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Contents

1 Overview and introduction 1

2 Progress since Second Report and Remaining Issues 4
   2.1 Biogeochemistry, Biology, and Ecosystems 4
      2.1.1. Dissolved oxygen observations 4
      2.1.2 Ecosystem observations 6
      2.1.3. Derived data products 7
   2.2 Modelling Studies and Progress 8
   2.3 Update on TPOS Data Flow and Access 10
   2.4 Backbone Moorings 12
      2.4.1 Latitudes of the northern extensions 13
      2.4.2 Latitudes of the southern extension, under the SPCZ 14
      2.4.3 Salinity Sensors on the TMA 15
      2.4.4 Velocity measurements 19
   2.5 The LLWBC/ITF system 26
      2.5.1 Introduction 26
      2.5.2 Progress to date 26
      2.5.3 Unresolved and ongoing issues 28

3 Beyond TPOS 2020 30
   3.1 Success against TPOS 2020 Terms of Reference 30
   3.2 Emerging Methods and Roadmap for Evaluation and Inclusion 31
   3.3 International and Intergovernmental Organizations: The broader relevance and impact of TPOS 2020 32
   3.4 Governance and ongoing structure 35

References 39

Appendix A – Acronym List 45

Appendix B – Summary of Recommendations and Actions 49

Appendix C – Pilot and Process Studies: Updates and Lessons Learned 58
   C.1 Pilot Studies 58
      C.1.1 China Experimental Observing Project in the Western Tropical Pacific 58
      C.1.2 Flux Surface Glider Experiment 58
      C.1.3 NOAA GOMO - TPOS Technology Development Projects 59
   C.2 Process Studies 60
      C.2.1 Air-sea interaction at the edges of the Warm pool 60
      C.2.2 NOAA CVP – TPOS: Pre-Field Modeling Studies 60
1 Overview and introduction

Authors: William S. Kessler

Overview
This third and final report of the TPOS 2020\textsuperscript{1,2} 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 reiterated in Appendix B). Instead, we refer specifically 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.

Following our reports R1 and R2, the TPOS 2020 Steering Committee agreed to focus on implementation and not revisit the substance of our redesign; subsections of the present Chapter report progress in a few specific areas. These include biogeochemical observations (2.1), prediction modeling (2.2), data management and access (2.3), the backbone moored array (2.4) and the tropical Pacific’s western boundary currents and connections to the extratropics (2.5). Unfortunately, some of these issues are still difficult! Even where we cannot now provide specific recommendations for some important measurements with enough confidence to define their place in the sustained backbone, we are able to specify the needs and goals for our successors.

Beyond the design, it is clear that that ongoing scientific advice will be necessary for the future evolution of the arrays, and as a “WIGOS Pre-operational Regional Pilot” the project requires clear connections to the intergovernmental entities. Chapter 3 proposes a governance structure to enable scientific evaluation of potential changes (3.2) and intergovernmental issues (3.3).

Approach
The TPOS 2020 project was formed in response to the twin crises of the TAO and TRITON moored buoy arrays in 2012-2014. 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. Our approach has tried to broaden the stakeholder and user base of TPOS observations by enabling the data to speak more comprehensively. The result would

(a) increase the value of the arrays to the agencies supporting these expensive 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.

\textsuperscript{1} 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.

\textsuperscript{2} See Appendix A for all acronyms; in many cases, we have elected not to spell them out, to retain flow and brevity.
We argue 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.

We recognize that observations alone will not deliver the fuller picture we seek. Combining the very different characteristics of these platforms requires integration through advancing model/data assimilation systems. The societal value of a modern observing system comes primarily as the output of a comprehensive model assimilation, or from statistical methods that incorporate the strengths of multiple observing techniques. That's the main way TPOS data reaches most users. The added value of the consistent combination of information provided by assimilation is as important as any of the in-the-water observing components.

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. 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 based on 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 drastically 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 is 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.

**Conclusion: Successes, failures and the future**

One might have thought that six years would have been enough to devise and implement these goals. It certainly seemed so in 2014! TPOS 2020 delivered meaningful successes: Our analyses motivated sponsors to invest significantly towards the observations and model experiments we advocate, 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 crisis as an opportunity to systematically think through the observing networks; their careful work greatly invigorated agency and scientific interest in the tropical Pacific.

But still, at the end of 2020, we have seen only first steps towards implementation of the backbone observing system, and of the recommended expansions in the western and eastern boundary regions. One obstacle has been that we are trying to do big things, but bureaucracies move slowly. Another is that international cooperation and coordination is hard, fraught with extraneous issues that often carry more weight with governments than the benefits of fostering scientific observation. The patience and persistence needed to build trust and cooperation with and among the nations involved in these boundary regions is an ongoing challenge.

So while the TPOS 2020 project will end with this report, some work remains unfinished. Some aspects of the backbone recommendations are not yet settled (2.4). Several agencies are funding pilot studies that will guide further evolution of the backbone, while focused process studies for model advancement are likely (Appendix 6.2). Although we have begun to consider how ecosystem observations could be integrated into the arrays (2.1.2), implementation remains fuzzy.

These ongoing issues will need careful scientific evaluation and assessment to find their place in the new TPOS while ensuring the integration at the heart of our plans. With the framework of the backbone largely specified, we propose a modified governance structure (3.2); it retains a Scientific Advisory Committee (SAC), but creates a parallel Implementation and Coordination Group (ICG). Coordination among the agencies and institutions deploying these arrays, and among the modeling centers, will require substantial focus. The SAC and ICG will be charged to oversee the complex and interacting aspects of evolution and implementation, as well as oversee the data quality, consistency, availability, and integrity of the climate record (2.3). An observation has many lives; we must ensure TPOS data are collected and maintained in adherence with long-standing international standards (2.3) to assure maximum value will be returned on this important investment.

We have finished one stage of this work, which has shown the path forward. The next years will require working closely with our agency sponsors to bring our vision of an integrated backbone to reality, so it can support the wide range of advances we have described in these reports.
2 Progress since Second Report and Remaining Issues

2.1 Biogeochemistry, Biology, and Ecosystems

Authors: Peter G. Strutton, Adrienne J. Sutton, Olaf Duteil, Yassir A. Eddebbar and Boris Dewitte

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 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. 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 1000 m along each TMA line by servicing cruises, at every degree of latitude between 8°N and 8°S and every 0.5° between 2°N and 2°S at a frequency of at least once per year. Twice per year sampling is optimal and could be augmented by GO-SHIP and other ships of opportunity.

By comparison, a different but complementary recommendation was also presented in R2:

R2/Recommendation 5.3: A pilot study along 95°W installing dissolved oxygen sensors to 200 m and an ADCP is recommended at the equator, with additional dissolved oxygen and current sensors on 2°N and 2°S if at all possible.
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-Morriberon 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 NDH (Dirección de Hidrografía y Navegación, Peruvian Navy). 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 95°W 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 5 cm/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 model, 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 modelling
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 gliders could potentially perform transects
of the order of 500km in length, penetrating to 1000m (Jakoboski et al., 2020).

BGC-Argo O2 measurements provide a lower temporal resolution picture of dissolved O2, but
a far superior broad spatial scale perspective. Climatological O2 products as well as long term
trends in O2 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). 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 et al., 2015). For this final report,
TPOS 2020 emphasizes that moorings and BGC-Argo serve two important and separate but
complementary purposes.

2.1.2 Ecosystem observations

When read in the context of the GOOS essential ocean variables (EOVs), the biogeochemistry
sections of TPOS 2020 reports 1 and 2 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, greater effort needs to 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, 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 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.

### 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, 4.2.1 and Fig 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 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/Rec. 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 model ‘currency’. 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/Rec. 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.

The current and future TPOS contributes to global $pCO_2$ 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 $pCO_2$ 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/Rec. 12).

Gridded products are extremely useful for tracking global trends in ocean CO₂ 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, O₂ profiles from ships and moorings, moored surface pCO₂ 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.

2.2 Modelling Studies and Progress

Authors: Arun Kumar, Yuhei Takaya, Harry Hendon

Providing information for the initialization of weather and climate predictions is one of the foremost justifications for the global observing systems. Thus, for sustaining operational predictions from days to seasons, it is essential that corresponding requirements for model based prediction systems (including for data assimilation) are adequately incorporated in the TPOS design. Although observational design recommendations by TPOS 2020 were formulated only after careful assessment, an optimal utilization of observations themselves also requires (a) improving the modeling infrastructure, and (b) monitoring 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 discussed 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, evaluating and validating models, and analyzing climate variability. In the last decade, operational predictions based on atmosphere-ocean coupled models from days to decades have commenced, and continual advances are being made.

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. Although models are now more realistic, they still suffer from systematic errors. 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 (and forgotten) during the initial stages of the forecast.

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/Rec.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. Observations from process studies are anticipated to be used for further developing the parameterization schemes to better represent the interaction between the atmosphere and ocean boundary layer (R2/Rec.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 also (via recommendations for process studies, C.2). In addition, TPOS 2020 recommendations also include 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 removing their inclusion in assimilation. In addition, observing system simulation experiments (OSSEs), which are idealized simulations with candidate future observations, are also recommended to ensure that no degradation in current observational capabilities occurs (R1/Rec. 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 the ocean analysis and seasonal prediction; however, much less is currently known for the subseasonal predictions. Recently, OSEs of the subseasonal prediction have been carried out with ECMWF and 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 the TPOS 2020 recommendations, the ocean analysis community and S2IP community are currently discussing possible coordinated efforts. In the ocean analysis community, there are two international groups that exchange knowledge and coordinate international activity: OceanObs TT-OSEval and CLIVAR GSOP. TT-OSEval 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 center providing ocean outputs currently is ECMWF. 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 the Operation 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.

### 2.3 Update on TPOS Data Flow and Access

**Authors: Kevin O'Brien, Neville Smith**

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.

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, that may be handled by another coordination body, remains however
a primary step toward an integrated, international observational program for the region (see
also R2/2.5)
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.umrcnrm.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.

2.4 Backbone Moorings

Authors: Sophie Cravatte, Susan Wijffels (with the Backbone Task team members + PBL co-chairs)

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, and for the southern extension under the SPCZ, was not determined. This section aims to clarify these aspects where possible, and if not, to provide elements to guide a future decision for our successors.

2.4.1 Latitudes of the northern extensions

Authors: Sophie Cravatte and Susan Wijffels

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:

a) 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 (e.g., R1/5.1.1);

b) 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);

c) 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;

d) provide in situ sampling of multi-decadal signals over a broader domain.

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 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/Fig.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 (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. Research to clarify these issues will be needed. We leave this work and these decisions to our successors.
2.4.2 Latitudes of the southern extension, under the SPCZ

Authors: Sophie Cravatte

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 Tier1 mooring, sampling both the oceanic mixed layer and the surface atmosphere at high-frequency, is the only platform that would allow observing these coupled phenomena and their modulations at seasonal and interannual timescales.

A difficulty of choosing a specific site arises from the numerous EEZs in the Southwest Pacific (see Figure 2). With these unresolved physical and logistical complications, we leave the specific locations to our successors and sponsors, emphasizing that the moorings should be first deployed as a pilot experiment, and 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.
2.4.3 Salinity Sensors on the TMA

Authors: Janet Sprintall, Andrew Wittenberg, Sophie Cravatte, Ken Ando, Steve Penny, Billy Kessler, Ken Connell, Dean Roemmich

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 δ¹⁸O), 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. 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. Typically TAO salinity
sensors were/are located near-surface, at 5m and 10 m, while TRITON sampled salinity at all
instrument depths (1m, then every 25m to 150m, then sparser to 750m; see Figure 4). 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, on some occasions such as when the mooring is subject to blow-down from
strong currents, then the time of sampling by each physical sensor is not concurrent and this
lag can result in salinity spiking. Salinity spiking is particularly evident 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).
Nonetheless, the historical record of salinity measured on the TMA remains incomplete, with
many significant gaps in the time series when sensors failed and could not be replaced in a
timely fashion.

Pacific regimes that need TMA 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 50-100 m 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 Madden Julian Oscillations (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 and barrier layers because of their coarser vertical structure and inadequate rain forcing.

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., 2002a; 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 (~20-40 m) 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 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 of the historical record. The wet regimes of the atmospheric convergence zones could also benefit from higher-frequency 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.

Surface salinity measurements are needed with higher resolution in the near-surface layer and probably every 10 m in the upper ~100 m for detecting barrier layers. Below 100 m, the relationship between temperature and salinity should allow proxy estimates of salinity from temperature sensors. Tighter vertical spacing 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 3:

- **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°), **historical sites** (0°,140°W; 0°,110°W), off equatorial 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; at 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 are most useful when the mixed layer is resolved, thus at 1m, 5-30m by 5m, 30-80m by 10m, and 100m.

- Salinity 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 3: Recommendation for salinity sensors on tropical moorings: Red = Highest priority; Blue = Second priority. Color shading indicates the barrier layer thickness maximum from monthly climatological values, in meters (produced from Mignot et al., 2007; colorbar at right).

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.

2.4.4 Velocity measurements

Authors: Susan Wijffels, Andrew Wittenberg, Sophie Cravatte + the BB TT

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, CO2 and tracer 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 and salinity 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 capture 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 distribute quantities fluxed across the sea surface into the water column: momentum, heat, CO2 and tracer species;
• Responses of the tropical near-surface zonal current systems and shallow meridional 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 oceanic upwelling near 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 provide in addition enhanced velocity profiles in the upper-ocean (sampling the 10-50m layer; see Figure 4), for example using upward-looking ADCPs to sample the upper 50 m, 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., 2020) and analysis of where ocean velocity measurements are most needed.”

Figure 4. (from R2): Configurations of existing TAO and TRITON moorings, and the proposed 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).

Some conclusions based on these recommended enhancements are reported here.

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 (Figure 5);
- 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 6; 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. We conclude 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 rationale 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., 2020) show that systematic downward-propagating diurnal jets are present where the Equatorial Undercurrent (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 140°W transport array (2°S, 1°S, 0°, 1°N, 2°N) 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 2°S and 2°N on alternating meridians** should be considered as possible upgrades to Tier 2. 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 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 165°E meridian extends into both convergence zones, while the 140°W line extends into the ITCZ. One of the highest rainfall sites is at the northern extension at 110°W. In addition, 156°E 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 interconnections 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. 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 5: Mean surface EKE (Eddy Kinetic Energy; cm²/s²) determined from drifter velocity data. From Laurindo et al. (2017).
Figure 6: (a) Mean difference (%) between a surface stress ($\tau_a$) estimated using only the absolute 10-m wind, and a stress ($\tau_r$) estimated using the difference between the 10-m wind and the oceanic surface current. Both $\tau_a$ and $\tau_r$ 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 Recommendations

Based on these target phenomena and rationales, we propose two levels of priority for near-surface currents and Tier 2 sites (Fig.7):

**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

**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:**
(Recommend 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 2°S, 0°, 2°N, 5°S

**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

**Figure 7:** 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.

### 2.5 The LLWBC/ITF system

Authors: Janet Sprintall, Billy Kessler, Sophie Cravatte
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. No observing array for the tropical Pacific can be complete without this element, 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, 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 500 m showed favorable agreement between the inflow and outflow measurements of the Solomon Sea over the common 19 month time period (Anutaliya, PhD thesis, 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 Unresolved and ongoing issues

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 to speak to the technologies that can meet them. Yet, as noted in previous reports, progress has been difficult because this work inherently engages multiple agencies and international programs, each with their own mandates 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 (often 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 a model
solution constrained and verified by carefully chosen in situ measurements. Such an exercise
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 modelling 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
bathymetry, 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.
In this section we provide a self-evaluation of the TPOS 2020 project, a look at how the project has engaged with international and intergovernmental partners, and provide a framework for the TPOS governance moving past 2020.

### 3.1 Success against TPOS 2020 Terms of Reference

Authors: Neville Smith

The TPOS 2020 Project was charged:

- 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 modelling 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 Third Report has provided additional elaboration.

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3 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 parameterisation and modelling 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.

3.2 Emerging Methods and Roadmap for Evaluation and Inclusion

Author: Billy Kessler

Today is a fertile time for new ocean instrumentation. New capabilities, new types of autonomous vehicles, and improved realtime 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 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 forecast centers, scientists and others make of the data, and how it fits into other pieces of the observation/model/product puzzle. These multiple “lives” of an observation are difficult to perceive in real time, certainly not when a technology is new. Yet choices must be made in real time, guided as objectively as possible. 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/Rec.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.

3.3 International and Intergovernmental Organizations: The broader relevance and impact of TPOS 2020

Authors: Katherine Hill, Neville Smith, Bill Large, Etienne Charpentier, Toste Tanhua, Emma Heslop

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 2020 project was established under the direction of an international group of agency sponsors/stakeholders – 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 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 modelling community, through WMO (The Inter-programme Expert Team on Observing System Design and Evolution, IPET-OSDE), Ocean Predict (GODAE Oceanview), and WCRP modelling 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;
- organisational 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, 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 Ocean Decade 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 organisations) favours nimbleness and focus, but it 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 modelling 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.

- 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.

### 3.4 Governance and ongoing structure

**Authors:** David Legler, Neville Smith, Cheyenne Stienbarger, Brittany Croll

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/](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.
The TPOS 2020 project was aligned with such principles but faced limitations in authority and accountability which were discussed in the 2nd Report. 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 and the Steering Committee held a series of discussions to further consider and refine these core elements. The proposed structure (Figure 8) 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.

Scientific Advisory Committee

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. 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

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is recommended that a connection to the intergovernmental organizations remain similar to the current approach initially. Similarly, understanding how TPOS will connect to WMO going forward will require further definition including the next steps for TPOS as a WIGOS pilot project. Updating the functional 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 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 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.

*Functional aspects of the dotted lines will be further fleshed out.

**Figure 8.** The TPOS proposed post-2020 governance structure.
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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).

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADCP</td>
<td>Acoustic Doppler Current Profiler</td>
</tr>
<tr>
<td>AOU</td>
<td>Apparent oxygen utilization</td>
</tr>
<tr>
<td>AUV</td>
<td>Autonomous underway vehicle</td>
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<tr>
<td>BGC</td>
<td>Biogeochemistry/biogeochemical</td>
</tr>
<tr>
<td>BMKG</td>
<td>Badan Meteorologi, Klimatologi, dan Geofisika</td>
</tr>
<tr>
<td>BSISO</td>
<td>Boreal summer intraseasonal oscillation</td>
</tr>
<tr>
<td>BS-TT</td>
<td>(GOOS OOPC) Boundary Systems Task Team</td>
</tr>
<tr>
<td>CDA</td>
<td>Coupled [ocean-atmosphere] data assimilation</td>
</tr>
<tr>
<td>CEOS</td>
<td>Committee on Earth Observation Satellites</td>
</tr>
<tr>
<td>CLIVAR</td>
<td>Climate and Ocean: Variability, Predictability and Change</td>
</tr>
<tr>
<td>CMIP</td>
<td>Coupled Model Intercomparison Project</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>CTD</td>
<td>Conductivity-temperature-depth/pressure [sensor]</td>
</tr>
<tr>
<td>DA</td>
<td>Data assimilation</td>
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<tr>
<td>Dec-cen</td>
<td>Decadal to centennial</td>
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<tr>
<td>DNA</td>
<td>Deoxyribonucleic acid</td>
</tr>
<tr>
<td>DOI</td>
<td>Digital object identifier</td>
</tr>
<tr>
<td>ECMWF</td>
<td>European Centre for Medium-Range Weather Forecasts</td>
</tr>
<tr>
<td>EEZ</td>
<td>Exclusive economic zone</td>
</tr>
<tr>
<td>ENSO</td>
<td>El Niño Southern Oscillation</td>
</tr>
<tr>
<td>EOVs</td>
<td>Essential Ocean Variables</td>
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<tr>
<td>EPAC/EP</td>
<td>Eastern Pacific</td>
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<tr>
<td>Acronym</td>
<td>Full Form</td>
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<tr>
<td>---------</td>
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</tr>
<tr>
<td>ERA</td>
<td>ECMWF global atmospheric reanalysis product</td>
</tr>
<tr>
<td>EUC</td>
<td>Equatorial Undercurrent</td>
</tr>
<tr>
<td>ET-OCPS</td>
<td>(WMO) Expert Team on the Operation Climate Prediction Systems</td>
</tr>
<tr>
<td>FAIR</td>
<td>Findable, Accessible, Interoperable, Reusable</td>
</tr>
<tr>
<td>FOO</td>
<td>Framework for Ocean Observing</td>
</tr>
<tr>
<td>GCOS</td>
<td>Global Climate Observing System</td>
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<tr>
<td>GODAE</td>
<td>Global Ocean Data Assimilation Experiment</td>
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<tr>
<td>GOMO</td>
<td>(NOAA) Global Ocean Monitoring and Observation [Program]</td>
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<tr>
<td>GOOS</td>
<td>Global Ocean Observing System</td>
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<tr>
<td>GO-SHIP</td>
<td>Global Ocean Ship-based Hydrographic Investigations Program</td>
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<td>GOOS Regional Alliance for the Southeast Pacific</td>
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<td>GRO</td>
<td>GNSS radio occultation</td>
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<td>GTS</td>
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<td>ICG</td>
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<td>IOC</td>
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<td>IOOS</td>
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<td>ITCZ</td>
<td>Intertropical Convergence Zone</td>
</tr>
<tr>
<td>ITF</td>
<td>Indonesian throughflow</td>
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<td>JAMSTEC</td>
<td>Japan Agency for Marine-Earth Science and Technology</td>
</tr>
<tr>
<td>JCOMM</td>
<td>Joint Technical Commission for Oceanography and Marine Meteorology</td>
</tr>
<tr>
<td>JCOMMOPS</td>
<td>Joint Technical Commission for Oceanography and Marine Meteorology in situ Observations Programme Support</td>
</tr>
<tr>
<td>JMA</td>
<td>Japan Meteorological Agency</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
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</tr>
<tr>
<td>LLWBC</td>
<td>Low-latitude western boundary current</td>
</tr>
<tr>
<td>MJO</td>
<td>Madden-Julian Oscillation</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>NDH</td>
<td>Dirección de Hidrografía y Navegación, Peruvian Navy</td>
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<tr>
<td>NECC</td>
<td>North Equatorial Counter Current</td>
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<td>NOAA</td>
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<td>NPOCE</td>
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<td>NWP</td>
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<td>O2</td>
<td>Dissolved oxygen</td>
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<td>(GOOS) Observations Coordination Group</td>
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<td>OMZ</td>
<td>Oxygen minimum zone</td>
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<td>OSE</td>
<td>Observing system experiment</td>
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<td>PBL</td>
<td>Planetary Boundary Layer</td>
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<td>pCO2</td>
<td>Partial pressure of carbon dioxide</td>
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<td>PIES</td>
<td>Pressure Inverted Echo Sounders</td>
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<td>PISTON</td>
<td>Propagation of Intra-Seasonal Tropical Oscillations</td>
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<tr>
<td>PMEL</td>
<td>Pacific Marine Environmental Laboratory [a NOAA lab]</td>
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<tr>
<td>PRAWLER</td>
<td>Profiling Crawler [an instrument developed at PMEL]</td>
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<td>R1</td>
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<td>R2</td>
<td>[Second Report of TPOS 2020]</td>
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<tr>
<td>SAC</td>
<td>TPOS Scientific Advisory Committee [post 2020]</td>
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<td>S2IP</td>
<td>Seasonal to interannual prediction</td>
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<td>S2S</td>
<td>Subseasonal to seasonal</td>
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<td>SC</td>
<td>TPOS 2020 Steering Committee</td>
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<td>SENAMHI</td>
<td>Servicio Nacional de Meteorología e Hidrología</td>
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<td>SOA</td>
<td>State Oceanic Administration</td>
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<td>SPCZ</td>
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<td>SPICE</td>
<td>Southwest Pacific Ocean Circulation and Climate Experiment</td>
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<td>SSH</td>
<td>Sea surface height</td>
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<td>SSS</td>
<td>Sea surface salinity</td>
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<tr>
<td>SST</td>
<td>Sea surface temperature</td>
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<td>TAO</td>
<td>Tropical Atmosphere-Ocean [mooring array]</td>
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<tr>
<td>TIWs</td>
<td>Tropical instability waves</td>
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<td>TMA</td>
<td>Tropical Moored Array</td>
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<tr>
<td>TPOS</td>
<td>Tropical Pacific Observing System</td>
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<tr>
<td>TPOS 2020</td>
<td>Tropical Pacific Observing System 2020 Project</td>
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<td>TRITON</td>
<td>Triangle Trans-Ocean Buoy Network [mooring array]</td>
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<tr>
<td>UN</td>
<td>United Nations</td>
</tr>
<tr>
<td>VOSClim</td>
<td>Voluntary Observing Ship Climate (Fleet)</td>
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<td>WCRP</td>
<td>World Climate Research Programme</td>
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<tr>
<td>WGNE</td>
<td>Working Group on Numerical Experimentation</td>
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<td>WGSIP</td>
<td>(WCRP) Working Group on the Subseasonal to Interdecadal Predictions</td>
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<tr>
<td>WIGOS</td>
<td>WMO Integrated Global Observing System</td>
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<td>WMO Information System</td>
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<td>World Meteorological Organization</td>
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<td>WP-TT</td>
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<td>Code</td>
<td>Description</td>
</tr>
<tr>
<td>------</td>
<td>-----------------------------------------</td>
</tr>
<tr>
<td>XBT</td>
<td>Expendable bathythermograph</td>
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<tr>
<td>YMC</td>
<td>Years of the Maritime Continent</td>
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Appendix B – Summary of Recommendations and Actions

All Recommendations and Actions from the First and Second Reports.

B.1 Second Report Recommendations

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

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

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

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

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

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

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

Recommendation 4.2. TPOS 2020 recommends CTDs with dissolved oxygen and optical sensors (chlorophyll fluorescence, particulate backscatter, transmissometer) and water samples (a minimum for chlorophyll and nutrients) should be performed to 1000 m along each TMA line by servicing cruises, at every degree of latitude between 8°N and 8°S and every 0.5° between 2°N and 2°S at a frequency of at least once per year. Twice per year sampling is optimal and could be augmented by GO-SHIP and other ships of opportunity.
**Recommendation 5.1.** The existing TMA line along 95°W should be maintained and updated to full-flux sites (see section 7.3.1).

**Recommendation 5.2.** Increase Argo density for the EPAC as soon as possible (see section 7.4.4 and Figure 7.19 for initial implementation guidance). A coordination of South American countries to execute the doubling of Argo will be required. (Also see **Recommendation 4.1** and **Action 7.9**).

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

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

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

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

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

**Recommendation 7.3.** Improvement of dedicated capacities on servicing ships to allow repeated ancillary measurements. Underway measurements such as Shipboard Acoustic Doppler Current Profilers, $p$CO$_2$ and sea surface salinity should be systematically acquired.

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

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

**Recommendation 8.3** TPOS 2020 should develop a project around the management of all TMA data including, to the extent possible, recovery and re-processing of other relevant mooring data.
**Recommendation 8.4** TPOS 2020 should develop a pilot project, in conjunction with the WMO Information System effort, to explore the global distribution of TPOS data in near-real time.

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

### B.2 Second Report Actions

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

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

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

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

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

**Action 5.5.** Work with the Intergovernmental Oceanographic Commission to include the eastern Pacific in the Roadmap for the United Nations Decade of Ocean Science for Sustainable Development (2021–2030), as the benefits of capacity development are disproportionately large for this region compared to other regions in the tropical Pacific.
Action 6.1 Studies should be undertaken to better understand sampling errors in scatterometer wind products and the impacts of sampling differences between satellite and buoy winds (Section A.2).

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

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

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

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

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

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

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

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

Action 7.6. Underway pCO₂ observations should be continued or established on all mooring servicing vessels. Pilots of pCO₂ measurements from AUVs (e.g., Saildrone or Wave Glider) should continue as a potential means to drive up spatial and temporal sampling.

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

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

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

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

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

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

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

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

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

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

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

**Action 10.1.** The TPOS 2020 Resource Forum and Steering Committee, in consultation with the broader TPOS community, further develop and seek agreement on post-2020 governance arrangements.

**B.3 First Report Recommendations**

**Recommendation 1** A constellation of multi-frequency scatterometer missions and complementary wind speed measurements from microwave sensors to ensure broad-scale, all-weather wind retrievals over 90% of the tropical Pacific Ocean every 6 hours for the next decade and beyond with different equatorial crossing times to capture the diurnal cycle.

**Recommendation 2** In situ vector wind measurements, with particular emphasis on extending the in situ based climate data records, and intercalibrating different satellite wind sensors especially in the equatorial Pacific and in tropical rainy areas.
Recommendation 3  Sustaining satellite measurements of SST, using infrared sensors for higher spatiotemporal sampling; passive microwave sensors filling gaps under clouds; and the diversity of satellite and in situ platforms contributing to intercalibration.

Recommendation 4  Maintenance of the current level of in situ SST observations and improvement of drifter SST quality. Both will contribute to satellite SST calibration and validation, as well as providing an independent reference dataset for the SST climate record. Specifically target convective and rainy areas for SST ground truth, while keeping SST in situ measurements on moorings in the equatorial region.

Recommendation 5  Continuation of the high-precision SSH measurements via the Jason series of satellite altimeters for monitoring large-scale SSH, and the continuing development of wide-swath altimetry technology to measure meso- and submesoscale SSH variations that are particularly energetic in crucial regions including the western boundary.

Recommendation 6  Maintenance of in situ tide gauge measurements for the calibration and validation of satellite SSH, upgraded with global navigation satellite system referencing and complemented by sustained temperature and salinity profile measurements.

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

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

Recommendation 9  Continuation and expansion of open-ocean in situ precipitation measurements for the evaluation and improvement of satellite-derived products, especially for providing a long-term climate record.

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

Recommendation 11  Continuation of technological developments to measure ocean surface currents remotely, and of in situ measurements of surface and near-surface currents, particularly near the equator. Provide collocated measurements of wind and surface currents.

Recommendation 12  Continuation of high-frequency, moored time series and broad spatial scale underway surface ocean $pCO_2$ observations across the Pacific from 10°S to 10°N.

Recommendation 13  Continuation of advocacy for ocean color satellite missions with appropriate overlap to facilitate intercalibration for measurement consistency. In situ measurements of chlorophyll-a and optical properties for the validation of satellite ocean color measurements are required.

Recommendation 14  From 10°S to 10°N, observations of subsurface biogeochemical properties are required, including chlorophyll concentration, particulate backscatter, oxygen
and nutrients. Enhanced focus is needed for the eastern edge of the Warm Pool and the east Pacific cold tongue.

**Recommendation 15** Enhancing in situ observations of state variables needed to estimate surface heat and freshwater fluxes in the west Pacific warm pool, along the equator, and along meridional lines from the seasonal southern ITCZ across the equator, the frontal zone and Northern Hemisphere ITCZ in the western Pacific, the trade wind region of the central and eastern Pacific and the southerly regime of the eastern Pacific.

**Recommendation 16** A combination of fixed-point moorings, profiling floats and lines/sections from ships to meet the sustained requirement for subsurface temperature and salinity observations. Integration through data assimilation and synthesis is needed to produce the required gridded fields.

**Recommendation 17** Enhancing meridional resolution of temperature and salinity in the equatorial zone through a mix of (a) additional moorings near the equator and (b) targeted enhancement of Argo profiles in the equatorial zone (approximately doubling density).

**Recommendation 18** Enhancing vertical temperature and salinity resolution from the TMA via additional upper ocean sensors on moorings from the top of the thermocline to the surface, and returning Argo profiles at 1 dbar resolution from 100 dbar to the surface (or as close as is practical).

**Recommendation 19** Maintenance and, potentially, augmentation of the sampling depth range of current profiles on the existing equatorial moorings, and enhancement of the meridional resolution of velocity along targeted meridians by additional moorings near the equator.

**Recommendation 20** Doubling the density of Argo temperature and salinity profile observations through the tropics (10°N–10°S), to deliver improved signal-to-noise ratios (better than 4:1) at weekly timescales, starting with the western Pacific and the equatorial zone.

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

**Recommendation 22** A coordinated program of (a) data assimilation studies to assess the effectiveness of the TPOS 2020 Backbone design; and (b) studies on the utilization and influence of observational data among an appropriate subset of ocean analysis systems.

**B.4 First Report Actions**

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

**Action 2** Argo deployments should immediately be doubled equatorward of 10° in the west (especially outside the TMA-occupied region) to maintain subsurface temperature and salinity sampling and compensate for the declining TMA.
**Action 3**  Argo float deployments should be doubled over the entire tropical region 10°S-10°N, and return increased upper ocean vertical resolution.

**Action 4**  Through the TPOS 2020 Backbone Task Team and the Argo Steering Team, further explore how to optimize float deployments and missions to better deliver to TPOS goals.

**Action 5**  Moorings at 1°S and 1°N at selected longitudes should be added to enhance the resolution of near-equatorial dynamics. Enhancement of instrumentation on all moorings spanning 2°S and 2°N at these longitudes should be targeted, including velocity profiles as feasible.

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

**Action 7**  Promote and support sensitivity and impact studies of wind and wind vector data inputs on operational analysis and reanalysis and specialized wind stress products, including their application to climate change detection. The effectiveness of rain metadata flags and various approaches to cross-calibration of scatterometers should also be considered.

**Action 8**  Renew and help coordinate efforts to understand the sensitivity and diagnose the impact of TMA air-sea flux variables in weather prediction, atmospheric reanalyses and coupled models, including through existing activities focused on the impact of observations.

**Action 9**  The Transition and Implementation Group (see section 7.7) should initiate discussion with TPOS stakeholders on sustainable solutions for the distinct implementation problems of the western and eastern Pacific regions, especially for the needed TMA contributions.

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

**Action 11**  Meridional lines of flux sites should be extended from the equator to intersect both the SPCZ and ITCZ in the west, and across the ITCZ, the cold tongue and the seasonal southern ITCZ in the east.

**Action 12**  Underway $p$CO2 observations should be continued or reinstated on all mooring servicing vessels, and the present network of moored $p$CO2 measurements should be maintained and possibly extended. Measurements of dissolved oxygen from the surface to about 1500 m should be made on ships where practical, and oxygen sensors should be considered on each mooring.

**Action 13**  To mitigate risks in meeting surface flux requirements associated with changes in the TMA, TPOS 2020 seeks (a) enhanced sampling by VOSClip and other in situ systems for flux variables, (b) support for relevant new technology developments and (c) encourages efforts to improve the realism of reanalysis and possibly real-time NWP flux products through output correction/flux adjustment techniques.

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

**Action 15** In consultation with key stakeholders, including GOOS, JCOMM, WMO/WIGOS and GCOS, a transition process should be initiated, including the creation of a TPOS 2020 Transition and Implementation Group, for overseeing implementation of TPOS 2020 Recommendations and Actions
Appendix C – 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

The Second Institute of Oceanography of the Ministry of Natural Resources (SIO/MNR) is funded with a two-year pilot project from 2020 to 2021 to support TPOS 2020. The Chinese experimental observing project consists of three moored buoys in the western equatorial Pacific, and approximately 20 core Argo floats and 2 BGC-Argo between the equator and 20°N. The project is designed as a pilot effort of China in contribution to TPOS 2020 focusing on the western Pacific. Two steps of assessments will be conducted, one nearshore inter-comparison in the Chinese coast and one land inter-comparison for meteorological sensors and system integration with TPOS partners, for example, NOAA. All these buoys will be set up similar to Tier-1 buoy with 17-layer underwater temperature and salinity sensors in addition to meteorological sensors at surface. The pilot project and follow-up work led by SIO/MNR could be a substantial part of China’s contribution to fulfill the gap left by the withdrawal of TRITON buoys in the western Pacific (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 establish air-sea heat and momentum flux measurements on Wave Gliders for future enhancement of TPOS in situ flux observations. 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 Gliders 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.

Operational use for the air-sea flux observation in TPOS and further improvement of the measurements should be considered at the next step (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 six technology development projects to address observational requirements and gaps in the Tropical Pacific Ocean region in support of NOAA’s contribution to TPOS 2020. Four projects were funded in 2016 including Saildrone expeditions, enhanced TAO moorings, BGC Argo floats and the development and deployment of a Direct Covariance Flux System (see R1/10.2 and R2/9.2 and https://cpo.noaa.gov/Meet-the-Divisions/Earth-System-Science-and-Modeling/AC4/ArtMID/6339/ArticleID/873 for more information).

Two 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. The 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 (pCO2, alkalinity, DIC) from the standard suite of Argo physical and biogeochemical measurements. The Scripp’s 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.

Detailed descriptions of the six pilot projects, including Outcomes and Relevance to the TPOS 2020 Strategy, can be found on the TPOS 2020 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

The purpose of the study at the northern edge of the warm pool was to capture the multi-scale structure of the BSISO through high-resolution in situ observations in both the atmosphere and ocean and to understand the primary mechanisms maintaining the frontal structure at the eastern edge. The PISTON Project, led by the US, conducted a field campaign as part of the YMC in August-October 2018 at 12°–17°N, 135°E. JAMSTEC also conducted an ocean-atmosphere observational cruise in the same region in August 2018. In addition to capturing detailed structure of air-sea processes including the diurnal cycle and meso-scale convective activity, dual-Doppler radar observations from shipboard polarimetric radars on the 2 research vessels during the PISTON and YMC field campaigns successfully captured the fine three-dimensional structure of the precipitation systems. In addition to the NOAA Saildrone mission in 2018, an observational cruise was conducted 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. 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 R1/6.2.2.2 and 10.1.1.1, and R2/7.4.6.2 and 7.4.6.3 for more information; also https://tpos2020.org/pilot-and-process-studies/).

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 2015-16 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/).

Reference: