tropics as a whole, the ultimate goal of this effort.

Future progress will rely on a closely integrated modeling and observational plan as the development of model tools will make it possible to test different combinations of array components that might be difficult to assess from observations alone. The present observing programs provide a good basis for beginning those studies, and with high-resolution models capable of representing the narrow currents we can attack the harder problems, including strong bathymetric effects, mixing and tides (e.g., Melet et al., 2011). However, the TPOS 2020 effort has not yet effectively engaged the modeling community, and these modeling challenges are difficult. Explicit funding for model experiments could lead to significant progress in this area.

R3/Recommendation 17 Encourage community workshops (e.g., under the auspices of the CLIVAR PRP) to bring together the three regional-focus efforts (northern and southern WBCs, ITF) towards an organized combined sampling program.

R3/Recommendation 18 Encourage engagement of modeling efforts towards solving the difficult problems of strong bathymetry, mixing and tides, and the strong narrow near-shore currents that characterize this system.

Chapter 3 Considerations for the Future

In this section we discuss other matters that should be taken into account when considering the future of TPOS. These matters include a self-evaluation of the TPOS 2020 project, emerging technology, how the project has engaged with international and intergovernmental partners, and elements of a future TPOS governance framework.

3.1 Success against TPOS 2020 Terms of Reference

The TPOS 2020 Project was charged[4] by TPOS stakeholders:

- To redesign and refine the TPOS to observe ENSO and advance scientific understanding of its causes,
- To determine the most efficient and effective observational solutions to support prediction systems for ocean, weather and climate services, and
- To advance understanding of tropical Pacific physical and biogeochemical variability and predictability.

In R1 and R2, this charge was translated into the five key functions of the backbone:

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 five functions above capture the main uses and societal benefit areas of the TPOS and thus provided a lens for developing a comprehensive analysis of requirements, expressed in terms of essential ocean/climate variables (for example, see R1/Chapters 2 and 3). From those requirements, we developed a set of recommendations in R1 (updated in R2, see Appendix B in this report) that covered the general scientific response to requirements, with reference to established and emerging scientific and technical methods, but not to specific platforms or national contributions. Finally, R1 and R2 provided a roadmap for implementing those recommendations; this Final Report has provided additional elaboration.

[4] https://tpos2020.org/prospectus/

We would thus argue that the three Reports of TPOS 2020 fully responded to the charge of the Project. The Prospectus referenced above also detailed some of the expected benefits from the Project:

a) A refreshed and more effective design for the TPOS, promoting sustainability, and making full use of new and emerging technologies;
b) Greater cooperation and coordination among the international sponsors and contributors to the TPOS, delivering efficiency, reduced risk and greater robustness;
c) Facilitation of experiments and studies in process parameterization and modeling to guide improvements in climate prediction and associated applications;
d) Integration of biogeochemical and biological sampling into the TPOS design and implementation;
e) Fuller assessment of climate change signatures and the impacts in the tropical Pacific.

Some of these benefits have been fully realized, but others remain a work in progress. For (a), we argue that this has been achieved with the three Reports, though we will not know its actual effectiveness until all changes have been implemented. Good progress has also been made against (c) as evidenced by the funding of many pilots and process studies described in R1 and R2; there is on-going work that will stretch over into TPOS post-2020. Biogeochemical sampling is fully integrated into the design but as discussed earlier in this Report, biological and ecosystem aspects of the design are a task for the future. Topic (e) became a major focus of R2, with strong engagement from the research community. The design and recommendations were adjusted to take account of requirements from decadal and longer change, with some trade-offs required. The effectiveness of the design needs to be tested as part of the rolling evaluation.

Aspect (b) has been challenging. The Terms of Reference for the Project required us to "embrace contributions from multiple agencies and countries, through a coordinated portfolio of resources and high-level oversight of the scientific and technical design, sub-projects and interfaces to the user community". The consultations of both the Steering Committee and the Resource Forum did establish dialogue with new stakeholders and, in principle, enhanced the prospect of a broader base of support. However, this has been slower to materialize than expected, exacerbated by the withdrawal of some significant resources in the Western Pacific. The Resource Forum and implementation mechanism are still well short of a coordinated portfolio of resources and contributions.

R3/Recommendation 19 Develop a rolling evaluation of the overall and ongoing effectiveness of the TPOS for research and prediction system goals.

3.2 Emerging Methods and Roadmap for Evaluation and Inclusion

Today is a fertile time for new ocean instrumentation. New capabilities, new types of autonomous vehicles, and improved real-time transmissions allow us to consider sampling that previously had been difficult or very expensive. Some of these possibilities were described in R2/9.2 and 9.3.

R2 proposed a framework to assess the readiness and missions of backbone technology (R2/9.4). This framework tried to categorize a method according to its technological readiness, the relevance of its measurements, and its potential roles in the context of existing networks. Lacking an impartial group to evaluate the projects, in practice the framework was only partly successful towards its goal of informing our sponsor agencies of possibilities relevant to their mandates.

Considerations for more detached and independent evaluations were discussed in the Second Report (R2/9.5), noting that the key metrics are ultimately the uses that forecast centers, scientists and others make of the data, and how they fit into other pieces of the observation/model/product puzzle. These multiple “lives” of an observation are difficult to perceive in real time, especially when a technology is new. Yet choices must be made in real time, guided as objectively as possible. Ongoing and proposed pilot and process studies (Appendix C) provide an excellent avenue for defining the role of emerging technologies in the observing system and testing their technical readiness, robustness and relevance in context of the other pieces of the TPOS.

R2 recommended that the readiness level framework be further developed (R2/Recommendation 9.1). We expect that a formal independent evaluation will be necessary as projects come towards maturity, and expand on R2 to recommend consideration of methods to do this.

We further recommend that the new guiding bodies (Scientific Advisory Committee and Implementation Coordination Group, see 3.4) consider an explicit structure to assess the capabilities, role and readiness of possibilities for inclusion in the backbone.

R3/Recommendation 20 Develop an explicit, independent structure to assess the capabilities, role and readiness of possibilities for inclusion in the backbone.

3.3 International and Intergovernmental Organizations: The Broader Relevance and Impact of TPOS 2020

The TPOS 2020 project was established under the direction of an international group of agency sponsors/stakeholders, a group that became the TPOS 2020 Resource Forum. It provided a new mode whereby a component of the global observing system was effectively taken "offline" for review, redesign and renewal. The TPOS 2020 Steering Committee reported to the GOOS Steering Committee annually on progress.

The TPOS 2020 project addressed challenges common across regional and global ocean observing systems. The 'deep dive' undertaken by TPOS 2020 in a tropical Pacific context, and the learnings and outcomes from the project thus have broader relevance and impact. The challenges included:

- Exercising the Framework for Ocean Observing (FOO; Lindstrom et al., 2012), including articulating observing system requirements in a way that informs observing system design, independent of details of observing system networks.
- Balancing stability with innovation in the evolution of the observing system design process.
- Optimising the design for efficiency and effectiveness.
- How to ensure both the observing system and the prediction systems in concert improve the quality and usefulness of information delivered to end users.
- How to energise new participation and engagement.

The TPOS Resource Forum (TRF) was formed to enable direct engagement of the agency sponsors in the project. Regular engagement of active TRF members was productive in guiding TPOS 2020 efforts, but the TRF didn't live up to expectations of providing/coordinating resourcing. In addition, the term 'Resources Forum' was polarising for some, who interpreted it as the expectation they would bring a 'checkbook' to meetings. This impacted the ability to engage organizations without significant resources, or those benefiting from a resilient and responsive TPOS. In reality, TPOS 2020 needed a range of resources, including intellectual input, and alignment of activities—e.g., modeling activities, use cases and pilot projects. A more inclusive name, such as a 'Stakeholder Forum' may have enabled broader engagement. The lessons learnt included:

- Demonstration of the utility of such a project mode with all stakeholders engaged in the design of the end-to-end system;

- Experience with a design that explicitly included sustained and experimental observation contributions;

- Feedback on the utility of the FOO in guiding the design process;

- Experience in the use of multiple drafting rounds with both external and internal review;

- A demonstration of the power of basin-focused regional approaches;

- Managing engagement with all relevant intergovernmental entities: GCOS, GOOS, JCOMM (now dissolved), IOC and WMO (through WIGOS);

- The critical need for dialogue with relevant research groups, such as the World Climate Research Programme/CLIVAR project; and
- The importance of collaboration with the modeling community, through WMO (The Inter-programme Expert Team on Observing System Design and Evolution, IPET-OSDE), Ocean Predict (GODAE Oceanview), and WCRP modeling activities among others.

TPOS 2020 was used as a constructive example of how increased engagement with Met Services could work positively for the ocean observing system. Met Services are critical users of observing system information and as such their experience and intelligence is important for guiding the observing system, through analyses, evaluations, etc. Some Services are also providers of capability and TPOS 2020 was able to draw on their experience with observing system design, coordination and impacts.

Through engagement with WMO, TPOS 2020 was established as a WIGOS Pre-operational Regional Pilot. Effectively, the challenges that TPOS was grappling with resonated with those faced by WMO, including modes of regional coordination. These challenges spanned

- research and operational drivers, funders, implementers and users;
- organizational constructs (e.g. GRAs, WMO regions, etc.);
- observational networks.

The tropical Pacific has a dominant driver in ENSO, and TPOS has a strong and established connection to operational applications—especially seasonal prediction. Given the nature of air sea interaction in the tropics, and its influence on severe weather and climate (intraseasonal and longer), engagement from the meteorological services in the tropical Pacific was regarded as essential.

The links between WIGOS, the former JCOMM and TPOS 2020 meant we were able to include resolutions in WMO Congress and Executive Council papers to ensure that TPOS was visible, and hence we could ensure it was a recognised entity when engaging with regional met services (e.g., BMKG Indonesia, Australian Bureau of Meteorology, SENAMHI Perú, Japan Meteorological Agency). TPOS 2020 helped motivate discussions across research, observations and prediction systems and services, which led to broader discussions within WMO about how integrated Ocean Observation and Prediction was important for the delivery of the broad range of services that WMO cares about. At Congress in 2019, there was a coordinated set of high-profile resolutions across the WMO Congress agenda, and strong messages from the members on the floor that if Met Services wanted to improve and extend forecast capability, they needed to invest more in engaging in ocean activities.

The TPOS 2020 Project also faced several challenges and, in some cases, fell short of expectation.

The Project was principally constituted from scientists and sponsors directly engaged in TPOS, and so was less effective or able to engage with users and stakeholders more broadly, including those from Small Island Developing States.

For the first time in the history of the development of the TPOS, the eastern Pacific oceanographic community has been involved in the discussion on how to engage in its implementation. The interest is there, as evidenced by the strong regional participation when TPOS 2020 SC met in Peru and in the second Resource Forum, and in contribution to the Eastern Pacific Task Team. However, engagement with the eastern Pacific oceanographic community was challenging, across the spectrum of needed activities from data sharing to resourcing major initiatives. TPOS post-2020 needs to build from this engagement and find commitment on feasible and practical steps toward implementation. We hope the UN Decade of Ocean Science for Sustainable Development may be able to inspire major change and improved capacity.

While efforts were made to engage with activities outside the tropical Pacific (such as with the parallel reviews of the Indian Ocean and tropical Atlantic observing systems), ultimately the task of harmonisation has been left to higher bodies such GOOS and GCOS.

The TPOS 2020 offline approach (that is, the project was not controlled by or directly connected to any of the intergovernmental organizations) favours nimbleness and focus. The project was able to spin up rapidly in response to a crisis (e.g. not waiting for the next annual round of meetings and approvals), engage key agency partners and gain commitments to supporting the observing system while mobilising the scientific community to undertake the design work. Such a community response was impressive.

However, such an offline approach also creates a risk of inconsistency (TPOS 2020 developing bespoke approaches and solutions) and conflicting purposes (for example, the different set up for the three tropical ocean reviews); TPOS SC worked hard to mitigate such risks but there may be better ways of managing the multiple interfaces, particularly within GOOS.

Similar issues arose with the research community. While the interactions with the modeling community were generally constructive and positive, it was in hindsight inevitable that research may take a different perspective on some issues compared with the TPOS 2020 Project and while the ensuing discussions added considerable value to the work, they also caused delays and created a level of uncertainty. GOOS may want to consider best practices regarding engagement of the broad stakeholder community in advancing the global system, while recognising the strong stake that the research community has in the development of the observing system, as it works to deliver the GOOS 2030 strategy.

While the Project began with an expectation that cost-effectiveness would be discussed in detail, in practice it was extremely difficult to generate consistent and reliable cost/investment estimates across TPOS. The Project provides general rather than specific guidance. For the ocean observing system this remains a challenge.

Lastly, it is hoped that TPOS 2020 might be a pathfinder for how Ocean Observing governance may work into the future. TPOS 2020 was run as a flexible, responsive and relatively fast-moving project outside of the intergovernmental system but maintained links into the WMO and IOC governing bodies and relevant structures such as WIGOS.

R3/Recommendation 21 Encourage GOOS to consider best practices for broad stakeholder engagement, including both research and operational drivers.

3.4 Governance and Ongoing Structure

The TPOS 2020 project used a governance structure suited for considering and evaluating the redesign of the system: (1) a group representing the key stakeholders, the TPOS 2020 Resource Forum, and (2) a group to steer and provide oversight, specifically for scientific and technical aspects, the TPOS 2020 Steering Committee. Sub-groups and/or task Teams were created as needed. The Terms of Reference of these groups can be found at https://tpos2020.org/.

Post-2020 the focus of the project will shift to implementation of the redesign and therefore the governance structure will also need to shift to meet this new purpose. The Second Report of TPOS 2020 (Kessler et al., 2019b) outlined an initial proposal for the governance of TPOS post-2020. Some of the functions of the current structure are still necessary and retained. These include scientific advice on observing system design and engagement with and consultation among stakeholders. However, there is a need to address some of the shortcomings of the current structure in order to enable TPOS to continue to be the innovative effort it set out to be.

A study by Tanhua et al. (2019) on the evolution of the Global Ocean Observing System and its governance described some of the key principles behind good governance:

- *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.

The TPOS 2020 project was aligned with such principles but faced limitations in authority and accountability which were discussed in R2. For example, some sections of the research community felt disenfranchised, which detracted from the overall respect that the TPOS community was working to cultivate. The project also did not publish strict measures of success other than the commitment to publish three Reports. The concept of a TPOS 2020 science capability matrix was developed but did not progress beyond those preliminary discussions and as such was not implemented. The proposed post-2020 governance structure below is intended to address those identified limitations.

The three core elements of the 2nd Report post-2020 governance proposal were:

(i) A **Scientific Advisory Committee** to build on the work of the current Steering Committee and its Task Teams.
(ii) A **Stakeholders Forum for TPOS stakeholders to engage and contribute** to coordination and commitment to the operation of the observing system.
(iii) An **Implementation Coordination Group** to work on the implementation of the observing system, including through the transition period.

The TPOS 2020 Resource Forum (RF) and the Steering Committee (SC) held a series of discussions to further consider and refine these core elements.[5] The proposed structure (Figure 9) retains the functions identified in the core elements with minor changes to the specific groups. Recognizing this is a transitional period, the proposed governance will be carried out in a phased approach to ensure that all of the necessary functions are retained and that new functions can be incorporated and adjusted to be most effective.

We are working to establish the SAC, along with the other groups described below. The current TPOS 2020 SC will nominate the new chair and co- (or vice-)chair who will be formally endorsed by the Resource Forum. We will then work with the RF to appoint members of the SAC and ICG who have either been nominated or volunteered to serve in these groups.

<u>Scientific Advisory Committee</u>

The Scientific Advisory Committee (SAC) of TPOS post-2020 will continue the role of the current TPOS 2020 Steering Committee to lead on design and assessment and ensure better integration across the value chain. A variety of pilot and process studies will bear fruit during the coming years (3.2, Appendix C); these will need expert assessment to find their place in the future design. The SAC will also provide the task teams with overarching guidance and will work with the teams to set expectations. We recognized that the SAC needed to be more directly engaged in the analysis, design and actions of the Backbone Task Team (TT). Therefore, some of the functions of the current Backbone TT will be absorbed into the new SAC. In addition, the SAC will help to ensure a smooth transitioning of the functions of the current Steering Committee and Implementation Group into the new structure.

This group will also be responsible for reporting on the state of TPOS relative to its aims by maintaining responsiveness to the new Stakeholders Forum. This connection will help facilitate better coordination with stakeholders. The TPOS 2020 Project was initiated by TPOS stakeholders, and can be regarded as a contribution from agencies/nations to the broader GOOS, GCOS and JCOMM initiatives. However, there remain questions over lines of reporting to GOOS since the former JCOMM is still in a state of transition. In order to address this uncertainty, it is recommended that a connection to the intergovernmental organizations remain similar to the current approach initially. Similarly, understanding how TPOS will connect to

[5] The TPOS 2020 Resource Forum met alongside the OceanObs '19 Conference and discussed governance and the transition roadmap for TPOS post-2020.

WMO going forward will require further definition including the next steps for TPOS as a WIGOS pilot project. Both the WMO and IOC are grappling with how to engage with projects similar to TPOS, indicating this could be an opportunity for TPOS to help better define the functional relationship. Updating this relationship and establishing shared expectations between TPOS and GOOS will be part of a phased approach toward implementing the new governance structure.

Lastly, this group should also develop stronger ties to regional/local partners who could leverage TPOS efforts to advance their capacity and plans for regionally integrated ocean observing systems; and utilize TPOS-based knowledge for developing new products and services of local and regional interest.

Stakeholders Forum

The Stakeholders Forum will assume a similar role to the current Resources Forum. It will focus on accountability and on better alignment of resources for TPOS and stakeholder needs. It will be representative of the diverse interests in TPOS with an emphasis on implementation and responsiveness. The Stakeholders Forum will be responsible for coordinating with the SAC to establish a set of performance metrics that can be tracked and evaluated to strengthen the accountability mechanisms. These metrics will be periodically reviewed and updated to ensure that TPOS continues to make progress through implementation of the recommendations, continues to innovate, continues to encourage new partners and contributors, and better engages with stakeholders throughout the value chain.

Task Teams

Small, focused Task Teams have brought great value to the TPOS 2020. The details of potential new Task Teams (TT) and/or expert groups are yet to be determined and will be formed on an ad hoc basis since the need for these groups will evolve. For example, further work with the eastern Pacific community and some of the rapidly evolving areas (e.g., BGC) would benefit from continued focus.

Implementation Coordination Group

The word "coordination" has been added for the implementation group to emphasize that its role is as much about coordination as it is hands-on technical advice on implementation and change management. The TPOS Implementation Coordination Group (ICG) will develop documentation on standards and core TMA functionality so the array remains a seamless backbone across the agencies deploying it.

To implement the core TMA, the ICG's responsibilities include a) specifications for common mooring configuration, including instrumentation, sampling rates, and possible regional variations; b) implementation procedures (e.g., intercomparison studies); and c) data management principles, common procedures for data quality control and dissemination. The ICG should also seek to coordinate cooperative resolution of EEZ issues as they come up (e.g., 2.4.1, 2.4.2 and 2.5.3).

The TPOS ICG will work closely with the SAC on the implementation of the observing system, especially during the initial transition period. The ICG will work on evaluating the current role of the group and determine how those roles can/should transition to the SAC and/or Task Teams as appropriate. This group will also help the SAC develop the expectations for the relationship with intergovernmental bodies like GOOS. Once those relationships are established then the ICG may dissolve if its primary functions can be assumed by the SAC and Stakeholders Forum.

R3/Recommendation 22 We recommend a three-part primary governance structure, centered on a Scientific Advisory Committee to provide scientific advice to sponsoring agencies and the intergovernmental bodies, and to integrate new knowledge from the research community. A Stakeholder group would work to align resources and assess success. An Implementation Coordination Group would provide a forum for sharing technical advice and considerations, and coordinate field operations, sampling specifications and testing (Figure 9).

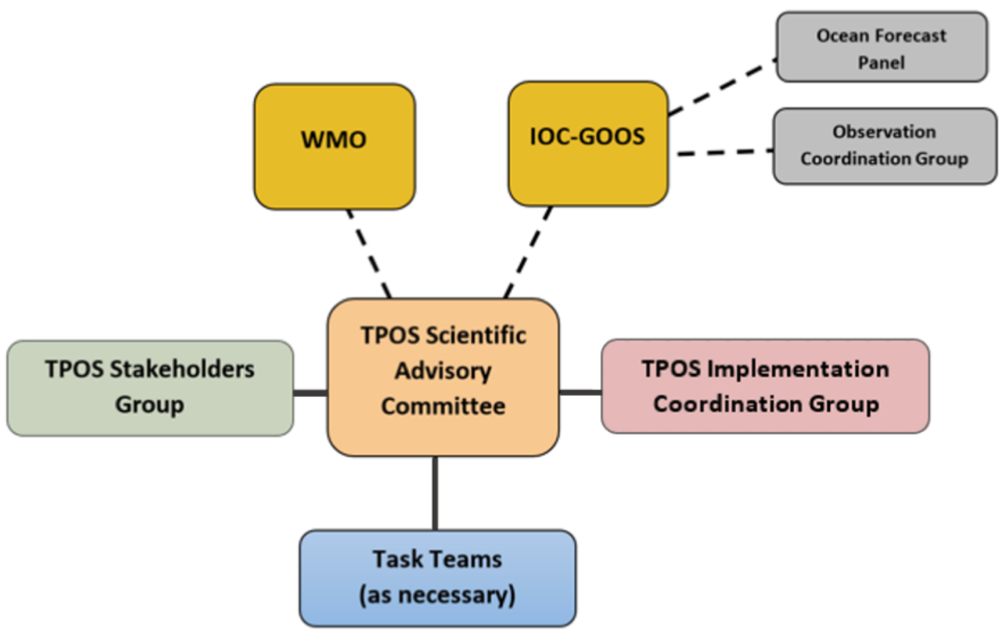

Figure 9: The proposed post-TPOS 2020 governance structure.

* The dashed lines indicate that the functional connections to the intergovernmental structure remain to be built.

Chapter 4 Conclusion

TPOS 2020 has delivered meaningful successes: Our analyses motivated sponsors to invest significantly towards the observations and model experiments that propelled the redesign, and those investments are paying off. Including international participation from the beginning of this process has led to notable strides in commitment to the free and open access of data by partners historically protective of their investments. Researchers and data users across a broad range of specialties took the initiating crisis as an opportunity to systematically think through the observing networks; their careful work greatly invigorated agency and scientific interest in the tropical Pacific.

We defined a varied set of missions for a redesigned TPOS, including biogeochemistry, the eastern and western boundary regions, and multi-scale variability from sub-daily to seasonal to decadal. ENSO, the driver of the TPOS since its inception four decades ago, remains a strong motivation for the observing networks, and maintaining their climate record remains a key imperative. These user-focused goals enabled us to define the combination of variables and scales to be sampled, independent of the technologies to be used. We sought sampling complementarities—in spatial and temporal scales, and in variables whose combined measurement produces more than the set of individual pieces (e.g., co-located ocean-atmosphere measurements). We argued for targeted research and community coordination guiding model advancement towards actionable goals. All of this is dissected in detail in our reports, and the resulting vision enthusiastically received by scientists, program managers and agencies around the world. The large amount of effort produced a credible plan.

A hallmark of our work has been our willingness to prioritize, to say—after exhaustive consultation and analysis—that some measurements meet today's requirements better than some others, while some might even have been superseded as measuring techniques and scientific understanding have evolved. We accept the reality of tradeoffs and have tried to clarify their basis, with the goal of honing a plan that can both be funded and that fits together as a whole.

The tropical Pacific will remain undersampled no matter what we do, so it is easy to recoil at prioritizing. We have grown up with a scarcity of observations, each hard-won, each valuable. The push-back from colleagues has sometimes been strong. But our experience tells us that our most important asset has been the credibility of presenting an honest evaluation that includes stating priorities high and low, not a wish-list. This approach has won us attention and acceptance at the highest levels of our agency sponsors. It is what might make it possible to accomplish the redesign we advocate.

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Appendix A – Acronym List

Table A.1: List of all acronyms from the Final Report, including [information for reference or relatability] and (additional parts of the acronyms that are not part of the acronym proper).

Acronym	Definition
ADCP	Acoustic Doppler Current Profiler
AOU	Apparent oxygen utilization
AUV	Autonomous underwater vehicle
BGC	Biogeochemistry/biogeochemical
BMKG	Badan Meteorologi, Klimatologi, dan Geofisika
BSISO	Boreal summer intraseasonal oscillation
BS-TT	(GOOS OOPC) Boundary Systems Task Team
CDA	Coupled [ocean-atmosphere] data assimilation
CEOS	Committee on Earth Observation Satellites
CLIVAR	Climate and Ocean: Variability, Predictability and Change
CMIP	Coupled Model Intercomparison Project
CO_2	Carbon dioxide
CTD	Conductivity-temperature-depth/pressure [sensor]
DA	Data assimilation
Dec-cen	Decadal to centennial
DIHIDRONAV	Dirección de Hidrografía y Navegación de la Marina de Guerra del Perú
DNA	Deoxyribonucleic acid
DOI	Digital object identifier
ECMWF	European Centre for Medium-Range Weather Forecasts
EEZ	Exclusive economic zone
ENSO	El Niño Southern Oscillation

EOVs	Essential Ocean Variables
EPAC/EP	Eastern Pacific
ERA	ECMWF global atmospheric reanalysis product
ENFEN	Estudio Nacional del Fenómeno El Niño
ERFEN	Programme for the Regional Study of the El Niño Phenomenon in the Southeastern Pacific
EUC	Equatorial Undercurrent
ET-OCPS	(WMO) Expert Team on the Operation Climate Prediction Systems
FAIR	Findable, Accessible, Interoperable, Reusable
FOO	Framework for Ocean Observing
GCOS	Global Climate Observing System
GODAE	Global Ocean Data Assimilation Experiment
GOMO	(NOAA) Global Ocean Monitoring and Observation [Program]
GOOS	Global Ocean Observing System
GO-SHIP	Global Ocean Ship-based Hydrographic Investigations Program
GSOP	Global Synthesis and Observations Panel
GRAs	GOOS Regional Alliances
GRASP	GOOS Regional Alliance for the Southeast Pacific
GRO	GNSS radio occultation
GSOP	Global Synthesis and Observations Panel (CLIVAR)
GTS	Global Telecommunication System
ICG	TPOS Implementation and Coordination Group [post 2020]
IOC	Intergovernmental Oceanographic Commission (of UNESCO)
IOOS	(US) Integrated Ocean Observing System
IPET-OSDE	Inter-programme Expert Team on Observing System Design and Evolution
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
JMA	Japan Meteorological Agency
LLWBC	Low-latitude western boundary current
MJO	Madden-Julian Oscillation
NASA	National Aeronautics and Space Administration
NECC	North Equatorial Counter Current
NOAA	National Oceanic and Atmospheric Administration
NPOCE	Northwest Pacific Ocean Circulation and Climate Experiment
NWP	Numerical Weather Prediction
PBL	Planetary Boundary Layer
O_2	Dissolved oxygen
OS-Eval TT	OceanPredict Observing System Evaluation Task Team
OCG	(GOOS) Observations Coordination Group
OLR	Outgoing longwave radiation
OMZ	Oxygen minimum zone
OSE	Observing system experiment
OSSE	Observing system simulation experiments
PBL	Planetary Boundary Layer
pCO_2	Partial pressure of carbon dioxide
PIES	Pressure Inverted Echo Sounders
PISTON	Propagation of Intra-Seasonal Tropical Oscillations
PMEL	Pacific Marine Environmental Laboratory [a NOAA lab]

PRAWLER	Profiling Crawler [an instrument developed at PMEL]
PRP	Pacific Regional Panel (CLIVAR)
QC	Quality control
R1	First Report of TPOS 2020
R2	Second Report of TPOS 2020
R3	Final Report of TPOS 2020
SAC	TPOS Scientific Advisory Committee [post 2020]
S2IP	Seasonal to interannual prediction
S2S	Subseasonal to seasonal
SC	TPOS 2020 Steering Committee
SENAMHI	Servicio Nacional de Meteorología e Hidrología del Perú
SOA	State Oceanic Administration
SPCZ	South Pacific Convergence Zone
SPICE	Southwest Pacific Ocean Circulation and Climate Experiment
SSH	Sea surface height
SSS	Sea surface salinity
SST	Sea surface temperature
TAO	Tropical Atmosphere-Ocean [mooring array]
TIWs	Tropical instability waves
TMA	Tropical Moored Array/Tropical Moored Buoy Array
TPOS	Tropical Pacific Observing System
TPOS 2020	Tropical Pacific Observing System 2020 Project
TRITON	Triangle Trans-Ocean Buoy Network [mooring array]
TT	Task Team
UN	United Nations
VOSClim	Voluntary Observing Ship Climate (Fleet)

WCRP	World Climate Research Programme
WGNE	Working Group on Numerical Experimentation
WGSIP	(WCRP) Working Group on the Subseasonal to Interdecadal Predictions
WIGOS	WMO Integrated Global Observing System
WIS	WMO Information System
WMO	World Meteorological Organization
WP-TT	TPOS 2020 Western Pacific Task Team
XBT	Expendable bathythermograph
YMC	Years of the Maritime Continent

Appendix B – Summary of Recommendations and Actions

All Recommendations and Actions from the First/R1, Second/R2 and Final/R3 Reports.

B.1 First Report Recommendations

R1/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.

R1/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.

R1/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.

R1/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.

R1/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.

R1/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.

R1/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.

R1/Recommendation 8 Continuation and enhancement of international collaboration for precipitation-measuring satellite constellations to sustain the spatiotemporal sampling of precipitation measurements in the tropics.

R1/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.

R1/Recommendation 10 Continuity of complementary satellite and in situ SSS measurement networks, with a focus on improved satellite accuracy.

R1/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.

R1/Recommendation 12 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.

R1/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.

R1/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.

R1/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.

R1/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.

R1/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).

R1/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).

R1/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.

R1/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.

R1/Recommendation 21 Continued support for in situ observations from drifters, ships, tide gauges and reference mooring sites.

R1/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.2 First Report Actions

R1/Action 1 Six TMA sites in the western Pacific within 2°S to 2°N should be maintained or reoccupied.

R1/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.

R1/Action 3 Argo float deployments should be doubled over the entire tropical region 10°S-10°N, and return increased upper ocean vertical resolution.

R1/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.

R1/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.

R1/Action 6 A staged reconfiguration of the TMA should emphasize enhancement in key regimes.

R1/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.

R1/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.

R1/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.

R1/Action 10 All equatorial mooring sites should be upgraded to flux moorings.

R1/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.

R1/Action 12 Underway $p\mathrm{CO}_2$ observations should be continued or reinstated on all mooring servicing vessels, and the present network of moored $p\mathrm{CO}_2$ measurements should be maintained and possibly extended. Measurements of dissolved oxygen from the surface to about 1500m should be made on ships where practical, and oxygen sensors should be considered on each mooring.

R1/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.

R1/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.

R1/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.

B.3 Second Report Recommendations

R2/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.

R2/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.

R2/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.

R2/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 R2/3.3.3.1 and R2/3.3.3.2; also R2/7.2.1.1]

R2/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 R2/3.2, R2/3.3.1 and R2/3.3.2]

R2/Recommendation 3.3 Promote and engage with the WGNE-WCRP Subseasonal-to-Seasonal subproject on Ocean Initialization and Configuration. [R2/3.4]

R2/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. [R2/4.3, R2/4.4]

R2/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 1000m 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. [R2/4.3.2, R2/4.4; R2/Recommendation 7.3]

R2/Recommendation 5.1 The existing TMA line along 95°W should be maintained and updated to full-flux sites [R2/7.3.1].

R2/Recommendation 5.2 Increase Argo density for the EPAC as soon as possible [see section R2/7.4.4 and R2/Figure 7.19 for initial implementation guidance]. A coordination of

South American countries to execute the doubling of Argo will be required. [Also see R2/**Recommendation 4.1** and R2/***Action 7.9***].

R2/Recommendation 5.3 A pilot study along 95°W installing dissolved oxygen sensors to 200m 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 [R2/5.1.4].

R2/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 [R2/5.2].

R2/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.[R2/7.3.1]

R2/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. [R2/7.2.1.2, R2/7.4.4]

R2/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.*

R2/Recommendation 7.3 Improvement of dedicated capacities on servicing ships to allow repeated ancillary measurements. Underway measurements such as Shipboard Acoustic Doppler Current Profilers, pCO_2 and sea surface salinity should be systematically acquired. [R2/7.5; R2/Recommendation 4.2]

R2/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. [R1,R2/8.1,R2/8.2]

R2/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. [R2/8.4]

R2/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. [R2/8.4]

R2/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. [R2/8.5]

R2/Recommendation 9.1 That the Backbone Readiness Level framework be further developed and refined by TPOS 2020 before adoption. [R2/9.4]

B.4 Second Report Actions

R2/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.

R2/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.

R2/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.

R2/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.

R2/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.

R2/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.

R2/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).

R2/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).

R2/Action 6.3 The directional dependence of buoy/scatterometer wind differences needs to be investigated and understood (Section A.4).

R2/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.

R2/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.

R2/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.

R2/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.

R2/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).

R2/Action 7.5 Continue to highlight the ongoing need and benefits of follow-on satellite SSS missions as a key component of the TPOS.

R2/Action 7.6 Underway pCO_2 observations should be continued or established on all mooring servicing vessels. Pilots of pCO_2 measurements from AUVs (e.g., Saildrone or Wave Glider) should continue as a potential means to drive up spatial and temporal sampling.

R2/First Report, updated Action 1 *The TMA sites in the western Pacific within 2°S to 2°N should be maintained or reoccupied.*

R2/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.

R2/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.

R2/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).

R2/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.

R2/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)

R2/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.

R2/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.

R2/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.***

R2/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.

R2/Action 9.1 TPOS 2020 to assess all candidate technologies, platforms and methods against the Backbone criteria for efficiency, effectiveness and extension.

R2/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.5 Final Report Recommendations

R3/Recommendation 1 We reaffirm the complementarity between oxygen observations on moorings along 95°W (for high temporal resolution) and BGC-Argo (for broader sampling). [2.1.1]

R3/Recommendation 2 Annual CTD O_2 and biogeochemical sampling from instrumented TMA service vessels is needed. Twice per year sampling is encouraged, including additional inorganic carbon variables when achievable. [2.1.1]

R3/Recommendation 3 A BGC-Argo strategy for independent validation of sensors is needed, likely via discrete bottle samples on TMA service cruises. [2.1.1]

R3/Recommendation 4 Greater effort should be devoted to entraining ecological observations from moorings and ships (could include acoustic observations of zooplankton and fish, listening for tagged fish, environmental DNA). Consultation with relevant international panels on fisheries and ecosystems are recommended. [2.1.2]

R3/Recommendation 5 Develop gridded biogeochemical products from expanded TPOS observations (chlorophyll, carbon, nitrate, O_2, pH, pCO_2). [2.1.3]

R3/Recommendation 6 Encourage the evolving coordination between prediction centers to better document the model biases, and to monitor the efficacy of observations used in S2S forecast runs. These should include periodic assessments across the operational centers, and coordinated OSE or OSSE experiments in multiple forecast systems.[2.2]

R3/Recommendation 7 Encourage process studies leading to improved process parameterizations, towards reducing the model biases that degrade the efficacy of observational initializations. [2.2]

R3/Recommendation 8 Improve interoperability and integration of data, working through the GOOS Observations Coordination Group. [2.3]

R3/Recommendation 9 New moorings are required at 10°N at 110°W, 170°W, 165°E. Moorings further poleward are also recommended, but research is required to specify the measurements needed and their specific locations (Figure 2). [2.4.1]

R3/Recommendation 10 Pilot moorings enabling research on the SPCZ are needed before specific sites can be recommended (Figures 2 and 4). [2.4.2]

R3/Recommendation 11 Highest priority for TMA salinity measurements are shown in Figure 5: In the warm pool and its eastern extension: at moorings along the equator from 137°E to 170°W, and on the 165°E meridional line from the SPCZ at 5°S across the equator to 5°N. Also at two long-term historical sites (0°,140°W; 0°,110°W), and under the ITCZ at 8°N,110°W. [2.4.3]

R3/Recommendation 12 Second priority (highly desired) for TMA salinity measurements are most of the other Warm Pool sites (and near its eastern edge) at 2°N and 2°S from 137°E to 170°W. Also at the remaining equatorial sites, under the SPCZ further south (8°S,165°E), and at 140°W, 2°S and 2°N (Figure 5). [2.4.3]

R3/Recommendation 13 Salinity should be measured at dense vertical resolution (1m; every 5m to 30m, then every 10m to 80m, then 100m). The complementary role of short-cycle Argo floats should also be considered. [2.4.3]

R3/Recommendation 14 Highest priority for near-surface point current meters are shown in red in the top panel of Figure 8: Equatorial sites where longterm subsurface ADCPs already exist; along 140°W from 2°S to 2°N where subsurface ADCPs will be added; and on all Tier 2 moorings (thus also at 5°S and 5°N,140°W). [2.4.4]

R3/Recommendation 15 Second priority for near-surface point current meters are shown in blue in Figure 8: at all other equatorial sites, and at 2°S-2°N at 110°W, 140°W, 170°W, 165°E. Also at 9°N,140°W under the ITCZ. [2.4.4]

R3/Recommendation 16 We recommend that Tier 2 sites (giving mixed layer ADCP velocity profiles above about 60m) be rotated among several locations during the next few years to gain more experience before providing final recommendations. Figure 8 (bottom panel) suggests likely locations for these pilot sites. [2.4.4]

R3/Recommendation 17 Encourage community workshops (e.g., under the auspices of the CLIVAR PRP) to bring together the three regional-focus efforts (northern and southern WBCs, ITF) towards an organized combined sampling program. [2.5.3]

R3/Recommendation 18 Encourage engagement of modeling efforts towards solving the difficult problems of strong bathymetry, mixing and tides, and the strong narrow near-shore currents that characterize this system. [2.5.3]

R3/Recommendation 19 Develop a rolling evaluation of the overall and ongoing effectiveness of the TPOS for research and prediction system goals. [3.1]

R3/Recommendation 20 Develop an explicit, independent structure to assess the capabilities, role and readiness of possibilities for inclusion in the backbone.[3.2]

R3/Recommendation 21 Encourage GOOS to consider best practices for broad stakeholder engagement, including both research and operational drivers. [3.3]

R3/Recommendation 22 We recommend a three-part primary governance structure, centered on a Scientific Advisory Committee to provide scientific advice to sponsoring agencies and the intergovernmental bodies, and to integrate new knowledge from the research community. A Stakeholder group would work to align resources and assess success. An Implementation Coordination Group would provide a forum for sharing technical advice and considerations, and coordinate field operations, sampling specifications and testing (Figure 9). [3.4]

Appendix C – Pilot and Process Studies: Updates and Lessons Learned

The purpose of this section is to provide an update about the pilot and process studies that have been funded during the TPOS 2020 project. Some of these projects were introduced in the First Report (R1/10.2), with an early evaluation in the Second Report (R2/9.2). Here, we share information not previously highlighted about projects that will guide the future TPOS configuration.

For details on each projects, including lessons learned, see

https://tpos2020.org/pilot-and-process-studies/

C.1 Pilot Studies

C.1.1 China Experimental Observing Project in the Western Tropical Pacific

Authors: Feng Zhou, Dake Chen, Fei Chai, Xiaohui Xie, Weidong Yu

As part of the China Experimental Observing Project, four buoys with configurations similar to Tier 1, two subsurface moorings, and 28 Argo floats were deployed in the western tropical Pacific during the implementation cruise of the Ding Array between Dec. 2020 to Feb. 2021. Specifically, three moored buoys were deployed in the Ding array at 0, 147°E, 0, 156°E, and 12°N, 156°E in The buoys were set up similar to the Tier-1 buoy configurations with 17-layer underwater temperature and salinity sensors in addition to meteorological sensors at the surface. An experimental buoy was deployed at 17°N, 156°E with a new structure different from the other three. Two subsurface moorings with ADCP were deployed at 0, 156°E and 12°N, 156°E. There will be two steps of assessment conducted: one nearshore intercomparison along the Chinese coast and one land intercomparison for meteorological sensors and system integration with TPOS partners. The nearshore intercomparison was conducted from 28 Oct. 2020 to 25 Nov. 2020. This is anticipated to be a substantial part of China's contribution to fulfill the buoy gap in the western Pacific.

The timing of the implementation cruise was actually not ideal for deploying these buoys due to the bad weather in winter. The better periods to deploy or maintain these buoys is later spring or summer avoiding tropical storms. However, the R/V resource, international cooperation policy in addition to Chinese funding policy are also very important limitations. Regional cooperation must be emphasized among all stake-holders at any time. Also, the two-year experimental project is just a start. A much longer project is definitely needed to construct and maintain the array. The Chinese side will keep moving on with the present buoys and try to find out any lessons that might help to improve the system. More efforts also are needed to change the financial policy that could grant us continuous support in the next five-year-plan. (Also see https://tpos2020.org/pilot-and-process-studies/).

C.1.2 Flux Surface Glider Experiment

Authors: Iwao Ueki, Tatsuya Fukuda, Makito Yokota, Ken Ando, and Yasuhisa Ishihara

The goal of this project was to pilot surface Wave Gliders® to measure air-sea heat and momentum flux for potential integration for the in situ observing system. The Wave Glider® payload units for air-sea heat and momentum flux measurements were developed by JAMSTEC, based on the technology of long-term TRITON moorings. Inter-comparison experiments with mooring observations demonstrated that air-sea flux measurements, including winds, sea surface temperature, air temperature, relative humidity, shortwave radiation, longwave radiation, and surface currents, were in agreement thus demonstrating the feasibility of using in situ Wave Glider® observations for estimating bulk fluxes, radiative fluxes, and currents. The demonstrations might be helpful to consider for making a flux observation network using Wave Gliders® in the tropics. This project was funded by JAMSTEC.

Three field experiments have been completed: 1. South of Japan (July 26-Aug. 15, 2016) to establish Wave Glider® operations by small boat and conduct 1-month observation in the open ocean; 2. South of Republic Palau (Nov. 3-Dec. 16, 2016) to establish Wave Glider® operations by small diving boat near a tropical island and compare glider and mooring observational data; and 3. Eastern Indian Ocean (Dec. 9-29, 2017) to conduct inter-comparison with mooring observations. JAMSTEC plans to conduct 3 observation lines associated with TRITON moorings [137°E, 147°E and 156°E].

Results showed that the flux glider can capture comparable variability of surface flux associated variables with mooring observations, including detection of finer salinity structure; basic payloads for air-sea flux observations have been established and shown to capture comparable variability as moorings; deployment and recovery operations can be completed using small boats with relative ease; the stability of sensors over weeks to months were relatively good. Challenges included decreased performance in severe weather conditions and some sensors needed reinforcement from water intrusions.

(Also see https://tpos2020.org/pilot-and-process-studies/).

C.1.3 NOAA GOMO - TPOS Technology Development Projects

Authors: Kathy Tedesco, Sarah Purkey, Stephen Riser, James Edson, Meghan Cronin, William Kessler

NOAA's Global Ocean Monitoring and Observing Program (GOMO) funded 6 technology development projects to address observational requirements and gaps in the tropical Pacific Ocean region in support of NOAA's contribution to TPOS 2020. The following four projects were funded in 2016 (see also and R1/10.2 and R2/9.2):

1. ***Autonomous Surface Vessels as Low-Cost TPOS Platforms for Observing the Planetary Boundary Layer and Surface Biogeochemistry*** M. Cronin, A. Sutton, C. Meinig (NOAA/PMEL); D. Zhang (UW/CICOES)

Emerging technologies, such as Uncrewed Surface Vehicles (USV), hold great potential for providing important air-sea interaction observations without shiptime. Saildrone USV, manufactured and piloted by Saildrone, Inc., are powered by wind and the Sun, and are capable of traveling ~16,000 nm, for up to 1-year. The sensor suite includes a 3-dimensional sonic anemometer mounted atop the mast at 5m, and a suite of sensors that could be used to estimate air-sea heat, momentum and carbon dioxide fluxes, and potentially even direct covariance fluxes of momentum (i.e. wind stress) and buoyancy flux.

Three missions were conducted to the central and eastern tropical Pacific as part of this pilot study. Comparisons of saildrone and SPURS2 moored buoy data showed excellent agreement for all physical measurements, including for wind speed, sea surface temperature (SST), air-temperature, humidity, solar and long-wave radiation (Zhang et al., 2019). The sea surface salinity (SSS) measurements by long term moorings tend to drift near the end of deployments due to biofouling; the newly deployed Saildrones provided useful records to correct these drifts. The study also demonstrated that Autonomous Surface Vehicle CO2 (ASVCO2) systems are capable of long-term oceanic deployment and robust collection of air and seawater pCO_2 within ± 2 µatm based on comparisons with established shipboard underway systems, with previously described Moored Autonomous pCO_2 (MAPCO2) systems, and with companion ASVCO2 systems deployed side by side (Sabine et al., 2020). Finally, it was demonstrated that Saildrone USV can resolve atmospheric cold pools, identified as a 1.5°C drop in 10 minutes (Wills et al., 2021).

Saildrone USV were shown to provide high quality measurements for meteorological, oceanic (Zhang et al., 2019) and carbon parameters (Sabine et al., 2020), with excellent resolution of sharp fronts and rapid variability (Wills et al., 2021). In addition, Saildrone USV are not reliant on research vessels since they can be deployed from shore, use wind and solar power, adaptive sampling, and are scalable. However, precise navigation is difficult in parts of the tropics (e.g., equatorial cold tongue) due to low winds and strong ocean currents. More missions are needed to determine how these USV might perform in other parts of the tropics, such as the western equatorial Pacific Warm Pool and its eastern edge, where the Trade Winds are weak and to develop robust adaptive sampling strategies. In addition, the cost might be prohibitive for wide usage such as a sustained observing platform. (See also R1/10.2.2 and R2/9.2.1)

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Zhang, D., M. Cronin, C. Meinig, T. Farrar, R. Jenkins, D. Peacock, J. Keene, and A. Sutton, 2019: Air-sea flux measurements from a new unmanned surface vehicle compared to proven platforms during SPURS-2 field campaign. *Oceanography*, **32**(2), 122–133, doi: 10.5670/oceanog.2019.220

2. ***Enhanced Ocean Boundary Layer Observations on NDBC TAO Moorings*** K. Grissom (NOAA/NWS/NDBC); W. Kessler, M. Cronin, J. Massich (NOAA/PMEL)

Ocean-atmosphere feedback are mediated through the coupled boundary layers, which are the least understood and most poorly modeled element of the tropical climate system (R1/2.6.5). Meeting this challenge requires co-located observations of surface flux variables and the ocean mixed layer at high temporal and vertical resolution, including the diurnal cycle and its role in communicating heat and momentum between the surface and the thermocline (R1/3.1.3). These capabilities were recommended by both previous reports (R1/Recommendation 3; R2/Recommendation 3.1) but have not been available on present-generation TAO or TRITON moorings.

Temperature sensors were added to eight operational TAO moorings to achieve 5m spacing in the upper 30m, and an upward-looking ADCP at 65m, with one or two point current meters for checking and additional resolution (R1/10.2.4). All data were transmitted in real time; for the velocity data new transmission capabilities were developed. The new observations were implemented on operational moorings without interfering with their existing functions, demonstrating that these capabilities can be straightforwardly added to the sustained backbone arrays. The tested enhancements were essentially the Tier 2 moorings recommended in R2/7.3.1.1 (R2/Figure 7.3).

Analysis of the diurnal cycle across several regimes of the tropical Pacific showed that the strongest diurnal penetration occurred above the equatorial undercurrent, where strong background shear set up a persistent state of marginal instability (Masich et al., 2021). This suggests an initial focus for Tier 2 deployments should be near the equator. However, the eight sites tested did not fully explore the potential regimes; other potential targets include the east edge of the warm pool and the TIW region. Because the tested sites were only deployed for about a year, they also could not explore interannual variability; it remains unclear whether the Tier 2 sites need to be sustained indefinitely, or whether a better use would circulate them around the array to build a broader picture of the mixed layer that could guide model improvement.

3. ***Profiling Floats Equipped with Rainfall, Wind Speed, and Biogeochemical Sensors for Use in the Tropical Pacific Observing System*** S. Riser (UW/Oceanography); J. Yang (UW/APL)

This project built 15 Argo-type profiling floats with an advanced suite of sensors (dissolved oxygen, pH, chlorophyll fluorescence and particulate backscatter, and rainfall and wind speed using passive acoustic methods) and deployed them in the tropical Pacific as part of a test of enhancing the Tropical Pacific Observing System. This work represents the first time that this particular set of sensors has been used together. Numerical models and analysis of the existing Argo dataset have shown that many of the capabilities of the TAO array in the equatorial Pacific can be duplicated with an expanded array of Argo profiling floats at a reduced cost.

Results demonstrate the feasibility of collecting useful data in the Equatorial ocean using biogeochemical profiling floats over extended periods. The floats, all drifting at 1000m and profiling from 2000m at 10-day intervals sampling the strong seasonal variability in the upper ocean that is characteristic of the low-latitude Pacific such as late summer maxima in temperature, dissolved oxygen, and pH, accompanied by a late summer minimum in salinity. For floats located elsewhere in the region, the seasonal maxima and minima occur at different times and amplitudes. In addition, wind and rainfall clearly also show seasonal signals, especially rainfall.

These are new observational tools in the Equatorial ocean and hint at what might be possible with a much larger fleet of such floats in the region. It is also possible to use the data collected to infer other unmeasured, biogeochemical parameters, such as pCO_2, nutrients, silicate, and titration alkalinity. This has been done previously for other regions with BGC-floats, such as the Southern Ocean, and is now underway for the global ocean, including the equatorial Pacific region. (See also R1/10.2.1 and R2/9.2.5)

4. ***Development and Testing of Direct Covariance Turbulent Flux Measurements for NDBC TAO Buoys*** J. Edson, T. Farrar (WHOI); M. Cronin (NOAA/PMEL); C. Fairall (NOAA/PSD)

A Direct Covariance Flux System (DCFS), developed at WHOI, was deployed on a stand-alone enhanced flux mooring (see Enhanced Ocean Boundary Layer Observations on NDBC TAO Moorings project described above) on the equator at 165°E in October 2019. The DCFS successfully computed and telemetered fluxes, means and wave statistics via Iridium every hour over the course of the deployment, which ended on April 21, 2020.

The DCFS was modified to measure all of the variables necessary for direct covariance and bulk flux estimates (i.e., Tair, RH, Pair, Precipitation and Tsea) including radiative fluxes (i.e., long and shortwave radiometers).The enhanced DCFS worked almost flawlessly during its deployment. The realtime DCFS has now been deployed on a number of research buoys including our TPOS mooring, the X-Spar, OOI surface moorings and the recently concluded INCOIS deployment in the Bay of Bengal. As a result, the DCFS is reliable and ready for deployment on the Tier-2 moorings. (See also R1/10.2.5 and R2/7.4.5.4)

Two additional projects were funded in 2019 by GOMO, in partnership with CPO's Climate Variability and Predictability Program and NASA's Ocean Biology and Biogeochemistry Program as part of the National Ocean Partnership Program:

5. ***Improvements to Profiling Float Technology in Support of Equatorial Pacific Biogeochemical Studies*** S. Riser (UW/Oceanography); K. Johnson (MBARI); B. Carter (UW/CICOES); T. Mitchell (Seabird)

6. ***Developing an Autonomous Biogeochemical Profiling Float to Monitor Biological Productivity, Ocean-Atmosphere CO_2 Fluxes, and Hypoxia in the Tropical Pacific Ocean*** S. Purkey, T. Martz, L. Talley, D. Roemmich, M. Mazloff, D. Rudnick, A. Verdy (SIO-UCSD); N. Bogue (MRV Systems LLC); K. Johnson (MBARI)

These projects represent a joint partnership between academia, private industry, and the governmental sector to redesign the Sea-Bird BGC Navis float and the MRV SOLO-II float and integrate all six BGC-Argo variables (i.e., temperature, salinity, oxygen, pH, nitrate, chlorophyll-a, backscatter and downwelling irradiance) with a potential pathway for commercialization.In addition to the float development, the University of Washington team will implement a new region specific, multiple linear regression (MLR) model for the tropical Pacific that will allow for the estimation of other parameters of the inorganic carbon system ($p CO_2$, alkalinity, dissolved inorganic carbon) from the standard suite of Argo physical and biogeochemical measurements. The Scripps team will couple a biogeochemical model to the Tropical Pacific Ocean State Estimate (TPOSE) to assess temporal and spatial length scales of the climate variability. Results from the length scale and formal mapping error analysis will be used to help advise TPOS 2020 on how to design the most optimized biogeochemistry observing system for the tropical Pacific, in line with TPOS 2020's requirements, and will provide a major BGC analysis tool. See

https://cpo.noaa.gov/News/News-Article/ArtMID/6226/ArticleID/1777/NOAA-Research-Awards-3-Million-for-Biogeochemical-Argo-Float-Research .

More information about these projects, including publications, can be found on the TPOS website under NOAA-funded TPOS 2020 Technology Development Projects.

C.2 Process Studies

C.2.1 Air-sea Interaction at the Edges of the Warm Pool

Authors: Masaki Katsumata, Akira Nagano, Kunio Yoneyama, Iwao Ueki, Ken Ando, Meghan Cronin, and Dongxiao Zhang

Process studies of air-sea interaction at the northern and eastern edges of the warm pool were conducted by several institutions. The study at the northern edge of the warm pool began in 2017 to capture the multi-scale structure of the Boreal Summer intraseasonal oscillation (BSISO) through high-resolution in situ observations in both the atmosphere and ocean, in collaboration with the international effort "Years of the Maritime Continent (YMC)" led by BMKG in Indonesia, NOAA/PMEL in the US and JAMSTEC in Japan. The PISTON project, led by the US, conducted field campaigns as part of the YMC in August-October 2018 and September 2019. JAMSTEC also conducted ocean-atmosphere observational cruises in the same region in August 2018 and August 2020. These campaigns succeeded in capturing the detailed structure of air-sea processes including the diurnal cycle, variations before and after the generation of a tropical depression, etc. Furthermore in 2018, the dual-Doppler radar observations by two shipboard polarimetric radars from the US and Japan successfully captured the fine three-dimensional structure of the precipitation systems.

This was followed by an observational cruise in February-March 2020 with detailed air-sea measurements at a SST front in the eastern edge of the warm pool. Detailed air-sea structures at both sides of the front were observed. The detailed air-sea interaction processes were captured by the meso-scale network over the open ocean. Results show the warm water at the west of the eastern edge migrated eastward through the substantial air-sea interaction, as evidenced by the coincidence of sea surface zonal current and wind anomaly directions from March 11 and 12 and active heat release from the ocean to the atmosphere. In addition, a Doppler radar installed on the R/V *Mirai* observed active convection along with the air-sea interaction. It is suggested that monitoring for short-term variability associated with air-sea interactions need high-frequency multi-parameter observations. Another field campaign to evaluate this concept is planned in 2021. Data analysis is ongoing and the results will contribute to planned process studies, such as the "Ding" array project by the SOA of China. (See also R1/6.2.2.2 and 10.1.1.1, and R2/7.4.6.2 and 7.4.6.3 and https://tpos2020.org/pilot-and-process-studies/ for more information).

C.2.2 NOAA CVP – TPOS: Pre-Field Modeling Studies

Authors: Aneesh Subramanian, Meghan Cronin, Bill Large, Sandy Lucas

In 2018, the NOAA-Climate Variability and Predictability (CVP) Program partnered with TPOS-2020 to implement process studies identified and justified in the First and Second Reports

(R1/6.2, R2/7.4.6). These proposed process studies guided by the pre-field modeling studies can make a step-change in our understanding of upper-ocean mixing as well as air-sea interaction processes in the tropical Pacific. The long term prospects are for improved sub-seasonal to seasonal prediction skill and for increased confidence in forced climate projections on longer timescales. To that end, the goal of the “Pacific Upwelling and Mixing Physics” (PUMP) study is to provide the observations to constrain the ocean circulation and mixing associated with equatorial upwelling, and thereby enable faithful modeling of the essential connection between the cold thermocline and the warmer atmosphere. Similarly, the "Air–sea Interaction at the eastern edge of the Warm Pool" study is focused on a unique region of complex physical processes that plays a key role in climate variability (e.g. ENSO, MJO and monsoons) through strong interaction between the upper ocean and overlying atmosphere. In contrast with the upwelling induced cold tongue to the east, the warm pool is a major heat reservoir that extends over a large area of permanent surface temperature >28°C.

In order to inform the planning for a possible field campaign, eight modeling projects were selected for 2 years of work (September 2018 to August 2020, and up to additional 2 years of no-cost extension) to frame tractable questions and hypotheses. (See the project list: https://cpo.noaa.gov/News/News-Article/ArtMID/6226/ArticleID/1679/NOAA%E2%80%99s-Climate-Variability-and-Predictability-Funds-Eight-New-Projects-in-Support-of-TPOS-Process-Studies). The expected outcomes are an understanding of model capabilities and deficiencies, which will inform pre-cruise planning and field campaign measurement and sampling strategies. The high resolution modeling and the analyses of observations performed by this group show important contributions of fine scale flow features to mixing in the thermocline across the basin. Accounting for this mixing in ocean models and coupled models can influence the SST evolution and air-sea interaction significantly and thus, play an important role in getting ENSO forecasts right in this region. Specific information from PUMP modeling includes the spatial structure and temporal variability of vertical velocity and of vertical mixing and stratification, as modulated by internal ocean processes, such as Tropical Instability Waves. EEWP modeling will provide insight into the movement of the front marking the extent of the warm pool, and the responsible processes. Progress and highlights from the eight projects are shared at monthly PI teleconferences.

To date, there are several accomplishments from these studies that demonstrate the value of the high-resolution modeling approach. One paper examines the submesoscale and smaller‐scale turbulence heterogeneity in modeling the ocean mixed layer and its impact on the physical‐biogeochemical response to a storm front. The overall results show that submesoscale heterogeneity in a frontal zone significantly modifies the physical‐biogeochemical response to the storm compared to otherwise identical scenarios without the submesoscales (Whitt et al., 2019). Ocean modelers need to be careful when using turbulence parameterizations as they do not account for the fine-scale variability that can impact the overall ocean response. Another effort is the Tropical Pacific Ocean State estimate (Cornuelle, B and A. Verdy, data), which is used to compute budgets for heat, salt and mass in the equatorial Pacific for the period 2010 to 2018 using overlapping 4-month hindcasts. This data product can be used to test mechanisms involved in events such as the 2015-2016 El Niño, or the variability in the eastern edge of the warm pool. Additionally, a workshop has been planned for the spring 2021. Topics will include the current state of the science, gaps in research, and planning for a possible field campaign in 2023 or beyond. (Also see https://tpos2020.org/pilot-and-process-studies/).

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Appendix D – Acknowledgements

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