TPOS 2020

Tropical Pacific Observing System

Second Report

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Executive Summary

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Second Report of TPOS 2020

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Executive Summary

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

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

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

New Areas of Review

Three new topics are reviewed in this Second Report:

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

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

Coupled models for subseasonal to interannual predictions

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

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

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

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

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

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

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

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

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

Observational requirements of coupled weather and subseasonal prediction

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

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

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

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

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

The following recommendations would advance these goals:

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

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

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

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

Requirements: The First Report Reprised and Extended

Biogeochemical and ecosystem Backbone observations

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

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

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

- Maintain and extend the pCO_2 climate record [4.3.1; First Report, Rec. 12; ***Action 7.6***]
- Address the broader goals of the Biogeochemical Argo community through 31 BGC-Argo float deployments per year in the 10°N to 10°S band.

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

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

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

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

Eastern Pacific observing system

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

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

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

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

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

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

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

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

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

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

Tropical Pacific decadal variability and long-term trends

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

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

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

The Northwestern Pacific Ocean

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

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

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

Air-sea fluxes and the planetary boundary layers

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

Wind stress

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

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

Heat and moisture fluxes

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

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

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

Freshwater fluxes

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

Other considerations

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

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

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

The Backbone Observing System

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

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

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

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

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

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

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

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

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

Progress with Implementation

Progress with implementation since the First Report has been very encouraging and TPOS 2020 has achieved significant buy in. We provide a schematic update of the status of the main Backbone Essential Ocean Variables which shows around half are in a satisfactory state (requirements met adequately or better), but for the remainder there is considerable work to do. For wind, and building on Recommendation 1 from the First Report, TPOS 2020 must drive further dialogue with agencies to explore ways to improve data availability and the diurnal spread of sampling by vector wind measuring satellite missions if the TPOS requirements are to be met (***Action 7.4***, 7.4.1, First Report, Rec. 1). For sea surface salinity, the community must continue to highlight the ongoing need and benefits of follow-on satellite missions (***Action 7.5,*** First Report Rec. 10). Underway measurements of pCO_2 fall short of requirements and TPOS 2020 must act to establish measurements on all mooring servicing vessels and promote pilots of pCO_2 measurements from autonomous underway vehicles (***Action 7.6***; 4.3.1; First Report, Rec. 12).

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

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

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

These are core sites, and all should be supported.

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

Several specific actions are highlighted:

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

Of these, 31 should be equipped with biogeochemical sensors. [***Action 7.9***; ***Recommendation 4.1***]
- TPOS 2020 should develop and detail whole-of-system assessment activities, describing them in the final TPOS report (or earlier). Part of the assessment should include examining the tradeoffs between the number of sites versus the ability to maintain continuous records. [***Action 7.10***]
- For each specialized data stream or platform, ensure the creation of an engaged team of experts to oversee sensor management, develop quality control (QC) procedures and guide the delayed-mode QC for the TPOS data streams. [***Action 7.11***; ***Recommendation 8.3***]

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

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

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

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

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

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

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

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

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

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

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

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

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

Additional Areas of Review

TPOS data flow and access

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

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

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

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

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

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

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

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

Emerging technologies

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

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

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

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

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

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

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

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

Next Steps

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

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

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

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