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Tropical Pacific Observing System

First Report

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

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

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

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Errata in the First Report of TPOS 2020

Corrected in the electronic versions of the Executive Summary and Full report:

Author Lisan Yu was inadvertently omitted from the original author list.

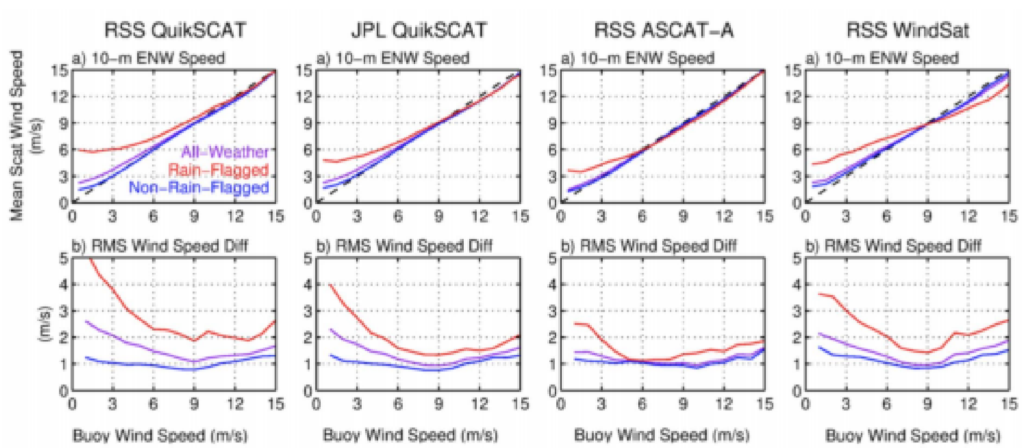
Corrected in the final electronic and printed versions of the Executive Summary:

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

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

Errata in the final version of Chapter 3:

Figure 3.2 should have been:



Contents

Executive Summary

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

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

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

(1) Provide data in support of, and to evaluate, validate and initialize, ENSO prediction and other forecasting systems and to foster their advancement;
(2) Provide observations to quantify the evolving state of the surface and subsurface ocean;
(3) Support integration of satellite and in situ approaches including calibration and validation;
(4) Advance understanding and modeling of the climate system in the tropical Pacific, including through the provision of observing system infrastructure for process studies; and
(5) Maintain and extend the tropical Pacific climate record.

The redesign builds on the foundations of the 1985-1994 Tropical Ocean – Global Atmosphere (TOGA) program and the many innovations and enhancements since that era [2.2, 2.3]. The many public benefits stemming from ENSO monitoring and prediction and its supporting scientific research remain a primary motivation for the TPOS. The network also provides a foundation for improved weather and ocean forecasts, as well as climate and marine environmental monitoring services. Such public good services demand a reliable, effective sustained TPOS [2.1, 2.2, 2.4]. This report outlines both the initial recommendations and actions to meet the demands of 2020 and beyond [5, 7].

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

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

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

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

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

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

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

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

REQUIREMENTS AND RECOMMENDATIONS

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

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

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

Recommendation 2 In situ vector wind measurements, with particular emphasis on extending the in situ-based climate data records, and intercalibrating different satellite wind sensors, especially in the equatorial Pacific and in tropical rainy areas.

❑ Unbiased and accurate high-resolution long-term ***sea surface temperature (SST)*** sampling is required, with particular focus on persistently cloudy and rainy regions and sharp horizontal gradients in the cold tongue region. Ideally, for improved understanding of processes near the surface, sampling should resolve the diurnal cycle and thus be able to characterize near-surface temperature profiles in regions where diurnal variability is large [3.1.1.1, 3.3.1, 3.3.2, 5.2]. TPOS 2020 recommends:

Recommendation 3 Sustaining satellite measurements of SST, using infrared sensors for higher spatiotemporal sampling, passive microwave sensors filling gaps under clouds and the diversity of satellite and in situ platforms contributing to intercalibration.

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

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

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

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

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

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

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

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

❑ Broad-scale ***sea surface salinity (SSS)*** sampling is required, with sufficient resolution to characterize sharp salinity fronts in the equatorial zone [3.1.1.6]. For understanding key processes and phenomena, higher-resolution salinity sampling is particularly important in the west Pacific warm pool and in frontal regions [3.3.1, 3.3.2, 5.5]. In situ and satellite measurements together provide complementary observations of SSS to meet TPOS needs. In situ measurements provide accurate near-surface salinity measurements. Argo provides coverage on larger space scales; tropical moorings provide high-frequency measurements, Voluntary Observing Ships (VOS) provide high spatial resolution measurements along tracks and a long climate data record. Satellites provide SSS with near-uniform sampling that resolves gradients, as well as better coverage in coastal oceans and marginal seas. TPOS 2020 recommends:

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

❑ ***Surface current*** (speed and direction) is required with a high spatial and temporal resolution, especially in the equatorial band, to facilitate the assimilation and synthesis of satellite and in situ wind measurements [3.1.1.2]. Time series of equatorial ***subsurface currents*** are widely used in model validation and development and will continue to be needed for future model data assimilation [3.1.3.2]. For improved understanding of processes and phenomena, TPOS 2020 identifies requirements for enhanced vertical resolution of current measurements to resolve near-surface shear; meridional sampling near the equator to resolve the circulation; and improved monitoring of other key circulation elements such as low-latitude western boundary currents and intermediate depth currents [3.3.1, 3.3.3, 3.3.4.1, 3.3.4.2, 5.6]. TPOS 2020 recommends:

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

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

❑ Air-sea carbon dioxide (CO_2) flux requirements are partially addressed by the existing high-quality sea surface partial pressure of CO_2 (***p*CO₂**) sampling. These observations quantify the seasonal to interannual variability in CO_2 fluxes impacted by ENSO and advance understanding of natural variability in the context of human-induced change [3.1.1.4, 3.3.5]. TPOS 2020 recommends:

Recommendation 12 Continuation of high-frequency, moored time series and broad spatial scale underway surface ocean $p\mathrm{CO}_2$ observations across the Pacific from 10°S to 10°N .

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

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

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

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

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

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

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

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

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

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

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

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

TPOS 2020 recommends [4, 5.9]:

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

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

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

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

❑ Other existing in situ components should continue to be supported. These include the surface drifter network; underway data collected from Voluntary Observing Ships and Ships of Opportunity (including ancillary measurements on service vessels); high-resolution expendable bathythermograph transects; deep, long regular hydrographic transects (known as GO-SHIP); fixed-point reference sites under OceanSITES; and tide gauges for calibration and monitoring sea level change [3.1.1.1, 3.1.1.3, 3.1.1.4, 3.1.1.6, 3.1.2.4, 3.1.3]. TPOS 2020 recommends:

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

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

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

IMPLEMENTATION

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

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

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

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

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

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

Action 2 Argo deployments should immediately be doubled equatorward of 10° in the west (especially outside the TMA-occupied region) to maintain subsurface temperature and salinity sampling and compensate for the declining TMA.

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

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

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

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

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

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

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

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

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

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

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

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

Action 11 Meridional lines of flux sites should be extended from the equator to intersect both the South Pacific and Intertropical Convergence Zones in the west, and across the Intertropical Convergence Zone, the cold tongue and the seasonal southern Intertropical Convergence Zone in the east and central Pacific.

❑ Reduction of horizontal coverage away from these key regimes should be accompanied by assessments of impacts on subsurface fields, surface fluxes (including wind stress), and underway and ancillary data collection, especially for pCO_2 data [7.4.4.2, 7.4.6]. The earlier Actions 1 and 2 for the western Pacific will provide a valuable reference for the actions here.

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

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

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

Also see Action 13 below.

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

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

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

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

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

Action 12 Underway pCO_2 observations should be continued or reinstated on all mooring servicing vessels and the present network of moored pCO_2 measurements should be maintained and possibly extended. Measurements of dissolved oxygen from the surface to about 1500 m should be made on ships where practical, and oxygen sensors should be considered on each mooring.

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

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

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

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

Pilot Studies/Programs for the Backbone

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

Process studies

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

Examples of funded new technology projects

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

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

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

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

1 Introduction

1.1 Background of the tropical Pacific observing system

The foundation of the current tropical Pacific Ocean observing system were laid about 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 (SOOP; 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 El Niño (McPhaden et al., 1998; see Chapter 2 for further background).

By the end of TOGA, a design for a global ocean observing system was available (OOSDP, 1995), 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). For over two decades, the tropical Pacific Ocean observing system has served the community well, delivering fundamental information to advance our ability to describe, understand and predict the El Niño/Southern Oscillation (ENSO; McPhaden et al., 2010; GCOS, 2014a). The Tropical Atmosphere Ocean (TAO) / Triangle Trans-Ocean Buoy Network (TRITON) array of tropical moorings has been and continues to be one of the core contributions to this success, in this case due to the long-term efforts of the United States National Oceanic and Atmospheric Administration (NOAA) and Japan's Agency for Marine-Earth Science and Technology (JAMSTEC), respectively. Legler et al. (2015) provide a description of the current status of the real-time in situ Global Ocean Observing System.

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, this is the first study dedicated to the review and assessment of the design of the Tropical Pacific Observing System (TPOS) as a comprehensive whole, taking into account the emergence of altimetry, Argo and satellite wind and ocean color measurements as mature technologies (among others).

1.2 TPOS 2020 Project

The TPOS 2020 Project[3] emerged from a workshop and review of the TPOS during 2013-2014, which were motivated by a reduction in data return from the TAO/TRITON array (GCOS, 2014a); also see tpos2020.org and references therein). The reduction (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 Pacific Tropical Moored Buoy Array (TMA; meaning the TAO/TRITON combination) data return rates of 80-90% to around 40%. The rate has since returned to better than 80% but the risk is now demonstrated. The second factor was the decision by JAMSTEC to reduce its investment in TRITON based on new competing priorities for research funds. By early 2017 the TRITON contribution will have been reduced from 12 moorings to just 3. The reduction of TRITON exemplifies the fundamental problem of sustaining longer-term observations using research funds.

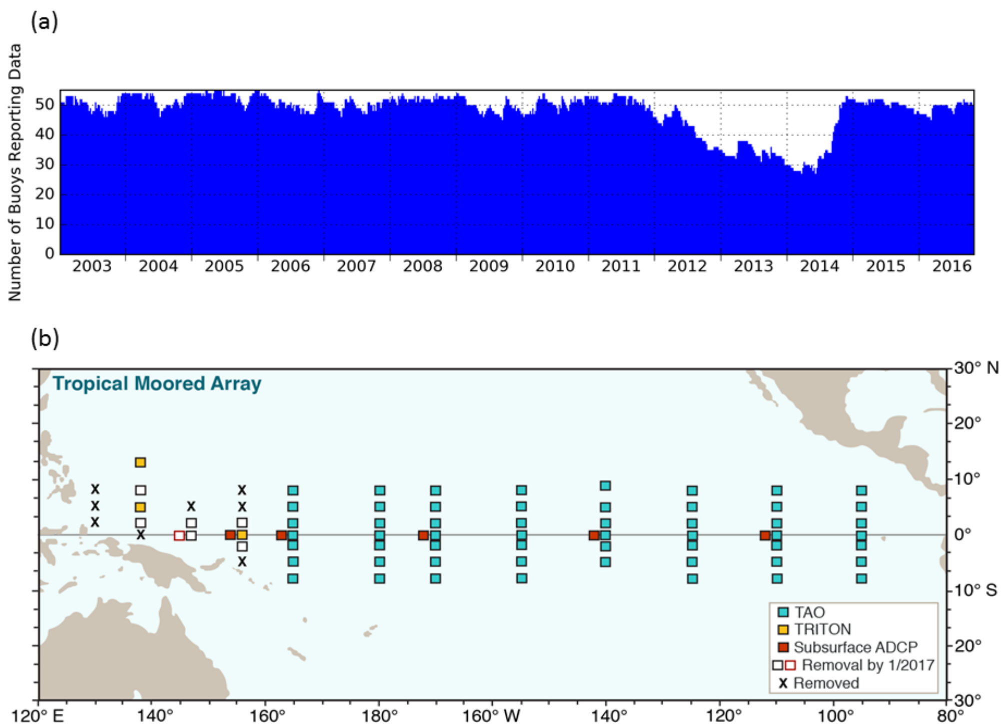


Figure 1-1: (a) Number of TAO moorings returning data 2003-2016 (courtesy NOAA/PMEL). (b) The TAO/TRITON array in the Pacific. TRITON sites where operation has ceased are marked with a cross. Locations that are planned to cease in early 2017 are shown as open squares (latest information provided by JAMSTEC).

[3] 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.

The TPOS 2020 Workshop proposed several activities and provided recommendations to evolve the TPOS to a more robust and sustainable system, including initiation of the 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 the needs of operational prediction centers that are the 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/ecosystem variability and predictability.

1.3 Initial focus of TPOS 2020

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

1. Backbone: Specification of the Backbone of the observing system (fundamental, core, sustained contributions);
2. Planetary Boundary Layer: Elaboration of the scientific need and feasibility of observing the planetary boundary layers, including air-sea fluxes, near surface processes and diurnal variability;
3. Eastern Pacific: Evaluation of targets and approaches to the distinct phenomena of the eastern Pacific region;
4. Western Pacific: Evaluation of targets and approaches to the distinct phenomena of the western Pacific region;
5. Biogeochemistry: Development of rationales, requirements and strategy for biogeochemical observations; and
6. Modeling and Data Assimilation: Consideration of approaches to advancing modeling, data assimilation and synthesis.

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

In oceanography, the concept of "sustained observations" has been used to distinguish routine, systematic and essential (core, fundamental) observations from those that are taken for experimentation or for limited periods. The concept has been built into the GCOS Strategy (GCOS, 2010) and GOOS Framework for Ocean Observing (UNESCO, 2012), but without a precise definition of sustained or essential.

The National Plan for Civil Earth Observations (Office of Science and Technology Policy (OSTP), 2014) provides a more precise definition, still consistent with the concept above, but focusing on the demonstrated commitment, with the advantage of simplicity and ease of use. We adapt that definition for the design of this report:

- Sustained observations are defined as measurements taken routinely that TPOS agencies have committed to on an ongoing basis, generally for seven years or more. These measurements are primarily for public good services or for research in the public interest (see section 2.4.1), but will usually support both.
- Experimental observations are defined as measurements taken for a limited observing period, generally seven years or less, that TPOS agencies are committed to for research and development purposes. These measurements serve to advance knowledge, explore technical innovation and/or lead to improvements in the effectiveness and efficiency of the TPOS.

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

(1) Provide data in support of, and to evaluate, validate and initialize, ENSO prediction and other forecasting systems and to foster their advancement;
(2) Provide observations to quantify the evolving state of the surface and subsurface ocean;
(3) Support integration of satellite and in situ approaches including calibration and validation;
(4) Advance understanding and modeling of the climate system in the tropical Pacific, including through the provision of observing system infrastructure for process studies; and
(5) Maintain and extend the tropical Pacific climate record.

These functions are an adaptation of the Terms of Reference for the Backbone Task Team (refer to tpos2020.org for details).

The requirements discussed in sections 3.1 and 3.2 are predominantly ongoing and thus aligned with sustained observations (see Chapters 5 and 7). The requirements discussed in section 3.3 demand both sustained and experimental observations, but with the focus on the latter (see Chapter 6).

In setting the mandate for the TPOS 2020 Project (GCOS, 2014a) “ocean observing activities” were taken to include relevant surface and near-surface atmospheric observations, and the functions should be interpreted in this context. 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 observations focus on fields with timescales from weekly to interannual/decadal, many processes in the near-surface atmosphere and ocean occur at shorter timescales, and rectify into lower frequencies. Higher data rates (especially resolving the diurnal cycle) will be needed in such cases.

The White Papers from the 2014 Review Workshop in La Jolla (GCOS, 2014a,b) provide a rich resource for this report and are used and cited extensively for the science behind Chapters 2 through 7.

1.4 Outline of the report

The report is cast within the global context provided by the GOOS Framework for Ocean Observing (FOO) and their Essential Ocean (and Climate) Variables (EOVs/ECVs; UNESCO, 2012), the WMO Integrated Global Observing System (WIGOS) and its Rolling Review of Requirements[4] and the GCOS Implementation Plan[5]. The 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 outlined here but without recommendations at the present stage.

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

- Changes to the design for observing the physical systems, with expectations that changes to requirements and recommendations for biogeochemical and ecosystem observations will be covered in more detail in future TPOS reports;
- The coupled ocean and atmosphere system—the deep ocean and free atmosphere are not in scope; and
- The open ocean, including 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 pointing to expected priorities for the near-term and long-term evolution of the observing system;
- An outline of the principles of 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.

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

[5] http://www.wmo.int/pages/prog/gcos/Publications/gcos-138.pdf and GCOS (2016)

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 modeling, computing and communication, and basic research, have yielded impressive dividends in the form of improved monitoring, understanding and forecasting of ENSO. McPhaden et al. (1998) gives a comprehensive overview.

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. Expanding on the technological developments of our forerunners offers the 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, and accelerated after Bjerknes' (1969) 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 Gary Meyers began compiling historical wind observations from ships. Meyers and Jean-Rene Donguy built the first tropical Pacific subsurface ocean monitoring network, taking advantage of cargo ships making regular trans-equatorial voyages from Auckland or Nouméa to Japan, California and Panama, thus providing three quasi-regular tracks. Beginning in 1979, this Ship-of-Opportunity Program (SOOP) took systematic measurements using XBT probes, typically at 6-hour intervals (roughly 100 km 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 (McPhaden et al., 2010). 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.

Stan Hayes, David Halpern, Hugh Milburn and collaborators built simple moorings that could be mass-produced and maintained in unprecedented numbers, making possible the TAO array that for the first time provided sustained, real-time, fixed-point, consistent subsurface ocean and surface meteorology data across the basin (Hayes et al., 1991; McPhaden et al., 1998). TAO data were 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 1994, and evolved into the jointly maintained TAO/TRITON array in 2000 (Ando et al., submitted), hereafter referred to as the TMA/Tropical Moored Array.

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 (McPhaden et al., 1998). Although TAO's design was motivated primarily by the need for basin-wide monitoring to initialize and evaluate seasonal climate forecasts, it also addressed 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 could be built. It has demonstrated enormous success in both respects (McPhaden et al., 1998, 2010).

Around the same time, Peter Niiler championed the development and utility of surface drifters, which provide a unique platform to directly measure near-surface velocity, typically via a drogue at 15 m depth. Under TOGA, these observations were organized as the Surface Velocity Program (SVP), and the drifters have become additionally valuable as a means to measure sea surface temperature (SST) and barometric pressure throughout the global ocean (Niiler et al., 2003; Lumpkin and Garzoli, 2005).

2.3 Post-TOGA developments

Since the early 1990s, the most profound development impacting the TPOS and related services has been the development of the globally coordinated constellation of Earth Observing Satellites (EOS; TPOS WP#9, Lindstrom et al., 2014; Bonekamp et al., 2010; Drinkwater et al., 2010; Le Traon et al., 2015). Real-time satellite data streams of SST, surface waves, sea level, winds, precipitation 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 and other in situ 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 flux variables. Development of the EOS 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. Argo addresses some of the shortcomings of the TMA by sampling temperature and salinity more densely zonally and vertically, 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 zonal spacing is more closely matched to the mesoscale phenomena represented by present-generation models than the 15° longitude between TMA pickets, 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

This section is necessarily a brief survey of the socio-economic impacts and benefits of TPOS, mostly seen through the lens of ENSO. The impacts were discussed by Harrison et al. (2014–TPOS WP#2), Chavez et al. (2014–TPOS WP#7), Wiles et al. (2014–TPOS WP#8b) and Takahashi et al. (2014–TPOS WP#8a; also see summary in GCOS, 2014a). Key points included:

- The societal impacts of ENSO are large and global, broadly associated with floods, droughts and extreme events, the weakening or cessation of upwelling and widespread depletion or redistribution of economically important fish stocks.
- The regions feeling the largest impact (of ENSO) are in the eastern and western tropical Pacific.

- For western South America, El Niño events bring heavy rainfall, while La Niña events bring drought. Mud slides, tropical storms and other life-threatening extreme events have been associated with El Niño.
- The Pacific Islands are highly vulnerable to climate change and extremes. Wave and sea level information were highlighted as of particular importance due to the vulnerability of low-lying Pacific Islands to storm surge events, exacerbated by large-scale ENSO wind-driven sea level changes as well as anthropogenic sea level rise.

Whereas the above White Papers focused on societal impacts of ENSO (and hence the indirect benefit of TPOS), this section looks across the broad benefit areas relevant to TPOS and focuses more on evidence of socio-economic benefit. The socio-economic benefit areas are similar to those used in OSTP (2014) and in GEO (the Group on Earth Observations; see https://www.earthobservations.org/index.php).

2.4.1 Building the value chain

TOGA was the starting point for the development of a socio-economic context for tropical Pacific observations. 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 global climate model that used ocean data to initialize an operational system model (Ji et al., 1994) were major milestones and, as discussed below, represented early examples of production chains, from ocean observations 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” (goods for the benefit or well-being of the public):

- Acting in an area of market failure—difficult for the private sector to justify investment or deliver a return on investment;
- Requires international collaboration and open exchange to work as a system;
- Once produced, data can be provided to additional users at small incremental cost;
- Difficult to exclude users ("non-rivalrous" and "non-excludable"), limiting return on investment; and
- Largely directed at global services that require free and open exchange of data.

The pioneering work of TOGA and others to have free and open exchange of data, in real time, brought such research observation 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. Through a process of quality control and analysis, then integration and 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 that represents the socio-economic 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 observations but also on the effectiveness of the processing and service provision. 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 long-term success of TPOS (see also OSTP, 2014). Our Backbone will require maintaining international partnerships and funding over decades, among agencies with distinct national mandates.

2.4.2 Socio-economic benefit areas

This section examines socio-economic benefits in four areas, seeking to understand the benefit that might derive from tropical Pacific Ocean observations. The examination is selective and not a comprehensive review of the literature; further detail can be found in the White Papers discussed above and through the references cited herein.

2.4.2.1 Climate (ENSO) services

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; Podesta et al., 1999; Cashin et al., 2014; Al-Amin and Alam, 2016). The methodology applied by Lazo et al. (2011) typifies the leading edge. They estimated the climate sensitivity of different sectors in the US by examining interannual 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 that 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 cautioned 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 AUD110 million per year. The study further argues that the potential value summed over Australia may be in the range AUD1-2 billion.

Al-Amin and Alam (2016) look at the impact of El Niño on the agricultural sector in Malaysia and the surrounding region and proposed actions that may reduce the vulnerability to such events; the impacts were not quantified. TMA data were used extensively in the study. Cashin et al. (2014) employed advanced modeling to look at macroeconomic global impacts of El Niño. The modeling accounts for not only direct exposure of countries to El Niño shocks but also indirect effects through third markets. The economic consequences of El Niño differ across the 19 countries studied; some suffering negative impacts while for others an El Niño event had a growth-enhancing effect.

In summary, 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. Regional studies (e.g., Al-Amin and Alam, 2016; Podesta et al., 1999; TPOS WP#8a, Takahashi et al., 2014; TPOS WP#8b, Wiles et al., 2014) further note the regional sensitivity to ENSO, e.g., fisheries, which, depending upon the region, may experience even larger relative impacts because of the significant contribution to gross domestic product.

2.4.2.2 *Climate change services*

Information and services focused on 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, 2014), including for tracking carbon exchanges and circulation.

The Intergovernmental Panel on Climate Change (IPCC) reports include assessments of the literature on impacts of, and vulnerability to, climate change, by sector and by region, as well as a chapter devoted to the economics of adaptation (further information and references are provided in the Working Group II Summary for Policy Makers; IPCC, 2014). The relevance of observations is most clearly evident in the Working Group II chapter on detection and attribution (Cramer et al., 2014).

The COP[6] 21 agreement calls for achieving "a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century." Annual carbon dioxide (CO_2) flux from the tropical Pacific can be as high as total annual emissions from the entire European Union. The type of carbon accounting necessary to meet this COP 21 goal is not possible without tracking CO_2 flux from the tropical Pacific Ocean (see section 2.6.7 for additional elaboration).

One example of services using observations is the recently initiated Copernicus Climate Change Service (C3S) (http://climate.copernicus.eu/), which will "combine observations of the climate system with the latest science to develop authoritative, quality-assured information about the past, current and future states of the climate in Europe and worldwide." C3S aims to deliver substantial economic value to Europe

[6] COP refers to the Conference of the Parties to the UN Framework Convention on Climate Change. COP 21, held in Paris in 2015, was the 21st meeting of the parties to that agreement.

by informing policy development for climate-related hazards; improving planning of mitigation and adaptation practices and promoting the development of new services for the benefit of society.

The establishment of the Global Framework for Climate Services (GFCS) attests to the high importance attached to such services, globally. In their words[7], 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 …."

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 (see section 3.2) as well as for climate change services.

2.4.2.3 Weather prediction services

The literature on the socio-economic impact of weather prediction and weather services (including surface waves) is rich (e.g., see 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 Numerical Weather Prediction (NWP) out to 14 days and longer, effectively bridging the gap with climate (e.g., Brassington et al., 2015). For NWP, the impact of TPOS data is through SST and boundary layer observations. For extreme events, such as tropical cyclones and storm surges, where regional coupled models may be used, the impact is higher and includes upper ocean observations.

For coupled extended-range weather prediction in general, where the upper ocean comes into play, the impact can be significant (see Brassington et al., 2015, for examples). Subseasonal prediction (weeks to 1-2 months) is an area of growing interest, with research coordination focused in the Subseasonal to Seasonal Prediction Project (http://www.s2sprediction.net/). The Working Group on Societal and Economic Research Applications has a number of projects focused on articulating the benefits of subseasonal predictions and services (see http://www.wmo.int/pages/prog/arep/wwrp/new/documents/WWRP_SERA.pdf).

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

In summary, weather prediction services have high socio-economic value. TPOS data are important for constraining the surface boundary conditions and for validating satellites (e.g., SST, wind).

2.4.2.4 Ocean prediction services

Operational ocean and marine prediction services are relatively new application areas, 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 a focus of this TPOS report.

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

TPOS data are the foundation for understanding the link between physical drivers and higher trophic levels in the tropical Pacific Ocean. Understanding how ocean variability impacts biological productivity is critical to ecologically and economically important fisheries such as the Peruvian anchovy fishery, which is the largest single-species fishery in the world, and the western tropical Pacific tuna fishery, which makes up over 50% of the global tuna fishery and is a key resource for the region's island nations (Chavez et al., 2003; Lehodey et al., 1997). In Peru, where ENSO variability impacts the economy not only through extremes in weather but also in fish catches, real-time TMA data are critical to present-day fisheries management decisions.

The Copernicus Marine Environment Monitoring Service (CMEMS, http://marine.copernicus.eu/) exemplifies the modern application of ocean prediction data assimilation and modeling techniques to produce societally relevant services. The services and user groups stretch over many different socio-economic benefit areas including search and rescue, ocean health, extreme events and regional services. CMEMS is a prominent provider of capability (data integration, modeling, assimilation and prediction services) for TPOS data and provides a number of services that depend on TPOS data.

The United Nations Conference on Sustainable Development (UNCSD), also known as Rio+20, was the third international conference on sustainable development and included the "Blue Economy" as a prominent focus. The broad relevance of the oceans, including the common heritage of the High Seas, was seen as representing the final frontier for humanity and its quest for sustainable development (see https://sustainabledevelopment.un.org/content/documents/2978BEconcept.pdf). TPOS represents a major source of information for the Blue Economy.

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 quantify the socio-economic impact and the added research value through citations and other uptake of IMOS data. NOAA's Pacific Marine Environmental Laboratory (PMEL) has gathered statistics on TAO/TRITON publications for around 30 years and this catalogue does show the diverse, international research uptake of the data (consistent with regarding research contributions to TPOS as "Public Goods").

2.5 Context for the report

As sections 2.2 and 2.3 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 3.3 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 longer 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 3.2 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.

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 levels of scientific maturity. We might describe these regimes as the interior ocean, plus the several "boundary layers": the near-surface layers of the ocean and atmosphere, 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 surface spatial detail. The TMA provides continuous, fixed-point sampling over a very wide band of frequencies, allowing careful temporal filtering and spectral diagnoses, as well as intercalibration across satellite missions and observation in satellite gaps (e.g., scatterometer winds in rainy regions), and uniquely adds the surface heat fluxes and ability to directly measure currents. Argo uniquely resolves the detailed vertical density structure over the global ocean, and adds the otherwise very sparsely sampled salinity. Argo's consistent broad-scale sampling is central to its value in mapping temperature and salinity structure, and in estimating spatial scales and their variability. The joint interpretation of Argo baroclinic structure and satellite altimetry adds value to both measurements. 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 (see Chapter 4).

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 observations of the partial pressure of CO_2 (pCO_2) 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 oxygen minimum zone (OMZ) 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 scales: those that can be determined from existing observations and models, and those that arise from understanding the dominant phenomena. 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.

While it is essential that the TPOS 2020 Backbone meet the needs of operational seasonal climate forecasting, it is unknown whether the skill of existing forecast systems—with their well-known major biases—is a sufficient guide to the utility of observations across the full range of predictability (Kumar et al., 2014). 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 Intertropical Convergence Zone (ITCZ) problem (Li and Xie, 2014), that degrade and effectively reduce the value of observations by requiring them to perpetually correct the background rather than initialize variability (model biases are further discussed in section 2.6.8). A more complete observational diagnosis that illuminates now poorly understood processes thus offers the possibility of a jump in model skill.

2.6 Phenomenological background

Section 2.6 is a reference for key phenomena of the tropical Pacific, and defines terms that are used throughout this report. Several background figures are provided as further reference, again cited later in the document. These subsections are collected here for convenience, to avoid breaking the flow of subsequent sections where the information here is needed and cited.

These may be passed over to go directly to section 3, but kept in mind for later use as needed.

2.6.1 Ocean-atmosphere coupled feedbacks and ENSO

Section 2.2 touched on the historical role of ENSO in motivating development of the TPOS; here we highlight physical phenomena that underlie the rationale for a redesign.

The striking features of tropical Pacific climate (warm pool, cold tongue, trade winds, equatorial upwelling, sloping thermocline, and strong atmospheric convection, Figure 2-1) arise from tight two-way atmosphere-ocean coupling, which can in turn generate strong responses when the system is perturbed. The coupling mechanisms are more fully described in TPOS WP#3 (Kessler et al., 2014); a few key aspects are reviewed here.

In normal conditions, equatorial easterly winds force both a westward frictional surface current and Ekman divergence that induces equatorial upwelling. The surface current drives warm water westward, deepening the western thermocline and building the Warm Pool while lifting the eastern thermocline and providing a ready source of cool water to the surface there. The resulting zonal SST gradient focuses atmospheric convection in the west and subsidence in the east, which sustains the equatorial surface easterlies in a positive feedback. Below the surface frictional layer, the eastward pressure gradient generated by the sloping surface (usually about 50 cm higher in the west than the east) induces a narrow eastward Equatorial Undercurrent (EUC). The result is mirrored ocean and atmosphere circulations in the zonal-vertical plane (Figure 2-1).

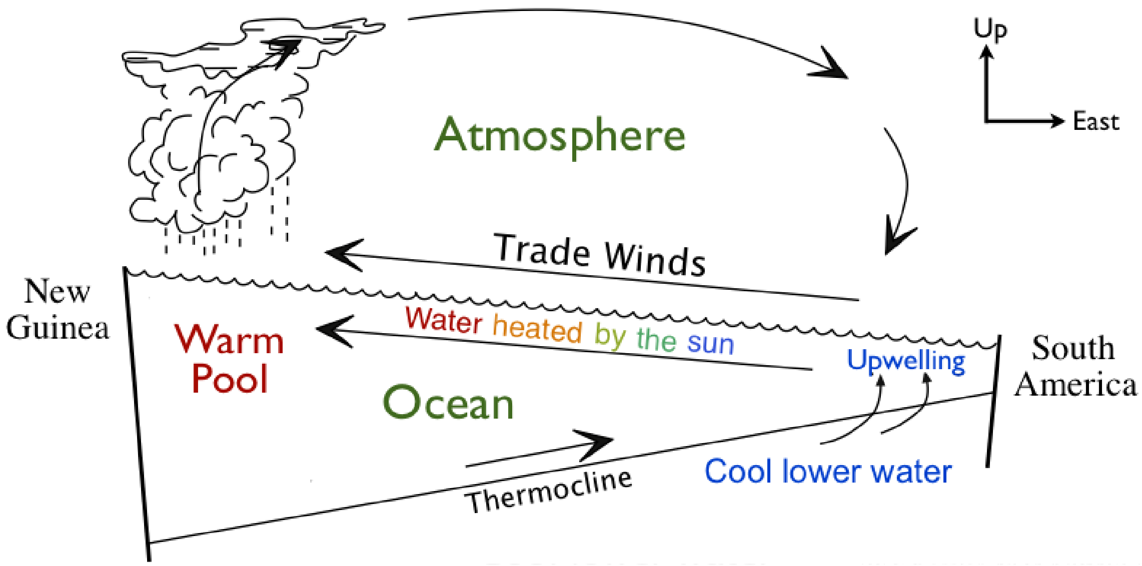


Figure 2-1: The Bjerknes feedback in the normal state of the equatorial Pacific. Easterly trade winds produce eastern upwelling, fostering higher SST and convection in the west. That in turn strengthens the easterlies in a positive feedback.

While this system appears stable, the fact that it is maintained by positive feedbacks means that a change in any element can lead to an acceleration away from equilibrium, enabling large-amplitude climate variations like ENSO. Different regions have different sensitivities: In the east, a shallow thermocline leads to strong vertical temperature gradients near the surface, so SST there is particularly sensitive to wind-induced variations in upwelling strength and thermocline depth. In the central Pacific where the thermocline is deeper and the zonal SST gradient is strong, zonal advection within the surface-layer can dominate. Over the west Pacific warm pool, winds and convection are very sensitive to subtle changes in SST gradients that can arise from variations in the surface solar or evaporative heat fluxes.

Bjerknes feedback denotes the rapidly adjusting (~2-3 month) equatorial zonal feedback loop described above, coupling the zonal SST gradient, trade winds, upwelling, thermocline slope and zonal currents. It is a fundamental feature of the tropical climate, due to dynamics particular to the equator: directly downwind and down-gradient currents, and Ekman divergence-driven upwelling. It also depends on a large region—the west Pacific warm pool—which is above the 26-28°C SST threshold that allows deep atmospheric convection to develop in response to heating from below. And it requires the rapid timescales of the oceanic equatorial waves, adjusting over long zonal reaches in weeks (Bjerknes, 1969; Wyrkti, 1975).

While oceanic Rossby and Kelvin wave propagation itself is well understood and simulated, this is not the case for either the responses of the surface mixed layer and SST to these waves, or for the drivers of the surface wind stress variations (arising largely from horizontal shifts in atmospheric deep convection) that generate these wave adjustments. These more subtle and complex processes require observational guidance to explain and to properly implement in model simulations, and thus are a principal target of TPOS 2020.

In the mean, the Bjerknes feedback maintains the structure shown in Figure 2-1, but it also provides a mechanism for breakdown of this structure. Weakening the equatorial trade winds leads to both weaker upwelling and an eastward sloshing (via equatorial Kelvin waves) of the Warm Pool, which relaxes the thermocline slope, warming the subsurface waters upwelled into the eastern Pacific. That relaxes the zonal SST gradient, thereby further weakening the trade winds, thus producing a positive (amplifying) feedback. Even a few weeks of westerly winds over the equatorial wave guide can induce the warmest SST and atmospheric convection to shift eastward, fostering additional westerly winds (blowing toward the convection) in a growing expansion of the Warm Pool toward the eastern Pacific.

With these multiple elements and feedbacks operating concurrently, depending on local conditions at each longitude, their combinations give rise to the diversity of ENSO, a principal feature of the observational record of these events (see section 2.6.2). Deciphering the complexity of their interactions, with the underlying background climate and with each other, demands a clear picture of the evolving upper ocean temperature and currents, and the air-sea fluxes. The feedbacks define the rapid timescales of the tropical climate, and are the basis for many of the observational requirements of the TPOS.

2.6.2 ENSO diversity and decadal modulation

Historical and paleoclimate records, as well as model simulations, indicate that ENSO exhibits substantial diversity in evolution, impacts and predictability from event to event, and is strongly modulated from decade to decade (Vecchi and Wittenberg, 2010; Wittenberg, 2015; Capotondi et al., 2015a). This diversity and modulation of ENSO's interannual variability rectifies into multidecadal-scale climate signals (Ogata et al., 2013), which can then obscure or interact with other modes of decadal variability around the globe. Because the instrumental record is brief and the historical climate forcings are poorly known, it is unclear whether the variance and predictability of ENSO modulation in the real world resembles that in models (Karamperidou et al., 2014; Eade et al., 2014). However, model studies suggest that multidecadal epochs of extreme ENSO behavior (i.e., very strong, very weak or very regular) can be disrupted by even tiny perturbations to initial conditions (Wittenberg et al., 2014). Yet while there may be a substantial unpredictable component of ENSO modulation and its global effects, ENSO modulation may also spawn an opportunity, since active-ENSO epochs tend to yield greater overall global climate predictability than do inactive epochs (Goddard and Dilley, 2005).

Variability of ENSO can arise from the chaotic nature of the multiscale tropical climate. For example, an unlikely sequence of random events, such as a sequence of strong westerly wind events in the west Pacific, can unexpectedly amplify an apparently moderate El Niño event into a monster; indeed, this may have been the case for the very strong 1997 and 2015 El Niños, which substantially exceeded the forecast ensemble-means (van Oldenborgh, 2000; Vecchi et al., 2006a; L'Heureux et al., 2016).

A generation of scientists grew up seeing a succession of El Niños of the 1980s and 1990s whose SST anomalies intensified toward the east. Then in the 2000s, several events had maximum anomalies in the central Pacific with relatively weaker signatures in the east. Some studies argued that these demonstrated distinct types of events while others concluded that there is no clear evidence for discrete categories but rather a continuum of variability with some interesting extremes (see Capotondi et al., 2015a, for a review). The instrumental record of no more than 15 events is too short to resolve this controversy. It does appear that El Niños are more diverse than La Niñas, and compared to weaker El Niños, stronger El Niños tend to exhibit their peak warm SST anomalies farther east, with a relatively greater role in the ocean mixed layer heat budget for thermocline motions, as opposed to oceanic zonal advection and air-sea heat fluxes that are more typically primary in the central basin (see discussion in section 2.6.1).

Future changes in tropical Pacific climate and ENSO

The response of the tropical Pacific to future climate changes remains uncertain. Multi-model studies suggest an already detectable anthropogenic warming of the western Pacific (Knutson et al., 2014), but changes in eastern Pacific climatological SSTs are much harder to detect, in part because the ENSO SST variance there is so strong. Although model projections suggest eventual basin-wide warming of tropical Pacific SSTs, enhanced surface warming near the equator, intensification of the equatorial thermocline and weakening of the equatorial trade winds, these slow trends occur against a backdrop of strong decadal variability and so may not be clearly detectable for decades in observations (Vecchi et al., 2006b; Xie et al., 2010; Collins et al., 2010; Vecchi and Wittenberg, 2010; Christensen et al., 2014).

The future of ENSO is less certain, since it depends on a subtle balance of future climate changes that oppose each other (DiNezio et al., 2012). In addition, ENSO may be modulated by both intrinsic chaos and natural forcings over the next several decades, obscuring detection of changes from anthropogenic causes (Wittenberg, 2015). Model projections diverge regarding the future of ENSO, with projections ranging from strengthening, to weakening, to a change in spatial pattern, to no significant change. Models do at least project that ENSO will neither vanish nor explode over the coming century, with the IPCC Fifth Assessment concluding that *"there is high confidence that ENSO very likely remains as the dominant mode of interannual variability in the future… However, natural modulations of the variance and spatial pattern of ENSO are so large in models that confidence in any specific projected change in its variability in the 21st century remains low"* (Christensen et al., 2014).

Given the continuing reliance of society on models in order to anticipate future changes in tropical Pacific climate and ENSO, it is crucial that their simulations and sensitivities be brought in better agreement with reality. Both long-term, broad-scale observations of ENSO's phenomenology and impacts and focused process studies of the background climate features and key ENSO feedbacks are essential to constraining the models and theories upon which predictions are based.

2.6.3 Westerly wind events and the Madden-Julian Oscillation (MJO)

The development of some recent El Niño events suggests a pivotal role for the MJO: enhanced MJO activity has been observed to precede the onset of El Niño by a few months (Kessler et al., 1995; McPhaden, 1999, Bergman et al., 2001; Zhang and Gottschalck, 2002). The MJO is thought to intensify a developing El Niño event because its eastward propagating, westerly stress anomalies efficiently excite downwelling oceanic Kelvin waves (Hendon et al., 1998), which remotely act to warm the central and eastern Pacific. The MJO also acts to cool the western equatorial Pacific by increasing the ocean-atmosphere heat flux (Figure 2-2; Shinoda and Hendon, 2002). Both of these mechanisms act to reduce the east-west SST gradient, which then promotes subsequent sustained westerly anomalies via the Bjerknes feedback (section 2.6.1) to result in a further eastward shift of the Warm Pool (Kessler and Kleeman, 2000).

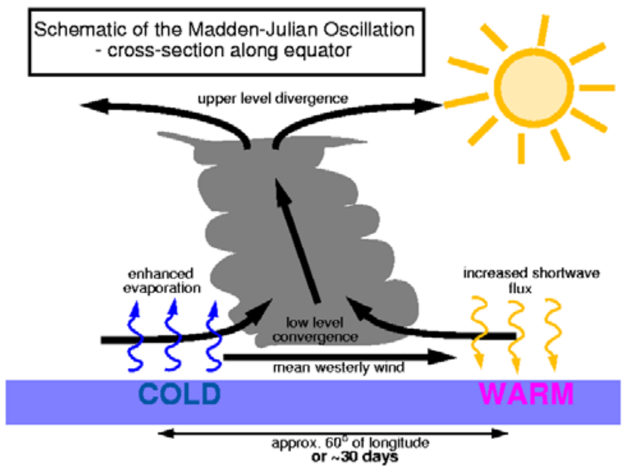


Figure 2-2: Schematic processes within a westerly, convection-favorable period of an MJO event. Winds blowing into the convection cool SST to the west by evaporation, while SST warms to the east by increased solar shortwave flux. The Bjerknes feedback (section 2.6.1) fosters eastward movement of the convection and SST maximum.

Although MJO events are observed propagating around the entire equatorial belt at the 200 hPa level, its surface signature, due to deep convection, is only found over warm SST; thus, it is confined to the Indian Ocean and the west Pacific warm pool. MJO surface signatures tend to extend further east when El Niño events broaden the warm pool, giving a positive feedback–longer fetch for MJO westerlies increasing their effect on the ocean and serving to further expand the region of warm SST—during the growth phase of an El Niño. However, because MJO events originate over the Indian Ocean and depend on conditions there, they potentially introduce an externally forced modulation to the tropical Pacific.

The MJO is also important because of the role it plays in modulating tropical cyclone activity from the western Indian Ocean to the northeast Pacific (Liebmann et al., 1994). There is about a 4:1 increase in the likelihood of tropical cyclogenesis in the active versus inactive convective phases of the MJO, which provides a basis for multiweek predictions of tropical cyclogenesis (e.g., Leroy and Wheeler, 2008). Dynamical forecast models with good depictions of the MJO and of tropical cyclones are now capable of skillful prediction of occurrence of tropical cyclones to 3-week lead time (e.g., Vitart et al., 2010). The MJO also drives teleconnections to the extratropics that enhance rainfall on the west coast of North America

(Bond and Vecchi, 2003), cause extreme temperatures in eastern North America (Lin et al., 2010a) and swings in the North Atlantic Oscillation (Cassou, 2008; Lin et al., 2009), thus also providing a basis for multiweek prediction of climate variability in the extratropics (Lin et al., 2010b).

The best forecast systems are able to predict the MJO itself to lead times of 25-30 days (e.g., Neena et al., 2014). Prediction of the MJO requires both a model that has a good depiction of the MJO and excellent initial conditions (e.g., Fu et al., 2011). Coupled models achieve roughly 7-day better predictions than uncoupled models (Fu et al., 2013), indicating the role for intraseasonal variations of SST for promoting the MJO. Improved prediction of the MJO thus motivates improved representation and initialization of the ocean and atmosphere mixed layer.

2.6.4 Background mean currents

The upper tropical Pacific away from continental boundaries is dominated by zonal currents extending across the entire basin. The nominal 15 m currents of Figure 2-3, obtained from surface drifters, show the poleward near-surface Ekman flow in both hemispheres. This divergence is the principal driver of equatorial upwelling (section 6.2.2)

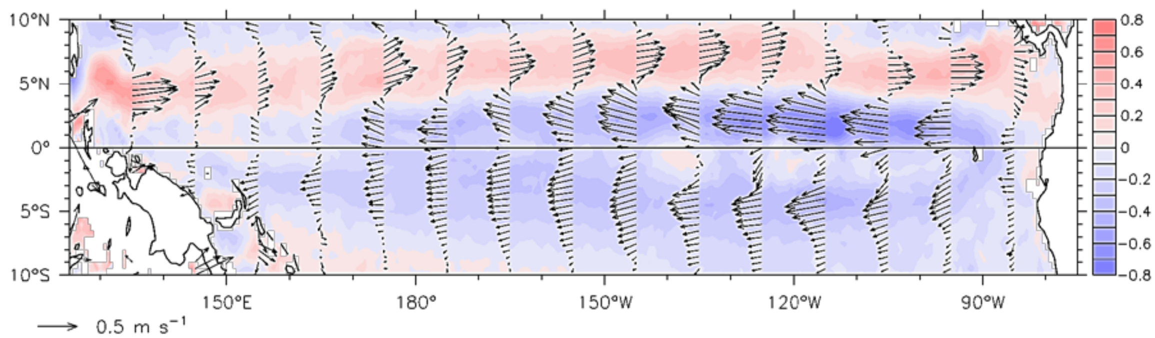


Figure 2-3: Nominal 15 m mean currents from surface drifters. Color shading shows the magnitude of the zonal component (scale at right); vector scale at lower left. The North Equatorial Countercurrent (NECC) is the eastward flow along 3°-9°N, while the two lobes of the South Equatorial Current (SEC) span the equator (Lumpkin and Johnson, 2013).

A vertical section of zonal currents in mid-basin (Figure 2-4), shows the eastward Equatorial Undercurrent (EUC), with its core speed of more than 1 m s^{-1} near 110 m at this longitude; it flows along the thermocline, so is deeper further west and shallower to the east. The two lobes of the westward South Equatorial Current (SEC) appear draped over the EUC, and the eastward North Equatorial Countercurrent (NECC) is found above 150 m at 5°-9°N. Below the SEC lobes are the paired eastward Tsuchiya Jets near 4.5°S and 4°N below 150 m.

All these currents are approximately geostrophic in the long-term mean, as suggested by the isotherm slopes (white contours in Figure 2-4), but this is not the case for their transient adjustment. The upward bowing of isotherms above the EUC core near 20°C signifies equatorial upwelling, which also advects the

EUC's eastward momentum upward to split the SEC branches along the equator (Figure 2-3). Important unresolved issues of the near-equatorial circulation include: The downward penetration of heat and momentum that balances upwelling of several meters/day (see the process study described in section 6.2.2; the temporal and spatial structures of the response of the EUC-SEC system to wind changes; the structure and variability of Ekman divergence, most of which occurs in the largely unsampled layer above 25 m; and the role of the cold tongue front along ~2°N, where tropical instability waves (TIWs) produce an equatorward heat flux of the same order as the upwelling heat flux (Bryden and Brady, 1989; Swenson and Hansen, 1999).

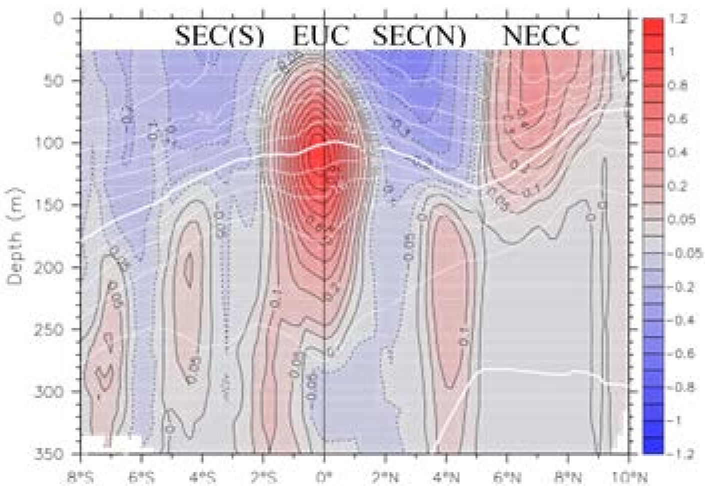


Figure 2-4: Vertical meridional section of mean zonal speed at 140°W (color shading, scale at right) and temperature (white contours) (Johnson, et al., 2002). Shipboard ADCPs do not sample the upper 25 m (blank region at top).

2.6.5 The role of the diurnal cycle in mixed layer dynamics

Efficient propagation of wind-driven equatorial waves along the sharp tropical thermocline is crucial to ENSO (section 2.6.1), but the actual mechanisms by which the thermocline responds to the wind are poorly understood and parameterized in many models. The few observations of stratification and shear in the near-surface layers suggest that much of the transmission of heat and momentum from the surface to the thermocline occurs via processes acting through the mixed layer diurnal cycle.

Although stratification within the tropical near-surface layer is often weak by traditional criteria, especially under persistent trade winds, a shallow mixed layer and diurnal jet forms in response to intense afternoon heating. The 7-month composite at 2°N, 140°W (Figure 2-5) shows that in response to a temperature difference never more than 0.18°C, afternoon velocity at 5 m depth is more than 12 cm s^{-1} stronger than at 25 m, and becomes much closer to the direction of the wind.

The heating and velocity signal appears to propagate downward through the evening, suggesting a mechanism in which momentum trapping in the shallow stratified layer leads to shear overcoming the stratification, with downward mixing 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 (Figure 2-5), hours after the surface heating has disappeared. Nighttime convective mixing sets the temperature of the early-morning mixed layer. In this way, diurnal warming enhances deep penetration of mixing, allowing the thermocline to respond to the wind stress and its variability.

Very sparse observations of turbulent dissipation in the same region indicate that this process extends downward into the equatorial thermocline (Lien et al., 1995), producing large diurnal excursions of mixed layer depth, and appears to convey surface forcing to the level of the EUC. Some model experiments show these dynamics (Danabasoglu et al., 2006).

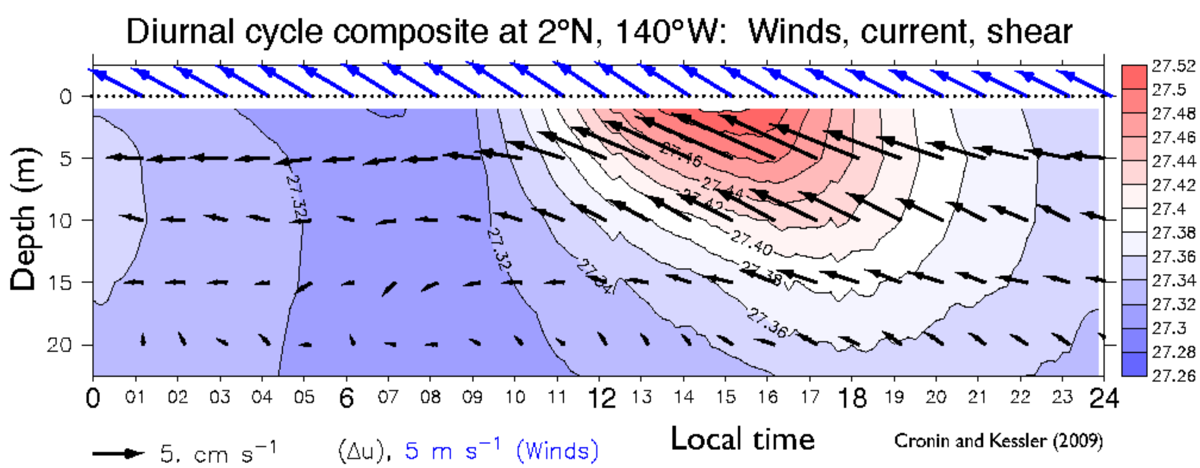


Figure 2-5: Mean diurnal composite during 24 May 2004–7 October 2005. Wind (blue vectors at top), temperature (color shading), and currents relative to 25 m (black vectors). The vector scale for winds and currents is at bottom right. The green overlaid arrow suggests the downward lagged transmission of heat and shear.

2.6.6 Barrier layers and bio-optical feedbacks

A barrier layer is a well-mixed layer above the thermocline that is separated from a surface mixed layer by stratification (Figure 2-6). Typically, this occurs as a result of a salinity gradient within a nearly uniform thermal layer. The disconnection of the two mixed layers insulates the surface mixed layer from cool thermocline water, and also isolates the barrier layer and thermocline from surface forcing. The depth difference between the isothermal layer and the bottom of the surface mixed layer is the barrier layer thickness (Figure 2-6).

Barrier layers were first described during the TOGA-COARE experiment in the west Pacific warm pool (Lukas and Lindstrom, 1991), which identified their generation by rainfall producing "fresh pools" floating above a now-separated but still thermally well-mixed layer above the thermocline (Figure 2-6). Strong wind events (e.g., associated with the MJO, section 2.6.3) episodically mix such barrier layers down to the top of the thermocline.

Barrier layers can trap solar heating and wind momentum in a shallower layer than would be expected from temperature stratification alone, acting much as the afternoon warm layer described in section 2.6.5. When they occur near the equator during a westerly wind event, the initial effect is to intensify the eastward near-surface jet produced by such winds.

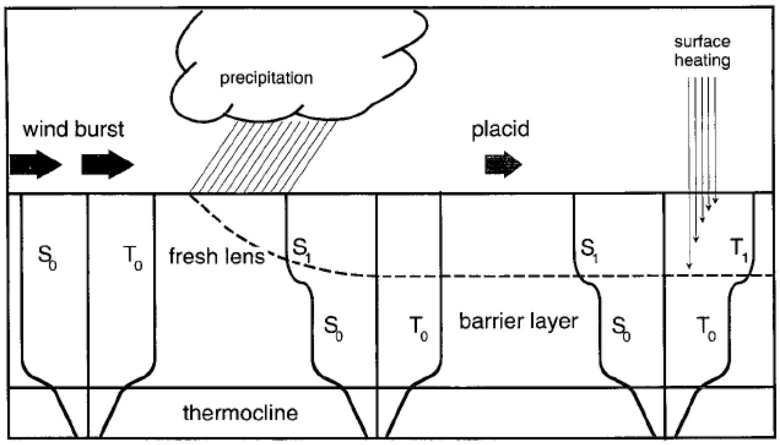


Figure 2-6: Sequence of salinity and temperature profile evolution in a "fresh pool" barrier layer. Left: Strong westerly winds mix both temperature and salinity to the thermocline. Middle: Rainfall creates a near-surface fresh lens, with a halocline at 20-40 m depth within the isothermal layer. Mixing tends to be confined above the halocline. Right: Surface heating warms only the surface layer. After Anderson et al. (1996).

More recently, an additional generating process has been described, in which the background vertically oriented salinity front at the east edge of the Warm Pool is tilted by surface-intensified eastward jets forced by westerly wind events. In this case, low-salinity Warm Pool water is pushed above higher-salinity cold tongue water. Momentum trapping in this case can intensify the oceanic effects of westerly winds, and feedback to extend the fetch of those winds (discussed further in section 3.3.2).

A different mechanism affecting the trapping of surface inputs in a shallow layer is produced by biological growth. Phytoplankton and inorganic matter absorb sunlight in the upper ocean. This determines both the amount of light available to photosynthetic organisms at depth (Piazena et al., 2002), and the thermal stratification of the ocean mixed layer (Manizza et al., 2005). By impacting the local mixed layer structure, the details of solar penetration directly affect SST, which alters winds and ocean heat transports and can influence remote climates (Sweeney et al., 2005; Patara et al., 2012). These effects on mean climate, combined with higher frequency bio-optical -physical coupled feedbacks, can then affect ENSO (Anderson et al., 2009; Park et al. 2014), the MJO (Jin et al., 2013), and tropical cyclones (Gnanadesikan et al., 2010).

2.6.7 Biogeochemical processes of the tropical Pacific

The tropical Pacific develops unique and highly variable biogeochemical signatures over a broad range of space and time scales. Interannual to decadal variations in trade wind forcing, which control the depth of the thermocline and strength of upwelling of nutrient- and CO_2-enriched water, drive these patterns (Figure

2-7; see TPOS WP#6, Mathis et al., 2014). The upper ocean waters of the eastern and central tropical Pacific are broadly characterized as high nutrient-low chlorophyll (HNLC) habitats, which implies that upwelling of nutrients, notably nitrate, exceeds their consumption. The favored hypothesis is that iron deficiency due to weak input from airborne dust is responsible for this HNLC condition, and large phytoplankton blooms only occur when the EUC delivers iron to the cold tongue. The EUC recruits this iron from the continental shelves of New Guinea, so seasonal and interannual variability is modulated by the south Pacific western boundary currents feeding the EUC (section 3.3.4.1).

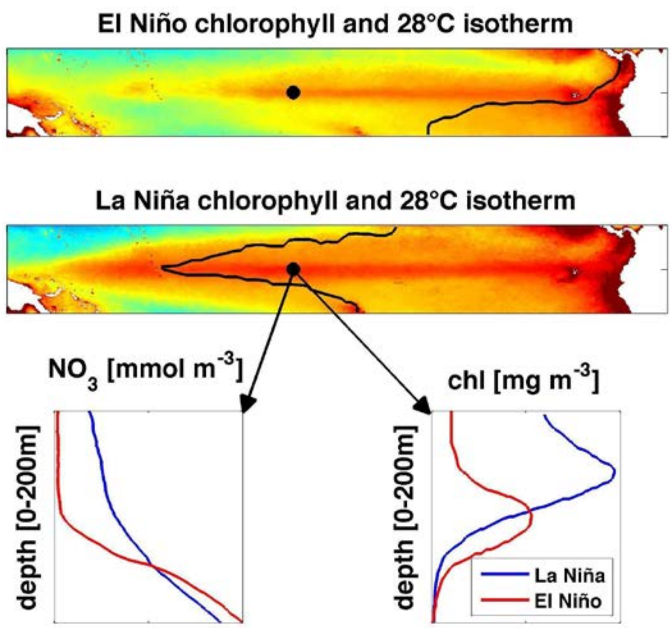


Figure 2-7: Spatial gradients and their variability driven by El Niño: Upper panels show El Niño and La Niña chlorophyll maps from the SeaWiFS satellite with the 28°C isotherm. Figure 2-8 shows similar longitudinal interannual changes for *p*CO_2. Lower panels from 155°W on the equator show the vertical structure of nitrate and chlorophyll concentration for El Niño and La Niña.

The organic matter produced in the eastern and central tropical Pacific that escapes breakdown or transformation in the upper ocean is exported to the deep ocean and sequesters carbon. In the Warm Pool on the other hand, biogeochemical patterns are very different. Salinity stratification and a deeper thermocline restrict vertical nutrient fluxes, resulting in nutrient depletion, low primary productivity and little carbon export.

Despite the limitations to nutrient uptake, the tropical Pacific is a globally significant region of biological production. The southeastern tropical Pacific supports large anchovy and sardine populations, and tuna populations thrive in the low productivity Warm Pool (see TPOS WP#7, Chavez et al., 2014). Abundance and distribution of these fish populations correlate with ENSO, and in some cases the Pacific Decadal Oscillation (PDO). However, it is not fully understood how the coupling between physics and biogeochemistry drive changes at these higher trophic levels. While mooring and satellite networks have been of great value for validation of next generation ecosystem and operational fisheries models, a broader range of biogeochemical data are necessary to improve these models and better understand the impacts of climate variability and change on biological production in the tropical Pacific.

In addition to delivering nutrient-enriched water to the surface, the vast area of equatorial upwelling and the HNLC condition make the tropical Pacific the largest oceanic source of CO_2 to the atmosphere. While the tropical oceans are a net source of CO_2 outgassing, the rest of the ocean is generally a sink. Net global ocean uptake is 2-2.5 petagrams (Pg) of anthropogenic carbon per year with an uncertainty of ±0.5 Pg (Le Quéré et al., 2015; Wanninkhof et al., 2013). The tropical Pacific contributes 0.5-1 Pg carbon per year to the atmosphere (La Niña conditions increase the outgassing flux and El Niño reduces the flux). The 30-year observational record of surface ocean partial pressure of CO_2 (pCO_2) shown in Figure 2-8 has been instrumental in defining this ENSO-driven interannual variability and is beginning to identify decadal patterns in seawater pCO_2 (see TPOS WP#6, Mathis et al., 2014).

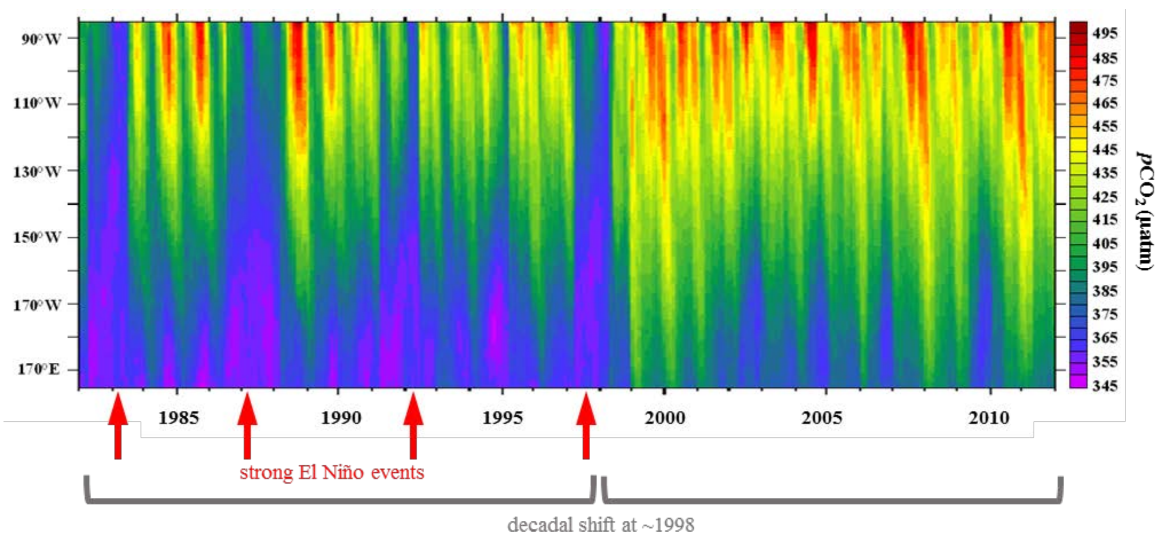


Figure 2-8: The 30-year record of observation based estimates of surface seawater partial pressure of CO_2 (pCO_2) in the 85°W-165°E, 10°S-6°N region illustrating interannual and decadal variability. (Figure by R.A. Feely, NOAA PMEL).

Because CO_2 emitted from this region includes (1) CO_2 produced during the breakdown of organic matter during the ~10-year transit of intermediate waters from the subtropics to the EUC and (2) anthropogenic CO_2 absorbed when these waters were last in contact with the atmosphere, a better understanding of source water variability and change is critical to separating the natural and anthropogenic CO_2 signals. Without this information, it is not possible to predict long-term change in CO_2 flux and ocean acidification in the tropical Pacific. Indeed, Nakano et al. (2015) have shown that transport from the extra tropics is perhaps the dominant driver of the transient increasing trend in tropical Pacific pCO_2.

Another result of increasing atmospheric CO_2 is the global ocean decline in dissolved oxygen (O_2) due to ocean warming and stratification. Climate models suggest tropical OMZs, or subsurface low-O_2 zones have expanded both horizontally and vertically, and if this pattern continues, reduced habitat could shift distributions of marine species and change ecosystem structure (Stramma et al., 2008).

The range of parameters that can be observed from satellites continues to expand, but direct measurements of CO_2 fluxes are not currently possible. Satellites are also unable to capture physical and biogeochemical processes driving productivity below the surface layer. The current generation of ocean models does not fill this void. For these and other reasons, TPOS 2020 needs surface and subsurface sampling of ocean physics, CO_2, chlorophyll, oxygen and nutrients at sufficiently dense time and space scales to understand their variability and their impact on higher trophic levels. What these time and space scales are will be informed by archival data, modeling and process studies.

2.6.8 Coupled ocean/atmosphere models and forecast systems

Predicting the evolution of the climate system requires a framework based on coupled models; see the fuller discussions in TPOS WP#4 (Balmaseda et al., 2014) and TPOS WP#5 (Fujii et al., 2014). Useful predictions of climate processes include seasonal forecasts of ENSO, subseasonal forecasts of the MJO (section 2.6.3), and seasonal hurricane/tropical cyclone outlooks.

Climate models are also essential for reconstructing the global climate state from sparse and intermittent observations, and for forecasting climate variations and projecting future climate changes. Yet despite significant modeling progress over the past few decades, many aspects of tropical Pacific climate remain poorly simulated in coupled GCMs (Capotondi et al., 2015b; Guilyardi et al., 2016). Thus, a key goal for TPOS 2020 is to provide observations that support the development of improved models and forecasts.

Prediction by coupled ocean-atmosphere models requires initialization, validation and model improvements, all of which depend on availability of observational data. Initialization requires state estimates of variables to be predicted, including ocean temperature, salinity and currents. Sustained observations of these variables are therefore needed within the upper ocean, over a depth range that depends on the phenomenon and lead time of interest; in general, longer lead predictions will require ocean observations over greater depths. Evaluation of forecasts and communication of forecast skill to the user community also requires observations, along with estimates of their quality and precision.

The predictable signals associated with ENSO are largely carried by seasonal-to-interannual "memory" contained in slow variations of the ocean thermocline. Because the ocean and atmosphere are tightly coupled over the tropical Pacific (section 2.6.1), simulating the influence of thermocline variations on SST—a particularly difficult problem given the multiple factors that modify SST—is crucial to skillful prediction of ENSO.

The tropical Pacific interacts with the global ocean and atmosphere, thus requiring a planet-sized model grid in both the ocean and atmosphere. The tropical Pacific climate further involves tight coupling across a wide range of space and time scales, necessitating spatially dense grids, high-frequency time stepping, and detailed modeling and parameterization of the physics of the ocean, atmosphere and their interactions. Due to the tight coupling mentioned above, initially small errors in a model component can amplify and propagate through the other components, causing the model climate as a whole to drift away from that of the real world.

Coupled models therefore have biases in their prediction and simulation of tropical Pacific climate variability (e.g., Capotondi et al., 2015a). These biases stem from misrepresentation of processes that may occur in either the atmosphere, ocean, or their interaction: e.g., ocean mixing, atmospheric convection, stratiform cloud decks, and air-sea fluxes. Model biases also prevent assimilation systems—many of which presuppose a model that is physically consistent with the real world—from fully utilizing the available observations. This may cause an assimilation to miss some of the predictable signal.

Improving models requires specialized sets of observations beyond what is needed for prediction alone. An example is the simulation of fluxes associated with surface processes by the models, whose validation will require direct measurements (or credible estimates) of latent heat and shortwave flux. The critical need for model improvement thus expands the requirements for the observing system beyond routine monitoring and initialization, to include observations of variables and processes that will support advancement in understanding and model physics.

A major driver for both model development and TPOS enhancements is the expectation that better models and the right mix of observations will improve the skill of ENSO forecasts. Although the fundamental limits of predictability for the real-world ENSO are unknown (Kumar et al., 2014), "perfect model" studies (in which a model is used to predict itself, eliminating all sources of error except those arising from intrinsic ENSO chaos) have suggested a potential predictability perhaps extending beyond two years (Wittenberg et al., 2014). This is much longer than the current horizon of real-world skill for ENSO forecasts (Becker et al., 2014). Thus, there is realistic hope that improving models and assimilation techniques, combined with sufficient observations to initialize and evaluate models, will further extend their forecast skill.

3 Requirements for the TPOS Backbone

The revised TPOS Backbone is designed to meet three overarching goals, described below, that address the five key functions of the Backbone (section 1.3).

The first goal of the Backbone (section 3.1) is to provide observations, both from satellite and in situ networks, to meet forecast requirements: initialization, verification and validation. We also seek to advance our ability to document the evolution of the coupled system, in particular by improving satellite retrievals through calibration, and analyses through assimilation. The first three functions of the Backbone are addressed by this first goal:

- *Provide data in support of, and to evaluate, validate and initialize, ENSO prediction and other forecasting systems and to foster their advancement.*
- *Provide observations to quantify the evolving surface and subsurface ocean.*
- *Support integration of satellite and in situ approaches including calibration and validation.*

Observations needed for these "public good" services (see section 1.3) should be sustained.

The second goal (section 3.2) is to provide observations that will improve our ability to monitor long-term evolution of the tropical Pacific coupled system, including ENSO modulation at decadal timescales, and maintain and extend the climate record. This goal speaks directly to the fifth function of the Backbone, for which sustained observations are clearly needed.

- *Maintenance and, as appropriate, extension of the tropical Pacific climate record.*

The third goal (section 3.3) is to provide observations that illuminate critical processes that are poorly known and are inadequately represented in models. This goal addresses the fourth function of the Backbone:

- *Advance understanding of the climate system in the tropical Pacific*.

It also addresses the first Backbone function, using observations to validate and challenge models, and thereby foster their advancement. Specific targets of the third goal include more complete descriptions of near-surface ocean physics, frontal processes in key regions and the near-equatorial ocean circulation, all of which are critical to the evolution of the Pacific climate but not well simulated in present models. Observations are also needed to provide a better understanding of the carbon cycle, as well as to monitor key circulation elements that are not currently well observed, including low-latitude western boundary currents. These more experimental observations will serve both public good services and research needed to advance forecast and monitoring capabilities. Some of these elements vary on long timescales, so limited-term process studies may be insufficient. At least several years of data are required to evaluate model performance and provide the ability to interpret the impacts of the phenomena under various climate regimes.

3.1 Sustaining forecasts and monitoring the state of the coupled system

Broad-scale observations delivered in real time are critical for forecasting services through their role in constraining the initial state of the coupled system and via their ingestion in data assimilation systems. In addition, both forecasters and researchers extensively rely on gridded products that are end results of combining satellite and in situ observations. These gridded products, constructed either via statistical data syntheses or dynamically through data assimilation, add value through their consistent integration of information from diverse sources.

The ocean and atmosphere state estimates are also widely used for climate and ocean monitoring and risk assessments, engineering design, insurance, marine resource management and many more (see section 2.4). By supporting and improving these products and services, the changes to the TPOS will have broad and immediate impact and uptake.

The outcomes of TPOS 2020 will improve the gridded state estimates via two pathways

1. Delivering improved broad-scale observations that underpin initialization of model state variables via assimilation analyses and mapping, for both the surface, subsurface ocean and the planetary boundary layer.
2. Providing targeted sampling with a high temporal resolution in key regimes to support improved satellite retrievals and the representation of relevant processes in statistical and dynamical models.

For delivering essential services, observations will comprise both satellite and in situ data. Satellite data streams, for example, of sea surface temperature (SST), salinity (SSS), and height (SSH) as well as significant wave height (SWH) and ocean surface wind and stress vectors, provide broad-scale observations that are now crucial for reanalyses, analyses and forecasts at different lead times. In situ observations, complementing satellite observations, are also important to improve satellite measurements by providing independent ground-truth information for the calibration, validation and verification of many satellite measurements; to provide high-frequency measurements that help de-alias signals that may not be adequately sampled by satellites (e.g., diurnal signals) and to sample subsurface oceans.

We describe below the needs for variables that TPOS 2020 will provide in support of delivering and maintaining essential services. These needs, in great part, are derived from the TPOS WP#4 (Balmaseda et al., 2014) and TPOS WP#5 (Fujii et al., 2014) on operational forecasting and data assimilation systems.

They are also built on the TPOS WP #9 (Lindstrom et al., 2014), TPOS WP#10 (Roemmich et al., 2014) and TPOS WP#11 (Cronin et al., 2014), describing the status and gaps of in situ and satellite observing systems, and of air-sea flux observations.

3.1.1 Surface ocean and atmosphere exchanges

3.1.1.1 Sea surface temperature (SST)

SST is a critical mediator of ocean-atmosphere interactions. On climate timescales, it largely governs the atmospheric response to the ocean. SST gradients are important to governing density and pressure gradients within the atmosphere, which in turn drive surface winds. SST has also proven to be an effective means for monitoring climate and detecting climate change.

Accurate SST determination is the foremost requirement across timescales for NWP, subseasonal to seasonal and interannual prediction models; high-resolution SST analysis is specifically important with continuing increases in model resolution. Accuracy requirements depend on the operational system and timescale (TPOS WP #5, Fujii et al., 2014). The seasonal to interannual prediction target sampling and accuracy, for example, is set at 0.1 K, 50 km and 3-hour temporal sampling. Ocean forecasting data assimilation systems impose the most stringent accuracy (±0.05 K, over 0.1°) and climate research and monitoring purposes impose long-term stability requirements on satellite-derived SSTs. Over scales of order 100 km, the absolute accuracy requirement is ±0.1 K and the stability requirement is ±0.04 K per decade (TPOS WP#9, Lindstrom et al., 2014).

Observing surface temperature variability is currently 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, but with an accuracy in the range of 0.15-0.4 K), voluntary observing ships (VOS), the TMA and Argo. The tropical Pacific's SST is currently well monitored by satellites, both infrared (IR) and passive microwave (PMW), with some limitations: IR sensors are not able to measure SST through clouds; some sensors are affected by water vapor (a significant problem in the tropics) and are subject to biases from atmospheric aerosols, especially for Advanced Very High Resolution Radiometer (AVHRR)-like single-view IR sensors. For example, the Along Track Scanning Radiometers (ATSR) series of IR SSTs are less affected by water vapor and aerosols; the PMW SST retrievals are able to retrieve SST through clouds and aerosols, but are degraded by rain.

In situ measurements of SST remain important for validation and calibration of remotely sensed SSTs (SST calibration and validation needs are discussed in detail in TPOS WP#9 (Lindstrom et al., 2014)). In situ measurements are of particular importance over regions where satellite measurements face limitations: (1) the cloudy and/or rainy convergence zones (west Pacific warm pool, SPCZ and ITCZ) because of the persistence of the clouds obscuring the surface to IR, and the rain degrading the PMW retrievals; (2) the cold-tongue front on the north side of the equatorial upwelling region, because of the persistent and significant biases from sampling errors in the satellite-derived IRs, introduced by clouds formed preferentially on the warm side of the front (TPOS WP#9, Lindstrom et al., 2014) and (3) the stratus region near South America.

Translating skin measurements seen by satellites to the depth of in situ drifter SST by better accounting for the aliasing effect of the diurnal cycle remains an ongoing challenge (TPOS WP#9, Lindstrom et al., 2014). Beyond the strong requirement to continue the major satellite missions measuring SST (see Chapter 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.

3.1.1.2 Ocean surface wind

The surface wind stress is the fundamental atmospheric driver of the tropical Pacific Ocean variability. Wind-SST feedbacks lie at the heart of ENSO evolution (see section 2.6.1). The ocean is highly sensitive to horizontal gradients of the wind stress, in particular, the wind stress curl, which has dynamically important variance on small spatial scales. Winds are a fundamental ocean forcing in data assimilation systems, and thus, for initializing forecasting models. This is especially true for tropical winds, which have global reverberations because of the efficient coupled feedbacks of the tropics (section 2.6.1). Synoptic-scale wind events such as westerly wind bursts, easterly wind surges and intraseasonal surface winds related to MJO events have been shown to strongly influence ENSO onset and evolution, and should be resolved by the observing system. Accurately measuring winds over the oceans is also critical for improving estimates of air-sea coupling, particularly of surface fluxes of heat and moisture (sections 3.1.1.3, 3.3.1, 5.8; TPOS WP#11, Cronin et al., 2014). Winds are also a major source of energy for upper ocean mixing. Improving wind and vector wind stress estimates over the tropical Pacific is one of the most critical requirements, and a challenging goal of TPOS 2020.

Prior to the era of satellite winds, the TMA was the primary means by which tropical Pacific winds were monitored in real time. However, over recent decades, satellite scatterometers (from missions including NSCAT, ERS, QuikSCAT, ASCAT and OSCAT) have proven vital to improving surface wind measurements. In atmospheric analyses and forecasts systems, scatterometers and other indirect satellite sources of information for surface wind greatly outnumber the information drawn from surface-based platforms. The spatial coverage and accuracy provided by the satellites is considered to be acceptable for the needs of NWP (TPOS WP #4, Balmaseda et al., 2014). However, wind stress estimates from reanalyses products and satellites have not converged, affecting the mean, variability and trends (see Figure 3-3 below). In situ observations, therefore, remain a critical source of information for improving the quality of model and satellite products, and in particular to identify spurious trends (Chiodi and Harrison, in press). Thus, for wind stress estimation, the role of the in situ network has now changed greatly since TOGA.

In situ wind measurements and satellite retrievals each have their strengths and weaknesses. Winds from moorings are sparse, and are point measurements not necessarily representative in regions with small spatial scale changes, especially near fronts and in convective regions associated with small-scale updrafts and downdrafts. However, they provide all-weather measurements at high temporal resolution. Scatterometer winds have a much wider spatial coverage but suffer several systematic problems in some regimes: heavy rain, high winds and very low winds. Rain effects on scatterometer measurements are especially problematic over the tropical Pacific, reducing valid estimates substantially (Figure 3-1) and introducing systematic wind errors on both synoptic and longer timescales (section 5.1; TPOS WP#11, Cronin et al., 2014; TPOS WP#9, Lindstrom et al., 2014). Thus, direct wind measurements in rainy convective regions are particularly valuable for improving and validating satellite wind products. Additional description of the values of in situ wind measurements for calibrating and evaluating satellite winds is provided in Chapter 5.

For wind calibration, it is also useful to have direct in situ measurements across a series of regimes. In addition, satellite scatterometers tend to be placed in sun-synchronous orbits, which leads to aliasing of inadequate sampling of the sometimes substantial diurnal and semi-diurnal wind variability.

Sustained in situ measurements of winds at locations with long high-quality data records are absolutely vital 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). Of particular importance are (1) along the equator where wind variations are important to the evolution and diversity of ENSO events and where small errors in zonal winds have global ramifications and (2) areas associated with strong convection and precipitation such as the ITCZ and SPCZ regions. Good quality reference long-time series (>30 years), stable in time and representative in space, is also a strong requirement from the operational centers for bias correction, validation and verification (TPOS WP #4, Balmaseda et al., 2014), even if the spatial sampling needs have not been clearly identified.

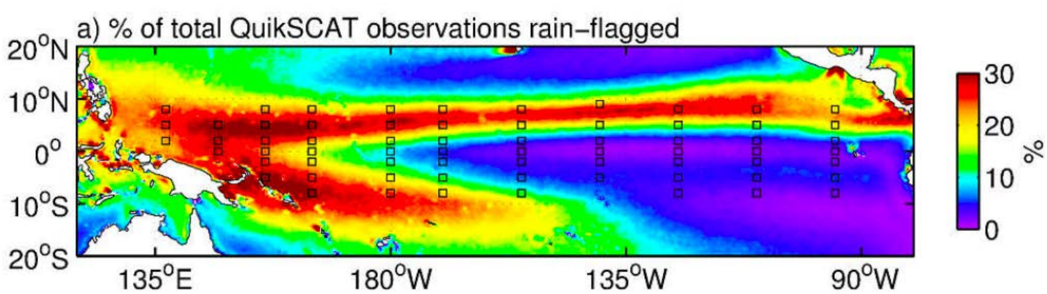


Figure 3-1: Map of the QuikSCAT rain-flag frequency over the 10-year period August 1999-July 2009. Over much of the tropical Pacific, about 25% of the QuikSCAT measurements are flagged as having a larger-than-zero probability of encountering rain at least within part of QuikSCAT's footprint. This may introduce systematic error. Courtesy of Larry O'Neill.

Scatterometers measure backscatter and provide estimates of ocean surface wind stress, or winds relative to the moving ocean surface, not absolute winds. In contrast, buoys provide absolute wind (i.e., relative to the stationary reference frame on Earth). For ocean models and coupled ocean-atmosphere simulations it is the surface wind stress, not the absolute wind that is the most needed observational constraint. NWP and atmospheric reanalysis systems assimilate scatterometer backscatter using a transfer function for wind that ignores surface current effects. In the tropics, surface currents can be strong and winds relatively weak. Therefore, estimation of wind stress and its curl using absolute winds requires a correction of the surface current effects; otherwise, it can result in misleading constraints for ocean/atmosphere models. Therefore, neglect of the ocean surface velocity on wind stress estimation can degrade wind products. Measurements of near-surface currents (see section 3.1.3.2), with high spatiotemporal resolution (at least at all wind calibration sites) would facilitate comparison and synthesis of relative winds obtained from scatterometers with absolute winds derived from buoys and NWP models.

Wind measurements derived from satellite scatterometers have demonstrated good consistency with wind measurements obtained from moorings, with an average RMS difference (between satellite and mooring winds) of approximately 1 m s^{-1} (Figure 3-2). This does not reflect only the uncertainty of the satellite wind measurements, but also contributed by a number of other factors. These factors include the uncertainty of the mooring winds, the scale-mismatch between satellite and mooring measurements (i.e., averages within satellite footprint versus point-wise measurements). However, the limited sampling by satellites cause sampling errors that affect satellite-derived gridded wind products (Figure 3-3) and the differences of these products from mooring winds that can be more substantial than the uncertainty of the satellite measurement per se. It is important not to confuse the measurement error with the sampling error. Increasing satellite coverage with a variety of orbits to capture diurnal variability can alleviate the sampling errors. Since the 2000s, the coverage of the ocean by scatterometers is approximately 60% at the 6-hourly interval (Atlas et al., 2011). An enhancement of coverage from 60% to 90% at the 6-hourly interval can provide a much more adequate constraint on estimates from NWP models and from synthesized wind products.

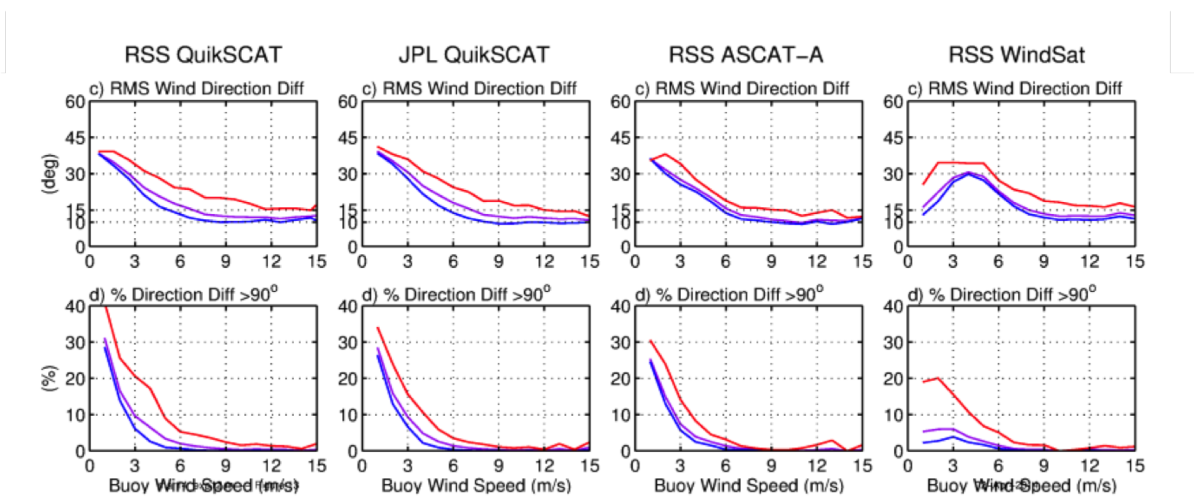


Figure 3-2: Satellite wind speeds compared with collocated buoy measurements, separated for all-weather, rain-free, and raining conditions: (top row) Binned satellite wind speeds as functions of buoy speed; (bottom row) RMS wind speed difference between satellite and buoys as a function of buoy wind speed. Each column represents one of the four satellite instruments considered in this analysis. Courtesy of Larry O'Neill.

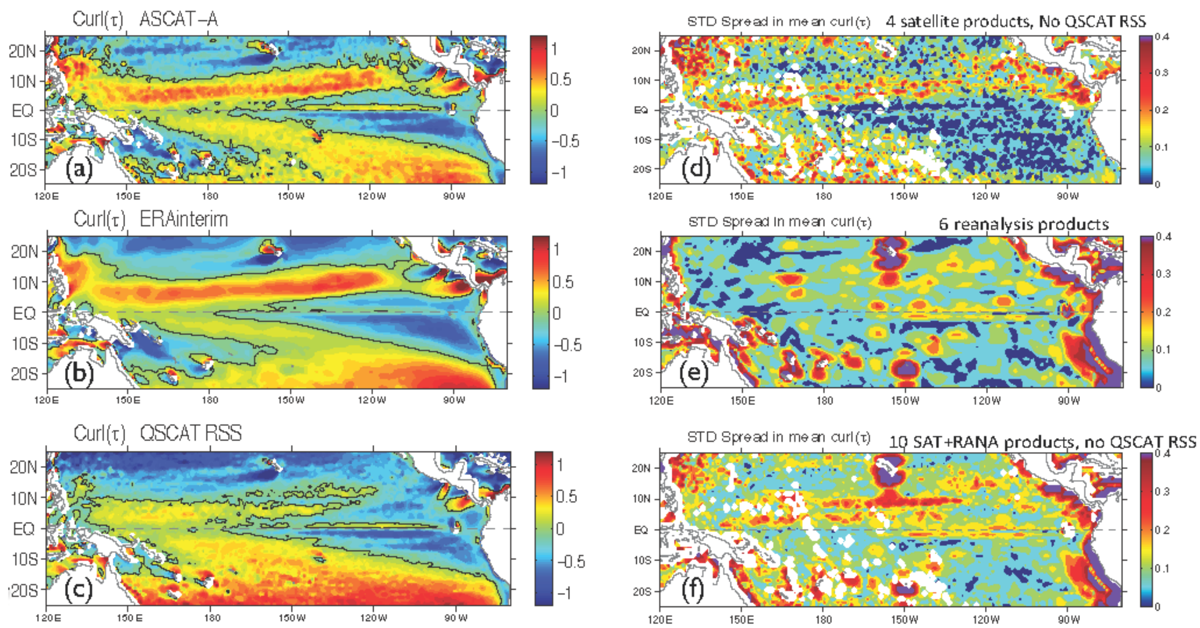


Figure 3-3: Mean wind stress curl averaged over the two-year ASCAT/QuikSCAT overlapping period 11/2007-10/2009 (a) ASCAT-A; (b) ERA-interim; (c) QuikSCAT RSS (mean pattern altered when rain-flagged wind vector cells are removed); STD mean differences between (d) 6 reanalysis products (CFSR, ERAi, JRA55, MERRA, NCEP1, NCEP2), (e) satellite (ASCAT-A, QSCAT JPL, QSCAT RSS+rain, WindSAT) and (f) satellite and reanalysis products for the same period. Courtesy of Lisan Yu.

3.1.1.3 Sea surface air temperature, humidity and radiation

The ocean and atmosphere communicate through air-sea heat and moisture fluxes. Air-sea heat flux allows surface air temperature to adjust to SST, affecting the boundary layer pressure gradient and the stability of the air column, which affect the atmospheric low-level circulation and eventually the middle and upper troposphere. An accurate representation of the fluxes and the coupling physics between the ocean and atmosphere is needed for a correct simulation of tropical cyclones, the MJO, ENSO, the seasonal march of the tropical convergence zones in both hemispheres and the mean state.

The basic state variables for turbulent air-sea heat fluxes are ocean skin temperature, surface air temperature, humidity, wind and surface currents. For some newer air-sea heat flux algorithms, barometric pressure and surface wave state properties are also state variables (see sections 3.1.2.3, 3.1.2.4). Evaporation can be estimated directly from the latent heat flux estimate. Net moisture flux is then estimated as evaporation minus precipitation (see section 3.1.1.5). 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 skin temperature. In addition to SST, wind and surface currents, already discussed, air temperature and humidity and sea surface pressure are the key atmospheric variables used for atmospheric model initialization (TPOS WP#4, Balmaseda et al., 2014). As described in TPOS WP#11 (Cronin et al., 2014) air-sea fluxes and the state variables that define them are used as forcing and initialization in ocean data assimilation systems, and for validating the performance of numerical models.

At present, surface air temperature and humidity can only be accurately measured in situ. These include the TMA and OceanSites buoy networks (Figure 3-4), and less consistently from VOS. However, the spatial sparseness of in situ measurements means that they cannot provide the large area integrals required to drive ocean models or significantly impact atmospheric state estimates. Estimation of turbulent and radiative fluxes over the oceans from satellites is still an evolving field, with large uncertainties remaining in satellite-based retrievals of fluxes and near surface temperature and humidity, for which the satellites are fundamentally blind. While NWP products have good coverage and spatial resolution, they generally exhibit significant biases (TPOS WP#11, Cronin et al., 2014, Figure 3-5) in both turbulent and radiative heat fluxes and should be confronted with in situ observations. While some ocean models are forced by the net air-sea heat, moisture and momentum fluxes, more commonly the numerical models include their own bulk algorithms and are forced by flux parameters (e.g., SST for atmospheric models). Errors in NWP products can be due to model physics, inadequate assimilation schemes (e.g., Josey et al., 2014), or improper treatment of flux state variable, such as aliasing of the diurnal cycle, or rain-contamination of satellite retrievals (sections 5.1, 5.8; TPOS WP#11, Cronin et al., 2014). Since the bulk flux algorithm is strongly nonlinear, improper treatment of the SST diurnal cycle or wind gustiness can introduce large and potentially systematic errors. Likewise, because convection can have large-scale patterns associated with the MJO, ITCZ and ENSO, errors can be coherent and introduce large-scale biases.

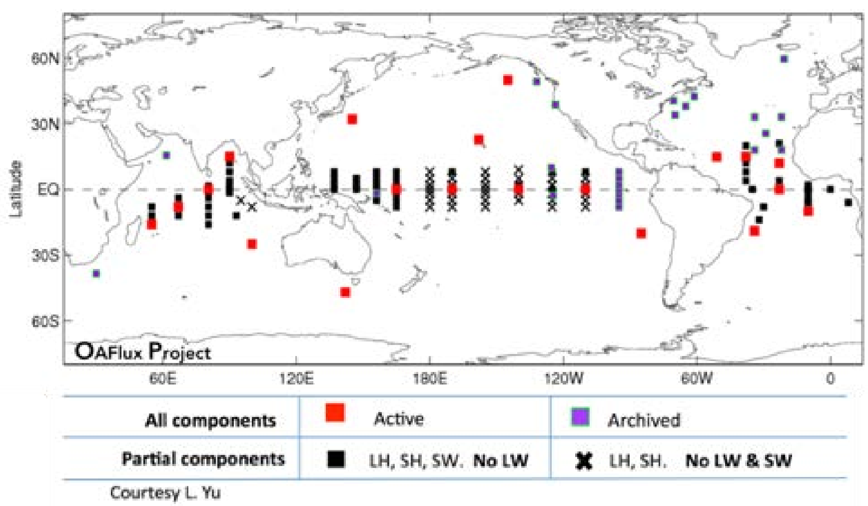


Figure 3-4: Global distribution of flux and flux parameter observation sites.

In situ observations of fluxes and their state variables are however crucial for validation, verification and model improvement; this is likely to become more prominent as centers move toward coupled assimilation systems. As satellite heat and moisture fluxes remain highly uncertain and ocean moorings are very sparsely distributed, the spatial scales required for these observations remains poorly known. An approach to this issue is to have sufficient in situ observations of all flux state variables in key climatic/weather regimes (e.g., windy, calm, gusty, rainy, cloudy, clear, humid, dry, day, night, low versus high clouds) and key oceanic regimes (warm pool, cold tongue, frontal, equatorial, trade wind). The convergence zones and the western and far eastern Pacific warm pools, where changes in deep convection on various timescales are associated with dramatic latitudinal and longitudinal variations in both cloudiness, precipitation and solar forcing, should be key targets for in situ flux variable data. Solar radiation, SST, air temperature and wind need their diurnal cycle resolved in near-real time.

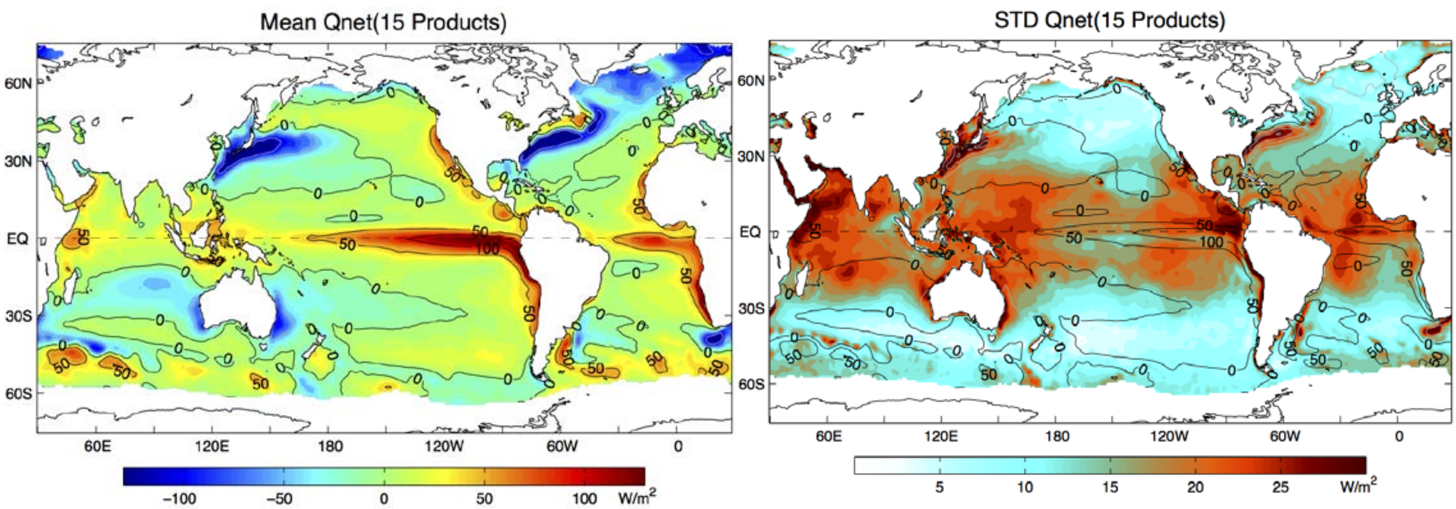


Figure 3-5: Mean net surface heat flux from 15 products (left) and standard deviation of these 15 products (right). Products include: NCEP1, NCEP2, CFSR, MERRA, MERRA-2, ERA40, ERA-interim, ERA-20C, 20CR, JRA55, NOCS2, COREv2, OAFluxHR+CERES, OAFlux+ISCCP and OAFlux+SRB. Courtesy of Lisan Yu, updated from Cronin et al. (2014).

3.1.1.4 CO_2 flux and ocean color

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.

CO_2 flux

Sea surface pCO_2 observations are a critical element to tracking the state of ocean CO_2 flux and long-term trends in ocean CO_2 flux, and to what extent these trends impact the global carbon budget (see section 2.6.7). Air-sea CO_2 flux is calculated using the difference between seawater and air pCO_2 and the air-sea gas transfer rate (parameterized as a function of wind speed). Global mapping of surface seawater pCO_2, necessary for estimating CO_2 flux, has relied largely on underway pCO_2 observations from VOS and research vessels, with the more recent addition of moored pCO_2 observations. These data are provided through the Surface Ocean CO_2 Atlas (SOCAT) in regular releases of quality controlled and fully documented synthesis and gridded products (Bakker et al., 2016). This product is used in annual estimates of the global carbon budget, which rely on direct measurements of CO_2 in the atmosphere and ocean to constrain the remainder of the budget, i.e., the terrestrial CO_2 sink (Le Quéré et al., 2015). Because ENSO dominates the interannual signal in the global ocean carbon sink, tropical Pacific observations are essential to this annual global carbon budgeting (see section 2.6.7). SOCAT gridded products are also used to inform process studies and initialize or validate ocean carbon models and coupled climate-carbon models.

In order to capture the full spatial signal of tropical Pacific CO_2 flux, underway pCO_2 observations on the TPOS mooring servicing ship and other VOS crossing the tropical Pacific need to span the 85°W-165°E, 6°N-10°S region. One method for developing high-resolution, large-scale estimates of the regional fluxes is to apply relationships between VOS pCO_2 and SST observations to satellite temperature fields (Figure 2-8). These relationships need to be updated every 5-10 years as the ocean changes in response to anthropogenic carbon uptake and thus rely on a sustained observing effort. Moored surface pCO_2 observations with high temporal resolution (3-hourly) can be used to validate these estimates at the existing locations across the equator and in the Warm Pool. Recent work (Rödenbeck et al., 2015) has emphasized the impact that observational inputs other than SST can make to estimating surface pCO_2 fields. Going forward, the TPOS must accommodate measurements of other carbon parameters (for example, DIC, pH and alkalinity) so that their role in driving CO_2 fluxes can be deduced from SST.

While emerging technologies may reduce the reliance on ship-based data (see Chapter 6, section 6.1.3), the current state of technology requires that the vessel(s) maintaining the TPOS mooring array have pCO_2 underway measuring capabilities. In addition to the utility of gridded pCO_2 products, existing sea surface pCO_2 observations in the tropical Pacific have emerged as globally significant climate records (over 30 years on VOS and as long as 20 years on moorings) revealing decadal-scale shifts in tropical Pacific sea surface pCO_2 (see section 3.3.5; TPOS WP#6, Mathis et al., 2014; Figure 2-8). Maintaining these high-quality climate time series is not only critical to developing annual global carbon budgets but also providing validation measurements for any future transition of the climate record to new and emerging surface pCO_2 platforms and sensors.

Ocean color

Continuous ocean color measurements began in August 1997 with the launch of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS), followed by the MODerate resolution Imaging Spectrometer (MODIS-Aqua) in 2002. Since then, there has been at least one ocean color satellite in operation, providing near-global coverage on a daily basis. In recent years, satellite missions from Asian and European agencies have played a greater role in meeting the needs for the community. NASA’s next major ocean color mission will be PACE (Plankton, Aerosol, Cloud, ocean Ecosystem), anticipated in 2020.

SeaWiFS was essential for quantifying the biological impact of the 1997-98 El Niño event and the following sequence of strong La Niña events. Over the course of the 1997-98 event, chlorophyll concentrations varied approximately twenty-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 (see TPOS WP#7, Chavez et al., 2014). Aside from the biogeochemical applications, satellite ocean color can also be used in ocean models as forcing fields for depth of solar penetration (see TPOS WP#4, Balmaseda et al., 2014). These data are routinely disseminated by space agencies as gridded near-real time data and climatologies, and climate models have the capability to incorporate this information to improve the ocean heat budget.

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. One of the space agencies' goals is to eventually obtain a well-calibrated decadal time series of global ocean color that can be used as a climate record to detect long-term change (see section 3.2). This goal will be facilitated by the satellite sensor calibration requirements just mentioned but also requires overlap and redundancy of sensors to ensure intercomparison and high precision and accuracy. In addition, recent work has emphasized the importance of regional as opposed to global algorithms for satellite ocean color. This would require measurements of water-leaving radiance (see section 5.7) or pigments, or both, in situ or from moorings.

3.1.1.5 Precipitation

In addition to being societally important over land, precipitation (freshwater flux) is a direct indicator of the atmospheric latent heating: a crucial link in how SST influences the atmospheric circulation. Precipitation (and its associated latent heating) also places strong constraints on the atmospheric energy balance. For example, on sufficiently long timescales, global precipitation must balance global evaporation, and latent heat release associated with precipitation balances atmospheric radiative cooling. In addition, precipitation changes are also an indicator of changes to the global hydrological cycle. As such changes are projected under global warming, accurate measurements of all branches of the hydrological cycle are required. Over oceans, this includes surface latent heat and freshwater fluxes.

Precipitation estimates are also important for model validation and, in the case of ocean models, provide the freshwater forcing. Precipitation estimates are also required for ocean forecast initialization through their impacts on SSS, and on the near-surface stratification. There is thus an ongoing need for broad-scale precipitation measurements over the open ocean.

Satellites such as the Tropical Rainfall Measuring Mission (TRMM) and Global Precipitation Mission (GPM), jointly launched by National Aeronautics and Space Administration (NASA) and the Japanese Space Agency (JAXA), have provided such broad-scale precipitation measurements since 1998 based on the latest microwave and space-borne precipitation radar technologies, with the earliest IR satellite global precipitation products dating back to the late 1970s. Satellite-based precipitation products have greatly improved over this time, currently providing the spatial distribution of precipitation across the tropics on subdaily timescales and in near-real time. However, there remains significant variability among satellite precipitation products in both magnitude and spatial distribution. New satellite technologies and algorithms still need to be verified by long-time series of in situ precipitation measurements across diverse climate regimes and timescales in data sparse regions like the open oceans.

As precipitation is exceptionally intermittent in space and time, verification of satellite measurements against in situ measurements is complicated by sampling errors. These errors arise from the differences between the spatial representativeness of in situ point measurements when compared with an instantaneous satellite overpass averaging a broad footprint. High time resolution measurements over long time periods are thus needed to provide statistical information on precipitation intermittence and to assess the appropriate time and space scales by which tropical precipitation can be compared. Thus, the combined satellite and in situ measurements collected across diverse climate regimes and timescales serve as an important link in assessing precipitation and the global hydrological cycle.

Measuring precipitation is also important for assessing uncertainties in other remote measurements. Precipitation measurements can contribute to improved retrievals of winds and SST products. Therefore, collocated precipitation intensity with wind speed and direction measurements in the convective regions of the western equatorial Pacific, ITCZ and SPCZ is especially useful.

3.1.1.6 Sea surface salinity (SSS)

Although SSS is not directly involved in air-sea exchanges, it affects ocean circulation and thus influences SST and air-sea interaction indirectly. An example is its direct effects on mixed-layer density which, together with near-surface density stratification, influence vertical mixing of heat to regulate SST and surface heat flux (see section 2.6.1). SSS variations associated with tropical instability waves (TIWs) also contribute to eddy-mean flow interaction in the mixed layer (e.g., Grodsky et al., 2005, Lee et al., 2012, 2014). SSS variations associated with MJO have also been found to affect surface density and available potential energy significantly (Guan et al., 2014), although the subsequent effect on MJO-related air-sea interaction needs to be investigated. On multi-decadal timescales, SSS variability (e.g., associated with the fresh pool or interbasin SSS contrast) can be used to infer changes of the water cycle (e.g., Cravatte et al., 2009, Terray et al., 2012), which has advantages over the use of the more uncertain evaporation minus precipitation (E-P) products to infer changes of the water cycle.

Historically, SSS observations relied on a sparse in situ network mainly from voluntary observing ships, some TMA moorings and Argo (whose shallowest measurements are currently at 1-5 m depths). The Argo array has provided near-global measurements of near-surface salinity (as well as profiles down to 2000 m), which revolutionized the salinity observing system. 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)—has pioneered space-based measurements of global SSS. SSS is also being retrieved from the Soil Moisture Active-Passive (SMAP) satellite (launched January 2015) even though it was designed for land applications. Recent studies have demonstrated the capabilities of satellite SSS to improve understanding of tropical ocean features such as TIWs (Lee et al., 2012, 2014; Yin et al., 2014), Rossby waves (Menezes et al., 2014) and SSS fronts (Kao and Lagerloef, 2015), as well as variability associated with ENSO (Qu and Yu, 2014) and MJO (Grunseich et al., 2013, Guan et al., 2014). Satellite SSS have also been shown to improve seasonal prediction (Hackert et al., 2014).

The representation of SSS variability in ocean models and assimilation remain an issue in part due to the large uncertainty of E-P forcing and the relatively common use of SSS relaxation toward seasonal climatology to prevent model drift. This is compounded by the adverse effect due to the use of climatological river discharges. An ideal requirement for SSS accuracy to constrain ocean data assimilation is 0.1 psu on 100-km scale (TPOS WP#5, Fujii et al., 2014), although significant discrepancies in SSS (>0.1 psu) still exist among different ocean analysis products. A similar threshold is also required for studying subseasonal to seasonal variability and improving prediction (National Academy of Sciences, 2016). Additional complementary in situ measurements of salinity near the surface is also necessary, and will be discussed in section 3.1.3 under "near-surface salinity focus."

Sharp SSS gradients exist in the tropical Pacific Ocean in the equatorial zone that may have important implications to ocean dynamics and an indirect effect on ocean-atmosphere coupling. However, there are discrepancies in terms of the sharpness of meridional SSS gradients in the equatorial zone among satellite and in situ products, likely due to the differences in spatial resolution. The in situ network currently does not have sufficient meridional sampling to characterize the sharp SSS gradients near the equator seen from satellites. Enhancement of spatial sampling of in situ SSS in the equatorial zone could 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 could be a useful approach.

3.1.2 Sea surface height, ocean mass, ocean waves and sea level pressure

3.1.2.1 Sea surface height (SSH)

Island sea level was one of the first oceanic measurements that helped elucidate the ENSO phenomena (see section 1.1). Sea level measurements, both in the open ocean and along coasts, now have a wide spectrum of scientific and operational applications. They are used in ocean data assimilation for seasonal climate and ocean forecasting, for inferring the ocean circulation and its variability, resolving mesoscale activity and monitoring equatorial waves and ENSO evolution (TPOS WP#9, Lindstrom et al., 2014). They are also critical for climate change issues such as sea level rise and the 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 is playing a fundamental role in improving the understanding of ocean and climate variability and change.

Satellite SSH will continue to be an important Backbone dataset used by most operational centers in ocean data assimilation, and helps constrain the upper thermal structure by projection onto the baroclinic ocean density structure (TPOS WP#5, Fujii et al., 2014). For seasonal-to-interannual forecasts, the required sampling scales are 1° at global scale and 10 days. Considering the possibility that small-scale structures (e.g., TIWs) affect ENSO, observed SSH data with higher resolution may be more beneficial and may be better exploited in higher-resolution ocean models. For ocean forecasting systems, which assimilate SSH in eddy-permitting/resolving ocean models, the sampling requirements are more demanding: 0.1°, daily (TPOS WP#5, Fujii et al., 2014). In some operational centers, altimetry is also used in ocean wave analysis and initialization of ocean wave models.

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.

3.1.2.2 Ocean mass

The assimilation of altimeter sea level needs additional information about the geoid that can be derived from gravity missions. In addition, gravity missions can provide bottom pressure information, which can be used globally to constrain the nonsteric part of global sea level variations. Gravity-derived variations of the global mass field are also useful for verification of ocean reanalyses (TPOS WP#4, Balmaseda et al., 2014).

Time-varying ocean mass or bottom pressure (OBP) measurements have been provided by the Gravity Recovery and Climate Experiment (GRACE) since 2003. 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 compared 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.

In situ ocean bottom pressure observations are also useful for the detection of tidal and tsunami wave propagation. Further, a 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. Therefore, both satellite and in situ OBP measurements in the tropical Pacific are useful for studying global ocean mass variation.

TPOS 2020 will explore the readiness of stable, high-precision deep pressure measurements at moored equatorial sites to help gravity mission calibration.

3.1.2.3 Ocean waves

From storm waves exceeding 20 m in height to swells that radiate across the world oceans, surface waves act as the gearbox between the atmosphere and the ocean. Waves combine with shoreline geometry to create a multi-scale pattern of coastal hazards. Extreme water levels in the western tropical Pacific can be associated with remote swells (Hoeke et al., 2013) and have very important contributions to extreme water levels (e.g., Albert et al., 2016).

Swells also have a clear impact on wind stress at wind speeds less than 7 m s^{-1} (e.g., Grachev et al., 2003; Kara et al., 2007) but only few experiments have documented this variability of air-sea fluxes (however, see sections 6.1.4 and 7.4.4.4, which refer to the Salinity Processes in the Upper Ocean Regional Study 2 - SPURS2).

Aside from coastal moorings, there is today only one wave-measuring buoy in the tropical Pacific, the Stratus mooring off Peru (Weller, 2015; see section 7.4.4.4), after the retirement of the Kiribati buoy in 2013. We also note the very poor coverage provided by VOS (e.g., Gulev and Grigorieva, 2006).

The only routine measurements of waves today in the tropical Pacific are thus provided by satellites. These include altimeters that report a significant wave height (SWH) and backscatter power from which a mean square slope can be derived. Altimeter data have been very useful in revealing patterns of SWH associated with ENSO and PDO (e.g., Stopa et al., 2015) but they can miss many swell and storm events that are short-lived. The other type of routine satellite data is the wave mode from European SARs (ERS, Envisat and now Sentinel-1 with planned coverage until 2026).

While real-time wave data from buoys are currently not assimilated in operational wave models the data are critical to the validation of current and future global wave models. Wave buoys measure continuously at discrete points the complete frequency-direction spectra of surface waves, which is the quantity that the wave models compute. From this frequency-direction spectrum, all wave parameters such as wave height, direction and period of all swell components can be derived. A detailed investigation of coastal hazards and air-sea fluxes would also benefit from a few permanent directional wave buoys in the tropical Pacific to complement and validate the satellite data.

3.1.2.4 Sea level pressure (SLP)

Sea Level Pressure (SLP) is a fundamental weather measurement and also an essential variable for ocean monitoring. SLP data are required for accurate measurements of sea level, and most of the Pacific Ocean tide gauge sites routinely gather SLP and other weather variables. While it is not a high-impact variable for most of the primary functions listed in section 1.3, Centurioni et al. (2016) found SLP drifter data are the most valuable contribution on an impact per observation basis for NWP, based on forecast sensitivity observation impact analysis. Horányi et al. (submitted) undertook additional data denial experiments and concluded the removal of surface drifter SLP data has a large and negative impact. SLP-based atmospheric reanalysis over an extended period provide the longest gridded record of atmospheric variability (Compo et al., 2011). The requirement for SLP data is strongest in the extra-tropics but weaker in the tropical region (±10° of the equator) where the impact is reduced.

3.1.3 Subsurface Ocean

3.1.3.1 Upper ocean: temperature and salinity

In situ measurements of subsurface temperature are needed to initialize models and support forecast systems, to resolve the vertical structure of the equatorial internal waves and their effects on thermocline depth (see, for example, sections 2.6.1 and 2.6.3), and to accurately infer the heat content that is known as a precursor for El Niño events (section 2.6.1). Salinity is also an essential variable, both for its influence on the dynamics and as a tracer of the large-scale circulation; for these reasons salinity should be well-represented in all forecasting systems. If measured simultaneously, salinity also contributes to the assimilation of temperature data by providing better constraints for density fields (TPOS WP#4, Balmaseda et al., 2014; TPOS WP #5, Fujii et al., 2014).

Requirements for tropical Pacific observations vary across the types of ocean data assimilation system as described in Fujii et al. (2014, TPOS WP#5). The spatial sampling differs for seasonal to interannual forecasting, for short to medium range forecasting, and for ocean state estimations used for climate research. The depth over which the observations are needed also depends on the phenomenon and lead time of predictions. At present, specific guidance on salinity sampling requirements from ocean and climate models is lacking, but it is usually assumed the temperature and salinity spatial and temporal requirements will be similar.

For seasonal to interannual (S-I) forecasting, Fujii et al. (2014, TPOS WP#5) considered the horizontal scale of the main 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, a timescale of around 1 to 5 days, and a vertical resolution of 10 m in the first 250 m and 50 m to 1000 m. The current TPOS observing system (including the TMA and the Argo array) resolves these scales relatively effectively, with the complementarity of both arrays playing an essential role. Current shortcomings that could be addressed in the new design are a too-coarse meridional resolution and a too-sparse sampling in the vicinity of the equator, especially in the eastern Pacific, where temperature profiles are indispensable information for forecasting systems to correct persistent model biases and drifts during the data assimilation cycle.

Increasing resolution of forecasting systems is likely to drive a demand for more frequent sampling (e.g., resolving the diurnal cycle) and higher resolution in all three spatial dimensions both for forecast initialization and validation; thus, a requirement for finely resolved profiles is likely to increase.

Short to medium range ocean forecasting systems serve a variety of applications (ocean security, search and rescue, monitoring of pollutants, ship routing, etc.). These are based on eddy permitting/resolving ocean models, and targeting smaller scales, such as the variability linked to TIWs and mesoscale eddies. For those systems, subsurface temperature observations with a higher horizontal resolution (200 km or better), and similar vertical resolution as for seasonal prediction would be valuable. Process or pilot studies of sampling strategies at these scales are needed to challenge and develop these systems. Satellite altimeter observations are 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. While altimeter-derived sea-level observations can be helpful to constrain the mesoscale upper thermal structure, in situ profiles are important in constraining model drifts in the water mass properties. When drift is not constrained, the altimeter does not effectively correct model currents. This highlights the importance of complementary in situ and altimeter data.

For reanalyses of ocean targeting slower timescale climate fluctuations and initializing decadal predictions, long-term observations of temperature and salinity with deeper extent (ideally to the bottom), with a 10-day to one month resolution are required. The data should have stable and high quality over a long period. High-accuracy observations will be required to detect climate variations with smaller signals that might be key for decadal prediction.

Near-surface salinity focus

A special focus on the near-surface properties, and especially salinity, is also needed. In the western Pacific, the mixed layer depth is often governed by shallow salinity stratification and associated barrier layers (section 2.6.6), which impact the SST response to wind events, and possibly influence ENSO onset and intensity. These barrier layers can be very localized and of short-term duration (porosity), but can only effectively obstruct the heat transfer if they are sufficiently persistent over a large area (Mignot et al., 2009). In addition, the sharp salinity front at the eastern edge of the Warm Pool is a key feature for ENSO dynamics (section 3.3.2). The front and its location has implications for rainfall predictions, atmospheric teleconnections, biogeochemistry (it is a frontal zone in chlorophyll-a, pCO_2 and nutrients) and ENSO dynamics, and is often incorrectly simulated in coupled models (Brown et al., 2013).

Better tracking mixed layer properties is a key goal, especially for subseasonal forecasts. Advancing forecast skill for the coupled atmosphere-ocean MJO (section 2.6.3) with its implications for subseasonal forecasts requires improved representation and initialization of the ocean mixed layer (TPOS WP#4, Balmaseda et al., 2014). Proper initialization of the barrier layer and, more generally, near-surface salinity can also result in improved prediction of ENSO (Zhao et al., 2014; Zhu et al., 2014).

Replicating near-surface salinity in models is difficult due to large uncertainty in precipitation estimates as well as the relatively common use of relaxation of SSS to seasonal climatology (as mentioned in section 3.1.1.6), which tends to suppress non-seasonal variability. Satellite and in situ SSS are thus important to improve the fidelity of models in representing near-surface SSS changes.

Under rainbands, satellite SSS tends to be systematically fresher than that measured by in situ sensors such as at 1 m by moorings, and more so, at 5 m by Argo floats (e.g., Boutin et al., 2013). Salinity stratification above the sensor depth is a likely contributing factor while errors in satellite retrieval (e.g., correction of the roughness effect due to rain) may also contribute (Boutin et al., 2015). Enhancing the vertical resolution of near-surface salinity measurements (in the upper few meters) would help decipher these two effects, and could be accomplished through process-oriented experiments.

The redesigned TPOS network should be able to monitor barrier layer thickness and its horizontal distribution at weekly timescales to infer its porosity, and track the displacement of the sharp equatorial near-surface salinity front at the eastern edge of the Warm Pool. Increasing the number of well-resolved near-surface salinity profiles (with a vertical resolution of 5 m or better) in the Warm Pool and frontal area 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 3.3.1; a process study will be described in Chapter 6.

3.1.3.2 Upper ocean: currents

Knowledge of tropical near-surface currents (the upper few tens of meters) is important for a variety of uses, including fisheries management and recruitment, monitoring and forecasting the motion and dispersion of floating material and search and rescue efforts. Such measurements would also be useful for understanding the distribution of planktonic species and biological connectivity. For the physical climate, the upper few tens of meters contain most of the equatorial Ekman divergence, important for large scale ENSO monitoring, diagnostics and prediction (section 3.3.1). This depth range also contains the mixed layer diurnal jet (section 2.6.5), essential to understand the impact and penetration of surface momentum and heat fluxes into the ocean. Observed near-surface currents are also used for ocean model validation and reanalyses verification (TPOS WP#4, Balmaseda et al., 2014).

Currently, near-surface currents are provided by the Global Drifter Program; these observations are a valuable source of current information, used as a reference for altimetric height products, and recently in ocean data assimilation (TPOS WP#10, Roemmich et al., 2014). Several near-surface current products are also derived from altimetric sea level, and scatterometer winds (e.g., OSCAR, GEKCO), based on geostrophic, Ekman and thermal wind assumptions. However, there are larger uncertainties in these products near the equator, which imply a need to better directly measure surface currents within about 5° of the equator. High temporal and spatial resolution would resolve the varying current structures, including sharp gradients and the diurnal cycle (see further discussion in section 3.3.1).

Below the near-surface layer, an adequate simulation of the velocity fields, and in particular of the EUC (see section 2.6.4), is essential in ocean circulation models. Realism of this aspect is crucial for the ability of coupled general circulation models to simulate ENSO and decadal variability. It is also fundamental for a realistic transport of nutrients and micro-nutrients to the upwelling region, and the resulting primary productivity there (sections 2.6.7 and 3.3.5; TPOS WP#6, Mathis et al., 2014; TPOS WP#7, Chavez et al., 2014). Direct measurements of subsurface currents remain sporadic and scattered. They have been provided mainly by the TMA moorings at five locations (110°W, 140°W, 170°W, 165°E and 147°E), and only on the equator. Currents above about 700 m depth are also measured by shipboard Acoustic Doppler Current Profiler (ADCP), and 10-day means of 1000 m velocity can be inferred from Argo float trajectories. Off-equator, below the surface layer and away from the boundaries, large-scale low-frequency currents are largely geostrophic and can be indirectly inferred from density observations.

Subsurface ocean currents are presently assimilated only in a few ocean data assimilation systems because of severe contamination from tidal and shorter timescale variability, and because of the difficulty of constraining the modeled oceanic state from velocity data alone. However, ocean current data are crucial as an independent validation of reanalyses and ocean models. The long moored equatorial current records, in particular, are highly valued by the modeling community and are routinely used to validate the quality of ocean data assimilation and simulations.

Present direct velocity observations mentioned above do not resolve the near-equatorial meridional and zonal structures, nor the temporal variability of the mixed-layer velocity. They are not able to monitor either the low-latitude boundary currents or the TIWs. The observations needed to improve our understanding of these crucial processes are described later in section 3.3.

3.1.3.3 Intermediate and deep ocean

The needs for TPOS 2020 described in this section on intermediate (~ 1000 m) and deep ocean (below 2000 m) requirements are mostly not specific to the tropical Pacific. They are mainly being driven from beyond TPOS, and are part of a global observing system that needs global consistency, and are less relevant for seasonal-to-interannual predictions. However, as stated above, long-term observations of temperature and salinity below 1000 m would be beneficial for decadal prediction. They would be also beneficial for ocean reanalyses, and to detect smaller decadal climate variations. These measurements should ideally go to the bottom, with a 10-day to monthly resolution (TPOS WP#4, Balmaseda et al., 2014; TPOS WP #5, Fujii et al., 2014).

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). The GO-SHIP data have provided evidence of the deep ocean trends in temperature, salinity and other ocean properties such as oxygen, nutrients and carbon, and of decadal variability, as well as a 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 data in deeper oceans in the present observing system precludes the possibility of closing the critical budgets through direct measurement. However, observations show that the deep ocean is warming, and models suggest that it will absorb an increasing amount of heat over time. 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 timeseries. 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 include regional elements of global systems plus elements that are specific to the TPOS domain:

- 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.
- Reduce the present 2000 m discontinuity in ocean observations, for improvement of forecast model initialization and ocean data assimilation modeling.
- 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 change signals are often an order of magnitude smaller than those in the upper ocean, they remain challenging to resolve both from a sensor stability viewpoint 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.

3.2 Preservation and improvement of the climate record

A Climate Record (CR) refers to a set of measurements of sufficient extent, resolution, consistency, and/or continuity to detect climate variability and change. A Climate Data Record (CDR) is a time series of *observations that are believed to be associated with climate variation and change (National Research Council, 2004).*

The ocean and atmosphere are both changing in response to natural internal variability and climate change, 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 CRs is a fundamental function of TPOS 2020. CRs 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.

Observations are needed to determine the evolution of the coupled atmosphere-ocean system. Climatologies of many phenomena are derived from observational CRs and so provide a basic reference for research. Climate change monitoring and detection poses special challenges for observing systems like TPOS, due to their stringent requirements for accuracy, duration and continuity. 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 using broad-scale observations (e.g., from satellites) that provide a spatial mapping capability. In general, climate change detection based on spatial patterns from co-varying variables is more robust than fixed-location, single-variable time series. However, 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), observations must be broad-scale in time as well. The newly evolving TPOS is expected to play a major role in forming the tropical Pacific CR. The international community proposed a set of Global Climate Observing System (GCOS) Climate Monitoring Principles (GCMPs, see Appendix A) that provide a framework for TPOS 2020 in the preservation, improvement and extension of the climate record.

3.2.1 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 detected over long time periods to help attribute change. Section 3.1 discussed the requirements by variable for TPOS 2020 to track the evolution of the ocean and climate system and to support predictions. In this section, we discuss requirements for the climate record and associated climatologies and provide the scientific rationale for the continuity of these requirements as part of the TPOS key function to “maintain and extend the tropical Pacific climate record” (see section 1.3).

Uncertainty regarding past SST trends, especially in the eastern equatorial Pacific where the instrumental record is sparse, has hindered understanding of the future response to climate change. 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 that, in turn, will affect tropical Pacific 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 (Liu et al., 2005; Xie et al., 2010; Vecchi and Wittenberg, 2010). Although these SST changes are small, they occur over a wide area and in regions of convective sensitivity such as near the Warm Pool, and so have strong impacts on ENSO behavior, thus placing important constraints on the accuracy of SST climate data records.

Tropical Pacific trade winds undergo substantial decadal-scale and longer variability. Recent decadal strengthening of the easterly trade wind stress from 1998 to 2014 was about 50% of the long-term mean in the central equatorial Pacific (England, 2014). However, on centennial timescales, coupled models project that the equatorial winds will gradually weaken due to anthropogenic forcing, primarily because of the change in the equatorial zonal SST contrast (Xie et al., 2010), as discussed above. The stronger warming of SST at the equator than off would induce enhanced meridional convergence of the trade winds toward the equator; this would be detectable on shorter timescales. Coupled Model Intercomparison Project 5 (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. Climate records of surface winds are essential to detect these changes. Because the tropical Pacific surface winds are largely determined by surface pressure gradients, measurements of surface pressure (see section 3.1.2.4) will also provide an additional constraint for long-term changes in the trades, particularly in combination with model reanalyses.

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 (section 2.6.1). In the future, the equatorial thermocline is expected to sharpen and shoal due to the gradual weakening of the trade winds. The isotherm near the center of the thermocline (presently 20°C) is also projected to warm. These changes would 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. 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 influence the presence and distribution of barrier layers. CRs of subsurface temperature and salinity are thus essential as a reference to determine the patterns and depths of variability and trends in global ocean heat uptake.

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 Equatorial Undercurrent (EUC), the intensity of equatorial upwelling and the momentum budget of the various currents are not well known. Vertical shear above the EUC is a delicate balance between upwelling and downward mixing, and thus a sensitive diagnostic of mixing processes; for this reason, these variables are a key for model-observation comparison (e.g., section 6.1.7). Future changes in the pattern of the Pacific trade winds and shoaling of the equatorial thermocline are also likely to affect the structure of the upper-ocean currents and upwelling.

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, freshening the near-surface layer as discussed above. This has important implications at scales ranging from tropical cyclones to ENSO. Model projections also suggest 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, although climate models presently do a relatively poor job at representing these characteristics even in today's world. An extended climate record of winds and rain are required to cover the expected shifts in these convective regimes. In a warmer world, evaporation is expected to increase over the tropical oceans, and ocean evaporation and near-surface relative humidity may prove critical in detecting the impact of climate change on the oceanic and atmospheric energy budgets and tropical rainfall.

Although the past SSS record is relatively spotty and sparse, a direct link is evident between water cycle intensification, SSS and climate change (Cravatte et al., 2009; Durack and Wijffels, 2010). Model simulations and observed global changes of SSS support the "wet get wetter, dry get drier" pattern. However, future model projections of the tropical Pacific suggest SST changes will move this more toward a "warmer get wetter, colder get drier" pattern (Vecchi and Wittenberg, 2010). SSS measurements will enable better understanding of these long-term changes in the water cycle as well as providing the necessary information to ground-truth satellite missions and validate the climate projections.

Long-term changes in winds, heat and freshwater content will drive regional sea level change. In addition, sea level rise will come from both net warming and land-ice melt. TPOS aims to track the drivers of global and regional sea level rise by ensuring that the regional sea level climate record is maintained and extended, and explore the idea of using bottom pressure measurements to help calibrate satellite gravity missions that track increasing ocean mass.

A critical question is how ENSO behavior and teleconnections may change in the future (see TPOS WP #3, Kessler et al., 2014). ENSO's diversity from event to event still continues to surprise us (see section 2.6.2). Existing CRs appear too short with an inadequate number of realizations to constrain the ENSO dynamics and impacts in models. The inter-event diversity of ENSO and its remote impacts will require better records of ENSO's spatiotemporal patterns and mechanisms. ENSO predictability and model forecast skill are modulated from decade to decade making it difficult, based on the limited observational record, to assess the fundamental limits of ENSO predictability. Thus, the maintenance of key broad-scale and regime sampling of the tropical Pacific environment within which ENSO occurs remains important.

3.2.2 The value of redundancy and resilience to maintain consistent climate records

As suggested by the examples above, a consistent climate record for winds, air-sea fluxes, currents and temperature/salinity is a zero-order function of the observing system, for understanding and quantifying the natural and anthropogenic variability. To do this effectively, we must build in the redundancy of multiple data sources to provide cross-checking and context, but also to improve resiliency through insurance against failures of the system components that can irreparably damage the CRs.

The value of redundancy is illustrated by the deterioration of the TMA array in 2014, just as conditions appeared to be ripe for a strong El Niño. This example demonstrates that unexpected failure can occur at the worst possible time. Other examples include unpredictable drifts of sensors on satellites, moorings and Argo floats and XBT fall rate errors, which may be difficult to detect and correct without complementary observations from other platforms. Some redundancy reduces risks of network failure and allows internetwork corroboration. With redundancy, the climate record can typically trade off in losses in temporal sampling at one location against comprehensive sampling in space and so develop a degree of resilience. Lack of redundancy could result in lasting damage to the climate record or doubts about its accuracy.

The global climate observing system, by including both satellite and in situ observations, provides a measure of redundancy. Satellite measurements, while providing high resolution and broad-scale coverage, must be carefully calibrated to in situ observations. Historically, the TMA has been an important component for the global calibration and validation of a suite of satellite data (e.g., SST, SSS, wind, precipitation). SST data from the global TMA near-surface thermometers are essential to assess stability of the satellite-derived SST climate records. 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 intercalibrating measurements of the same parameter (e.g., ocean surface wind) from different satellite missions that allow consistency in the climate record. Maintaining long continuous records for the climate record requires such validation, calibration and cross-referencing among the different satellite missions. Independent in situ-based observations provide additional confidence to strengthen the climate record.

Intercalibration can also be achieved through comparison of sensor measurements from the various observational components of the network. The full-depth property profiles collected through GO-SHIP (e.g., temperature, salinity, oxygen, nutrients) are used to calibrate property measurements collected as part of core Argo, as well as Bio-Argo and Biogeochemical (BGC)-Argo. Argo and the near-surface sensors of the TMA are used to validate SST and SSS from VOS and surface drifters. Underway SSS collected from the VOS are amongst the longest time series of SSS to date, and preserving this CDR is crucial for its unique ability to infer changes in the water cycle.

Another 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 Increased understanding of critical processes and phenomena

This section describes requirements primarily aligned with the fourth function of the Backbone: to "advance understanding of the climate system in the tropical Pacific." These are, in general, extensions of the present requirements identified in section 3.1, targeted at phenomena that can now be identified as critical to improve the realism of analyses, model representations and data products, and are also at or close to readiness to be included in a redesigned Backbone. Other targets are less understood or less ready; those are described in Chapter 6 below. Some of the requirements described here fall into a gray area in which the observational needs are well-defined, but particulars of the sampling strategies need pilot work to fully specify; some of these pilot studies are also discussed in Chapter 6.

The observations here do not necessarily arise from assimilation requirements for products or analyses; in some cases, because assimilation systems need development to take full advantage but would serve to improve data products by sampling regions and phenomena with systematic errors and uncertainties in present models. These requirements would also guide development of model parameterizations and assimilation techniques. An example from the present TPOS illustrating this kind of requirement is the equatorial velocity profiles now made from moorings (section 3.1). These are not now used in forecast initializations for several reasons (see section 3.1), but must still be sustained for their irreplaceable ongoing validation and evaluation of critical phenomena in model products.

Other observations under the "increased understanding of critical processes" function include short-term studies (described in Chapter 6), but those discussed in this section are intended to be sustained.

3.3.1 Better resolution of near-surface ocean physics

Near-surface sampling in the tropical Pacific is necessary for two principal 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 an intermediary connecting surface fluxes to the thermocline, where equatorial waves carry signals efficiently around the basin (section 2.6.1).

These reasons point to sampling the tropical mixed layer, which has more demanding requirements than that needed for the layers below.

Near-surface physical processes that bring tropical feedbacks into play and can thereby produce non-local consequences include:

- the diurnal cycle (section 2.6.5)
- frontal and barrier layer evolution at the eastern edge of the Warm Pool (section 3.3.2)
- westerly wind burst forcing penetrating into the subsurface ocean (section 2.6.6)
- the structure of Ekman divergence from the equator (section 3.3.3)
- the mixed layer above the equatorial undercurrent in response to varying winds (section 3.3.3)
- evolution of the cold tongue front and its tropical instability wave fluctuations (section 3.3.2)
- intense mixing and coupling due to tropical cyclones (sections 2.6.3 and 2.4.2.3)

Although these phenomena typically vary at time (and in some cases, space) scales 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.

Some of the particular phenomena listed above are discussed in other sections as noted, but are listed together here because near-surface processes are key to their operation and effects. As a result, they have many commonalities in their sampling requirements.

Sampling to describe these phenomena should resolve temperature and salinity profiles, and velocity where feasible (see section 3.1.3), with a resolution of about 5 m from the surface to a depth of at least 30 m, and then at intervals of about 10 m to at least 100 m. The requirement is designed to describe fluctuations of the properties and depth changes of the mixed layer. Salinity sampling is especially important in the west Pacific warm pool region, perhaps at reduced vertical resolution. The diurnal cycle is a key element of mixed layer variability, modulating its depth and connection with the winds and fluxes, and providing a strong constraint on the mixed layer’s ability to transmit properties (section 2.6.5). Thus, the sampling timescale should be able to resolve, at least, the diurnal cycle. Since the near-surface phenomena respond rapidly to wind changes and in some cases feed back to the atmosphere, collocated surface meteorology measurements or other means of determining changes on both sides of the interface are vital. The potentially large roles of dissolved organic matter and the subsurface chlorophyll maximum in mediating solar penetration (section 2.6.6) suggest that sampling of near-surface optical properties would improve evaluations of climate model simulations.

Some near-surface processes in the list above occur over wide regions (e.g., the diurnally varying mixed layer), but most are confined to particular regimes. The spatial requirements for their sampling in each case are described in the subsections below.

3.3.2 Monitoring frontal air-sea interaction processes

Fronts play important roles in tropical air-sea interaction, and should be a target for a redesigned TPOS Backbone. The tropical Pacific supports several types of fronts that produce particular enhanced effects in either the atmosphere or the ocean. Although the fronts themselves are narrow and often fast-changing features that are thus hard to sample in situ, in the right circumstances these interactions rectify into much larger scales and low frequencies.

Two semi-permanent fronts produce systematic effects on tropical Pacific climate:

The “cold tongue front” along about 2°N separates the cold, equatorially upwelled water of the east Pacific cold tongue from warmer water further north (Figure 3-6). Instantaneous SST gradients are as large as 3-4°C over 100 km. Models and sparse observations suggest that the cool water subducts at the front. The front is distorted by westward propagating TIWs whose cusp-like meanders effect an equatorward heat transport of comparable magnitude to that of upwelling itself (Bryden and Brady, 1989). The TIW are primarily caused by shear instability between the EUC and the north lobe of the SEC (Figure 2-4; Massina et al., 1999).

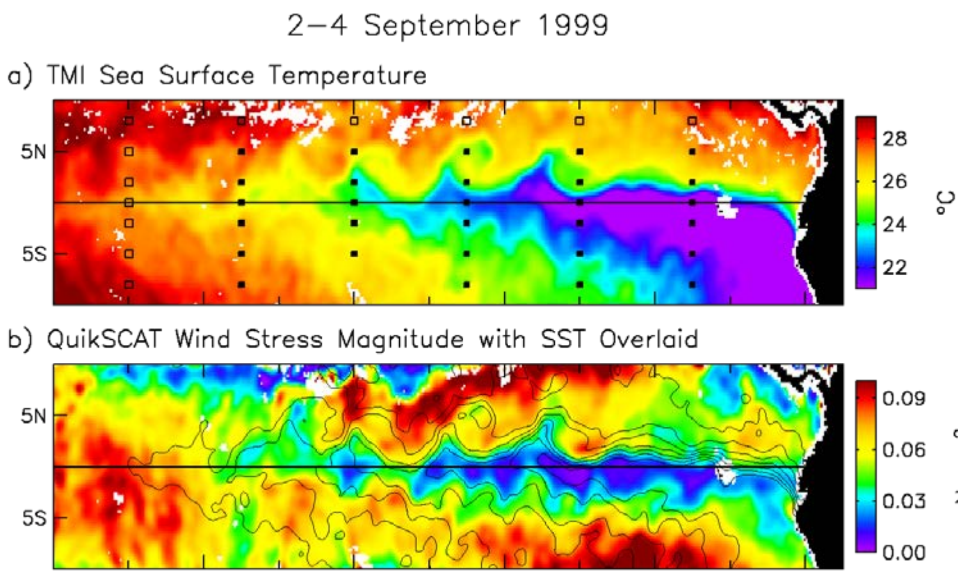


Figure 3-6: Example of the SST front along the north side of the equatorial cold tongue, showing a snapshot during 2-4 September 1999. a) SST from the Tropical Rainfall Measuring Mission satellite. b) Wind stress magnitude from the QuikSCAT satellite, with SST contours overlaid. Note the cusp-like signatures of TIW visible in both fields (After Chelton et al., 2001).

A different type of semi-permanent front occurs at the eastern edge of the west Pacific warm pool (near 180°), where cool, salty water carried west by the SEC dives under the warmer, fresher Warm Pool water (Figure 3-7). The Warm Pool is a region of heavy precipitation while in the subsidence region over the cold tongue evaporation dominates (section 2.6.1; Figure 2-1). Consequently, a fresh pool exists in the western equatorial Pacific, with its eastern edge defined by a zonal salinity gradient that is often collocated with the temperature front defining the eastern edge of the Warm Pool. Unlike the cold tongue front in a region of strong zonal (thus along-front) winds and background currents, the warm pool / fresh pool front(s) occur in conditions of relatively weak (and primarily cross-front) mean winds and currents.

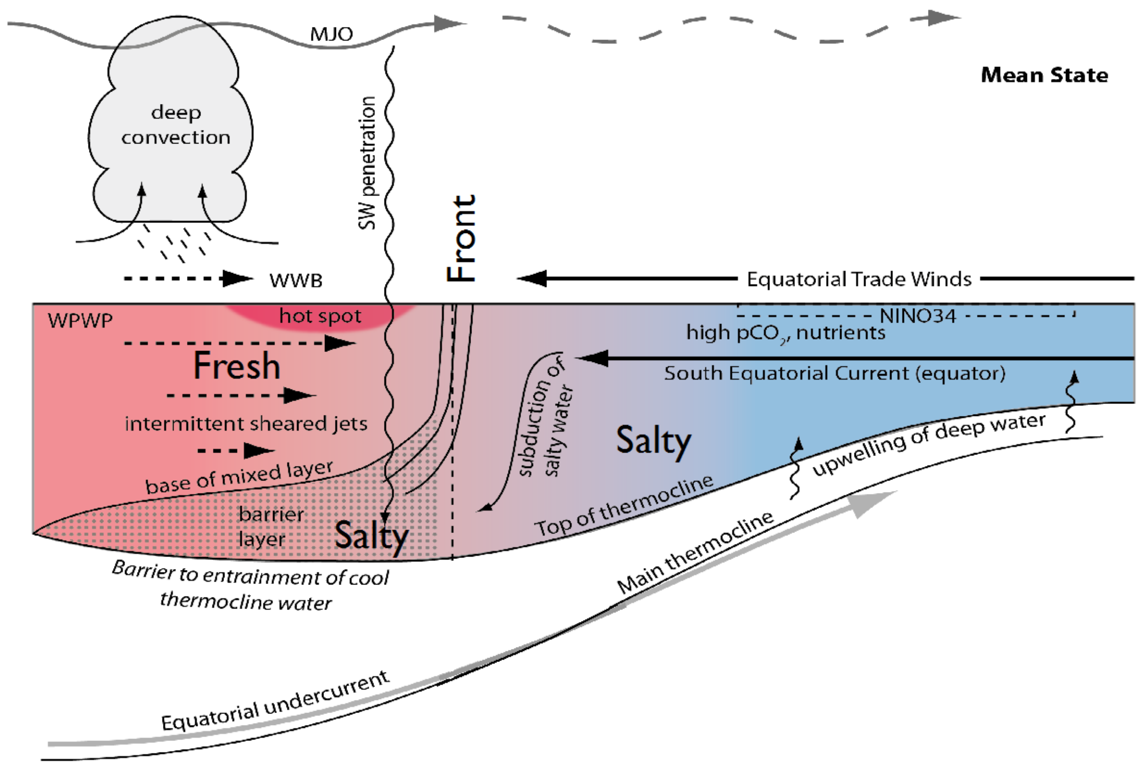


Figure 3-7: Schematic zonal section along the equator, showing the front at the eastern edge of the Warm Pool (after Brown et al., 2015).

Two mechanisms of ***atmospheric*** response to ocean fronts have been identified. Both occur because ocean fronts typically have shorter scales than atmospheric adjustment, so as winds blow across an ocean temperature front the overlying atmosphere can become out of equilibrium with the SST. The consequences can involve the particular feedbacks of the near-equator (section 2.6.1) and allow fronts to be active players in ENSO as well as for the annual cycle of the cold tongue. The two mechanisms are:

1. When winds blow from cool to warm water the atmosphere can be destabilized (Figure 3-6), as southeasterly trade winds cross the cold tongue front. Over the cold tongue itself, a thin atmospheric boundary layer is chilled from below, stratifying the layer and isolating it from the free atmosphere above; as a result, wind speeds slow by boundary friction. When these winds pass the front and blow over the warmer water to the north, boundary layer convection mixes momentum down from the faster winds aloft, increasing the speed of the surface winds. Chelton et al. (2001) showed that the speed gradient at the cusp-like front forms systematic 100 km-scale patterns (Figure 3-6) according to the angle of the front to the winds: divergence where the front is nearly perpendicular to the winds, and positive wind stress curl where the front is nearly parallel. The resulting strip of positive curl along about 2°N has enhanced importance to ocean

evolution because it is zonally oriented and its forcing is felt as a long zonal integral (Kessler et al., 2003).

2. SST gradients produce pressure gradients in the atmospheric boundary layer, with lower pressure over warm SST. Away from the equator, geostrophic winds supported by this pressure gradient are parallel to the front. Along the equator, winds blow toward warm SST, acting as in the Bjerknes feedback (section 2.6.1; Lindzen and Nigam, 1987; Cronin et al., 2003).

Two ***oceanic*** mechanisms produce larger-than-expected consequences in the ocean when winds blow over fronts:

1. The salinity front at the east edge of the west Pacific warm/fresh pool (Figure 3-7) interacts with westerly wind events, typically associated with an MJO (section 2.6.3) at the start of an El Niño event. Westerlies force eastward, surface-intensified, equatorial jets that tilt the front toward the east near the surface, creating a barrier layer (section 2.6.5) with fresh Warm Pool water over cooler, saltier water from the cold tongue. This shallow salinity-stratified mixed layer traps wind-input momentum in a thin surface layer, which amplifies the surface eastward jet. This, in turn, lengthens the zonal extent of warm SST, fostering additional westerly winds extending further east in a Bjerknes feedback that acts to intensify a developing El Niño (section 2.6.1).
2. The cold tongue front (Figure 3-7) supports a different set of processes, primarily because zonal (trade) winds have a strong along-front component. These winds imply continuous northward, cross-front Ekman transport, which cannot be the case because the front persists as a sharp feature. Instead, the presence of the front modifies the Ekman ocean response: the strong surface geostrophic shear associated with the front partially balances the wind stress, leading to a significantly reduced Ekman poleward transport at the front with convergence on its cold side and divergence on its warm side (Cronin and Kessler, 2009). Consequently, the northward flowing cool water subducts approaching the south side of the front, replaced by shallow upwelling of warm water on the north side, which continues to flow north. The Ekman frontal response thus is critical for sharpening and maintaining the cold-tongue front and by extension, the cold tongue itself.

Satellite SST and SSS sampling (section 3.1.1) can usually specify the position of these fronts, and scatterometer winds (section 3.1.1.2) adequately describe the air-sea interaction scales for these purposes (tens of kilometers, evolving on weekly or shorter timescales), but do not constrain their subsurface characteristics. However, both diagnostic and assimilation/prediction applications require subsurface information to infer the development of these fronts as they interact with surface winds and radiative forcing. Required in situ information is similar to that described in section 3.3.1: finely-resolved temperature, salinity and shear profiles in the upper 50-100 m. Particular foci of this sampling for frontal interactions are in the central Pacific equatorial region to sample the eastern edge of the Warm Pool, and along the cold tongue front just north of the equator in the eastern-central Pacific. Collocated ocean profiles and surface meteorology sampling are especially valuable in frontal regions because distinct air-sea interaction, modifying both fields, is expected on either side of a sharp front.

3.3.3 Resolve near-equatorial ocean physics across the ENSO cycles and regimes

The Pacific equatorial circulation is the crucial upward limb of the cell driving the connection of the equator to the subtropics. With the Coriolis parameter near zero, strong oceanic vertical motions become possible, and potent air-sea coupling (section 2.6.1) engages the global climate as a whole. This cell and its coupled consequences is the principal way the tropical Pacific affects weather and climate around the world.

Background on the interacting elements of the cell is given in sections 2.6.1 and 2.6.4, with Figures 2-1 and 2-4. Easterly trade winds drive downwind surface currents and also build up higher sea level to the west. The surface SEC is therefore westward, but below a frictional layer the eastward pressure gradient force dominates, driving the opposite-direction 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 at the equator that compensates their near-surface mass divergence. The equatorial wave dynamics of these processes impose their short meridional scales, and narrow equatorial upwelling produces sharp property gradients; both of these entail demanding sampling requirements.

While this system is straightforward to describe in these general terms, the details are far murkier: the transition from the EUC to the SEC above it depends on a competition between 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 several possibilities: rapid vertical speeds concentrated tightly on the equator, or patchy and episodic small-scale events, or a slower, broader upwelling pattern—any of these capable of satisfying the mass imbalance due to the poleward Ekman divergence, but producing very different patterns of SST variation that will interact with the atmosphere. Distinguishing among these depends on knowing the structure of the shallow Ekman currents in a zone a few hundred kilometers wide around the equator, which 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 these are now well understood or confidently modeled (e.g., Figure 6-2), yet the crucial response of near-equatorial SST to wind variability depends directly on them.

This range of possibilities has important consequences for upwelling of properties like CO_2 concentrations (section 2.6.7) and especially for temperature, since upwelling-forced SST changes feedback on the atmosphere and modify the winds that produced the phenomenon in the first place. Although the atmospheric scales are in general large, the sharp SST gradients of the equatorial region force small-scale atmospheric vertical circulations (section 3.3.2), and also control the location of deep convection.

Our description of this system is built on imperfect and indirect inferences that are a barrier to improvement of either quantitative diagnoses or models of the equatorial system as a whole, yet realism of this aspect of the circulation is essential for models to simulate ENSO and decadal variability well. Further development of model parameterizations of this complex of interacting processes demands observational guidance that is now unavailable. This is a key target for the new TPOS.

Resolving near-equatorial climate processes across ENSO cycles and regimes requires sampling the short meridional scales of this region, where velocity, surface flux and property gradients are sharp and not well-sampled by present systems, the timescales are short and the potential for air-sea feedbacks is high.

Requirements focus on the equator-spanning region in and above the undercurrent core in several regimes along the equator: the shallow-thermocline east, the strong trade wind central region and the deep Warm Pool with weak mean winds and episodic westerly wind events. Variables should include temperature, salinity especially in the west and velocity sampling sufficient to take meaningful meridional gradients, thus at a spacing of about 100 km or less. Collocated winds and flux sampling would add great value.

Sampling should resolve timescales from diurnal to decadal. Consistent sampling over long timescales is especially important because of the strong feedbacks (section 2.6.1) that make these dynamics sensitive to very small zonal wind changes. At low frequencies, the main phenomenon of interest is the vertical-meridional structure of the EUC and its seasonal and ENSO-timescale changes. The existing velocity profiles directly on the equator are highly valued as a sensitive diagnostic of physical parameterizations in models, and a latitudinally broader measure of the equatorial current system would for the first time depict the full structure of the equatorial current system, including its interaction with the surrounding strong SEC.

Direct velocity sampling in the near-but-off-equatorial region would also give a more complete measurement of EUC transport variability by including the region where geostrophy is uncertain at timescales less than a few months; it would also help resolve the effects of EUC meandering that can introduce a systematic low bias into equator-only estimates of the transport (Leslie and Karnauskas, 2014).

At higher (daily to weekly) frequencies, the spin-up of the vertical-meridional circulation in response to wind changes, and the shallow tropical cells and their modulation by TIWs would be sampled regularly for the first time, in concert with fine-resolution satellite SST and SSS.

Sustained velocity sampling spanning the equator would provide the background and context to guide process studies (section 6.2.2), identifying targets and helping to define effective sampling strategies. In turn, a limited-term process study might provide enough information to subsequently infer upwelling variability from sparser sustained velocity measurements.

3.3.4 Improved monitoring of key circulation elements

3.3.4.1 Monitoring 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. They also serve as pathway for micro-nutrients (especially iron) that are a strong constraint on primary productivity in the eastern cold tongue (TPOS WP#7, Chavez et al., 2014). A key conclusion from the community consensus on sustained ocean observations, including both OceanObs'99 (Smith et al., 2001) and OceanObs'09 (Fischer et al., 2010), was that sustained boundary current and interbasin exchange observations are primary missing elements of the global ocean observing system.

The Pacific Western Boundary Current 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 (Figure 3-8). The LLWBCs supply waters essential for the mass and heat balance of the west Pacific warm pool and equatorial Pacific thermocline, and serve as a major pathway of the "recharge-discharge" life cycle of ENSO and decadal variability (Jin, 1997). The volume, heat and freshwater budget of the equatorial Pacific Ocean cannot be closed without a good understanding of the variability of these LLWBCs (see the pilot study “Wyrtki Challenge” in the Annex to Chapter 6, section 10.1.3).

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

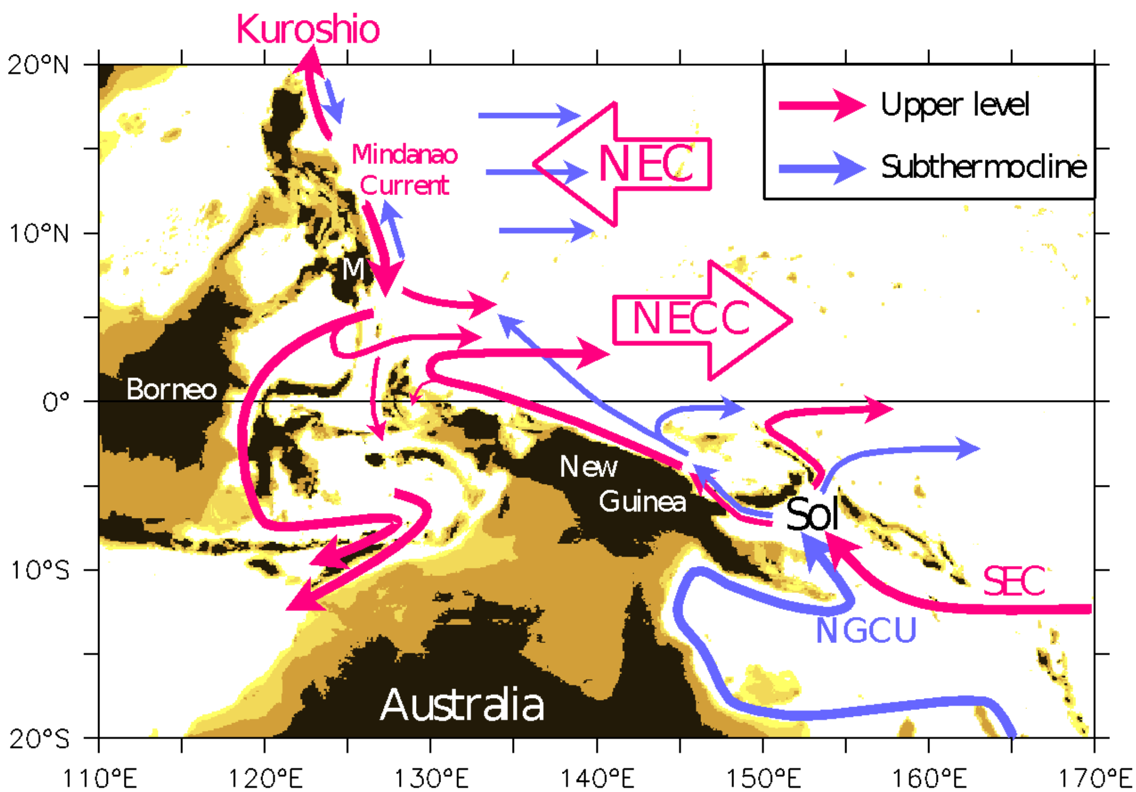


Figure 3-8: Schematic current system of the western equatorial Pacific. Upper-level (thermocline and above) currents are shown in pink, subthermocline currents in purple. The equatorward western boundary currents are the Mindanao Current in the Northern Hemisphere and the New Guinea Coastal Undercurrent (NGCU) in the Southern Hemisphere. Other named currents are shown in Figure 2-4. "Sol" abbreviates the Solomon Sea; "M" marks the island of Mindanao.

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. 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.

Sampling in these regions should include temperature, salinity and velocity in order to resolve the volume, heat, carbon, nutrient and freshwater transport variations on timescales of intraseasonal and longer. Full-depth measurements may be needed in channel flow over sills. Credible measures of mass and property transport require a means to interpret the cross-stream characteristics of the boundary current: either direct sampling across the entire current or other means to determine the cross-stream structure. This might be done for the open-ocean LLWBCs by remote sensing (e.g., of SSH; section 3.1.2.1) or by assumption of the structure in narrow confined straits. Section 6.1.1 describes a pilot study that might enable these measurements to evolve into the TPOS Backbone. Issues to be resolved by the pilot include the utility of remote sensing, the appropriate locations to characterize each LLWBC and ITF and the time and space scales to adequately represent the transport variability.

3.3.4.2 Monitoring 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 only sparse direct measurements of currents are available from ADCP profiles and Shipboard ADCP sections. Despite this, available measurements reveal that zonal currents below 300 m in the near-equatorial band are well organized into a complex series of stacked jets (Firing et al., 1998; Johnson et al., 2002). There is also evidence of alternating zonal jets flanking the equator at intermediate depths (Cravatte et al., 2012). 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 2000 m, 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 at least 1000 m along the equator would improve our knowledge of the intermediate current variability, and pilot studies embedded in the array should be considered.

3.3.5 Biogeochemical (BGC) processes

Core uncertainties remain regarding the drivers and impacts of natural variability and long-term change in carbon, oxygen, nutrients and primary production in the tropical Pacific. Some of these uncertainties need to be addressed through targeted process and pilot studies (section 6.1.3). However, key observations provided by the TPOS Backbone will underpin the research required to better understand the physical drivers, connections to higher trophic levels and potential climate impacts (section 2.6.7).

TPOS moorings, and the ship-based cruises that service the moorings, have provided dual platforms to investigate the biogeochemical response to physical variability both regionally and temporally. Moored observations illustrated the utility of collocated pCO_2 and bio-optics (chlorophyll as a proxy for phytoplankton biomass) for better understanding the biogeochemical response to the 1997-98 El Niño (TPOS WP#7, Chavez et al., 2014). Chlorophyll fluorescence, backscatter, oxygen, nitrate, and pH are also a common suite of sensors deployed on BGC-Argo floats (Biogeochemical-Argo Task Team, 2016), although there have been no BGC-Argo deployments in the tropical Pacific prior to a recent TPOS pilot study (section 10.2.1). These mature sensing technologies have been incorporated into other observing networks (e.g., OceanSITES and IMOS).

Sustained, long-term biogeochemical observing in the upwelling and warm pool regions can track many of the key processes described in section 2.6.7 by the addition of chlorophyll fluorescence, particulate backscatter and oxygen sensors at critical locations. The temporal resolution requirements of these parameters differ. Ideally oxygen measurements should be approximately hourly to capture the diurnal signal. Chlorophyll fluorescence is strongly photo-inhibited during the day, so daytime data are often discarded, and particulate backscatter generally has little diurnal signal. In reality, sensor power consumption means that all three of these parameters can be sampled hourly (which would be more than adequate) or even more frequently for deployments of 6 to 12 months. Chlorophyll and backscatter should be measured in the euphotic zone (surface to 100 m) and oxygen in the upper 1500 m with higher resolution between 50 and 300 m. Initial recommendations are to focus these measurements in the western tropical Pacific, to observe the migrating edge of the Warm Pool and in the east and to observe the highly productive waters and extensive OMZ there. Existing data should be used to inform the sampling resolution because the vertical structure of O_2 is distinct in the east and west. A zonally varying measurement strategy is required. Special attention should be paid to measurement technologies for extremely low O_2 concentrations in the OMZs.

Maximizing the horizontal spatial extent of biogeochemical measurements is also a requirement of the TPOS Backbone. To date, high spatial resolution surface data have mostly consisted of satellite ocean color and underway $p\mathrm{CO}_2$. These are arguably the two most important climate records we have for the tropical Pacific. They should be continued and, where possible, augmented with collocated measurements of chlorophyll fluorescence, particulate backscatter and oxygen. In addition, autonomous measurements must be validated by high-quality, ship-based measurements.

These additions would meet multiple requirements: validating and improving algorithms for satellite ocean color (section 3.1.1.4), establishing a climate record for tracking the decline of dissolved O_2 and expansion of low-O_2 zones, and investigating the physical and biogeochemical processes controlling primary production. These observations would also serve as a foundation for understanding how physics and biogeochemistry drive changes at higher trophic levels and contribute to developing ecosystem and operational fisheries models (section 2.6.7). These requirements will be refined through the pilot work described in section 6.1.3.

3.4 Summary of requirements

3.4.1 Sustained requirements by variable

This is a summary of the sustained requirements, by variable:

SST

- Provide unbiased and accurate high-resolution SST estimates, with particular focus on persistently cloudy and rainy regions.
- Resolve the SST diurnal cycle and characterize near-surface temperature profiles in regions where diurnal variability is large.
- Resolve SST horizontal gradients in the cold tongue region.
- Provide long-term accurate SST measurements.

Surface wind

- Provide unbiased accurate surface wind/wind stress with good spatial and temporal coverage, including in high rain regions and low- and high-wind regimes.
- Maintain long time series of in situ winds for intercalibration purposes, especially in the equatorial Pacific and strong convection and precipitation areas.

Air-sea fluxes and precipitation

- Comprehensive sampling of the state variables for turbulent heat fluxes (SST, air temperature, humidity, wind and surface currents) and for radiative fluxes (downwelling solar radiation, downwelling longwave radiation and emissivity) in key climatic/weather regimes (e.g., windy, calm, gusty, rainy, cloudy, clear, humid, dry, day, night) and key oceanic regimes (warm pool, cold tongue, frontal, equatorial and trade wind).
- Broad-scale precipitation measurements, evaluated against in situ measurements across diverse climate regimes.
- Rain-rate collocated with wind speed and direction measurements in the convective regions of the western equatorial Pacific, ITCZ and SPCZ.

CO_2 flux and ocean color

- Maintain high-quality sea surface pCO_2 sampling regime in the tropical Pacific.
- Maintain broad-scale surface ocean color measurements, with sufficient spatial resolution to identify fronts and changes in regimes, and with sufficient accuracy to diagnose temporal changes.
- Remotely sensed ocean color validated with in situ sampling for chlorophyll-a is required.

SSS

- Maintaining broad-scale SSS sampling with sufficient resolution to characterize sharp SSS fronts in the equatorial zone (also see **Subsurface salinity**).

Sea level

- Maintain high-accuracy, broad-scale sea surface height as well as high-resolution sampling for initialization of ocean "weather".
- Maintain ocean mass and SLP measurements.
- A few permanent directional wave buoys in the tropical Pacific to complement and validate the satellite data and for the validation of current and future wave models.

Subsurface temperature and salinity

- Provide broad-scale sampling of T and S, enhanced resolution through the tropics (approximately 2° x 2°) and better meridional spacing (100 km) and increased vertical resolution (10 m) in the equatorial region.
- Enhanced near-surface salinity measurements under rain bands to study near-surface salinity stratification.
- Strive for the ability to monitor near-surface salinity stratification, specifically in the Warm Pool region, at its eastern edge and under rain bands.
- Provide stable and accurate deep T and S profiles.

Ocean currents

- Surface vector current with a high spatial and temporal resolution, especially in the equatorial band is an emerging requirement to facilitate the assimilation and synthesis of satellite and in situ wind measurements.
- Time series of equatorial subsurface currents for model validation and testing.

3.4.2 The climate record

- Climate change monitoring and detection has stringent requirements for accuracy, duration and continuity.
- The climate record demands redundancy and resiliency against failures of the system components that might otherwise cause damage.
- The diversity of ENSO and its expected future changes will require sampling of the tropical Pacific environment to follow ENSOs spatiotemporal patterns and underpin improved understanding of ENSO prediction and model forecast skills.

3.4.3 Phenomena and processes

This is a summary of requirements for understanding key processes and phenomena; experimental and sustained systems will be needed to meet these requirements.

The near-surface ocean

- Temperature and salinity profiles, and velocity as feasible, with a vertical resolution of about 1 m from the surface to a depth of at least 50 m, and then at intervals of about 10 m to at least 100 m.
- Salinity sampling of the near-surface is particularly important in the west Pacific warm pool.
- Resolve the diurnal cycle of near-surface variables.

Monitoring frontal processes

- Vector wind fields must resolve gradients at scales no larger than 50 km.
- SST (especially) and SSS (as feasible) should resolve space scales of 50 km or smaller in frontal regions, and timescales of a few days at most. These requirements are most critical for the very sharp cold tongue front that varies rapidly.
- Temperature and salinity profiles in the west-central equatorial region (near the time-varying east edge of the Warm Pool) should resolve phenomena at timescales no longer than 5 days.
- Collocated ocean and surface meteorology sampling is especially valuable near frontal regions.

The near-equatorial ocean

- Sampling within 2°S-2°N should include temperature, salinity especially in the west and velocity profiles sufficient to take meaningful meridional gradients, thus at a spacing of about 100 km or less.
- Profiles should include the near-surface (to 5-10 m depth) to resolve the Ekman-diverging layer.
- Sustained monitoring of the near-equatorial system would gain value from a limited-term focused study that sampled more densely and included mixing parameters (section 6.1.2).
- Describing the physical regimes requires observations at targeted representative longitudes.

LLWBCs

- Sustained observing in these regions should include temperature, salinity and velocity sufficient to resolve the volume, heat and freshwater transport variations on timescales of intraseasonal and longer.
- A pilot study should evaluate solutions to meet these requirements most effectively (section 6.1.1).

Intermediate currents

- Velocity measurements to 1000 m or deeper at the equator would add to our understanding and ability to model equatorial dynamics, so pilot studies to do this should be explored.

Biogeochemical processes

- Required measurements at semi-annual timescales spanning the region from 10°S to 10°N include: temperature, salinity, dissolved inorganic carbon, total alkalinity, oxygen and nutrients, from the surface to 2000 m.

- High-frequency observations from 10°S to 10°N of upper ocean properties including chlorophyll fluorescence, particulate backscatter, oxygen, nitrate and pH at critical locations. Enhanced focus on the eastern edge of the Warm Pool, and the east Pacific cold tongue.

4 Design Principles

We have endeavored to generate a design where individual observing 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 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 observations for calibration and validation. Advances in data assimilation systems have also facilitated an integration of observations from diverse array of platforms into products that are readily used by the operational and research communities.

A second fundamental tenet of the design is that the optimal observing system will be an integrated combination of platforms, each bringing particular values and impacts relative to the need. The combination of measurements has greater impact than the sum of the individual contributions through mutually reinforced support. For example, a combination of altimetry, profiling floats and high-density XBT lines can address heat budget requirements in ways that are not possible with any one of the networks alone. Similarly, continuity of measurements and a multiplicity of related measurements, or redundant ones, is absolutely necessary to maintain climate records (see section 3.2.2). Such combinations bring resiliency, both to failure of individual components, and by cross-checking the performance of each component. Chapters 5, 6 and 7 apply this principle in our recommendations for TPOS 2020.

The complementarity and trade-offs provided by different technologies adds to the strength of the observing system. For example, Argo provides high vertical resolution necessary to diagnose water mass variability, but is less able to sample the short timescales. Argo is unable to meet surface meteorology and flux requirements, which must be done by other means. On the other hand, the TMA has rather wide spacing and its vertical sampling is too limited to describe either the mixed layer or the thermocline. However, the TMA provides collocated subsurface and surface meteorology observations that will be important for coupled data assimilation systems. When maintained over time, these fixed-point measurements also provide important climate data records. Given the strengths and weaknesses of different measurement technologies, it is obvious that the observing system design should seek to meet observational requirements so as to exploit the strengths and mitigate the weaknesses of the different technologies.

The question of how to make the best use of these unique capabilities of moored sampling is a central issue in considering the design of the future TPOS. In Chapter 7 we will propose a new balance in the configuration of the TMA: from a grid sampling strategy using many simple moored systems (as implemented currently) to a regime-focused configuration employing more capable moored systems. This change requires careful consideration.

One advantage of the current TMA grid-like configuration is that it allows large-scale fields to be mapped or dynamically analyzed from a single, consistently sampled platform. 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 climate record. With the advances in data assimilation systems that can now integrate diverse sets of spatially sampled data into gridded products, however, the requirements for a grid-like array may be of less importance for some variables. Nevertheless, the grid-like array provides the only present means of mapping the variables that are not directly measured from other platforms (specifically, surface humidity, surface air temperature, and surface air pressure).

The mapping capability of the current TMA grid has important limitations due to being spatially coarse and confined to 8°S-8°N. In some cases, the TMA grid has been shown to track large-scale, but high-frequency (< 3 days) phenomena that may not be well sampled by satellites or the Argo array; examples include Deser and Smith (1998), for diurnal and semidiurnal wind signals, and Farrar and Durland (2012) for oceanic equatorial inertia-gravity and mixed Rossby-gravity waves having periods of days. Yet many other important modes of tropical Pacific variability are not well resolved by the present grid. The typical oceanic first-vertical-mode radius of deformation is 2.2°, so the meridional structures of almost all oceanic equatorial wave modes are poorly detected by the array (e.g., Farrar and Durland, 2012; Farrar, 2008). Tropical instability waves (TIWs), with zonal wavelengths comparable to the nominal 15° spacing of the moorings (e.g., Qiao and Weisberg, 1995), are severely aliased in longitude. The current spacing at 2°S, 0° and 2°N is too broad to characterize the response of the equatorial cold tongue to wind and remotely forced waves (section 3.3.3). These limitations in the ability of the present TMA configuration to observe phenomena that have risen in importance since its original design suggest that a rethinking is timely.

With reduced requirement for grid-like TMA sampling across the entire Pacific basin, a strategy for a regime-based and more complete parameter sampling configuration will target calibration and validation of satellite instruments, particularly in rainy and convective regions (section 3.1.1 and Chapter 5), and will allow addressing of specific deficiencies in the current generation of models. Such a refocusing will take advantage of the unique capabilities of moorings to make progress on the critical phenomena discussed in section 3.3.

Efficiency and effectiveness are of paramount importance for sustained observation systems like the Backbone of TPOS. The response to the requirements in Chapter 3, spelled out in Chapters 5–7, provides recommendations based on the scientific value and technical feasibility of different approaches. Approaches, or their combinations, are recommended based on their ability to address most, if not all of the identified requirements, but also considering efficiency. For example, excellent resolution and/or coverage will cost more but may only achieve an incremental increase in socio-economic benefits. On the other hand, a more expensive system may be more cost-effective if redundancy is essential for a particular variable. One measure of the value or cost-effectiveness of the TPOS is the impact divided by the cost. In our design, we seek to maximize this ratio, usually balancing between an expensive and high-impact solution versus a cheaper but inadequate solution. The opportunity and challenge of the TPOS 2020 design is to try to strike the optimal balance.

Another strategy to enhance impact and cost-effectiveness is to exploit platforms for ancillary observations; the cost of the platform is spread over all the observations enabled by the platform, not just those for which the platform is deployed. For example, ship time to deploy and service moorings and other platforms will continue to be a major expense; however, these cruises provide many opportunities for ancillary work, either as part of the Backbone (e.g., underway shipboard measurements, biogeochemical sampling, deploying autonomous vehicles), or testing new instruments and techniques. Maximizing the use of these cruises offers many opportunities that otherwise would not be possible.

In section 1.3, we introduced general definitions for sustained and experimental observations. The latter category includes trials and pilots of new technology. The TPOS design includes new technology as an integral component (see Chapter 6 and section 7.5), contributing to the evolution in the Backbone within the TPOS 2020 Project timeline and beyond, and complementing the sustained observation response described in Chapter 5.

We note that consideration also needs to be given toward an evolving TPOS 2020 as the data assimilation systems advance and become more reliable in synthesizing a diversity of observations, which may either reduce observational requirement or may call for a different balance. Improvements in data assimilation systems will also facilitate in providing better informed guidance for the evolution for the design of the TPOS 2020 to meet the various requirements discussed in Chapter 3 in a more efficient and cost effective manner.

The OceanObs ’99 Conference (Koblinsky and Smith, 2001) articulated the change in paradigm from proprietary data streams to free and open exchange (observation services as a public good; section 2.4); this had been the hallmark of the Tropical Ocean-Global Atmosphere (TOGA)-era TPOS network. For systems like TPOS, and GOOS and GCOS more generally, this is now considered the norm. The importance of sharing information as quickly as possible (in real time or near-real time), while their relevance and utility to the operational community are at their peak, is understood but is emphasized here to underline its importance for the design; the impact and socio-economic benefits are greatly diminished if the availability of data in real-time is not given priority. In some cases, it is not feasible or practical to do this, but those cases are the exception, not the rule. Delayed-mode exchange of data (with better quality control) is also important, particularly for maximizing information available for reanalyses.

These Principles should be read in conjunction with the GCOS Climate Monitoring Principles (GCOS, 2010; Appendix A) and the WIGOS Observing Network Design Principles (see http://library.wmo.int/pmb_ged/wmo_1160_en.pdf).

The options presented in the following chapters 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 Integrating Satellite and In Situ Observations: Recommendations for the Backbone

The recommendations for TPOS 2020 Backbone systems are based on the sampling requirements across variables (Chapter 3) and the design principles (Chapter 4). The recommendations exploit the complementarity of the satellite and in situ elements of the envisioned Backbone system to meet the requirements of sampling, accuracy, and regime coverage (section 3.1) and to address the science targets (section 3.3).

The most important overall findings of this chapter are to:

- Maintain the continuity of space-based broad-scale measurements of the essential ocean surface variables (vector winds, SSH, SST, SSS, precipitation and ocean color);
- Maintain sufficient in situ measurements to improve the calibration, evaluation and validation of the satellite measurements, and to intercalibrate different satellite missions and instruments;
- Enhance in situ observations of state variables needed to estimate surface heat and freshwater fluxes, focusing on key climate regimes;
- Reconfigure the moored array with more capable moorings, targeting the equatorial circulation, the mixed layer and its interaction with the atmosphere, and key regimes;
- Double subsurface temperature and salinity profiling throughout the tropics through an enhanced Argo presence; and
- Initiate pilot and process studies to guide the future design using the most effective combination of platforms and technologies.

5.1 Ocean surface wind and wind stress

Section 3.1.1.2 has discussed the importance of and requirements for wind (both speed and direction) and wind stress measurements for TPOS 2020, as well as the strengths and limitations of wind and wind stress measurements from different platforms. In particular, wind stress measurements from satellite scatterometers not only provide broad-scale coverage, but with near-uniform and finer spatial sampling that allows estimates of wind stress curl and divergence that are necessary to diagnosing oceanic and atmospheric circulations. However, the accuracy of satellite measurements of wind and wind stress is still an issue in rainy regions, at low or high wind conditions, and varies across different satellite missions (as described below). Ocean models are sensitive to small differences in wind stress products. Therefore, synergistic use of satellite and in situ wind measurements is vital for TPOS 2020.

5.1.1 Issues in rainy/convective regions

Past and current satellite scatterometers are mostly Ku-band (e.g., NSCAT and QuikSCAT) or C-band (e.g., ERS and ASCAT). Ku-band sensors are more susceptible to rain contamination (e.g., Figure 3-1) due to their higher frequency and shorter wavelength comparing to C-band sensors (e.g., ASCAT). Rain contamination is also an issue for C-band scatterometers, though less than for the Ku-band. Rain contamination and differences in how it is flagged result in relatively large discrepancies among satellite wind products in rainy regions (section 3.1.1.2). The lower frequency, longer wavelength L-band scatterometers such as those on Aquarius and Soil Moisture Active-Passive (SMAP) have much less rain contamination. However, these L-band scatterometers have poor sensitivity at low winds. Therefore, none of these scatterometers alone 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. Therefore, in situ wind measurements in rainy regions are important to the evaluation and intercalibration of wind measurements from different satellite wind sensors. Rainy regions are often associated with small-scale wind variations (e.g., updrafts/downdrafts) that are captured differently by satellite wind sensors of different footprint sizes and by fixed-point in situ sensors. This scale-mismatch between satellite and in situ measurements and between satellite measurements with different fields of view can contribute to differences among satellite and in-situ wind measurements in rainy regions, as well as between satellite measurements of different footprints in rainy regions, and thus needs to be accounted for in intercomparisons.

5.1.2 Issues related to the diurnal cycle

Most satellite scatterometers are on sun-synchronous orbits with fixed local equatorial-crossing times (e.g., 6:30 am ascending for QuikSCAT and 9:30 pm ascending for ASCAT), and thus subject to aliasing of the diurnal cycle onto lower frequencies and the time mean. A constellation of scatterometers with local equatorial crossing times that spread across the diurnal cycle will help alleviate this problem. The Ku-band RapidScat on the International Space Station (ISS) does not have a fixed equatorial crossing time (non-sun-synchronous), and thus captures the diurnal cycle in a two-month period over the entire tropical Pacific with 10 realizations at each location. ISS-RapidScat data are thus important for cross-calibration of sun-synchronous scatterometers. However, ISS-RapidScat was not planned as a long-term mission, and is expected to end in a few years. Without it, hourly measurements of buoy winds become more important in de-aliasing diurnal variability in winds captured by sun-synchronous satellites.

In addition to evaluating and intercalibrating satellite wind products in rainy regions and de-aliasing diurnal variability from satellite wind measurements, in situ wind measurements are particularly important for the development of a credible climate record of winds in the equatorial zone. The need for long-term consistency in this region is especially demanding because the global ocean-atmosphere system is highly sensitive to small changes of equatorial zonal wind stress. Long-term records of consistently sampling equatorial winds are therefore required to reference successive generations of scatterometers.

The European MetOp-B satellite and its potential follow-on are the only scatterometer missions that has publicly available, climate-quality vector wind measurements. It is important for the data from ongoing and future scatterometers from countries such as China to become publicly available to enhance the scatterometer constellation. Moreover, the long time series of wind speed measurements from passive microwave (PMW) sensors, such as the SSM/I series, needs to be continued.

Given the requirements described in section 3.1 and issues described above, TPOS recommends:

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

Recommendation 2 In situ vector wind measurements, with particular emphasis on extending the in situ based climate data records, and intercalibrating different satellite wind sensors especially in the equatorial Pacific and in tropical rainy areas.

5.2 Sea surface temperature

SST is one of the most critical variables of the coupled ocean-atmosphere system. As discussed in section 3.1.1, satellite IR sensors provide high-resolution SST measurements in cloud-free regions while PMW sensors provide lower-resolution SST measurements without being obscured by clouds. Diurnal variation of SST and the related air-sea interaction are important to lower-frequency variability of the coupled tropical Pacific Ocean and atmosphere system (sections 2.6.5 and 3.3.1). Both geostationary IR SST sensors and the high-inclination orbit of the GPM Microwave Imager (GMI) are extremely useful for diurnal variability studies, although the former is subject to cloud obscuring while the latter has lower resolution. Despite having lower spatiotemporal resolutions, PMW sensors provide essential measurements through clouds and atmospheric aerosols, and allow accurate correction of the effect of high atmospheric water vapor present in the tropical Pacific. It is likely that by 2020, GMI will be the only operational PMW SST sensor. In contrast to PMW SST, IR SST is relatively well ensured (e.g., the NOAA series AVHRR sensors, and the soon-to-be launched NOAA/NASA Geostationary Operational Environmental Satellite – R Series, or GOES-R, and ESA missions such as the Sentinel-3 series).

Both IR and PMW sensors are affected by rain, potentially producing systematic errors (section 3.1.1.1). This makes in situ SST measurements particularly important for the calibration and validation of satellite SST in rainy regions. The need to translate satellite-derived skin SST to bulk SST further underlines the importance of in situ SST measurements. Drifter-derived SST measurements have broader coverage than

TMA; however, surface drifters cannot maintain the needed spatial coverage at the equator because they tend to diverge from the equator.

Given these considerations, TPOS 2020 therefore recommends:

Recommendation 3 Sustaining satellite measurements of SST, using infrared sensors for higher spatiotemporal sampling; passive microwave sensors filling gaps under clouds; and the diversity of satellite and in situ platforms contributing to intercalibration.

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

5.3 Sea surface height

Future continuity of satellite SSH is reasonably ensured at least until 2030 with the recent launch of Saral/Altika, Jason-3, Sentinel-3 and the planned Jason-CS and the high-resolution Surface Water Ocean Topography (SWOT) mission (scheduled for launch after 2020). However, for TPOS 2020, this continuity is critical to 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 spatiotemporal sampling to capture the energetic eddy variability associated with low-latitude western boundary currents (sections 3.3.4.1 and 6.1.1). SWOT will provide sufficient spatial resolution but insufficient temporal resolution to monitor the eddy variability.

The continuity of ocean bottom pressure (OBP) measurements is important for understanding the nature of regional sea level change through synergistic use of satellite SSH and OBP measurements with Argo observations. Time-varying ocean mass or OBP measurements have been provided by the Gravity Recovery and Climate Experiment (GRACE) since 2003. The GRACE Follow-On mission that is scheduled for launch in mid-2017 is expected to continue the global OBP measurements beyond GRACE. For TPOS, particular emphasis is given to in situ measurements in the central equatorial Pacific, where the weak background OBP variability allows the long-term change in global ocean mass to be most easily detected (see section 3.1.2.2).

TPOS 2020 recommends:

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

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

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

5.4 Precipitation

The GPM Core Observatory, launched in 2014, is extending the 17-year legacy of TRMM (1998-2014) and is expected to provide improved precipitation measurements, including on diurnal and synoptic timescales. International collaboration in the context of GPM is essential to ensure a constellation of precipitation-measuring satellites to enhance the spatiotemporal coverage of precipitation measurements, especially in light of the transient, patchy nature of precipitation (section 3.1.1.5).

Continuation of precipitation satellite missions in the coming decades is critical for TPOS 2020. The current generation of precipitation sensors still has low signal-to-noise ratio under light rain conditions. Satellite precipitation products also show significant differences in tropical deep convective regions (e.g., Liu and Zipser, 2014). Substantial differences in precipitation exist in much of the western and central tropical Pacific as well as under the ITCZ among various precipitation estimates (including observation-based and reanalysis products). In situ measurements of precipitation are thus important to the evaluation of different precipitation products. The patchiness of precipitation, however, means that point in situ measurements of precipitation may not be a good representation of the spatial averages derived from satellites except in long time averages. Despite this, the abilities of in situ measurements to resolve diurnal variations and long-term changes of precipitation are important to the evaluation of different broad-scale precipitation products.

TPOS 2020 recommends:

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

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

5.5 Sea surface salinity

The Argo array has revolutionized the broad-scale monitoring of SSS (sections 3.1.1.6 and 3.1.3.1) and can characterize large-scale (hundreds of kilometers) SSS variability, but does not provide SSS measurements with sufficient spatiotemporal sampling to depict the finer-scale features, such as the sharp meridional SSS gradients and fronts whose importance has been described in section 3.1.1.6.

Satellite SSS, with progressive improvement in quality in the past few years (the recently released Aquarius Version-4 SSS has reached 0.1 psu accuracy over much of the tropics on monthly timescales; Lee, 2016) is complementary to Argo and VOS TSG data by filling in spatiotemporal sampling gaps of the sparser Argo/VOS array and enhancing the capability to characterize SSS fronts at scales not adequately resolved by Argo, or sampled at very high-resolution (1-2 km) but only along specific lines by the VOS. The higher-frequency measurements of SSS from the TMA further fill the temporal sampling gap by allowing spectral diagnoses that shed light on the patchiness of SSS, and provide an additional and independent dataset to evaluate satellite SSS. Satellite SSS (in the top cm), TMA buoy measurements of SSS (at 1 m), VOS TSG measurements representative of the 0-10 m layer, and Argo measurements of salinity (2-5 m) together are helpful to study near-surface salinity gradients which contribute to the difference between satellite SSS and in situ measurements of near-surface salinity. Specialized in situ instruments, such as Argo floats equipped with the Surface Temperature and Salinity (STS) sensors and drifters that are equipped with shallow sensors in the top tens of cm, can be used in process-oriented mode to further study the physics associated with near-surface stratification.

With the loss of NASA's salinity-measuring Aquarius satellite and with ESA's Soil Moisture and Ocean Salinity mission 6 years into operation, the continuity of SSS measurements is in doubt. NASA's Soil Moisture Active-Passive (SMAP) was designed for land applications. Even though SSS is being retrieved from its radiometer, achieving the accuracy of Aquarius SSS (e.g., as described in Lee, 2016) remains a great challenge due to the loss of SMAP's radar that would otherwise deliver surface roughness measurements that are critical for SSS retrieval. There is currently no ocean salinity satellite mission planned for the next decade and beyond. The increasing use of satellite SSS to study tropical ocean dynamics and climate variability (especially on spatiotemporal scales not afforded by in situ platforms) and the continuing improvement of satellite SSS retrievals support the need to continue the space-based SSS measurements.

TPOS 2020 recommends:

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

Specialized in situ sensors with near-surface (in the top meter) sampling capability are needed to further study the processes associated with near-surface salinity stratification. Enhancement of in situ meridional sampling in the equatorial zone is needed to evaluate satellite-derived SSS gradients and resolve the dynamics there.

5.6 Ocean surface currents

Satellite wind stress measurements characterize the momentum transfer between the ocean surface wind and the moving ocean surface. In situ wind measurements that have coincident measurements of ocean surface currents allow a better evaluation of satellite-derived wind stress. As mentioned in section 3.1.3.2, satellite-derived estimates of surface currents near the equator are subject to larger uncertainty. Direct measurements of ocean surface currents therefore become even more important near the equator. Moreover, the bulk (averaged) Ekman currents over the mixed layer estimated from scatterometer-derived winds do not represent the Ekman velocity at the surface of the ocean (because of the Ekman spiral). Remote sensing technologies to measure surface currents directly (e.g., using satellite Doppler radar) are being developed, but experimental missions are some years away.

Some progress may come from efforts to directly measure velocity to within a few meters of the surface (section 3.3.1). These efforts are motivated by the need to diagnose the mixed layer diurnal cycle and also the structure of Ekman divergence from the equator. While not the surface current itself, such measurements would give insight into the structure of near-surface shear and a clearer understanding of the response of near-surface currents to winds and their relationship to stress.

TPOS 2020 recommends:

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

5.7 CO_2 flux, ocean color and biogeochemistry

As discussed in section 3.1.1.4, satellite ocean color measurements are important to the studies of tropical Pacific Ocean biogeochemistry and can also be used in ocean models to determine the depth of solar penetration (also see TPOS WP#4, Balmaseda et al., 2014). The Coastal Zone Color Scanner (CZCS) pioneered ocean color measurements from space from the late 1970s to the mid-1980s. After a long gap, the SeaWIFS provided ocean color measurements from 1997 to 2010. The Moderate Resolution Imaging Spectroradiometer (MODIS) on Terra and Aqua satellites and Medium Resolution Imaging Spectrometer (MERIS) continued the legacy since the 2000s. This is followed by the Visible Infrared Imager Radiometer Suite (VIIRS) and the recently launched Sentinel-3A. These current missions, together with planned missions in the future such as ocean color sensors on the planned Plankton, Aerosol,-Cloud,-ocean Ecosystem (PACE), Global Change Observation Mission for Climate Research (GCOM-C) and VIIRS on the Joint Polar Satellite System, are expected to sustain satellite ocean color measurements into the 2020s.

While previous retrievals of satellite ocean color were focused on global calibration, recent work has emphasized the importance of regional retrievals. Continued in situ sampling of the tropical Pacific that includes color would facilitate high-quality algorithms for this moderately productive region. As described in Report #13 of the International Ocean Color Coordinating Group (IOCCG, 2012, page 74), water-leaving radiance is the principal in situ measurement needed for calibrating satellite ocean color sensors. These observations can be made from moorings, but data quality is easily compromised by bio-fouling. A better strategy would be to make automated above-water measurements from ships.

Measurements of other biogeochemical processes and air-sea CO_2 flux cannot be made using satellites and require in situ observations (sections 3.1.1.4 and 3.3.5). Given the significant interannual and decadal variability observed in the physical state of the tropical Pacific Ocean, the potential effects of climate change, impacts on ecosystems and considering the requirements discussed in sections 3.1.1.4 and 3.3.5, TPOS 2020 recommends:

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

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

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

5.8 Surface heat and freshwater fluxes

Surface fluxes are critical to diagnosing the processes associated with ocean-atmosphere coupling (see section 3.1.1.3). Climate prediction centers around the world are developing coupled ocean-atmosphere data assimilation systems. As these strive to estimate surface fluxes consistent with the state of the ocean and atmosphere simultaneously, observation-based surface flux measures become even more important. Surface heat and freshwater fluxes cannot be observed directly by satellites, but are rather estimated from state variables using bulk formula for the turbulent (latent and sensible heat) components of surface heat flux and for the evaporation component of surface freshwater flux (sections 3.1.1.3 and 3.3). These estimates are subject to relatively large error due to the uncertainties of the state variables as well as the transfer functions and coefficients. The spatial and temporal scales of these are often not well enough resolved to confidently calculate fluxes that depend on several variables at once. 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 (TPOS WP#11, Cronin et al., 2014). This is compounded by the lack of satellite measurements of surface air temperature and relative humidity.

As explained in Chapter 3 (section 3.1.1.3), an approach to these challenges is to target comprehensive in situ observations of all flux state variables in key climatic/weather regimes and key oceanic regimes. While the current TMA spans nearly the full zonal extent of the basin between 8°S and 8°N, the sampling does not extend across the tropical convergence zones and into the trade wind regime, and only a few sites along the equator allow long records of the full air-sea heat and moisture fluxes to be estimated (Figures 3-4 and 3-5).

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 timescales 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 timescales 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, resolving the diurnal cycle is crucial (section 3.3.3). 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.

For air-sea flux fields, in particular for heat, freshwater and carbon, the design options are limited by the lack of available broad-scale measurements and by the high premium placed on quality. In general, we do not have multiple lines of complementary information, and the ability to use models to supplement direct observations is limited.

As discussed in sections 3.1.3.2 and 3.4, the design gives priority to impacts in understanding and consequent improvements in models as the main line of benefit (see also section 3.3). The observational requirements flow from testing and validating standalone and coupled ocean and atmosphere models and, in particular, the boundary layer components of those models. There is, however, a complementary monitoring (climate record) element (section 3.2).

A consequence for the design is that resources should be directed to those places, times and regimes where this impact of the observations will be greatest. The value derives from increased understanding of critical processes and phenomena (section 3.3) rather than routine applications, at least until there are significant advances in the representation of planetary boundary layers in operational models. The impact is likely to be highest when such campaigns coincide with and support intensive observations of the boundary layers and surrounding regions.

Based on the discussion in Chapters 3 and 4 and the considerations above, TPOS 2020 recommends:

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

5.9 Subsurface ocean observations

Recommendations for subsurface observations build on the premise that we must meet variable requirements with an integrated mix of observational types, exploiting the characteristics and strengths of each through an integrated observational response that is more powerful than the capability of any single approach (section 2.5; Chapter 4).

The Recommendations respond to the variable requirements discussed in sections 3.1.3 and 3.2, but also consider the base (reference) measurements needed for improved understanding (section 3.3).

We recognized in the design (Chapter 4) and acknowledge again here that models and data assimilation are an essential part of the observational response, synthesizing disparate information into regular forms and spreading (extrapolating) information in space and time. However, at this point in the evolution of the TPOS, the additional capability provided by models and data assimilation for subsurface ocean fields is modest and not at the level of Numerical Weather Prediction (NWP) and associated atmospheric reanalyses. TPOS 2020 recommends:

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

Further elaboration is below.

5.9.1 Equatorial ocean and surface mixed layer

Meridional and vertical scales are shorter in the equatorial and mixed layer regions, respectively, and temporal scales shorter in both (see section 3.1.3). Only fixed-point or new float technologies with rapid cycling can resolve these, but no one technology can fully meet all of the requirements and a mix of technologies and/or enhancements is needed to respond fully:

- Moorings for high temporal resolution and reference (point) climate records;
- A combination of moorings and profiling floats are needed to resolve the mixed layer;
- Selected mooring line enhancements and/or enhanced profiling float densities for near-equatorial meridional resolution;

- Selective use of current meters on moorings to improve understanding of mixed layer dynamics;
- Use a combination of moorings and profiling floats to meet zonal sampling requirement; and
- Line measurements for meridional sections where possible.

TPOS 2020 recommends:

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

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

As explained in section 3.1.3.2, the ADCPs on equatorial moorings, which give currents at 110°W, 140°W, 170°W, 165°E and 147°E, are highly valued by the modeling community and routinely used to validate ocean data assimilation and simulations. TPOS 2020 recommends:

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

Because moorings are also essential for meeting surface meteorological and flux requirements, they are the core element of the mix. Note also that space-based measurements make an indirect contribution (see SSH Recommendation 6 above).

5.9.2 The tropics out to ~10°S/N

Away from the near-equatorial zone, the temporal observation demands ease, but zonal scales shorten with a transition to a mix from equatorial and mesoscale variability. Initialization of models is governed more by ocean weather requirements (the mesoscale) than equatorial dynamics. Chapter 3 concludes that temperature- and salinity-scale requirements should be more demanding, in effect requiring a doubling of the number of profiles (see section 3.4 in particular).

Profiling floats can more effectively meet such variable requirements, especially when considered in conjunction with SSH measurements (see SSH Recommendation 6 above). The high temporal sampling rates of fixed-point observations are not as critical (at least for temperature and salinity profiles) as they are in the equatorial zone but still contribute to meeting requirements, particularly in areas where the signal-to-noise ratio is low and frequent observations are needed. TPOS 2020 recommends:

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

5.9.3 Boundary current regions

In the low-latitude western boundary current (see section 3.3.4.1) and eastern coastal regions the cross-boundary scales are small, and to this point, no single technology has been proven as a complete observation solution. These regions are important for mass and heat balance over long timescales, so the need for accuracy is demanding. As section 3.3.4.1 notes, observational solutions have remained elusive, partly because of the technical demands and partly because of the cost. Gliders or similar technologies offer promise but are not yet established as a sustained observation solution.

Chapter 6 discusses Pilot Projects to determine the optimum mix of observational technologies (see section 6.1.1 in particular) and the specific Action in Chapter 7.

5.9.4 The TPOS region in general

Poleward of 10° latitude the designs of Argo and satellite altimetry specifically target the variable requirements. There are specialist roles for ship-of-opportunity XBT/XCTD lines, GO-SHIP deep surveys and point measurements for high-quality records (OceanSITES; see http://www.oceansites.org/).

The fact that profiling floats and fixed-point measurements contribute observations through all these regions means that we will have a blended solution stretching from the equatorial zone of the tropical Pacific to midlatitudes. The integrated observational solution removes artificial boundaries arising from the limited meridional extent of the TMA. Together, the current Argo array and the TMA are able to capture subsurface temperature variability for timescales longer than 30 days (Gasparin et al., 2015; see also Figure 5-1) but would needed enhancement to capture shorter periods (see discussion in Chapter 7).

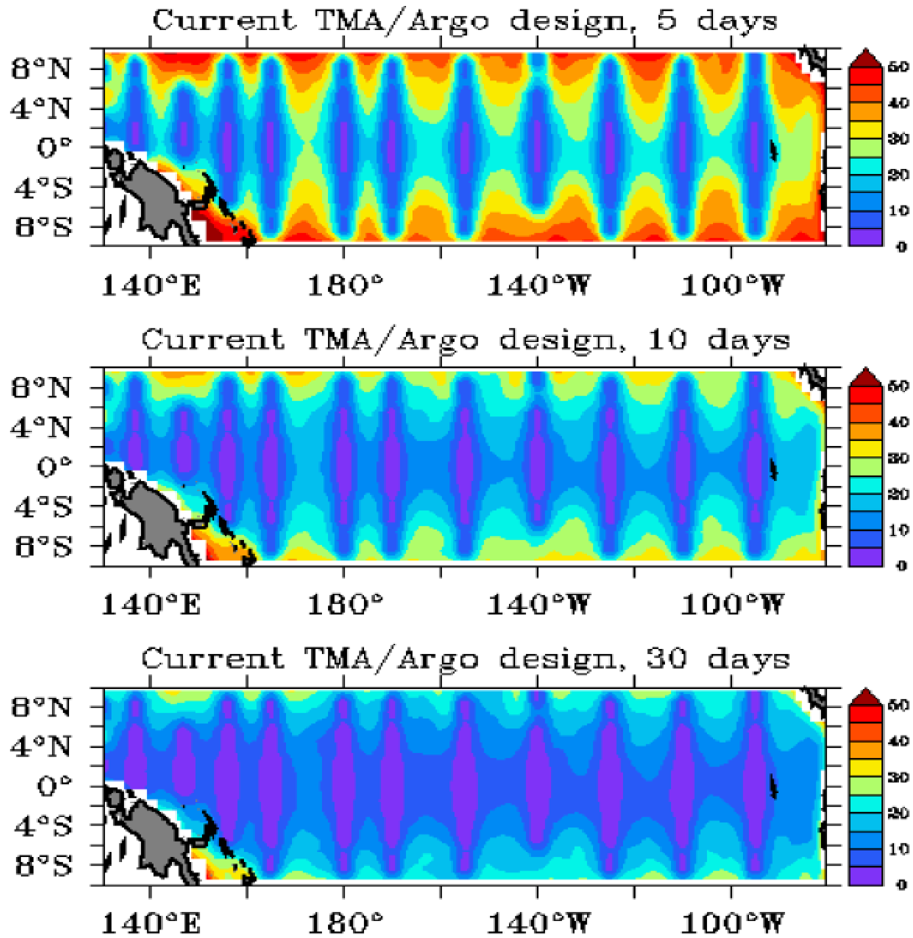


Figure 5-1: A calculation of the error as a percentage of the temperature variance signal at σ=25 depth that can be recovered using current TMA and Argo sampling designs. The covariance function is the one used in Gasparin et al. (2015), with percentage errors estimated at different timescales: 5 days (upper), 10 days (middle) and 30 days (lower). Red denotes large errors and poor signal recovery. Courtesy of Florent Gasparin.

6 Evolution of the Observing System

Chapter 1 noted the difference between sustained and experimental observations. Chapter 5 provides recommendations for sustained observations as part of the Backbone, directly responding to the requirements articulated in Chapter 3, and following the Principles introduced in Chapter 4. These sustained observations primarily support public good services such as seasonal forecasting systems, but have an additional role as infrastructure for research and development.

Figure 6-1 (an adaptation of a figure from the Framework for Ocean Observing; UNESCO, 2012) attempts to show the relationship of this Chapter with the preceding Chapters and with the Chapter on transition and implementation (Chapter 7). The Pilot and Process studies introduced here are an integral component of the TPOS framework, improving the design and the effectiveness and efficiency of the Backbone, including its implementation.

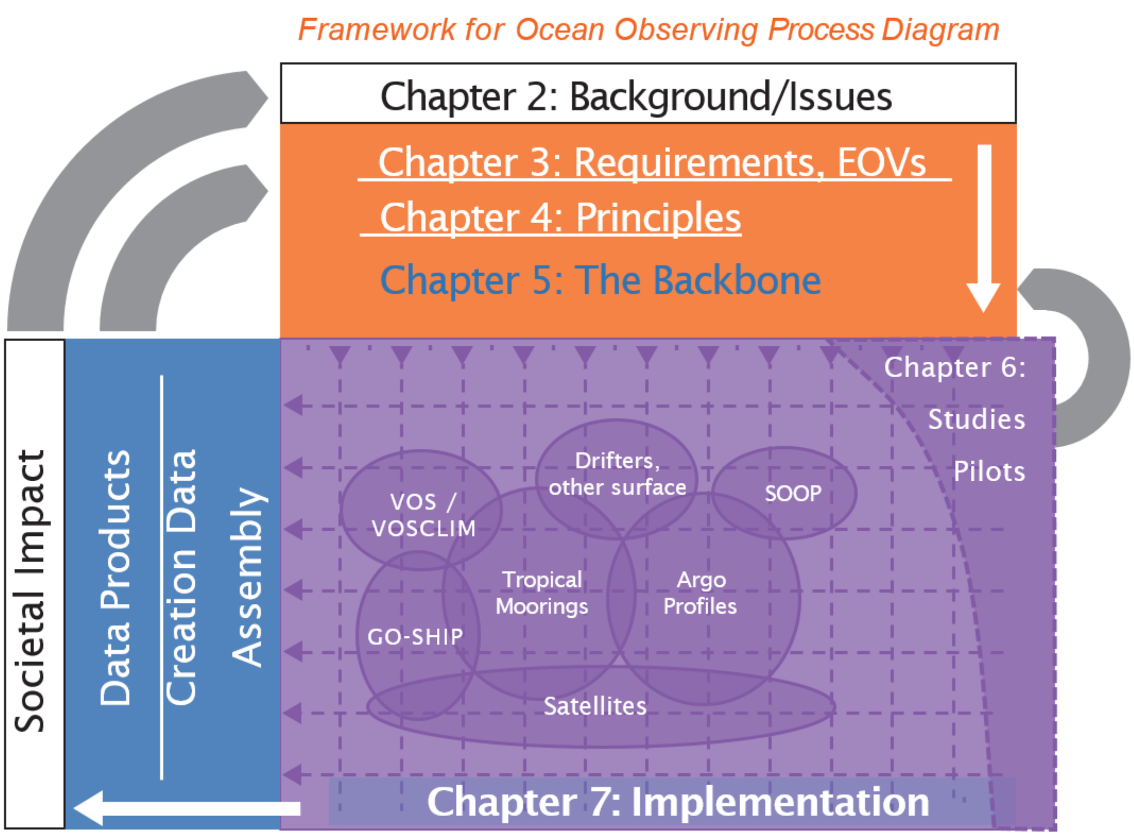


Figure 6-1. Schematic showing the chapter flow of the report, including Chapter 6, referenced against the architecture of the Framework for Ocean Observing (UNESCO, 2012). Pilot and Process studies are an integral part of the evolving design and implementation.

This Chapter introduces a number of proposals for guiding the evolution of the observing system, either through specific pilots, primarily associated with section 3.3, or through process studies and other activities that will improve our understanding and/or improve the efficiency and effectiveness of the design and implementation of TPOS.

The following terminology is adopted.

A "**Pilot**" is a small-scale preliminary activity/study conducted in order to evaluate feasibility, cost, risks and sampling strategy ahead of a full-scale campaign. A "**Pilot Study**" (or Pilot Experiment) is thus a research study conducted before the full Process Study or Experiment. They are usually implemented on a smaller scale.

A "**Pilot Program**" (sometimes Project) is a feasibility study or trial, usually conducted on a small scale or for a limited period, to evaluate feasibility, cost, risks and observational options ahead of sustained implementation. In the context of TPOS and GOOS, such Pilots allow the community to prove the effectiveness and sustainability of an approach before sustained commitments. The outcome is a tested and evaluated contribution to the TPOS Backbone. The outputs are sampling requirements, platform-mix recommendations, etc.

In this Chapter we use the term "**Process Study"** for research experiments, usually with a phenomenological focus, where the outcomes are scientific and the outputs might include improved knowledge, parameterizations and techniques. The results of a Process Study might point to future sustained observations or refinement of the Backbone sampling. The Process Studies in section 6.2 have been chosen to focus on phenomena that are central to Pacific climate, but where too little is known to design a sampling strategy, or where the need for sustained observations has not been demonstrated.

There is a tendency in the literature of ocean observing systems to use the terms "Pilot Study", "Pilot Project" and "Pilot Program" interchangeably. This is particularly the case where the Pilot has mixed objectives, which is often the case for the Pilots introduced below.

The proposals seek to advance knowledge, explore technical innovation, and/or lead to improvements in the effectiveness and efficiency of the TPOS. In some cases, the target period is wholly within the time-frame of TPOS, while in other cases the period may go beyond 2020.

A number of relevant proposals have been funded as part of a NOAA technology initiative explicitly in support of TPOS 2020. Abstracts of these proposals are included in an annex to this Chapter.

6.1 Pilot studies/programs for the Backbone

6.1.1 Observing Western Boundary Current systems: A Pilot study

Summary

This project is a pilot study aimed at providing guidance in the design of an optimal sampling strategy to resolve the mass, heat and freshwater transports within the low latitude western boundary currents (LLWBCs) of the Pacific Ocean.

Background

The LLWBCs of the Pacific, including the interbasin exchange of the Indonesian Throughflow (ITF), play crucial roles in ocean dynamics and climate variability on both regional and global scales. As a key pathway by which the tropical Pacific interacts with the subtropical ocean, we see a clear need to integrate their measurement with that of the region to the east (see section 3.3.4.1; Hu et al., 2015; Ganachaud et al., 2014; Sprintall et al., 2014). A key conclusion from the community consensus on sustained ocean observations, including both OceanObs'99 (Smith et al., 2001) and OceanObs'09 (Fischer et al., 2010), was that sustained boundary current and interbasin exchange observations are primary missing elements of the global ocean observing system.

Three major LLWBC programs have taken place over the past 10 years, mostly coordinated through **CLIVAR**. Southwest Pacific LLWBCs have been measured, modeled and analyzed within the **CLIVAR-SPICE** program since 2008 (www.spiceclivar.org). Monitoring of the New Guinea Coastal Undercurrent system has been achieved in the inflow region through gliders / Profiling Inverted Echo Sounder (PIES) moorings and in the outflow region through a mooring array. Similarly, a moored array within the northwest Pacific LLWBCs has been maintained through the **CLIVAR-NPOCE** program since 2010 (npoce.qdio.ac.cn). The **INSTANT** program from 2004 to 2006 simultaneously equipped the inflow and outflow passages straits of the ITF with moorings so that transports, pathways and water mass transformations could be quantified for the first time. More recent ITF observations are maintained through individual programs sponsored via various international efforts. While these LLWBC programs have improved our knowledge of these important components of the large-scale circulation, many fundamental questions about the pathways, structure and variability of these boundary currents on climate timescales remain unanswered. Clearly there is a need to develop an integrated strategy toward an internationally sustained LLWBC observing system.

Building on our knowledge from the past efforts in the LLWBCs, we propose to develop a pilot array consisting of a variety of observations from multiple and complementary platforms that simultaneously survey the major elements. The recent ITF, SPICE and NPOCE programs include some synchronous measurements and therefore provide a valuable starting point to sustained measurements. The fundamental idea is to evolve these international short-term process-oriented boundary measurements to a larger coordinated pilot array and then toward a sustained system.

Proposed Action

Sustained observing in these regions should involve coverage of temperature, salinity and velocity in order to resolve the volume, heat and freshwater transport variations of the major water mass streams on timescales of intraseasonal and longer. The future TPOS for the LLWBCs should be built using knowledge garnered from the past and existing measurement arrays. However, no single observational technology is presently available that adequately samples the full latitude/longitude/depth/time structure of the tropical LLWBCs. For example, while single point moorings provide high-resolution simultaneous time series of velocity and properties in the boundary currents, they often lack temperature and salinity measurements in the near-surface layer where the instruments are more vulnerable to strong tidal currents, shipping traffic and vandalism. For the same reason, few of these moorings have air-sea flux measurements of the planetary boundary layer. Transects from gliders and new technology, such as wave gliders and Saildrones, offer some possibility of obtaining the near surface measurements, although these measurement platforms could potentially suffer from temporal aliasing of signals because of slower survey patterns. Clearly LLWBC observations will be best achieved through a combination of measurement platforms of line-mode transect networks, including shipboard repeat hydrography, High-resolution XBT lines (HRX), gliders and moorings, along with broad-scale in situ (e.g., Argo, drifters) and remotely sensed measurements.

The goal of the pilot study would be to develop an integrated network design consisting of these multiple in situ observational types, including synergistic high-resolution satellite measurements to determine the right mixture of spatial, depth and temporal sampling characteristics required to sample the boundary current regions.

Expected Outcome

The pilot array would determine the key observational sites in the LLWBCs, decide on the variables to be observed in terms of priority and readiness of technology, and most importantly, determine the time and space scales that must be resolved in order to develop a sustained boundary observing system.

Relevance to TPOS Strategy

Building on the interest and international impetus from existing programs within the Pacific boundary regions, an internationally driven pilot study would foster continued and focused interaction and collaboration between the TPOS and these international programs. A pilot array 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.

The pilot array would also contribute to the "Wyrtki Challenge" (see Task Team activities in Chapter 10). For example, high-resolution model simulations dedicated to the Wyrtki Challenge might provide guidance for the Pilot Study in terms of the necessary horizontal and vertical scales required to adequately resolve the heat and freshwater transports of the LLWBCs. In turn, the Pilot Study will provide key boundary current measurements to test the veracity of the model simulations.

By quantifying the volume fluxes into the TPOS region, this pilot would make a significant step toward understanding biogeochemical tracer fluxes. The pilot study and the observing criteria that emerge from it should include, where possible, measurements of carbon, oxygen, nutrients and trace metals—in particular iron, which is associated with plankton variations in the central Pacific.

6.1.2 Eastern Pacific equatorial-coastal waveguide and upwelling system

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, high levels of ocean productivity, extensive oxygen minimum zones (OMZs), 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 (TPOS WP#8a, Takahashi et al., 2014). Within TPOS 2020, current efforts focus on two major themes: the equatorial/coastal waveguide and upwelling (this section), and the ITCZ/warm pool/cold tongue/stratus system (section 6.2.5).

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., 1999, 2003; 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 at higher densities on subweekly timescales; one way to do this would be a regional enhancement of the proposed Argo density increase (sections 7.3 and 7.4), with some of the floats on rapid cycles and the maintenance of some existing coastal measurements. Additionally, the connections between the coastal environment and the open ocean, through mean currents and/or mesoscale circulations (Montes et al., 2010, 2014) are not well known but are important for ecosystem management and understanding the role of the east Pacific upwelling system on climate change (i.e., the biological pump).

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[8] data) to reduce their errors, particularly in cloudy regions such as the coastal upwelling and convective regimes. Atmospheric and ocean observations across the coastal upwelling zone would elucidate the ocean-atmosphere interaction processes, including the controls of surface fluxes, the vertical and cross-shore structure of upwelling and the resulting effects on SST and the emergence of biogeochemical properties. This would also shed light on local influences on the passage of remotely forced Kelvin waves, and the effect of those waves on the local environment.

On interannual timescales, 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., TPOS WP#8a, Takahashi et al., 2014), necessitating focused attention to mechanisms. Better understanding of the physical processes, particularly ocean upwelling and mixing, will require observations 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 Planetary Boundary Layer (PBL) and Eastern Pacific (EP) task teams will propose a design for the necessary oceanic and atmospheric observations.

Proposed Action

Study the feasibility of a pilot array to observe the coastal upwelling zone off Peru. Potential elements would include in situ winds and surface fluxes (including coastal sites), and direct observation of ocean vertical structure. Ongoing and historical cruise data should be used to guide possible sampling strategies and spatiotemporal scales to resolve the cross-shore and vertical patterns of ocean subsurface temperature evolution in response to wind changes on intraseasonal and lower frequencies. Consideration should be given to the inclusion of biogeochemical variables in this sampling, in particular surface productivity, $p\mathrm{CO_2}$ and the depth structure of oxygen to resolve the OMZ. Adequacy of high-resolution satellite products in coastal upwelling regions will be assessed.

6.1.3 Determining the critical time and space scales for biogeochemistry in TPOS

Summary

In contrast to the level of knowledge around surface ocean $p\mathrm{CO_2}$ and air-sea CO_2 fluxes, surface and subsurface gradients in other carbon parameters, nutrients and oxygen are poorly known. This section outlines the pilot program necessary to inform the backbone biogeochemistry observations for the TPOS.

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[8] Group for High Resolution Sea Surface Temperature; https://www.ghrsst.org/

Background

The 30-year record of pCO_2 measurements, mostly collected from mooring servicing voyages, has provided the most significant biogeochemical climate record for the tropical Pacific (Figure 2-8 in section 2.6.7). These data have made it possible to determine the change in the basin-wide air-sea CO_2 flux in response to ENSO, and shown that the magnitude of the flux (0.5 to 1.0 PgC per year) is significant in the context of global anthropogenic emissions (Feely et al., 2006). At the peak of the observational program, each mooring line was occupied twice yearly, which resolved the interannual variability in the basin-wide fluxes, but not the intra-annual changes in zonal and meridional gradients. Variability at these scales will be important to quantify in the context of future emissions accountability. In contrast to the level of knowledge around CO_2 fluxes, surface and subsurface gradients in other carbon parameters, nutrients and oxygen are poorly known. Oxygen is in need of greater attention because its consumption at depth is related to carbon uptake at the surface, low oxygen zones are important sites of nitrous oxide production, and expanding OMZs would reduce habitat for marine life. The Global Ocean Oxygen NEtwork (GO_2NE) is at least partially addressing this issue via a retrospective analysis of O_2 observations. This section outlines the analyses and pilot program necessary to inform TPOS biogeochemistry observations.

Proposed Action

Two of the pilot projects recommended by the BGC Task Team (TT) in 2015 have been funded by NOAA/CPO to evaluate new technologies for TPOS. First, the Saildrone project (see section 10.2.2) will test the ability to make climate-quality pCO_2 measurements from an autonomous surface vessel. The long term goal of this project is to supplement the zonal and meridional coverage of pCO_2 observations previously made by the TAO mooring servicing ship (section 2.6.7). Second, standard Argo temperature/salinity floats will be equipped with sensors to measure dissolved oxygen, pH and chlorophyll in the upper 2000 m of the ocean, plus acoustic wind speed and rainfall measurements (see section 10.2.1). These highly resolved profile data will contribute to the BGC TT's efforts to determine the time and space scales for subsurface biogeochemistry measurements in TPOS. Below is a proposal for additional important analyses on this same theme.

A coordinated process and modeling study is also needed to further resolve the spatial scales for BGC implementation in TPOS. This would be facilitated by analyzing vertical and horizontal gradients in three related data sets:

1. A retrospective analysis of existing data. From the NOAA voyages in the late 1980s and early 1990s, to measurements on TAO deployment cruises from the late 1990s to early 2000s, there exists a large body of water column data spanning physics, nutrients, oxygen, carbon, chlorophyll and productivity. JAMSTEC also conducted shipboard observations of nutrients, carbon and productivity in the western part of the tropical Pacific in the late 1990s and early 2000s.

2. New hydrographic surveys along existing TMA lines with full water column physical and biogeochemical observations. The first survey would be completed prior to 2020 with the goals of improving model parameterizations, such as carbon export, and informing the final TPOS Backbone design. This survey could be paired with the equatorial upwelling and mixing process study proposed by the PBL and EP TTs. In order to constrain biogeochemical processes across different modes of ENSO and decadal variability and to validate TPOS biogeochemical sensors, these hydrographic surveys should be repeated as a part of dedicated field surveys. The two major differences between these surveys and the existing data described in point 1, are that the coverage will be quasi-synoptic and will include a more comprehensive and standardized set of parameters.
3. Modeling. The existing model output collections and new simulations informed by points 1 and 2 should be analyzed to determine the critical scales of biogeochemical parameters as well as the timescales over which biogeochemical fields emerge above the noise level of natural variability.

Much of the data and model outputs for points 1 and 3 above already exist, and point 2 can be achieved through participation in process studies being proposed by other TTs (e.g., section 6.2.2).

Phenomena and scales of particular interest:

Spatial gradients associated with vertical mixing, downwelling Kelvin waves, and TIWs will be discerned from model output, because these phenomena are not accurately captured by synoptic ship surveys.

The extent of low oxygen zones (regions of nitrous oxide production) and the impact of ENSO and Pacific Decadal Oscillation (PDO) phase would be assessed from both model output and shipboard data.

The subsurface CO_2 source pathways to the EUC need to be understood (see also section 6.2.2). 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 timescales by ENSO and the PDO (McPhaden and Zhang, 2002, 2004). Hydrographic surveys described above, separated by several years and in conjunction with modeling would help to address this question.

Other key phenomena that need be addressed by the Backbone system and targeted process studies include: (1) the role of the EUC is in oxygenating the ecosystem; (2) the consequences of variability and long-term change in primary productivity for higher trophic levels; (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.

Expected Outcome

The most significant unknown for the BGC TT is the range of spatial scales at which we need to observe nutrients, oxygen and productivity. This pilot program will determine the key time and space scales that must be resolved by sustained biogeochemical observations in TPOS.

Relevance to TPOS Strategy

These activities, conducted in the context of already funded biogeochemistry projects (see sections 10.2.1 and 10.2.2) and other recent work (Rodgers et al., 2015), will inform TPOS decisions to prioritize biogeochemical assets on ships, moorings and other autonomous platforms.

6.1.4 Direct measurements of air-sea fluxes, waves and role in air-sea interaction

Summary

This pilot study will test the ability to measure direct covariance fluxes (wind stress and air-sea buoyancy flux) and surface waves from moored buoys and autonomous surface vehicles (e.g., wave gliders and Saildrone) in the tropics. Wave measuring surface drifters will also be tested. The effect of waves on air-sea fluxes and upper-ocean mixing will be studied.

Background

The ocean and atmosphere interact through air-sea fluxes. Turbulent air-sea fluxes of momentum (wind stress) drive the ocean gyres and set up the equatorial current structure, and turbulent air-sea latent and sensible heat fluxes are the primary means by which the ocean forces the atmosphere. Due to the Clausius-Clapeyron relation, latent heat flux is particularly strong over warm water, such as found in the equatorial Pacific Warm Pool and along the thermal equator north of the geographic equator, where the ITCZ is found. Yet direct measurements of turbulent fluxes are very limited. Direct measurements rely upon the direct covariance (or eddy correlation) method. This method requires careful accounting of platform motion and flow distortion. For this reason and because of the power requirements, the vast majority of open ocean observations come from research-grade flux systems on oceanographic research vessels (e.g., Edson et al., 1998; Fairall et al., 1996). In contrast, numerical models and most autonomous platforms such as from moored buoys rely upon a bulk algorithm to compute these turbulent fluxes from state variables. For most bulk algorithms, these state variables include wind speed, air temperature, humidity and SST. Other state-of-the-art bulk algorithms (e.g., Fairall et al., 1996, 2003; Edson et al., 2013) also include sea surface currents as state variables, and this can be particularly important in the tropics where the winds are weak and the currents can be strong (Kelly et al., 2001). At the forefront of this research is determining how the wave state of the air-sea interface influences these turbulent fluxes. In particular, swell generated from afar cannot be parameterized in terms of local wind speed and therefore may need to be directly measured as a state variable. In the tropical Pacific, it is particularly important to measure the fluxes directly as it is an expansive region with most of the factors that can lead to biases in bulk fluxes: contributions from large ocean swell, surface currents, light winds, variability associated with convective downdrafts and decoupling of the stress and wind vectors.

In addition to affecting the air-sea exchanges, waves can also generate Langmuir circulations that can result in enhanced ocean mixing. Understanding and forecasting waves also has its own importance, particularly for island nations and ship traffic. Through this pilot study we hope to develop strategies for making air-sea flux and wave in situ observations.

Proposed Action

In this pilot study we propose measuring direct covariance fluxes from a variety of different platforms, including research vessels (this would be the reference for intercomparisons), TPOS surface buoys, and autonomous vehicles such as from wave gliders and Saildrone. Recent technological advances in low-power ultrasonic anemometers and platform motion correction systems have allowed deployment of Direct Covariance Flux System (DCFS) on discus buoys in the CLIvar MOde Water Dynamic Experiment (CLIMODE) and the SPURS-I. Such a system could potentially be deployed as a standalone system, with its own power and telemetry, on the tower ring of a TPOS moored buoy. The location of the system package would be carefully tested to be sure that it did not interfere with the operational observations (e.g., wind).

The navigational systems on these platforms are now sufficient to estimate wave characteristics. The issue, though, is whether these platforms are truly wave-following. For a reference platform, the Datawell waverider tethered moored buoy is considered the gold standard and would be used as the reference. Un-drogued drifters and surface autonomous vehicles also provide new exciting ways to measure waves and will be tested here. The research vessel, mooring and floats will also provide upper ocean profiles to study the effect of these waves on mixing.

For the intensive observational period with the ship observations, a location will be chosen that will likely have large swell and a variety of wind conditions. A follow-on study in a high-wind region (e.g., typhoon alley) could involve the moored buoy and autonomous surface vehicles enhanced with these wave and flux systems.

Aspects of this proposed action have been supported in a new technology Project (see section 10.2).

Expected Outcome and Relevance to TPOS Strategy

The pilot study will determine the best strategy for measuring direct fluxes and waves within TPOS. Direct flux observations from TPOS buoys would reduce the current bulk-derived turbulent heat flux uncertainty of 11 W/m^2 to 5 W/m^2 on a 1-month average (TPOS WP#11, Cronin et al., 2014) and would add significantly to the scientific value of TPOS buoy observations (Fairall et al., 2010). Direct measurements of surface stress will add greatly to the value of the buoys for calibration and validation of satellite scatterometers (because they are sensitive to wind stress rather than wind speed).

6.1.5 Pilot climate observing station at Clipperton Island for the study of East Pacific ITCZ

Background

The tropical eastern Pacific is a critical region for ENSO development, a unique ITCZ-cold tongue complex with the lowest equatorial SST and strongest large-scale gradient in SST in the tropics, and the highest density of tropical cyclones per unit area. The eastern Pacific ITCZ is of particular interest as it is in this region that persistent systematic biases and errors continue to be found in global climate models, most notably the generalized double ITCZ syndrome. The in-depth understanding of the associated physical processes necessary to assess and to correct the biases and errors in climate models—particularly those related to the atmospheric mechanisms associated with convection in the ITCZ and its interaction with the ocean—remains rudimentary, and most information available for this purpose is either indirect (satellites or model-based products) or from short-term field campaigns (e.g., TEPPS[9], EPIC[10] 2001).

One key limitation for direct in situ measurements in the ITCZ is that present-day mooring systems and ships are not able to provide the continuous atmospheric profiling necessary for monitoring on sufficient timescales. In the Tropical Ocean-Global Atmosphere (TOGA) program, this was addressed by using islands as platforms, leading to a network of equatorial wind-profiler radars. No similar effort was done for the off-equatorial tropical region, particularly in the ITCZs, and the island network is no longer active.

Proposed Action

Clipperton Island (10°N, 110°W; see Figure 6-4) is an uninhabited, low-elevation (< 30 m) ring of land with an approximate 3 km diameter enclosing a stagnant lagoon, located within the Northern Hemisphere ITCZ during most of the year. Associated with the seasonal migration of the ITCZ, rainfall on Clipperton Island is maximum in June-August and minimum in December-April, when the ITCZ is further south and the climatological double ITCZ is present in nature. Thus, Clipperton Island is an ideal site for establishing a pilot climate research observatory for monitoring the eastern Pacific ITCZ.

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[9] Tropical Eastern Pacific Process Study

[10] **E**ast **P**acific **I**nvestigation of **C**limate Processes in the Coupled Ocean–Atmosphere System

The Clipperton Climate Observatory will initially include a set of automated instruments selected to address three scientific questions:

1. What are the primary controls on ITCZ convection in the eastern Pacific on diurnal-to-subseasonal timescales?
2. What is the mean vertical structure of the east Pacific ITCZ during the rainy season (April-November) and what are the dominant subseasonal to seasonal timescales of variability in ITCZ convection?
3. What characterizes the mean atmospheric circulation within the ITCZ during the double ITCZ season (April) and how does it contrast that of the dry (February) season when model biases are present?

The required observations include: surface meteorology (winds, air temperature and humidity, barometric pressure), precipitation, integrated column water vapor, cloud base or a camera to identify clouds overhead, precipitation vertical structure, boundary layer turbulent fluxes and vertical profiles of temperature, humidity and winds (horizontal and vertical). Methods of estimating surface heat, moisture, momentum and freshwater fluxes over the ocean in the region of Clipperton Island should also be considered. The existing TAO buoy at 8°N, 110°W could be used for surface moisture and momentum fluxes in the region, but an eddy-covariance system offshore of Clipperton would be preferred. Such a mooring equipped with oxygen sensors would constitute a unique opportunity to start a long time series of oxygen measurements in one of the largest OMZs of the global ocean.

This proposal presents the scientific questions that could be addressed with the establishment of a climate research observatory on Clipperton Island focused on the climatological structure of ITCZ convection and circulation and the large-scale and local thermodynamic controls on ITCZ precipitation, from diurnal to seasonal timescales. Longer deployments would also be justified to better understand and document the atmospheric branch of the cross-equatorial energy budget, which is projected to adjust under climate change, but such questions are not meant to be addressed by this pilot project.

Expected Outcome

Better understanding of the processes controlling East Pacific ITCZ convection and vertical mean structure. In addition, it is expected that these observations and a better understanding of the mechanisms associated with the Northern Hemisphere East Pacific ITCZ will lead to model improvement.

Relevance to TPOS Strategy

This pilot climate observing station will provide new insights and guidance as to the observations necessary in a future TPOS, such as the boundary layer turbulent heat, moisture and momentum fluxes, integrated water vapor-precipitation relationship and atmospheric vertical structure, needed to better understand processes controlling East Pacific ITCZ convection and vertical mean structure. The Northern

Hemisphere East Pacific ITCZ is a critical part of the ENSO system and thus is highly relevant to the objectives of TPOS going forward.

6.1.6 Assessing the impact of changes in the TPOS backbone

Summary

This pilot study aims to formulate a well-defined framework through which specific TPOS backbone observing system recommendations can be objectively evaluated in terms of their impact on ocean state estimation and near-term prediction. This project will focus on the observing system evaluation of two aspects of TPOS 2020 considerations:

- Increasing subsurface Argo profiling throughout the tropics and reconfiguring the Tropical Mooring Array, while
- Maintaining the existing high-resolution SST and SSH satellite assets.

Background

The relative impacts of the existing TMA on ocean prediction have been assessed through various Observing System Experiment (OSE) studies (e.g., Lea et al., 2014; Fujii et al., 2015; Oke et al., 2015). These have consistently demonstrated the importance of the TMA in the tropical Pacific, even with the assimilation of Argo and altimetry. However, given the evolution of different observing system capabilities, a strong case is made by TPOS 2020 to consider the transition of the TMA from its present grid structure between 8°S and 8°N to a refocused array designed to sample the varied regimes of the tropical Pacific, and further, while recommending an enhancement in Argo deployments equatorward of 10°. It is essential that the expected outcomes for analysis and forecast activities is robustly assessed.

Proposed Action

Depending on the capabilities of participating modeling and data assimilation groups, we propose to use a combination of OSEs, Observing System Simulation Experiments (OSSEs) and (possibly) alternative techniques such as Degree of Freedom System (DFS; Cardinalli et al., 2004) and Forecast System Observation Impact (FSOI; e.g., Langland and Baker, 2004), to assess the impact of the recommended TMA reconfiguration and the increase in Argo profile density while maintaining existing SSH and SST coverage. The assessment should be approached in the context of at least the following three applications: (i) forecasting of ENSO state out to 2 years, (ii) subseasonal prediction of medium-range phenomena such as MJO, tropical cyclones and TIW variability and (iii) ocean monitoring activities such as those at NCEP[11]. If sufficient interest and capabilities exist, participating partners in this project will be encouraged to leverage these activities to explore the impact on specific process-studies and/or medium-range weather

[11] See http://www.cpc.ncep.noaa.gov/products/GODAS/ocean_briefing.shtml

prediction performance. We recommend calibrating any OSSEs that are performed by requiring that they be paired with corresponding OSEs. Calibration can be achieved by simulating the full existing observation network and performing OSEs to assess the impact of withholding individual simulated observation types. The results of the OSSEs with simulated observations can then be compared with OSEs performed with the real observation network. If the simulated observations are well calibrated, the observation impact of the real and simulated observations should be consistent. Similar calibration practices are planned for the Atlantic Observing System (AtlantOS) OSSEs.

If possible, we encourage the use of complementary assessment techniques such as DFS and FSOI, and potentially simpler techniques such as the observation-minus-forecast method proposed by Todling (2012). Both the DFS and FSOI have the advantage that they assess the impact of observations when the full observation network is assimilated (as opposed to OSE/OSSEs where a particular observation type is withheld/introduced). Furthermore, development of these more novel techniques within this framework will contribute to development of systems enabling us to monitor the influence of TPOS observations in data assimilation in near-real time (see section 6.1.7).

It is important to note that the results from these experiments will strongly depend on the design of the data assimilation systems used and the forecast initialization approach adopted. To ensure robust conclusions it is therefore essential that participation of three or more modeling groups with diversity of data assimilation systems are involved in the joint experiment and assessment. While it is impossible to fully define the experimental protocol before named groups have committed to the project, priority should be put on the inclusion of the main categories of state-of-the art systems in use: namely, ensemble and variational methods. Participating groups with systems capable of assimilating in coupled mode should be encouraged to explore this option since best practices for both subseasonal and seasonal prediction are for consistent initialization of both the ocean and atmosphere systems. Efforts should be made in coordinating start dates from 1990 to present (inclusive of the altimetry era), number of ensembles in the forecasts and a consistent set of atmospheric and ocean observations to be used in the assimilation. Existing best practices for the seasonal and subseasonal prediction experimental protocols assessment can be followed (Kirtman et al. 2014).

To find suitable partner groups, TPOS 2020 should engage with GODAE OceanView (GOV) task teams (primarily the OSEval data assimilation task team), CLIVAR- Global Synthesis and Observations Panel (CLIVAR-GSOP) and operational centers that maintain ENSO class forecast systems. These groups can provide crucial expertise on the design and assessment of OSE/OSSEs and links to any ongoing work in this area. Where there is planned OSSE work we should engage with the projects and look for opportunities for assessments to be extended into the tropical Pacific. Ongoing projects such as AtlantOS may provide such opportunities.

Expected Outcome

The proposed study will provide objective and robust information about the expected consequences (positive, negative or neutral) of reconfiguring the TMA and increasing the density of Argo floats while maintaining the use of the SSH and SST satellite assets. In this pilot study, we are considering this assessment in regard to changes in expected skill at the subseasonal to seasonal prediction range. Another outcome of this work will be the development of infrastructure, strategy, and collaborative partnerships that can be called upon in the future to assess different configuration options for the future evolution of TPOS 2020.

Relevance to TPOS Strategy

Most directly, this project is relevant to the TPOS 2020 strategy because it will provide an assessment of a currently recommended change to the status quo observing network. Indirectly, this project is also relevant to a number of the broad TPOS 2020 design principles (Chapter 4). Namely, this work looks at design choices that reconfigure different platforms and looks across two target forecast time scales (subseasonal and seasonal). This project also supports the objective assessment of an evolving TPOS. One of the key areas of focus for this pilot will be on developing assessment infrastructure, strategy and partnerships that can be generalized to facilitate informed guidance a wide variety of TPOS choices in an efficient and robust manner.

6.1.7 Comparison of analyses and utilization of TPOS observations

Summary

Along with the investments in the TPOS and its redesign, it is important to quantify how (and what) observations are being utilized for routine ocean monitoring and predictions, and what is their influence. There are several aspects under this activity, and we recommend that efforts and consideration for resources toward their development and sustainment for this activity should be given.

Background

At present, there are several operational centers that maintain routine ocean analysis for predictions on weather-to-seasonal time scales. These predictions depend on estimate of ocean state for forecast model initialization, which in turn utilize ocean observations as part of data assimilation. It remains unclear, however, what observations are being received by various centers in a timely manner, and further, which observations are ingested in the data assimilation system and which may get rejected due to quality control issues. It is also remains an outstanding problem that influence of those data is not routinely monitored. In the current status, it is not possible to demonstrate influence of a change in the observing system on the ocean analyses and its value to the society and stakeholders in a timely manner. In addition, information on which observations of the atmosphere and the sea surface by moorings and other elements of TPOS are ingested in the atmospheric data assimilation system is also indispensable. To assess the utility of TPOS, it is important to develop an activity where this information is easily available and is shared across operational centers.

Proposed Action

We propose that TPOS 2020 invest and develop an activity where information on observational data ingested in data assimilation systems over the tropical Pacific, and their influence, is routinely shared and compared among operational centers, particularly for the ENSO class prediction systems. The exchange and sharing of information will include: what observational data are ingested in the assimilation, quality control flags on ingest of the observational data, analysis increments and fit to observations, etc. While observations are being ingested via the ocean data assimilation system, their efficacy in constraining the ocean state estimation and quality of data assimilation systems and influence of model biases can also be assessed from this activity. A similar activity has been successfully conducted by GODAE Ocean View (GOV) although they mainly focus on short-range ocean forecasting. For example, GOV recently experimented with comparison of analysis increments, along with exchange of information on ingested observations (Martin et al. 2015). Collaboration with GOV for developing those activities for the ENSO class prediction systems is desirable.

It will also be valuable to extend the information-sharing and comparison activity to the wind stress analysis, which forces ocean data assimilation system. Although multiple estimates of wind stress from atmospheric reanalyses are available, studies have shown a wide range of discrepancies among them. To date, there has not been a systematic effort that brings ocean and atmospheric analysis communities together to understand causes for these differences. Given the importance of surface wind stress in constraining ocean analysis and influencing subsequent prediction, we recommend developing a concerted effort to understand causes of differences among various atmospheric reanalyses products.

The scope and utility of the above activities can be further enhanced by periodic delayed-mode intercomparison of ocean reanalyses extending back in time. Such products (often referred as reanalysis) are often generated as part of the real-time analysis and prediction activities, and their intercomparisons can provide information on the influence of past and future observing systems in constraining the state estimation, and further about the interaction between the observed data and the various data assimilation systems. An example of such an activity that is currently developed is the intercomparison of ocean temperature and salinity among various operational analysis that are run for seasonal predictions (http://www.cpc.ncep.noaa.gov/products/GODAS/multiora_body.html ; http://poama.bom.gov.au/project/salinity/). This activity has been originally started following the recommendation made by the TPOS 2020 Workshop in 2014. We recommend a continuous support for sustaining this activity.

In addition, we also support development of systems that enable us to monitor impacts of TPOS in data assimilation systems in near-real time through sophisticated techniques such as Degree of Freedom of System (DFS) and Forecast System Observation Impact (FSOI).

Expected Outcome

The proposed activity will facilitate access to information that we currently lack – what TPOS observations are being used in the data assimilation systems at operational centers, and what is their influence on monitoring and prediction of the tropical coupled system on different time-scales.

Relevance to TPOS Strategy

The proposed activity will help TPOS 2020 in evaluating the effectiveness of elements of the observing system and making informed decisions about future evolution

6.2 Process studies

6.2.1 Pacific Upwelling and Mixing Physics (PUMP)

Summary

Upwelling and mixing in the east-central equatorial Pacific play a central role in ocean-atmosphere dynamics of the Pacific (section 3.3.3) that engages the entire global climate. Despite its importance, the spatiotemporal variability and dynamical mechanisms of this interaction remain poorly understood and poorly constrained in climate models. Here, we sketch a limited-term measurement program that will improve understanding of these physical processes, enabling more realistic model parameterizations. The results will also guide development of proxies for these processes that can be observed within the sustained Tropical Pacific Observing System.

Background

Equatorial upwelling is a poorly observed aspect of the climate system, yet a principal initiating mechanism for the vigorous ocean-atmosphere coupling of the equatorial Pacific (section 2.6.1). The most consequential equatorial upwelling occurs in the eastern and central Pacific Ocean, where the Equatorial Undercurrent (EUC) and thermocline rise from west to east, bringing cold water (<20°C) with high concentrations of nutrients and CO_2 to within 100 m of the surface. The upwelling found in the eastern Pacific is driven largely by Ekman pumping forced by the southeast trade winds blowing along and across the equator and into the ITCZ.

Mean upwelling transport at 50 m depth east of the dateline between 5°N and 5°S in the Pacific is on the order of 50 Sv (Johnson et al., 2001, Meinen et al., 2001). This massive upward volume flux, with its transport of cold water rich in nutrients and CO_2, is a key process of the Earth's climate system. Net heat uptake by the oceans peaks on the equator and is much larger in the eastern equatorial Atlantic and Pacific Oceans than anywhere else; this is largely due to the reduction of evaporative heat loss over cool upwelled SST. The heat input near the equator is transported poleward by the ocean's shallow meridional overturning circulation cells to warm the atmosphere at higher latitudes.

Since isotherm depths are observed to be quasi-stationary despite upward advection of several meters per day, downward mixing of surface heat fluxes must be correspondingly intense. Sparse measurements of turbulence and velocity fine-structure during TAO/TRITON service cruises in the western and central Pacific show that mixing within and above the thermocline is strongly modulated by ENSO events (Richards et al., 2012). Equatorial vertical exchange processes dominate high surface chlorophyll concentration in the equatorial Pacific (section 2.6.7); thus, upwelling/mixing physical processes are also key to understanding biogeochemical variability (section 6.1.3).

Cool SSTs in the eastern equatorial Pacific and Atlantic are a balance among upwelling, vertical mixing and horizontal advection, all of which can be expected to vary on timescales from diurnal to decadal. Neither upwelling nor vertical mixing are well-quantified by observations, so ocean models and assimilation systems have essentially no constraints on their representations of these processes; unlike the EUC where TMA-measured profiles provide a validating check on zonal speeds, models are seen to differ greatly in their depictions of these vertical structures and mechanisms. Similarly, observational estimates of heat and salt balances typically leave upwelling and mixing as a combined residual term (e.g., Wang and McPhaden, 1999), making it hard to separate the influence of these distinct processes on upper-ocean properties, interpret the consequences of their variability or evaluate the realism of model forecast runs.

The complexity of processes suggests the difficulty of evaluating models without better observational guidance. Consider the response to an easterly wind anomaly (stronger trades) in the eastern Pacific: SST cooling will occur due to increased latent heat fluxes, increased mixing and increased upwelling, all on similar short timescales. It is thus possible for a model to simulate the correct SST variation while getting the mechanism entirely wrong, so model developers are unable to assess improved parameterizations. The PUMP experiment is designed to enable this progress.

Recent intercomparisons of the tropical Pacific circulation in contemporary oceanic GCMs (OCGMs; Tseng et al., 2016) using identical surface forcing (Large and Yeager, 2009) show better agreement with observations of the zonal slope of SSH, thermocline depth and the speed of the EUC than those of previous generations. However, model biases persist even in modern models, particularly in their failure to maintain the strong meridional shear north of the equator or the sharp thermocline stratification in the eastern basin. Notably, the largest inter-model differences (up to a factor of 2 in speed) are in the near-surface Ekman diverging layer, where direct observations are lacking; this translates into large differences in the modeled upwelling.

While there is reasonable agreement in the broad-scale equatorial divergence and time-average total upwelling across present-generation models (which in bulk must be similar to Ekman divergence averaged over a broad region), qualitative differences are seen in key details that mediate ocean-atmosphere coupling: the structure of upwelling within the equatorial zone still differs substantially among modern models, as illustrated in Figure 6-2. Coarse-resolution models, typical of those used in IPCC coupled climate simulations, produce broad upwelling across the width of the cold tongue. On the other hand, higher-resolution simulations, as well as the relatively high-resolution experiment described in Perez and Kessler (2009), suggest suppressed upwelling directly on the equator and maximum mean vertical velocity displaced 0.5° to 1° poleward within the mixed layer. Since these are highly transient features, the mean examples in Figure 6-2 underestimate the transient differences, and because the atmosphere responds to SST on short timescales, the long-term means shown here may not reflect the coupled interactions during critical periods, especially during ENSO evolution. The primary target of this study is the spatial and temporal variability of upwelling and mixing in response to varying winds, and their subsequent influence on the coupled system.

New measurements of this complex of processes are the only way forward to resolve the model discrepancies and guide their improvement.

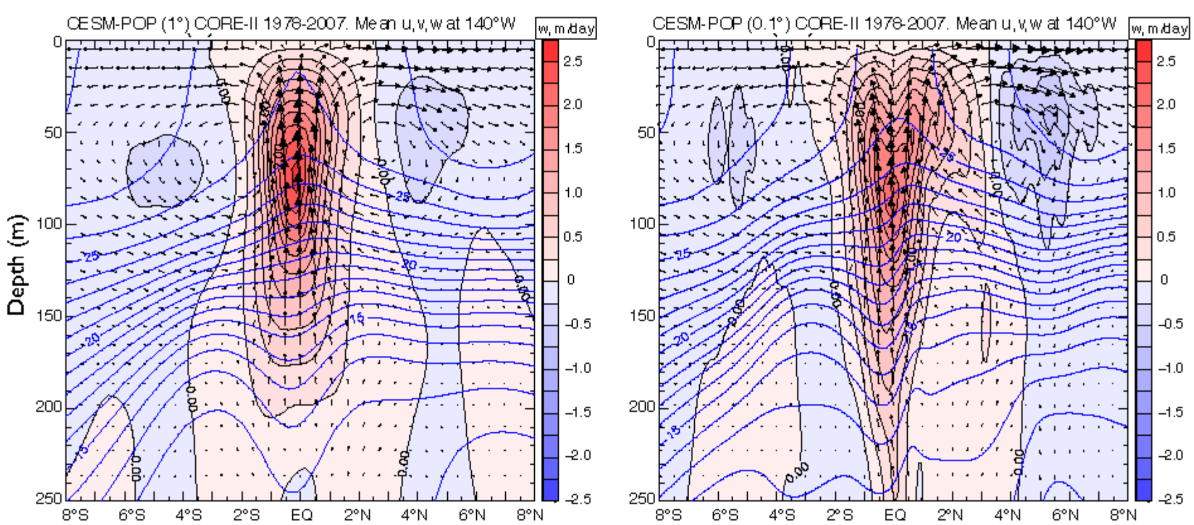

Figure 6-2. Circulation in the meridional plane at 140°W in coarse (1° in longitude, left) and fine resolution (0.1°, right) versions of the Community Earth System Model (CESM) OGCM forced by identical Common Ocean Reference Experiment fluxes (Tseng et al., 2016). Vertical velocity is shaded in units of meters/day. Vectors represent 10-day displacements. The parameterization of small-scale vertical mixing in the low- and high-resolution models is identical.

Proposed Action

The concept, objectives and much of the implementation strategy described in Kessler et al. (2005) remain relevant for PUMP today. Some aspects of that plan have been demonstrated on a limited basis in the intervening decade, and advances in technologies such as extended time series of moored microstructure measurements (Moum et al., 2013) and autonomous vehicles, make the objectives more readily attainable. An array design that would permit simultaneous estimates of the vertical-meridional structure of vertical velocity driven by the divergence of the mass flux, and the cross-isothermal motion due to the mixing heat flux, is key to understanding the relationship between upwelling and mixing and would provide an important benchmark and constraint for climate models.

Expected Outcome and Relevance to TPOS Strategy

The first outcome is increased information for upwelling/mixing physics and its parameterization schemes in ocean circulation and climate models. Better understanding of the processes of vertical exchange (ocean uptake and storage of heat and atmospheric gases) in the thermocline is also expected. The results will also illuminate key processes mediating biogeochemical features of the equatorial Pacific.

A hypothesis of PUMP is that much of the variability of equatorial upwelling can be estimated from the convergences and divergences of the poleward Ekman flow. If the process study shows that this is the case, upwelling could be monitored with a meridional section of near-surface current profiles (section 7.4.4.1, Action 5), with zonal and meridional thermocline structure observed by Argo floats. Combined with surface flux measurements, the sustained TPOS could then produce an ongoing picture of this core phenomenon of the equatorial Pacific.

PUMP will define sampling characteristics and variable targets to guide future sustained observations. While PUMP is a process study, it is also a pilot study to determine the minimum observations needed to quantify the upwelling, and to determine its relevant time and space scales.

6.2.2 Air-sea interaction at the northern edge of the west Pacific warm pool

Understanding northward propagating Boreal Summer Intra-Seasonal Variability (BSISV) and the ITCZ

Background

As an ENSO mechanism, the warm water volume (WWV) is regarded as an important index in the “recharge-discharge” paradigm. In particular, the transport on the Northern Hemisphere side has more impact to WWV variation (Ishida et al., 2008). Thus, the formation and transportation of the warm water at the northern edge of the west Pacific warm pool is important to understand, to monitor and for ENSO prediction.

The west Pacific warm pool is characterized by warm and fresh water. The heat and fresh water are primarily provided as a surface flux. Thus, the atmospheric variability is important to understanding how the WPWP was generated. Of special note is the Boreal Summer Intra-Seasonal Variability (BSISV/ISV) that propagates northward beyond 20°N (Kikuchi and Wang, 2010), modulating the impact of the heat, momentum and freshwater fluxes to the ocean (e.g., Kemball-Cook and Wang, 2001; Figure 6-3). Atmosphere-ocean coupling is suggested as the important mechanism of BSISV in the western Pacific (Chou and Hsueh, 2010). An atmosphere-ocean coupled model is able to better reproduce BSISV than an atmospheric model alone (e.g., Fu and Wang, 2004). However, the latest CMIP5 models are still inaccurate in their ability to reproduce the BSISV (Sabeerali et al., 2013). Since the ISV is a multi-scale phenomenon, involving smaller-scale features (e.g., diurnal cycle, typhoon) and relating to seasonal and larger-scale features, a multi-scale atmosphere-ocean perspective is required as part of the observational process study.

Proposed Actions

A process study to capture in situ simultaneous evidence of the BSISV both in atmosphere and ocean is required. Because of the multi-scale structure of BSISV, the observations should be designed to resolve the mesoscale atmospheric convection and its impact to the environmental atmosphere and oceanic mixed layer, both spatially and temporally. In order to capture the behavior of the heat and freshwater in detail, oceanic observations are needed that highly resolve the near-surface upper 10 meters. The observations should be long enough to at least cover one or more cycles of BSISV in order to capture the different stages of the BSISV during the period of northward expansion of the Warm Pool. In addition, the oceanic observations need to resolve the mesoscale eddies and mixing in the upper ocean in order to understand the horizontal and vertical transport of the heat and salinity, and their impacts on the upper ocean.

Expected Outcomes

The process study is expected to contribute to a better understanding of the processes responsible for the variation of the warm water in the northern part of the west Pacific warm pool. By capturing the oceanic and atmospheric processes in BSISV, the complicated air-sea and multi-scale interactions, including their influence on the generation of atmospheric Pacific-Japan patterns (e.g., Nitta, 1987), are expected to be more comprehensively understood.

Relevance to TPOS Strategy

Buoy observations along 137°E are expected to be enhanced as part of TPOS 2020. The proposed process study will contribute to the observational design of the 137°E line, and further enhance this transect with higher resolution and coverage in dimensions of space, time and parameters.

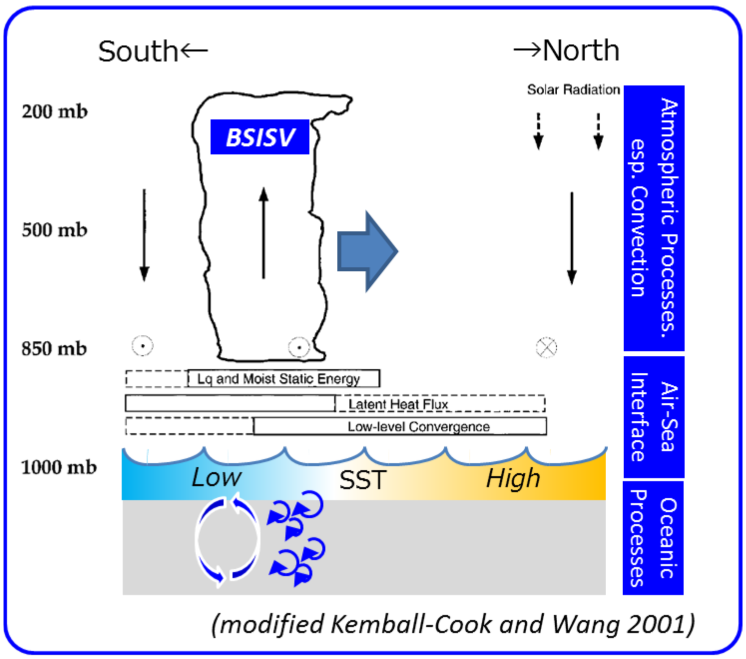

Figure 6-3: Schematic of the meridional cross-section of BSISV. The variability and processes below the sea surface have not as yet been fully investigated (modified from Kemball-Cook and Wang, 2001).

6.2.3 Air–sea Interaction at the eastern edge of the Warm Pool

Summary

This project is an air-sea interaction process study focused on understanding the role of upper ocean salinity stratification (barrier layer) in maintaining the warm SSTs at the eastern edge of the west Pacific warm pool, in particular focusing on the air-sea coupling on intraseasonal timescales.

Background

The western Pacific is characterized by a warm and fresh pool as a result of the warm water accumulation by the equatorial trade winds in the central Pacific and the heavy rainfall associated with ITCZ, SPCZ and MJO variability in the western Pacific. Within the Warm Pool thick, long-lived salinity-stratified barrier layers are observed (Lukas and Lindstrom, 1991) that form in response to both excess rainfall in the presence of weak winds and as a dynamical response to westerly wind burst and/or trade wind forcing acting on the fresh pool front (Cronin and McPhaden, 2002). The formation, thickness and duration of barrier layers changes on subseasonal to interannual timescales (Sprintall and McPhaden, 1994; Ando and McPhaden, 1997). In the presence of a barrier layer, fluxes of heat, freshwater and momentum into the ocean are trapped in a thinner surface layer, which enhances their impacts (Godfrey and Lindstrom, 1989). In addition, the presence of a barrier layer will reduce or eliminate entrainment cooling at the base of the mixed layer, thereby affecting SST. Maes et al (2006) found a tight relationship between the salinity front and the warmest SSTs at the eastern edge of the west Pacific warm pool, suggesting that the intensity of SST-wind coupling might be mediated by the presence of salinity barrier layers. Because warm SSTs are needed for atmospheric convection to occur these results present a compelling link between the barrier layer and air-sea coupling over the Warm Pool. Together with the anomalous impact to the dynamic height by the additional freshwater, an eastward surface fresh jet is generated along the equator in the warm, fresh pool (Roemmich et al., 1994). The fresh jet is believed to accelerate SST warming in the central and eastern Pacific in combination with the impact of thermocline deepening in the central and eastern Pacific due to the oceanic Kelvin waves, which are primarily generated by MJO events (see section 2.6.3) on intraseasonal timescales.

Most of our knowledge of the barrier layer evolution and impact stem from the TOGA-COARE experiment in the western equatorial Pacific during the 1990s. It is not known whether the same mechanisms are responsible for barrier layer formation and thickness at the eastern edge of the Warm Pool, although clearly the atmospheric and oceanic conditions are different. The surface circulation at the salinity front is unique (see Figure 3-3). We hypothesize that the presence of a barrier layer is favorable for the role of air-sea fluxes to contribute to the warm SST and freshwater pool. Our premise is that at the frontal zone, the eastward SEC subducts below the Warm Pool, supplying the high-salinity water that could act to support formation of a barrier layer. At the surface, the eastward pressure gradient due to the surface freshwater layer would tend to weaken the surface current. Because of this balance, a barrier layer will be maintained as long as the SEC subducts, and thus directly contribute to the warmest SSTs found west of the front. Alternatively, surface-intensified eastward currents forced by westerly wind bursts in the warm / freshpool could be the active driver, tilting the salinity front associated with the freshpool eastern edge into a salinity stratification, thereby generating a thick barrier layer at the eastern edge of the freshpool.

Proposed Action

We propose a process study to understand the frontal structure at the eastern edge of the west Pacific warm/fresh pool. What are the primary mechanisms maintaining this front and contributing to its variations on diurnal to annual timescales? On what timescales do the eastern edges of the warm and fresh pools act independently? Surface flux mooring(s) as part of the TPOS, with near-surface current profiles and T and S sensors to resolve the barrier layers, can provide a backbone time series. However, additional measurements will be necessary to understand the zonal and meridional frontal structure in the ocean and atmosphere and its interaction. The basic strategy will be to use the TPOS Backbone (moorings, Argo, remotely sensed winds, SST and SSS) to provide context, with additional measurements to allow a better mechanistic understanding of processes. Underwater glider, wave glider and micro-float measurements will be used to provide a high-resolution survey of the salinity front, along with an enhanced and intensive observation campaign by research vessels with atmospheric cloud-resolving radar and oceanic turbulence, and an island-based atmospheric sounding.

Expected Outcome

Better understanding of the salinity front mean structure and variations, including the dynamical balances. The measurements of downward momentum transfer for various cases of salinity stratification and atmospheric condition will reveal fundamental differences in the dynamics responsible for the eastward (and westward) shifts of the Warm Pool.

Relevance to TPOS Strategy

This study will help determine the relative role of frontal processes acting on the shifting eastern edge of the Warm Pool and will test emerging technologies for observing these sharp fronts. This process-oriented observation campaign will provide new insights and guidance as to the observations necessary in a future TPOS, such as upper ocean current profiles, needed to improve our detection of the frontal movement and variations. In turn, it is expected that these observations and a better understanding of the mechanisms driving frontal movement will also lead to model improvement.

6.2.4 East Pacific ITCZ/warm pool/cold tongue/stratus system

Background

The double ITCZ bias refers to the overestimation of precipitation in the tropical southeastern Pacific in nearly all climate models over several generations (Zhang et al., 2015) yet no qualitative progress has been made to improve this issue. Processes including convective coupling to SST (Bellucci et al., 2013; Oueslati and Bellon, 2015), the vertical structure of latent heating and the meridional circulation (Schumacher et al., 2004; Back and Bretherton 2006, 2009; Huaman and Takahashi, 2016), meridional heat transports (Masunaga and L'Ecuyer, 2011), gap winds across Central America and surface cooling of the eastern Pacific (de Szoeke and Xie, 2008) and cloud radiative effects (Voigt et al., 2014; Harrop and Hartmann, 2016) are all relevant to this problem but are not well observed by the current network, particularly in the case of the double ITCZ in nature (Huaman and Takahashi, 2016).

Proposed Action

In order to address the double ITCZ bias, the TPOS 2020 EP TT is designing a process study for observing the atmosphere and ocean from the stratocumulus region off the coast of South America (20°S), northward into the tropical northeast Pacific ITCZ region (110°-85°W, 15°N) to sample the ocean-atmosphere processes in the east Pacific ITCZ/warm pool/cold tongue/stratus system during boreal spring, when the double ITCZ is present (Figure 6-4), and in fall when the natural ITCZ is not present but

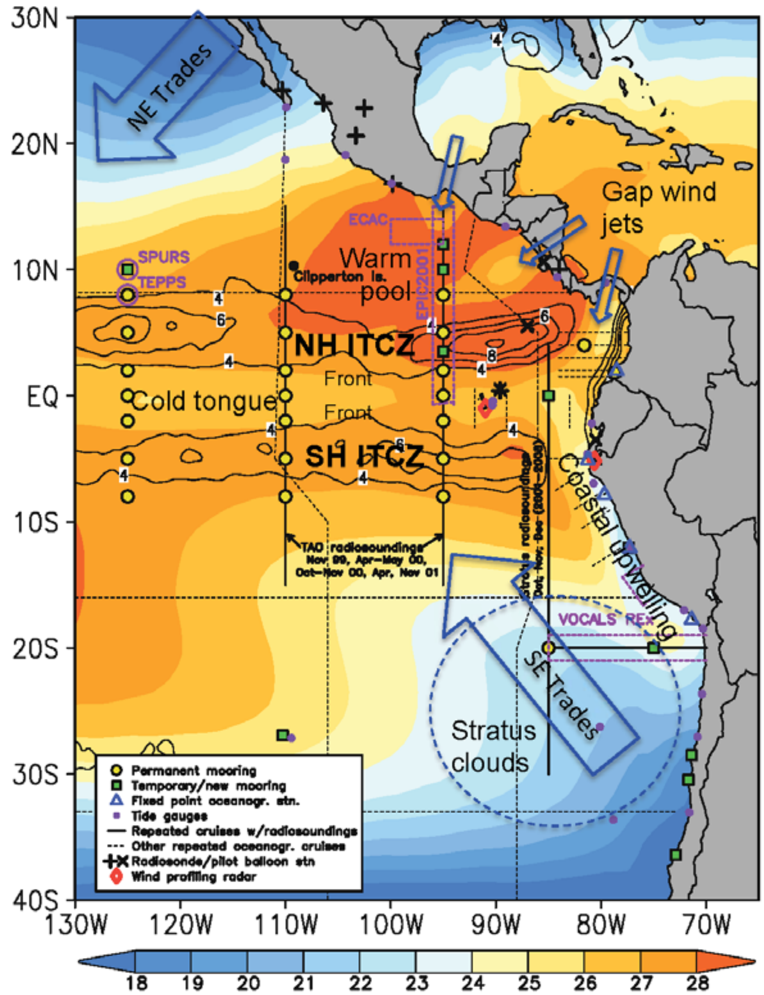

Figure 6-4. April 1998-2010 climatology of NCEP OI SST (filled contours) and TRMM 3B42 rainfall (contour lines). Existing and relevant past measurement platforms (e.g., TAO and WHOI stratus moorings) are also shown, see legend for details. Key features of the ITCZ/cold tongue/stratus complex are illustrated for reference. Clipperton Island is shown at 10°N, 110°W.

remains active in the models (see also section 6.1.5). Among our objectives are to estimate the meridional heat transports in both the atmosphere and upper ocean, estimate the surface heat and moisture fluxes across the region, characterize clouds and their radiative forcing, characterize atmospheric deep convection and levels of latent heating and document the basic state of the atmosphere and upper ocean on diurnal-to-monthly timescales. Some previous studies have documented aspects of this proposed study (Figure 6-4) but the gaps in time and space make fulfilling all of our objectives over the needed time and space scales impossible. Thus, we propose a combination of enhanced permanent and field campaign observations as part of TPOS 2020.

Expected Outcome

Better understanding of the processes controlling the double ITCZ in nature and its seasonality. In addition, it is expected that these observations and a better understanding of the mechanisms associated with the double ITCZ in nature will lead to model improvement.

Relevance to TPOS Strategy

This process-oriented observation campaign will provide new insights and guidance as to the observations necessary in a future TPOS, such as cross-equatorial ocean and atmospheric heat transports, needed to improve representation of the processes controlling the latitude of the East Pacific ITCZ and the seasonality of the southern hemisphere ITCZ in April. The East Pacific ITCZ is a critical part of the ENSO system and thus is highly relevant to the objectives of TPOS going forward.

6.3 Other Task Team activities and new technology

TPOS, through its various Task Teams, has outlined a program of work to be initiated during the TPOS 2020 Project. In addition to the Pilots and Process Studies introduced above, several projects have been outlined that will also contribute to the evolution of the Backbone Observing System. Elements of this work may be spun-off as Pilots or Studies. The existing work program includes:

- Upper-ocean processes and air-sea interaction during Years of the Maritime Continent (YMC)
- Attribution and possible alleviation of common coupled model biases
- The Wyrtki Challenge

More detail can be found in section 10.1.

A number of the stakeholders in TPOS, such as JAMSTEC and NOAA, are also promoting new technology as a contribution to TPOS. Five initiatives have recently been supported by JAMSTEC and the Climate Observations Division of NOAA:

- Enhanced ocean boundary layer observations on the TAO moorings (NOAA; section 10.2.1)
- Profiling rainfall, wind speed and biogeochemical sensors for use in the Tropical Pacific Observing System (NOAA; section 10.2.2)
- Flux surface glider experiment (JAMSTEC; section 10.2.3)
- Autonomous surface vessels as low-cost TPOS platforms for observing the planetary boundary layer and surface biogeochemistry (NOAA; section 10.2.4)
- Development and testing of direct (eddy covariance) turbulent flux measurements for NDBC TAO buoys (NOAA; section 10.2.5)

Further detail is included in the Annex to this Chapter (section 10.2).

7 Implementation and Transition

7.1 Principles for implementation

Chapter 4 introduced a number of Principles that applied to the design of TPOS and to the recommendations on observational needs (Chapters 5 and 6). Here we introduce some further Principles that apply to implementation where the realities of resource constraints and differentiated capabilities with the TPOS stakeholders come to the fore.

1. TPOS is not stationary, neither in its design nor in its implementation.
    - It is not “perfect” but is a pragmatic solution to the stated requirements based on current science and available capabilities.
    - TPOS 2020 must achieve improved efficiency and effectiveness.
    - TPOS will lose functionality from time to time, either by design or through failures in technology or support.
    - As the TPOS evolves, the GCOS Principles (Appendix A) remain a key consideration.

2. TPOS has an integrated design (Chapters 3-6) and requires an integrated implementation plan.
    - Where possible, employ platforms that have multiple, and usually integrated instrumentation.
    - Different platforms working together to provide solutions.
    - Different agencies working together to support/maintain the networks.
    - Many nations working together and within intergovernmental frameworks for cooperation and data exchange.

3. Implementation will be staged.
    - TPOS will be changed over the term of the Project through 2020 and, if appropriate, beyond.
    - Seek solutions for critical gaps now.
    - Recommend changes where there is clear evidence for doing so.
    - Flag areas of likely change that will be subject to additional study.
    - Understand and manage change and risks.

4. Resource requirements for implementation should encourage broad participation and sharing of the implementation load.
    - TPOS implementation requirements must broadly align with stakeholder expectations and capabilities.
    - Plans must be inclusive of existing and potential TPOS stakeholders.
    - Wherever practical, the utility of platform resources such as deployment and service ships should be maximized, including to enable ancillary observation.

5. Implementation will focus on sustained observations for the Backbone, but must also include research observation infrastructure and resources for the evolution of the system, toward more efficient and effective operation.

6. The implementation of TPOS involves both global systems and regional targeted solutions.
    - There are differences in regional capability, both for supporting sustained and experimental networks.
    - Regional capabilities and imperatives will guide support for both sustained and experimental networks.

7. Satellite systems and constellations will increasingly provide broad-scale surface observations.
    - At present, this capability does not extend to all essential surface variables nor meet all accuracy needs.
    - In situ surface observations play a critical supportive role for satellites for calibration and validation.
    - High-quality in situ observations have increased priority for long-term climate monitoring and climate change detection; for many, they represent a trusted reference.

8. In situ systems provide the basis for subsurface broad-scale sampling and for surface regimes where either satellites and/or models are ineffective or where profiles of the boundary layers are important.

7.2 Current status

The observational requirements provided by Chapters 3 and 5, and the observational capability today (Chapters 2 and 3; Figure 7-1) lead to the following conclusions.

1. Nowhere in the tropical Pacific do we find obvious oversampling or clearly wasted redundancy; put another way, the TPOS redesign and statement of observational requirements does not on its own demand a reduction of the *status quo*. Rather, the introduction of new technologies and/or new sampling capabilities from existing technologies offers opportunities for improved effectiveness and/or efficiencies; trade-offs may enable more to be achieved within a given resource envelope (see the Principles in section 7.1 and sections below).
2. West of the dateline, with the deterioration of TRITON (see section 1.2), we note multiple observational requirements at the surface and in the subsurface ocean that are currently not being met.
3. We are not fully meeting surface requirements in regimes where satellites have sampling difficulties and/or potential errors; we cannot completely address this shortfall in spatial sampling with in situ observations, but we can at least mitigate the impact on important climate records and ensure an appropriate baseline of observations are available.
4. The space-time sampling of presently available remotely sensed vector wind is inadequate, particularly with respect to the diurnal cycle (see Recommendations 1 and 2, Chapter 5).

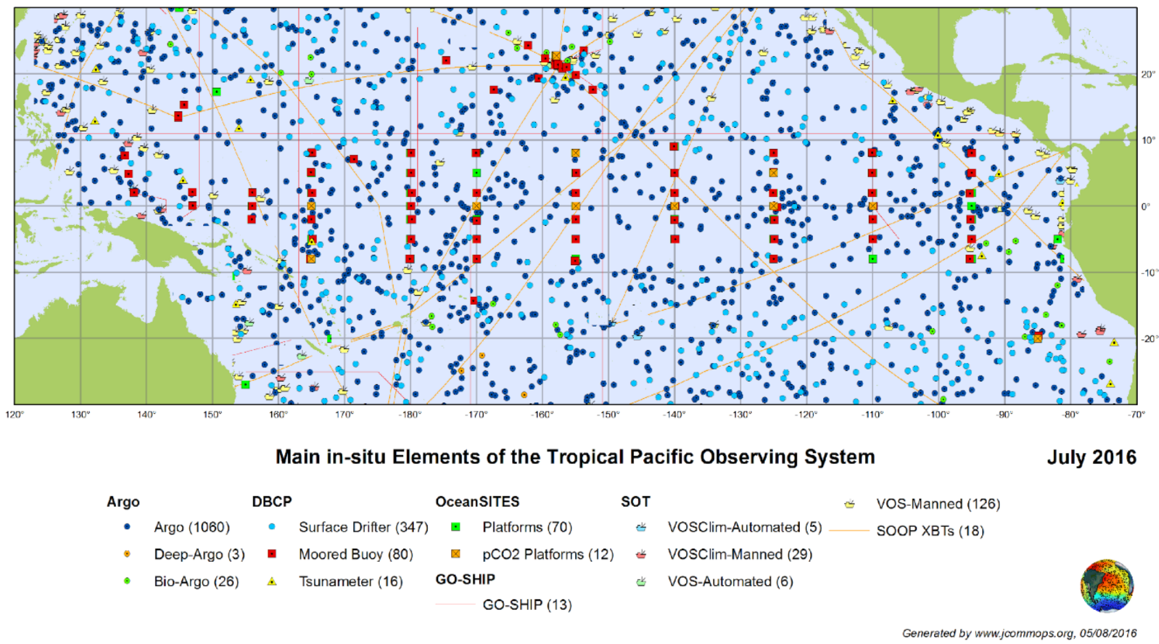

Figure 7-1. Current observations for the TPOS (courtesy of JCOMMOPS).

5. In the eastern Pacific, an inability to implement and maintain planned observation designs, particularly for the TMA, means there are persistent gaps and observational shortfalls. Moreover, as section 3.1 and Chapter 6 noted, there are emerging new requirements in the east that need to be addressed.
6. Biogeochemical observations are sparse against all requirements except for ocean color.
7. Requirements in the vicinity of the convergence zones are only partially being met: ITCZ in the eastern Pacific; ITCZ and SPCZ in the western Pacific.
8. We are not meeting requirements in the surface mixed layer, especially for the diurnal cycle that mediates ocean-atmosphere interaction in many regimes (sections 3.1.1.1, 3.3.1, 3.3.2, and 5.2).
9. The current observing system satisfies T and S(z) requirements at a marginal-to-acceptable level through the tropics, but is marginal or worse for S(z) in the equatorial region.
10. The flux/PBL requirements in key regimes are only partially being satisfied; those regimes include where models and satellite retrievals have persistent, systematic errors, and regions that are the focus of important processes for coupled model development (section 5.8).
11. Meridional scales of T, S and velocity spanning the equator are much shorter than are now being sampled. The additional requirements identified in section 3.3 are largely unmet, even on an experimental basis. In particular, LLWBCs are presently not being observed routinely, and we are unable to observe critical near-equatorial processes that affect the basin-scale coupled climate.
12. Systematic errors in the current generation of coupled models and the current state of data assimilation systems does not allow optimal utilization of TPOS observations. Systematic errors in the coupled models need to be reduced and data assimilation techniques need to be improved.

Given resource limitations, and the fact that implementing agencies have different mandates, different capacities and capabilities, and different constraints on timelines for response, the following sections attempt to lay out a sequence of actions that will lead TPOS toward a more effective configuration to partially or wholly address these deficiencies. These actions include trade-offs and adoption of new approaches and technologies, while at the same time trying to ensure that the overall impact of TPOS is maintained and enhanced.

7.3 The eventual in situ Backbone in 2020 and beyond

The gaps and shortfalls outlined in section 7.2 are mostly within the in situ observing system (item 4 is the exception), so the focus here will be predominantly on that component. The ocean variable requirements outlined in section 3.3 and addressed in part by Chapter 6 are covered here only when we are recommending a TPOS Pilot Program to develop sustained capability.

It is useful, first, to paint a picture of the likely TPOS in 2020 and its major elements, particularly the TMA and Argo. This evolution will be staged (sections 7.1 and 7.4) and responds to the highest priority gaps outlined in section 7.2.

As noted in section 2.5, and consistent with the principles of Chapter 4 and section 7.1, the TMA configuration will move toward approaches focused on the particular challenges of more comprehensive sampling of the varied tropical Pacific regimes, which include the interior ocean, plus the several "boundary layers": the near-surface layer that interacts directly with the atmosphere, the near-equatorial region, and the eastern and western coastally influenced regions. It will also give priority to areas where the broad-scale networks have systematic failings. Such changes are not driven by failings of the TMA but by a desire to maximize the impact of the TMA with the advent of other technologies that can better meet some of the requirements that were originally the target of the TMA.

TMA.

The configuration of the TMA will evolve to focus on sites where the unique capabilities of moorings are critical (see Figure 7-2):

a. retain all existing and historical near-equatorial sites at 2°S, 0°, 2°N across the basin;
b. reduce priority for moorings in the broad trade wind regions away from the equator;
c. several TMA extensions to cross the ITCZ and SPCZ regimes (section 7.4.4.4) along historical TMA lines (see Figure 1-1 for the present array);
d. increase meridional mooring density near the equator (new sites at 1°S and 1°N at one or a few longitudes); and
e. possible future augmentation for western regimes through additional sites developed by partners.

Such a change will need to be carefully managed, taking account of the priorities listed in the previous section, and with due attention to the overarching need to maintain adequate climate records (section 3.2.2).

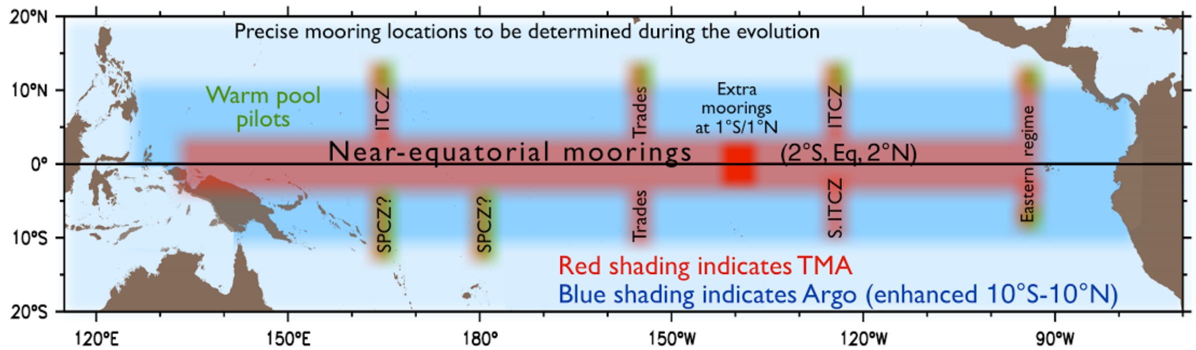

Figure 7-2. The eventual configuration of the sustained moored and Argo networks. Red shading indicates TMA moorings, blue indicates Argo, enhanced within 10°S-10°N (darker blue shading; section 7.4.3). The reconfigured TMA consists of near-equatorial sites (broad red stripe centered on the equator), plus several extensions to cross the ITCZ and SPCZ (section 7.4.4.4). Precise sites are "fuzzy" (green shading) in some details, for example, how far north and south the extensions will go and whether the SPCZ line will be along 165°E or along 180°. Two extra moorings at 1°S and 1°N will increase the equator-spanning meridional resolution at 140°W (bright red square; section 7.4.4.1). Possible future western augmentation is here labeled "Warm pool pilots."

The focus of the future TMA sampling should be shifted up toward the near-surface layer. More capable moorings will:

a. include more complete measurements of air-sea flux variables;
b. enhance sampling of the rapidly-varying mixed layer, including some near-surface velocity; and
c. reduce temperature sampling below 300 m, except on the equator.

Argo

The observational requirements outlined in section 5.9 and addressed by Recommendation 17 demand a doubling of the number of Argo profiles in the 10°S-10°N band. As discussed below, this implementation will be staged; there will also be specific actions targeting improved resolution in the equatorial region.

Within the staged increase of Argo density, some increases are designed to compensate for loss of subsurface data where the TMA is or will be reduced (see above), to ensure that subsurface sampling provides:

a. seamless or improved subsurface data for assimilation and forecast systems; and
b. continuation of credible climate records of subsurface conditions.

Boundary Regions

The eventual in situ TPOS will expand to include the eastern and western boundary regions:

a. in the west to monitor mass and heat transports entering and leaving the tropical Pacific; and
b. in the east to describe and quantify the coastal upwelling circulations and their heat and biogeochemical consequences.

Biogeochemical Observations

Current sustained biogeochemical observations are limited, particularly below the surface, and we anticipate major changes over the lifetime of TPOS 2020 and beyond. At present, pCO_2 and underway biogeochemical observations take advantage of platforms/logistics that are primarily in place for other purposes. However, we should anticipate networks and platforms that will increasingly have their primary purpose as biogeochemical observations. Section 6.1.3 refers to a number of projects, including those that are associated with BGC-Argo, which has recently released an implementation plan for the global network (Biogeochemical-Argo Task Team, 2016). New requirements for sustained networks will emerge from similar efforts.

7.4 Staged implementation actions

This section addresses implementation, roughly ordered by urgency, and provides guidance and advice (but is not prescriptive) on platform and technical aspects, within the context of the broader picture of evolution painted in section 7.3 and consistent with the requirements outlined in Chapters 3 through 6.

The need for a staged implementation is driven by the sequencing necessary to ensure adequate overlap of technical and configuration changes, the timetables of technical advances and testing and the need to respond to externally imposed technical and management issues.

7.4.1 Sustain key components of the existing in situ observing system

The existing in situ components of the observing system other than TMA and Argo (see Figure 7-1 and WP#10, Roemmich et al., 2014) remain important components of the TPOS and should be maintained (see also section 7.2). Satellite recommendations were provided in Chapter 5 and options for Argo and the TMA are discussed in more detail below.

The surface drifter network is vital for SST calibration/validation, for surface currents and for sea level pressure observations, especially outside the equatorial region. The cost/benefit of upgrading to higher accuracy thermistors for SST should be explored.

Underway data collected from Voluntary Observing Ships, including SSS, are a critical and quasi-unique source for observing and understanding small-scale 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 gradients.

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.

GO-SHIP provides important full-depth long transects of the ocean on a regular basis which, while not directly addressing high-level TPOS requirements, provides extremely important complementary information in the intermediate and deeper waters, as well as valuable reference data for calibration of floats. Similarly, **OceanSITES** provides coordination of important fixed-point reference sites.

Tide gauges continue to play a key role for calibration of satellite SSH observations and monitoring sea level change (see section 5.3 and Recommendation 6), and the network should be sustained.

TPOS 2020 recommends:

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

7.4.2 Address the decline of the TMA in the west

The decline of the TMA array in the western tropical Pacific (see Chapter 1, Figure 1-1) poses an immediate threat to TPOS capability and data streams. The most crucial degraded observations, especially along the equator, are of ocean surface wind and wind stress (section 5.1 and recommendations therein), subsurface temperature and salinity observations (section 5.9) and surface heat and freshwater fluxes (section 5.8) in this key region, where satellites have known deficiencies.

Given the reduction in the sustained TMA in the west, the response here focuses on restoring critical capabilities, which might involve new technologies and new array designs.

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

> ***Action 2*** Argo deployments should immediately be doubled equatorward of 10° in the west (especially outside the TMA-occupied region) to maintain subsurface temperature and salinity sampling and compensate for the declining TMA.

The increase required will depend upon how rapidly the 2°S to 2°N western part of the TMA can be restored and progress should be monitored through the Transition process (section 7.7). Action 1 is likely to cost around US$1M per annum. Action 2 would cost around US$500,000 per annum. Planning and implementing these actions can begin now. Action 1 must begin immediately to secure sustained support for contributions to TPOS in this region (see later Action 9).

7.4.3 Argo: Double profiles in the tropical region[12]

Sections 3.4 and 5.9 made the case for enhanced subsurface profiling. The deployments would target a density of one profile every 5 days per 3° x 3° square or, equivalently, one profile per 2.1° x 2.1° square every 10 days; in the equatorial region this translates to a requirement of 1 profile per 150 km x 700 km box every 5 days (see Recommendations 17, 18 and 20). Such a profiling density is a good match with the assimilation requirements of ocean models, except near the equator where the higher frequency and fixed-point sampling of TMA is critical.

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

The increase would be staged as follows:

1. The western Pacific (see section 7.4.2).
2. The eastern Pacific, to pick up sharper meridional gradients in temperature and salinity.
3. The trade wind regions (beyond 2°S/2°N) in the central Pacific (approximately 165°E to 125°W), partly to meet additional requirements and partly to enable evolution of the TMA.
4. Finally, the entire tropical region.

The profiling improvements remain marginal for high-frequency variability, emphasizing the need for complementary Argo and TMA networks. A combination of increased Argo profiling and TMA would typically reduce analysis errors to 30% or less of the variability at timescales of 5 days and greater, given a reasonable choice of the analysis covariance function (F. Gasparin, personal communication).

Argo technology and deployment strategies can potentially be adjusted to partially or wholly deliver improved tropical outcomes (Gasparin et al., 2015). For example, seeding could target equatorial scales, or different cycling rates (5 days) could be used. In both cases the overall strategy of Argo would still be followed but greater impact in the tropics might be achieved. Further study is needed.

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

7.4.4 Moorings: Focused and more capable

As outlined above, TPOS 2020 believes there is a strong case for beginning the transition of the TMA from its present grid structure between 8°S and 8°N to a refocused array designed to sample the varied regimes

[12] Although "the tropics" is strictly defined as the region between the Tropic of Cancer in the Northern Hemisphere and the Tropic of Capricorn in the Southern Hemisphere, we use the term to refer to the region equatorward of 10°.

of the tropical Pacific (see sections 3.1.1.3, 3.3.3 and 5.8). Any such change would follow the Principles given above (section 7.1), particularly the GCOS Principles and the need to secure important climate records. Part of such a change has been forced upon TPOS in the west (section 7.4.2), but there may be further opportunity to rationalize and improve the array, part of which has been outlined above.

The new moored sites could be more capable in several ways, but in particular we have noted their unique capability to sample the quantities needed to diagnose ocean-atmosphere interaction and fluxes (sections 3.1 and 3.3). These quantities include the full suite of surface meteorological variables, along with the ability to adequately describe the rapidly varying near-surface layer of the ocean. The inclusion of a mixed layer velocity measurement is crucial to define the relative wind, which depends on the difference between the wind and surface current velocities (section 3.1.1.2, Recommendations 11 and 19).

A standard mooring in the refocused TPOS should sample:

- On the buoy:
    - The previously standard SST, air temperature, humidity and winds
    - Short and longwave radiation
    - Sea-level pressure
    - Precipitation
- In the ocean:
    - Enhanced vertical resolution (typically 5 m) of temperature in the upper 50 m, and salinity where appropriate
    - A point sample of near-surface vector current (typically at 5 or 10 m depth)

Consistent with usage in other moored arrays (PIRATA, RAMA), a site with this sampling will be referred to as a “flux mooring” and will be considered the standard for all recommended moorings unless otherwise noted.

We note that some of these recommendations may be superseded through future technological advancements, either in situ measures of surface flux variables (see section 7.5.2) or satellite measures of surface currents (section 5.6). At present, however, moorings are the only proven solution for these critical needs.

Certain sites may provide justification for additional enhancement, which could include velocity profiles, either just within the near-surface layer or over a larger depth range (this would generally be on and near the equator), and biogeochemical sampling. These are discussed in the subsections below.

Figure 7-2 shows the revised TMA. The rationale for the reconfiguration is discussed in more detail in the sections below.

7.4.4.1 Denser near equatorial moorings

We recommend increasing the meridional density of enhanced fixed-point sampling spanning the equator at one or several longitudes along the cold tongue by adding well-instrumented moorings, initially in the central Pacific (probably at 140°W) from 2°S to 2°N at 1-degree intervals (see sections 3.1.3, 3.4, 3.3.3 and 5.9.1, Recommendation 17).

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

This strategy will bring the near-equator network closer to sampling the short meridional scales of key variables and phenomena of this region (section 3.3.3). In addition, the cold tongue front will pass repeatedly back and forth across eastern sites, giving many samples of its vertical structure and its (two-way) interaction with the southeasterly winds.

A similar enhancement should be considered at sites in the separate regimes of the eastern and western Pacific.

Velocity profiles (as presently taken at only four equatorial sites) on the enhanced lines spanning 2°S to 2°N would add great value in tracking the varying structure of the equatorial undercurrent and the diverging Ekman flows that produce equatorial upwelling.

7.4.4.2 Reconfigured TMA presence in the trade wind regions

In the presence of Argo (with the recommended increased deployments that will improve sampling of subsurface temperature and add salinity; section 7.4.3), and the ability of scatterometers to sample the trade winds (sections 3.1.1.2 and 5.1), there is the possibility to refocus the TMA with fewer sites committed to a grid (see section 7.4.4); the negative impact of the observation losses is expected to be tolerable.

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

Impact and benefit studies should accompany each stage of the reconfiguration, including impacts on underway and ancillary data collection, especially for $p\mathrm{CO_2}$. Real-world experience as Argo sampling increases should be evaluated to ensure that the data stream of subsurface conditions remains adequate for operational users and that a credible climate record is maintained. Results from the earlier Actions 1 and 2 for the western Pacific will provide a valuable reference for the actions here.

Previous chapters (particularly Chapter 3) have highlighted the paucity of studies on the impact of TMA surface meteorological data in NWP and associated atmospheric reanalyses, which ingest the full range of available satellite data streams. In particular, there are significant differences in wind and flux products within the tropical region.

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

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

We note that the recent Sixth WMO Workshop on the Impact of Various Observing Systems on NWP included the following draft recommendation:

> *NWP and modelling communities to continue to develop modeling and assimilation approaches relevant to surface flux measurements and subsurface ocean observations and to undertake relevant data sensitivity and impact studies when possible.*

Changes in mooring service cruises may lead to reductions in ancillary and underway data collected. While there are some potential technical solutions (see section 7.5.2 below), these have yet to be deployed and tested in experimental mode through observing system pilots, and so are probably some years away from replacing part or all of the lost capability if that is later determined to be a priority.

TPOS 2020 recognizes the need for easy to access, reliable and timely plots of the state of the equatorial Pacific based on blended analyses from all of the GOOS platforms.

As is common in boundary regions, vandalism has been a recurrent problem for the key 95°W TAO mooring line and lack of a robust strategy for its sustainability resulted in lack of measurements during the recent 2015-16 El Niño.

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

7.4.4.3 Regime coverage: Equatorial flux mooring enhancement

Due to the 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 (section 3.3.2), we recommend retaining and upgrading all the equatorial TMA sites to the flux mooring standard (section 7.4.4). This ensures that this critical and poorly understood regime, whose fast wave processes and surface/thermocline coupling act on the entire tropics, is well monitored, with phenomena resolved down to hourly timescales.

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

The estimated cost is US$35-40K per annum per mooring site.

7.4.4.4 Regime coverage: Extend the TMA into the convergence zones

As noted in section 7.2 the observational coverage for certain regimes is inadequate. Chapter 5 (Recommendation 2) recommended regime-based in situ wind measurements, with particular emphasis on extending in situ vector wind sampling into high-rain areas where there is potential contamination and uncertainty of scatterometer winds. Recommendation 13 called for enhanced in situ observations of state variables needed to estimate surface heat and freshwater fluxes in the western Pacific as well as under the ITCZ and SPCZ, to help evaluate and improve satellite-based surface flux estimates, atmospheric reanalyses and coupled data assimilation validation.

The existing TMA, limited within 8° of the equator, provides only partial coverage of key climatic regimes (see discussion in section 3.1) and does not have adequate flux sampling.

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

In the west Pacific warm pool, a line of flux mooring sites along 165°E is the minimal response 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. A secondary priority is additional moorings at 12°N and 13°S, at an appropriate longitude, to sample the inflows into the atmospheric convergence zones, monitor the SPCZ's interannual and decadal displacements and characterize the southwest Pacific cyclone genesis region (section 3.1).

The far western Pacific is a different regime, and this is also where we have a drastic reduction in mooring capabilities (see section 7.4.2). In the event the historical 137°E TMA line is reoccupied (for example, as part of a Pilot), we recommend equipping it with flux moorings. In addition, a flux mooring at 13°N, at the northern edge of the ITCZ/typhoon prone region, would help understanding typhoon development and dynamics.

In the eastern Pacific, the initial priority is additional flux mooring sites along the 125°W meridian at the historic sites (2°N, 5°N, 8°N), and extending north to sample seasonal and interannual variability under the extreme rainfall of the eastern ITCZ. 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.

We also support sampling under the poorly known seasonal southern ITCZ with a flux mooring at 125°W, 5°S, noting the higher rainfall in austral autumn between 2°S and 7°S with a maximum around 5°S.

Depending upon the implementation challenges at 95°W (see Action 9), we also support extended flux measurements along this line.

We also recommend maintaining the Stratus mooring at 20°S, 85°W, which was implemented in 2000 as part of the EPIC project and is the only continuous record of ocean-atmosphere interaction in the stratus regime that covers much of the southeast Pacific (Weller, 2015).

In the central Pacific, flux mooring enhancements should be considered at the existing 155°W sites to sample the drier and less cloudy conditions of the trade wind regime, which will provide better spatial resolution for basin-wide description of surface meteorological observations that are uniquely made from buoys (humidity and surface air temperature; sections 3.1.1.3 and 3.2.1]).

While recognizing the logistical and support challenges, we believe this array of mooring sites is an appropriate solution in response to the requirements articulated in section 3.1 and the recommendations of Chapter 5.

7.4.5 Biogeochemical observations

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

The equatorial moorings and their service cruises are the primary platform for sampling pCO$_2$ on subseasonal to interannual timescales. Existing moored pCO$_2$ systems on the equator at 110^{o}W, 125^{o}W, 140^{o}W, 155^{o}W, 170^o W and 165^{o}E and at 8^{o}S, 165^{o}E should be maintained. New moored pCO$_2$ systems should be expanded to off-equatorial sites on the selected meridional TMA lines (see section 7.4.4.4) to map carbon fluxes across the upwelling region and observe the migrating edge of the warm pool/cold tongue and the low oxygen zone, respectively. While 95^{o}W would be ideal for capturing the broadest area of intense upwelling, the high levels of vandalism on this line suggest a cautionary approach to the use of biogeochemical sensors at these sites. Additional presence of the TPOS mooring servicing ships (e.g., twice a year) along the 95^{o}W line will be critical to addressing vandalism.

Each of the existing and new pCO$_2$ moorings should measure the full suite of flux variables (i.e., flux moorings as defined in section 7.4.4) needed for calculating CO_2 flux. These sites should also be augmented where relevant with collocated oxygen sensors for mapping the OMZ and optical sensors for phytoplankton biomass in the near-surface for mapping primary production and improving algorithms for satellite ocean color (also see Recommendation 13 of Chapter 5).

Maximizing the use of mooring servicing cruises is a critical component for Backbone biogeochemical observations (see Principles in section 7.1). In particular, service ships should continue underway measurements for pCO_2 to ensure continuity in the record of CO_2 flux, to serve as validation for moored measurements and new technologies, and to provide context for spatial variability between moored observations. Opportunities should be considered for biogeochemical measurements from the service cruises that cannot be made autonomously, including dissolved organic carbon (DOC), and nitrogen (DON), N_2O, tracers (e.g., chlorofluorocarbons, oxygen isotopes) and iron throughout the water column.

As new sensor and platform technologies such as BGC-Argo floats and gliders are tested and further developed, the proposed BGC Backbone design may be modified to make the best use of new technologies (see sections 6.1.3 and 10.2).

7.4.6 Risk mitigation strategies for air-sea flux variables

Sections 7.4.1 to 7.4.5 provide a number of actions for the reconfiguration of the Tropical Pacific Observing System. A number of studies are suggested to guide implementation and to understand impacts.

When the TMA is refocused, a particular risk arises for surface flux variables that are not replaceable by satellite observations, and Actions 7 and 8 address studies that are needed to improve understanding of the impact of TMA data. A number of other actions are possible to further mitigate any risks.

First, there are other platforms measuring high-quality surface flux variables, such as the Voluntary Observing Ship Climate (VOSClim) fleet, although VOS sampling will always be sparse in space, infrequent, and less consistently sampled than TMA measurements. Wherever possible, these efforts should be enhanced to support the reconfigured TMA array.

New technology also offers some promise to address priorities not addressed by the reconfigured TMA (see section 7.5.2 and 10.2).

Reanalysis products offer the promise of improved global flux products, but such products continue to have significant systematic errors and fall well short of meeting requirements (see section 3.1.1.3; Josey et al., 2014). The refocusing of the TMA on regimes is in part aimed at improving such systems and thus indirectly improving the estimates of flux fields.

Another approach is to seek to rescale and/or offset reanalysis fields so that bias relative to observations is reduced. Such techniques are similar to the Model Output Statistics methods of NWP (e.g., Wilks and Hamill, 2007). One such example uses the Japan Meteorological Agency 55-year reanalysis (http://jra.kishou.go.jp/JRA-55/index_en.html). Following Large and Yeager (2004, 2009), all variables, except for sea level pressure, are modified from the original fields by applying scaling or offsetting factors to fit the reference fields derived from observations or other reference data sets. These factors are determined for each month of a climatological annual cycle and take into account changes in the observation systems and the data assimilation methods as noted by Kobayashi et al. (2015). In the case of surface air temperature and specific humidity, for example, an ensemble mean approach is taken to obtain a reference data set, based on seven atmospheric reanalysis products. Version JRA55-v08 has prepared for close scrutiny by colleagues and participants of the September 2016 meeting of the CLIVAR Ocean Model Development Panel (OMDP) and a report on findings is being prepared.

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

7.5 Actions for evolving TPOS

7.5.1 Pilot and Process Studies

Chapter 6 outlined a number of Pilot and Process Studies, as well as ongoing work being led by TPOS 2020 Task Teams. Some of these studies are precursors needed to guide sampling strategy and to refine the approach toward sustained networks. Here we list those studies, roughly ordered according to the likely impact on TPOS in the long term:

Pilot Studies/Programs for the Backbone

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

Process studies

- 6.2.1 Pacific Upwelling and Mixing Physics
- 6.2.2 Air-sea interaction at the northern edge of west Pacific warm pool
- 6.2.3 Air –Sea Interaction at the eastern edge of Warm Pool
- 6.2.4 East Pacific ITCZ/warm pool/cold tongue/stratus system

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

The study at section 6.1.6 (“Assessing the impact of changes in the TPOS Backbone”) is a necessary modeling complement to the other Pilot and Process studies listed above (for example, section 6.1.3 "Determining the critical time and space scales for biogeochemistry in TPOS"). As outlined in Chapter 4, modeling and data assimilation are an integral element of the TPOS design and critical for delivering products of value to the user community. The Modelling and Data Assimilation Task Team has developed a work program that includes work on the attribution and possible alleviation of common coupled model biases (section 10.1.2) and a project for comparison of ocean analyses and utilization of observations (section 6.1.7). TPOS 2020 recommends:

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

7.5.2 Existing technological developments

Several experiments to develop and test technological improvements that are close to readiness have recently been funded by the NOAA Climate Program Office and JAMSTEC (see the Annex to Chapter 6, section 10.2). These have begun testing new solutions to meet the requirements in Chapter 3. Results of these now-underway studies could result in more effective sampling strategies, especially for the near-surface layer and for biogeochemical sampling. With the experiments already putting instruments in the water, results should be becoming clear by in 2018. The potential changes that might evolve from these tests include:

- Near-surface pCO_2 sampling from the Saildrone might reduce the need for these measurements from moorings and mooring service cruises. More extensive biogeochemical sampling than is presently possible might become feasible (sections 3.1 and 3.3.5).
- Saildrone measurements might also increase flexibility in describing surface meteorology and air-sea fluxes, and their scales of variability (section 3.1.1.4). Success of these tests could guide planning for future TMA needs.
- Flux measurements from wave gliders provide an additional potentially complementary approach to flux moorings.
- Argo enhancements include additional biogeochemical samplers: pH, oxygen and nitrates (section 2.6.7). These have the potential to provide much better spatiotemporal resolution of the biogeochemistry of the upper ocean than has been possible, and potentially reduce the need for such sampling from cruises and moorings. Acoustic rain measurements from floats will also be tested (section 5.4)

- Mooring near-surface velocity tests would evaluate and compare methods of measuring mixed layer velocity, enabling a better description of the communication between the surface and the thermocline (section 3.3.1). These tests will indicate if sustained monitoring is needed, prove methods to accomplish it, and guide decisions about the configuration of future TMA instrumentation.

Several technologies are presently employed for research projects that point to additional monitoring opportunities for TPOS 2020. Two such platforms are autonomous underwater gliders and pressure-equipped inverted echo sounders (PIES). Gliders can provide profiles of pressure, temperature, salinity, velocity and potentially biogeochemical quantities such as dissolved oxygen, CO_2 and nitrate. A pair of PIES moorings can be used to infer geostrophic velocity, or if a time-mean bottom velocity is available, this can be added to produce a time series of absolute velocity perpendicular to the PIES transect. Both of these platforms have been used with success in various programs around the Pacific, although there remain some issues about their present suitability for sustained implementation. PIES still require ship support for deployment and data interrogation, although there are ongoing efforts to automate data telemetry. While gliders transmit their data in real time, their operation in strong currents (e.g., LLWBCs, which are a likely target for gliders) require attentive piloting. In addition, studies are still needed about the spatial and temporal sampling requirements in many regimes to understand how many gliders might be required to satisfactorily sample the mass, heat and freshwater of the upper ocean (e.g., section 6.1.1). Nonetheless, in the near term, these platforms may prove appropriate technology to fill gaps in our sustained observing systems.

7.5.3 Dependencies and priorities

The Actions prioritized in sections 7.4 and 7.5 have a number of interconnections and dependencies. One of the initial challenges will be in the western Pacific (section 7.4.2): the resources needed to partially restore the TRITON capability and to enhance Argo profiling have yet to be identified. This might put additional pressure on existing commitments.

For the evolving role of the TMA (section 7.4.4), experience in the western Pacific will be very important, acting in effect as a “pilot” for elsewhere. The Actions of sections 7.4.3 and 7.4.4 also require further work and study by the TPOS 2020 Steering Committee and its Task Teams, in consultation with the group coordinating transition (see section 7.7).

One of the more critical relationships is between the evolving TMA and increased Argo profiling. The studies cited in Chapter 5 and in section 7.4.4 give us confidence that the required subsurface sampling can be met through a new combination of Argo and TMA, but this will require further study on Argo deployment strategies. The changed TMA configuration may impact the availability of underway data from service cruises and restrict opportunities for ancillary data collection.

Mitigating the impact of the loss of some high-frequency subsurface and surface meteorological sampling will also be a challenge. With the initial focus on the western Pacific (section 7.4.2) there is an opportunity to undertake further analysis of the impacts (for example, Action 7).

Chapter 5 and section 7.4.1 above make certain assumptions about the maintenance and, in some cases enhancement of existing satellite and in situ networks. This will not be trivial and the Transition and Implementation Group will need to work closely with WIGOS and JCOMM on these issues.

7.6 Assessment and evolution

As with any major change project, implementation of the Recommendations and Actions of this Report will require good project management, two elements of which will be ongoing assessment of the impact of the changes and careful attention to the planned benefits of the changes.

At least some of this assessment can be done through real-time and/or offline system sensitivity studies as mentioned above and discussed in the Annex to Chapter 6. The ocean and climate communities are now able to follow data flows much more carefully than was the case 20 years ago, and groups such as the GODAE Oceanview OSEval Task Team[13] have developed a number of innovative approaches to observing system evaluation. The Process Studies mentioned in section 7.5.1 will also play an important role.

Benefit realization is often harder to quantify. OceanObs '19[14] provides one opportunity to test whether the planned benefits have been realized. The TPOS 2020 Steering Committee has also flagged a post-Project conference to assess the success of TPOS 2020.

One lesson taken from the unanticipated data losses during 2012-2014 is that greater focus needs to be given to the risks of observing system failures. This will be a focus of the transition process.

7.7 Transition

At the Second Meeting of the TPOS 2020 Steering Committee (see the report on tpos2020.org) it was agreed that early consideration should be given to the transition process.

The Steering Committee noted that advice and recommendations from TPOS 2020 would emerge through three reports, in 2016 (this report), 2018 and 2020 (see Figure 7-3). In this context, "transition" refers to the staged adoption and implementation of this advice and recommendations (including development of

[13] https://www.godae-oceanview.org/science/task-teams/observing-system-evaluation-tt-oseval-tt/

[14] http://ioc-unesco.org/index.php?option=com_oe&task=viewDocumentRecord&docID=17352

any new governance bodies and processes), for the phased transfer of responsibility from the Project to relevant bodies and agencies.

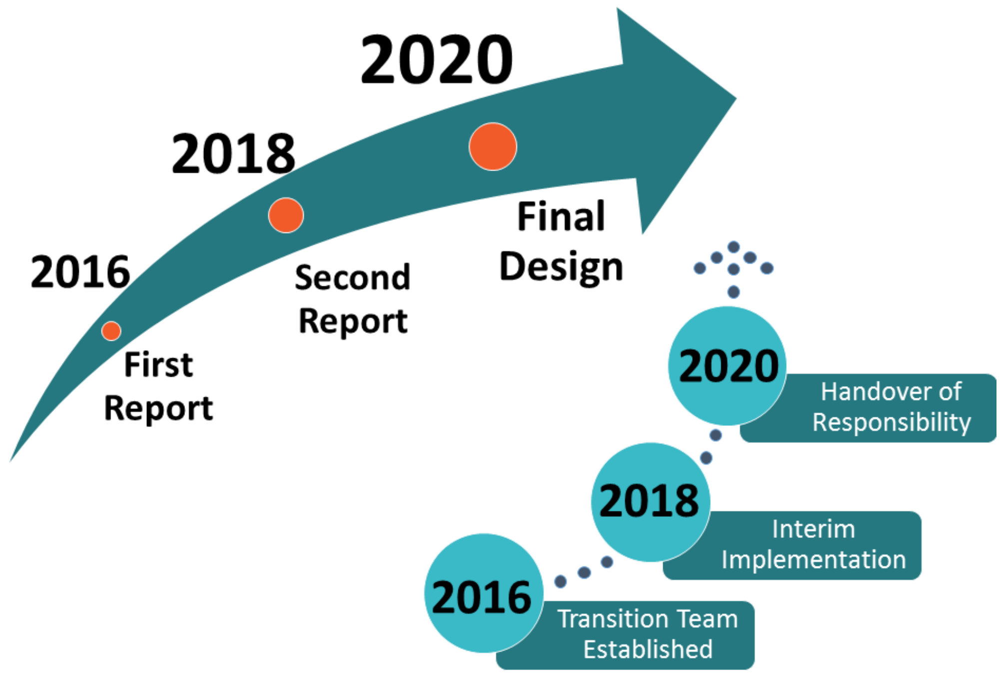

Figure 7-3. Schematic showing the report sequence and the transition process. The transition process will be formally initiated in parallel with the publication of this report, in late 2016. We do not expect changes and actions to occur immediately, but by the time of the Second Report in 2018 implementation actions should be underway. The TPOS 2020 Project concludes in 2020 with the publication of the final design, and at this point there must be full handover of responsibility.

It was agreed that the transition process should be initiated in parallel with the publication of this report and that appropriate change management/transition mechanisms should be operated in parallel with the staged delivery of advice. The Steering Committee noted that Implementation typically lags recommendations on design by around two years, so the handover of responsibility will occur progressively from 2016 through to 2020 (refer to Figure 7-3); however, a variety of stakeholders will be contemplating and reacting to the recommendations, despite their "interim" nature, so we have tried to be as specific as the current situation allows.

The Steering Committee emphasized the need to identify and manage risks, such as insufficient overlap of old and new networks and inadequate resources for transition (see section 7.6).

The WMO and IOC and relevant subsidiary bodies and expert panels will play a key role in the transition process, so some initial consultation has taken place to understand the likely settings that will be needed.

In the case of WMO, TPOS 2020 believes it is important to fully engage the National Meteorological and Hydrological Services (NMHSs) of the tropical Pacific Ocean region, and some preliminary consultation has taken place with the WMO Integrated Global Observing System (WIGOS). Several important messages bearing on the transition process emerged:

- There was strong encouragement to initiate this engagement early and not wait until all recommendations have emerged.
- The best route to engage NMHSs is through consultation with existing WMO mechanisms, particularly those associated with the Rolling Review of Requirements for observing systems.
- The idea of a regional governance mechanism post-TPOS 2020 is well aligned with changes being contemplated by WIGOS.
- The next WMO Congress in May 2019 would be an ideal time to have WMO to consider and, as appropriate endorse key recommendations, noting that the timing of the mid-term report was well aligned with such a target.

For IOC, there has been some informal consultation around the relevance of the GOOS Regional Alliances but without firm conclusion. It is also important to note that AtlantOS, an initiative similar to TPOS 2020 but with an Atlantic focus, will be making recommendations over a similar timeline, and that the responsibility for ensuring consistency will largely fall to GOOS and its implementation arm, WMO/IOC JCOMM. Similar considerations apply to the Deep Ocean Observing System (DOOS) and the Southern Ocean Observing System (SOOS), though they have rather different timelines and levels of maturity.

We should also be cognizant of the fact that some stakeholders may not work through either WMO or IOC for implementation.

7.7.1 Initial considerations

This report draws on the GCOS Climate Monitoring Principles to emphasize that changes must be managed so as to minimize negative impacts and to allow sufficient overlap for cross-calibration of climate records based on changing data sources. The 2016 GCOS Implementation Plan was developed in parallel with this report, and the transition process will need to consider how overlapping actions are to be managed.

A strong theme of this report is the recognition of the fundamental contribution of satellites to the integrated TPOS design, a role that has increased substantially since the end of TOGA. The changes discussed above will impact these roles (in fact, we aim to strengthen the synergies) and it will be important to test this integration in the transition process as well (for example, through direct engagement with GHRSST or the Ocean Vector Wind Science Team, OVWST).

Ships remain the only way to deploy and service moorings, as well as make measurements that cannot be made from moorings, Argo or satellites. This report recognizes that these ships represent a significant element of the cost and logistical burden for maintaining the TPOS, but they are fully justified in terms of the return. A successful TPOS requires consistent ship availability and capability, so that core TPOS observations like underway pCO_2 can be maintained, and future ancillary measurements and technology development can be accommodated.

This report refers to new and emerging technologies as well as several emerging lines of R&D, but conclusions based on the adoption of such developments are expected to emerge in later reports. We fully expect a strong biogeochemistry push in the later stages of TPOS 2020 and, again, the transition process must be formulated in such a way to accommodate these emerging requirements and observing network contributions.

7.7.2 An example of regional transition and implementation: The eastern Pacific

The overarching goal is to provide advice on how the implementation and transition can be shaped to broaden engagement and investment in the eastern Pacific area of TPOS, identifying specific regional motivations/value for effort; encouraging conversation/dialogue with regional stakeholders and discussing different approaches and workable solutions for the unique challenges of the eastern Pacific region.

Eastern Pacific marine ecosystems are directly affected by ocean-atmosphere variability associated with ENSO, by coastal upwelling and several modes of tropical intraseasonal variability in the atmosphere, and are vulnerable to the impacts of climate change. The impact of ENSO motivated the establishment of the El Niño Regional Study (ERFEN, in Spanish), an initiative among southeastern Pacific countries for monitoring and research of ENSO. Thus, historically there has been great interest among the countries in this region in maintaining observations for ocean and climate monitoring and prediction, to understand and manage the marine ecosystems, as well as for integrated coastal management and ocean carbon related research.

Transition and implementation of TPOS 2020 recommendations can take advantage of regional structures such as ERFEN/CPPS, the Regional Committee for Hydrological Resources/Central American Integration System (CRRH/SICA in Spanish) or the GOOS Regional Alliance for the Southeast Pacific (GRASP). For example, TPOS 2020 regional partner institutions, such as IMARPE and DHN from Peru, have interest in initiatives supporting the maintenance of the 95°W mooring line. There also exists a possibility that routine national or regionally funded surveys (e.g., the CPPS Southeastern regional Oceanographic Research Cruise) could contribute to the maintenance of such a mooring line. The CPPS provides a potential regional mechanism for coordination of TPOS 2020 activities.

As is common in boundary regions, vandalism has been a recurrent problem for the key 95°W TAO mooring line, and lack of a robust strategy for its sustainability resulted in lack of measurements during the recent 2015-16 El Niño (also see section 7.4.4.1 and Action 9). Bilateral or regional cooperation mechanisms such as noted above could be explored for enhanced ship time.

There is enthusiasm for a dialogue around data sharing and standardization, which has been a difficult issue. National Data Centers at CCCP (Colombia), INOCAR (Ecuador), DHN (Peru) and SHOA (Chile) are active within the framework of IOC/IODE protocols, and there has been some interest within GRASP in reporting some of the regional data in real time. Additionally, the strengthening or implementation of "super sites" on islands and at coastal locations, particularly in nationally protected areas (e.g., Galapagos, Coco and Malpelo Islands), could be a sustainable strategy.

A number of regional stakeholders see virtue in the establishment of high-level cooperation between TPOS 2020 and the regional mechanisms above and other potential contributors, possibly within the Transition and Implementation Group process. Such cooperation would likely benefit from the organization of an international meeting in the eastern Pacific region with the support of international agencies (IOC, WMO and JCOMM) to reach basic agreements on the scientific and operational aspects. Financial support for TPOS 2020 contributions to global/regional initiatives such as Blue carbon, the GEF Large Marine Ecosystems Programme or others could be later sought in meetings with donors.

Finally, regarding implementation by the national institutions in the eastern Pacific, the TPOS 2020 recommendations would be more effective if they are channeled through a regional body such as CPPS (and activities such as GRASP). Involvement of programs such as IOC-IODE, GCOS JCOMMOPS for technical assistance and support for data management would make the transition more feasible.

7.7.3 Governance

Governance responsibilities will need to be clarified but we might anticipate TPOS 2020 sharing responsibility with those responsible for implementation (e.g., JCOMM).

Based on the considerations above, the Transition process (and Group associated with it) needs to consider:

- Articulation of the purpose and goals of the transition process, and a statement of the expected outcomes;
- References to the key contributions and major areas of change (definition of scope);
- Likely participation, initially a balance between scientific and technical advice (TPOS 2020 Project advice) and implementation expertise (e.g., from the WMO, IOC and other groups mentioned above), but shifting more toward the latter as we approach 2020;
- A description of how the transition process will operate (initial discussion favored an open-ended TPOS 2020 Implementation Group);
- A consultation/engagement mechanism with the R&D community, who may assume leadership of TPOS 2020 Project initiatives that will live beyond 2020; and

- A consultation/engagement mechanism for those dependent activities that are not explicitly included in TPOS 2020, especially data and information management (including for new data streams), capacity building and products and services.

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

8 Summary

This report has provided a number of recommendations and actions for consideration by the community. The recommendations apply to required observations (Chapter 5), which in turn respond to the TPOS variable requirements provided in Chapter 3. Finally, Chapter 7 provided a set of implementation actions based on the recommendations of Chapter 5 (and detail therein; see also section 7.5.1), which will allow TPOS sponsors to approach implementation in a systematic and orderly way.

8.1 Recommendations

TPOS 2020 recommends (Chapters 5 and 7):

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

Recommendation 2 In situ vector wind measurements, with particular emphasis on extending the in situ based climate data records, and intercalibrating different satellite wind sensors especially in the equatorial Pacific and in tropical rainy areas.

Recommendation 3 Sustaining satellite measurements of SST, using infrared sensors for higher spatiotemporal sampling; passive microwave sensors filling gaps under clouds; and the diversity of satellite and in situ platforms contributing to intercalibration.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

8.2 Actions

The Actions from Chapter 7, “Implementation and Transition” are:

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

Action 2 Argo deployments should immediately be doubled equatorward of 10° in the west (especially outside the TMA-occupied region) to maintain subsurface temperature and salinity sampling and compensate for the declining TMA.

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

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

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

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

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

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

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

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

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

Action 12 Underway pCO_2 observations should be continued or reinstated on all mooring servicing vessels, and the present network of moored pCO_2 measurements should be maintained and possibly extended. Measurements of dissolved oxygen from the surface to about 1500 m should be made on ships where practical, and oxygen sensors should be considered on each mooring.

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

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

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

8.3 Conclusion

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

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

9 References

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10 Annex to Chapter 6

10.1 Task Team activities

10.1.1 Upper-ocean processes and air-sea interaction during Years of the Maritime Continent (YMC)

YMC is a two-year (July 2017–July 2019) international project designed to advance our knowledge of the multi-scale interaction of the atmosphere-ocean-land system in the Indo-Pacific Maritime Continent (MC) region. Its overarching goal is *observing the weather-climate system of the Earth's largest archipelago to improve understanding and prediction of its local variability and global impact*. Scientific themes include upper-ocean processes, air-sea interaction and atmospheric convection in the MC region.

One of the scientific targets of YMC is to clarify linkages of rainfall, air-sea interaction and upper-ocean processes in MC coastal regions over a large range of timescales from the diurnal to the seasonal cycle. The Asian summer monsoon (ASM) and the Madden-Julian Oscillation (MJO) are the two large-scale phenomena of particular interest to YMC. They actively modulate complex air-sea-land interaction in the MC and cast remote influences on higher latitudes through atmospheric teleconnections and on the eastern Pacific through atmospheric and oceanic wave propagation. Presumably, air-sea interaction in the marginal and semi-enclosed shallow waters of the MC region is different from that in the open, deep waters of the Indian and Pacific Oceans. The complex terrain of the MC region blocks and channels the large-scale atmospheric flows associated with the ASM and MJO to generate intensive terrain-modulated rainfall patterns. The strong diurnal cycle over land and its associated land-sea breezes interact with the ASM and MJO circulations to affect rainfall over the adjacent water. Coastal upwelling, the throughflow of water from the Pacific to Indian Oceans and mixing due to tidal and near-inertial motions add to air-sea interaction processes driven by surface flux variation.

The multi-scale air-sea interaction under influences of land in the context of the ASM and MJO in the MC region has been studied observationally only to a very limited extent, because of the lack of in situ measurement there. For the same reason, a rich body of numerical simulations awaits to be validated by in situ observations. However, the current TPOS 2020 Backbone design covers only part of the MC region.

The field campaign of YMC will strive to provide air-sea interaction observations from several platforms, including ship- and air-borne measurement, and autonomous devices (moorings and drifting buoys, gliders, etc.), though only for short periods. Figure 10-1 shows five focused YMC observing areas. In each area, there will be focused Intensive Observing Periods (IOPs) with measurements taken from ships, aircraft, autonomous devices, and land-based facilities. These field IOPs will be augmented by observations from the regional observing networks (radiosondes, radars, surface meteorological stations, etc.). Observations in each area will be taken by scientists from different institutes with their own specific objectives, but all will include air-sea interaction.

Particularly relevant to TPOS 2020 are YMC moorings that will be deployed in the waters in the eastern part of the MC (Figure 10-1). One will be at 13°N, 137°E, which is a northward extension of TRITON moorings with full air-sea flux measurement. South of it is a surface mooring at 2°N. At the equator an ocean mooring will be deployed next to the TRITON mooring at 160°E. Several ocean moorings will be deployed in straits and inner basin of the Indonesian Seas. These moorings will provide information to supplement the TRITON moorings that will be reduced in 2017-19. It is noted that there will be more temporary moorings during YMC in the western (Indian Ocean) part of the MC than its eastern part.

Observations of air-sea interaction and related upper-ocean and atmospheric processes in the MC region will enhance our understanding of multi-scale interaction associated with convective heating of the ASM and MJO. New knowledge to be gained will help improve prediction of the monsoon onset, MJO propagation through the MC, and their local and remote impact. The YMC field campaign can serve as a TPOS 2020 process study on upper-ocean processes and air-sea interaction on the western edge of the Pacific Warm Pool and in the MC waters. This can also help to assess the needs and feasibility of possible expansions of the TPOS Backbone design to cover the MC waters.

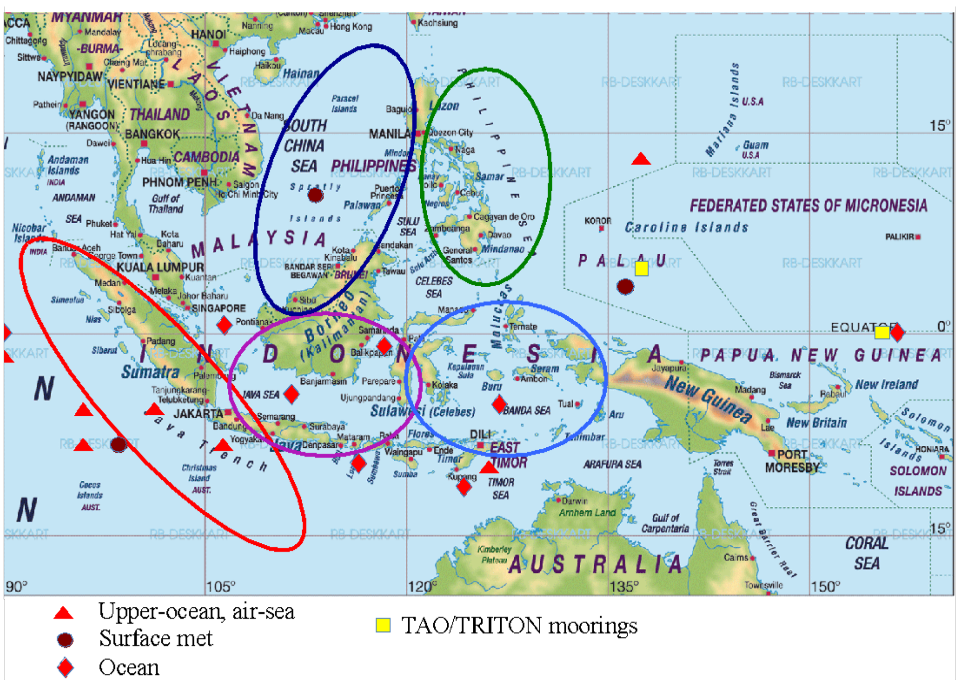

Figure 10-1. Five focused observing areas (ovals) of YMC and mooring locations during YMC in the region of the Indo-Pacific Maritime Continent and its adjacent waters.

10.1.2 Attribution and possible alleviation of common coupled model biases

Background

Coupled GCMs exhibit well-known tropical Pacific biases: an overly intense and westward-shifted equatorial Pacific cold tongue, which is too disconnected from the cold regime near the South American coast; an overly zonal SPCZ and a seasonally alternating "double" ITCZ in the east Pacific; clouds with the wrong location, extent and/or type for a given convective or subsident regime; and an ENSO with the wrong amplitude, spatial structure, seasonal timing, frequency, physical mechanisms or diversity (Guilyardi et al., 2012, 2016). The sources of these biases are often nonlocal in both space and time.

To address these issues, a two-pronged observational approach is needed: (1) continued Backbone measurements to extend the longest available climate records, in order to sample seasonal-to-multidecadal climate variations in a way that minimizes unnecessary shifts due to changes in the observing platforms and locations themselves; and (2) shorter-term, intensive field programs to illuminate essential physics, and better constrain the subgrid-scale physics of climate models. Item (1) is a primary thrust of the proposed TPOS Backbone system (sections 3.1 and 3.2). For item (2), future measurements should be targeted at those poorly-understood subgrid-scale processes that exert the most leverage on climate simulations—namely, atmospheric convection and clouds, vertical mixing in the upper ocean and air-sea fluxes.

Past field campaigns (including TOGA-COARE, EPIC, VOCALS, DYNAMO and SPICE) have provided a trove of data that could be used to better constrain tropical simulations. Before proceeding with a new field program, it is important to ensure that modelers are taking full advantage of existing data. It is also a priority to understand and address differences among existing air-sea flux datasets over the tropics, especially for the surface wind stress, so that modelers have clearer observational targets for the large-scale heat and momentum transfers (sections 3.1.1.2, 3.1.1.3 and 5.1).

Beyond that, a promising avenue for a future field program—which would be facilitated by the proposed meridional refinement of the TMA near the equator (section 7.4.4.1)—would be to focus on the structure, seasonality and physics of upwelling and mixing near the equator (section 6.2.2). Horizontally-dense profile measurements of temperature, density, currents and surface fluxes could be used to evaluate local mixed layer heat budgets, especially if combined with broad-scale surface flux measurements sufficient to drive high-resolution ocean simulations during the measurement period. Such simulations could then be intercompared, evaluating their diurnal-to-subseasonal buoyancy forcing and small-scale shears, as well as the rectified effects of those rapid forcings on the seasonal-to-interannual "effective" diffusivity, viscosity, entrainment, mixed layer depth and temperature, thermocline/EUC structure and SST.

Proposed actions within the Modeling & Data Assimilation (M&DA) TT:

In this context, we envision two types of actions to be promoted with the M&DA TT: (1) short-term low hanging fruits that will not require efforts beyond the task team and (2) longer-term exploratory efforts that would require substantial time from one or more scientists.

1. **Short-term actions (next year):**
    a. Workshop on tropical biases: link with the Working Group on Numerical Experimentation (WGNE) to organize a joint TPOS session at the upcoming systematic errors workshop.
    b. Document and understand the sources of spatiotemporal differences among existing observational level 3 or 4 wind stress products, especially for the zonal component along the equator. A key goal would be to provide a clear recommendation regarding the "array" or "mapping" requirements for the TMA, in order to sufficiently constrain model simulations, reanalyses, forecast initialization and detection and attribution of climate variations and change.
    c. Design and run a survey about the uptake and utilization of existing field campaign data by ocean/atmosphere/coupled modelers, possibly in collaboration with the CLIVAR Ocean Model Development Panel (OMDP). This would help to identify opportunities to better leverage existing data from past campaigns and also identify gaps that should be addressed by future campaigns.
2. **Longer-term actions:**
    a. Identify the key metrics and observations needed to evaluate tropical Pacific climate and ENSO in models, in collaboration with the CLIVAR Research Focus on ENSO.
    b. Provide modeling perspective for a new field campaign, e.g., the one proposed by the EP TT (section 6.1.2). This could include test cases for the modeling community, both for 1D (analogous to the ARM sites used for atmosphere parameterization) and nudged/guided 3D simulations.

10.1.3 The Wyrtki Challenge

A stringent test of the effectiveness of the TPOS 2020 design would be closing the heat budget of the equatorial Pacific Ocean. We can draw an analogy to "Wyrtki's Challenge" of estimating equatorial upwelling in the Pacific (Wyrtki, 1981), which sought to close the volume budget. Closing the heat budget would be a much bigger challenge but would represent great progress.

The first step, proposed here, is to use high-resolution assimilating model output to understand the effects of high-frequency, short-spatial-scale variability: Are the roughly monthly, 1° × 5° fields to be collected by the TPOS 2020 arrays adequate to constrain the volume and heat budgets of the tropical Pacific? How large are the uncertainties in basin integrals calculated from our relatively sparse sampling? Do those uncertainties vary by timescale (e.g., ENSO)? The TPOS 2020 backbone described in Chapter 7 will not adequately sample the tropical instability waves (TIW) along the cold tongue front; we expect that TIW mass transports approximately balance in the basin integral, but not their heat transports. How large are the resulting errors? What choice of northern boundary for the heat budget calculation would minimize these?

TPOS 2020 would work with the Global Ocean Data Assimilation Experiment (GODAE OceanView) to conduct these feasibility studies. Ultimately, a heat budget would balance the surface heat fluxes, but with the great difficulty in estimating those, we initially consider only the oceanic contribution.

We consider a full-depth region bounded by 5°S-5°N, or perhaps a wider latitude range out to 10°S-10°N, the western boundaries (Maritime Continent) and the eastern boundary (American continent). Estimating the advective heat transport convergence into this region requires monitoring the interior transports (Ekman and geostrophic) east of the western boundaries, along with western boundary contributions: the low-latitude western boundary currents (LLWBCs, e.g., Mindanao Current in the north and New Guinea Coastal Undercurrent in the south; sections 3.3.4.1 and 6.1.1), and Indonesian throughflow (ITF).

Initial insight would come from evaluating the volume budget. How do the elements of mass transport into the region balance at various timescales? Which terms are important during the seasonal and ENSO cycles?

Heat transport is undefined when there is a net volume flux as we know occurs: the flow entering the tropical Pacific across its southern boundary that eventually exits through the ITF. Therefore, we focus the discussion on temperature flux (i.e., the inner product of velocity and temperature), according to the following method:

1. In the ocean interior away from LLWBCs, Argo gives estimates of meridional geostrophic currents on monthly and longer timescales; satellite scatterometers provide estimates of meridional Ekman transports (on timescales 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 the MONTHLY inner product of total (geostrophic + Ekman) meridional velocity, V_m, and temperature, T_m, i.e., $V_m(x,5°N,z)T_m(x,5°N,z)-V_m(x,5°S,z)T_m(x,5°S,z)$ integrated over the interior longitudes and depth. The subscript m indicates monthly average.
2. In the LLWBC regions, glider measurements can provide MONTHLY estimates of meridional velocity and temperature and thus estimates of meridional temperature flux convergence based on inner products of MONTHLY meridional velocity, V_m, and temperature, T_m, as for the interior.
3. In the ITF region: mooring measurements provide estimates of temperature flux (products of velocity and temperature) that can resolve submonthly variations.

The total temperature flux convergence is 1 + 2 + 3. The question we seek to address here is whether the above method, based on monthly fields like those the TPOS 2020 Backbone will provide, can yield sufficiently accurate estimates of the temperature flux convergence into the region. Uncertainty arises from the unknown, but potentially large, submonthly variability across the boundaries that may contribute significantly to temperature flux through V'T', where V' and T' are submonthly variations of velocity and temperature associated with features such as TIW in the interior and eddies in the LLWBC regions.

GODAE OceanView's high-resolution systems can provide an assessment of the significance of the V'T' contribution. This can be done by comparing the temperature flux convergence calculated using high-frequency output of the systems (daily should be sufficient) at eddy-permitting or resolving spatial resolutions, versus that calculated from monthly V and T products decimated to 5-degree longitude resolution (comparable to the spatial resolution provided by Argo on monthly timescales). The calculation should explore the choice of latitude boundaries because a wider band might be less susceptible to influence by tropical instability waves.

As noted above, the temperature flux across boundaries does not measure the heat budget because temperature flux depends on the arbitrary definition of zero temperature (0°C or 0°K). However, the temperature of an element of boundary flux can be referenced to the time-dependent volume-averaged temperature of the defined tropical Pacific upper-ocean domain, using the formulation of Lee et al. (2004). This removes the dependence on the choice of zero temperature reference. The method quantifies the influence of flow across any boundary segment at each instant: Is that element of flow warming or cooling the volume of water within the defined domain of the tropical Pacific upper ocean? Note that this is equivalent to the full heat budget if done over the complete boundaries of a domain, but provides additional insight by allowing examination of the contribution by any boundary segment. This alternate analysis should also be tested using the GODAE OceanView systems.

The result of these experiments would clarify the capabilities of the array design described in this document. It should also lead to an evaluation of the uncertainties of the sampling we propose as they affect the challenge of describing the evolving heat balance of the tropical Pacific.

10.2 New technology initiatives

10.2.1 Profiling floats equipped with rainfall, wind speed and biogeochemical sensors for use in the Tropical Pacific Observing System

S. Riser (University of Washington) and J. Yang (University of Washington Applied Physics Laboratory)

Abstract

We propose to examine the utility of profiling floats in the tropical Pacific equipped with auxiliary sensors beyond Argo, by building and deploying 7 floats per year during the period 2016-2018 and analyzing the data produced by these floats. In addition to carrying a standard Argo CTD, each of these floats would be outfitted with sensors to measure near-surface *T* and *S*, dissolved O_2, pH, chlorophyll and particulate backscatter in the upper 2000 m of the water column, and passive acoustics to measure wind speed and rainfall. It is important to note that all of these sensors have already been used on floats built by the University of Washington float group, and only a minor amount of new engineering will be required to produce floats in this configuration. No dedicated ship time is required for the deployment of these floats. All of the data will be streamed in real time via the Argo data system and also at MBARI (*www.mbari.org/chemsensor/floatviz.htm*), as has been successfully done with data produced from the ongoing NSF-sponsored Southern Ocean Carbon and Climate Observations and Models (SOCCOM) program. The data will be corrected in delayed mode at approximately 6-month intervals. S. Riser will be responsible for building and deploying the floats and managing the data and J. Yang will provide the passive acoustic sensors and analyze the data. We will collaborate in the analysis of the data produced with Dr. Ken Johnson of MBARI (an expert in biogeochemical sensors and data analysis) and also collaborate with PIs from other related projects. The autonomous data collected in this project will be used to examine the variability of the ocean circulation and heat storage in the upper ocean in the tropical and subtropical Pacific and the connection of this variability with the carbon cycle in the region.

The NOAA Climate and Modeling program supports projects that provide high-quality environmental data that can be used in support of climate and oceanographic research and in forecasting and the general benefit of society. The work proposed here is consistent with this general goal in that the data collected will be highly relevant to research concerning the uptake of heat by the ocean and the carbon cycle in the tropics and subtropics; topics central to the improvement of coupled ocean-atmosphere models and climate forecasting.

This proposal is also highly relevant to the long-term goals and objectives of NOAA's Next Generation Science Plan (NGSP). The work proposed here will certainly aid in the long-term goal of Climate Adaptation

and Mitigation by helping to provide an improved assessment of the current and future state of the climate system. The project will also contribute to the goal of maintaining healthy oceans and fisheries through an improved understanding of marine ecosystems, via high-quality observations of the carbon cycle in the upper ocean in the tropical and subtropical Pacific.

10.2.2 Autonomous surface vessels as low-cost TPOS platforms for observing the planetary boundary layer and surface biogeochemistry

Meghan Cronin and Christian Meinig (PMEL), Dongxiao Zhang and Adrienne Sutton (Joint Institute for the Study of the Atmosphere and the Oceans (JISAO) at the University of Washington.)

Abstract

Since the late 1980s, the backbone of the El Niño and Southern Oscillation (ENSO) observing system has been an array of ~70 Tropical Atmosphere and Ocean (TAO) buoys measuring surface meteorology and upper ocean temperature in the tropical Pacific. In this proposed project, titled "**Autonomous Surface Vessels as Low-Cost TPOS Platforms for Observing the Planetary Boundary Layer and Surface Biogeochemistry,**" a new unmanned sailing vessel, developed by Saildrone, Inc. in partnership with NOAA Pacific Marine Environmental Laboratory (PMEL), will be tested that could modernize and lower the cost of the current observing system. In particular, this project will demonstrate the Saildrone's ability to make climate-quality meteorological, oceanic and biogeochemical observations that might eventually replace observations made from some TAO buoys. While the Saildrone can potentially hold station, providing a time series at a given site, the vessels can also make transects of fronts and have adaptive sampling strategies, surveying features as they develop.

These capabilities have already been successfully demonstrated during a 97-day test in the Bering Sea. Here we propose to test these capabilities in the tropical Pacific environment.

In this proposed project, two 6-month missions will be performed. Each mission will deploy two Saildrones apiece, outfitted with a full suite of meteorological, biogeochemical, oceanic and engineering sensors to estimate the wind stress and the air-sea exchanges of heat and CO_2. Missions will begin and end in San Francisco Bay, and will involve a brief intercomparison at the California Current Ecosystem (CCE) moorings off Santa Barbara, California, enroute to the tropics. Performance under unique tropical Pacific conditions will be tested, including: low wind, gusty wind, strong currents, currents flowing against the wind and strong air-sea interaction at fronts. The first Saildrone mission will test the quality of the acquired data through intercomparisons against the Woods Hole Oceanographic Institute (WHOI) buoy, drifters, gliders,

and research vessels deployed at 10°N, 125°W as part of the NASA Salinity Processes in the Upper Ocean Regional Study-2 (SPURS-2). This mission will also involve intercomparisons against existing TAO moorings along 125°W, including the TAO mooring at 0°, 125°W, which is enhanced with a PMEL Moored Autonomous pCO_2 ($MAPCO_2$) system. The second mission will focus on the ability of the Saildrone to make observations along the equator, and will involve intercomparisons against various TAO moorings. The exact course of this mission will depend upon conditions of ENSO and mesoscale events, with the route to be directed by the principal investigators while the vessel is underway, highlighting the adaptability of the Saildrone.

This proposed project requires *no ship time*. Saildrones offer a low-cost means of obtaining planetary boundary layer and surface biogeochemical observations within the Tropical Pacific Observing System (TPOS 2020) project. This proposal responds to the NOAA Climate Observations Division solicitation, inviting "proposals to advance the readiness of in situ observing platforms and assess their potential to address observational requirements and gaps in the tropical Pacific Ocean region." The proposed work is guided by the GCOS Climate Monitoring Principles and contributes to the first two objectives of NOAA's long-term climate goal by addressing the core capabilities and societal challenges of: "Understanding and modeling," "Observing systems, data stewardship, and climate monitoring" and "Changes in extremes of weather and climate."

10.2.3 Flux surface glider experiment

Iwao Ueki, Makito Yokota, Yasuhisa Ishihara, and Kentaro Ando (JAMSTEC)

Abstract

The TAO/TRITON array has been a major component of the ENSO observing system since 2000. In this project, we aim to develop a possible complementary approach to surface flux measurements of TMA, particularly in the region with less wind speed and high wave height region, with the Saildrone experiments in section 10.2.2 above. The basic set of the flux wave glider includes three sets of meteorological sensors and 300 Khz ADCP to be installed on the surface floats, surface ocean temperature cables along umbilical cable. The group of meteorological sensors are air-temperature, relative humidity, wind speed and directions, rain gauge, shortwave and longwave radiations and atmospheric pressure, which allow to estimate full set of surface heat and freshwater fluxes.

The first and second experiments were conducted in Sagami Bay in 2015 and off Okinawa island in 2016, respectively. The final experiment will be performed in November 2016 from Palau island for one month. After accomplishment of flux surface wave glider, the surface flux glider will be in place to accomplish measurements of surface flux in the area identified in Action item 1 as a pilot study to check if the Surface Flux Wave Glider can be an operational tool.

In addition, we plan to test installing biogeochemical instruments and/or pH/CO_2 instruments for a further evolution of this potential TPOS platform.

10.2.4 Enhanced ocean boundary layer observations on NDBC TAO moorings

William Kessler (PMEL), Karen Grissom (NDBC), and Meghan Cronin (PMEL)

Abstract

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 of the ocean and atmosphere, which are the least understood and most poorly modeled element of the tropical climate system.

The proposal **"Enhanced ocean boundary layer observations on NDBC TAO moorings"** responds to the NOAA Climate Observations Division call for "proposals to advance the readiness of in situ observing platforms and assess their potential to address observational requirements and gaps in the tropical Pacific region." We propose to enhance operational NDBC TAO moorings in eight regimes to better resolve near-surface stratification and currents.

Principal targets include the diurnal cycle, processes at the eastern edge of the Warm Pool and at the cold tongue front and Ekman divergence from the equator. The goal in all of these is to develop and prove methodologies to accomplish this near-surface sampling in a rebuilt tropical Pacific observing system. The TPOS 2020 Project seeks to use moorings where their special capabilities are needed, and to define their role in the observing system; here we will test, evaluate and demonstrate methods to make fullest use of this asset.

The proposed observations would enhance the vertical resolution of temperature (and in some cases salinity) in the upper 50 m, upgrade the meteorological sampling to include radiation (and some rainfall) and resolve the velocity structure of the ocean mixed layer in eight regimes that span the phenomena of the tropical Pacific. Difficult technical issues have stymied these observations in the past; we propose several strategies to surmount these problems that will provide guidance to the TPOS 2020 Project as it seeks to expand its focus to include the boundary layers.

All work would be done on existing operational TAO moorings, and implemented so as not to interfere with that sampling. The objective is to enable boundary layer sampling that will be consistent with the ongoing array and that can be straightforwardly integrated into it. As a joint project of PMEL and NDBC,

the proposed work will build collaboration between the operational and research elements that contribute to NOAA's efforts in the tropical Pacific.

The year-long deployments proposed here will help determine whether adequate sampling of the boundary layers can be accomplished by limited-term process studies, or if long-term monitoring is needed. If process studies are to be relied on, how many must be done and where? Or perhaps a few "supersites" would be appropriate; if so, where should these be located? We will provide a basis for the TPOS 2020 Project to base its decisions on facts that are not now available.

Individual components of the work proposed here have high technical readiness levels (TRL; 6-8), having been previously implemented in the TPOS region and shown to work. The TRL of the *system*, as an element of a sustained observing array providing information that can be integrated into the whole, has not been demonstrated. Here we will assess methods of accomplishing and using observations of the near-surface tropical ocean.

The proposed work contributes to NOAA's Climate Goal by addressing the core challenges of "improved scientific understanding of the changing climate system," "assessments of current and future states of the climate system" and "improved basis for confidence in understanding key oceanic components of the climate system."

10.2.5 Development and testing of direct (eddy covariance) turbulent flux measurements for NDBC TAO buoys

J. Thomas Farrar (WHOI), James Edson (University of Connecticut), Meghan Cronin (PMEL), and Chris Fairall (ESRL)

Abstract

This is a project to transition recent advances in buoy-based air-sea flux measurements to operational TAO buoy array (R2X). To *develop and transition new observing technologies into operations … working in close collaboration with its governmental, international, regional, and academic partners* is a key objective of NOAA's Science and Technology Enterprise. In this proposed project a low power direct covariance flux system (DCFS) developed at WHOI would form the technology base for future deployment on selected NDBC TAO buoys. The DCFS would be derived from the most recent system developed at WHOI and UConn for the OOI. Direct flux observations from TAO buoys would reduce the current bulk-derived turbulent heat flux uncertainty of 11 W/m2 to 5 W/m2 on a 1-month average. Direct measurements of surface stress will add greatly to the value of the buoys for satellite intercomparisons. Two versions of the DCFS would be

developed, one with fast humidity (referred to as DCF-H) and the other without (referred to as DCF). The DCF-H will be built using existing funds for the SPURS-2 experiment in the tropical Pacific. This will provide an opportunity for further development of design details prior to building the stand-alone systems for operational use in this proposal.

Two additional DCF systems would be built in Year 1 as part of this proposal. The power requirements of the DCF (i.e., without the IRGA) is low enough for it to be operated on a standard TAO buoy with its own battery supply. These units would compute the momentum and buoyancy fluxes in near real time and would have integrated telemetry systems to transmit the fluxes and associated mean values. As part of this project, we will build a buoy identical to the ones currently used in the TAO mooring array, but with an additional insert to accommodate the additional batteries needed for the DCF system. The buoy and DCF systems would be prepared for deployment under this project so that field deployments of the new systems can be carried out in future projects.

Appendix A: 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) recognizes 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. In situ oceanic climate observing system components

Component Network	**ECVs**	**Coordinating Body**	**International Data Centers 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 vapor	Current	Ocean tracers
	Ocean color (for biological activity)	Phytoplankton
	Carbon dioxide partial pressure (pCO_2)	

Appendix B: Major Acronyms or Abbreviations

Acronym	Full Title
ADCP	Acoustic Doppler Current Profiler
AGCM	Atmospheric GCM
AtlantOS	Atlantic Ocean Observing System
AVHRR	Advanced Very High Resolution Radiometer
BGC	Biogeochemistry/biogeochemical
BSISV	Boreal Summer Intra-Seasonal Variability
CESM	Community Earth System Model
CLIVAR	Climate and Ocean - Variability, Predictability, and Change
CMEMS	Copernicus Marine Environment Monitoring Service
CMIP	Coupled Model Intercomparison Project
COP	Conference of Parties
CR	Climate Record
CZ	Convergent zone
DCFS	Direct covariance flux system
DFS	Degree of Freedom System
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'
ERFEN/CPPS	Regional El Niño Study (ERFEN in Spanish) of the Permanent Commission for the South Pacific (CPPS in Spanish)
ERS	European Remote Sensing satellite
ESA	European Space Agency
EUC	Equatorial undercurrent
FOO	Framework for Ocean Observing
FSOI	Forecast System Observation Impact
GCM	General Circulation Model
GCMPs	GCOS Climate Monitoring Principles
GCOS	Global Climate Observing System
GEO	Group on Earth Observations
GFCS	Global Framework for Climate Services

GFDL-MOM	Geophysical Fluid Dynamics Laboratory-Modular Ocean Model
GHRSST	Group for High Resolution Sea Surface Temperature
GMI	Global Microwave Imager
GO2NE	Global Ocean Oxygen NEtwork
GODAE	Global Ocean Data Assimilation Experiment
GOES-R	NOAA/NASA Geostationary Operational Environmental Satellite – R Series
GOOS	Global Ocean Observing System
GO-SHIP	Global Ocean Ship-Based Hydrographic Investigations Program
GOV	GODAE OceanView
GPM	Global Precipitation Mission
GRACE	Gravity Recovery and Climate Experiment
GRASP	GOOS Regional Alliance for the Southeast Pacific
HNLC	High nutrient-low chlorophyll
HRX	High resolution XBT
IMOS	Integrated Marine Observing System
INSTANT	International Nusantara Stratification And Transport
IOC	UNESCO's Intergovernmental Oceanographic Commission
IOCCG	International Ocean Color Coordinating Group
IPCC	Intergovernmental Panel on Climate Change
IR	Infrared
ISS	International Space Station
ISV	Intraseasonal variability
ITCZ	Intertropical Convergence Zone
ITF	Indonesian Throughflow
JAMSTEC	Japan Agency for Marine-Earth Science and Technology
JAXA	Japanese Space Agency
JCOMM/JCOMMOPS	WMO-IOC Joint Technical Commission for Oceanography and Marine Meteorology/ JCOMM in situ Observing Platform Support Centre
LLWBCs	Low Latitude Western Boundary Currents
MERIS	Medium Resolution Imaging Spectrometer
MJO	Madden-Julian Oscillation
MOC	Meridional Overturning Circulation
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NDBC	National Data Buoy Center

NECC	North Equatorial Countercurrent
NGCU	New Guinea Coastal Undercurrent
NMHS	National Meteorological and Hydrological Services
NPOCE	Northwest Pacific Ocean Circulation and Climate Experiment
NWP	Numerical Weather Prediction
OBP	ocean mass or bottom pressure
OGCMs	Oceanic GCM
OMZ	Oxygen Minimum Zone
OSCAT	Oceansat-2 Scatterometer
OSCAR	Ocean Surface Current Analyses Real-time
OSE/OSSE	Observing System Experiment/Observing System Simulation Experiment
OSTP	Office of Science and Technology Policy
OVWST	Ocean Vector Wind Science Team
PACE	Plankton, Aerosol, Cloud, ocean Ecosystem
PBL	Planetary Boundary Layer
pCO_2	Partial pressure of carbon dioxide
PDO	Pacific Decadal Oscillation
PIES	Profiling Inverted Echo Sounder
PMEL	Pacific Marine Environmental Laboratory
PMW	passive microwave
PUMP	Pacific Upwelling and Mixing Physics
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SEC	South Equatorial Current
SLP	Sea level pressure
SMAP	Aquarius and Soil Moisture Active-Passive
SMOS	Soil Moisture and Ocean Salinity
SOCAT	Surface Ocean CO_2 ATlas
SOOP	Ship-of-Opportunity Programme
SOOS	Southern Ocean Observing System
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
SSM/I	Special Sensor Microwave Imager
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
SVP	Surface Velocity Program

SWH	Significant Wave Height
SWOT	Surface Water Ocean Topography (SWOT)
TAO	Tropical Atmosphere Ocean
TIWs	Tropical instability waves
TMA	Tropical Moored Array
TOGA	Tropical Ocean – Global Atmosphere program
TOGA-COARE	Tropical Ocean Global Atmosphere – Coupled Ocean Atmosphere Response Experiment
TPOS	Tropical Pacific Observing System
TPOS WP	2014 TPOS Workshop White Paper
TRITON	Triangle Trans-Ocean Buoy Network
TRMM	Tropical Rainfall Measuring Mission
TSG	Thermosalinograph
TT	Task Team
UNCSD	United Nations Conference on Sustainable Development
VIIRS	Visible Infrared Imager Radiometer Suite
VOS	Voluntary Observing Ships
VOSClim	Voluntary Observing Ship Climate
WBC	Western Boundary Currents
WCRP	World Climate Research Programme
WIGOS	WMO Integrated Global Observing System
WMO	World Meteorological Organization
WOCE	World Ocean Circulation Experiment
WPWP	West Pacific Warm Pool
WWV	Warm water volume
XBT	eXpendable BathyThermograph
XTD/XCTD	eXpendable Conductivity, Temperature, Depth profiling system
YMC	Years of the Maritime Continent

Appendix C: Acknowledgments

Coordinating Lead Authors

Sophie Cravatte	LEGOS, Institut de Recherche pour le Développement, Université de Toulouse, IRD,CNES, CNRS, UPS, Toulouse	FRANCE
William Kessler	NOAA Pacific Marine Environmental Laboratory	USA
Neville Smith	GODAE Ocean Services	AUSTRALIA
Susan Wijffels	CSIRO Oceans and Atmosphere	AUSTRALIA

Authors

Kentaro Ando	Japan Agency for Marine-Earth Science and Technology	JAPAN
Meghan Cronin	NOAA Pacific Marine Environmental Laboratory	USA
Tom Farrar	Woods Hole Oceanographic Institute	USA
Eric Guilyardi	IPSL/LOCEAN, Paris, France NCAS–Climate, University of Reading, UK	FRANCE
Arun Kumar	NOAA/NWS/NCEP Climate Prediction Center	USA
Tong Lee	Jet Propulsion Laboratory, California Institute of Technology	USA
Dean Roemmich	Scripps Institution of Oceanography	USA
Yolande Serra	University of Washington Joint Institute for the Study of the Atmosphere and Ocean	USA
Janet Sprintall	Scripps Institution of Oceanography	USA
Pete Strutton	University of Tasmania, Australian Research Council Centre of Excellence for Climate System Science	AUSTRALIA
Adrienne Sutton	University of Washington Joint Institute for the Study of the Atmosphere and Ocean NOAA Pacific Marine Environmental Laboratory	USA

Ken Takahashi	Instituto Geofísico del Perú	PERU
Andrew Wittenberg	NOAA Geophysical Fluid Dynamics Laboratory	USA
Lisan Yu	Woods Hole Oceanographic Institute	USA

Contributors

Eric Alfaro	Universidad de Costa Rica	COSTA RICA
Oscar Alves	Bureau of Meteorology	AUSTRALIA
David Anderson	European Centre for Medium-Range Weather Forecasts (retired)	UNITED KINGDOM
Fabrice Ardhuin	Univ Brest, LOPS,CNRS, IRD,Ifremer,IUEM, Brest	FRANCE
Anton Beljaars	European Centre for Medium-Range Weather Forecasts	UNITED KINGDOM
Frank Bryan	National Center for Atmospheric Research	USA
Fei Chai	University of Maine	USA
Francisco Chavez	Monterey Bay Aquarium Research Institute	USA
Dake Chen	Second Institute of Oceanography, SOA	CHINA
Simon De Szoeke	Oregon State University	USA
Boris Dewitte	LEGOS, Institut de Recherche pour le Développement, Université de Toulouse, IRD,CNES, CNRS, UPS, Toulouse	FRANCE
Michael Ek	NOAA National Centers for Environmental Prediction	USA
Chris Fairall	NOAA Earth System Research Laboratory	USA
Richard Feely	NOAA Pacific Marine Environmental Laboratory	USA
Yosuke Fujii	Japan Meteorological Agency, Meteorological Research Institute	USA
Alexandre Ganachaud	LEGOS, Institut de Recherche pour le Développement, Université de Toulouse, IRD,CNES, CNRS, UPS	FRANCE
Florent Gasparin	Mercator Ocean	FRANCE
Chelle Gentemann	Earth and Space Research	USA
Carmen Grados	Instituto del Mar del Perú	PERU

Dimitri Gutierrez	Instituto del Mar del Perú	PERU
Yoo-Geun Ham	Chonnam National University	SOUTH KOREA
Harry Hendon	Bureau of Meteorology	AUSTRALIA
Masao Ishii	Japanese Meteorological Agency	JAPAN
Dongchull Jeon	Korea Institute of Ocean Science and Technology	SOUTH KOREA
Kris Karnauskas	University of Colorado	USA
Alicia Karspeck	National Center for Atmospheric Research	USA
Gustavo Laos	Dirección de Hidrografía y Navegación, Marina de Guerra del Perú	PERU
William Large	National Center for Atmospheric Research	USA
Jae Hak Lee	Korea Institute of Ocean Science and Technology	SOUTH KOREA
Kitack Lee	Pohang University of Science and Technology	SOUTH KOREA
Xiaopei Lin	Ocean University of China	CHINA
Rodney Martinez	Centro Internacional para la Investigación del Fenómeno de El Niño	ECUADOR
Yukio Masumoto	Observational Research System for Global Change	JAPAN
Shayne McGregor	Monash University	AUSTRALIA
Akihiko Murata	Japan Agency for Marine-Earth Science and Technology	JAPAN
Larry O'Neill	Oregon State University	USA
Bo Qiu	University of Hawaii	USA
Willington Renteria	Instituto Oceanográfico de la Armada Oceanografía	ECUADOR
Efrain Rodriguez-Rubio	Independent Scientist	COLOMBIA
Roberto Rondanelli	University of Chile	CHILE
Christopher Sabine	NOAA Pacific Marine Environmental Laboratory	USA
Wolfgang Schneider	Universidad de Concepción	CHILE

Tim Stockdale	European Centre for Medium-Range Weather Forecasts	UNITED KINGDOM
Toshio Suga	Tohoku University	JAPAN
Val Swail	Environment and Climate Change Canada	CANADA
Iwao Ueki	Japan Agency for Marine-Earth Science and Technology	JAPAN
Hailia Wang	Xiamen University	CHINA
Jennifer Waters	Met Office	UNITED KINGDOM
Matthew Wheeler	Bureau of Meteorology	AUSTRALIA
Yan Xue	NOAA/NWS/NCEP Climate Prediction Center	USA
Weidong Yu	First Institute of Oceanography, SOA	CHINA
Dongliang Yuan	Institute of Oceanology, Chinese Academy of Sciences	CHINA
Chidong Zhang	NOAA Pacific Marine Environmental Laboratory	USA

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Reviewers

Susan Avery	Consortium for Ocean Leadership	USA
Magdalena Balmaseda	European Centre for Medium-Range Weather Forecasts	UNITED KINGDOM
David Behringer	NOAA/NWS/NCEP Climate Prediction Center	USA
Anton Beljaars	European Centre for Medium-Range Weather Forecasts	UNITED KINGDOM
Hans Bonekamp	European Organization for the Exploitation of Meteorological Satellites	GERMANY

Mark Bourassa	Florida State University	USA
Jaclyn Brown	CSIRO	AUSTRALIA
Antonietta Capotondi	NOAA Earth System Research Laboratory	USA
Kim Cobb	Georgia Institute of Technology	USA
Gary Corlett	University of Leicester	UNITED KINGDOM
Thierry Delcroix	LEGOS, Institut de Recherche pour le Développement, Université de Toulouse, IRD,CNES, CNRS, UPS, Toulouse	FRANCE
Boris Dewitte	LEGOS, Institut de Recherche pour le Développement, Université de Toulouse, IRD,CNES, CNRS, UPS, Toulouse	FRANCE
John Eyre	Met Office	UNITED KINGDOM
Richard Feely	NOAA Pacific Marine Environmental Laboratory	USA
Yosuke Fujii	Japan Meteorological Agency, Meteorological Research Institute	USA
Katy Hill	World Meteorological Organization	SWITZERLAND
Tony Hirst	Bureau of Meteorology	AUSTRALIA
Ken Holmlund	European Organisation for Meteorological Satellites	GERMANY
Masao Ishii	Japanese Meteorological Agency	JAPAN
Kris Karnauskas	University of Colorado	USA
George Kiladis	NOAA Earth System Research Laboratory	USA
David Legler	NOAA Climate Program Office	USA
Matthieu Lengaigne	LOCEAN/IPSL, Institut de Recherche pour le Développement, Sorbonne Universités, CNRS, IRD, MNHN, Paris	FRANCE
Pierre-Yves Le Traon	IFREMER and Mercator Océan	FRANCE

Eric Lindstrom	NASA	USA
Shannon McArthur	NOAA National Data Buoy Center	USA
Shayne McGregor	Monash University	AUSTRALIA
Michael McPhaden	NOAA Pacific Marine Environmental Laboratory	USA
Mark Merrifield	University of Hawaii	USA
Art Miller	Scripps Institution of Oceanography	USA
Paul Poli	Météo-France	FRANCE
Gilles Reverdin	LOCEAN/IPSL, CNRS, Sorbonne Universités, CNRS, IRD, MNHN, Paris	FRANCE
Michel Rixen	World Meteorological Organization/World Climate Research Programme	SWITZERLAND
Keith Rodgers	Princeton University	USA
Dan Rudnick	Scripps Institution of Oceanography	USA
Toshio Suga	Tohoku University	JAPAN
Val Swail	Environment and Climate Change Canada	CANADA
Kathy Tedesco	NOAA Climate Program Office	USA
Iwao Ueki	Japan Agency for Marine-Earth Science and Technology	JAPAN
Jérôme Vialard	LOCEAN-IPSL, Institut de Recherche pour le Développement, Sorbonne Universités, CNRS, IRD, MNHN, Paris	FRANCE
Robert Weller	Woods Hole Oceanographic Institute	USA
Matthew Wheeler	Bureau of Meteorology	AUSTRALIA
Pingping Xie	NOAA/NWS/NCEP Climate Prediction Center	USA
Yan Xue	NOAA/NWS/NCEP Climate Prediction Center	USA

Lisan Yu	Woods Hole Oceanographic Institute	USA
Chidong Zhang	NOAA Pacific Marine Environmental Laboratory	USA
Dongxiao Zhang	University of Washington Joint Institute for the Study of the Atmosphere and Ocean	USA

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