TPOS 2020

Tropical Pacific Observing System

2016 Interim Report – First Draft

April 12, 2016

V1

Project Website: www.tpos2020.org

Interim Report

Initial Backbone advice

Draft

12 April 2016

Coordinating Lead Authors: Sophie Cravatte[1] and Susan Wijffels[2]

Contributing authors: Ken Ando[3], Meghan Cronin[4], Tom Farrar[5], Alexandre Ganachaud[1], Billy Kessler[4], Tong Lee[6], Dean Roemmich[7], Yolande Serra[8], Neville Smith[9], Janet Sprintall[7], Pete Strutton[10], Adrienne Sutton[4], Ken Takahashi[11], Lisan Yu[5], Matthew Wheeler[12], Andrew Wittenberg[13], Dongliang Yuan[14] and contributions from others.

Author Affiliations:

1. LEGOS, Institut de Recherche pour le Développement, Université de Toulouse, CNES, CNRS, UPS, FRANCE
2. CSIRO Oceans and Atmosphere, Hobart, Tasmania, AUSTRALIA
3. Japan Agency for Marine-Earth Science and Technology, Yokosuka, JAPAN
4. NOAA, Pacific Marine Environmental Laboratory, Seattle, WA, USA
5. Woods Hole Oceanographic Institute, Woods Hole, MA, USA
6. Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA
7. Scripps Institute of Oceanography, San Diego, USA
8. University of Washington, Joint Institute for the Study of the Atmosphere and Ocean, Seattle, WA, USA
9. Ocean Scientist, GODAE Ocean Services, AUSTRALIA
10. University of Tasmania, AUSTRALIA
11. Instituto Geofísico del Perú, Lima, PERU
12. Bureau of Meteorology, AUSTRALIA
13. NOAA, Geophysical Fluid Dynamics Laboratory, Princeton, NJ, USA
14. Institute of Oceanology, Qingdao, CHINA

Executive summary

The Tropical Pacific Observing System (TPOS) 2020 project is an international, limited-term effort to enhance and redesign Observing System in the Tropical Pacific Ocean. It emerged from a workshop and review of the TPOS during 2013-2014, triggered by the deterioration of the TAO mooring array in 2012-2014. The project now seeks to find opportunity in that crisis: new science issues have come to the fore, and the sophistication of the analyses, modelling, and predictions systems and services have evolved considerably. Observational technology - both satellite and in situ - has greatly advanced since the TOGA-era arrays were designed, making a redesign timely. There have also been significant changes in our understanding and appreciation of the socio-economic impact of climate variability and change in the tropical Pacific and their consequences which manifest well beyond the tropical Pacific region.

While ENSO and seasonal prediction remain a primary emphasis, the targets have broadened to include a focus on the ocean mixed layer and the surface fluxes that interact with it, which requires resolving the diurnal cycle, unique equatorial coupled physics, as well as on biogeochemistry, especially the large carbon signal of the tropical Pacific. Approaches to observe the Pacific boundary regions are also evaluated. Many other key application areas draw benefit from TPOS, including climate monitoring and climate change detection and attribution, weather and ocean prediction services, and these users will also drive observational requirements.

This Interim Report lays out the rationale and plans for the first step of the redesign of TPOS. It focuses on the fundamental and core contributions to the sustained observing system, herein referred to as the Backbone of the TPOS. This backbone has five key functions:

- Observe and quantify the state of the ocean, on time scales from weekly to interannual/decadal;
- Provide data in support of, and to validate and improve, forecasting systems;
- Support integration of satellite measurements into the system including calibration and validation;
- Advance understanding of the climate system in the tropical Pacific, including through the provision of observing system infrastructure for process studies; and
- Maintenance and, as appropriate, extension of the tropical Pacific climate record.

There are numerous existing and new demands on the TPOS, which we have split into two major thrusts. The first is to improve our ability to track the state of the system – present and into the future. Recognizing that both forecasters and researchers now routinely use gridded products, combining both satellite and in situ observations, constructed either via statistical data syntheses or dynamically through data assimilation, the path to this goal relies on improving these gridded state estimates. TPOS 2020 can contribute by delivering improved broadscale observations, and by providing detailed sampling with high temporal resolution in key regimes to improve both satellite retrievals and the parameterizations used in statistical and dynamical models. Observations needed for oceanic variables and for air-sea exchanges are discussed. In particular, it is highlighted that accurate measurements of wind and wind stresses over the tropical oceans is critical for improving estimates of air/sea coupling. Two decades ago we required sampling from a grid of moorings to map the winds; we now rely on satellites. The latter, however need careful in situ validation, especially in rainy regions, and the different generations of vector wind satellites need seamless high quality in situ series to reference for continuity. Better in situ support for improving satellite retrievals (and their errors) are a high priority in the new TPOS.

The second need is to improve our knowledge of critical processes that are poorly understood and badly represented in models and which are therefore stymieing progress in improving prediction services. These include:

- near-surface ocean physical processes, requiring enhanced near-surface vertical resolution of temperature and current measurements, and resolving the diurnal cycle.
- monitoring frontal air-sea interaction processes
- near equatorial ocean physics across the ENSO cycles and regimes
- key circulation elements such as the low-latitude western boundary currents, equatorial undercurrent meridional structure and transport, and the equatorial intermediate circulation.

Preserving, improving and extending the climate record is a fundamental goal of TPOS 2020. Reliable records are crucial for detecting, understanding, attributing and projecting natural and anthropogenic changes, particularly on decadal and longer timescales. The tropical Pacific is a region of particular interest, since its fluctuations reverberate efficiently to climate globally. We follow the GCOS Climate Monitoring Principles that provide important guidance in the preservation and improvement of the TP climate record, particularly with respect to calibration and overlapping data streams during any changes to the sampling.

The new design takes a multi-purpose and multi-use approach, as espoused by the Framework for Ocean Observations and the GCOS Implementation Plan. It is integrated: the design treats the satellite and in situ parts of the observing system as fully interdependent and comprising essential elements of the whole. Satellite systems provide a spatial and temporal observational coverage of the surface that is unachievable by in situ networks, but depend on high quality and fit-for-purpose calibration and validation in situ observations. In situ systems deliver information below the surface and on essential climate variables that cannot be directly measured from space. The design balances the strengths and weaknesses of different approaches and platforms. It seeks a balance between regime and grid sampling, consistent with the overall aims of the Backbone.

The report presents three options for the redesign of the TPOS: option 1 is the minimum believed to meet all five key backbone functions; it allows credible forecasts and their advancement, but remains vulnerable to failure of individual elements. Option 2 (the preferred choice) meets these but is more robust and entails lower risk through targeted redundancy and backup sampling. Option 3 includes all the new functions plus retains all the current elements of the TPOS. Each option has different risks or tradeoffs. Adequate overlap and careful assessment of each aspect of the new design compared to present arrays must be done before any permanent change to avoid damaging the climate record.

The major design changes include greatly enhancing the tropical moored array's capabilities, focusing it on: high-frequency sampling in the near-surface ocean, and the ability to make co-located ocean, surface meteorology and flux measurements, and greatly enhanced high frequency circulation and property sampling along the equator. We recommend that most moorings sample the full suite of basic atmospheric and surface ocean parameters required to estimate all components of the air/sea fluxes of heat and water. Moorings continue to be indispensable near the equator, and we recommend an increased meridional resolution in the 2°S-2°N band at key longitudes; and to expand moored velocity observations to span the equatorial undercurrent at several longitudes. We also recommend extending a few mooring lines farther north and south than the present TAO/TRITON array to sample more regimes and cross the ITCZ and SPCZ. In addition, Argo will increasingly supplant moored subsurface temperature and salinity measurements where the fast sampling capabilities of moorings have been little used, and where Argo offers better vertical resolution and much enhanced salinity measurements. We propose to double coverage by Argo in the 10°S-10°N region. Key satellite observations are fundamental and the key ocean missions of the Constellation of Earth Observing Satellites must be maintained. However, TPOS is especially dependent on key data streams that require attention: multi-frequency vector wind missions, passive microwave sea surface temperature and satellite sea surface salinity.

Existing global supporting networks– Surface drifters, Voluntary Observing ships, High Resolution XBT lines, continue to play important roles and should be retained. It is also essential to exploit the ship servicing cruises of the tropical moored array for making additional measurements (in particular CTDs, pCO2, underway ADCP) that cannot be done otherwise.

There is risk associated with giving up some mapping capabilities that have been done largely from the present grid of moored sites, particularly for the near-surface ocean and surface meteorology. In Option 1 of the design, we would lose some capability to map quantities like humidity, surface air temperature and pressure from in situ measurements along, and there is always risk of failure or the disabling of satellite sensors. We therefore strived to ensure that the combination of moorings, Argo and satellites has some resilience and redundancy, but is consistent with reasonable cost. The design presented as option 2 (and further 3) helps reducing some of the risks identified in option 1 and offers less vulnerability.

Potential future directions for the design are presented. Some issues still need exploration to frame a design of observations that are feasible to conduct as part of the backbone. The far eastern Pacific and the western Pacific regions require research and pilot studies to define suitable sampling sustained strategies. Current efforts focus on two major themes: the equatorial/coastal waveguide and upwelling, and the ITCZ/warm pool/cold tongue/stratus system. The roadmap for biogeochemical integration into TPOS is also described: Biogeochemical sampling sufficient to describe carbon, oxygen, nutrients, and primary productivity variability and change, in the context of drivers and pathways to the tropics are considered. Finally, our design recognizes that today is a fertile period for autonomous ocean sampler development, and will invest in such new technology that may, over the next decade, reduce the need for expensive research vessel time.

Table of Contents

1 Goals/Scope

1.1 Background on the tropical Pacific observing system

The foundations of the current tropical Pacific Ocean observing system were laid around 40 years ago through pioneering work on sea level monitoring from Pacific islands (e.g., Wyrtki 1984) and eXpendable BathyThermograph (XBT) measurements from the early days of the Ship-Of-Opportunity Program (e.g., White et al 1985). The Tropical Ocean – Global Atmosphere Program (TOGA; 1985-1994; see International TOGA Programme Office, 1992) built on these early efforts to establish an observing system that was capable of monitoring the state of the tropical Pacific Ocean in real-time and delivering the improved understanding and initial conditions needed to make useful and timely predictions of ENSO (see Section 2 for further background).

By the end of TOGA, a design for a global ocean observing system was available (OOSDP, 1995), very much following the integrated and systematic approach of TOGA, and benefitting from the additional work undertaken by the World Ocean Circulation Experiment (WOCE; WOCE SSG, 1986).

Various elements of the global system have been reviewed over the last twenty years including the in situ sea level system (OOPC, 1998), the upper ocean thermal network (Smith et al 2001) and the Tropical Moored Buoy Network (OOPC, 2002). However, there has not been a study dedicated to the review and assessment of the design of the Tropical Pacific Observing System (TPOS) as a whole, taking into account the emergence of altimetry, Argo and satellite wind measurements as mature technologies (among others), and the changed requirements over the last two decades (for example, biogeochemistry).

1.2 TPOS 2020 Project[1]

The TPOS 2020 project emerged from a workshop and review of the TPOS during 2013-2014 which were motivated by an unplanned collapse in the data return from the TAO/TRITON array (see TPOS 2020 (2014); also see tpos2020.org and references therein). The collapse (Figure 1.1) was triggered, first, by the withdrawal of the NOAA ship Ka'imimoana from service, leading to a 2012 and 2013 reduction in the Tropical Moored Array (meaning the TAO/TRITON combination) data return rates from around 80% to around 40%. The rate has since returned to better than 80% but the risk is now demonstrated. The second factor was the decision of JAMSTEC to reduce its investment in TRITON based on competing priorities for research funds. By early 2017 the TRITON contribution will have been reduced from 12 moorings to just 4, but with continuing pressure even on those resources.

---

[1] We use the term "Tropical Pacific Observing System" (TPOS) to refer to the observing system as a whole, at any time. "TPOS-2020" refers to the present time-limited project to rethink the TPOS.

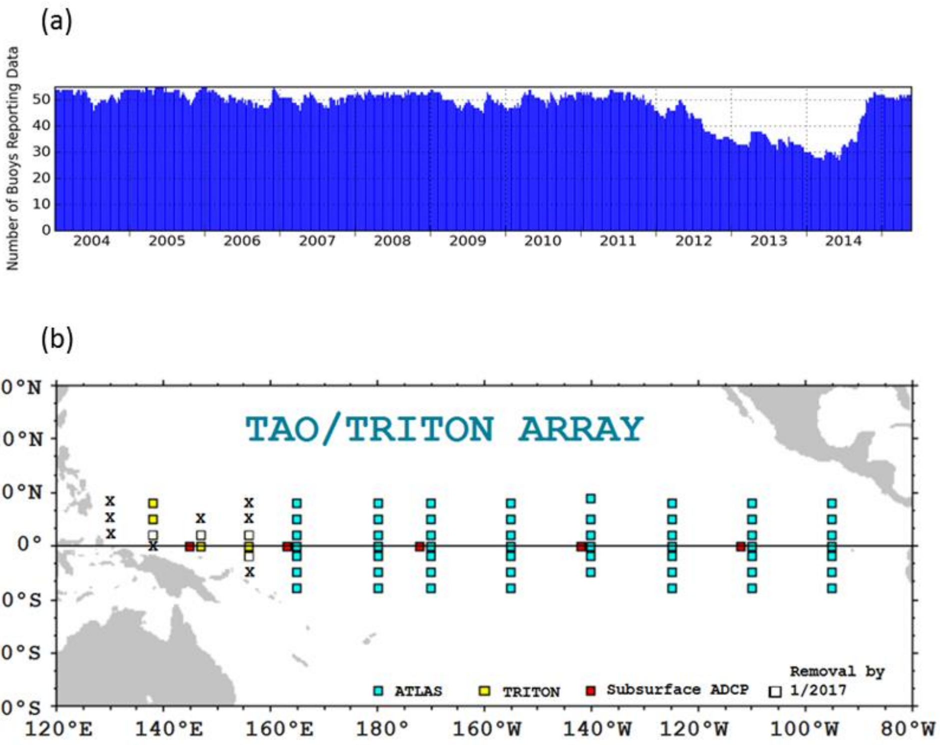

Figure 1.1: (a) Number of TAO moorings returning data 2003-2015 (courtesy NOAA/PMEL). (b) The TAO/TRITON array in the Western Pacific. Sites where operation has ceased are marked with a cross. Locations which are planned to cease in early 2017 are shown in yellow (latest information provided by JAMSTEC).

The TPOS 2020 Workshop proposed several activities and provided recommendations to evolve to more robust and sustainable system, including initiation of a TPOS 2020 Project to achieve this change (Smith et al, 2015). The TPOS 2020 Project will evaluate, and where necessary change, all elements that contribute to the TPOS to achieve enhanced effectiveness for all stakeholders, including for operational prediction models that are primary users of TPOS data. The TPOS 2020 design will embrace the integration of diverse (and new) sampling technologies, with a deliberate focus on robustness and sustainability, and will deliver a legacy of improved governance, coordination and supporting arrangements (see the TPOS 2020 Prospectus at http://tpos2020.org/prospectus/ for further detail). The review of the design will take account of scientific and technical advances over the last 20 years. The specific objectives are:

- 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.

1.3 The Backbone and other Tasks

Five Task Teams have been formed to support the work of TPOS 2020:

1. Determination of the Backbone of the observing system (fundamental, core, sustained contributions),
2. Elaboration of the scientific need and feasibility of observing the planetary boundary layers, including air-sea fluxes, near surface processes and diurnal variability,
3. Evaluation of approaches to observation of the eastern and western boundary regions,
4. Development of rationales, requirements and strategy for biogeochemical observations, and
5. Consideration of approaches to advancing modelling, data assimilation and synthesis.

The first of these tasks is the focus of this Interim Report which will contain initial recommendations for the design of the Backbone as well as a synopsis of initial results and plans for other activities of TPOS 2020. Mid-term (2018) and Final Reports (2020) will provide further elaboration and additional recommendations.

The Interim Report focuses on five key functions of the Backbone:

- Observe and quantify the state of the ocean, on time scales from weekly to interannual/decadal;
- Provide data in support of, and to validate and improve, forecasting systems;
- Support integration of satellite measurements into the system including calibration and validation;
- Advance understanding of the climate system in the tropical Pacific, including through the provision of observing system infrastructure for process studies; and
- Maintenance and, as appropriate, extension of the tropical Pacific climate record.

These functions follow the goals for the Backbone given in the Terms of Reference for the Backbone Task Team (refer to tpos2020.org for details).

In setting the mandate for the TPOS 2020 Project (GCOS, 2014) “ocean observing activities” were taken to include relevant surface and near-surface atmospheric observations and the functions should be interpreted in this context. The third goal/function has been varied so as to emphasize the integration of remote/satellite and in situ measurements. The Tropical Pacific Backbone Observing System supports advances in understanding of the climate system in numerous ways; the fourth function draws attention to one of these roles.

Although the backbone focuses on timescales from weekly to interannual/decadal, many processes in the near-surface atmosphere and ocean occur at timescales shorter than that, and rectify into lower frequencies. Measurements at higher frequency (resolving the diurnal cycle) will be needed and also be a target for the sustained backbone network.

1.4 Structure and Scope of the Interim Report

The Interim Report will be cast within the global context provided by the GOOS Framework for Ocean Observations (FOO) and their Essential Ocean (and Climate) Variables (EOVs/ECVs; UNESCO 2012), WIGOS and its Rolling Review of Requirements[2] , and the GCOS Implementation Plan[3]. The Interim Report will give a description of the Backbone and an initial set of recommended changes. We recognize the need for additional aspects that are expected to evolve and mature over the course of TPOS-2020; these are described here but without recommendations at the present stage.

The report will focus on the following aspects within the broader context provided above:

- Changes to the design for observing the physical systems, with expectations that evolving requirements and recommendations for biogeochemical and ecosystem observations will be detailed in future TPOS reports; and
- The subsurface ocean and the atmospheric surface – the observing system for the free atmosphere is not in scope;
- The open ocean (and the large-scale boundary currents), with expectations that recommendations for coastal observing systems may augment the design in future TPOS reports.

Consistent with the FOO and WIGOS, the following Chapters will include:

- An articulation of the user requirements, in terms of established applications and, for completeness, relevant research themes – the latter point to expected priorities for the near-term and long-term evolution of the observing system;
- Implications for sampling of the state variables – resolution, accuracy and quality;
- An outline of the approach to the design: robustness, efficiency, effectiveness and sustainability; fitness for purpose; integration (across platforms, across fields); and multi-purpose and multi-use data streams;
- Global-scale network contributions, such as from satellites;
- In situ contributions; and
- A description of the evolution during and beyond TPOS 2020.

---

[2] https://www.wmo.int/pages/prog/www/wigos/monitoring.html

[3] http://www.wmo.int/pages/prog/gcos/Publications/gcos-138.pdf (currently being updated)

2 Background

2.1 Foundations of the TPOS

The global impacts of seasonal-to-interannual variability – primarily ENSO – motivated investments in the TPOS for much of its history. These investments, together with efforts in climate modelling, computing and communication, and basic research, have yielded impressive dividends in the form of improved monitoring, understanding, and forecasting of ENSO.

Today, the motivations for a sustained observing system are broader. The present effort to rethink and rebuild the TPOS enlarges its scope beyond ENSO, to also encompass weather and climate change, resolution of physical mechanisms, and biogeochemistry. In devising the new observational network, we are informed and guided by the strong foundation of many groups' decades of effort to observe the tropical Pacific. These earlier efforts have illuminated new targets – for example a focus on the planetary boundary layers in the atmosphere and ocean – and also provide the basis for requirements to sustain advances in prediction. Technological developments expanded by our forerunners also offer promise for enhanced yet more cost-effective observations.

2.2 History of ENSO and tropical Pacific observations

Large-amplitude interannual variability has been known to occur in the tropical Pacific since Sir Gilbert Walker's demonstration, over a century ago, of global-scale connections among local fluctuations of surface pressure. ENSO became the subject of more intense research in the 1950s, especially after Bjerknes' 1965 realization that the same ocean-atmosphere feedbacks that sustained basin scale oscillations might impart predictability of large-scale climate – and efforts began to devise systems to monitor Pacific climate.

In the mid-1970s, Klaus Wyrtki assembled tide gauge records from about 15 island stations to produce indices of surface velocity extending back to 1950; these were instrumental in demonstrating the basin-scale phenomenology of ENSO. Around the same time, Wyrtki and Meyers began compiling historical wind observations from ships. Meyers and Donguy built the first tropical Pacific sub-surface ocean monitoring network, taking advantage of cargo ships making regular trans-equatorial voyages between Auckland or Nouméa to Japan, California and Panama – thus providing 3 quasi-regular tracks. Beginning in 1979, this Ship-of-Opportunity Programme (SOOP) took systematic measurements using XBT probes, typically at 6-hour intervals (roughly 100km apart). By the mid-1980s, the combination of ships approached monthly, 1° latitude sampling along each track.

The SOOP was capable of describing annual cycle and interannual thermal structure variability on these averaged meridional transects, and the broad structure of the zonal geostrophic currents. However, the tracks left large data voids between them, and neither the tide gauge nor the SOOP had real-time reporting capability – data became available only months later.

Following the unpredicted and practically unobserved (at least in real time) El Niño of 1982-83, nations around the Pacific began a substantial effort to establish a real-time, dense tropical monitoring network, founding the international TOGA program that explicitly aimed to provide data to support seasonal climate forecasts. New theories showed that equatorial oceanic internal waves, and their boundary reflections, could impart ocean predictability over months or more – and early-generation coupled ocean-atmosphere models began to explore this predictability. Models demonstrated that knowledge of the tropical ocean state and the wind stress could be exploited to make useful seasonal predictions, helping to drive demand for systematic observations of the subsurface ocean and the overlying wind and flux fields. TOGA measuring programs embraced progress in telemetering ocean observations, essential for forecast and assimilation systems to take full advantage of new observational capabilities.

Hayes, Halpern, Milburn and collaborators built simple moorings that could be mass-produced and maintained in unprecedented numbers, making possible the Tropical Atmosphere Ocean (TAO) array that for the first time provided sustained, real time, fixed-point, consistent subsurface ocean and surface meteorology data across the basin. TAO data was publicly distributed in convenient formats in near real time, helping to drive its widespread use. TAO was an early model for internationally-coordinated and deployed sustained ocean observations, with substantial contributions by the U.S., Japan, Australia, France, and China; the present array was complete by 1991, and evolved into the jointly-maintained TAO/TRITON array in 2000 – hereafter referred to as the Tropical Moored Array (TMA).

Begun before most satellite measurements, TAO sampled both the winds and surface meteorology, and the subsurface ocean through the thermocline. The TAO network design was based on what was then known about the scales of this disparate collection of phenomena and regimes. TAO's design balanced a tension we face again today: between its primary purpose of basin-wide monitoring to initialize and evaluate seasonal climate forecasts, and the need to sample the wide range of space and time scales on which the physical phenomena occur, and thereby provide for improved diagnoses, understanding, and numerical modeling upon which better forecasts can be built.

2.3 Post-TOGA developments

Since the early 1990’s, the most profound development impacting the TPOS and related services has been the development of the globally-coordinated constellation of Earth Observing Satellites (EOS; Lindstrom et al, 2014 (TPOS WP#9); Bonekamp et al 2010; Drinkwater et al 2010; Le Traon et al 2015). Real-time satellite data streams of sea surface temperature (SST), surface waves, sea level, winds, precipitation, salinity and cloud properties, now dominate the information available for state estimates and forecasts, and have become essential in ocean and climate state tracking. The global coverage, high spatial resolution and repeat sampling of satellite platforms captures a larger fraction of the spatial scales of variability, and potentially provides more reliable large-scale integrals (e.g. wind fetch) and derivatives (wind curl and divergence) compared to the TMA measurements. The imaging capability for some variables (at increasing horizontal resolution) delivers new understanding of mesoscale and submesoscale ocean processes, and multi-sensor coverage allows satellite based estimates of some ocean/atmosphere fluxes. Development of the EOS constellation is central to the new TPOS.

Achieving global coverage in 2006, Argo autonomous floats began globally-consistent, fine-vertical resolution ocean sampling on weekly timescales and at a nominal spatial resolution of 3° latitude and longitude. This addresses some of the shortcomings of the TMA, by sampling temperature and salinity more densely in all three spatial dimensions, providing geostrophic currents on scales appropriate for diagnoses of low-frequency phenomena. Argo's sampling choices are based on a different philosophy than that of TMA: focusing especially on the high vertical resolution necessary to diagnose water mass variability. Argo horizontal spacing is more closely matched to present-generation model spatial grids, but is less able to sample the short timescales that underlie many of the key physical processes in those models.

2.4 Socio-economic context

2.4.1 Building the value chain

TOGA was really the starting point insofar as developing a socio-economic context for tropical Pacific observations is concerned. At the outset of TOGA, it was recognized that monitoring and prediction of ENSO had enormous potential value (see for example Ropelewski and Halpert, 1987, and the discussion above). The first successful prediction of ENSO (Cane and Zebiak, 1985) and the first coupled GCM that used ocean data to initialise an operational system model (Ji et al., 1994) were major milestones and, as discussed below represented early examples of processing chains from ocean data to users, a production line that is critical for ensuring long-term socio-economic benefit and impact.

The TPOS has the character of “Public Goods”:

- Acting in an area of market failure - difficult for the private sector to justify investment in an observations service.

- Requires international collaboration and open exchange to work as a system.

- Once produced, data can be provided to additional users, including the international community at small cost.

- Difficult to exclude users, again making it difficult for the private sector to harness value from its investment ("non-rivalrous" and "non-excludable").

- It is largely directed at global services for weather, ocean, climate and climate change which require free and open exchange.

It is interesting to observe that the pioneering work of TOGA and others to have free and open exchange of data, in real-time, brought such research networks into the realm of “Public Goods” since scientific value was not restricted to the researchers operating the network but was available to all who wished to exploit the information, including operational agencies and the private sector.

The benefits and socio-economic impacts of observational systems are almost always indirect; little value derives from the raw data. Rather, through a process of quality control and analysis, then merging with other sources of information (including scientific knowledge), a suite of products and services are produced for a diverse range of uses and users, both public and private. It is the social and economic value-add from these services that we can document and/or measure and represents the benefit and impact.

It is this measure of benefit against the cost that we use to guide the scale of investment in observing systems like TPOS, taking care to recognize that the benefit is not only dependent on the data, but also on the effectiveness of the processing and service provision; value may be limited if, for example, the models and data assimilation are not effective, or if the reach and penetration of the service is sub-optimum. Such measures, even if they are largely qualitative, also provide guidance on the potential impact of new technologies.

Quantifying the benefits will be essential to the longterm success of the new network. Our backbone will require maintaining international partnerships and funding over decades among agencies with distinct national mandates; the difficulty is illustrated by the reduction in Japanese support for the TRITON array.

2.4.2 Socio-economic benefits by Sector

The socio-economic benefits of TPOS were discussed by Harrison et al., 2014 (TPOS WP#2), Wiles et al., 2014 (TPOS WP#8b) and Takahashi et al., 2014 (TPOS WP#8a) as part of the TPOS 2020 Review in early 2014 and are summarised in TPOS 2020 (2014). For this Interim Report it is useful to remind ourselves of the key application areas that draw benefit from TPOS.

2.4.2.1 Climate (ENSO) Prediction

There have been many studies of the socio-economic relationships between ENSO and different sectors (e.g. Solow et al. 1998; Lazo et al. 2011; Centre for International Economics 2014a, b). The methodology applied by Lazo et al. (2011) typifies the leading edge. They estimated the climate sensitivity of different sectors by examining inter-annual variation in US economic activity that could be attributed to climate variability. The sensitivity ranged from as low as 2.2% of GDP for the wholesale trade sector to 14.4% for the mining sector; the sensitivity estimate for agriculture was 12%.

The Centre for International Economics (2014a, b) have completed a similar study for Australia. While the agriculture study was hampered by the lack of good data, they concluded agriculture is highly sensitive to climate conditions and, given Australia is more exposed to climate variability, suggested the sensitivity is likely to be higher than the 12% estimated for the US. Estimates of the impact from recent drought periods suggested agricultural output was reduced by up to 30%, and perhaps as high as 60% for wheat.

They caution that the practical value of forecasts (which do depend on TPOS data) will be much lower than the sensitivity, but the total value of forecasts to the agriculture industry was still estimated to be around A$110m per year. The study further argues that the potential value summed over Australia may be in the range A$1-2 billion.

In summary (based on studies for the US and Australia), the sensitivity of all economic sectors to climate is significant (though different from one nation to the next), and the current value, and potential future value of climate forecasts is large. Takahashi et al. (2014) and Wiles et al. (2014) further note the sensitivity of regional communities to ENSO, e.g. fisheries which, depending upon the community, may be even larger because of the relative contribution to GDP.

2.4.2.2 Climate monitoring and climate change detection and attribution

We are not aware of any socio-economic studies that have quantified the societal value of such services. Information and services related to climate change are often regarded as the most prominent example of "Public Goods" since they are increasingly important at the international and global levels (e.g., Kotchen, 2012), including for tracking carbon exchanges and circulation.

The establishment of the Global Framework for Climate Services (GFCS) attests to the high importance attached to such services, globally. In their words[4] GFCS "… believes that the widespread, global use of improved climate services, provided through the Global Framework for Climate Services will provide substantial social and economic benefits. The Framework presents an important, cost effective opportunity to improve wellbeing in all countries through contributions to development, disaster risk reduction and climate change adaptation. A global mobilisation of effort and an unprecedented collaboration among institutions across political, functional, and disciplinary boundaries is required …". The Copernicus Climate Change Service (http://climate.copernicus.eu/) is one example of significant investment at the service end, with assumptions about the continued provision of suitable high-quality data.

In short, we expect the benefits to manifest globally and across nations, with high-quality physical and biogeochemical data from the tropical Pacific Ocean representing an important input. The emphasis will be on quality and the fitness of the data streams for climate change detection and attribution – that is the climate record (see Section 3.3).

---

[4] http://library.wmo.int/pmb_ged/wmo_1065_en.pdf

2.4.2.3 Weather Prediction Services

The literature on the socio-economic impact of weather prediction and weather services (including surface waves) is quite rich (see, for example, WMO 2012; Gunasekera, 2004). The benefit areas are quite diverse, but with safety and security of life and property prominent. The time horizons range from nowcasts to the emerging area of extended coupled NWP out to 14 days and longer, effectively bridging the gap with climate (e.g., see Brassington et al. 2015). For classical NWP, the only direct input of TPOS data is through SST and boundary layer observations, so the contribution of TPOS to the value chain is important but relatively small. For extreme events, such as tropical cyclones and storm surges), where regional coupled models may be used, the impact is higher. For coupled NWP in general, where the upper ocean comes into play, the impact can be significant (see Brassington et al. 2015 for examples).

In summary, weather prediction services have high socio-economic value but the role of TPOS data, though important for constraining the surface boundary conditions and for validating satellites (e.g., SST, wind), is relatively small.

2.4.2.4 Ocean Prediction Services

Operational ocean and marine prediction services are a relatively new application area, but growing (see Bell et al. 2015 for examples). Several socio-economic studies have examined the value of such services (e.g., Sassone and Weiher 1997; Flemming 2001; Steedman 2006) and they have generally concluded there are high benefit-to-cost ratios (typically around 20). As in other cases discussed above, TPOS data constitute just one of many important inputs. There are also related coastal impacts but these are not presently a focus of TPOS.

Applications for defence and technology development are also relevant but there is little literature quantifying the socio-economic benefit (however, see Flemming 2001 and references therein).

2.4.2.5 Research and Other Applications

As far as we are aware, there have not been any studies that attempt to quantify the value of research that use ocean data. Since research is one of the inputs for each of the application areas above, we can assume its value in advancing all the others is understood.

A recently published study of US business activity in ocean measurement, observation and forecasting (see http://www.ioos.noaa.gov/ioos_in_action/ocean_enterprise_study.html) represented a first attempt to assess the scale and scope of this important sector. Academic research was one of the sectors. The overall revenue for all Ocean Enterprise-related businesses activities was estimated at US$58 billion, with US$7 billion of this specifically from ocean enterprises.

The Integrated Marine Observing System (IMOS) which is part of Australian research infrastructure does attempt to follow both the socio-economic impact and the research value add, principally through citations and other uptake of IMOS data. PMEL has gathered statistics on the use of TAO/TRITON data for around 20 years and these data do display the diverse, international research uptake of the data (consistent with us regarding research contributions to TPOS as “Public Goods”).

2.5 Context for the Interim Report

A useful way to look at the challenges of devising a backbone array recognizes that no single approach will suffice for the diverse regimes we need to sample, each of which has distinct scales, and also different maturity levels. We might describe these regimes as the interior ocean, plus the several boundary layers: the surface layer, the equatorial region, and the eastern and western coastally-influenced regions. We must span both the physical and biogeochemical states. The earlier "broad scale" terminology was appropriate mostly to the interior ocean. For this interior regime, we can fairly well describe the needed sampling scales from decorrelation statistics based on existing data. The boundary regimes are much less understood, and will require further studies to define sampling strategies. Some of these have already begun.

Each of the three major mature technologies available for our backbone has its particular strengths, and these are complementary. Satellite measurements give both global coverage and fine spatial detail in both x and y. The TMA provides continuous, fixed-point sampling over a very wide band of frequencies, allowing careful temporal filtering and spectral diagnoses, as well as inter-calibration across satellite missions, filling of gaps in satellite observations (e.g. scatterometer winds in rainy regions), and uniquely adds the surface heat fluxes, sea level pressure, and ability to directly measure currents. Argo resolves the detailed vertical density structure of the ocean, and uniquely adds the salinity. Argo’s consistent broadscale sampling is central to its value in mapping T and S structure, and in estimating spatial scales and their variability. Each of these technologies thus fills sampling weaknesses of the others, and together enable a more complete diagnosis. The combination also gives resilience, both to failure of individual elements and to unforeseen phenomena.

Today, environmental forecasting has grown beyond ENSO and beyond physical parameters alone. The tropical Pacific produces the largest natural oceanic carbon signal in the world, and is home to diverse ecosystems and food chains upon which entire economies rely. As the importance of this variability has come to the fore, the recognition that tropical Pacific physical fluctuations have a deep impact on the carbon flux has led to pCO_2 observations from both the TMA buoys themselves and the cruises that service them. Yet new understanding of tropical Pacific biogeochemistry, such as the global significance of biological productivity and the expanding oxygen minimum zone in this region, coupled with the emergence of new technologies necessitate further consideration of biogeochemical observations in an integrated TPOS 2020.

Our design will be guided by a combination of the phenomena to be sampled and the scales that can be determined from existing observations. The difficulty of finding this balance is especially problematic in the boundary layer regimes where the target phenomena can often be stated, but the scales are poorly known. Research and understanding (human mental models) tend to focus on phenomena, and that is where most of the burning questions are. But the technologies (observational challenges, model development, parameterizations, assimilation) focus more on scale, and thinking about decorrelation scales, avoiding aliasing, etc. is essential to a cost-effective design. An analogy might be a scalpel (phenomena focus) vs. a sieve (scale competence) – both useful but in different ways.

While it is essential that the TPOS-2020 Backbone meet the needs of operational forecasting, we do not think that present forecast skill sensitivity to observations is a good guide to the impact of observations across the full range of predictability. Perfect-model experiments suggest potential predictability out to a few years in some situations, for example after a strong El Niño. However, present-generation coupled models still develop intractable biases (e.g., the well-known cold tongue/double Inter Tropical Convergence Zone (ITCZ) problem) that degrade and effectively reduce the value of observations by requiring them to perpetually correct the background rather than initialize variability. A more complete observational diagnosis that illuminates now poorly-understood processes thus offers the possibility of a jump in model skill.

As Sections 1.3 and 1.4 indicated, there are fundamental phenomena now poorly understood where observations offer the opportunity to guide model improvement by adding physical realism. Sections 3.1 and 3.2 provide more detail. None of these phenomena are well understood or well modeled at present, indeed their representation will entail development of new parameterizations and assimilation techniques, both requiring significant observational guidance.

Some of this development may be accessible through limited-term process studies, but in many cases these signals have interannual or climate timescales. We will need long-term background climate records to identify the scales of the phenomena and the range of regimes to be observed, and this will have to be provided by the sustained backbone (see Section 3.3 for a discussion of the climate record). The backbone array also provides essential context for process studies, both material (ships and platforms that make embedded studies feasible) and intellectual (regional and temporal context to define climatologies, background and the range of variability).

The backbone we design today will be the basis for the development and initialization of forecast systems for two decades or more. It thus should not be designed solely for the needs of present-generation models and assimilation systems, but must collect the information future models will need. Looking back from 2030, what will we wish we had started sampling in 2016?

The Backbone must change to meet these challenges, and preserve or extend the most important functions of the current TPOS.

3 New demands on the TPOS Backbone

The capabilities of the revised TPOS Backbone design are designed to meet two goals.

The first goal is to improve our ability to track the state of the system – both past, present and into the future. As explained below, the pathway to this goal relies on improving gridded state estimates. In section 3.1, we will thus discuss the observations (both from satellites and *in situ* networks) needed for improving gridded products. We will first consider observations needed for oceanic variables, then for air-sea exchanges, and finally for ocean color gridded state estimates.

The second goal is to improve our knowledge of critical processes that we believe are poorly understood and inadequately represented in models and are therefore stymieing progress in improving prediction services. Since some of these vary on long timescales, limited-term process studies are insufficient, and sustained sampling is required. In section 3.2, we will discuss observations (both from satellites and in situ networks) needed to better resolve near-surface ocean physics, frontal processes in key regions, near equatorial ocean circulation, and will then discuss observations needed for monitoring key circulation elements that are not currently well observed.

Below we discuss in detail the opportunities and requirements for the TPOS to better deliver to the two broad goals outlined above.

3.1 Improved state tracking for better gridded products and model initialisation

To track the state of the ocean/atmosphere system, both forecasters and researchers now routinely use and rely on gridded products, combining both satellite and in situ observations, constructed either via statistical data syntheses or dynamically through data assimilation. These gridded products add value through their consistent integration of information from diverse sources.

These ocean and atmosphere state estimates are also widely used beyond research for climate and ocean assessments, risk assessments, engineering design, defense applications, insurance, marine resource management and many more. By supporting and improving these products, the impact of changes to the TPOS will have broad and immediate impact and uptake.

TPOS 2020 can improve the gridded state estimates via two pathways

1. Delivering improved broadscale observations that underpin mapping and assimilation analyses – for both the surface, subsurface ocean and the planetary boundary layer. Broadscale observations that are delivered in real-time are also critical for forecasting services through their role in constraining the initial forecast state via real time data assimilation.

2. Providing detailed sampling with a high temporal resolution in key regimes to improve satellite retrievals, the parameterizations used in statistical and dynamical models, and be used to validate products and quantify their error statistics.

A key aspect of this goal is supporting the preservation and improvement of long climate records with sufficient coverage and accuracy to detect and monitor multidecadal changes.

Broadscale observations comprise both satellite and in situ data. Satellite data streams of sea surface temperature (SST), salinity (SSS), and height (SSH), as well as significant wave height (SWH), ocean surface wind and stress vectors, precipitation, ocean bottom pressure (or ocean mass), and variables related to ocean color (e.g., chl) now dominate state estimates of atmospheric conditions, and have become essential in ocean state tracking. These satellite measurements are complementary to in-situ observations. For example, satellite altimetry and gravimetry in combination with Argo have enabled a comprehensive study of sea level and the relative contribution of steric and mass contributions. Satellites and mooring data together have greatly facilitated the studies of mixed-layer heat budget.

In-situ observations are also important to improve satellite measurements by providing independent ground truth information for the calibration and validation of many satellite measurements. High-frequency measurements of some in-situ data (e.g., from moorings) help de-alias signals that may not be adequately sampled by satellites (e.g., diurnal signals). Moreover, in-situ data provide information about vertical structure below the sea surface that cannot be measured by satellites.

In the new TPOS Backbone, we address below the specific opportunities to improve tracking the state of the tropical Pacific, describing together the needs for both satellite and in situ observations.

We begin in 3.1.1 with a discussion of the oceanic variables, focusing upon the surface, subsurface, and deeper layers. In Section 3.1.2 we discuss the importance of sea level and ocean mass observations. In Section 3.1.3 we discuss the surface meteorological observations and air-sea exchanges, the mechanisms by which the atmosphere forces the ocean and is influenced by the ocean. In section 3.1.4 we discuss biogeochemistry and ocean color needs.

3.1.1 Temperature and salinity

The tropical Pacific Ocean responds relatively rapidly to variations in wind-forcing through a set of equatorial waves that displace the thermocline vertically, allowing the surface and subsurface ocean to “feel” the effects of remote forcing rapidly, and are crucial elements of the onset and evolution of ENSO. Especially important are the downwelling Kelvin waves generated by westerly wind bursts in the western equatorial Pacific that cross the basin in 2 to 3 months, deepening the normally shallow eastern thermocline by tens of meters and resulting in remotely driven SST warming. The westward propagating Rossby waves, with a transit time of about a year, provide a memory of previous events that allow for “delayed-oscillator” coupled feedbacks.

In addition to the subsurface variability, strong heat and freshwater fluxes controlled largely by atmospheric variability drive large changes in SST and SSS. The vertical structure of the surface layer, including the depth of mixed layer anomalies and formation of fresh 'barrier layers', are being recognized as increasingly important to air-sea coupling and possibly the predictability of weather and climate. The difficulties in making accurate and adequate observations of wind stress and air-sea fluxes, either through satellite or in situ observations, further contributes to the need for subsurface observations that are made with a high degree of accuracy and good spatial resolution.

The current status and elements of the existing observing network is detailed in Roemmich et al, 2014 (TPOS WP#10) for in situ and Lindstrom et al, 2014 (TPOS WP#9) for satellite networks.

3.1.1.1 Surface Ocean

3.1.1.1.1 Sea Surface Temperature

SST is a critical mediator of ocean-atmosphere feedbacks, since on climate time scales it largely governs the atmospheric response to the ocean. SST gradients are particularly important, since they directly affect the density and pressure gradients within the atmospheric boundary layer, which in turn drive surface winds. It remains a scientific and technological challenge to remotely observe SST accurately enough to constrain the subtle changes expected in the future -- especially the changes in horizontal SST gradients and extrema, which may have an outsized impact on how atmospheric convection, rainfall, and winds respond to climate change.

Tracking surface temperature variability is dominantly reliant on the constellation of imaging satellites supported by a sparse in situ network of mixed accuracy and quantity from surface drifters (most plentiful), volunteer observing ships, the TMA and Argo. The tropical Pacific's SST is currently well monitored by satellites, both infrared (IR) and passive microwave (PMW). The IR SST retrievals have the advantage of high spatial resolution (750m to 4 km), multiple satellites (both polar and geostationary), and a long observing record (since 1981, the NOAA AVHRR series). However, IR sensors are not able to measure SST through clouds and are subject to biases from aerosols. Thus a large volcanic event could significantly impact the availability and accuracy of the IR SST. The PMW SST retrievals are able to retrieve SST through clouds and aerosols, but not rain. They also have lower resolution: the three PMW satellites currently measuring SST have a resolution of 25 km, which is significantly lower than those of IR SST (1-10 km).

In situ measurements of SST remain vital for validation and calibration of remotely sensed SSTs, and are of particular importance in cloudy and rainy regions. In addition, maintaining in situ SST returns along and near to the equator (where surface drifters cannot operate) and increasing the accuracy of drifting buoy temperatures are also necessary to improve retrievals and products.

Translating skin measurements seen by satellites into 0.3m 'bulk' SST by better accounting for the aliasing effect of the diurnal cycle remains an ongoing challenge. Besides the strong requirement to continue the major satellite missions measuring SST (see section 5), increased measurements of very near surface temperature structure from the in situ network, particularly where diurnal temperature cycles are strong, will help improve future SST products.

3.1.1.1.2 Sea Surface Salinity

Sea Surface Salinity (SSS) is also an essential climate variable. In the tropical Pacific, it is particularly important for its effect on near-surface stratification and the detection of interannual to decadal changes in the water cycle. It is also an essential variable for data assimilation (Balmaceda et al, 2014, TPOS WP#4 and Fujii et al., 2014, TPOS WP#5), given the large uncertainty in the surface fresh water fluxes.

Until recently, SSS observations relied on a sparse in situ network mainly from volunteer observing ships, the TMA and Argo (shallowest measurements currently between 1-5m). The recent successful launch and operation of two satellite salinity missions – the Aquarius (August 2011 to June 2015) and the Soil Moisture and Ocean Salinity (SMOS) (2010-present) have been a major step change for SSS field estimates. SSS is also being retrieved from the Aquarius and Soil Moisture Active-Passive (SMAP) satellite even though it was designed for land applications.

SSS from Aquarius and SMOS capture variability on smaller spatial and temporal scales never before resolved by the existing in situ networks. Examples include the use of satellite SSS to study tropical instability waves, river plumes, and eddies. Satellite SSS also covers often poorly monitored coastal oceans and marginal seas that are important regions linking the regional terrestrial water cycle with the ocean, and polar regions that are only sparsely populated by in-situ networks. During summertime when the surface thermal fronts on meso- and sub-mesoscales tend to be damped or erased by solar heating, the persisting surface haline fronts become more important in regulating the surface density, which have important implications to ocean dynamics and the marine ecosystem.

However, significant time-mean and seasonal biases afflict present generation satellite SSS measurements, with the integration of satellite SSS with in situ estimates is still a work in progress. The uncertainties of satellite SSS is currently 0.1-0.2 psu in the tropics (see section 5), and thus in situ data vital for validation and calibration. The maintenance of the existing in situ SSS observing network remains a priority; increasing the quality and quantity of near surface in situ SSS will help extract more information of investments in SSS missions.

Under rain bands, satellite SSS tend to be systematically fresher than those measured by in-situ sensors (e.g., at 1 m by moorings and more so at 5 m by Argo floats). Near-surface salinity stratification is a potential contributing factor. Errors in satellite retrieval (e.g., correction of roughness effect due to rain) may also contribute. Enhancing the vertical resolution of near-surface salinity measurements (in the upper few meters) would help decipher these two effects.

Satellite SSS infer much sharper meridional SSS gradients and fronts than those inferred from in-situ data, especially on shorter time scales (e.g., monthly maps) in the equatorial zone and near the ITCZ and South Pacific convergence zone (SPCZ). Tracking the sharp equatorial salinity front in near-surface at the eastern edge of the Warm Pool, and its zonal displacement is also desirable. Currently neither the TMA nor the Argo are sufficient to track the zonal location of this front. There are discrepancies between Aquarius and SMOS SSS in terms of the magnitude of the SSS gradients, likely due to the difference in spatial resolution. Enhancement of spatial sampling of in-situ SSS, in the equatorial zone for example, can improve the ground-truth information needed to evaluate the satellite SSS gradients. While this does not necessarily need sustained in-situ measurements, process experiments to address this question as part of TPOS 2020 is a useful approach.

3.1.1.1.3 PLACEHOLDER: Surface currents

Surface current product from satellite winds and sea level, drifters? SWOT? Radar altimeters?

3.1.1.2 Subsurface upper ocean

The in situ observing system must improve its capability to map the subsurface temperature and salinity, so as to adequately support forecast systems and initialize models, to resolve the vertical structure of the equatorial waves and their effects on thermocline depth, and to accurately infer the heat content that is known as a precursor for El Nino events. This capability should be considered both within the individual systems (Argo, TMA) where sampling consistency gives interpretive value, and for the creation of syntheses that could also include satellite SSH.

Requirements for Tropical Pacific observations depend on the ocean data assimilation system as described in Fujii et al., 2014 (TPOS WP#5). The spatial sampling required differ for seasonal to interannual forecasting, for short to medium range forecasting, and for ocean state estimations used for climate research. These are detailed below.

For seasonal to interannual (S-I) forecasting, Fujii et al., 2014 (TPOS WP#5) considered the horizontal scale of the Kelvin and Rossby waves and estimated the required subsurface temperature sampling intervals in the zonal and meridional directions to be 500-1000 km, and 200 km, respectively, and around 1 to 5 day intervals. The current TPOS observing system (including the TMA and the Argo array) resolves these scales relatively effectively, with the complementarity of both arrays appearing as essential. Shortcomings that could be addressed in the new design are: the TMA 20-50m vertical sampling resolution in the thermocline is insufficient and should be increased in the equatorial band to 10m as a minimum. Further increased near surface resolution is needed to allow mixed layer properties to be tracked and better constrained in the models.

At present, high-temporal sampling of the TMA is not fully used for the S-I data assimilation systems, and the data are often temporally averaged before being assimilated, although this will likely change for the next generation of models. Argo profiles, with higher vertical resolution, consistent global coverage, but lower temporal resolution, are more effective for S-I data assimilation systems. Their meridional sampling resolution, is however, too coarse and an increased number of floats able to stay in the vicinity of the equator would be valuable. Moored data along the equator remains indispensable information for forecasting systems, especially in the eastern Pacific where they are needed to correct persistent model biases.

PLACEHOLDER: New generation of models with higher horizontal and vertical resolution are being developed. Which observations would be needed for these? Will high frequency measurements (sub-daily) be used?

Short to medium range ocean forecasting systems are used for a variety of applications (ocean security, pollution, rescue, monitoring of polluting material, etc). They are based on eddy permitting/eddy resolving ocean models, and aim at reproducing smaller scales, and the variability linked to tropical instability waves and mesoscale eddies. For those systems, subsurface temperature observations with a higher spatial resolution (200 km) than that of the current observing system would be valuable. Process or pilot studies of sampling strategies at these scales should be considered to challenge and develop these systems. Satellite altimeter observations can also be used to derive synthetic vertical profiles through statistical methods, providing temperature and salinity fields at high temporal resolution and at the fine scales of satellite altimetry spatial resolution.

PLACEHOLDER: Which other observations are needed for ocean state estimations (reanalyses) and decadal prediction? Add a paragraph on that. (long time-series? Higher accuracy?)

Salinity is also recognized as an essential variable, both for its influence on the dynamics and as a tracer of large-scale circulation; for these reasons salinity should be well-represented in all forecasting systems. The spatial and temporal sampling requirements for subsurface salinity appear similar to those for subsurface temperature, although current models' need for observational guidance remains unclear.

In the western Pacific, near-surface salinity stratification and associated barrier layers, impact mixed layer depth, its heat budget and SST, the ocean response to wind events, and possibly influence ENSO onset and intensity. From a data assimilation point of view, replicating near-surface salinity is difficult due to large errors in precipitation estimates and predictions. The value of SSS measurements may be greatly enhanced in the future as coupled data assimilation systems develop.

Due to the likely role they play in mediating air-sea fluxes in the sensitive Warm Pool regions, TPOS should strive to monitor barrier layer thickness and its horizontal distribution at weekly timescales. This drives a requirement to better sample temperature and salinity at high vertical resolution in the near-surface layer. The current Argo array is able to depict the global coverage and the slow evolution of the barrier layer at monthly timescales. However, barrier layers can be very localized and of short-term duration, and the zonal fronts can be very sharp. Increasing the number of well resolved near surface salinity profiles in the Warm Pool area (out to its eastern edge) will enable better spatial and temporal tracking of barrier layer variability. The observations needed for a better understanding of the role of the barrier layer in trapping heat and momentum will be described later in section 3.2.1.

3.1.1.3 Intermediate and Deep Ocean

At present, systematic areal and temporal coverage of temperature and salinity in the tropical Pacific Ocean (and the global ocean) is largely limited to the upper 2000 m, augmented by sparse but highly accurate full depth hydrographic transects obtained decadally via the internationally coordinated Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP) program. The latter have provided evidence of deep ocean trends in temperature, salinity and other ocean properties such as oxygen, nutrients and carbon, and of decadal variability, as well as preliminary estimation of deep ocean circulation, including major elements of deeper basin-mode meridional overturning circulations. While ocean heat gain, steric sea level, and other climate indices are primarily controlled by upper ocean changes, the lack of deep data in the present observing system precludes the possibility of closing the critical budgets through direct measurement: residual calculations to infer deep ocean contributions are inconsistent and often have error bars larger than the expected signals. The oceanic fingerprints of climate variability and change extend into the deep ocean, and can only be explored, quantified, and understood with systematic observations that span the entire water column. The required observations, as in the upper ocean, include areal modes, line modes, and fixed-point time-series. There is no question that extension of the observing system into the deep ocean is of high value, and should be pursued as new technologies are demonstrated that make "whole ocean" sampling feasible and practical.

Scientific needs for deep ocean observations in the tropical Pacific Ocean, including regional elements of global systems plus elements that are specific to the TPOS domain are to:

- Estimate full-ocean-depth heat content anomalies on timescales of a year and longer (Johnson et al., 2015).
- Close regional sea level budgets, on annual and longer periods, through estimation of the deep steric component, for integration with sea surface height, upper ocean steric, and mass (bottom pressure) components.
- Detect changes in temperature/salinity characteristics on interannual/decadal timescale in the deep ocean, in relation to high latitude water mass variability and formation rates.
- Quantify equatorial wave characteristics and propagation over the full ocean depth, for timescales as short as intraseasonal.
- Eliminate the present 2000 m discontinuity in ocean observations, for improvement of forecast model initialization and ocean data assimilation modelling.
- Complete the volume (and heat?) transport budget for the Equatorial Pacific, including meridional interhemispheric transports in the ocean interior and the deep elements of western boundary exchanges.

Since deep ocean variability and changes signals are often an order of magnitude smaller than those in the upper ocean, they remain challenging to resolve both form a sensor stability view point and signal to noise aspect. Thus, special attention must be paid to intercalibration of networks and sensors. For instance, ship-based high precision observations and well calibrated moored series can be utilized to help detect any biases in sensors on either autonomous or expendable platforms.

3.1.2 Sea level and ocean mass

As discussed in section 2, sea level was one of the first ocean measurements the helped elucidate the ENSO phenomena. Sea level measurements, both in the interior ocean and in coastal regions, now have a wide spectrum of scientific and operational applications. They are essential for state estimates, seasonal climate and ocean forecasting, for inferring the ocean circulation and its variability, and resolving mesoscale activity; they are used for monitoring equatorial waves and ENSO stages. They are also critical for global issues such as the sea level rise and heat budget.

SSH has been continuously measured by precision altimeters since late 1992 following the launch of the TOPEX/Poseidon satellite. The Jason-1 and -2 missions have provided continuity of the SSH measurements into the present, augmented by measurements from other missions such as Cryosat and Altika/Saral. The nearly two-and-half decades of continuous, consistent record of SSH data record have been playing a fundamental role in improving the understanding of ocean and climate variability and change. Satellite SSH is an important backbone dataset used by most operational centers engaging in seasonal-to-interannual forecasts.

Sea level from tide gauges provide invaluable independent information to validate satellite SSH, ocean reanalyses, and for global sea level long-term reconstructions. Their high temporal sampling are also of great value for regional applications. This network should be maintained and upgraded with global navigation satellite system (GNSS) sampling to track vertical ground motion which impacts on local relative sea level variability.

PLACEHOLDER: observations needed for improving the monitoring of regional and coastal sea level rise and extreme events (see WCRP challenge): for the next TPOS report?

Time-varying ocean mass or bottom pressure (OBP) measurements have been provided by the Gravity Recovery and Climate Experiment (GRACE) since 2003. The data have been used synergistically with satellite SSH measurements and Argo-derived steric heights to study the nature of global and regional sea level changes as well as other oceanic phenomena away from the tropical Pacific (e.g., Southern Ocean variability, inferring deep volume transport associated with the North Atlantic Meridional Overturning Circulation). Ocean bottom pressure variations tend to be interpreted in terms of barotropic variability due to the dominance of this mode, in particular as amplitudes grow towards higher latitudes. However, a study by Piecuch (2013) used GRACE data to confirm earlier theoretical (e.g., Gill and Niiler, 1973) and numerical studies that demonstrated the existence of bottom pressure variations associated with baroclinic modes in the tropical Pacific associated with ENSO. The signal-to-noise ratio of GRACE data in the tropical Pacific is small due to the weak signal of OBP in the tropical Pacific comparing to higher latitudes. Therefore, in-situ OBP measurements in the tropical Pacific are effective in identifying calibration issues of satellite gravity data.

On the other hand, the excellent temporal stability of the GRACE data also provides an opportunity to identify potential drift of in-situ bottom pressure gauge measurements.

A recent study by Hughes et al. (2012) suggests that OBP variations in a region of the central tropical Pacific Ocean provide a good indicator of the global ocean mass variation (after multiplying by an amplification factor of about 1.16). Therefore, both satellite and in-situ OBP measurements in the tropical Pacific are useful for studying global ocean mass variation. TPOS 2020 should explore the readiness of stable, high precision deep pressure measurements at moored equatorial sites to help gravity mission calibration.

3.1.3 Air-sea exchange

As detailed by Cronin et al (2014), estimating air-sea fluxes over the TPOS is a vital but challenging endeavor – both from limitations in parametric estimation and due to sensor accuracy. The current TPOS is returning an uneven and somewhat sporadic in situ coverage of the base parameters required to fully diagnose the air-sea fluxes, and does not cover the troublesome but important deep convection regimes very well. Data streams from the EOS can be better exploited for flux estimation if enabled with the right in situ measurements. We thus believe there are many opportunities to greatly improve the accuracy of air-sea exchange estimates over the TPOS region.

3.1.3.1 Ocean surface wind stress

The surface wind stress is one of the key ways the atmosphere drives the tropical Pacific Ocean. Wind-SST feedbacks lie at the heart of ENSO generation and decay, as the tropical ocean response to wind anomalies can lead to amplifying coupled feedbacks. The ocean is also sensitive to horizontal gradients of the wind stress -- in particular the wind stress curl, which varies on relatively small spatial scales. Accurately measuring wind stresses over the oceans is critical for improving estimates of air/sea coupling, particularly of surface fluxes of heat and moisture (Cronin et al, 2014). The turbulent kinetic energy imparted by winds is also a major source of energy for upper ocean mixing. Winds are also fundamental in forcing and initializing seasonal forecasting models, playing a major role in preconditioning the ocean state along with in situ profile and surface data. Improving wind and vector wind stress estimates over the tropical Pacific is one of the most critical and challenging goals of the new TPOS design.

Previous to the satellite wind age, the TMA was the primary means by which tropical Pacific winds were monitored in real time. However, over recent decades, satellite scatterometers (from missions such as ERS, NSCAT, QuikSCAT, ASCAT, and OSCAT) have proven vital to improving understanding of wind stress variability and their associated scales. Operational forecast centers now largely rely on wind speed and direction from scatterometers for marine forecasts and warnings (e.g., Atlas et al., 2001; Isaksen and Janssen, 2004; von Ahn et al., 2006; Chelton et al., 2006; Brennan et al., 2009). In atmospheric state estimates and forecasts, scatterometers, along with cloud tracking and ingestion of other satellite data streams, now swamp any impact of winds measured in situ. Thus, for wind stress estimation, the role of the in situ network has now effectively changed greatly since TOGA.

Biases in winds, however, even if small, can have profound effects on ocean circulation models and seasonal prediction systems where often the winds are assumed to be without error. This is especially true for tropical winds, which have global reverberations because of the efficient coupled feedbacks of the tropics. The resulting subsurface imbalances impact both short- and long-term predictions. However, there are several opportunities to greatly improve and better qualify errors in satellite winds and their associated products.

Scatterometer winds suffer from several systematic problems associated with some regimes: high rain, high winds, and very low winds. Rain effects on scatterometer measurements are especially problematic in the tropical Pacific, reducing valid estimates substantially (Figure 3.1) and introducing wind errors on both synoptic and longer timescales (Cronin et al 2014). Thus, direct wind measurements in rainy convective regions are particularly valuable for improving and validating satellite wind products, particularly for dealing with rain contamination. For calibration, it is also useful to also have direct measurements across a series of regimes.

In addition, satellite scatterometers tend to be placed in sun-synchronous orbits to reduce sun-glint errors, which leads to aliasing of inadequate sampling of the relatively substantial and ubiquitous diurnal and semi-diurnal wind variability. The aliasing of diurnal variability to lower frequency not only causes systematic biases in wind estimates and inter-sensor differences, but poses a difficulty in studying diurnal ocean-atmosphere coupling in the tropical Pacific that regulate the variability on longer time scales. To quantify and reduce diurnal cycle-linked errors in wind estimates, and to cross-calibrate satellite wind sensors with different equatorial crossing times high-frequency measurements - a temporal resolution of minutes - of in situ winds in areas with strong diurnal variability are needed.

To produce a consistent, satellite-based climate data record from different satellite sensors at different frequencies (e.g., Ku-, C-, and L-band) and missions (e.g. SSM/I series), sustained in-situ measurements of winds at locations with long high quality data records are absolutely vital.

Satellite measured wind stresses are more directly related to the relative wind rather than the absolute wind. In the tropics, where surface currents can be strong and winds relatively weak, neglect of the ocean surface flow on wind estimation can be significant. Thus collection of near-surface currents at all wind calibration sites will help bound and reduce this error.

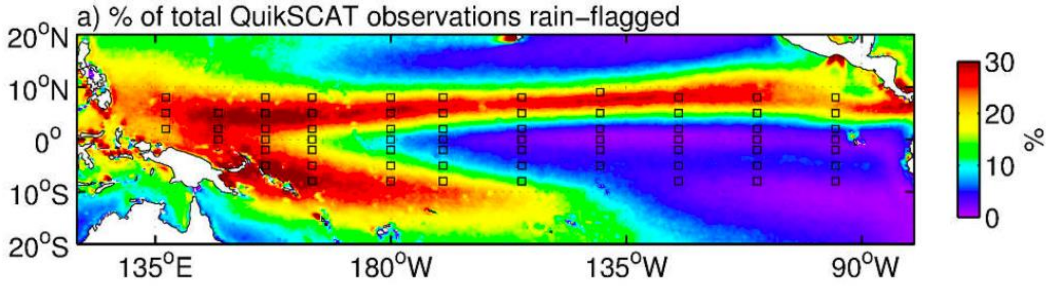

Figure 3.1: Map of the QuikSCAT rain-flag frequency over the 10-year period August 1999-July 2009. Over much of the tropical Pacific, about 25% of the QuikSCAT measurements are flagged as being potentially invalid due to rain, which can contribute to problematic wind biases.

3.1.3.2 Heat and Freshwater flux estimation

The mechanism by which the ocean forces the atmosphere is through air-sea heat and moisture fluxes. Air-sea heat flux allows the surface air temperature to adjust to the SST, affecting the barometric pressure gradient and the stability of the air column, both of which can affect the atmospheric low-level circulation. Air-sea moisture flux can also release heat at higher levels in the air-column, affecting deep atmospheric convection, which in turn can have teleconnections on far-field weather and climate. The basic state variables for turbulent air-sea heat fluxes are SST, air temperature, humidity, wind and surface currents. Basic state variables for the radiative heat fluxes are downwelling solar radiation, albedo (often taken to be a constant), downwelling longwave radiation, emissivity (often taken to be a constant), and again SST.

Observations of these surface meteorological and oceanic variables as well as some direct measurements of these air-sea heat, moisture (precipitation minus evaporation), and momentum (i.e., wind stress) are required for further improvements to our understanding and parameterization of these processes in our prediction models. These fluxes are a crucial component of the coupling between the ocean and atmosphere, and their accurate representation remains as a significant source of uncertainty for diagnosing weaknesses in our understanding and simulation of tropical cyclones, the Madden-Julian Oscillation, ENSO, the seasonal march of the ITCZs in both Hemispheres, and the mean state. In-situ measurements still remain the most accurate method for estimating these fluxes, but they cannot provide the large area integrals required to understand climate-relevant processes, drive ocean models or impact atmospheric state estimates directly. However, we have identified opportunities to improve these fluxes via targeted in situ and satellite data collection.

Satellite retrieval algorithms and/or flux parameterizations require in situ observations to determine the empirical coefficients in the multiparametric retrievals. For example, if the state variables used to estimate the fluxes do not fully resolve gustiness (which can be the case for satellite winds) or the diurnal variability in SST, the errors in the bulk flux can be large (Cronin et al, 2014). This is a particularly challenging problem in the western tropical Pacific. Ideally, one would like to have sufficient in situ observations in key climatic/weather regimes, including (e.g. windy, calm, gusty, rainy, cloudy, clear, humid, dry, day, night) and key oceanic regimes (warm pool, cold tongue, frontal, equatorial, off-equatorial). While the current TMA spans nearly the full zonal extent of the basin between 8 °S and 8 °N, sampling does not extend across the ITCZs and into the Trade wind regime and only a few sites along the equator have long records of full air-sea heat and moisture fluxes.

Expanding regime coverage of in situ flux sites can be efficiently achieved by sampling along north-south lines that intersect both the SPCZ and ITCZ in the west, intersect the ITCZ - cold tongue – stratus regime in the east, and include sampling of the intermediate regimes in the central Pacific.

In the western and eastern Pacific, changes in deep convection on various time scales are associated with dramatic latitudinal and longitudinal variations not only in cloudiness and precipitation, but most importantly in solar forcing, which together produce the multiple time scales seen in the warm pool regions. Because the ocean's response to daytime stratification and nighttime cooling can be a conduit from the surface to the thermocline, the diurnal cycle is a crucial element (see section 3.2.1). Sampling of the diurnal cycle is necessary to guide improvements in model parameterizations of radiative transfer and the air-sea exchanges of heat, moisture, and momentum.

3.1.3.3 Rainfall

In addition to being societally important over land, rainfall is a direct indicator of latent heating of the atmosphere -- a crucial link in how SST affects the atmospheric circulation at both small and large scales, and is part of the freshwater flux into the ocean. Rainfall and its associated latent heating also place strong constraints on the atmospheric energy balance -- including the surface evaporation and shortwave fluxes, and top-of-atmosphere outgoing longwave radiation (OLR). For example, on long time scales global rainfall must balance global evaporation -- thus broad-scale rainfall measurements can help constrain the surface latent heat flux. Intense rainfall can also lead to rapid freshening of the surface ocean -- generating salinity barrier layers, which have been suggested to play an important role in El Niño events (see section 3.1.1.2).

More than other climate-related variables, rainfall is exceptionally intermittent in space and time. As a result individual in situ measurements are often not representative of the broad scale. Thus broad-scale satellite measurements, which must be calibrated to in situ measurements across diverse climate regimes, serve as an important link in assessing overall rainfall and the global hydrological cycle.

Satellites such as the Tropical Rainfall Measuring Mission (TRMM) and Global Precipitation Mission (GPM), jointly launched by NASA and JAXA, have provided global precipitation measurements since 1998. TRMM launched in 1997, used both active and passive sensors in a non-sun-synchronous orbit to measure rainfall in the tropics. GPM is an international constellation of sensors to measure rain and snow. The core satellite, launched in 2015, will serve as the calibration standard of the companion sensors for research or operational applications. GPM has the advantage over TRMM in the global coverage and improved sensitivity to light rain and snow. Improvement and validation of rain products are being vigorously pursued.

A key question is whether the spatial patterns and intensity distribution of tropical Pacific rainfall may change in the future. The SST threshold for convection is also expected to change, as the upper troposphere warms. Warmer SST will moisten the atmospheric boundary layer by about 7%/K, boosting the rain rate for a given convective mass flux and surface wind convergence. This has important implications at scales ranging from tropical cyclones to El Niño. Thus, it is important for TPOS to improve our ability to accurately assess the trends in both tropical Pacific rainfall and near-surface humidity.

3.1.4 **$C0_2$ flux and ocean color**

The tropical Pacific is the largest oceanic source of CO_2 to the atmosphere but equatorial waters are also relatively productive and sequester globally-significant amounts of carbon to the deep sea (Mathis et al., 2014, TPOS WP#6). This productivity, driven by upwelling of nutrient-rich water contributes disproportionately to global marine primary production and its interannual variability, underpinning the region's importance for global marine resources (Chavez et al., 2014, TPOS WP#7).

Core uncertainties remain regarding the drivers and impacts of natural variability and long-term change on carbon, primary production, oxygen, and nutrients (see Section 9). Initial recommendations for integrating biogeochemistry into the backbone design focus on sustaining and expanding established observations in the tropical Pacific: air-sea CO_2 flux and ocean color. These observations must be collocated.

Tracking the broadscale changes in pCO_2 is currently reliant on a combination of equatorial moored measurements and ship-of-opportunity measurements. In the past the TMA servicing ships have been vital in this endeavor. The backbone TPOS must provide the key observations that will underpin a better understanding of both the climate impacts of tropical Pacific biogeochemical variability and connections to higher trophic levels.

Continuous satellite ocean color measurements began in August 1997 with the launch of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS), which was essential for quantifying the biological impact of the 1997-98 El Niño and the following sequence of strong La Niña events. Recent studies have also documented the different biological impact of eastern- vs. central-Pacific El Niño events. In situ optical measurements are critical for improving algorithms for satellite ocean color and to mapping primary production across the tropical Pacific. They may also be used to develop regionally-tuned retrieval algorithms.

The eastern equatorial Pacific is a region of particular biogeochemical significance due to the intense upwelling of nutrient- and carbon-rich water. The spatial extent of this region and the intensity of the CO_2 flux varies over seasonal to interannual timescales. It is thus essential to make in situ observations in this region and along the equatorial band. To map the upwelling region and estimate the volume of carbon released to the atmosphere, at least two meridional lines of moored biogeochemical observations are required, at 170°W and 110°W. These data would capture the variability in the size and significance of the upwelling zone and warm water pool. They would also support critical research questions associated with CO_2 flux, low oxygen, nitrogen cycling, and the linkages to higher tropic levels.

3.1.5 Summary

As discussed above, there are many opportunities to improve state estimation by the future TPOS, either by increased broadscale sampling and by driving more comprehensive regime and fit for purpose measurements that will enable improved used of the EOS data streams.

3.2 Increased understanding of critical processes and phenomena

In this section, we wish to describe the observations needed to better understand critical processes and phenomena; these observations would not necessarily be directly ingested into state estimates, but would indirectly improve them by helping to progress on model parameterizations and physics. Better models and data assimilation systems will improve the physical realism of data products and analyses, but more importantly, may help lead to more accurate climate predictions.

3.2.1 Better resolution of near-surface ocean physics

Near-surface sampling in the tropical Pacific is necessary for two main reasons: the sensitivity of the coupling between ocean and atmospheric boundary layers in the tropics, and the special role of the tropical ocean mixed layer as intermediary connecting surface fluxes to the thermocline where equatorial waves carry signals efficiently around the basin.

The interaction between zonal winds and the equatorial thermocline is the fundamental feedback distinguishing the tropical climate, and that allows coupled variability like ENSO to evolve. This crucial feedback is mediated through the planetary boundary layers, which are among the most poorly understood and modeled elements of the tropical climate system.

Important processes to be sampled include the diurnal cycle, frontal and barrier layer development and collapse at the east edge of the warm pool, westerly wind burst forcing penetrating into the subsurface ocean, evolution of the cold tongue front and its tropical instability wave fluctuations, the structure of Ekman divergence from the equator, and the mixed layer above the equatorial undercurrent in response to varying winds. Although all these phenomena occur at timescales shorter than might be the target of a sustained sampling network, they also all rectify into lower frequencies and are thus crucial to a diagnosis at weekly to 10-day timescales. The TPOS of 2020 must therefore resolve the oceanic mixed layer and near-surface velocity profile at high frequency across key regimes in order to adequately capture the transmission of momentum from the surface to the thermocline and the processes resulting in the evolution of SST.

Sparse observations show that while turbulent mixing can be strong during westerly wind and other synoptic events, enhanced downward transmission of wind energy into the interior ocean also occurs during relatively quiescent periods that allow formation of strong diurnal warm layers. Daytime heating and the consequent trapping of momentum in a thin surface layer produces shear that overcomes the layer's stratification and results in shear-instability mixing and downward transmission of momentum and heat. Once again setting up shear at the base of the now-deeper surface mixed layer, the process repeats, layer by layer, extending into the thermocline through the early evening. In this way, diurnal warming enhances deep penetration of mixing, allowing the thermocline to respond to the wind stress and its variability.

Shallow mixed layers can also be formed through salinity stratification when, as noted above, "barrier layers" are present, and similarly trap momentum near the surface. Strong barrier layers can develop on the eastern edge of the fresh pool when vertical shear associated with the salinity front's pressure gradient or through westerly wind forcing causes the vertical salinity front to tilt into a vertical stratification within a deep isothermal layer; this process evolves over the course of a few days. While the Argo array depicts the slow largescale evolution of these barrier layers (see section 3.1.1.2), moored observations will be needed to quantify the impact on and feedbacks with the near-surface current profiles.

For that purpose, we recommend to enhance the vertical resolution of the TMA in key regimes with temperature and velocity sensors every 5m to 50m, then every 10m to 100m, at high frequency. In the western Warm Pool, the sampling should also include salinity. Although its forcing and dynamics are local and often occur on short timescales, ocean mixed layer variations produce systematic effects on heat and momentum transfer in the tropical Pacific. The Backbone Task Team see an opportunity to maximize the utility of the large commitment of shiptime and technical effort by getting the most out of each mooring to complement the less-demanding requirements for temporal sampling below the mixed layer that can often be accomplished by Argo.

3.2.2 Monitoring frontal air-sea interaction processes and better resolve near equatorial ocean physics across the ENSO cycles and regimes

Zonal and meridional ocean fronts deserve a particular focus. In addition, many near equatorial processes with consequences on air-sea coupling (the Bjerknes Feedback) are not well resolved by the current TPOS. We need to directly measure the near-equatorial physics across ENSO cycles and regimes – thus beyond the scope of most process studies.

3.2.2.1 Frontal air-sea interaction processes

Because ocean fronts typically have shorter scales than atmospheric adjustment, as the wind blows across the ocean temperature front the overlying atmosphere can become out of equilibrium with the sea surface temperature; the resulting feedbacks can amplify the effects of an originally-small feature. In this way, fronts and their consequences can be crucial for ENSO as well as for the annual cycle of the cold tongue.

Satellite sampling can describe many surface fronts with unequaled resolution, but their subsurface extent is poorly constrained. Thus observational capabilities for the subsurface temperature fronts will be greatly improved through an enhancement of the Argo sampling. Autonomous or piloted vehicles may eventually provide adaptive sampling schemes for capturing narrow and wandering frontal variability, but these remain to be developed and tested. For the present backbone, it is critical that the near-equatorial moorings be maintained and enhanced for their capability to monitor the air-sea fluxes, ocean currents, and biogeochemical response to the zonal fronts. The needed enhancements are described in section 3.2.2.2. below.

3.2.2.2 Near equatorial physics

The Pacific equatorial circulation is unique and comprises several elements. Easterly trade winds drive downwind surface currents and also build up higher sea level to the west. The surface South Equatorial Current (SEC) is therefore westward, but below this frictional layer the eastward pressure gradient dominates, driving the opposite-direction equatorial undercurrent (EUC). This balance holds locally on timescales as short as 10 days, and at basin scale on timescales of a few months (the time for equatorial Kelvin and Rossby waves to adjust to the wind forcing). The easterly winds also drive shallow poleward Ekman flows in both hemispheres, with upwelling in the center that compensates this near-surface mass divergence.

While this system is straightforward to describe in these general terms, the details and scales are far murkier: the transition from the deeper EUC to the shallow SEC depends on a competition between several meters/day upwelling against downward mixing processes, which must therefore be exceptionally strong. The situation directly on the equator is not the whole story, because Ekman upwelling depends on the meridional gradient of poleward near-surface flow. One could imagine rapid vertical speeds concentrated tightly on the equator, or a slower, broader upwelling pattern, either of these capable of satisfying the mass imbalance due to the poleward Ekman divergence. Distinguishing between these depends on knowing the structure of the Ekman currents in a zone a few hundred km wide around the equator, which still remains undescribed. In addition, the depth from which upwelling emanates depends on the depth of penetration of the Ekman currents themselves, as well as the depth scales of the frictional wind stress and downward mixing, none of which is well understood or presently confidently modeled.

The range of possibilities has important consequences for both the emergence of properties like CO_2 concentrations (section 9.4) and especially for temperature, since SST changes feed back on the atmosphere and modify the winds that produced the phenomenon in the first place. Our description of this system is built on imperfect and indirect inferences that are a barrier to improvement of either quantitative diagnoses or of improving models of the equatorial system as a whole. Further development of model parameterizations of this complex of interacting processes demands observational guidance that is unavailable. This is a key target for the new TPOS.

These requirements can be met for the first time by broadening the TMA velocity sampling: increasing the meridional density of fixed-point sampling spanning the equator at several (2-4) longitudes, from 2°S to 2°N (or ideally from 3°S to 3°N to fully encompass the upwelling region) at 1-degree intervals. The fundamental rationale is to sample the short meridional scales of the near-equatorial region, where velocity, surface flux, and property gradients are sharp and not well-sampled by the present system, the timescales are short, and the potential for air-sea feedbacks is high. The additional moorings should be comparable to the present equatorial flux sites, including nearby subsurface velocity measurements, and adding near-surface velocity sampling to ensure that the diverging Ekman layer is measured. In the west, the sampling should include salinity.

The additional measurements would document for the first time the meridional/depth structure of velocity that occurs in the upper few 10s of meters and is probably the core feature of the equatorial upper ocean and its response to wind variability. Sampling should resolve timescales from diurnal to multiple decades. At low frequencies, the main phenomenon of interest is the vertical-meridional structure of the equatorial undercurrent and its seasonal and ENSO-timescale changes. What governs the transition of zonal current from the upper EUC to the opposite-direction SEC lobes on its flanks? This broader measure of the equatorial current system would be a new frontier in velocity measurements; it would for the first time depict the full structure of the equatorial current system, including its interaction with the surrounding strong SEC.

At higher (daily to weekly) frequencies, the shallow tropical cells and their modulation by tropical instability waves would be well-captured by for the first time, especially in concert with fine-resolution satellite SST and SSS. The cold tongue front would pass repeatedly back and forth across the moorings, giving many samples of its vertical structure and its (two-way) interaction with the southeasterly winds. Here, fine temporal sampling would, in effect, substitute for fine spatial sampling across the undulating front.

We believe that these observations would be a diagnostic of model realism and a challenge to model development equal to that of the equatorial profiles themselves, one of the things that our successors will look back to as signaling a fundamental advance, as we now look back on the decision to measure the equatorial profiles.

Even with the increased moored sampling proposed here and an increased Argo density, the combination will still be inadequate to resolve the short meridional scales of the near-equatorial region. Satellite sampling will be needed to resolve important fine structures, and to provide consistent weekly sampling between the moorings. Satellite SST products can now produce daily or better high-resolution depictions of the cold tongue front and the front at the east edge of the warm pool, neither of which is perfectly described by the other technologies. The SST will also give insight into patterns and structure of upwelling in response to wind anomalies that cannot be described by the in situ sampling. Satellite surface salinity does not give the same fine spatial resolution, but will be an essential complement to Argo salinity. As noted in section 3.1.1.1, satellite SSS observations infer much sharper meridional SSS gradients and fronts than those resolved by in situ data in the frontal zone.

Sustained observations would provide the background and context to guide proposed process studies of equatorial upwelling, identifying targets and effective sampling strategies. Although a single line of velocity moorings would not fully describe Ekman upwelling, the meridional gradient of velocity is probably its major piece, and a limited-term process study might provide enough information to subsequently infer upwelling from the sparser sustained measurements. Such moorings would also serve as platforms of opportunity for ancillary studies to elucidate the vertical-meridional pattern of the mixing that must balance upwelling.

3.2.3 Improved monitoring of key circulation elements

3.2.3.1 Monitoring of the Low Latitude Western Boundary Currents

The Low Latitude Western Boundary Currents (LLWBCs) of the tropical Pacific Ocean are conduits of tropical-subtropical interaction, supplying waters of mid to high latitude origin into the western equatorial Pacific. They contribute as much as the interior route to the recharge/discharge of the equatorial warm water volume. The leaky western boundary also allows exchange between the Pacific and Indian Oceans through the complex Maritime Continent via the Indonesian Throughflow (ITF). The ITF forms the only low latitude oceanic pathway for the global thermohaline circulation, and plays an important role in the interbasin transfer and global distribution of heat and freshwater. The LLWBCs and the ITF thus play crucial roles in ocean dynamics and climate variability on both regional and global scales, and need to be better understood. A key conclusion from the community consensus on sustained ocean observations, including both OceanObs'99 (Smith et al., 2001) and OceanObs'09 (Fisher et al., 2010), was that sustained boundary current and inter-basin exchange observations are primary missing elements of the global ocean observing system. The Backbone Task Team thus recommends that the LLWBCs properties, and their transport of mass, heat and freshwaters should be monitored through dedicated observations. Building on our knowledge from the past efforts in the LLWBCs, a pilot array consisting of a variety of observations from multiple and complementary platforms across the major elements simultaneously, has never been achieved and is now worth considering.

The Pacific WBC system is characterized by the unique presence of two equatorward LLWBCs - the Mindanao Current and Kuroshio/Luzon Undercurrent in the northwest and the New Guinea Coastal Current system in the southwest. The LLWBCs supply waters that are essential for the mass and heat balance of the western Pacific warm pool and ventilation of the equatorial Pacific thermocline, and thereby affect the life cycle of ENSO and Pacific decadal variability. The volume, heat and freshwater budget of the equatorial Pacific Ocean cannot be closed without a good understanding of the variability of these LLWBCs.

With a large vertical extent concentrated in powerful narrow jets that flow within a very narrow region (~100-200 km) off the coasts, LLWBCs remain poorly observed by systems that do not resolve their small time and space scales. In addition, due to their strong intrinsic variability on time scales from intraseasonal, interannual to decadal, along with possible aliasing from an energetic eddy field, there remains large uncertainty in the volume and heat/freshwater transport variability of these LLWBCs. Because they are the result of integrated forcing over the entire basin, their variability thus includes a wide range of phenomena and requires a strategy of frequent sampling. While some insight into the mass transport variability of these currents can be gained from satellite altimetry, their heat and freshwater fluxes still require in situ sampling.

Much of the impact of the LLWBCs on timescales beyond interannual and on climate forcing remote to the LLWBC regions is conducted through their linkage to the ITF. Connection between the ITF and the Pacific LLWBCs is complex, and a clear picture of the associated pathways and processes remains to be elucidated. The proportion of each hemispheric Pacific Ocean LLWBC water source for the ITF appears markedly different according to ENSO phase. The northeastern Indonesian seas are the primary inflow from the Southern Hemisphere and it has never been directly well observed, and yet provides the major salt contribution to the ITF. Finally because of the complex bathymetry of the Indonesian seas, the interbasin exchange consists of several filaments that make measurement of the total ITF logistically challenging.

Sustained observing in these regions should involve full-depth coverage of temperature, salinity, and velocity in order to resolve the volume, heat, and freshwater transport variations on timescales of intraseasonal and longer. However, no single observational technology is presently available that adequately samples the full latitude/longitude/depth/time structure of the tropical WBC and ITF regions at the desirable resolution of order 10 km and 10 days. LLWBC and inter-basin ITF exchange observations are best achieved through line-mode transect networks, including shipboard repeat hydrography, HRX, gliders, and moorings, in combination with broadscale in situ and remotely sensed measurements. An integrated network design consisting of these multiple in situ observational types including synergistic in situ and high-resolution satellite measurements provides the right mixture of spatial, depth, and temporal sampling characteristics required to sample the boundary current regions.

The future TPOS for the LLWBCs should be built using knowledge garnered from past and existing measurement arrays. Three major LLWBC/ITF programs have taken place over the past 10 years, mostly coordinated through **CLIVAR**. Starting with the **INSTANT** program in 2004, the different straits in the ITF were equipped with moorings so that transports, pathways and water mass transformations could be quantified for the first time and better understood. More recent ITF observations are presently maintained through individual programs sponsored via various international efforts. Southwest Pacific LLWBCs were measured and modeled / analyzed within the **CLIVAR-SPICE** program since 2008 (www.spiceclivar.org), and monitoring of the New Guinea Coastal Undercurrent system through gliders / PIES is sustained since 2008 through a NOAA/CORC funding project (Roemmich et al, 2014, TPOS WP#10).

Northwest Pacific LLWBCs have been measured and modeled / analyzed within the **CLIVAR-NPOCE** program since 2010 (npoce.qdio.ac.cn). NPOCE continues with extension into the Indonesian Seas; however as yet there is no perspective for sustained measurements. More details of these programs can be found in Roemmich et al, 2014 (TPOS WP#10).

The fundamental idea is to evolve these short term process-oriented boundary measurements to a larger coordinated pilot array and then towards a sustained system. The recent ITF, SPICE and NPOCE programs include some synchronous measurements, and therefore provide a valuable starting point to sustained measurements. Building on this interest and international impetus, an internationally driven pilot study would foster continued and focused interaction and collaboration between the TPOS and these international programs on the boundary regions.

The pilot array would enable the determination of the key observational sites in the LLWBC and ITF of the highest priority, decide on the variables to be observed in terms of priority and readiness of technology, and determine the time and space scales that must be resolved. In addition, a pilot would enable the exploration of potential opportunities to collaborate with regional and other international institutions for the implementation and maintenance of TPOS and its national components, to determine ways to share costs such as through ship time, instrument input and logistical capabilities. A western Pacific group is working on these recommendations: more details are given in section 9, “Future Directions”.

3.2.3.2 Monitoring the Equatorial Undercurrent transport

The Equatorial Undercurrent is a fundamental feature of tropical Pacific circulation. Centered on the equator with a width of about 400km, the EUC extends across the whole basin and is the main source of water upwelled in the equatorial cold tongue in the central and eastern Pacific. The EUC reaches velocities higher than 1 m/s in its core and transports around 30–40 Sv; it is a fundamental part of both subtropical and tropical shallow meridional overturning cells, and displays strong seasonal, interannual and decadal variations in mass and heat transport.

An adequate simulation of the full structure and transport of the EUC is essential in ocean circulation models. Realism of this aspect is also crucial for the ability of coupled general circulation models to simulate ENSO, and decadal variability. For all these reasons, EUC structure and transport is a key climate indicator that should be monitored in a sustained way.

In the present TPOS, velocity profiles are returned by the TMA at five locations (110°W, 140°W, 170°W, 165°E and 147°E), and only on the equator. This precludes being able to directly measure transport, though there have been indirect statistical attempts to infer it. The equatorial data are highly valued by the modelling community as they are routinely used to validate and tune models, and are a good diagnostic of the realism of simulations in the Tropical Pacific. Indeed, as explained in section 3.2.2, the EUC core depth, its strength and the transition from the EUC to the overlying SEC depends on a competition between upwelling and vertical and horizontal mixing processes. Testing the representation of this balance in ocean general circulation and climate models has become a sensitive diagnostic of the physical parameterizations in these models. For this reason, the long time series of current profiles that have historically been directly measured by the TMA on the equator must remain fundamental elements of the observing system.

Velocity observations extending to 300m, surrounding the equator at 1° intervals from 2°S to 2°N (encompassing the EUC and the tropical cell transport maximum), are recommended. Co-located with the 1°-resolution temperature-flux moorings and with the near-surface velocity sampling recommended in section 3.2.2, resolving lines should be implemented at three widely-separated longitudes to characterize the changes in EUC width, depth and transport along its route toward the eastern boundary. For the first time it will be possible to monitor the EUC heat and mass transport, will greatly improve our knowledge of the 3-D near-equatorial circulation and challenge models.

3.2.3.3 Monitoring of the intermediate currents

Our knowledge of the equatorial currents in the intermediate and deeper levels is very limited, as they are largely out of reach of current TPOS sampling and comes only from sparse and opportunistic direct measurements of currents obtained from Lowered Acoustic Doppler Current Profiler (ADCP) profiles and Shipboard ADCP sections. Despite this, available measurements reveal that zonal currents below 300m in the near-equatorial band are well organized into a complex series of stacked jets. However, ocean models, even at high-resolution, are unable to simulate these flows correctly, typically producing a very damped version of the intermediate currents. The large zonal transport variability of these flows raises questions regarding their importance for the zonal mass and heat balance of the equatorial Pacific Ocean and their role in the zonal distribution and mixing of biogeochemical water properties. Finally, the subthermocline currents feed the eastern thermostad and may be important contributors for the mass and oxygen transport to the coastal upwelling systems.

Off equator, low-frequency, sub-mixed layer currents may be inferred from geostrophy, and the spatial and temporal resolution of the Argo array may be sufficient to usefully describe the currents above 2000m, at least at seasonal timescales (still to be demonstrated). Near the equator however, direct measurements are the only way to sample the velocity and property transport variability. Direct velocity measurements at high temporal resolution down to 1000m along the equator would greatly improve our knowledge of the intermediate currents variability, and pilot studies embedded in the array should be considered.

3.3 Preservation and improvement of the climate record

A Climate Data Record (CDR) is "a time series of measurements of sufficient length, consistency, and continuity to determine climate variability and change" (National Research Council, 2004).

Climate is constantly changing and it is crucial to have reliable records for detecting, understanding, attributing and projecting such changes, particularly on decadal and longer timescales. Providing and improving CDRs is a fundamental function of TPOS 2020. CDRs provide reliable information to researchers and stakeholders about variations in the ocean and atmosphere, to aid understanding, simulations, predictions, and projections of future climate -- thereby helping society become more resilient to climate variability and change.

CDRs pose special challenges for observing systems like TPOS, due to their stringent requirements for accuracy, duration, and continuity. To guide the development of observing networks for CDRs, the international community proposed a set of Global Climate Observing System (GCOS) Climate Monitoring Principles (GCMPs, see Appendix 1). These GCMPs provide a framework for TPOS 2020 in the preservation, improvement and extension of the climate record.

3.3.1 What future climate signals do we need to observe?

To understand and monitor the trends, variability and feedbacks in a changing world, we first need to identify the key features that must be observed over long time periods to help detect and attribute change. Section 3.1 discussed the individual broadscale observations, both satellite and in situ, that are required as part of TPOS 2020 to track the state of the climate system. These observations include temperature and salinity (both surface and subsurface); sea level and ocean mass; and air-sea exchange parameters including surface wind stress, rainfall, ocean color and CO_2. Here we provide the scientific rationale related to the continuity of these observations as part of the TPOS key function to maintain and extend the tropical Pacific climate record.

Changes in both the equatorial zonal gradient and the cross-equatorial meridional gradient of SST will be strongly related to the future location of atmospheric convection and convective variability. This, in turn, will affect tropical Pacific rainfall, winds, and ENSO development. Coupled GCM projections of the tropical Pacific suggest enhanced warming on the equator relative to off the equator, and of the north relative to the south. Although these changes are small – the cross-equatorial SST change is O(0.3K) – they occur over a wide area and in regions of convective sensitivity such as near the warm pool. The strong sensitivity of the tropical Pacific convective zones to subtle changes in SST gradients places important constraints on the accuracy of CDRs. Near the equator, anthropogenic changes in SST may be most easily detectable in the western Pacific, where ENSO and decadal variations are much weaker than in the eastern equatorial Pacific.

SSS is turning out to be a very good indicator of long-term changes in the water cycle. Although the past SSS record is relatively spotty and sparse, a direct link is found between water cycle intensification, SSS and climate change. Model simulations and observed global changes of SSS support the “wet get wetter, dry get drier” pattern. However future model projections suggest that in the tropical Pacific, SST changes will move this more toward a “warmer get wetter, colder get drier” pattern, with areas of greater warming (such as the equator) tending to see increases in rainfall, and areas of lesser warming seeing decreases in rainfall. Increasing the spatial distribution and accuracy of in situ SSS measurements will be useful for understanding these long-term changes in the water cycle as well as providing the necessary information to ground-truth satellite missions.

One of the aims of TPOS 2020 is to better resolve the vertical structure and heat budget of the tropical Pacific surface layer that sets the oceanic feedback to the atmosphere. In the future the equatorial thermocline is expected to intensify and shoal and possibly flatten due to a gradual weakening of the trade winds. The isotherm near the center of the thermocline (presently 20°C) is also expected to warm. These changes are expected to play a critical role in changing the seasonal cycle and ENSO, although the direction of changes remains highly uncertain largely because of the climate biases still present in GCMs. Changes in the structure of the trade winds -- e.g. the trend toward meridional symmetry of the off-equatorial trade wind cores – will also alter the poleward Sverdrup transports, affecting the structure of the equatorial thermocline and the SST sensitivity to changes in thermocline depth. Relationships among thermocline depth, warm water volume, and sea level may also change in the future due to surface freshening from more intense rainfall in convective regions like the Pacific warm pool. This will also influence the presence and distribution of barrier layers. CDRs of subsurface temperature and salinity in the near surface and in the thermocline are thus essential to constrain the patterns and depths of variability and trends in global ocean heat uptake.

Changes in heat and freshwater content will drive regional sea level change in the region, likely highly related to long term wind changes. In addition, an average sea level rise will also come from both net warming and land-ice melt. The potentially valuable role TPOS can make, in tracking the drivers of global and regional sea level rise, besides ensuring that the long running regional sea level network continues and is upgraded with GNSS measurements, is to explore the idea of bottom pressure measurements to help calibrate satellite gravity missions which the increasing track ocean mass.

Tropical Pacific trade winds undergo substantial decadal-scale variability. The magnitude of a recent decadal strengthening of the easterly trade winds from 1998-2014 was about 50% of the long-term mean (0.2dPa) in the central equatorial Pacific. On centennial time scales, historical observations and model projections suggest that the equatorial trade winds will gradually weaken due to anthropogenic forcing, primarily because of the change in the equatorial zonal SST contrast. A more detectable anthropogenic signal, projected by CMIP models, is an enhanced meridional convergence of the trade winds toward the equator -- induced by stronger warming of SSTs at the equator than off-equator. CMIP5 models also project that the easterly component of the trade winds should weaken in the northern central Pacific, and strengthen in the southern central Pacific, a difference of about 1 m/s from spatial trough to spatial peak. Clearly we need to maintain long-term reliable CDRs of surface winds to detect these changes. Because the tropical Pacific surface winds are largely determined by surface pressure gradients, measurements of surface pressure will also provide an additional constraint for long-term changes in the Trades, particularly in combination with model reanalyses.

Because direct long-term measurements of the subsurface currents are presently only available at a few longitudes along the equator, critical parameters like the meridional width of the EUC, the intensity of equatorial upwelling, and the momentum budget of the various currents are not well known. Even ocean GCMs driven by observed winds and assimilating available subsurface temperature measurements have great difficulty reconstructing the structure of the real-world tropical Pacific currents. Future changes in the pattern of the Pacific trade winds, and shoaling of the equatorial thermocline, are likely to affect the structure of the upper-ocean currents and upwelling. The near-equatorial and near-surface currents in the Pacific have a substantial ageostrophic component, which is not well constrained by sea level measurements or estimates based on knowledge of the density structure. Thus the expanded subsurface current measurements as part of TPOS 2020 are much desired to initiate new CDRs of velocity and transport to help improve the models and correct for their biases.

It is uncertain how spatial patterns and intensity distribution of tropical Pacific rainfall may change in the future. Certainly the warmer tropical SST is expected to boost the rain rate for a given convective mass flux and surface wind convergence. This has important implications at scales ranging from tropical cyclones to El Niño. In addition to the projected increase in tropical rain, model projections also suggest that in the zonal mean, rain will increase even more in wet zones like the ITCZ and the SPCZ. But shifts are also expected in the meridional tilt, strength and location of these features. Thus it is important that TPOS 2020 carefully consider the in situ and satellite measurements of the winds and rainfall CDRs that will cover the expected shifts in these convective regimes. In a future warmer world, evaporation is expected to increase over the tropical oceans, and broad-scale measurements of ocean evaporation and near-surface moisture would be very helpful in detecting the impact of climate change on the oceanic and atmospheric energy budgets and tropical rainfall.

A critical question is how ENSO behaviour and teleconnections may change in the future. ENSO’s diversity from event to event still continues to surprise us. Existing CDRs appear to be too short to fully constrain the ENSO dynamics and impacts in models. Appreciation for the inter-event diversity of ENSO and its remote impacts will require better observations of ENSO’s spatiotemporal patterns and mechanisms -- especially for anomalies of SST, rainfall, wind stress, and the mixed layer heat budget – as part of the TPOS CDRs. ENSO predictability and model forecast skill are modulated from decade to decade making it difficult, based on the limited observational record available to date, to assess the fundamental limits of ENSO predictability, and the impacts on forecast skill of model and initialization improvements. Thus the maintenance of key broadscale parameters that capture the ENSO state remain a target.

3.3.2 The value of Redundancy and Resilience to maintaining consistent Climate Data Records

Maintaining a consistent climate record for winds, air-sea fluxes, currents and temperature/salinity is a zero-order function of the observing system. To do this effectively, we must build in redundancy to provide cross-checking and context, but also as insurance against failures of the system components that can irreparably damage the CDRs.

The value of redundancy is illustrated by two cautionary tales. In 1982, one of the strongest El Niños of the 20th century caught the scientific community off guard, because SST measurements from the NOAA-7 satellite were clouded by the April 1982 eruption of the El Chichón volcano. Then, in 2012, budget cuts within NOAA led to retirement of the Research Vessel Ka'imimoana which had been dedicated to maintaining the TAO array; the reduction in servicing was severe enough that by 2014 the array had been reduced to only 40% data return, just as conditions appeared to be ripe for formation of a strong El Niño. These examples demonstrate that unexpected failures can occur at the worst possible time. Other examples include unpredictable drifts of sensors on satellite, moorings and Argo floats, XBT fall rate errors, which are difficult to detect and correct without complementary observations from other platforms. Some redundancy reduces risks around network failure and allows inter-network corroboration. Thus lack of any redundancy at all could result in lasting damage to the climate record or doubts about its accuracy.

The global climate observing system includes both satellite and surface-based observations (GCOS, 2010) that provide a measure of redundancy. However, satellite measurements, while providing high resolution and broad scale coverage, must be carefully calibrated to in situ observations. There is also a need for validation, calibration and cross-referencing among the different satellite missions so that long continuous records can be maintained for climate purposes. The surface-based observations provide the necessary ground truth information.

In the Pacific, "in-situ data, including measurements from the TAO-TRITON array, have historically been an important component for the global calibration and validation of a suite of satellite data (e.g., SST, SSS, wind, precipitation)" (Lindstrom et al., 2014, TPOS WP#9). For climate purposes, the use of SST data from the Global Tropical Moored Buoy Array near-surface thermometers for stability assessment is essential to analyze long-term satellite derived SST records (Lindstrom et al., 2014, TPOS WP#9). This is particularly important given the concern that the continuity of microwave SST measurements, which have low spatial resolution but are much less affected by clouds than infrared, is at risk.

TPOS 2020 is also expected to play an important role in inter-calibrating measurements of the same parameter (e.g., ocean surface wind) from different satellite missions that form an important global CDR (see section 5). Examples include the inter-calibrations for satellite missions with different sensor characteristics (e.g., Ku-, C-, and L-band scatterometers), with different equatorial crossing times that sample different phases of the diurnal cycle, and over different periods. Consistency of the satellite measurements is critical to producing longer-term CDRs.

Inter-calibration can also be achieved through comparison of sensor measurements from the various observational components of the in situ network. The full-depth property profiles collected through the GO-SHIP program are used to calibrate temperature, salinity and dissolved oxygen measurements collected as part of Argo. Bio-Argo deployments, that at present can include additional measurements of chlorophyll fluorescence, optical scattering, pH, nutrients and light, will also increasingly rely on GO-SHIP measurements of these parameters for validation. Argo and the near-surface sensors of the TMA are used to calibrate SST and SSS from Volunteer Observing Ships (VOS) and surface drifters. Underway SSS collected from the VOS are amongst the longest time series of SSS to date, and so preserving this CDR is crucial for its unique ability to infer changes in the water cycle.

One way to improve redundancy is to measure multiple diverse variables and test them for dynamical consistency. For example, measuring trends in the equatorial zonal gradients of both sea level pressure and thermocline slope provide valuable checks against trends in the zonal-mean equatorial zonal wind stress. Similarly, measuring global precipitation provides a check against global evaporation. When all instruments are working as intended, this diversity enables researchers to test theories and models of the interrelationships among variables. Then if an instrument fails, the independent diverse observations help to shore up the resilience of the observing system until the failed component can be replaced.

3.3.3 Assessing Contributions to the tropical Pacific Climate Record

Climate features in the future may undergo subtle spatial shifts that have large impacts on variability. Experience shows that such shifts are easiest to detect and attribute using broad-scale observations (e.g. from satellites) that provide a spatial mapping capability. However, observations must be broad-scale in time as well -- since some climate shifts may come suddenly, or may only be recognized after-the-fact by averaging over long segments of time series with strong fluctuations (say, due to ENSO). A subset of the TMA, both the existing array and the new design implemented as part of TPOS 2020, is expected to play a major role in forming the tropical Pacific CDR. Key aspects to consider for a CDR include:

- Representativeness: extent to which features of different modes of spatial-temporal variability were and/or will be captured;
- Continuity, homogeneity and length of the existing record;
- Surface and depth coverage and quality and accuracy;
- The suite of measurements that have been maintained, and their complementarity

According to the GCMPs (Appendix 1), the operation of historically uninterrupted stations and observing systems should be maintained. Although every mooring in the TMA has had an interruption at some point of their history, the equatorial moorings at 165°E, 140°W, and 110°W began their records substantially before the rest of the array was completed in 1994 and are therefore important to maintain. These equatorial mooring locations, as well as 170°W, have the most complete suite of surface ocean/atmosphere ECV measurements for estimating surface energy and water fluxes. Nonetheless longwave radiation measurements at these sites began only in 2006, and most moorings still do not measure precipitation.

From a CDR perspective, we recommend maintaining and completing the suite of surface ocean/atmosphere ECVs measurements (including carbon), as well as the subsurface temperature measurements, on the equatorial moorings at 165°E, 170°W, 155°W, 140°W, 125°W, 110°W; to maintain the ADCP measurements on the equatorial moorings at 165°E, 170°W, 140°W, 110°W; to maintain the turbulence/mixing measurements at 140°W, 0°N; and to reestablish and maintain surface ocean/atmosphere ECVs measurements in the ITCZ along 95°W and the SPCZ and warm pool along 165°E. The "Stratus" mooring at 20°S, 85°W is the only continuous record of ocean-atmosphere interaction in the stratus region in the southeast Pacific and should be maintained. All these existing CDRs are extremely valuable, and are of the utmost priority to retain going forward.

TPOS 2020 also presents a unique opportunity to enhance or initiate new tropical Pacific CDRs. The GCMPs suggest that sampling should target data voids in spatio-temporal sampling, and illuminate poorly-observed parameters, regions sensitive to change (e.g. mixed layer depth, circulation), or regions central to model biases and gaps in understanding.

The convergence zones (where scatterometer winds suffer from systematic problems under heavy rain) and boundary regimes are not well sampled by the present observing system. These major climatological features of the tropical Pacific -- the cold tongue, warm pool, ITCZ, SPCZ, trade winds, and thermocline -- shift positions from month to month and year to year. Observations based on present-day climate and variability may not suit a future climate altered by anthropogenic forcings. The design of TPOS 2020, especially the addition of surface fluxes and meridional extension of mooring lines needed to resolve these features, should be carefully considered and in several cases, new records will have to be initiated. Each of these moorings should be fully instrumented with rainfall, net surface shortwave and longwave radiation so that the net surface heat flux can be determined within these diverse regimes. Additional measurements of surface meteorology and turbulent fluxes at off-equatorial moorings would help to further constrain broad-scale estimates from satellites and reanalyses.

Broad-scale mapping of wind stress via satellite scatterometers, especially using multiple bands and multiple equatorial crossing times is the most direct way to capture the wind stress and its spatial derivatives and integrals. These wind stress observations are sufficiently critical, that additional redundancy is needed in case of instrument failure. This could be achieved by retaining several more of the existing mooring ribs in the western and central Pacific, in addition to those at 165°E and 170°W.

We recommend that the enhanced CDRs implemented as part of TPOS 2020 would thus emphasize (1) broad-scale satellite measurements of SST, surface wind stress and wind speed, rainfall, sea surface height, and possibly salinity; (2) Argo measurements of subsurface temperature, salinity, and density; (3) detailed moored measurements of surface fluxes of heat, momentum, and water along the equator, in the western Pacific off-equator, and along meridional “ribs” along 165°E, 170°W, 140°W, 110°W, 95°W; and (4) new sampling of the oceanic mixed layer heat budget between 5°S and

5°N, via detailed observations of currents and temperature within the upper ocean, with increased density in the meridional and vertical direction.

3.4 Summary of opportunities and needs

As outlined above, we have identified many opportunities to improve the TPOS to better track the state of the system, address new research needs targeting poorly understood phenomena and at the same time improve the climate record of this region. Below we address more specifically how we will exploit these opportunities in a newly reconfigured TPOS under 3 resourcing levels.

4 Towards a new design

We have endeavored to generate a design where elements have multiple purposes and multiple uses, and one that is integrated in the sense that the satellite and in situ parts of the observing system are interdependent and comprise essential elements of the whole. This embraces a fundamental reality of modern day Earth observing, analysis and prediction activities. Satellite systems provide a spatial and temporal observational coverage of the surface that is unachievable by in situ networks, but are only reliable when the latter deliver very high quality and fit-for-purpose calibration (for tuning retrievals and tracking drift) and validation (for quantifying errors and bias) observations in key regimes. A major proposed change is a new balance in the configuration of the TMA between a grid sampling strategy using many simple moored systems (as implemented currently) and a regime sampling one employing fewer but more capable moored systems. This is trade-off is discussed below.

The question of how to make the best use of the unique capabilities of moored sampling is a central issue in considering how the future TMA is configured. Moored systems provide temporal sampling that is superior to that from almost all other measurement platforms (e.g., satellites, floats, drifters, ships, gliders). This enables comprehensive spectral diagnoses that illuminate the aliasing errors of sparser sampling characteristics of other platforms, particularly for short spatial scale phenomena. Surface moorings also provide a unique capability for collection of co-located atmospheric boundary layer and upper-ocean measurements, and allow measurement of some quantities that are difficult or impossible to measure from other platforms—for example- surface humidity, air temperature, surface atmospheric pressure, incoming infrared radiation and visible radiation.

One advantage of a grid-like array is that it allows large-scale fields to be mapped or dynamically analyzed from a single, consistently sampled platform, in the same way that it is useful to map temperature and salinity from Argo data alone. This mapping capability provides redundancy in the observing system for the variables that are measured from other platforms (e.g., wind, dynamic height, ocean temperature) – which helps mitigate impacts of a network outage on the TPOS CDRs as discussed above. Perhaps more importantly, the grid-like array provides the only means of mapping the variables that are not directly measured from other platforms (specifically, surface humidity, surface air temperature, surface air pressure).

The current TMA grid has limitations, being spatially coarse and constrained to 8°S-8°N. However, it does uniquely track large-scale, high-frequency (< 3 days) phenomena that may not be well sampled by satellites or the Argo array; examples include Deser and Smith (1998), which examined diurnal and semidiurnal wind signals, and Farrar and Durland (2012), which examined oceanic equatorial inertia-gravity waves and mixed Rossby-gravity waves having periods of days. However, many other important modes of tropical Pacific variability are not well resolved. The typical oceanic first-vertical-mode radius of deformation is 2.2° (Gill, 1982, p. 437), the meridional structures of almost all oceanic equatorial wave modes are poorly resolved by the array (e.g., Farrar and Durland, 2012; Farrar, 2008), and tropical instability waves, with zonal wavelengths comparable to the nominal 15° spacing of the moorings (e.g., Qiao and Weisberg, 1995), are severely aliased in longitude. As already discussed, some other components of the observing system now resolve the basin-scale (and smaller-scale) variability of upper-ocean temperature, salinity, winds, dynamic height, and other quantities. Thus a multi-platform approach will always be needed.

A regime-based, and more complete parameter sampling configuration, will make the surface moorings even more useful for calibration and validation of satellite instruments, particularly in rainy and convective regions, as discussed at length above. Surface moorings provide a unique capability for collection of co-located atmospheric boundary layer and upper-ocean measurements. A regime-based configuration would facilitate collection of these unique co-located measurements in dynamically interesting regions. It is not obvious that co-location of the measurements is essential on the large spatial scales resolved by the current grid-based configuration (for the very reason that these processes have large horizontal scales). Gridded fields, produced solely from moorings in a gridded configuration, will by necessity have limited spatial resolution.

Each of the 5 key functions of the Backbone (Section 1.3) were used to guide the configuration of observing system elements independently, which were then brought together into 3 levels of priority, which reflect assessments of their ability to deliver to these goals. Thus elements that deliver to nearly all the functions are priority 1, those that deliver to only a few are priority 2, and those that deliver to only 1 or 2 key functions are priority 3. Note that these ratings will always be qualitative and depend somewhat on an equal weighting of the 5 functions outlined above for the Backbone.

The options presented will represent different levels of resourcing, change, risk and benefit in meeting new requirements. It is thus important to articulate what major past gaps will be addressed and where opportunities for improvements are being proposed.

5 Backbone satellite observing system

High-level recommendations for TPOS 2020 satellite systems are provided here based on the synthesis of the requirements discussed in Section 3. The most important recommendation that applies to all satellite-measured parameters is continuity and overlap of the essential variables: ocean surface vector winds, SSH, SST, SSS, precipitation, ocean mass, and ocean color. The following discussion describes the specific issues related to sustained and enhancing satellite measurements of various oceanic parameters as part of the TPOS 2020.

While the continuity of infrared SST and altimetric SSH is reasonably assured (at least through 2030 for the latter), the continuity of other parameters is still uncertain. Of particular importance to TPOS 2020 is the continuity of scatterometer wind missions. Past and current satellite scatterometers are mostly Ku-band (e.g., NSCAT and QuickScat) or C-band (e.g., ERS and ASCAT). Ku-band sensors are more susceptible to rain contamination due to their higher frequency and shorter wavelength comparing to C-band sensors. Rain contamination is also an issue for C-band scatterometers even though it is less influenced by rain than Ku-band. Moreover, neither Ku- or C-band scatterometers can retrieve high winds because their backscatter signal saturate under high-wind conditions. The lower frequency, longer wavelength L-band scatterometers such as those on Aquarius and Soil Moisture Active-Passive (SMAP) have shown to have much less rain contamination and retrieve much higher winds. However, L-band scatterometers have poor sensitivity at low winds. Therefore, none of these scatterometers can provide all-weather wind measurements. Multi-band scatterometers or scatterometers with different frequencies flying in tandem in the future would significantly alleviate the limitations of wind measurements under rainy conditions (e.g., in convective regions) as well as at low- and high-wind conditions.

The only satellite scatterometer mission in the US operating currently is the Ku-band RapidScat sensor on the International Space Station (ISS). It does not provide a fixed equatorial crossing time (non-sun-synchronous), thus allows capturing the diurnal cycle in a two-month period over the entire tropical Pacific with 10 realizations of the diurnal cycle at each location. This is important for cross-calibration of polar-orbiting satellites carrying vector wind sensors with different equatorial crossing times to de-alias the partially sampled diurnal wind signals by these polar-orbiting satellites. However, ISS-RapidScat was not planned as a long-term mission. Without it, hourly measurements of buoy winds become more important in de-aliasing diurnal variability in winds captured by polar-orbiters. The European MetOp-B satellite and its potential follow-on is the single string of polar-orbiters with scatterometer on board that have publicly available, climate-quality-vector wind measurements. As the new TPOS design is highly reliant on wind retrievals from space we recommend:

- Ongoing multi-frequency missions to ensure all weather wind retrievals over the oceans and a follow-on mission for the ISS-RapidScat on non-sun-synchronous orbit to continue the capability for intercalibrating the sun-synchronous scatterometer data.

With the loss of NASA's salinity-measuring Aquarius satellite and with ESA’s Soil Moisture and Ocean Salinity mission 5 years into operation, the continuity of SSS measurements is a serious issue. NASA’s Soil Moisture Active-Passive was designed for land applications. Even though SSS is being retrieved from its radiometer, achieving the accuracy of Aquarius SSS is still a great challenge. All the aforementioned salinity-measuring satellites use L-band microwave radiometers, which have poor sensitivity to salinity at high-latitude oceans (giving rise to the much larger uncertainty in these regions as mentioned earlier), although this aspect is not relevant to TPOS 2020. Factors such as sensor configuration, contamination of ocean signals near land due to antenna side-lobe leakage, and radio frequency interference tend to degrade the measurements close to land. Moreover, satellite SSS still has lower resolution than PMW SST. Therefore, ongoing technological innovations are important to improve these aspects for satellite measurements of SSS. There is currently no ocean salinity satellite mission that is being planned for the next decade and beyond.

- As sustaining and enhancing SSS measurement is an important requirement we recommend a new SSS mission be planned.

Both geostationary IR SST sensors and the high-inclination orbit of the Global Precipitation Mission (GPM) Microwave Imager (GMI) are extremely useful for diurnal variability studies. It is likely that by 2020, GMI will be the only operational PMW SST sensor. PMW SST provides essential measurements through clouds and atmospheric aerosols, and allows accurate correction of the high atmospheric water vapor present in the Tropical Pacific.

- We thus recommend a robust program through international coordination to ensure the continuity of PMW SST.

Future continuity of satellite SSH is reasonably ensured at least until 2030 with the recent launch of Jason-3, the planned Jason-CS, and the high-resolution Surface Water Ocean Topography (SWOT) mission (scheduled for launch in 2020). However, the continuing advocacy from the ocean and climate research community, including TPOS 2020 for the continuity is critical maintaining the SSH climate data record. Even though satellites sample SSH in the interior of the tropical Pacific Ocean relatively well, the western boundaries still need better spatio-temporal sampling from satellites to capture the energetic eddy variability associated with low-latitude western boundary currents. SWOT will provide sufficient spatial resolution but insufficient temporal resolution to monitor the eddy variability.

- We recommend continuity of the high precision SSH measurements via the Jason series of sensors, and the continued development of the groundbreaking SWOT mission

Time-varying ocean mass or bottom pressure (OBP) measurements have been provided by the Gravity Recovery and Climate Experiment (GRACE) since 2003. The continuity of ocean OBP measurements is important for understanding the drivers ocean sea level change and extremes, a major impact area for regional nations.   GRACE Follow-On that is scheduled for launch in mid-2017 is expected to continue the global OBP measurements beyond GRACE.

- We recommend the further continuity of ocean mass measurements

Satellite ocean color measurements began in the late 1970s with the Coastal Zone Color Scanner, but as its name suggests, it did not focus on open ocean regions. Continuous ocean color measurements began in August 1997 with the launch of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS). Since then there has been at least one ocean color satellite in operation, providing near-global coverage on a daily basis.

SeaWiFS was essential for quantifying the biological impact of the 1997-98 El Nino event, and the following sequence of strong La Nina events. Over the course of the 97-98 event, chlorophyll concentrations varied approximately 20-fold from some of the lowest to some of the highest ever observed in the tropical Pacific, and were verified by in situ and mooring-based sampling (Chavez et al., 1999).

The requirements for ocean color observations of the tropical Pacific are no different than they are for the rest of the global ocean. Sensors must be rigorously calibrated pre-launch and preferably have an on-board calibration, like the lunar observations of SeaWiFS. A key goal is to obtain a well-calibrated decadal time series of global ocean color that can be used to detect long term change. This goal will be facilitated by the calibration requirements just mentioned, but also requires overlap and redundancy of sensors to ensure intercomparison and high precision and accuracy.

Recent work has emphasized the importance of regional as opposed to global algorithms for satellite ocean color. Continued in situ sampling of the tropical Pacific, in combination with ocean color in situ radiometry, will facilitate high quality algorithms for this moderately productive region. Given the significant decadal variability observed in the physical state of the tropical Pacific Ocean (including decadal variations of ENSO), the potential effects of climate change, and the associated effects on tropical Pacific ecosystem:

- We recommend the continuation of ocean color missions with appropriate to facilitate inter-calibration for measurement consistency, and adequate in-situ measurements for calibration and validation

The GPM core satellite, launched in 2015, is extending the 17-year legacy of TRMM (1998-2014) and expected to provide improved precipitation measurements, including on diurnal and synoptic time scales. International collaboration in the context of GPM is essential to ensure a constellation of precipitation measuring satellites to enhance the spatio-temporal coverage of precipitation measurements, especially in light of transient, patchy nature of precipitation. Continuation of precipitation satellite missions in the coming decades is critical for TPOS2020.

- We recommend the continuation and enhancement of international collaboration for precipitation measuring constellation of satellites to ensure the spatio-temporal sampling of precipitation measurements in the tropics

In addition to the parameters discussed above, there are ongoing mission concept studies to measure additional oceanic variables. For example, ocean surface current estimates from satellites are currently derived by combining the estimates of surface geostrophic currents derived from satellite SSH and Ekman currents derived from scatterometer winds. Technologies to measure surface currents directly (e.g., using satellite Doppler radar) are being developed. Technology is also being developed to measure mixed-layer depth in tropical oceans from space (e.g., using Lidar).

In summary, TPOS 2020 strongly recommends the continuity and enhancement of satellite missions for ocean surface wind, SSS, and microwave SST, SSH, as well as gravity (ocean bottom pressure) and ocean color. In addition to continuity, it is also necessary to ensure overlap of old and new satellite missions to facilitate cross-calibration and measurement consistency. The period should take into account the time needed to develop and test retrieval algorithms for new satellite measurements (typically several months). Compared to SST and SSH, other parameters such as ocean surface winds and SSS are not as well measured (nor as mature). Therefore, it is important to continue and enhance the latter measurements.

These recommendations for satellite systems (continuity, overlap, and focus on poorly-observed parameters, parameters with inadequate temporal resolution) adhere to the GCOS Climate Monitoring Principles (https://www.wmo.int/pages/prog/gcos/documents/GCOS_Climate_Monitoring_Principles.pdf).

6 Backbone in situ observing system

Three options for the in situ backbone TPOS are described below. As noted above, these have been sequentially constructed based on the five key functions of the backbone described in section 1.3, but also aim to deliver to the new needs and exploit the new science/technological opportunities described in section 3. Option 1 contains the minimum elements we believe meet all five key backbone functions, option 2 (the preferred one) meets these but is more robust and entails lower risks and option 3 has all the new functions plus retains all the current elements of the TPOS. Each option has a different risk/reward profile that we attempt to address and we hope can be helpful in assessing resource tradeoffs. Besides the strong and ongoing reliance on satellite observing systems and increased use of robotic systems, the new design employs moored systems in a different role (comprehensive regime/small scale phenomena measurement/satellite calibration/validation) rather than only in broadscale grid-based monitoring mode. The options presented below also rely largely on mature and proven technologies. In section 9 we note opportunities for further testing and development to support the use of newer technologies in the Backbone.

6.1 Option 1 – minimum backbone

The minimum configuration for an integrated observing system to meet the needs of the coming decades is presented in Figure 6.1 and described in detail below. It provides clear advances on present TPOS capabilities but does involve some serious trade-offs (listed in 6.2). As preserving the climate record is an essential goal, an adequate overlap and careful assessment of each aspect of the new design is needed before any permanent change is made (see section 8).

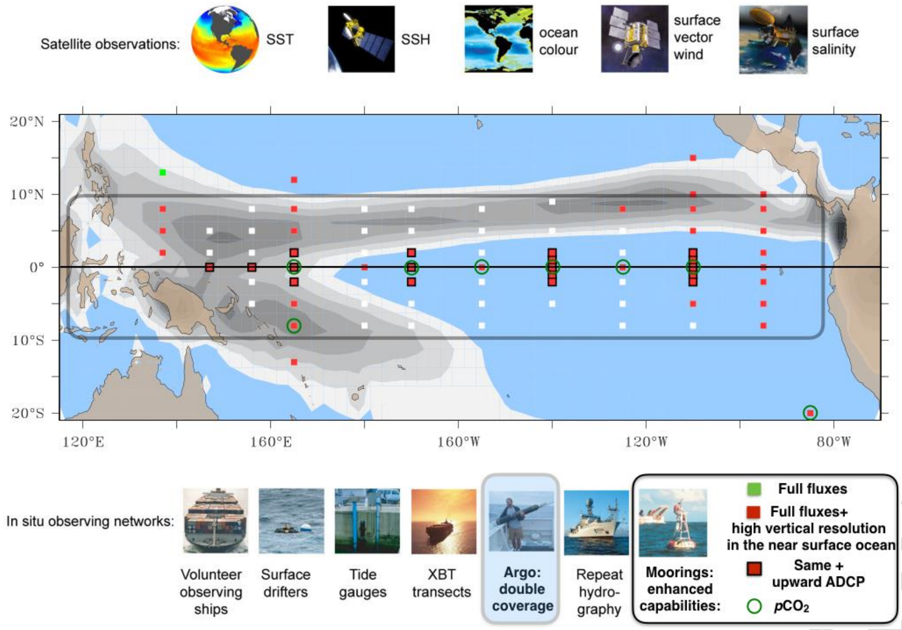

Figure 6.1: Option 1 – minimum recommended design. Key satellites observations must be maintained as recommended in section 5. Most of the present in situ observing networks remain the same, except to double Argo densities between 10°S and 10°N, and modify the configuration of the TMA as shown. The present TMA sites that will not be continued under Option 1 are indicated by white boxes. All moorings have enhanced capabilities described below, with a full suite of fluxes and a better vertical resolution in the oceanic surface layer. Upward ADCPs provide currents from 20 to 300m.

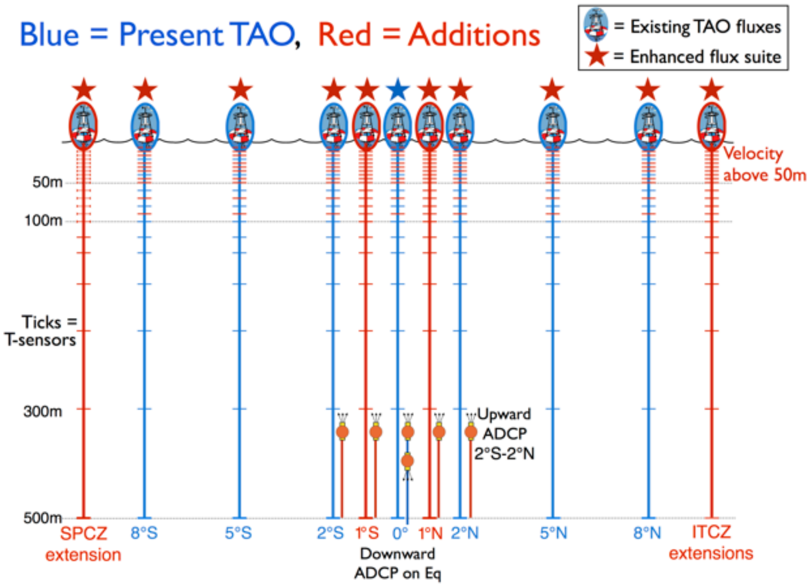

Figure 6.2: Schematic of the recommended meridional moored array featuring enhanced meridional extent, enhanced near equatorial resolution, increased vertical resolution, and enhanced velocity measurements at discrete depths within the 0-50m surface layer. There is no single meridional line corresponding exactly to this schematic; it can be considered as a composite between 165°E and 110°W lines.

6.1.1 Enhanced co-located atmospheric surface and upper-ocean measurements across key climate regimes of the tropical Pacific

As described in Section 3 there are multiple demands to resolve all components of the air/sea fluxes of heat and water, along with collocated measurements of the oceanic mixed layer across the major climate regimes and at high frequency. Thus we propose the widespread use of a more highly instrumented and capable tropical mooring – a mooring with a complete meteorological sensor suite combined with high vertical resolution upper ocean measurement capability – hereafter referred to as a flux mooring. The flux mooring would return a complete suite of atmospheric variables needed to calculate all heat and water fluxes (all radiation terms, air temperature and humidity, wind, SST, SSS, and precipitation). It would also resolve the oceanic mixed layer and near-surface ocean velocity profile at diurnal or faster timescales, by including sensors measuring hourly (or faster) temperature and velocity every 5m to 50m, then every 10m from 50 to 100m. In the western Warm Pool, the sampling should also include salinity. Temporal sampling resolution should be close to minutes to improve utility for satellite matchups and capture diurnal and higher frequency coupled responses.

6.1.2 Comprehensive regime coverage by enhanced flux moorings

Of crucial importance to the climate record, particularly for wind, air-sea flux and ocean velocity estimates are the longest equatorial moored records at the 165°E, 170°W, 140°W, 110°W. Their nearly continuous 20 year or longer wind measurements are vital for the intercalibration of satellite winds from different missions, especially among satellite sensors at different frequencies (e.g., Ku-, C-, and L-band). They are necessary to produce a consistent, continuous satellite-based climate data record of vector winds based on different scatterometer missions and other products. Their long SST records are similarly used in building and validating satellite based SST products. Sustaining and enhancing these sites (already close to the “Flux Moorings”) will ensure that the equatorial regime from the warm pool edge through to the cold tongue regimes undergo improved monitoring.

Due to special nature of the air-sea coupling along the equatorial cold tongue, and in particular the growing recognition of the interactions of diurnal cycling in the mixed layer and the upper ocean, we recommend retaining and upgrading all the equatorial TMA sites to flux mooring sites. This ensures this critically and poorly understood regime, along with its fast wave processes and surface/thermocline coupling, is well monitored with phenomena resolved down to hourly timescales.

The atmospheric tropical convergence zones, sites of deep convection and high rainfall, in both hemispheres are currently poorly sampled but feature persistent biases in models. In addition*,* in situ sampling is also needed to improve and calibrate satellite wind retrievals under heavy rainfall. The existing TMA, limited within 8° of the equator provides only partial coverage of these key climatic regimes. We therefore recommend several meridional lines of flux sites to extend from the equator to intersect both the SPCZ and ITCZ in the west, cross the ITCZ, the cold tongue and the seasonal southern ITCZ in the east, and include sampling of the intermediate regimes in the central Pacific.

In the eastern Pacific, we recommend additional flux mooring sites at the 110°W meridian at - 2°N, 5°N, 8°N, 10°N and 15°N- to sample the ITCZ's seasonal and interannual variability. This extended meridional section at 110°W would sample the cold tongue/stratus deck/ITCZ complex of the eastern Pacific where significant discrepancies between satellite and model estimates of cloudiness as well as rainfall have been reported.

We also recommend an enhanced mooring at 110°W, 5°S, to sample the seasonally present southern ITCZ, noting that the higher rainfall in spring is located between 2°S and 7°S with a maximum around 5°S. On this mooring also, the full suite of fluxes (rainfall, radiation, winds) would be needed to advance our understanding of potential boundary layer processes contributing to the formation of the double ITCZ and provide observations to help resolve the over strong double ITCZ bias often found in coupled models.

We also recommend a meridionally extended series of sites along 95°W. These would provide observations in a region of strong monsoonal wind forcing, sharp meridional contrasts in SST, cloudiness, surface heat fluxes, and rainfall. A pronounced seasonal cycle in this region, attributed to ocean-atmosphere-land interactions, is documented and affects rainfall variability both over the ocean and the adjoining land masses. It is recognized, however that this line is subject to high levels of vandalism, and an enhanced servicing strategy will need to be planned if this line is to instrumented (see section 8 for further discussion).

To extend coverage of the extremely high rainfall and highly convective eastern ITCZ region, we recommend an additional flux mooring at 125°W, 8°N (or possibly 10°N). During the Salinity Processes in the Upper Ocean Regional Study 2 (SPURS2) experiment, new technologies will be tested, and will provide further guidance about which sustained observations would be needed in that area.

As discussed above, the western Warm Pool regime is characterized by large scale convection, high rainfall, salt-stratified barrier layers and strong diurnal cycles, and active westerly wind bursts often associated with developing typhoons or cyclones. The proposed line of flux mooring sites along 165°E is the minimal design that samples this regime. Adding to its value, this meridian was one of the first to be instrumented under TOGA and thus has some of the longest records from the TMA. In addition to the existing TMA locations along 165°E, we recommend additional moorings at 12°N and 13°S to extend sampling the inflows into the atmospheric convergence zones, monitor the SPCZ's interannual and decadal displacements, and monitor the southwest Pacific cyclone genesis region.

The far western Pacific is a different regime, and we recommend equipping the historical TRITON 137°E line with flux moorings. In addition, a mooring with only the full suite of fluxes at 13°N, at the northern edge of the ITCZ/typhoon prone region would help understanding hurricane development and dynamics. At this location, measuring the near surface ocean at high vertical resolution might be less useful due to stronger mean winds and deeper well-mixed layers.

We believe this array of mooring sites is the minimum required to support the monitoring of equatorial westerly wind events that have been shown to be important for El Nino onset.

In the central Pacific, we recommend enhancing the existing 170°W sites at 2°S, 0° and 2°N, and those at 140°W, to sample the drier, calmer, and less cloudy conditions of the tropical Pacific cold tongue, and provide the better resolution for the near-surface ocean observations.

We also recommend maintaining the Stratus mooring at 20°S, 85°W which was implemented for the Eastern Pacific Investigation of Climate Processes (EPIC) project and is the only continuous record of ocean-atmosphere interaction in the stratus region in the southeast Pacific.

This set of complete flux sites, most with paired dense upper ocean sampling, covers a larger and more complete set of climate regimes than the existing TMA, particularly extending across regions of higher rain and wind stress due to the new meridional extensions into the CZs while retaining excellent coverage of the cold tongue regimes along the equator. Also, most regimes with known large diurnal cycles in SST – sunny low wind regions and those along the cold tongue – will be well instrumented.

6.1.3 Enhanced resolution of near equatorial dynamics over multiple ENSO phases

We recommend increasing the meridional density of enhanced fixed-point sampling spanning the equator at several (2-4) longitudes along the cold tongue by adding well instrumented moorings at 140°W and 110°W from 2°S to 2°N at 1-degree intervals (Figure 3). The fundamental rationale is described in section 3.2.2.2. Moorings are the only platform able to sample the short-meridional-scale ocean phenomena near the equator that have profound consequences for air-sea coupling. As written in section 3.2.2, the cold tongue front will pass repeatedly back and forth across the moorings, giving many samples of its vertical structure and its (two-way) interaction with the southeasterly winds. Here, fine temporal sampling by a flux mooring with collocated fine vertical resolution upper ocean sampling would, in effect, substitute for fine spatial sampling across the undulating front, will ensure that the Ekman-diverging layer is measured and resolve diurnal timescales and associated scale interactions.

In addition, we recommend adding nearby subsurface ADCP moorings (as presently done only at the four equatorial sites) to measure velocity above 300m depth at each of the moorings from 2°S to 2°N, at 140°W, 110°W, and 170°W and 165°E. As explained in section 3.2.2.3, these ADCPs, together with collocated near-surface velocity sampling, would allow ongoing monitoring the equatorial undercurrent transport across the basin, a goal not currently achieved by the existing TPOS. Besides the expected insight into the physics at work, the past utility of these velocity and in the future, transport series for the validation and improvement of ocean models raises this enhancement to priority 1 level.

6.1.4 Enhance Argo sampling to better resolve broadscale temperature and salinity to deeper depths

The proposed option 1 TMA will result in the cessations of many off equatorial subsurface temperature records. To both compensate for this loss and to greatly increase broadscale salinity and temperature tracking across the entire TPOS domain, we recommend a doubling of Argo coverage over the full Pacific domain from 10°S to 10°N. This would reduce the nominal float spacing from 3°x3° to about 2.1°x2.1°. Argo profiles are collected at 7–10 day intervals.

Recent improvements in profiling float technology that underpin this recommendation include (i) high vertical resolution (2 db) over the full 2000 m range, (ii) enhanced ocean surface layer (1–10 m) sampling, (iii) ability to change mission parameters when a float surfaces, and (iv) short residence time on the sea surface (15 minutes), which nearly eliminates equatorial divergence due to surface Ekman drift. Some floats also have passive equator-following software, which keeps a float on the sea surface for an additional 1–2 hours if it is drifting equatorward. This reduces mapping errors not only in the equatorial band but also off-equator, where the scales of variability are shorter and where the low mode Rossby waves have maximum amplitudes around 5°N and 5°S. The off-equatorial part of the Argo enhancement also improves the resolution of geostrophic circulation anomalies that are important elements in the assessment of tropical Pacific variability.

In addition to increasing the number of floats in the TPOS domain, attention should be directed toward the evenness of Argo coverage. Dedicated deployment opportunities should be utilized for systematic gap-filling, to limit spaces that open up through random drift. Argo floats in the tropical Pacific should sample as close to the sea surface as feasible (about 1 m) without compromising conductivity cells, and with high vertical resolution (1 m) in the upper 10 m. The ability to change mission parameters will be valuable, for example with rapid/shallow profiling along tropical cyclone tracks for estimation of net heat and freshwater storage.

This enhancement would also improve the observational capabilities for the surface and subsurface temperature and salinity fronts, in particular at the eastern edge of the Warm Pool. In the Western Pacific, better near-surface profiling will also help monitoring the barrier layer and mixed layer depth spatial distribution, which are crucial for model initialization and understanding of the coupled ocean-atmosphere interactions (see section 3.1.2).

6.1.5 Maintain and enhance $p\mathrm{CO_2}$ and ocean color measurements

Equatorial moorings are the primary platform for tracking $p\mathrm{CO_2}$ on subseasonal to seasonal time scales. Existing $p\mathrm{CO_2}$ systems on the Equator at 110°W, 125°W, 140°W, 155°W, 170° W, and 165°E and at 8°S, 165°E should be maintained. New flux moorings at 110°W from 2°S to 2°N (6.1.3) should also be enhanced with moored $p\mathrm{CO_2}$ systems in order to better resolve near equatorial $\mathrm{CO_2}$ flux in the strong upwelling zone across ENSO cycles. New moored $p\mathrm{CO_2}$ systems should also be expanded at off-equatorial sites on the 170°W and 110°W lines in order to map the upwelling region and observe variance associated with the migrating edge of the warm pool/cold tongue and the low oxygen zone, respectively. While 95°W is also an area of intense upwelling, the high levels of vandalism on this line suggest a cautionary approach to use of biogeochemical sensors at these sites be taken.

Each of the existing and new $p\mathrm{CO}_2$ moorings should measure the full suite of fluxes measurements needed for calculating CO_2 flux which include SST, SSS, winds and atmospheric pressure. These sites should also be augmented with collocated optical sensors for phytoplankton biomass in the near-surface for mapping primary production and improving algorithms for satellite ocean color.

Maximizing the use of mooring servicing cruises is a critical component for backbone biogeochemical observations. In particular, service ships should be equipped for autonomous measurements to serve as validation for moored measurements and new technologies and to provide context for spatial variability between moored observations. Opportunities should be considered for biogeochemical measurements from the service cruises that cannot be made autonomously, including dissolved organic carbon, total alkalinity, nutrients (silicate, nitrite, and phosphate), DOC, total dissolved nitrogen, $\mathrm{N_2O}$, tracers (e.g. CFCs, oxygen isotopes), and iron throughout the water column.

Particulary vital for carbon fluxes are the underway measuring capabilities for $p\mathrm{CO}_2$. This will ensure continuity in the record of CO_2 flux at broad spatial scales across the tropical Pacific and will serve as validation for moored $p\mathrm{CO}_2$ systems and carbon measurements on new and emerging autonomous platforms

As new sensor and platform technologies such as biogeochemical (BGC)-enhanced floats and gliders are tested and further developed, the proposed BGC backbone design may be modified to make the best use of new technologies (7.4).

6.1.6 Gravity and Sea level

The proposal for a high precision bottom pressure gauge to be installed on the equator at 110°W (cf section 3.1.2) should be further explored. If instruments exist with the required stability and precision, this would be a very valuable record as a calibration site for current and future gravity missions.

The utility and value of the existing sea level network for sea level rise detection and attribution, altimeter calibration/validation and for local applications is already very high. Further value can be gained in upgrading to include GNSS instrumentation to help remove land movements at these sites. TPOS 2020 recommends that this upgrade continue across the network.

6.1.7 Sustain key existing components of the observing system – Surface drifters, Voluntary Observing ships, High Resolution XBT lines.

The existing in situ components of the observing system (see Figure 1 and Roemmich et al. WP10, 2014) remain important components of the TPOS and should be maintained. Of key importance is the surface drifter network for SST calibration/validation. The cost/benefit of upgrading to higher accuracy thermistors in this sensitive domain should be explored. Underway SSS data collected from Voluntary Observing Ships are a critical and quasi-unique source for observing and understanding small scale SSS variability and provide quantitative information to understand the uncertainties in matching in situ observations with satellite data. They should be maintained, and reinforced in regions of high SSS gradients. The Argo Program has replaced the previous broadscale XBT network, allowing XBT sampling to focus on high resolution line-modes. The highest value function of High resolution XBT transects (HRX) is sampling the oceans' boundary currents and the fine-scale features of fronts and eddies in the ocean interior, particularly along transects with existing long time-series.

6.2 Option 1: Risk and Benefits

The above recommended TPOS first priority involves several serious tradeoffs that should be clearly understood and discussed:

1) The proposed new design improves the TMAs detailed regime-based sampling strategy but degrades its grid/mapping component. The many scientific benefits (section 3) are combined with the advantage of reducing the number of moored sites to maintain and ship time required for servicing the TPOS. Though the overall number of full flux sites increases around the equator, this change greatly degrades the standalone gridding capability of the in situ array for some surface atmospheric variables - explored further below. Option 1 thus depends heavily on satellite data streams for mapping the surface meteorological variables. This trade-off requires a careful and close review by the PBL Task Team, and assurance from Earth Observing community that the satellite data streams needs of TPOS will be met (section 5).

   Not well measured by satellite, and thus featuring high uncertainties and biases that make use of these gridded satellite fields suspect are remotely sensed air temperature and humidity. Buoy measurements of these variables are currently superior to those from satellite. Even wind, probably the most important meteorological measurement in the tropics, can have significant biases due to rain contamination when measured from satellites. In convective regions, the large-scale mapping of winds by the moored array may have advantages over those provided by satellite, even though its spatial sampling is much sparser. The view taken in the construction of option 1 design is that the gridded products are the major pathway to impact and are more likely to be improved via detailed regime and parameterization measurements than ongoing but sparse surface atmospheric measurements.

The degradation of the gridding capability of the TMA also makes the TPOS and its associated services dependent on seamless access to satellite data. In the advent of a satellite failure, or a cut to realtime access, the function of the TPOS will be badly impacted. Option 1 relies on multiple missions (with redundancy) in particular for vector wind scatterometers, sea level and SST. It also means that models must rely upon their internal dynamics rather than data assimilation for estimating humidity, a required state variable for turbulent air-sea heat fluxes, and will certainly degrade the gridded flux fields used to force ocean models.

2) The implied decommissioning of many off-equatorial moored sites will also imply a loss of high frequency measurements of subsurface ocean temperature at fixed but sparse depths. The current Argo array is able to reproduce subsurface temperature for timescales longer than 30 days (Gasparin et al., 2015; see also Figure 6.3). The proposed doubling of Argo will resolve large-scale variability down to 10 days. According to the GCMPs, some overlap and assessment between the two sampling regimes is ideal to quantify the consequences of this loss, in particular tracking of low meridional mode weekly or higher frequency off equatorial waves. However away from the existing TMA sites and across the entire domain, temperature sampling will be greatly improved under option 1 (Figure 6.3). Salinity sampling, a strong new operational and research requirement, will be enhanced everywhere.

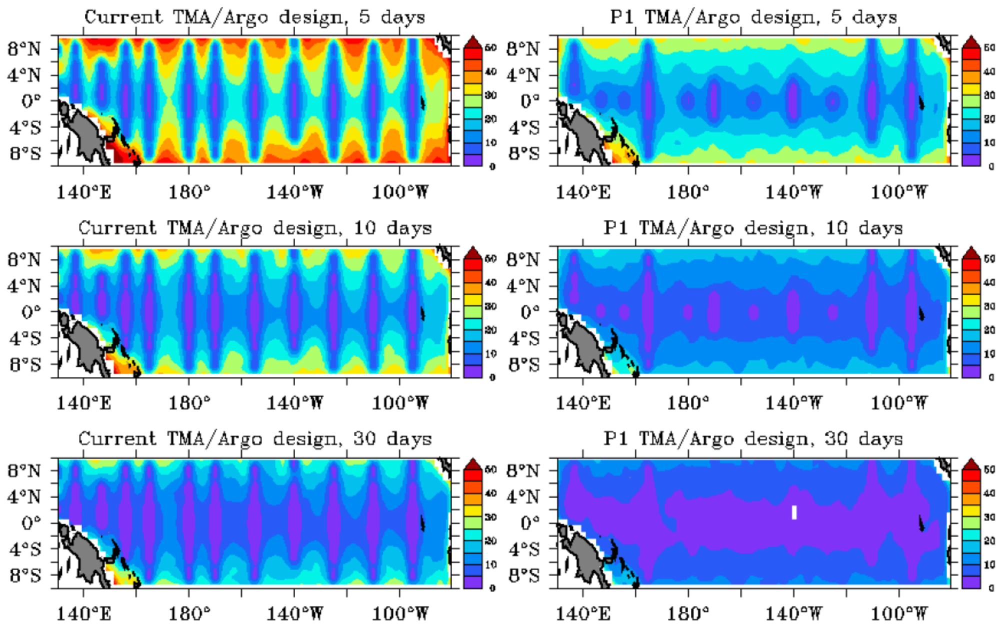

Figure 6. 3 RMS estimated errors as a percentage of temperature variance depending on sampling strategies. (left) Current TMA and Argo design; (right) Option 1 - refocused TMA and double Argo coverage. The covariance function is the one used in Gasparin et al. (2015), with errors estimated at different timescales: 5 days (upper), 10 days (middle) and 30 days (lower). Courtesy from Florent Gasparin.

3) By reducing the meridional extent of some of the moorings lines, associated underway measurements will be lost. This could be a serious problem for the pCO_2 measurements and the shipboard ADCP repeat sections that in the past, have provided valuable and unique diagnoses. Option 1 drives up the urgency to test and develop new and emerging surface $p\mathrm{CO}_2$ platforms that could mitigate this degradation of underway measurements.

6.3 Option 2: Preferred backbone

Option 2 includes all features of Option 1, with additions that improve the functions of several key goals of the backbone (Figure 6.4). This design is considered as the best overall compromise - it provides clear advances in TPOS capabilities, has fewer trade-offs and offers less vulnerability than option 1, but it is less cost-effective.

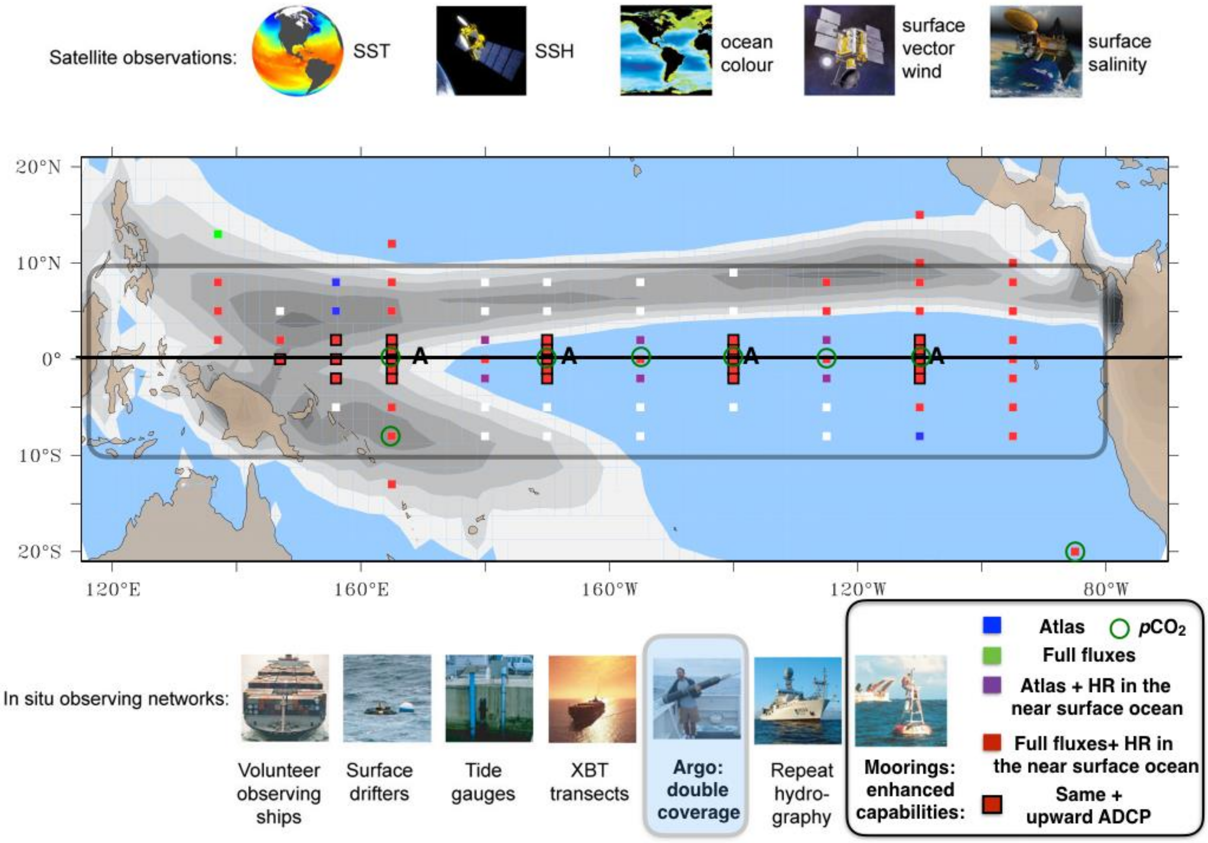

Figure 6.4: Option 2 recommended design. The mooring configuration includes all elements of Option 1 and is further augmented with moored sites. Flux moorings, with the full suite of fluxes and a high vertical resolution in the near-surface layer, are indicated in red. Standard Atlas moorings (but with precipitation) are in blue, and two other types of moorings, either with a full suite of fluxes without the high vertical resolution in the near-surface ocean (green), or with the high vertical resolution but standard fluxes measurements (purple). (A) indicates downward looking ADCP, sampling to 1000m depth. Key satellites observations must be maintained as recommended in Section 5. Most of the present in situ observing networks remain the same, except to double coverage of Argo in the 10°S-10°N box indicated, and modify the configuration of the tropical moored array (see Figure 6.2). Present TMA sites to be decommissioned in Option 2 are indicated by white boxes.

In our preferred configuration, we recommend, the following additional elements be added to the option 1 design.

6.3.1 Additional mapping capability for the TMA in critical regions

By retaining a larger number of existing TMA sites, the surface mapping capability of the in situ network for surface atmospheric variables is increased, in particular in regions where the satellites have deficiencies (as discussed above). We thus recommend maintaining moorings along 156°E from 2°S to 8°N, and along 147°E at 2°N, to increase the ability to track large-scale winds in the central Warm Pool convective area. This would in particular allow a better capture of the shape of the westerly wind events in case of scatterometer failure and when rainfall is very high. We also recommend to retaining all the moorings along the 125°W line from 2°S to 8°N, to add redundancy over the eastern cold tongue/ITCZ region, in particular in case of an interruption in the 110°W moorings line.

We also recommend retaining the existing 2°S and 2°N sites, but with enhanced vertical resolution in the near-surface ocean. This would enable an *in situ* wind mapping capability across the equatorial waveguide, and will resolve the oceanic mixed layer properties all along the equatorial band.

6.3.2 Enhance meridional resolution of the moored sampling

We recommend that across the cold tongue at 140°W and 110°W, but also at 165°E and 170°W moored sites are added at 1°N and 1°S. These will involve the full suite and increased vertical resolution in the near-surface ocean. In addition, they would have nearby subsurface ADCP moorings to measure velocity above 300m depth. This would allow monitoring the full vertical-meridional structure of the near equatorial currents, and to track the evolution of the equatorial undercurrent transport across the whole basin: the EUC evolves from being deeper (less direct effect of wind friction), and wider in the west to shallower and close to the surface in the east. A more complete characterization of this evolution of the EUC and how it changes across ENSO cycles will provide powerful guidance for model development and validation. These moorings in and at the east edge of the warm pool should also include salinity measurements.

6.3.3 Unprecedented monitoring of the near equatorial velocity profile

We recommend, enhanced velocity measurements at key equatorial sites: 110°W, 140°W, 170°W, 165°E to include both an upward looking and downward ADCPS, to enable 0-1000m velocity coverage. As described in section 3.2.2, these additional measurements would be a unique contribution to our knowledge of the intermediate circulation and assist in model validation of the unique dynamics of the near equatorial velocity field.

6.4 Option 2: Risk and Benefits

1) Due to the larger number of moored sites with much more complex sensor suites, this option will be more challenging and expensive to maintain. The challenges include larger amounts of ship time and many more highly complex instrument assemblies to manufacture and service. Piloting these new more highly capable systems is required in order to assess the cost and practicality of their widespread use.
2) The addition of the 125 °W line helps to ensure ongoing regime coverage in the likely face of high rates of vandalism to the 95 °W sites.
3) A major benefit is less reliance on satellite winds for coverage of the crucial equatorial strip and western and eastern convective regions, as well as the major gains in resolution both longitudinally and meridionally of the near equatorial systems.

6.5 Option 3: Enhancements plus existing capabilities

As a third option, the proposal is to implement the enhancements proposed above but to retain all the existing TPOS capabilities.

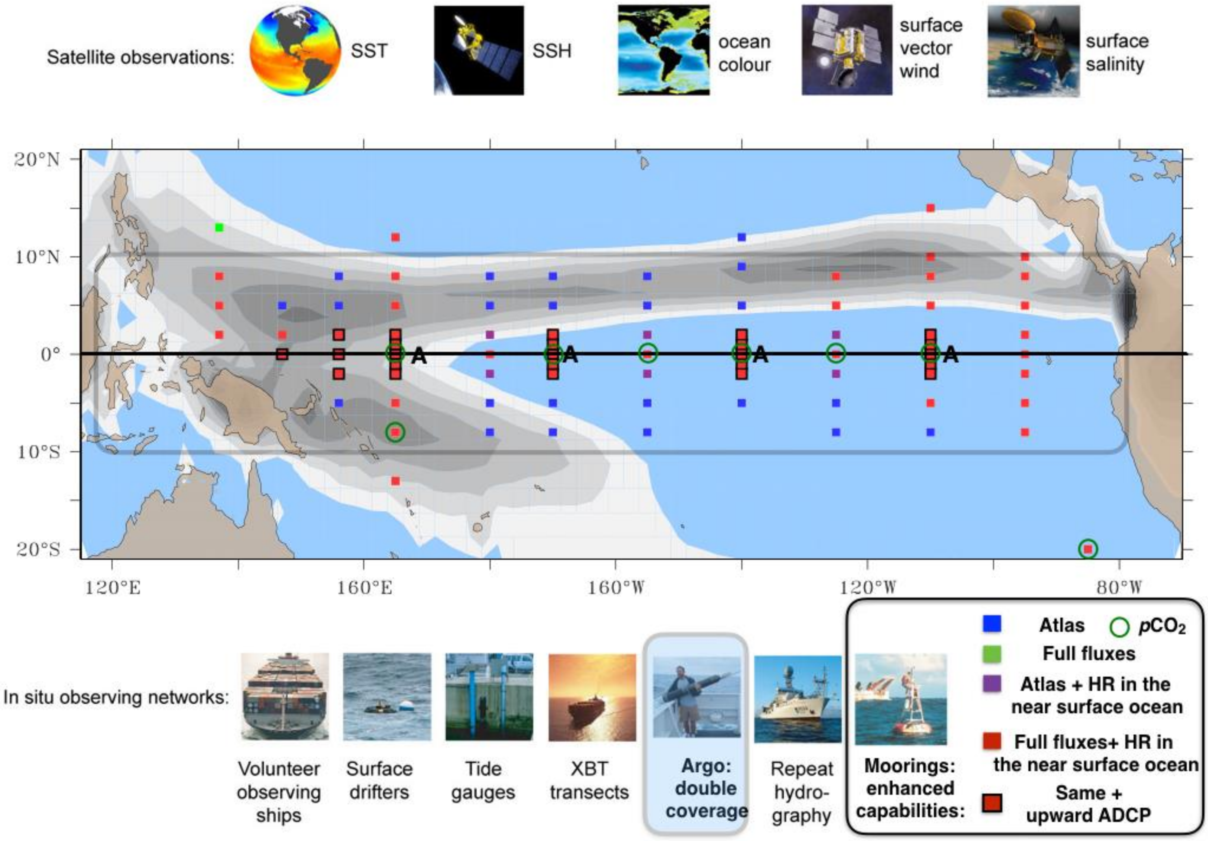

Figure 6.5: Option 3 recommended design. All satellite observations remain the same as in the current TPOS; in situ observing networks remain the same, except a double coverage of Argo in the box indicated, and enhanced capabilities for moorings (see Figure 6.2). The different mooring configurations are described in Figure 6.2.

This design is based on option 2, but in addition, recommends retaining all existing moorings that were not in options 1 or 2. The ultimate purpose of this design is to maintain the tropical climate record with the same temporal resolution, and retain the current gridding capability from original TMA design, while greatly enhancing its regime and phenomena resolving capabilities.

6.6 Option 3: Risk and Tradeoffs

1) While retaining all of the benefits of the options discussed above, this design option is less reliant on satellites for broadscale coverage of winds, relative humidity and air temperature.
2) It has much more redundancy for subsurface temperature coverage and there will be no loss of high frequency temporal information at TMA sites and sampling depths.
3) The major risk is the substantially larger resources required to implement and maintain this option, particularly shiptime.

6.7 Next steps for the design

Some aspects of the TPOS are still under development, and as such we cannot form clear recommendations for the Backbone at this time. One concerns the sustained observations needed in the far eastern Pacific and in the western Pacific regions. Within TPOS 2020, the Eastern Pacific Task team will focus on two major themes: the equatorial/coastal waveguide and upwelling, and the ITCZ/warm pool/cold tongue/stratus system. These themes are further developed in the “Future Directions” section (9.2). Plans for the western Pacific include enhanced observations of air/sea interactions through the *Year of Maritime Continent* campaign. Piloting a microfloat array in the west to better track barrier layer variability will also be considered. The Western Pacific group will also determine the components that might contribute to an LLWBC sustained observational system among the existing ITF/SPICE and NPOCE measurements foreshadowed in section 3.2.3.1.

Other aspects to be considered include observations of surface waves, systematic but possibly moveable atmospheric boundary layer eddy correlation campaigns to refine bulk formula across key regimes. The feasibility of closing the heat and volume budget of the equatorial Pacific Ocean from observations is also explored - so-called “Wyrtki’s Challenge”. More details are given in “Future directions” (Section 9.1). **Models and assimilation tools could also better help to guide the design. The modelling and assimilation task team is currently working on these aspects.**

Strategies, plans and technology for potential biogeochemical elements of the Backbone are also being developed by the Biogeochemistry Task Team. Biogeochemical sampling sufficient to describe carbon, oxygen, nutrients, and primary productivity variability, in the context of drivers and pathways to the tropics are considered. This roadmap for biogeochemical integration into TPOS is also given in “Future Directions” section.

7 Transition Management

PLACEHOLDER

Careful attention will be placed upon transition from the current TPOS to the future TPOS, following the GCOS principles (see Appendix). In particular, the impact of new systems or changes to existing systems should be assessed prior to implementation; before a larger roll out, enhanced capabilities (e.g. flux moorings with PBL measurements) will be tested in a few places to ensure these work well, and that we have a solid understanding of the costs including instrument cycling, data handling and stewardship.

A suitable period of overlap for new and old observing systems is also required: elements won't be decommissioned or thinned until compensating elements are already in place. A minimum overlap of 6 months to 1 year will be needed to avoid degrading the climate record.

It should also be ensured that satellite science and reanalysis teams are prepared and armed to ingest and exploit the new data streams as they come on line to assess learnings and impacts, and to possibly inform the roll out.

8 Summary and Conclusions

We have presented three options of the design of a new TPOS, based on our assessment of the major gaps and opportunities we have identified to drive improvement in how the Backbone delivers to its key functions. All three options represent a major step change in the level of integration between satellite and in situ observing systems, will allow us to track the system state in unprecedented detail, and vastly improve the power of the system to capture the complex and intricate interactions between the upper ocean and atmosphere across the tropical Pacific. If implemented, we believe the new TPOS will severely challenge existing models, underpin the development of their next generation, change our understanding of how key phenomena interact and lay the foundation for improved services and predictions that will save lives, livelihoods and improve the wellbeing of many of the nations impacted by ENSO and its associated climate impacts.

9 Future Directions

This section include all the aspects of the backbone TPOS that are still under development, and not ready to be included in this interim backbone report; that we know are essential, but for which we need additional guidance.

9.1 Wyrtki challenge - Western and eastern boundary current and ITF, monitoring and closing the eq. volume/heat/freshwater budgets.

One of the challenges for TPOS 2020 is to close the heat budget of the equatorial Pacific Ocean. We can draw an analogy of this challenge to the "Wyrtki's challenge" of estimating equatorial upwelling in the Pacific (Wyrtki 1981, JPO), which a challenge for estimating volume budget. The TPOS 2020 challenge is on heat budget, which is a much bigger challenge. TPOS 2020 is interested in working closely with Global Ocean Data Assimilation Experiment (GODAE OceanView) to test the feasibility of following design to address the heat budget.

Consider a region bounded by 5N-5S (or 10N-10S), the western boundaries (e.g., the Maritime continent) and eastern boundary (America), full depth. Estimating the advective heat transport convergence into this region requires the monitoring of the low-latitude western boundary currents (LLWBCs, e.g., Mindanao Current in the north and New Guinea Coastal Undercurrent in the south), the Indonesian throughflow (ITF), and the ocean interior away from the LLWBCs. Heat transport cannot be defined when there is a net volume flux such as the net volume transport into the southern boundary and out of the ITF region. Therefore, we focus the discussion on temperature flux (i.e., the inner product of velocity and temperature, VT).

1. In the ocean interior away from LLWBCs: Argo data provide vertical profiles of meridional geostrophic currents on monthly and longer time scales; satellite scatterometer provide estimates of meridional Ekman currents (on time scales longer than a few days). Together they allow the estimates of meridional advective temperature flux convergence into the interior portion of the region based on MONTHLY inner product of total (geostrophic+Ekman) meridional velocity V and temperature T, i.e. $\mathrm{Vm}(\mathrm{x}, 5\mathrm{N}, \mathrm{z})\mathrm{Tm}(\mathrm{x}, 5\mathrm{N}, \mathrm{z}) - \mathrm{Vm}(\mathrm{x}, 5\mathrm{S}, \mathrm{z})\mathrm{Tm}(\mathrm{x}, 5\mathrm{S}, \mathrm{z})$ integrated over the interior longitudes and depth. The subscript m indicates monthly average.
2. In the LLWBC regions, glider measurements provide MONTHLY estimate of meridional velocity and temperature (vertical profiles) and thus the estimates of meridional temperature flux convergence based on MONTHLY inner products of meridional velocity V and temperature T, i.e., $\mathrm{Vm}(\mathrm{x}, 5\mathrm{N}, \mathrm{z})\mathrm{Tm}(\mathrm{x}, 5\mathrm{N}, \mathrm{z}) - \mathrm{Vm}(\mathrm{x}, 5\mathrm{S}, \mathrm{z})\mathrm{Tm}(\mathrm{x}, 5\mathrm{S}, \mathrm{z})$ integrated over the LLWBC longitudes and depth. For simplicity we assume the glider lines to be zonal.
3. In the ITF region: mooring measurements provide estimates of temperature flux (products of velocity and temperature) that can resolve sub-monthly variations.

The total temperature flux convergence is 1+2+3. The question that needs to be addressed is whether the above design scenario can provide sufficiently accurately estimate of the temperature flux convergence into the region using monthly data to calculate the temperature flux convergence for the interior and LLWBC regions. This is necessary to address because of sub-monthly variability across the 5N-5S (or 10N-10S) latitudes that may contribute significantly to temperature flux through $V'T'$ where V' and T' are sub-monthly variations of velocity and temperature associated with features such as tropical instability waves or vortices in the interior and eddies in the LLWBC regions.

GODAE OceanView's high-resolution systems can provide an assessment of how significant the contribution by $V'T'$ is. This can be done by comparing the temperature flux convergence calculated from (1) high-frequency output of the systems (daily should be sufficient) at eddy-permitting or resolving spatial resolutions and from (2) monthly V and T products. For (2), the interior V and T should be decimated to 5-degree longitude resolution to be more comparable to the spatial scales resolvable by Argo on monthly time scale. The calculation should be performed for the region bounded by 5N-5S as well as 8N-8S because the latter is less susceptible to the influence by tropical instability waves and vortices across the 8N & 8S boundaries.

A more sophisticated assessment using GODAE OceanView systems is to example the interior based on Argo sampling, and the LLWBC regions based on glider sampling. This approach can also help addressed the potential aliasing issue (i.e., the representativeness of monthly averages based on Argo sampling in the interior and glider sampling in the LLWBC regions). This task would require much more work and should be pursued only if the assessment described earlier suggests that V'T' has little contributions. The reason is that the first assessment raises a significant issue, it is a moot point to pursue the second assessment.

9.2 Eastern Pacific enhancements and downscaling toward local impacts.

The far eastern Pacific forms a distinct set of regimes that require tailored sampling to resolve its particular features: the topographic gap winds off Central America, coastal upwelling, a very shallow equatorial thermocline, the double ITCZ in boreal fall, and the stratus clouds in the southeast Pacific. Countries in the region are directly influenced by the associated variability on intraseasonal to multidecadal timescales (Takahashi et al., 2014, TPOS WP#8a). Within TPOS 2020, current efforts focus on two major themes: the equatorial/coastal waveguide and upwelling, and the ITCZ/warm pool/cold tongue/stratus system. Here we briefly outline these themes.

9.2.1 Eastern Pacific equatorial-coastal waveguide and upwelling system

Intraseasonal variability and predictability in the eastern Pacific is dominated by equatorial Kelvin waves, whose structure and propagation are modified by the very shallow thermocline in this region (Giese and Harrison, 1990; Cravatte et al., 2003; Dewitte et al., 2003; Dewitte et al., 1999; Mosquera-Vásquez et al, 2014). The relevant processes are not well documented or sampled, but have importance for coastal impacts and for ENSO diversity (Dewitte et al., 2012; Takahashi and Dewitte, 2015). Effective sampling requires, at least, thermocline and upper layer structure, ideally at densities approaching 1°x1° on sub-weekly timescales; one way to do this would be a regional enhancement of the proposed Argo density increase (section 6.1), with some of the floats on rapid cycles.

Near-coastal measurements (regional cruises, fixed point oceanographic stations, gliders, moorings, tide gauges, etc.) are also critical for assessing the effect of these processes on the wave dynamics and the impacts on the local physical and biogeochemical environment, and to distinguish them from locally wind-forced variability. The real-time surface data could be blended into interpolated satellite products (e.g. Level 4 GHRSST data) to reduce their errors, particularly in cloudy regions such as the coastal upwelling and convective regimes.

On interannual time-scales, the connection between the eastern Pacific thermocline and the atmospheric circulation response is an essential ENSO feedback affecting the entire basin. However, climate model biases are particularly severe in this region (e.g. Takahashi et al., 2014, TPOS WP#8a), necessitating focused attention to mechanisms. Better understanding of the physical processes, particularly ocean upwelling and mixing, will require observations in that resolve the mixed layer and the diurnal cycle, including currents and turbulence measurements. Cruises servicing moorings will be valuable platforms for complementary atmospheric and oceanic measurements. The PBL and EP task teams will propose a design for the necessary oceanic and atmospheric observations.

9.2.2 Eastern Pacific ITCZ/warm pool/cold tongue/stratus system

The double ITCZ bias refers to the persistent overestimation of precipitation in the tropical southeastern Pacific in nearly all climate models (Zhang et al. 2015) with no progress on the issue to date. Relevant model processes include: convective coupling to SST (Bellucci et al. 2013; Oueslati and Bellon 2015), the vertical structure of latent heating and the meridional circulation in the atmosphere (Schumacher et al. 2004; Back and Bretherton 2006, 2009; Huaman and Takahashi 2016), meridional ocean heat transports (Masunaga and L'Ecuyer 2011) and cloud radiative effects (Voigt et al., 2014; Harrop and Hartmann, 2016). The paucity of in situ observations of the double ITCZ system, particularly of the southern branch in the boreal spring (e.g., Huaman and Takahashi 2016, Fig. 9.1), hinders progress on this issue.

In order to address this issue, the TPOS 2020 EP Task Team is designing a process study to observe the atmosphere and ocean in the eastern Pacific, from the stratocumulus region off South America (20°S), northward across the permanent ITCZ (i.e., to 15°N, 110°-85°W) to sample the ocean-atmosphere processes in the ITCZs/warm pool/cold tongue/stratus system during boreal spring, when the double ITCZ is present (Figure 9.1), and in fall when the double ITCZ is not present but remains active in some models. Among the objectives of the experiment are to estimate meridional heat transports in both the atmosphere and upper ocean and characterize clouds, air-sea fluxes, atmospheric deep convection and the basic state of the atmosphere and upper ocean on diurnal to monthly time scales across the region. The intended scientific outcome of this process study is a better understanding of the physical mechanisms controlling the eastern Pacific ITCZs and their seasonal variability. As a TPOS 2020 activity, the process study will identify the key observations in the eastern Pacific required to characterize the ITCZs and their variability, that may be incorporated into the backbone observing system in the future.

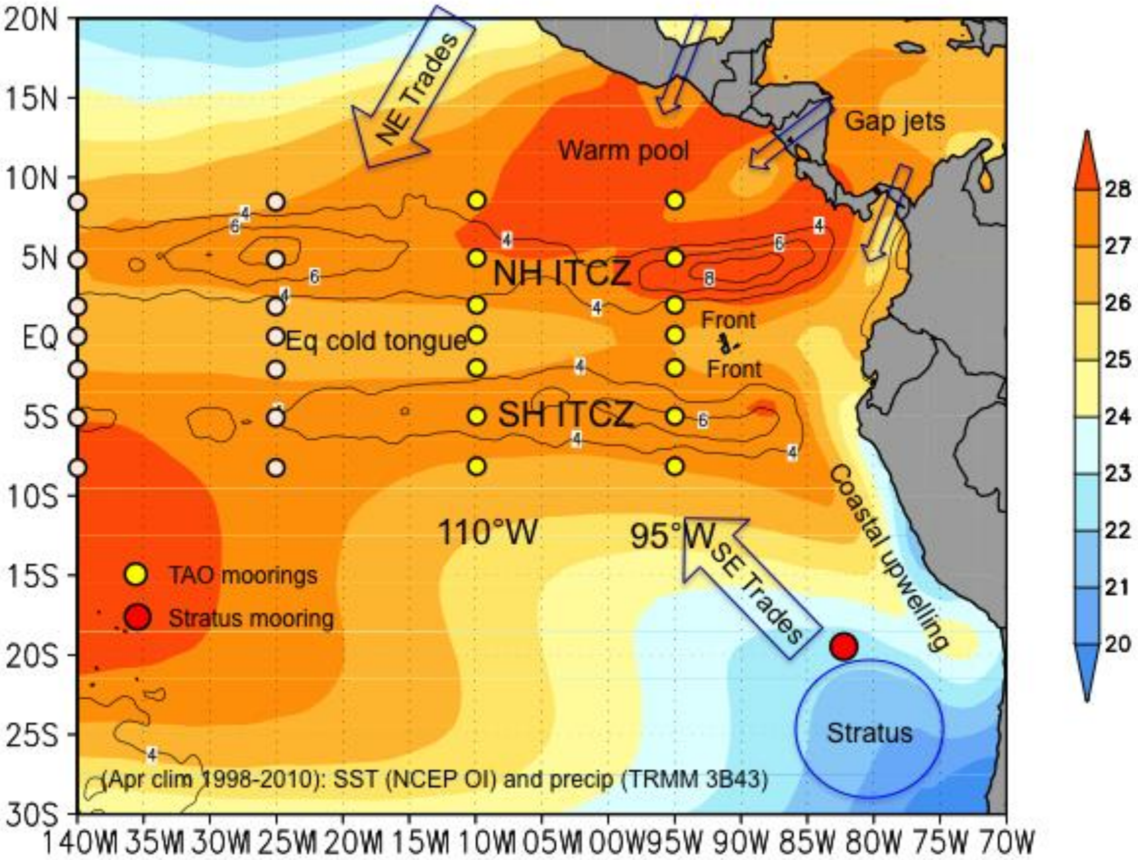

Figure 9.1 – April 1998-2010 climatology of NCEP OI SST (filled contours) and TRMM 3B42 rainfall (contour lines). Existing TAO (yellow circles) and WHOI stratus (red circle) moorings are also shown. Key features of the ITCZ/cold tongue/stratus complex are illustrated for reference.

9.3 Roadmap for biogeochemical integration into TPOS 2020

The TPOS-2020 BGC Task Team will continue to prioritise the variables and time and space scales that should be resolved.   This will happen in the context of uncertainties in the drivers and impacts of natural variability and long-term change on carbon, oxygen, nutrients, and primary productivity in the tropical Pacific.

The following phenomena, which span a broad range of time and space scales will provide physical context for the needed biogeochemical measurements:

(1) Vertical mixing, including entrainment from below and convective overturning. Mixing changes the air-sea gradient of $p\mathrm{CO_2}$, hence impacting the flux, and entrains nutrients from below.

(2) Downwelling Kelvin waves, which depress the thermocline (nutricline) and have been shown to decrease productivity (Chavez et al., 1998). This will likely require high resolution vertical sampling by nutrient and oxygen sensors between about 50 and 300 m on the equator.

(3) Tropical instability waves (TIWs), which propagate at about 50 km day^{-1} perturbing the physics and biogeochemistry on time scales of days to weeks.

(4) El Niño events, which are well known to decrease upwelling, warm SSTs, decrease surface nutrient concentrations and the outgassing of CO_2. Each El Niño event is different, in the rate at which they amplify and decay, and in the spatial and temporal extent of their anomalies (central vs eastern events). These differences will impact CO_2 flux, nutrient cycling, and productivity and will need to be resolved.

(5) Decadal modes such as the Pacific Decadal Oscillation (PDO) and climate change. These are basin scale and require sustained observations of high precision to detect their influence on carbon, oxygen, nutrients, and primary production.

(6) Changes in the spatial extent of oxygen minimum zones and nitrous oxide (N_2O) production – particularly relevant to the eastern tropical Pacific.

Targeted process studies are another critical tool to addressing TPOS science questions. One key issue that inhibits future predictions is our limited understanding of and inability to model the subsurface source pathways to the EUC. The length of time from the source (surface waters of the subtropics) to equatorial upwelling is approximately 10 years. This means that part of the $p\mathrm{CO_2}$ of water upwelled at the equator is a decade-old anthropogenic signature, but the circulation and entrainment pathways are complex. The circulation is also significantly modulated on interannual and decadal time scales by ENSO and the PDO (McPhaden and Zhang 2002, 2004). Addressing this important question will require coordinated process and modeling studies that leverage the new TPOS capabilities.

Other key issues that could be facilitated by the backbone system and targeted process studies include: 1) the role of the EUC is in oxygenating the ecosystem; 2) what the consequences of variability and long-term change in primary productivity are for higher trophic levels, including economically and ecologically significant fisheries; 3) whether tropical Pacific variability and ocean acidification expose Pacific coral ecosystems to corrosive carbonate conditions; 4) how do long-term changes in circulation patterns and ocean acidification affect dissolved organic carbon and nitrogen production, remineralization, and export; and 5) how changes in aeolian dust deposition will impact the productivity of the system, and processes that flow from it. Multi-disciplinary sub-decadal process studies across the tropical Pacific should address these issues about source waters and higher trophic levels that cannot be addressed by autonomous sampling. In turn, these studies would leverage and enhance interpretation of the observational monitoring.

9.3.1 Technological readiness and prospects for development

Existing technologies allow for autonomous measurements of the carbonate system ($p\mathrm{CO}_2$ and pH), dissolved oxygen, nitrate, and optics (phytoplankton, particulate backscatter, and POC) on moorings and VOS (as well as a subset of these measurements on floats and gliders). Feedback received from the BGC community thus far calls for enhanced biogeochemical measurements on the existing TAO $p\mathrm{CO}_2$ moorings on the equator at 110°W, 125°W, 140°W, 155°W, 170°W, 165°E and at 8°S, 165°E. Meridional sections should be highly resolved in space to capture dynamics within the equatorial band (±2°N/S). At 170°W and 110°W, broader meridional sections would observe variance associated with the migrating edge of the warm pool/cold tongue and the low oxygen zone, respectively. These measurements should be distributed vertically to 500 m with high resolution between 50 and 300 m with the temporal resolution needed to describe diurnal cycles.

New and emerging technologies could greatly expand biogeochemical measurements in TPOS and reduce costs associated with mooring and ship-based observations. Profiling moorings could reduce the number of sensors necessary in the upper 300 m. Floats, gliders, drifters, long-range AUVs, and drones enhanced with biogeochemical sensors would enhance spatial coverage. Most of these technologies are sufficiently developed that tropical Pacific pilot projects combining field deployments with ship-board validation would contribute to TPOS-2020 planning. The BGC TT will also explore the use of Observing System Simulation Experiments (OSSEs) to investigate the impact of the prospective TPOS (existing and new technologies) on tracking key biogeochemical processes.

10 References

Atlas, R., and Coauthors. 2001. The effects of marine winds from scatterometer data on weather analysis and forecasting. *Bull. Amer. Meteor. Soc.*, 82, 1965-1990.

Back, L. E., and C. S. Bretherton. 2009. A Simple Model of Climatological Rainfall and Vertical Motion Patterns over the Tropical Oceans. *J. Climate*, **22**, 6477–6497, doi:10.1175/2009JCLI2393.1.

Back, L. E., and C. S. Bretherton. 2006: Geographic variability in the export of moist static energy and vertical motion profiles in the tropical Pacific. *Geophys. Res. Lett*, 33, L17810, doi:10.1029/2006GL026672.

Balmaseda, M.A., A. Kumar, E. Andersson, Y. Takaya, D. Anderson, P. Janssen, M. Martin and Y. Fujii. 2014. Operational forecasting systems, White Paper #4, Report of the Tropical Pacific Observing System 2020 Workshop (TPOS 2020), VOLUME II – White Papers, 27-30th January 2014, Scripps Institution of Oceanography, San Diego, United States, publ. by GCOS – 184/GOOS – 206/WCRP – 6/2014, 64-101.

Bell, M., K. Haines, A. Schiller, N. Smith, and Z. Wills. 2015. Special Issue: GODAE OceanView – Parts 1 and 2, *J. Op. Ocean.*, 8, DOI:10.1080/1755876X.2015.1049875G.

Bellucci, A., and Coauthors. 2013. Decadal climate predictions with a coupled OAGCM initialized with oceanic reanalyses. *Climate Dyn*, **40**, 1483–1497, doi:10.1007/s00382-012-1468-z.

Bonekamp, H., and 10 co-authors. 2010: Transitions Towards Operational Space Based Ocean Observations: From Single Research Missions into Series and Constellations. In Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society (Vol. 1), Venice, Italy, 21-25 September 2009, Hall, J., Harrison, D.E. & Stammer, D., Eds., ESA Publication WPP-306, doi:10.5270/OceanObs09.pp.06

Brassington, B., M.J. Martin, H.L. Tolman, S. Akella, M. Balmeseda, C.R.S. Chambers, E. Chassignet, J.A. Cummings, Y. Drillet, P.A.E.M. Jansen, P. Laloyaux, D. Lea, A. Mehra, I. Mirouze, H. Ritchie, G. Samson, P.A. Sandery, G.C. Smith, M. Suarez & R. Todling. 2015. Progress and challenges in short- to medium-range coupled prediction, *J. Op. Ocean.*, Special Issue: GODAE OceanView Part 2, 8 (Supplement 2), DOI:10.1080/1755876X.2015.1027535, s239.

Brennan, M. J., C. C. Hennon, and R. D. Knabb. 2009. The Operational Use of QuikSCAT Ocean Surface Vector Winds at the National Hurricane Center. *Wea. Forecasting*, 24, 621-645.

Cane, M. A., and S. E. Zebiak. 1985: A theory for El Niño and the Southern Oscillation, *Science*, 228, 1085-1087, 1985.

Centre for International Economics. 2014a: Analysis of the benefits of improved seasonal climate forecasting for agriculture, Prepared for the Managing Climate Variability Program, March 2014, available from http://www.managingclimate.gov.au/publications/benefits-of-improved-forecasts/, 41 pp.

Centre for International Economics. 2014b: Analysis of the benefits of improved seasonal climate forecasting for sectors outside agriculture, Prepared for the Managing Climate Variability Program, March 2014, available from http://www.managingclimate.gov.au/publications/benefits-of-improved-forecasts/, 84 pp.

Chavez, F.P., A.J. Hobday, P. Strutton, M. Gierach, M.H. Radenac, F. Chai, P. Lehodey, K. Evans and R. Guevara. 2014. A Tropical Pacific Observing System in relation to biological productivity and living resources, White Paper #7, Report of the Tropical Pacific Observing System 2020 Workshop (TPOS 2020), VOLUME II – White Papers, 27-30th January 2014, Scripps Institution of Oceanography, San Diego, United States, publ. by GCOS – 184/GOOS – 206/WCRP – 6/2014, 152-170.

Chavez, F.P., P.G. Strutton, G.E. Freiderich, R.A Feely, G.C. Feldman, D.G. Foley, and M.J.McPhaden. 1999. Biological and Chemical Response of the Equatorial Pacific Ocean to the 1997-98 El Nino. *Science, 286*, 5447, 2126-2131.

Chavez, F.P., Strutton, P.G. and M.J. McPhaden. 1998. Biological-physical coupling in the central equatorial Pacific during the onset of the 1997-98 El Niño. *Geoph. Res. Lett*. 25, 3543-3546.

Chelton, D. B., M. H. Freilich, J. M. Sienkiewicz, and J. M. von Ahn. 2006. On the Use of QuikSCAT Scatterometer Measurements of Surface Winds for Marine Weather Prediction. *Mon. Wea. Rev*., 134, 2055-2071.

Cravatte, S., J. Picaut, G. Eldin. 2003. Second and first baroclinic Kelvin modes in the equatorial Pacific at intraseasonal timescales, *J. Geophys. Res.*, doi:10.1029/2002JC001511.

Cronin, M.F., M. Bourassa, C.A. Clayson, J. Edson, C. Fairall, D. Feely, D.E. Harrison, S. Josey, M. Kubota, B.P. Kumar, K. Kutsuwada, B. Large, J. Mathis, M. McPhaden, L. O'Neill, R. Pinker, K. Takahashi, H. Tomita, R.A. Weller, L. Yu and C.S. Zhang. 2014. Wind stress and air sea fluxes observations: status, implementation and gaps, White Paper #11, Report of the Tropical Pacific Observing System 2020 Workshop (TPOS 2020), VOLUME II – White Papers, 27-30th January 2014, Scripps Institution of Oceanography, San Diego, United States, publ. by GCOS – 184/GOOS – 206/WCRP – 6/2014, 272-298.

Deser, C., and C.A. Smith. 1998. Diurnal and semidiurnal variations of the surface wind field over the tropical Pacific Ocean. *J. Clim.*, 11, pp. 1730–1748.

Dewitte B., G. Reverdin and C. Maes. 1999. Vertical structure of an OGCM simulation of the equatorial Pacific Ocean in 1985-1994. *J. Phys. Oceanogr.*, 29, 1542-1570.

Dewitte B., S. Illig, L. Parent, Y. duPenhoat, L. Gourdeau and J. Verron. 2003. Tropical Pacific baroclinic mode contribution and associated long waves for the 1994-1999 period from an assimilation experiment with altimetric data. *J. Geophys. Research*., 108 (C4), 3121-3138.

Drinkwater, M. & Co-Authors. 2010. Status and Outlook for the Space Component of an Integrated Ocean Observing System. In Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society (Vol. 1), Venice, Italy, 21-25 September 2009, Hall, J., Harrison, D.E. & Stammer, D., Eds., ESA Publication WPP-306, doi:10.5270/OceanObs09.pp.17

Farrar, J.T. 2008. Observations of the dispersion characteristics and meridional sea-level structure of equatorial waves in the Pacific Ocean. *J. Phys. Oceanogr.*, 38, 1669-1689.

Farrar, J.T., and T.S. Durland. 2012. Wavenumber-frequency spectra of inertia-gravity waves and Yanai waves in the equatorial Pacific Ocean. *J. Phys. Oceanogr*. 42, 1859-1881.

Flemming, N.C. 2001. Dividends from investing in Ocean Observations: A European Perspective. In: Koblinsky, C.J., and Smith, N.R., 2001, (Eds.), Observing the Oceans in the 21st Century. Bureau of Meteorology, Australia, 66-84.

Fischer, A.S., Hall, J., Harrison, D.E, Stammer, D.and Benveniste, J.(2010). "Conference Summary-Ocean Information for Society: Sustaining the Benefits, Realizing the Potential" in *Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society (Vol. 1),* Venice, Italy, 21-25 September 2009, Hall, J., Harrison, D.E. & Stammer, D., Eds., ESA Publication WPP-306, doi:10.5270/OceanObs09.Summary

Fujii, Y., Cummings, J., Y. Xue, A. Schiller, T. Lee, M.A. Balmaseda, E. Remy, S. Masuda, O. Alves, G. Brassington, B. Cornuelle, M. Martin, P. Oke, G. Smith, and X. Yang. 2014. Evaluation of the Tropical Pacific Observing System from the data assimilation perspective, White Paper #5, Report of the Tropical Pacific Observing System 2020 Workshop (TPOS 2020), VOLUME II – White Papers, 27-30th January 2014, Scripps Institution of Oceanography, San Diego, United States, publ. by GCOS – 184/GOOS – 206/WCRP – 6/2014, 102-129

Gasparin, F., D. Roemmich, J. Gilson, B. Cornuelle. 2015. Assessment of the upper-ocean observing system in the equatorial Pacific: The role of Argo in resolving intraseasonal to interannual variability. *J. Atm. Oceanic Tech.* 32:1668-1688.

GCOS. 2014. Report of the Tropical Pacific Observing System 2020 Workshop (TPOS 2020), La Jolla, United States, 27-30 January 2014, GCOS report 184, vol. 1, 66 pp.

GCOS. 2010. Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC (2010 Update), August 2010, GCOS-138 (GOOS-184, GTOS-76, WMO-TD/No. 1523).

Giese B. S. and D. E. Harrison. 1990: Aspects of the Kelvin wave response to episodic wind forcing. J. *Geophys. Res.*, 95, 7289–7312.

Gill, A. E. 1982: *Atmosphere-ocean dynamics*. Academic Press (London), 1982, 662 pp.

Gill, A. E. and P. P. Niiler. 1973. The theory of the seasonal variability in the ocean. *Deep-Sea Res*., 20, 14-177.

Gunasekera, D. 2004. Economic issues relating to meteorological services provision, BMRC research report no. 102, Bureau of Meteorology, 121 p, 2004.

Harrison, D.E., N. Bond, L. Goddard, R. Martinez., and T. Yamagata. 2014. Some societal impacts of ENSO, White Paper #2, Report of the Tropical Pacific Observing System 2020 Workshop (TPOS 2020), VOLUME II – White Papers, 27-30th January 2014, Scripps Institution of Oceanography, San Diego, United States, publ. by GCOS – 184/GOOS – 206/WCRP – 6/2014, 4-26.

Harrop, B. and D. Hartmann. 2016. The role of cloud radiative heating in determining the location of the ITCZ in aqua planet simulations. *J. Climate.* In press. doi:10.1175/JCLI-D-15-0521.1

Huaman, L., and K. Takahashi. 2016. The vertical structure of the Eastern Pacific ITCZs and associated circulation using the TRMM Precipitation Radar and in situ data. Submitted to *Geophys. Res. Lett.*

Hughes, C.W., M.E. Tamisiea, R.J. Bingham; et al. 2012. Weighing the ocean: Using a single mooring to measure changes in the mass of the ocean. *Geophys. Res. Lett.* 39: L17602

International TOGA Project Office. 1992. Tropical Ocean Global Atmosphere (TOGA) International Implementation Plan, ITPO Rep. 1, World Clim. Res. Programme, World Meteorol. Organ., Geneva.

Isaksen, L., and P. A. E. M. Janssen. 2004. Impact of ERS scatterometer winds in ECMWF's assimilation system. *Quart. J. Roy. Meteor. Soc*., 130, 1793–1814.

Ji, M., A. Kumar, and A. Leetmaa. 1994. An experimental coupled forecast system at the national meteorological center: Some early results, *Tellus. Ser. A*, 46, 398-418.

Johnson, G., J.M. Lyman, and S.G. Pukey. 2015. Informing Deep Argo Array Design Using Argo and Full-Depth Hydrographic Section Data, *J. Atmos. Oceanic Technol*, 32, 2187-2198.

Kotchen, M. 2012. Public good, a draft chapter prepared for Environmental and Natural Resource Economics: An Encyclopedia, J. Whitehead and T. Haab (eds.), Santa Barbara, CA: ABC-CLIO, Inc.

Lazo, J.K., M. Lawson, P.H. Larsen, and D.M. Waldman. 2011. United States economic sensitivity to weather variability. *Bull. Am. Meteor. Soc.*, 35 pp, DOI: 10.1175/2011BAMS2928.1.

Le Traon, P.-Y., and Co-authors. 2015. Use of satellite observations for operational oceanography – recent achievements and future prospects. *J. Op. Ocean.*, Special Issue: GODAE OceanView Part 1, 8 (Supplement 1), 8, DOI:10.1080/1755876X.2015.1049875G , s12.

Lindstrom, E., M. Bourassa, D. Chelton, G. Corlett, T. Durland, T. Farrar, P. Janssen, G. Lagerloef, T. Lee, P. Minnett, L. O'Neill, and J. Willis. 2014. Satellite views of the Tropical Pacific, White Paper #9, Report of the Tropical Pacific Observing System 2020 Workshop (TPOS 2020), VOLUME II – White Papers, 27-30th January 2014, Scripps Institution of Oceanography, San Diego, United States, publ. by GCOS – 184/GOOS – 206/WCRP – 6/2014, 213-242.

Masunaga, H., and T. S. L'Ecuyer. 2011. Equatorial Asymmetry of the East Pacific ITCZ: Observational Constraints on the Underlying Processes. *J. Climate*, **24**, 1784–1800, doi:10.1175/2010JCLI3854.1.

Mathis, J.T., R.A. Feely, A. Sutton, C. Carlson, F. Chai, F. Chavez, M. Church, C. Cosca, M. Ishii, C. Mordy, A. Murata, J. Resing, P. Strutton, T. Takahashi, and R. Wanninkhof. 2014. Tropical Pacific biogeochemistry: status, implementation and gaps, White Paper #6, Report of the Tropical Pacific Observing System 2020 Workshop (TPOS 2020), VOLUME II – White Papers, 27-30th January 2014, Scripps Institution of Oceanography, San Diego, United States, publ. by GCOS – 184/GOOS – 206/WCRP – 6/2014, 130-151.

McPhaden, M. J., and D. Zhang. 2002. Slowdown of the meridional overturning circulation in the upper Pacific Ocean, *Nature*, 415(6872), 603-608.

McPhaden, M. J., and D. Zhang. 2004. Pacific Ocean circulation rebounds, *Geophys. Res. Lett.*, 31(18), L18301.

Mosquera-Vásquez K., B.Dewitte, S. Illig. 2014. The Central Pacific El Niño intraseasonal Kelvin wave. *J. Geophys. Res.*, doi:10.1002/2014JC010044.

National Research Council, 2004: Climate Data Records from Environmental Satellites. National Research Council, The National Academies Press Washington, DC, USA. doi:10.17226/10944.

Ocean Observations Panel for Climate (OOPC). 1998. Report on International Sea Level Workshop, 10-11 June, 1997, Honolulu, Hawaii, USA. GCOS #43/GOOS #55/ICPO #16, 133 pp.

Ocean Observations Panel for Climate (OOPC). 2002. International Workshop for Review of the Global Tropical Moored Buoy Network, 10-12 September, 2001, Seattle, Washington, USA.

OOSDP. 1995. Scientific Design for the Common Module of the Global Ocean Observing System and the Global Climate Observing System: An Ocean Observing System for Climate, Dept. of Oceanography, Texas A&M University, College Station, Texas, 265 pp.

Oueslati, B., and G. Bellon. 2015. The double ITCZ bias in CMIP5 models: interaction between SST, large-scale circulation and precipitation. *Climate Dyn*, **44**, 585–607, doi:10.1007/s00382-015-2468-6.

Piecuch, C. G. 2013. Dynamics of satellite-derived interannual ocean bottom pressure variability in the western tropical North Pacific. *J. Geophys. Res.-Oceans*, 118(10): 5117-5128

Portabella, M., and A. Stoffelen. 2001. Rain detection and quality control of SeaWinds. *J. Atmos. Oceanic Tech.*, 18, 1171-1183.

Qiao, L., R. H. Weisberg. 1995. Tropical instability wave kinematics: Observations from the Tropical Instability Wave Experiment. *J. Geophys. Res.*, 100, 8677–8693

Roemich, D. and S. Cravatte, T. Delcroix, F. Gasparin, D. Hu, C.G. Johnson, W.S. Kessler, R. Lumpkin, G. Reverdin, J. Sprintfall and S. Wijjfels. 2014. In situ temperature, salinity, and velocity observations. , White Paper #10, Report of the Tropical Pacific Observing System 2020 Workshop (TPOS 2020), VOLUME II – White Papers, 27-30th January 2014, Scripps Institution of Oceanography, San Diego, United States, publ. by GCOS – 184/GOOS – 206/WCRP – 6/2014, 243-271.

Ropelewski, C. F. and M.S. Halpert, M. S. 1987. Global and regional scale precipitation patterns associated with the El Niño/Southern Oscillation, *Mon. Weath. Rev.*, 115(8), 1606-1626.

Sassone, P.G., and R.F. Weiher. 1997. Cost benefit analysis of TOGA and the ENSO Observing System, In: *Operational Oceanography: The Challenge for European Co-operation*, JH Stel et al Editors, Elsevier Science B.V., pp 36-50, 1997.

Schumacher, C., R. A. Houze Jr, and I. Kraucunas. 2004. The Tropical Dynamical Response to Latent Heating Estimates Derived from the TRMM Precipitation Radar. *J. Atmo. Sci*, **61**, 1341–1358, doi:10.1175/1520-0469(2004)061<1341:TTDRTL>2.0.CO;2.

Smith, N., R. Bailey , O. Alves, T. Delcroix, K. Hanawa, D.E. Harrison, B. Keeley, G. Meyers, R. Molinari and D. Roemmich. 2001. The upper ocean thermal network. In: Observing the Oceans in the 21st Century, C.J. Koblinsky and N.R. Smith (eds), publ. International GODAE Office and the Bureau of Meteorology, Melbourne, 259-284.

Smith, N., W.S. Kessler, K. Hill and D. Carlson. 2015. Progress in Observing and Predicting ENSO, WMO Bulletin, **64**(1) 'Climate Knowledge for Climate Action', 31-34.

Solow, A.R., R.F. Adams, K.J. Bryant, D.M. Legler, J.J. O'Brien, B.A. McCarl, W. Nayda, W., and R. Weiher. 1998. The value of improved ENSO prediction to U.S. agriculture, *Climatic Change*, 39, 47-60.

Steedman, R. 2006. The Economics of Australia's Sustained Ocean Observation System, Benefits and Rationale for Public Funding, Report for the Australian Academy of Technological Sciences and Engineering and the Western Australian Global Ocean Observing System Inc., August 2006.

Stiles, B. W. and S. H. Yueh. 2002. Impact of rain on spaceborne Ku-band wind scatterometer data. *IEEE Trans. Geosci. Remote Sens.*, 40, 1973-1983.

Takahashi, K. and B. Dewitte. 2015. Strong and moderate nonlinear El Niño regimes. *Clim. Dyn.*, 46 (5), 1627-1645, doi:10.1007/s00382-015-2665-3

Takahashi, K., R. Martinez, A. Montecinos, B. Dewitte, D. Gutiérrez, and E. Rodriguez-Rubio. 2014. Regional applications of observations in the eastern Pacific: Western South America, White Paper #8a, Report of the Tropical Pacific Observing System 2020 Workshop (TPOS 2020), VOLUME II – White Papers, 27-30th January 2014, Scripps Institution of Oceanography, San Diego, United States, publ. by GCOS – 184/GOOS – 206/WCRP – 6/2014, 171-205.

TPOS 2020. 2014. Report of the Tropical Pacific Observation System 2020 (TPOS 2020) Workshop, Vol.1 - Workshop report and recommendations, La Jolla , United States, 27-30 January 2014, 66 pp.

UNESCO. 2012. A Framework for Ocean Observing. By the Task Team for an Integrated Framework for Sustained Ocean Observing, UNESCO 2012, IOC/INF-1284, doi: 10.5270/OceanObs09-FOO.

Vecchi, G. A., B.J. Soden, A.T. Wittenberg, I.M. Held, A. Leetmaa, and M.J. Harrison. 2006. Weakening of tropical Pacific atmospheric circulation due to anthropogenic forcing, *Nature*, 441(7089), pp. 73-76.

Voigt, A., S. Bony, J.L. Dufresne and B. Stevens. 2014. The radiative impact of clouds on the shift of the Intertropical Convergence Zone. *Geophys. Res. Lett.*, 41, 4308–4315,doi:10.1002/2014GL060354.

von Ahn, J. M., J. M. Sienkiewicz, and P. Chang. 2006. Operational Impact of QuikSCAT Winds at the NOAA Ocean Prediction Center. *Wea. Forecasting*, 21, 523-539.

Weissman, D. E., B. W. Stiles, S. M. Hristova-Veleva, D. G. Long, D. K. Smith, K. A. Hilburn, and W. L. Jones. 2012. Challenges to satellite sensors of ocean winds: Addressing precipitation effects. *J. Atmos. Oceanic Tech.*, 29, 356-374.

Weissman, D. E., M. A. Bourassa, and J. Tongue. 2002. Effects of rain rate and wind magnitude on SeaWinds scatterometer wind speed errors. *J. Atmos. Oceanic Tech.*, 19, 738-746.

White, W. B., G. Meyers, J. R. Donguy, and S. E. Pazan. 1985. Short term climate variability in the thermal structure of the Pacific Ocean during 1979-1982. *J. Phys. Oceanogr.*, 15, 917-935.

Wiles, P., B. Murphy, A. Ngari, R. White, J. Berdon, J. Hampton and J. Pahalad. 2014. The Tropical Pacific Observing System and the Pacific Islands, White Paper #8b, Report of the Tropical Pacific Observing System 2020 Workshop (TPOS 2020), VOLUME II – White Papers, 27-30th January 2014, Scripps Institution of Oceanography, San Diego, United States, publ. by GCOS – 184/GOOS – 206/WCRP – 6/2014, 206-212.

WMO. 2012. Proceedings of the WMO Regional Association VI Conference on Social and Economic Benefits of Weather, Climate and Water Services, available online at: http://library.wmo.int/pmb_ged/pws_23.pdf, World Meteorological Organization, PWS-23, 86 pp.

WOCE Scientific Steering Group. 1986. Scientific Plan for the World Ocean Circulation Experiment, WCRP Publications Series No. 6, WMO/TD-No. 122, July.

Wyrtki, K.. 1984. The slope of sea level along the equator during the 1982/1983 El Nino, *J. Geophys. Res.*, 89, 10,419-10,424.

Wyrtki, K. 1981. An estimate of equatorial upwelling in the Pacific. *J. Phys. Oceanogr*. 11, pp. 1205-1214.

Years of the Maritime Continent (July 2017-July 2019). Science Plan. Available online at: http://www.jamstec.go.jp/ymc/docs/YMC_SciencePlan_v2.pdf.

Zhang, X., H. Liu, and M. Zhang. 2015. Double ITCZ in Coupled Ocean-Atmosphere Models: From CMIP3 to CMIP5. *Geophys. Res. Lett*, 42, 8651–8659, doi:10.1002/2015GL065973.

11 List of Acronyms

Acronym	Full Title
ADCP	Acoustic Doppler Current Profiler
BGC	Biogeochemical
CDR	Climate Data Record (CDR)
CFC	Chlorofluorocarbons
chl	Chlorophyll
CLIVAR	Climate and Ocean - Variability, Predictability, and Change
CMIP	Coupled Model Intercomparison Project
CORC	Consortium on the Ocean's Role in Climate
CZ	Convergent zone
DOC	Dissolved Organic Carbon
ECV	Essential Climate Variables
ENSO	El Niño Southern Oscillation
EOS	Earth Observing Satellites
EOV	Essential Ocean Variables
EP	Eastern Pacific
EPIC	Eastern Pacific Investigation of Climate Processes'
EUC	equatorial undercurrent
FOO	Framework for Ocean Observations
GCM	Global Climate Model
GCMPs	GCOS Climate Monitoring Principles (GCMPs
GCOS	Global Climate Observing System
GMI	Global Microwave Imager
GNSS	Global Navigation Satellite System
GODAE	Global Ocean Data Assimilation Experiment
GO-SHIP	Global Ocean Ship-Based Hydrographic Investigations Program
GPM	Global Precipitation Mission
GRACE	Gravity Recovery and Climate Experiment
HRX	High resolution XBT
IMOS	Integrated Marine Observing System
INSTANT	International Nusantara Stratification And Transport
IR	Infrared
ISS	International Space Station
ITCZ	Inter Tropical Convergence Zone
ITF	Indonesian Throughflow
JAMSTEC t	Japan Agency for Marine-Earth Science and Technology
LLWBCs	Low Latitude Western Boundary Currents
MOC	Meridional Overturning Circulation
NOAA	National Oceanic and Atmospheric Administration

NPOCE	Northwest Pacific Ocean Circulation and Climate Experiment
NWP	Numerical Weather Prediction
OBP	ocean mass or bottom pressure
OLR	outgoing longwave radiation
OSSEs	Observing System Simulation Experiments
PBL	Planetary Boundary Layer
PDO	Pacific Decadal Oscillation
PIES	Profiling Inverted Echo Sounder
PMEL	Pacific Marine Environmental Laboratory
PMW	passive microwave
POC	particulate organic carbon
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SEC	South Equatorial Current
S-I	seasonal to interannual
SMAP	Aquarius and Soil Moisture Active-Passive
SMOS	Soil Moisture and Ocean Salinity
SOOP	Ship-of-Opportunity Programme
SPCZ	South Pacific convergence zone
SPICE	Southwest Pacific Ocean Circulation and Climate Experiment
SPURS	Salinity Processes in the Upper Ocean Regional Study
SSH	Sea Surface Height
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
SWOT	Surface Water Ocean Topography (SWOT)
TAO	Tropical Atmosphere Ocean
TIWs	Tropical instability waves
TMA	Tropical Moored Array
TOGA	Tropical Ocean – Global Atmosphere Program
TPOS	Tropical Pacific Observing System
VOS	Volunteer Observing Ships
WBC	Western Boundary Currents
WCRP	World Climate Research Programme
WMO	World Meteorological Organization
WOCE	World Ocean Circulation Experiment
XBT	eXpendable BathyThermograph

12 Appendix 1: GCOS Climate Monitoring Principles (GCMPs)

GCOS (2010b) proposes the following principles for effective climate monitoring systems:

1. The impact of new systems or changes to existing systems should be assessed prior to implementation.
2. A suitable period of overlap for new and old observing systems is required.
3. The details and history of local conditions, instruments, operating procedures, data processing algorithms and other factors pertinent to interpreting data (i.e., metadata) should be documented and treated with the same care as the data themselves.
4. The quality and homogeneity of data should be regularly assessed as a part of routine operations.
5. Consideration of the needs for environmental and climate-monitoring products and assessments, such as IPCC assessments, should be integrated into national, regional and global observing priorities.
6. Operation of historically-uninterrupted stations and observing systems should be maintained.
7. High priority for additional observations should be focused on data-poor regions, poorly-observed parameters, regions sensitive to change, and key measurements with inadequate temporal resolution.
8. Long-term requirements, including appropriate sampling frequencies, should be specified to network designers, operators and instrument engineers at the outset of system design and implementation.
9. The conversion of research observing systems to long-term operations in a carefully-planned manner should be promoted.
10. Data management systems that facilitate access, use and interpretation of data and products should be included as essential elements of climate monitoring systems.

Types of climate observation networks

GCOS (2010a) recognises four types of observation networks specific for climate:

- Global Reference observing networks, which provide highly-detailed and accurate observations at a few locations for the production of stable long time series and for satellite calibration/validation purposes.

- Global Baseline observing networks, which involve a limited number of selected locations that are globally distributed and provide long-term high-quality data records of key global climate variables and enable calibration for the comprehensive and designated networks.

- Comprehensive observing networks which include regional and national networks and, where appropriate/possible, satellite data. The comprehensive networks provide observations at the detailed space and time scales required to fully describe the nature, variability and change of a specific climate variable.

- Ecosystem monitoring sites, where long-term observations of ecosystem properties, including biodiversity and habitat properties, are made in order to study climate impacts.

In situ oceanic climate observing system components

The global observing system for climate is a composite "system of systems" (GCOS, 2015). The in situ components of the oceanic domain surface observing system as identified in GCOS (2010) relevant to the tropical Pacific are:

Table 1

Component Network	ECVs	Coordinating Body	International Data Centres and Archives
Global surface drifting buoy array on 5x5 degree resolution (1250)	SST, SLP, position-change-based Current	JCOMM DBCP	RNODC/DB: ISDM
Global tropical moored buoy network (~120)	Typically SST and Surface vector wind; Can include SLP, Current, Air-sea flux variables	JCOMM Tropical Moored Buoy Implementation Panel (TIP/DBCP)	NOAA/NDBC (all Pacific/Indian/Atlantic) JAMSTEC (Pacific/Indian TRITON subset)
VOSClim and VOS fleet	All feasible surface ECVs plus extensive ship metadata for VOSClim	JCOMM SOT	ICOADS (air/sea interface); WMO Pub. 47 (metadata); GOSUD (salinity)
Global reference mooring network (30-40)	All feasible surface ECVs	OceanSITES (JCOMM)	IFREMER Coriolis NOAA/NDBC
GLOSS Core Sea-level Network, plus regional/national networks	Sea level	JCOMM GLOSS	PSMSL
Carbon VOS	$p\mathrm{CO}_2$, SST, SSS	IOCCP, OOPC pilot activity	Individual project arrangements

Oceanic Essential Climate Variables

Following the GOOS Framework for Ocean Observing (Task Team for an Integrated Framework for Sustained Ocean Observing, 2009, hereafter GFOO09), the design of a baseline climate record (BCR) in the tropical Pacific will be framed in terms of the Essential Ocean Variables (EOVs) that intersect with the Essential Climate Variables (ECVs; GCOS, 2010; Bojinski et al, 2014):

Table 2. Oceanic ECVs

Atmosphere surface	Ocean surface	Ocean subsurface
Air temperature	Sea surface temperature (SST)	Temperature
Precipitation	Sea surface salinity (SSS)	Salinity
Air pressure, sea level pressure (SLP)	Sea level	Current
Surface radiation budget	Sea state	Nutrients
Wind speed and direction	Sea ice	Carbon
Water vapour	Current	Ocean tracers
	Ocean colour (for biological activity)	Phytoplankton
	Carbon dioxide partial pressure (pCO_2)	