GCOS – 184

GOOS – 205

WCRP – 6/2014

Tropical Pacific Observing System, 2020 Workshop (TPOS 2020)

Volume I: Workshop Report and Recommendations.

27-30th January 2014,

Scripps Institution of Oceanography, San Diego, USA.

http://www.ioc-goos.org/tpos2020

Sponsored by:

The Ocean Observations Panel for Climate (OOPC) is sponsored by the Global Ocean Observing System, the Global Climate Observing System and the World Climate Research Programme. OOPC provides advice on observations to the WMO-IOC Joint Technical Commission for Oceanography and Marine Meteorology.

<Blank>

Contents

Executive Summary

The Tropical Pacific Observing System (TPOS) was designed during the highly successful Tropical Ocean Global Atmosphere (TOGA) experiment, which was completed in 1994 and revolutionized observational understanding of the tropical Pacific and El Niño–Southern Oscillation (ENSO) dynamics; it also set the tone for real-time data availability and routine seasonal forecasts.

However, 20 years after the end of TOGA, sustaining the TPOS system is proving challenging, in particular the TAO/TRITON array of moored buoys. Since TOGA, a number of new observational technologies have emerged, and the sophistication of the analysis, modelling, and predictions systems has evolved considerably, as has understanding of tropical Pacific variability and predictability. Given these advances, a fresh articulation of requirements and system design was appropriate. Consequently, NOAA and JAMSTEC requested a review of the tropical Pacific observing system with the support of the Ocean Observations Panel for Climate (OOPC), to revisit the scientific and forecast requirements for the tropical Pacific observations, and to consider how the sustainable observing system could evolve most usefully

A TPOS Workshop was held January 27-30, 2014, at Scripps Institution of Oceanography. The Workshop was attended by 65 invitees from 13 countries and 35 institutes. There were various invited talks based on 14 whitepapers and 9 agency presentations and extensive time for discussion. The review committee was made up of the Scientific Organizing Committee plus 3 independent experts. The Terms of Reference for the review can be found in appendix 2, whitepapers can be found in Volume II of this report, to be available shortly.

The requirements for observations in support of ENSO research, modelling and forecasting were reinforced at the meeting, and the importance and value of long climate time series close to the Equator provided by TAO/TRITON moorings was strongly emphasized. Continued evaluation and improvement of the broadscale observing system was recommended. Gaps and new requirements were identified: in particular, observations at the air-sea interface, in the equatorial wave guide and eastern and western boundary regions. In addition, support for the integration of biogeochemical observations to improve understanding of the tropical Pacific in the global carbon budgets and ocean productivity was needed. Although modelling of the tropical Pacific and seasonal forecasting using coupled atmosphere ocean models have improved since the end of the TOGA experiment, much remains to be done, as models continue to be plagued by large errors. Consequently, a focused activity on the coordination of multi-model evaluations was recommended.

Organizationally, it was recommended to establish a TPOS 2020 project. This would oversee the transition to a more resilient and integrated observing system to meet the identified gaps as well as future needs as they are identified. It was considered essential that the organizations interested in tropical Pacific observations maintain proper dialogue.

The goals of the proposed TPOS 2020 project are:

- To refine and adjust the TPOS to monitor, observe and predict the state of ENSO and advance scientific understanding of its causes.
- To determine the most efficient and effective method for sustained observations to support prediction systems for ocean, weather and climate services of high societal and economic utility, including underpinning research.
- To advance and refine the knowledge of the predictability horizon of the tropical Pacific variability (physical and biogeochemical), as well as its impacts in global climate.
- To determine how interannual to multidecadal variability and human activities impact the relation between marine biogeochemistry and biology to carbon budgets, food security and biodiversity.

TPOS 2020 aims to achieve a significant change in all elements that contribute to the TPOS, including greater and continued efficiency, greater effectiveness, enhanced robustness and sustainability, and improved governance, coordination and supporting arrangements, and must facilitate and embrace contributions from multiple agencies and countries. To this end, presentations by a number of countries with an interest in observing the Pacific and developing, using and interpreting derived products were made (see section 7). A proposed structure for TPOS 2020 was developed, consisting, inter alia, of a Steering Committee to oversee scientific objectives, technical design and implementation issues, and a Resources Forum with representatives from sponsors.

In order to address more fully several issues raised at the Workshop, 4 Task Teams were proposed, with the following objectives:

- Evaluation of the broadscale aspects of the TPOS.
- Elaboration of implications of the desire to observe diurnal variability, air-sea fluxes and near-surface dynamics.
- Approaches to observation of boundary regions.
- Consideration of approaches to advancing modelling, assimilation and synthesis so that observations can achieve their designed impact.

Further details of the objectives of the Task Teams are given in appendix 5.

A number of important recommendations were made:

- Strong endorsement of NOAA’s offer to return TAO to 80% data return as soon as possible.
- An urgent need to explore strategies to minimize the impact of the reduction in the TRITON Array.
- The need to immediately improve communication and coordination among existing TPOS partners, particularly with respect to the mooring arrays.

- Initiate discussions with interested organizations to broaden engagement in supporting the TPOS, particularly with respect to ship support and the mooring array.
- Explicitly assess risks to the observing system as part of TPOS 2020, taking account of needed redundancy, sensor diversity, etc.
- Renew efforts to consider the observing system as an integrated whole (in situ, satellite, modelling, data management, etc.), articulating the strengths of a multi-platform approach.
- Identifying and sustaining critical long climate records.
- Take advantage of the opportunity to take additional observations from vessels involved in servicing moorings.
- Ensure appropriate levels of investment in data and information management (10% of the total effort is often used as an indicative level), particularly for emerging and prototype technologies.

1. Introduction and motivation for the study

The Tropical Pacific Observing System (TPOS) was conceived and implemented during the Tropical Ocean Global Atmosphere (TOGA) experiment (1985-1994), which also included a network of drifters, tide gauges, and ships of opportunity XBT lines, with the then objectives of understanding the dynamics of the equatorial Pacific and the link to El Niño–Southern Oscillation (ENSO), among other things. Assessing the degree to which ENSO was likely to be predictable and realizing that predictability were major objectives. The central component, the Tropical Atmosphere Ocean (TAO) array, was largely complete by 1993 and functioned well for a number of years. Unfortunately, in the last year or two, there has been a marked reduction in the data return from the array. NOAA has not been able to maintain the TAO moorings through lack of ship time; JAMSTEC has begun to withdraw some of its TRITON moorings. There are concerns as to whether the array can and/or should be maintained at its full complement of moorings. There has been a reduction in ship-based observations in the region, and consequently also deployment opportunities for other equipment such as Argo profiling floats and drifters.

Although the data return from TAO has declined, other observing systems have come online, in particular the international Argo array of profiling floats, which provides broad-scale global observations of temperature and salinity down to 2000 m, as well as routine satellite observations of sea surface temperature, sea surface height and winds and sea surface salinity measurements from recent satellite missions.

Understanding of ENSO and equatorial ocean atmosphere interaction has improved so that the research issues are unlikely to be the same as they were when the array was first conceived or last reviewed (2001). Requirements for biogeochemical and biological observations are better understood and, in addition, technologies are available to take routine observations, which was not possible 20 years ago. There have also been advances in ocean model formulation and methods for using the data in models (assimilation, verification), although considerable work is still needed to improve coupled atmosphere ocean models and initialization techniques in order to improve the skill of forecasts out to seasonal timescales, and possibly beyond.

It is against this background of a changing climate observing system and changing scientific issues and forecasting systems that it is timely to reassess the needs for the tropical observing system. (The Pacific is the main point of concern, though consideration of tropical Atlantic and Indian Ocean observation systems is also of interest). The review also considered the availability of new and emerging observing technologies that might contribute to a future sustained ocean observing system.

2. Review of the achievements of the TAO/TRITON array

2.1. The history of the TAO/TRITON array

The Tropical Atmosphere Ocean (TAO)/ Triangle Trans-Ocean Buoy Network (TRITON) is an array of deepwater moorings taking observations of the upper ocean and lower atmosphere and is designed to support climate research and forecasting. TAO/TRITON spans the tropical Pacific, forming part of the global Tropical Moored Buoy Array when combined with the Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA) in the Indian Ocean and the Prediction and Research Moored Array in the Atlantic (PIRATA).

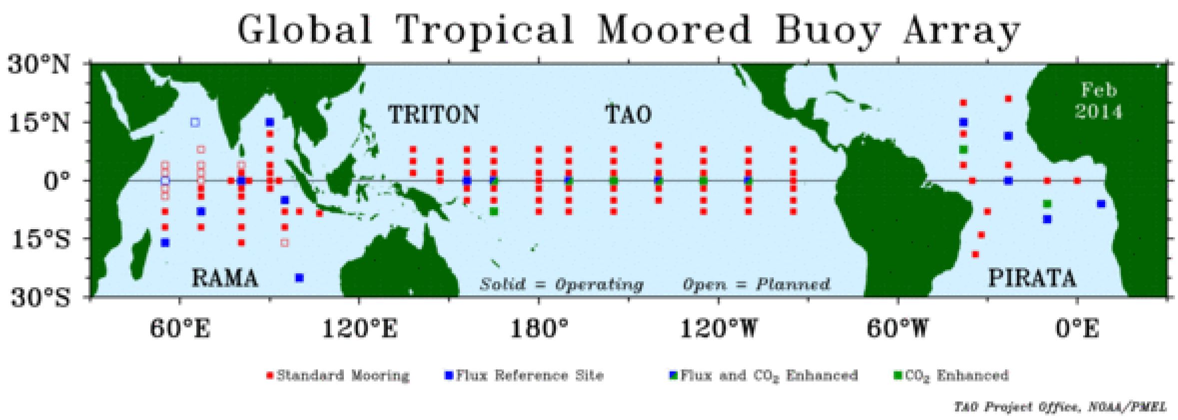

Figure 1: The Tropical Moored Buoy array and its components: RAMA, TAO/TRITON and PIRATA.

The Pacific basin was the first to be instrumented; following the 1982-83 El Niño event, which took the world by surprise, the Tropical Ocean Global Atmosphere (TOGA) experiment was established to, among other things, create an observing system for ENSO. The goals of TOGA were:

- To gain a description of the tropical oceans and the global atmosphere as a time-dependent system in order to determine the extent to which the system is predictable on time scales of months to years and to understand the mechanisms and processes underlying its predictability.
- To study the feasibility of modeling the couple ocean-atmosphere system for the purpose of predicting its variation on time scales of months to years; and
- To provide the scientific background for designing an observing and data transmission system for operational predication, if this capability is demonstrated, by coupled ocean-atmosphere models.

TOGA ran from 1985-1994, and the TAO array was a major outcome of the project. When JAMSTEC came on board in 2000 to instrument the western component of the array with TRITON moorings, the array became TAO/TRITON.

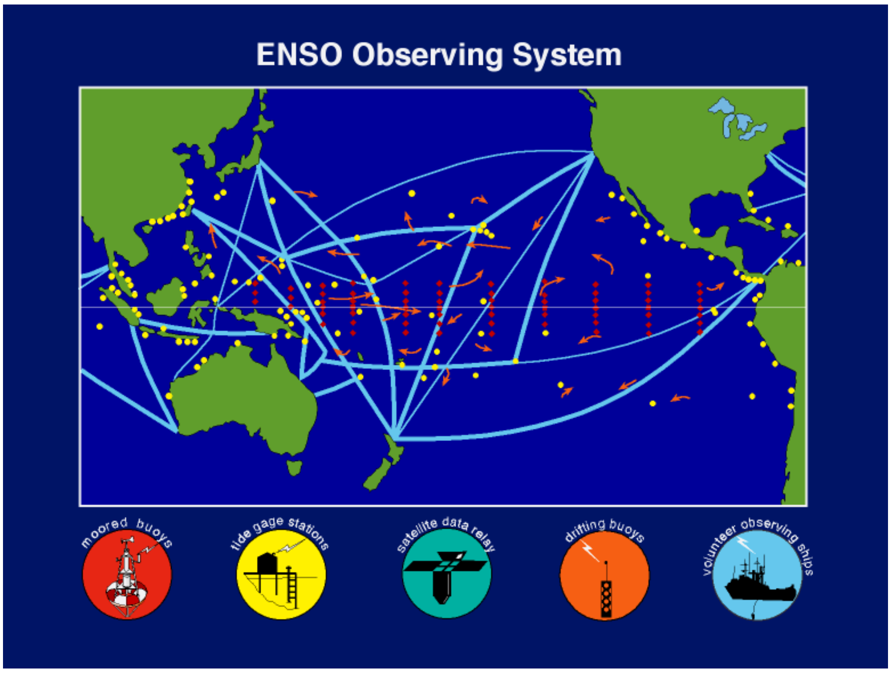

Figure 2: The ENSO observing system, following the TOGA experiment, 1994.

2.2. El Niño–Southern Oscillation research

El Niño and La Niña events shift the probability of droughts, floods, heat waves and extreme weather around the globe, which provides a societal imperative to develop and improve predictions of their onset and evolution as part of seasonal forecasting systems (see section 2.3. for more details). This has prompted a strong focus on ENSO research in the last 30 years in particular.

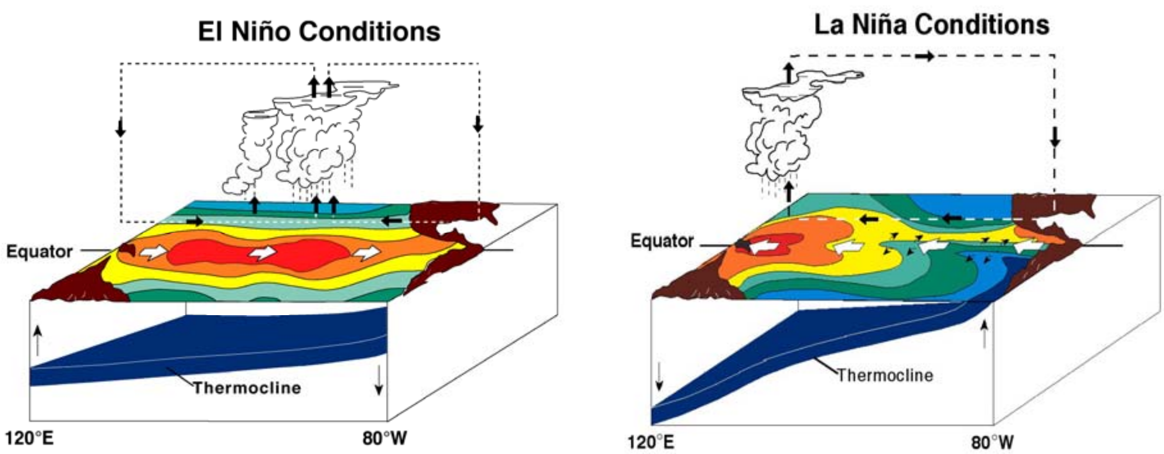

Figure 3: A schematic of the ocean/atmosphere conditions in the tropical Pacific during El Niño and La Niña, respectively. During El Niño (La Niña), the trade winds slacken (strengthen), westerly wind bursts develop in the west of the basin, the thermocline tilt flattens (steepens), the gradient of sea surface temperatures across the Tropical Pacific is reduced (increased), and convection over the tropical Pacific moves eastwards (westwards).

The TAO/TRITON Array has contributed significantly to our understanding of the ENSO mechanisms. The coincident ocean and atmosphere observations provided by this array have improved our understanding of this coupled atmosphere-ocean phenomenon, in particular, the role of westerly wind bursts and ocean temperature gradients in the onset and persistence of El Niño and the role of equatorial Kelvin waves in setting the timescales of variability (also known as the delayed oscillator theory). Observations have also shown that a build-up of excess heat along the Equator is a precondition to an ENSO event. Research suggests that the heat is purged to higher latitudes during an El Niño event, and the time between El Niños is determined by the time taken to recharge the equatorial heat content (known as the recharge oscillator theory).

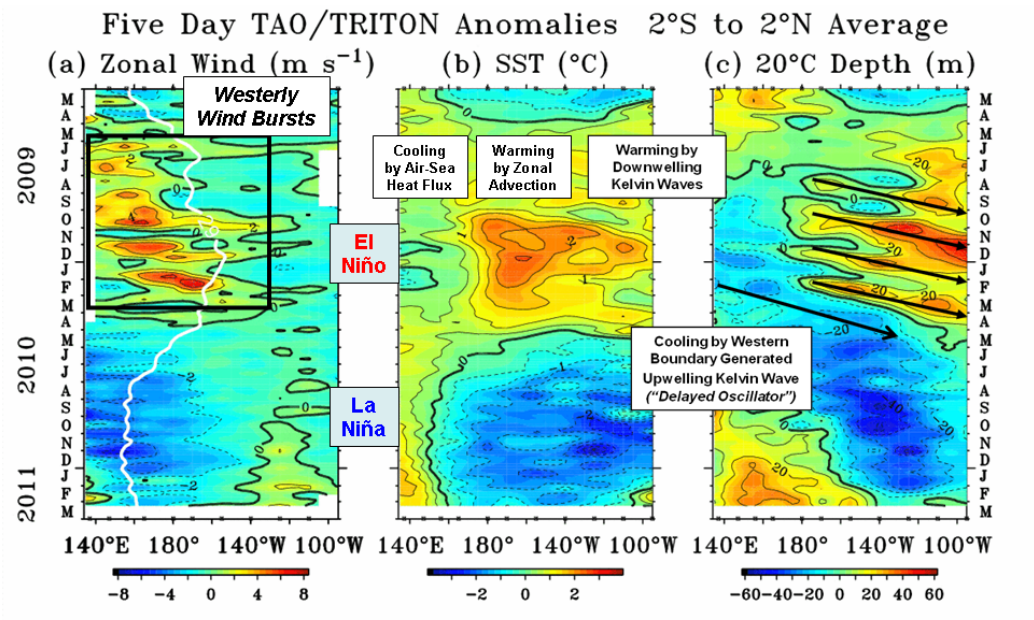

Figure 4: Hovmöller plots of (a) zonal wind, (b) sea surface temperature, and (c) depth of the 20˚C isotherm. Features such as westerly wind bursts, surface warming/cooling and Kelvin wave propagation identified.

2.3. ENSO Predictability and Prediction

ENSO is the most predictable year-to-year fluctuation of the climate system because of the way slow changes in ocean heat content precondition the system for warm and cold events to occur. The first successful El Niño prediction was in 1986, and now ENSO prediction is essential for delivering seasonal forecasts. Forecast models are now moderately skillful at up to 6-9 month lead times; however, predictability is limited by model bias, errors in initial conditions, and weather noise.

Ocean observations including TAO/TRITON, the Argo array of profiling floats and satellite altimetry are used to initialize predictions. These observations have been shown to improve forecast skill for both Niño 3.4 temperature and seasonal forecasts in general (see TPOS WP 4).

2.4. Future challenges: decadal variability and climate change

ENSO research and forecasting have been the main driver for TAO/TRITON and the broader tropical Pacific observing system and are likely to continue to be so for the TPOS, with a suite of new problems and challenges, including ENSO diversity (sometimes referred to as canonical and Modoki events), decadal modulation and possible changes of extremes under global warming and variations of predictability.

Further detail on research and forecasting status and challenges can be found in section 4.

3. Societal context: importance of the tropical observing system for the delivery of information and services of societal importance

The societal impacts of ENSO are large and global but hard to quantify. The composite-based "large picture" may not be applicable to individual events, particularly due to the diversity of ENSO events and the interactions between ENSO and other modes of variability. However, we can broadly associate El Niño/La Niña events with changes in the probability of floods, droughts and extreme events around the world (see figure 5), as well as other impacts, such as in fish stocks and their distributions.

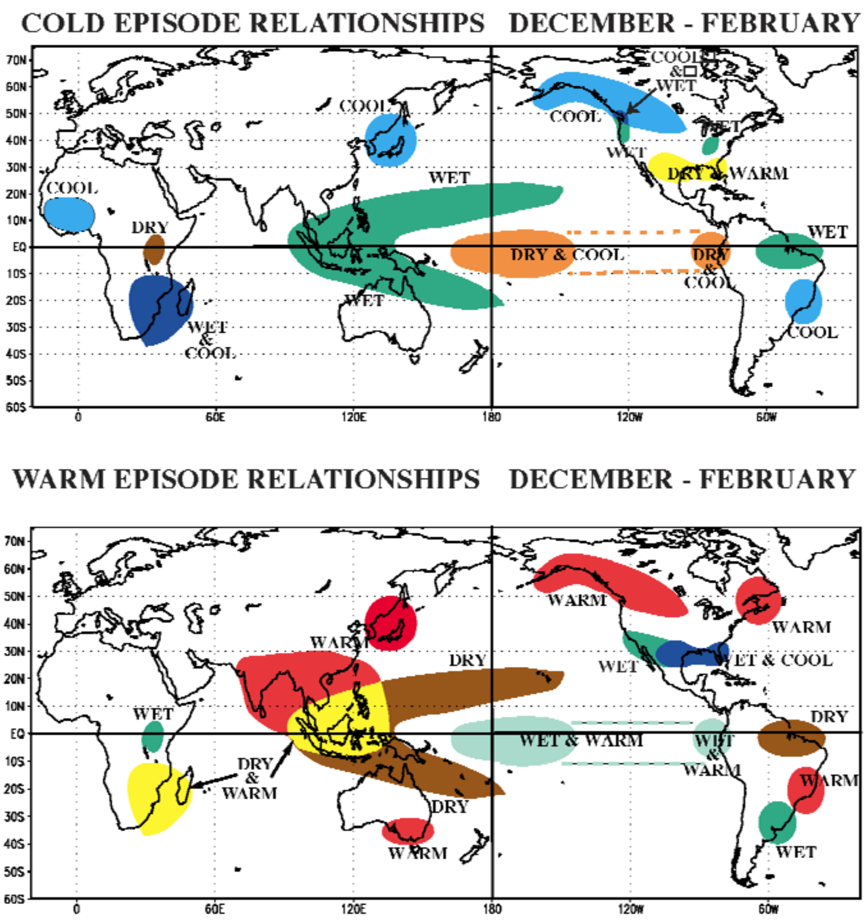

Figure 5: The seasonal climate impacts of El Niño and La Niña events.

A range of indices is used for the identification of ENSO events and, depending on the applications (and the aspects of ENSO of interest), some can prove more useful than others, i.e., the Southern Oscillation Index (SOI), Niño sea surface temperature anomalies, outgoing longwave radiation, etc. More research is needed on tuning the indices to respond to societal requirements.

There is a significant relationship between ENSO and tropical cyclone genesis areas, frequency and intensity. In the Atlantic, La Niña events are often associated with a more active hurricane season. The link between ENSO and extreme events such as cyclones is an ongoing area of research. The impact of ENSO on carbon fluxes, ecosystems and fisheries will be discussed further in section 4.

The regions feeling the largest impact are in the eastern and western tropical Pacific; but the impacts are global and countries more remote, such as those in North America and Asia, can be significantly affected. Here we focus on the west coast of Latin America and the Pacific Islands to discuss their data and information requirements.

Due to sheer proximity, western South America is expected to have the most pronounced impacts due to ENSO. 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 ENSO; so, predictive capability would enable countries in the region to plan for these risks. An El Niño event also has a catastrophic impact on regional fisheries, which collapse when the nutrient supply from upwelling is shut down. The ENSO signal can be clearly seen in satellite ocean color.

The Pacific Islands are highly vulnerable to climate change and extremes. The nations in the region have limited capability in routine ocean observations, but communities depend on various data and forecast products derived from the TPOS. Wave and sea level information (and its relationship with contributing factors) was highlighted as of particular importance due to the vulnerability of low-lying Pacific Islands to storm surge events. Notably, there is not currently a specific focus on wave observations in the tropical Pacific, though models are increasingly able to include a sophisticated wave component.

Regional capacity-building activities focus on how available data and information can be used and useful. In the tropical Pacific, the Climate and Oceans Support Program in the Pacific (COSPPac) develops statistical forecasts based on ENSO indices and works with communities to understand processes/consequences at a local level. Such work reinforces the need to develop indices that are ‘fit for purpose.’

4. Summary of applications, science context and evaluation of requirements

4.1. Applications, science context

Several key applications emerged from the presentations, including:

1. Monitoring of the state of the ocean and the state of the climate via direct observations and reanalyses of the earth system. This includes monitoring a wide range of spatial scales (mesoscale, synoptic events and planetary scale) and frequencies (from weather to climate trends). Monitoring is not restricted to physical variables, but includes biology and biogeochemistry variables needed for carbon fluxes, biodiversity and fisheries management.

2. Forecasting of ocean, atmosphere and biogeochemistry variability at different lead times: medium range, subseasonal, seasonal and decadal. Forecasting also involves the transformation of model output into products of societal relevance, such as management of natural resources and extreme event warning.

3. Research to advance knowledge of the climate system and improve forecast capability. Key research areas are feedback mechanisms, tropical air-sea interaction processes and physical, biogeochemical and ecosystem responses, on time scales from diurnal through to decadal. Forecasting system development includes model resolution, model parameterizations, new model components, data assimilation and development of user-driven forecast-products.

These foci are an expansion of the aims of the TOGA experiment, which provided the original rationale for the TPOS and TAO/TRITON in particular (see TOGA goals section 2.1). These application areas are necessarily overlapping and interconnected.

The quest for improved understanding of processes and mechanisms on intra-seasonal, seasonal and inter-annual timescales implies that the most stringent requirements will continue to be derived from research applications in terms of sampling range and from climate change applications in terms of quality and accuracy. Monitoring and forecasting systems are the most comprehensive and demanding in terms of sustained observation requirements. The routine observation requirements for biology and biogeochemistry are emerging and will likely be of increased importance in the future.

The evolution and broadening of requirements since the end of TOGA should be noted. While ENSO research and forecasting were the primary drivers for the observing system at the end of TOGA, there is now increased focus on tracking the role of the tropical oceans in decadal variability and climate change. The dominant role of the Pacific Ocean in the recent hiatus of the surface warming and related increased ocean heat uptake indicates that the Pacific is a key to understanding and predicting decadal variability and climate change. Ocean biogeochemistry is also important due to the role of the tropical oceans in CO2 flux exchange, ocean acidification, biology (including commercially important fisheries), and marine conservation, as they are strongly impacted by variability in the tropical ocean.

Requirements for operational forecasting (TPOS WP 4) and ocean data assimilation (TPOS WP 5) provide broad guidance in terms of sampling, but the Workshop expressed caution about using models alone for guiding decisions on how to achieve that sampling (i.e., prioritizing different types of measurement options). Both papers also highlighted the ‘many lives' of an observation, as the same observation would be used many times, for example, as initial conditions for medium range weather forecasting, subseasonal forecasting, seasonal forecasting and decadal forecasting, for model validation, for deriving climatologies and for reanalysis; the different applications could provide different guidance on the observation process.

Guidance on requirements for research was less specific (TPOS WP 3), and requirements will continue to evolve as understanding improves. This includes the biogeochemistry and biology communities, who will also need to provide input on their requirements for any underpinning physics and environmental data needed (TPOS WP 6). The need for a sustained backbone to support research is probably more stringent than for ocean and climate services or climate change, since greater use is made of higher resolution data, surface fluxes, and ocean current data. We might anticipate model requirements converging towards this requirement over the time frame of TPOS 2020, due to improvements in resolution and computational complexity.

For tracking climate change, including long-term variability, the requirements should be considered in the context of the global system, taking account of the intermediate and deep water circulation. The TPOS will be an important contribution because of the important role of the tropical Pacific in inter-annual to decadal variability (see section 2) and the potential of this variability to confound detection of climate change. The role of the tropical pacific is further emphasized when carbon fluxes are considered, as the region accounts for 70% of CO_2 outgassing from the ocean and has large interannual and decadal variability.

Biogeochemical and biological requirements will likely demand a broader range of observations but will also need to draw strongly on the physical data for information on context and drivers. There was no suggestion that the requirements for the physics observations in support of biogeochemistry and biology applications would be more stringent than those required for physics/climate applications. Maximum benefit would be extracted from coincident observations. Requirements for biogeochemistry and biology, both for research and for informing management, focus on capturing large-scale signals driven by tropical physical processes. Therefore, the need for observations coincident with physics data was emphasized, with the focus on broad spatial scale and high temporal scale observations.

There were numerous references to operational versus research communities and the advantages of addressing the requirements out of one or both of the communities. One implication from the analysis above is that the relative prominence of research and the need for both campaign and sustained data streams seems to favor one more than the other. Campaigns are more easily accommodated in research infrastructure, and the spill-over benefits of piggy-backs and underway measurements might be more readily managed. However, any improvement in model parameterisation or process understanding resulting from research activities should be used to improve operational models.

There was considerable discussion around the relative role of Observing System Experiments (OSEs) and Observing System Simulation Experiments (OSSEs). Much of the evidence presented at the Workshop derived from OSEs, but OSSEs can also be useful, as they reduce the impact of model error on the results. Observation system stakeholders have tended to favor the former, since at least in principle OSEs give a more direct line of sight from actual observing investments through to impact. The GODAE/OceanView OSEVal Task Team has been leading a number of OSE studies. One TAO wind OSE was discussed and although it revealed sensitivity, it indicated less than optimum use of the data. OSEs can have limitations that are not always fully recognized. In particular, dependency of the results on the system used in the experiments is recognized as a serious limitation. It is desirable to examine the consistency of results using a variety of models and assimilation systems, using a common set of metrics. Through such a coordinated activity, some general results that are largely common across systems and therefore potentially more robust should emerge. This point is discussed in TPOS WP 4 and 5.

Further work is needed to determine the minimum set of biological and biogeochemical parameters needed to model the growth rates, productivity, distribution, and abundance of key components of the ecosystems. Ecosystem modelers will need to be engaged in this activity. This is discussed further when the formation of Task Teams is introduced (section 5).

4.2. Evaluation of requirements

ENSO Research is still the dominant driver for many of the important requirements. Currently, the presence of significant systematic errors in coupled atmosphere-ocean models is a serious limitation, but the use of TPOS observations and process studies should lead to improved model formulation. The anticipated increased resolution and improvement of models in the coming decade should help inform observing system design. The requirements for observations for research (WP 3) were less specific, though none of the papers cited a reduced demand for observations. Looking to the future, the review was encouraged to consider processes and mechanisms in guiding the evolution of requirements. It is clear that some priority issues will need to be addressed through focused process studies and field campaigns, and the requirements in this context needs to be separated from requirements for sustained observation. In general, areas identified as requiring increased observational focus included:

- resolving the diurnal cycle and atmosphere ocean interface, including in the Intertropical Convergence zone (ITCZ) and the South Pacific Convergence Zone (SPCZ),
- the eastern and western boundary regions and the equatorial region,
- increased observations and integration of biogeochemistry and biology, and
- observing the intermediate and deep ocean.

These are discussed further from an observing system perspective in the next section (section 5).

4.3. Next steps

While the whitepapers gave a good summary of the status of research and modelling, the focus for future observations needs to be based on measuring underlying processes and next challenges. Time constraints at the Workshop meant that this could not be fully addressed; further work is needed to relate processes and mechanisms to specific requirements before this work can inform the design of the observing system. This will be discussed further in the next section. Model error both in models used for analysis and reanalysis and coupled models for prediction is serious and is limiting the development of definitive ocean analyses and forecasts, from days to decades. Based on past experience both in the oceanic and atmospheric modelling communities, model error is not easily reduced. A concerted effort on model development is needed; establishment of a Task Team was recommended, whose details are given in appendix 5.

The various TPOS WP are very comprehensive and contain a wealth of relevant information and suggestions for future evolution of the TPOS. The interested reader is encouraged to study these for further information.

Recommendation:

- A Task Team is needed to focus on modelling, assimilation, and synthesis to fast track updates and impact of observations on our modelling and prediction systems.

The Task Team will coordinate action on recommendations, including:

- A coordinated activity involving several different analysis and forecast groups to exploit multi-system approaches to identify robust impacts of the observation system, which are common in a majority of data assimilation and prediction systems.
- Targeted activity on modelling and data assimilation is required in the tropical Pacific, including identifying requirements for targeted process studies to reduce model error.

5. Assessment of the existing observing system

In this section, the adequacy of existing observing systems to deliver requirements for variables, including complementarities of satellite and in situ observation, is considered.

5.1. Satellite observations

The observing system has evolved considerably since the end of TOGA, with the introduction of routine satellite observations and the Argo array in particular delivering broadscale observations. A strong general message is that the observing system would benefit from being considered more as an integrated whole, including satellite observations, ships (including ships servicing moorings), in situ data and integrated data and information systems, since the observing system is much more than the sum of its parts. In particular, satellite data should be considered an integrated component of the observing system, providing a view of, for example, ENSO global teleconnections and mesoscale variability, and spatial context for in situ data. Some aspects of the propagation of Rossby and Kelvin waves and tropical instability waves are well observed in satellite datasets.

Satellite programmes have enthusiastically embraced the concept of essential climate variables (ECVs) and deliver to requirements for variables through constellations of satellites. Satellite contributions to ECV requirements now include sea surface temperature, sea surface salinity, sea surface height, sea state, ocean color, mass, wind speed, and wind stress. The satellite and in situ observing systems could benefit from developing and evolving in a more complementary manor. For instance, next generation satellites will be able to make higher resolution measurements in both space and time, enabling observations of diurnal processes. High resolution in situ observations at the air-sea interface will be needed to capitalize on this evolution in satellites. The new satellite sea surface salinity observations, which are still in their infancy, are another example where in situ data may be able to provide improved calibration and validation data. Satellite missions are planned 10 years ahead, so the in situ observing system should consider the needs of future satellite missions in observing system design.

Possible satellite enhancements in the pipeline include improved spatially resolved sea surface height (km scale, 120km swaths), providing 2-dimensional current maps and information on lakes and rivers (SWOT Satellite), and high temporal resolution wind data (RapidScat Satellite), with winds in the tropics measured from the International Space Station at diurnal resolution. New ECVs being considered include direct current measurements and mixed layer depth. There is reasonable confidence about the ongoing availability of existing ECV constellations, so the TPOS can look to satellite observations to deliver some of the broadscale mapping requirements for air-sea fluxes and surface ECVs (with associated Cal/Val). Sea surface salinity, run off, and improved rainfall data provide the opportunity to improve estimates of precipitation.

5.2. The in situ observing network

Discussions of in situ observing systems highlighted the difference between observing system requirements (which need to be ‘ideal’) and observing system design (which requires compromises). The tropical Pacific Ocean circulation and density field have structure and variability on many space and time scales, and there are important interactions between different space and time scales (see TPOS WP 3-12). The Workshop found it convenient to consider in situ observations under two headings: broadscale observations and high-resolution observations.

5.2.1. Broadscale

The broadscale networks, building on different instrument technologies, have fundamentally different sampling characteristics. It is these contrasts in spatial and temporal coverage and resolution that can be exploited for integrating the total information content of the datasets. For example, the moored observations of the TAO/TRITON network provide high temporal resolution at widely-spaced fixed point locations, while the Argo array provides denser spatial coverage at lower frequency and at varying locations. Each of these datasets can reveal what is missed by the other – the moorings document temporal aliasing by Argo's 10-day cycling, and the floats show the spatial patterns missed by the moored array. In the same way, Eulerian surface velocity measurements from moorings and Lagrangian velocity measurements from drifters are complementary. Drifters provide a broader spatial coverage, and moorings allow continuous time series, especially at the Equator, where drifters can diverge.

Broadscale sampling has as its goal the observation and quantification of the processes that control the monthly mean and longer time scale structure and variability. Its outcome includes the provision of information to efficiently constrain ocean state estimates of seasonal-to-interannual/decadal forecasting systems. Different spatial resolution is needed in different regions, as determined by the local gradients of the density, current, and biogeochemical variable fields. Temporal resolution needs also depend upon the region and variable of interest; in and near the equatorial waveguide, much higher time resolution of temperature, salinity, carbon system variables and currents are needed than in many extra-equatorial areas. For some variables and in some regions, the spatial scales that we wish to observe are well known; in others, it will be necessary to plan for an evolving sampling strategy as new information is gained.

The introduction of routine satellite observations of core variables and the international Argo array have improved our observations and understanding of the broadscale ocean. Based on analysis of satellite sea level and mooring data, Argo captures nearly all low-frequency variability but is less good at resolving the subseasonal variability. To resolve this variability better with Argo, the float density in the tropical Pacific would need to be increased. Based on analysis of Argo and satellite data, the zonal scales of decorrelation along the Equator are longer than had been previously assumed. This has implications for assimilation, as the errors in the decorrelation scale strongly impact the analysis. Moored time series data were essential to validate mapping accuracy (WP 10). It was also shown that Argo performs better away from the Equator. It should be emphasized that the long climate records of temperature, salinity and velocity on the Equator are a unique contribution of the TAO/TRITON array to the observing system; these are valuable and should be continued.

The initial ENSO observing system in the tropical Pacific depended upon a combination of repeat XBT tracks (some with ship-borne acoustic Doppler current profilers [ADCPs]), surface drifters, island tide gauges, the sparse TAO mooring array and some repeat hydrography; satellite oceanography was in its infancy at the beginning of this system. Considerable technological progress has been made since then. Satellite ocean observing is now an established technology and the Argo profiling float array is a proven source of temperature, salinity and float displacement observations and air-sea carbon flux observations are proven. New autonomous technologies such as gliders and wavegliders have been developed and also need to be considered in the future TPOS 2020 observing strategy. See TPOS WP 12 for a comprehensive discussion of emerging technology at various stages of readiness. The Global Climate Observing System (GCOS) Climate Monitoring Principles for the evolution of observing system elements comprise an important set of guidelines for the transition from the present into the TPOS 2020.

Recommendation:

The Workshop recommended that a Task Team be formed to articulate broadscale observing requirements and recommend improvements to the broadscale observing system. The terms of reference of this Task Team are given in appendix 5.

5.2.2. High resolution

High spatial resolution needs include western boundary currents, the Indonesian Throughflow, the equatorial boundary region, and tropical instability waves. Boundary regions were identified as a key gap in the current observing system, and requirements for sustained observations eastern, western and equatorial boundary regions need to be articulated. In the west, the low-latitude western boundary currents, in addition to the Indonesian Throughflow, transport heat and other properties away from the tropical Pacific.

In the western equatorial Pacific, major process studies are underway and should be able to provide guidance on the requirements for observations to be sustained in the longer term. In the east, new technologies may provide the opportunity to take measurements in regions prone to vandalism. Requirements for observations of eastern, western and equatorial boundary regions need articulating.

More attention to the ocean and coupled dynamics in the far eastern equatorial Pacific is required due to large model biases in the region, which are probably due to the deficiencies in maintaining a sharp thermocline and simulating the local ocean-atmosphere coupling. Observations of variability in the thermocline are required, particularly vertical velocities, due to the large model errors in the region. In the eastern Pacific, there is no focused process study in the boundary region and further work is needed to identify requirements in this region, engaging with the regional activities. Due to vandalism issues, there is a historical gap in observations, despite the importance of the region in ENSO dynamics. The observational requirements are likely to be more demanding here (e.g., to understand vertical circulation), which has implications for observation options. Emerging technology, such as gliders, might be a feasible alternative to damage-prone moorings.

A key remaining challenge is that the mass, heat and freshwater budget of the equatorial Pacific still cannot be closed; boundary currents are a major pathway for heat and other properties to be transported away from the Equator; however, observations have only been undertaken as part of limited time process studies, which have not left behind a sustained monitoring system. Mean and seasonal variability in boundary currents can be derived from high-density expendable bathythermograph (XBT) transects and Argo trajectories, using altimetry to derive the variability. The Southwest Pacific Ocean Circulation and Climate Experiment (SPICE) and the North Pacific Ocean Circulation and Climate Experiment (NPOCE) are examples of high-density process studies in the western boundary current regions that could be used to assess which observations need to be sustained long term. Continued research is needed, considering new technologies, to assess how best to monitor boundary currents in a sustained and efficient manner.

An increased focus on ocean and coupled dynamics in the eastern equatorial Pacific and coastal region is required. However, historically, regional observations have proved challenging due to high levels of vandalism when moorings have been trialed. Moorings in the region may need to be subsurface. Semi-autonomous platforms such as gliders may provide new opportunities in this region. For a practical example of glider deployments currently being trialed in the region, see TPOS WP 12.

> Recommendation:
>
> The Workshop recommended that a Task Team be formed to articulate observing requirements and recommend improvements to the observations of eastern, western and equatorial boundary regions. The terms of reference of this Task Team are given in appendix 5.

5.3. Air-sea fluxes

Air-sea flux products suffer from large errors and biases, with biases particularly large in the tropics. There was strong advocacy from the fluxes community for a greater focus on the air-sea interface, particularly the diurnal cycle. For instance, the diurnal cycle needs to be resolved in all state parameters: currently, from TAO moorings, daily averages are telemetered. Telemetry of hourly data was recommended, and this is possible with Iridium communications. In addition, flux estimates are biased by the diurnal warm layer, especially under the convergence zones. Currently, in situ measurements of skin sea surface temperature (SST) are not routinely made; most observations are of bulk SST. However, skin SST is needed for bulk flux algorithms. The Group for High Resolution Sea Surface Temperature (GHRSST) has well-articulated needs for skin and bulk SST measurements.

> Recommendations (specific):
>
> - TRITON moorings could be converted to flux reference sites by adding a longwave radiation sensor.
> - Humidity sensors should be added to moored time series.

The complementarities of satellite and in situ data for wind observations were identified. Scatterometers do not work as effectively in rainy regions, with QuikSCAT (Ku band) being badly affected. In convergence zones, coverage is lost 30% of the time, and this needs to be considered in the design and prioritization of in situ observations. Further work also needs to be done in mooring/satellite wind comparisons, since satellite scatterometer winds are relative to a moving surface, and moorings are relative to earth; this means the satellite data need to be interpreted taking account of the effect of the surface currents.

In terms of specific observing system recommendations, the need for more high-quality flux reference data was identified. There are currently only 4 high-quality flux reference sites, all of which are on the Equator. (This is fewer than in the Indian or Atlantic.) TRITON moorings could be converted into flux reference sites by simply adding longwave radiation sensors, which is relatively easy to do. Flux reference stations should extend into the trade wind belt (e.g., 15-20° latitude) and sample different flux regimes, such as the ITCZ and SPCZ, as well as the west Pacific warm pool and the eastern cold tongue. The error characteristics of the different regions are very different. Improved observations of humidity are also needed, as reanalyses have a dry bias, and satellite products have a wet bias. High-quality humidity sensors are available, cost effective, and should be put on TAO moorings as a priority.

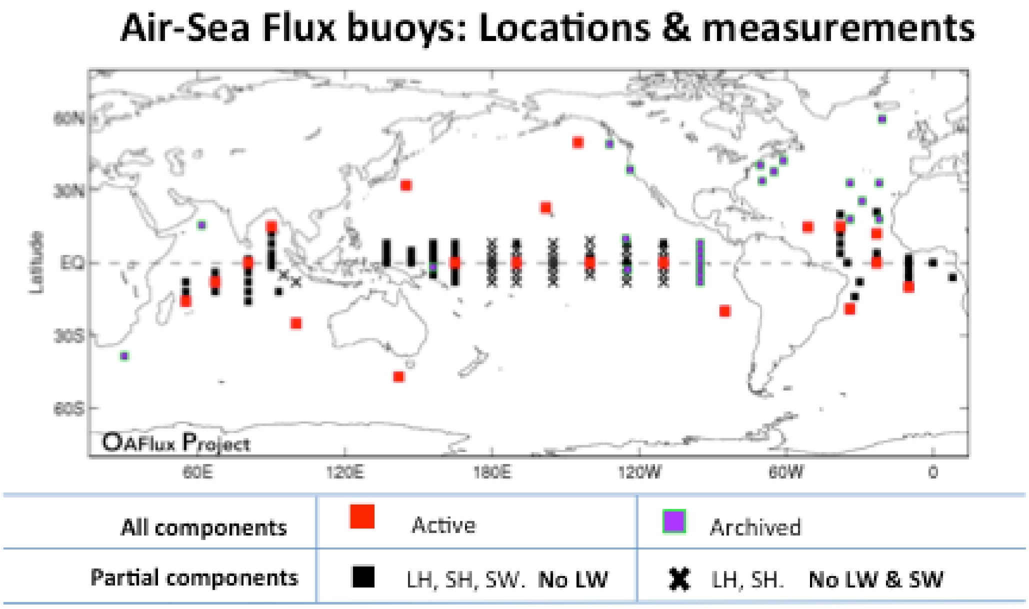

Figure 6: Locations of air-sea flux and flux parameter moorings.

There was strong advocacy from the fluxes community that the ship(s) servicing the TAO/TRITON moorings need to be instrumented with a core set of underway instrumentation, including an ADCP, a conductivity-temperature-depth (CTD) sensor, a high-quality meteorology package and partial pressure of carbon dioxide (pCO2) instrumentation.

Air-sea fluxes are currently calculated based on state observations above and below the air-sea interface. Direct flux sensors are available. The influence of waves on various flux processes is an area of active research that could be investigated using these sensors.

Tropical instability waves (TIWs) are energetic features in the tropical Pacific clearly seen in satellite imagery but spatially aliased by the in situ observation system (see further details in TPOS WP 4). There is strong air-sea interaction associated with these waves, but how best to progress representation of these waves was unresolved at the Workshop.

TPOS WP 11 highlights many actions that could improve understanding of air-sea interaction and improve representation and parameterization in numerical models used for numerical weather prediction through to climate. Some issues could be addressed by limited duration process studies; others pertain to the sustained observation system. The importance of the near-surface layer, air-sea interaction and observation of the diurnal cycle was raised in several white papers.

> Recommendation:
>
> In order to progress the specific needs of air-sea interaction, the Workshop recommended that a multidisciplinary Task Team be formed to articulate observing requirements and recommend improvements to the observations of the surface boundary layer. The terms of reference of this Task Team are given in appendix 5.

5.4. Biogeochemical and biological observations

The ocean plays an important role in the climate system as a large sink for anthropogenic carbon dioxide (CO_2) and thereby partially mitigates the large-scale effects of humankind's CO_2 emissions into the atmosphere. As a whole, the ocean takes up approximately 2.6±0.5 Pg C year^{-1} of the 8.6±0.4 Pg C year^{-1} that are emitted from the burning of fossil fuels. The tropical ocean is the ocean's largest natural source of CO_2 to the atmosphere and the annual contribution of CO_2 to the atmosphere from the oceanic equatorial belt is estimated to be 0.6–1.0 Pg C. Despite comprising a net source of CO_2 to the atmosphere, equatorial waters are characterized by relatively high rates of primary productivity and serve as globally significant regions of biologically-fueled carbon sequestration to the deep sea. However, changes in ocean circulation patterns along with regional and global-scale climate processes may significantly impact the biogeochemistry of equatorial regions and alter the uptake rates of CO_2 on decadal or longer time scales. The tropical Pacific is the major natural source of CO_2 from the ocean, contributing nearly 70% of the global flux to the atmosphere; and the tropical Pacific is the major source of CO_2 flux variability in the global oceans. Much of the CO_2 flux is controlled by the underlying physical and biogeochemical processes in the region, which are impacted by decadal and longer time-scale ocean and climate processes.

Specific recommendations on requirements for core biogeochemical observations and underpinning physical data are consistent with those noted earlier in this section; in particular, identifying the need to resolve the diurnal cycle. Specific requirements include high temporal resolution observations of the partial pressure of CO2 (pCO_2), pH, Oxygen, nutrients and chlorophyll (at around 10 sites), with coincident physics, including satellite wind and SST, plus subsurface profiles of temperature and salinity for calculating mixed-layer depth and hence the nutricline.

The biogeochemical observations in the tropical Pacific largely consist of augmenting the TAO moorings with sensor packages for, e.g., pCO2, and underway measurements from research vessels of core measurements. Oxygen and other biogeochemical sensors are now being trialed on Argo floats. There was a repeated call for the servicing ships for TAO to be considered a part of the observing system, taking a core set of observations including pCO2 and chlorophyll.

Because the diurnal warm layer depends fundamentally upon the absorption of solar warming within the water, which itself depends upon the biota in the water, the phytoplankton distribution can affect SST variability and even impact ENSO and the large-scale climate system. Photosynthetically active radiation (PAR) and subsurface optical absorption should thus be measured at one or more biogeochemical flux stations in a region of light wind where there may be feedbacks between the diurnal warm layer and phytoplankton blooms. Pending technology development, observations of the direct and diffuse radiation components at this station would provide invaluable information for the extinction profile in water, for ocean heat budgets, and for cloud studies.

The biogeochemical requirements for observations will need to be pursued through integration with the broader observing system; as a result, the Task Teams identified in this section will be multidisciplinary in membership and scope.

5.5. Identify gaps, inefficiencies and vulnerabilities

While inefficiencies need to be identified, some redundancy in the system is essential to mitigate against risks and for cross checks on quality. Observing systems have been adjusted as new platforms come online to capitalize on the unique contributions of different platforms; e.g., when the Argo array became established, the XBT network evolved to focus on high-resolution and frequently-repeated lines to derive transports. Although it is recognized that the TAO/TRITON array would evolve as necessary, the unique role of the moored time-series sites was highlighted, and the importance of the multi-decadal time-series sites emphasized.

The challenges in sustaining the TAO/TRITON mooring array were identified as a big concern, particularly considering the unique contribution in terms of high temporal resolution and multiple coincident observations that the moored time-series make to the observing system. The challenges sustaining this observing network (as highlighted in section 1) were discussed. The commitment from NOAA to return the TAO component to 80% data return was enthusiastically welcomed by the review committee and the Workshop participants, while noting that the longer term security of this funding was not ensured. Ways to mitigate the impact of the reduction in TRITON moorings, for instance, by deploying extra Argo floats need to be examined.

A drop in the number of CTD profiles that have been taken on TAO servicing cruises since the transfer of TAO implementation from research to operations in NOAA was also highlighted as a concern. ADCP and CTD data have been extremely valuable in providing spatial context, high-quality reference data; they meet requirements independent of the mooring arrays. The number of stations has fallen off rapidly since maintenance of TAO was moved from the NOAA Pacific Marine Environmental Laboratory (PMEL) to operational implementation. There was strong consensus on the need to bring back the valuable ancillary ship program, including complementary (ship based) sensor-based underway and water sample data for a broad range of biogeochemical, biological and flux variables, as well as physical variables.

In summary, it was concluded that there is limited redundancy in the observing system due to the complementary nature of networks. Multi-decadal records were considered particularly precious, especially equatorial time series. The benefits of satellite and in situ synthesis were highlighted, but some independence was needed to check on these datasets. It was noted that risks and vulnerabilities in the observing system need to be identified and mitigated, e.g., reliance on single sources of communications or sensors verses diversity of sources. The funding of data management was also identified as a key risk. It has been largely network driven and chronically underfunded in recent years (discussed further in section 7.1). The TPOS needs to identify these risks, and recommend mitigation strategies.

Following discussions in section 4 and 5, the formation of 3 Task Teams was recommended to further develop requirements, improve observing system design and address key gaps. Specific recommendations for observing system enhancements made in whitepapers (i.e., increasing the number of flux reference sites; extending some of the TAO/TRITON lines meridonally, and establishing eddy decorrelation reference sites; and enhancing and integrating biogeochemical observations) will be further explored in the context of these Task Teams. Where appropriate, a representative of new technology should be included in the membership. A fourth Task Team on modelling was recommended earlier.

6. Recommendations for adjusting, reconfiguring and enhancing the existing observing system

6.1. Recommended revisions/adjustments to the existing observing system to improve resilience/robustness, efficiency and integration

A consistent message expressed throughout the meeting on improving the resilience and integration of the observing system was the need for a strengthened focus on considering the observing system as an integrated whole and articulating the strengths of a multi-platform approach. Improving integration of the observing system will require strengthened scientific oversight and advocacy.

Recommendations: (immediate/specific)

- Ensure all components, including satellites, in situ, models and data and information management, are considered part of the observing system.
- Specifically, satellites should be considered an integral component of the observing system; e.g., explicitly consider calibration/validation dependencies, mission planning, and their role in tracking global teleconnections.
- Ships should be recognized as an essential component of the observing system. In particular, the ship used to service the moorings should be used to take a core set of observations of unique parameters or at benchmark accuracies not achievable by other elements and, where practical, for limited process studies.
- Any plan should allow for sufficient redundancy to ensure independent cross platform quality checks and to mitigate the risk of platform bias.

6.2. Reinforcing key priorities: areas for improvement

Regarding the existing observing system, there was no evidence to suggest that some requirements were no longer valid. The core principles of the observing system were reinforced. The unique scientific value of long time-series records in the tropical Pacific, delivered by over 20 years of TAO/TRITON observations, was particularly noted.

There have been challenges in sustaining broadscale observations in the tropical Pacific due to the divergent nature of the equatorial region and the loss of supplementary deployment opportunities associated with TAO servicing cruises. Moreover, the requirements for and design of broadscale observations need to be revisited; for instance, the design requirements and role of surface drifters should be assessed in the context of other broadscale observations such as the Argo array and satellite observations. Such an assessment should be progressed globally through OOPC but also specifically in the context of tropical Pacific requirements.

Recommendations:

- Identify and sustain critical long climate records as a priority.
- Maintain and improve broadscale sampling, taking into account all observing networks.
- Encourage development of biogeochemistry and biology.

6.3. Remaining gaps, inefficiencies, and issues to resolve

There were consistent messages from talks on both requirements and observing systems status and implementation regarding the remaining gaps and issues to be addressed in the observing system. Further work is needed to clearly articulate observing system requirements in these areas (see section 4.2) before we can discuss how best to address them. To this end, three Task Teams were recommended (see section 5). Engineers developing new technologies should be involved where appropriate. A fourth Task Team was recommended to advance model development. The modelling Task Team should liaise with the other Task Teams as appropriate.

6.4. Looking to the future: evaluation of new technologies

The new technologies paper (WP 12) focused on trends in technology development and advocated the need for collaboration between scientists and engineers in observing system design and development.

Lowering the cost per observation continues to be a strong driver for technology development, and research vessels continue to be a large cost overhead. As new technologies come online, research vessels will continue to have a role, but some new technologies can be installed on, or deployed from, smaller ships (including ships of opportunity and voluntary observing ships).

A range of emerging technology was presented and discussed, including deep Argo floats, gliders, wavegliders, lightweight moorings, acoustic and iridium communications, and bio-optical sensors. New technologies show promise in helping to address the new requirements, for instance, glider technology is likely to contribute to improved observations in boundary regions, and the development of biogeochemical sensors gives us the opportunity to expand biogeochemical observations. The next step would be to relate discussions of new technology to how delivery of existing requirements could be improved and to the potential to address new requirements. The authors of the emerging technology should be represented on the recommended requirements Task Teams to ensure this link is made.

7. Observing system implementation and delivery

7.1. Data and information delivery

Data and information (D&I) management is critical to the success and impact of an observing system. The availability and delivery of data was pioneered by the Sea Level Network: the TAO data system took things to the next level through real-time delivery of data. This was then built on by the Argo array, which now enables global access to real-time and delayed-mode data. However, the coordination of data management has not progressed significantly in the 5 years since the OceanObs'09 conference. For the concept of Essential Climate Variables to have the impact expected, D&I requirements need to be considered.

Data management is still network driven but chronically underfunded; and these efforts have been starved for 10 years, particularly for emerging contributions. The result is a system which is quite heterogeneous: some components are working well, others are struggling. The evolution of the data system must be stakeholder driven (provider and end user), and we need to begin to consider how the data system can evolve from the delivery of data and information to information and services. The curation of the climate record also needs attention. The Global Telecommunications System (GTS) delivers real-time data, but more focus is needed on coordination and curation of the delayed-mode data streams.

Better metrics are also needed to determine how the data are being used, as we need to continually advocate the benefits of ocean observing and its constituent elements. For scientific uptake, TAO/TRITON has a good bibliography; Argo has also put some effort in this, but this activity needs to be expanded to include uptake of data into products and projects that depend on the data (including PhDs).

Recommendations:

- As an underlying principle, around 10% of the total observing system effect should be directed towards data and information management, particularly for emerging and prototype technologies and a data and information management plan should be part of the TPOS 2020 implementation plan, to take account of opportunities to pilot new approaches.
- A future TPOS should be accompanied by a small set of performance indicators (metrics) that capture the technical performance and uptake/impact of the system data and information, particularly in terms of the ultimate socioeconomic impact.

7.2. Oversight and coordination

The recent challenges in sustaining the TAO/TRITON array have highlighted some vulnerabilities in the observing system, which need addressing if we are going to have a robust system into the future. The data return on TAO has dropped below 40% since the loss of the dedicated servicing vessel and cuts in the number of ship days for servicing. However, at the beginning of the meeting, NOAA committed to returning the TAO mooring array to 80% by the end of the calendar year, while work is carried out to redesign the observing system, including requirements for moorings. This was enthusiastically welcomed by the attendees. TRITON is also facing challenges due to ship time and is planning a staged withdrawal of some of the off-equatorial moorings at a rate of around 2 per year between 2013 and 2015, with plans to replace these observations with gliders and wavegliders. This loss of coverage was highlighted as a concern.

The lead time required for planning and implementation can lead to vulnerabilities. Significant lead time is needed for procuring ship time, securing expertise, and procurement/customs clearance processes, etc; which means that it is difficult to respond to short-term challenges. Therefore, more work is needed to anticipate risks and vulnerabilities in the system.

The small number of partners (two) supporting TAO/TRITON has left the system vulnerable as the two main partners face challenges in sustaining their commitments. With more partners involved, this risk could be mitigated. Vandalism is also an issue, and efforts are underway to try to educate and address this, including anticipating regions of high vandalism risk and considering new technology less prone to vandalism, albeit with perhaps slightly reduced capability.

For the broader observing system, dedicated cruises are becoming more of a priority, particularly as the ancillary measurements on the ships servicing the moorings have been reduced. In addition, there is a need to consider ship support for the observing system as a complete system: currently, the shipping requirements for each network are considered separately, with P.I.s contacting each other to find efficiencies, e.g., by deploying Argo floats or drifters from a ship servicing moorings, or on repeat-hydrography cruises. To this end, the JCOMM in situ Observing Platform Support Centre (JCOMMOPS) ships coordinator is developing a database of ships and cruises to help find synergies.

To determine the status of the observing system, metrics have been developed whereby progress can be assessed against a target deployment plan. However, the metrics and targets have historically been developed network by network, with a consequent lack of integration. The needs and usefulness of metrics to stakeholders also need to be considered, i.e., the status of observations by variable and delivery of products and information, and these are being developed at a global level through the OOPC and the JCOMM Observations Programme Area. The use of ocean indicators helps advocate for the importance of ocean observations, and the OOPC is developing these.

Moving forward in developing the next decade of the TPOS, we need to consider what governance is needed. Looking to the models in the Atlantic and the Indian Ocean, coordination is focused around requirements, facilitation, and scientific oversight. Scientific oversight was cited as key to the success of these activities. There is currently no formal scientific or implementation oversight of the TPOS. In particular, it was of great concern to the Workshop that the 3 main partners, NOAA NDBC, JAMSTEC, and NOAA PMEL, were not in routine communication. Scientific oversight and advocacy is considered essential, and the meeting strongly advocated much better dialogue between the three partners in particular and also in general with all interested parties as we plan to evolve the observing system.

7.3. Agency interests in implementing the future observing system

Presentations were made by 9 agencies and programmes with an interest in tropical Pacific observations.

NOAA and JAMSTEC are the major partners in the existing TPOS. In particular, they are the sole contributors to the TAO/TRITON mooring array.

NOAA currently supports about half of the global sustained observing system and emphasized that the TPOS is vital to delivering their goals: both research and operational. However, challenges in securing ship time, for mooring servicing in particular, has put the observing system at risk, since the main ship which carried out the servicing was decommissioned. A longer term plan is needed to support the observing system, including global coordination. NOAA is also investing in feasibility studies for emerging approaches to tropical Pacific observations, such as an enhancement of the Argo array in the equatorial region, underwater gliders, wavegliders, and evolving the TAO array technology (e.g., smaller surface expressions and 'prawler' profiling mooring technology).

JAMSTEC presented similar challenges to NOAA, highlighting the value of the mooring time series as essential while citing challenges in sustaining funding and ship time. The large vessels required for deploying TRITON moorings also limit the opportunities to engage other ships. JAMSTEC will work on developing new scientific products from tropical Pacific observations and also explore the use of emerging technologies while trying to ensure the climate record is sustained. JAMSTEC is a research agency, and the transition of the NOAA component of the array from the research to operational portfolio presented new challenges in sustaining the effort in JAMSTEC. In addition, collaboration in technology development has stalled. JAMSTEC presented a 'decay' plan for TRITON, which included removing 5 TRITON buoys between 2013 and 2015 and possibly 2 more in the future. Sites with a strong salinity signal and equatorial sites were maintained as a priority. They plan to replace these observations with new technologies, such as gliders and wavegliders, but unfortunately are unable to ensure overlap of new and old technologies.

Other partners provide substantial contributions to regional observations, but are unable to contribute to ship time. These include Australia's Integrated Marine Observing System (IMOS), and the French Institut de Recherche pour le Développement (IRD), which has an active lab in New Caledonia.

IMOS makes substantial contributions to both the Argo array (3rd largest contributor), the Ship of Opportunity Program (including observations for satellite calibration), and moored arrays for monitoring the major outflows of the Indonesian Throughflow. Broader support in the region is hampered by the limited ship resources, as Australia has just one bluewater research vessel.

IRD was one of the original partners in the TOGA experiment and initially supported TAO moorings at 156˚E and 165˚E. Their primary interests are now focused on the PIRATA array in the tropical Atlantic, development of the Voluntary Observing Ship (VOS) observations, including sea surface salinity, and research and capacity building. Their interests in the tropical Pacific span both research and operational requirements, including ENSO research, ocean data assimilation, numerical weather prediction, and ENSO monitoring. Looking to the future, IRD envisages contributing to the TPOS through technical expertise, capacity building, and instrumentation on moorings; however, IRD will not be able to contribute ship time. A governance structure for the TPOS was recommended so that agencies could discuss collaborations on both the science and implementation of the TPOS.

A number of agencies are expanding their activities and interests and are looking to engage more strongly in the TPOS in the future. These include the Korean Institute of Ocean Science and Technology (KIOST), the Chinese State Oceanic Administration (SOA), the Taiwan Ocean Research Institute (TORI), and the Instituto del Mar del Perú (IMARPE).

KIOST has significant research interests in the tropical Pacific, particularly related to the change in El Niño patterns. In recent years, they have recognized that direct current measurements would be useful and have contributed to the deployment of ADCPs on 2 TAO moorings along 165˚E. From December, 2015, KIOST will have a new research vessel, which they anticipate deploying mostly in the Pacific (50%) and Indian Ocean (40%). KIOST is proposing to take over 1 line of TAO moorings if NOAA can supply equipment and is suggesting 165˚E. They also have interests in joining RAMA, deploying subsurface moorings in the Indonesian Throughflow region, as well as coastal subsurface mooring activities in the eastern Pacific, and are looking to collaborate with JAMSTEC in the western Pacific region. As with JAMSTEC, KIOST has a strong science focus.

The State Oceanic Administration (SOA) Second Institute of Oceanography presented their interests in ocean observing. SOA is an operational agency for oceanography. Other relevant organizations are the Chinese Meteorological Agency (CMA) and the Chinese Academy of Sciences (CAS). Of these, SOA is best placed to support sustained ocean observations. SOA currently has 8 high frequency (HF) radar systems and 28 bluewater and coastal moorings/buoys deployed in the western Pacific and Indian Ocean. Their operational drivers include delivering information and prediction services for ENSO, the Madden-Julian Oscillation, monsoons, and typhoons. There would be a need to prove to the government that the TPOS observations would contribute to these requirements. SOA also has a new ship, with plans to focus on observations of the low-latitude western boundary current and Indonesian Throughflow. CAS has a large-scale research program in the region, deploying in excess of 40 moorings in this region between 2014 and 2018 as a short-term research activity. In conclusion, China has the resources and expertise to play a significant role in the TPOS, and there is consensus among Chinese scientists that they should contribute more. It should be noted that current projects are mostly research rather than operations oriented, and considerable efforts are needed to persuade the government of the need for sustained support.

IMARPE recognizes the importance of the TPOS to their interests, which include upwelling and current systems, decadal/multidecadal variability, delivery of socio-economic issues and early warnings. They monitor the TAO/TRITON mooring arrays locally and are motivated to support local moorings. They have expertise in deploying subsurface moorings and also collaborate in a joint regional survey annually. With regard to the TPOS, gaps were identified in the context of their requirements, including subsurface observations in the tropical southeast Pacific, improved connection with regional networks, and observations of oxygen and biogeochemistry. The agency develops a 5-year resource and activity plan. Currently, the RV Humboldt is resourced for 100 days per year in April/July and October/December. IMARPE is keen to discuss how they can support regional observations and, in particular, improve the connection between open ocean and regional/coastal observations in the eastern tropical Pacific.

TORI presented their interests in moored observations, which are primarily focused on typhoon impacts. However, they plan to expand their mooring activities in the future.

Further interests are from organisations with a clear need for data and information products from the tropical Pacific that are keen for further engagement in the use of data as well as capacity building to strengthen engagement in the future.

The Indonesian interests in the tropical Pacific are represented by Badan Meteorologi, Klimatologi, dan Geofisika (BMKG) and the Badan Pengkajian dan Penerapan Teknologi (Agency for the Assessment and Application of Technology; BPPT). Indonesia has 3 national research vessels and has been collaborating with JAMSTEC in deploying TRITON moorings (Ina-TRITON). Indonesia engages in a number of collaborations, including with the U.S.A, Japan, and France, and is keen to foster further collaborations. They require TPOS observations to support numerical weather prediction, monitoring and prediction of ENSO, variability of ocean and surface conditions, and the development of applications for marine resources. In terms of data products, they are particularly keen on development of indicators to improve climate prediction and collaboration to improve understanding and application of indicators. Other capacity building priorities include observing technology, modelling and data assimilation.

The Pacific Island nations were represented by the Secretariat of the Pacific Regional Environment Programme (SPREP), which represents 21 Pacific Island territories. A Pacific Islands Met Strategy (PIMS) focuses on requirements for marine weather services and climate and information predictions services. The importance of the TPOS in delivering to Pacific Island requirements was emphasized, and assistance was requested for setting up national programmes particularly focused on the use and applications of data. While Pacific Island nations can't assist in deploying and retrieving large moorings, there is potential to expand contributions through regional ships of opportunity as well as the deployment and retrieval of small autonomous platforms, such as the underwater gliders and wavegliders.

In summary, while NOAA and JAMSTEC are experiencing challenges in sustaining the ship time needed to support the TPOS, there are agencies looking to expand their role. In addition, there are opportunities for capacity building, in both the implementation and applications of observations. It should be noted that new interests in tropical Pacific observations are largely from research agencies with an interest in science and innovation, as opposed to operational agencies with a mandate for longer-term commitments.

A report from the Partnership for Observation of the Global Oceans (POGO) was also presented. POGO has representation from the directors of major oceanographic institutes globally and is well placed to respond to the issues discussed here, including coordination of interests; resources and shipping resources; capacity building; and technology transfer. POGO supports the development of a resources forum for the tropical Pacific and could also facilitate capacity building activities.

Recommendations

- The Workshop strongly endorses NOAA's offer to return TAO to 80% data return as soon as possible, while design/planning work is carried out for the future TPOS.
- There is an urgent need for the TPOS community to explore strategies to minimize the impact of the reduction in the TRITON array.
- The Workshop concluded that communication and coordination among existing partners needs urgent attention. In particular, given TAO and TRITON issues, regular communication is needed between PMEL, NDBC and JAMSTEC.
- Discussions with interested organisations should be initiated to broaden engagement in supporting the TPOS, enabling new partners to participate.
- Sufficient redundancy should be built in to ensure independent cross-platform quality checks and mitigate the risk of platform bias.
- Improved strategies for coordination and oversight of the observing system, including ongoing evaluation, are needed.
- Ongoing scientific oversight of the design, implementation, and evaluation of the TPOS and its components is needed.
- Routine communication between all nations and parties involved in developing/implementing TPOS is required.
- There should be a long-term plan for dedicated servicing support for the TPOS.
- An assessment of risks to the observing system and associated mitigation efforts/options, e.g., redundancy, sensor diversity, etc., is needed.

8. Next steps: establishing a TPOS 2020 Project

The overarching recommendation of the Workshop is the creation of a focused TPOS 2020 Project to achieve the transition from a loosely coordinated set of ocean observing activities in the tropical Pacific to a systematic and sustained TPOS by 2020.

8.1. TPOS 2020 Goals

TPOS 2020 Goals are:

- To refine and adjust the TPOS to monitor, observe and define the state of ENSO and advance scientific understanding of its causes.
- To determine the most efficient and effective method to support observation and prediction systems for ocean, weather, and climate services of high societal and economic utility, including underpinning research.
- To advance/refine the degree to which the tropical Pacific (physical and biogeochemical) and its climate impacts are predictable.
- To determine how interannual to multidecadal variability and human activities impact the relation between marine biogeochemistry and biology to carbon budgets, food security, and biodiversity.

To achieve this, the TPOS 2020 Project will:

- Focus on the tropical Pacific Ocean, but embrace partnerships with the meteorological and adjacent coastal/regional ocean communities, as appropriate.
- Begin as soon as practicable and work strategically towards establishing a TPOS by 2020.
- Achieve a significant change for sustained observing and leave a legacy for GOOS of a robust, efficient, and effective contribution in the tropical Pacific, engaging interests of research and other communities as necessary.
- Embrace contributions from multiple agencies and countries through a coordinated portfolio of resources and high-level oversight of the scientific and technical design, sub-projects and interfaces to the user community.
- Operate within the context of the Framework for Ocean Observation and build on existing activities while at the same leading needed change.

8.2. TPOS 2020 Governance

The Review recommends that TPOS 2020 should employ a “lite” Project governance model, with the focus on coordination and oversight of the resources and scientific and technical aspects. The Project should report to the GOOS Steering Committee but otherwise should exercise significant autonomy.

The key governance elements are:

- A TPOS 2020 Steering Committee responsible for oversight of in-scope activities, the System design and implementation plan, and coordination with other relevant scientific/expert panels and bodies.
- A Resources Panel/Forum broadly representative of the sponsors of TPOS 2020 and responsible for coordinating the variety of resources needed for the Project to succeed.
- An Executive, populated from the leadership of (1) and (2) and responsible for reporting and communication.
- A Project Office (1 or more people, as appropriate), with the office and coordination activities supported and resourced by the sponsors.
- The terms of reference of the proposed TPOS Project and its components can be found in appendix 5.

9. Summary

The list below details all of the recommendations and outcomes from the meeting: First, the recommendation to form a TPOS 2020, then other recommendations as they arose during the meeting. The 4 task teams should take into account several of these recommendations.

The overarching recommendation of the Workshop is the creation of a focused TPOS 2020 Project to achieve the transition from a loosely coordinated set of ocean observing activities in the tropical Pacific to a systematic and sustained TPOS by 2020.

9.1. TPOS 2020 Goals

TPOS 2020 Goals are:

- To refine and adjust the TPOS to monitor, observe, and define the state of ENSO and advance scientific understanding of its causes.
- To determine the most efficient and effective method to support observation and prediction systems for ocean, weather, and climate services of high societal and economic utility, including underpinning research.
- To advance and refine the degree to which the tropical Pacific (physical and biogeochemical) and its climate impacts are predictable.
- To determine how interannual to multidecadal variability and human activities impact the relation between marine biogeochemistry and biology to carbon budgets, food security and biodiversity.

9.2. Recommendations: advancing modelling

- A coordinated activity involving several different analysis and forecast groups to exploit multi-system approaches to identify robust impacts of the observation system, which are common in a majority of data assimilation and prediction systems.
- Targeted activity on modelling and data assimilation is required in the tropical Pacific, including identifying requirements for targeted process studies to reduce model error.

9.3. Recommendations: existing requirements

- Identify and sustain critical long climate records as a priority.
- Maintain and improve broadscale sampling, taking into account all observing networks.
- TRITON moorings could be converted to flux reference sites by adding a long wave radiation sensor.
- Improved humidity sensors should be added to moored time series.
- Encourage integration of biogeochemistry and biology.

9.4. Recommended revisions/adjustments to the existing observing system to improve resilience/robustness, efficiency and integration

A consistent message expressed throughout the meeting on improving the resilience and integration of the observing system was the need for a strengthened focus on considering the observing system as an integrated whole and articulating the strengths of a multi-platform approach. Improving integration of the observing system will require strengthened scientific oversight and advocacy. Immediate specific recommendations include:

- Ensure all components, including satellites, in situ, models, data, and information management, are considered part of the observing system.
- Specifically, satellites should be considered an integral component of the observing system. E.g., explicitly consider calibration/validation dependencies, mission planning, and the role in tracking global teleconnections.
- Ships should be recognized as an essential component of the observing system for taking a core set of observations of unique parameters or at benchmark accuracies not achievable by other elements and to be used, where practical, for limited process studies.
- Ensure that there is sufficient redundancy to ensure independent cross-platform quality checks, and mitigate the risk of platform bias.

9.5. New requirements

It is recommended that 3 multidisciplinary Task Teams are set up focused on defining requirements and observing approaches, and one focused on modeling. The scope of these Task Teams can be found in appendix 5. Emerging technology experts should be included in membership of TPOS Task Teams, and the modelling Task Team should interact with the others as appropriate. The focus of the Task Teams will be:

- Evaluating requirements and improving broadscale observations.
- Evaluating requirements and observing approaches for diurnal variability and air-sea fluxes.
- Evaluating requirements and observing approaches in eastern, western and equatorial boundary regions.
- In addition, a Task Team is needed to focus on modelling, assimilation and synthesis to fast track updates and impact of observations on our modelling and prediction systems.

See proposed Terms of Reference for these Task Teams in appendix 5. Specific observing system enhancements were suggested in whitepapers, which should be considered in the context of proposed Task Teams.

9.6. Delivery of data and information

- As an underlying principle, around 10% of the total observing system effect should be directed towards data and information management, particularly for emerging and prototype technologies and a data and information management plan should be part of the observing system implementation plan.

- A future TPOS should be accompanied by a small set of performance indicators (metrics) that capture the technical performance and uptake/impact of the system data and information, particularly in terms of the ultimate socio-economic impact.

9.7. Coordination of the observing system

- The Workshop strongly endorses NOAA’s offer to return TAO to 80% data return as soon as possible, while design/planning work is carried out for the future TPOS.
- There is an urgent need for the TPOS community to explore strategies to minimise the impact of the reduction in the TRITON Array.
- The Workshop concluded that communication and coordination among existing partners needed urgent attention. In particular, given TAO and TRITON issues, regular communication is needed between PMEL, NDBC and JAMSTEC
- Initiate discussions with interested organisations to broaden engagement in supporting the TPOS, enabling new partners to participate.
- Improved strategies for coordination and oversight of observing system, including ongoing evaluation, are needed.
- Ongoing scientific oversight of the design, implementation, and evaluation of the TPOS and its components is needed.
- Routine communication between all nations and parties involved in developing/implementing TPOS is required.
- There should be a long-term plan for dedicated servicing support for the TPOS.
- An assessment of risks to the observing system and associated mitigation efforts/options, e.g., redundancy, sensor diversity, etc., is needed.

Appendix 1. Agenda

Sunday 26th January
17.00 -19.00: Afternoon/evening briefing meeting for SOC and Independents (La Jolla Shores Hotel).

Monday 27th January

Time	Title	Speaker
8.30-9.00	Registration	
Session 1: Chair: Susan Wijffels, Rapporteur: Dake Chen.		
9.00-10.00	Welcome and Introductions	David Anderson and Toshio Suga, Kathleen Ritzman, Assistant Director, Scripps. Sponsors: GOOS/GCOS (Eric Lindstrom), NOAA (Craig McLean), JAMSTEC (Ken Ando), KIOST (Jae Hak Lee), SOA SIO (Dake Chen).
10-00 10.50 (30 +20)	Research and operational achievements of the TAO/TRITON	Mike McPhaden and Ken Ando
10.50-11.15	Coffee Break	
11.15-11-55 (25+15)	Societal impact and importance of Observing the tropical Pacific	Ed Harrison
11.55-12.45 (15+15+20)	Regional Applications. a) Latin America, b) Southwest Pacific.	Ken Takahashi and Brad Murphy
12.45-13.00	Discussion: Requirements for Science and Society	
13.00-14.00	Lunch	
Session 2. Chair: Jeremy Mathis, Rapporteur, Neville Smith.		
14.00-14.50 (30+20)	ENSO and Tropical Pacific research. Overarching science drivers and requirements for variables, assessment of gaps	Billy Kessler
14.50-15.40 (30+20)	Operational Forecasting Systems (NWP, Monthly, Seasonal)	Magdalena Balmaseda
15.40-16.10	Coffee break	
16.10-17.00 (30+20)	Evaluation of the Tropical Pacific Observing System from the ocean data assimilation perspective.	Yosuke Fujii
17.00-18.00	Discussion: requirements and insights from modeling, forecasting and data assimilation Discussion: recommendations from Monday sessions. (issues to resolve)	
18.00-19.00	Closed session: SOC + Independents	

18.30-20.30: Evening Reception, hosted by Scripps Institution of Oceanography.

Tuesday 28th January

Time	Title	Speaker
Session 3. Chair: Magdalena Balmaseda, Rapporteur: Tony Lee.		
8.30-9.00	Recap on previous discussion.	David Anderson/Toshio Suga
9.00- 9.50 (30+20)	Biogeochemistry applications in the Tropical Pacific : Requirements for observations, synergies, assessment of gaps	Jeremy Mathis
9.50-10.40 (30+20)	Biology and fisheries applications: Requirements for observations, synergies, assessment of gaps.	Francisco Chavez
10.40-11.10	Coffee	
11.10-11.30	Discussion: requirements of data and products for BGC and Fisheries, synergies (including with physics and climate requirements)	
Session 4. Chair: Yosuke Fujii, Rapporteur: Susan Wijffels.		
11.30-12.20 (30+20)	Satellite Views of the Tropical Pacific	Eric Lindstrom
12.20-13.20	Lunch	
13.20-14.10 (30+20)	In situ Temperature, Salinity, Current observations	Dean Roemmich
14.10-15.00 (30+20)	In Situ Wind stress, air sea fluxes observations	Meghan Cronin
15.00-15.30	Coffee Break	
15.30-16.20 (30+20)	Emerging Technologies: Requirements, readiness and Integration	Dan Rudnick, Chris Meinig
16.20-17.30	Discussion: Observations to meet requirements. Commonalities, synergies, issues, etc. Role of emerging technology.	
17.30-18.30	Closed session: SOC + Independents. To reflect on key points of the meeting so far.	

Wednesday 29th January

Session 5. Chair, Dake Chen, Rapporteur, Albert Fischer		
8.30-9.00	Recap from the previous day.	David Anderson/Toshio Suga
9.00-9.40 (25+15)	Data and information Delivery: Communication, assembly and uptake.	Neville Smith
9.40-10.30 (30+20)	Logistics, Resourcing and Coordination	David Legler/Ken Ando
10.30-11.00	Coffee break	

11.00-12.40 (10 minutes each)	Presentations by agencies with interests in engaging: (TBC) National Oceanic and Atmospheric Administration (NOAA) Japan Agency for Marine-Earth Science and Technology (JAMSTEC) Australia's Integrated Marine Observing System (IMOS) El Instituto del Mar del Perú (IMARPE) Korea Institute of Science and Technology (KIOST) Instituto Oceanográfico de la Armada (INOCAR) State Oceanic Association, Second Institute of Oceanography (SOA SIO) Institut de recherche pour le développement (IRD) Badan Meteorologi, Klimatologi, dan Geofisika (BKMG) Taiwan Ocean Research Institute (TORI)	 David Legler/Shannon McArthur Ken Ando Tim Moltmann Dimitri Gutierrez Sik Huh TBC Dake Chen Mike McPhaden (for Bernard Bourles) Noer Hayati Dr. Yang
12.40-13.10	Discussion of morning session	
13.10-14.30	Lunch	
Session 6. Chair: Rapporteur: Albert Fischer		
14.30-15.30	Discussion of material presented so far. Points of consensus, divergence, issues to resolve.	
15.30-16.00	Coffee	
16.00-17.00	Discussion continued	
17.00-19.00	Closed session: SOC + Independents	

Thursday 30th January

Session 7:, Rapporteur: Albert Fischer		
8.30-9.00	Recap from yesterday	David Anderson/Toshio Suga
9.00-10.30	Discussion, recommendations	
10.30-11.00	Coffee	
11.00-12.00	Discussion continued,	
12.00-12.30	Closing remarks	Co-chairs Sponsors: NOAA (Bob Deitrick), JAMSTEC (Ken Ando), Eric Lindstrom (GOOS/GCOS), Dake Chen (SIO), Sik Huh (KIOST)
12.30-13.30	Lunch and end of meeting.	
13.30-17.30	Closed session: TPOS SOC + Independents only	

Appendix 2. Terms of Reference

Phase 1: TPOS 2020 Workshop Goals/Scientific Organizing Committee (SOC)

Terms of Reference

1. Review the research and operations achievements of the TAO/TRITON component of the tropical observing system.

2. Highlight the impacts of the tropical Pacific observing system on the delivery of information/services of societal importance and relevance.

3. Evaluate (review/assess/prioritize) existing and potential requirements for sustained observations of ocean variables in the tropical Pacific Ocean* (15°S-15°N) and update them to reflect new knowledge and needs for a range of applications from scientific to societal. Key applications to be considered include: research on ENSO, coupled atmosphere-ocean variability, and circulation; climate monitoring; modelling and forecasting (climate, ocean, seasonal and weather prediction); biogeochemistry and fisheries.

4. Evaluate the adequacy of existing observing strategies to deliver requirements for variables, and characterize their impacts. Characterize how in situ (e.g., TAO/TRITON, Argo, drifters, etc.) and remote sensing observing systems are contributing to meet these scientific and functional requirements, and identify gaps, inefficiencies, and vulnerabilities.

5. Recommend revisions and/or adjustments to the current suite and configuration of observing systems to enhance their resilience and robustness in order to produce data in a more cost-efficient and sustainable manner feasible within the anticipated envelope of capability and resources.

6. Identify potential enhancement or reconfiguration of this sustainable observing suite to address gaps and new requirements.

7. Evaluate logistical requirements for implementation of the recommended Tropical Pacific Observing System (TPOS).

8. Assess interests, as well as potential contributing capabilities, of existing and new collaborators towards implementing tropical Pacific observing needs.

9. Recommend strategies (e.g., training, development assistance, technology transfer programs, and observing system management) to address long-term observing capabilities of potential contributors in order to improve robustness and resilience of observational data from the TPOS.

10. Evaluate requirements for delivery of data, and derived products and information, in real time and delayed mode (e.g., availability, quality, latency, integration/interoperability); evaluate the existing data systems for fitness for purpose.

11. Assess readiness of new technologies, their potential impact and feasibility in addressing requirements, and their potential to contribute towards addressing gaps, improving

robustness/resilience, and/or lowering costs per observation in the tropical Pacific Ocean region; recommend new technologies with greatest potential to meet critical requirements and suggest approaches to improve the readiness for inclusion in the sustained observing system.

12. Develop a report of this Workshop, with recommendations on the development of a process for the ongoing evaluation of the observing system.

* The needs, strategies, and recommendations, as they apply to sustained observing data of the Tropical Atlantic and Indian Oceans, may also be considered.

Phase 2: A Proposed TPOS Resources Forum (TRF)

Discussions on the potential to form a TPOS Resources Forum (TRF) will be carried out after the TPOS Workshop.

A TRF is proposed to support the TPOS 2020 plan for a sustained observing system in the tropical Pacific. The TRF will meet to monitor and critique the rationale for implementation of the TPOS Plan, as it is articulated by TPOS 2020, with input from the Ocean Observations Panel for Climate, the CLIVAR Pacific Science Panel, Pacific Island GOOS, DBCP TAO Implementation Panel (TIP), and other relevant expert bodies.

Based on its deliberations, the TRF will work to facilitate and coordinate the provision of the resources required for TPOS implementation and maintenance by member institutions. The TRF activity will promote contributions from institutions in the participating countries, with a view toward fully implementing the TPOS Plan by 2020 and sustaining TPOS thereafter.

Once fully implemented by 2020, sustaining TPOS is the biggest challenge that the TRF will need to address during its annual meeting.

Composition of the TPOS Resources Forum (TRF)

TRF members will be high-level representatives of institutions in their respective countries that have a stake in the development of the TPOS. Members will report at the annual meetings on the actions taken by their Nation/Institution during the past year to advance the implementation of the TPOS.

Further discussions on the potential to form a TRF, its terms of reference, and potential membership, will be carried out after the TPOS Workshop.

Appendix 3. Workshop Attendees

Scientific Organizing Committee

Dr David ANDERSON (co-chair)
Emiritus Fellow,
Department of Physics
University of Oxford.
United Kingdom
Email: dlta@btinternet.com

Magdalena BALMASEDA
European Centre for Medium-Range Weather Forecasts
Shinfield Park
Reading
RG2 9AX
United Kingdom
Email: magdalena.balmaseda@ecmwf.int

Prof. Dake CHEN
Professor
Second Institute of Oceanography, SOA
No.36 baochubei Road
310012 Hangzhou
Zhejiang
China
Email: dchen@sio.org.cn

Yosuke FUJII
Meteorological Research Institute of Japan Meteorological Agency, Ibaraki
1-1 Nagamine
Tsukuba
305-0052
Ibaraki
Japan
Email: yfujii@mri-jma.go.jp

Dr D. E. HARRISON
NOAA Pacific Marine Environmental Laboratory
7600 Sand Point Way NE
Seattle WA 98115
United States
Tel: +1 206 526 6225
Fax: +1 206 526 6744
Email: d.e.harrison@noaa.gov

Dr Jae Hak LEE
Research Scientist
Korea Institute of Ocean Science and Technology
787 Haeanlo
Ansan 426-744
Korea Rep
Tel: +82 (0)31 400 6121
Fax: +82 (0)31 408 5829
Email: jhlee@kiost.ac

Dr Tony LEE
Jet Propulsion Laboratory
M/S 300-323
4800 Oak Grove Drive
Pasadena, CA 91109
United States
Tel: +1 818 354 1401
Email: tlee@jpl.nasa.gov

Jeremy MATHIS
NOAA Pacific Marine Environmental Laboratory
7600 Sand Point Way NE, Bldg. 3
Seattle WA 98115
United States
Email: jeremy.mathis@noaa.gov

Dr. Neville SMITH
Deputy Director
Bureau of Meteorology, Melbourne
Bureau of Meteorology
Melbourne VIC 3001
Australia
Tel: +61 3 96 69 44 44
Fax: +61 3 96 69 4548
Email: n.smith@bom.gov.au

Dr Toshio SUGA (co-chair)
Tohoku University, Graduate School of Science and Faculty of Science
Aobayama Campus
6-3,Aramaki Aza-Aoba,
Aoba-ku
980-8578
Sendai
Japan
Tel: +81 22 795 6527
Fax: +81 22 795 6530
Email: suga@pol.gp.tohoku.ac.jp

Dr Susan WIJFFELS
CSIRO Marine and Atmospheric Research, Tasmania
Marine Laboratories
Castray Esplanade
GPO BOx 1538
Hobart Tasmania 7001
Australia
Email: Susan.Wijffels@csiro.au

Whitepaper Authors

Dr. Mark BOURASSA
Professor
Florida State University, Center for Ocean-Atmospheric Prediction Studies
Center for Ocean Atmospheric Prediction Studies
Tallahassee FL 32306-2840
United States
Tel: +1 850 644-6923
Fax: +1 850 644-4841
Email: bourassa@coaps.fsu.edu

Dr. Francisco CHAVEZ
Senior Scientist
Monterey Bay Aquarium Research Institute
7700 Sandholdt Road
Moss Landing California CA 95039
United States
Tel: (831) 775-1700
Fax: (831) 775-1620
Email: chfr@mbari.org

Dr Meghan CRONIN
NOAA Pacific Marine Environmental Laboratory
7600 Sand Point Way NE
Seattle WA 98115
United States
Email: Meghan.F.Cronin@noaa.gov

Jim CUMMINGS
Naval Research Laboratory
Oceanography Division
Code 7320
Monterey CA 93943
United States
Tel: +1 831 656-5021
Fax: +1 831 656-4769
Email: cummings@nrlmry.navy.mil

Tatuya FUKUDA
Japan Agency for Marine-Earth Science and Technology, Yokosuka
2-15 Natsushima
Yokosuka
237-0061
Kanagawa
Japan

Email: fukudat@jamstec.go.jp

Florent GASPARIN
University of California, San Diego, Scripps Institution of Oceanography
9500 Gilman Drive
Mail Code 0218
La Jolla California 92093-0218
United States
Email: fgasparin@ucsd.edu

Michelle GIERACH
NASA Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena CA 91109
United States
Email: Michelle.Gierach@jpl.nasa.gov

Eric GUILYARDI
Professor
Laboratoire d'Oceanographie et du Climat: Experimentation et Approches Numeriques, Institute Pierre Simon Laplace, University Pierre and Marie Curie
4 place Jussieu
75005 Paris
France
Email: Eric.Guilyardi@locean-ipsl.upmc.fr

Peter JANSSEN
European Centre for Medium-Range Weather Forecasts
Shinfield Park
Reading
RG2 9AX
United Kingdom
Email: peter.janssen@ecmwf.int

Dr Dongchull JEON
P.I. of POSEIDON Project/KORDI
Korea Institute of Ocean Science and Technology
787 Haeanlo
Ansan 426-744
Korea Rep
Tel: +82 010 3305 6124
Email: dcjeon@kiost.ac

William KESSLER
NOAA Pacific Marine Environmental Laboratory
7600 Sand Point Way NE, Bldg. 3
Seattle WA 98115
United States
Email: William.S.Kessler@noaa.gov

Dr. Arun KUMAR
Chief, Development Division
National Centers for Env
NOAA Center for Weather and Climate Prediction
5830 University Research Court
College Park Maryland 20740
United States
Tel: (1) 3016833385
Fax: (1) 3016831557
Email: arun.kumar@noaa.gov

Gary LAGERLOEF
President and Senior Scientist
Earth and Space Research
2101 Fourth Ave, Suite 1310
Seattle WA 98121
United States
Tel: +1206-726-2177
Email: Lager@esr.org

Dr Eric LINDSTROM
Physical Oceanography Program Scientist
NASA Headquarters
Earth Science Division, Room 3D74
Science Mission Directorate
NASA Headquarters
Mail Suite 3B74
300 E Street SW
Washington DC 20546
United States
Tel: +1 202 358-4540
Fax: +1 202 358-2770
Email: eric.j.lindstrom@nasa.gov

Shannon MCARTHUR
Program Manager
NOAA National Data Buoy Center
United States
Tel: +1 228 688 2830
Email: shannon.mcarthur@noaa.gov

Dr Michael MCPHADEN
Chair, Tropical Moored Buoy Implementation Panel (TIP)
NOAA/PMEL
Bldg. 3, Bin C15700
7600 Sandpoint Way N.E.
Seattle WA 98115
United States
Tel: +1 206 526 6783
Fax: +1 206 526 6744
Email: michael.j.mcphaden@noaa.gov

Mr Christian MEINIG
Leader, Engineering Development
NOAA Fisheries' National Marine Fisheries Service, Alaska Fisheries Science Center, Seattle
NOAA Pacific Marine Environmental Laboratory
7600 Sand Point Way N.E.
Seattle Washington 98115-0070
United States
Tel: +1 206 526 6149
Fax: +1 206 526 6744
Email: Christian.Meinig@noaa.gov

Dr Brad MURPHY
Bureau of Meteorology, Melbourne
700 Collins Street
Docklands
GPO Box 1289
Melbourne VIC 3001
Australia
Email: B.Murphy@bom.gov.au

Larry O'NEILL
Oregon State University, College of Oceanic & Atmospheric Sciences
104 COAS Administration Building
Corvallis Oregon OR 97331-5503
United States
Email: loneill@coas.oregonstate.edu

Dr Dean ROEMMICH
Professor (MLRG/PORD)
University of San Diego, Scripps Institution of Oceanography
Scripps Institution of Oceanography University of California, San Diego 9500 Gilman Drive, Mail Code 0230
La Jolla CA 92093-0230
United States
Tel: +1 (858) 534-2307
Fax: +1 (858) 534-0704
Email: droemmich@ucsd.edu

Dr. Daniel RUDNICK
Associate Professor of Physical Oceanography (PORD)
University of San Diego, Scripps Institution of Oceanography
United States
Tel: [8] (858) 534-2230
Fax: [8] (858) 534-2230
Email: drudnick@ucsd.edu

Dr Uwe SEND
Professor
Scripps Institution of Oceanography, University of California San Diego
United States
Tel: 01 858-822-6710
Fax: 01 858-534-9820
Email: usend@ucsd.edu

Dr. Awnesh SINGH
Postdoc
The University of the South Pacific
Private Mail Bag
Suva
Fiji
Tel: +679 3232666
Email: awneshsingh@gmail.com

Dr. Ken TAKAHASHI
Instituto Geofísico del Perú
Peru
Email: ken.takahashi@igp.gob.pe

Dr Yan XUE
CPC/NCEP
Room 3005, NCWCP
5830 University Research Court
College Park, MD 20740
College Park MD 20740
United States
Tel: +1 301 683-3390
Fax: +1 301 683-1558
Email: Yan.Xue@noaa.gov

Dr. Lisan YU
Senior Scientist
Woods Hole Oceanographic Institution
Woods Hole MA 02543
United States
Email: lyu@whoi.edu

Invited Experts

Takeshi DOI
Japan Agency for Marine-Earth Science and Technology, Research Center for Global Change, Yokohama
Yokohama Institute for Earth Sciences
3173-25 Showamachi, Kanazawa-ku, Yokohama City
Yokohama
236-0001
Kanagawa
Japan
Email: takeshi.doi@jamstec.go.jp

Dr. Robert KNOX
Associate Director and Research Oceanographer Emiritus
University of San Diego, Scripps Institution of Oceanography
United States
Tel: 1 858-534-4729
Fax: 1 858-535-1817
Email: rknox@ucsd.edu

Tim MOLTMANN
Director

Integrated Marine Observing System
University of Tasmania
Private Bag 110
Hobart Tasmania 7001
Australia
Tel: + 03 6226 276
Fax: + 0407 558 004
Email: tim.moltmann@imos.org.au

Coordination/Secretariat

Kentaro ANDO
Research Scientist
Japan Agency for Marine-Earth Science and Technology, Yokosuka
Research Institute for Global Change Japan Marine Science and Technology Centre 2-15
Natsushima-cho
Yokosuka
237-0061
Japan
Tel: +81-46-867-9462
Fax: +81-46-867-9835
Email: andouk@jamstec.go.jp

Albert FISCHER
Head, Ocean Observations and Services section
Intergovernmental Oceanographic Commission of UNESCO
1 rue Miollis
75732 Paris cedex 15
France
Tel: +33 1 45 68 40 40
Fax: +33 1 45 68 58 13
Email: a.fischer@unesco.org

Dr Katherine (Katy) HILL
GOOS/GCOS Programme Specialist
World Meteorological Organization
7bis, avenue de la Paix
Case Postale 2300
1211 Geneva
Switzerland
Tel: +41 (0)22 730 80 83
Fax: +41 (0)22 730 8052
Email: khill@wmo.int

Dr Sidney W. THURSTON
International Coordinator
NOAA, Climate Program Office
Climate Observations
1100 Wayne Ave., Suite 1200
Silver Spring MD 20910
United States
Tel: +1 301 427 2459
Fax: +1 301 427 0033
Email: sidney.thurston@noaa.gov

Organisation Representatives

Robert DETRICK
Assistant Administrator, NOAA Research Office
National Oceanic & Atmospheric Administration, Silver Spring
Silver Spring Metro Center
Bldg 3, Rm 11458
1315 East-West Highway
Silver Spring MD 20910
United States
Email: robert.detrick@noaa.gov

Ms Nelly FLORIDA RIAMA
Indonesian Meteorogical Climatological and Geophysical Agency
Agroclimate and Marine Climate Information
Jl. Angkasa I No.2 Kemayoran
Jakarta
Indonesia
Tel: 62-21-4246321 ext 4208
Fax: 62-21-4246703
Email: nelly.florida@bmkg.go.id

Gwo-Ching GONG
Taiwan Ocean Research Institute (TORI)
No.219, Sec.1, Dongfang Rd., Qieding Dist
852 Kaohsiung City
TAIWAN
China
Email: gcgong@narlabs.org.tw

Edward GORECKI
National Oceanic & Atmospheric Administration, Silver Spring
Silver Spring Metro Center
Bldg 3, Rm 11458
1315 East-West Highway
Silver Spring MD 20910
United States
Email: edward.gorecki@noaa.gov

Carmen GRADOS
Instituto del Mar del Peru
Esq Gamarra y Gral Valle S/N
CALLAO
LIMA
PO Box 22
Peru
Email: cgrados@imarpe.gob.pe

Dr Dimitri GUTIERREZ
Research Scientist
Instituto del Mar del Peru
Esq Gamarra y Gral Valle S/N
CALLAO
LIMA
PO Box 22
Peru
Email: dgutierrez@imarpe.gob.pe

Dr. Sik HUH
Head of International Cooperation Div.
Korea Ocean Research & Development Institute
Ansan 29
425-600
Seoul
Korea Rep
Tel: +82 (0)31 400 7750
Fax: +82 (0)31 406 6925
Email: sikhuh@kordi.re.kr

Morio ICHIHARA
Japan Agency for Marine-Earth Science and Technology, Yokosuka
2-15 Natsushima
Yokosuka
237-0061
Kanagawa
Japan
Email: ichiharam@jamstec.go.jp

Dr Neville KOOP
Secretariat of the Pacific Regional Environment Programme
PO Box 240
Apia
Samoa
Tel: +685 21929
Fax: +685 20231
Email: nevillek@sprep.org

Dr David LEGLER
National Oceanic and Atmospheric Administration Office of Oceanic and Atmospheric Research
1717 Pennsylvania Ave NW, Ste 250
Washington DC 20006
United States
Email: david.legler@noaa.gov

Ms Jennifer LEWIS
International Analyst
National Weather Service/National Oceanic Atmospheric Administration
NWS-NOAA Suite 17456
East West Hwy
Silver Spring MD 20109
United States
Tel: 301-713-0645x109
Email: Jennifer.Lewis@noaa.gov

Craig MCLEAN
National Oceanic & Atmospheric Administration, Silver Spring
Silver Spring Metro Center
Bldg 3, Rm 11458
1315 East-West Highway
Silver Spring MD 20910
United States
Email: craig.mclean@noaa.gov

Chris MOSES
National Oceanic & Atmospheric Administration, Silver Spring
Silver Spring Metro Center
Bldg 3, Rm 11458
1315 East-West Highway
Silver Spring MD 20910
United States
Email: christopher.moses@noaa.gov

Dr Wahyu PANDOE
Program Director
Badan Pengkajian dan Penerapan Teknologi, Agency for the Assessment & Application of Technology
BPPT 1st Bld, 18th floor, JLN. MH Thamrin 8
Jakarta 10340
Indonesia
Tel: +62-21-3168810
Fax: +62-21-3108149
Email: wahyu.pandoe@bppt.go.id

Helmut PORTMANN
Director, National Data Buoy Center
NOAA National Data Buoy Center
1007 Balch Blvd.
Stennis Space Center
MS 39529
United States
Tel: + 1 228-688-2805
Fax: + 1 228-688-1364
Email: helmut.portmann@noaa.gov

Jongyoung RU
Ministry of Oceans and Fisheries
Korea Republic
Email: ryujy862@gmail.com

Makishi SHINAGAWA
Japan Agency for Marine-Earth Science and Technology, Yokosuka
2-15 Natsushima
Yokosuka
237-0061
Kanagawa
Japan
Email: shinagawam@jamstec.go.jp

Kelly STROKER
Technical Coordinator, DBCP & OceanSITEs
JCOMM in situ Observing Platform Support Centre, JCOMMOPS
8-10 rue Hermès
Parc Technologique du Canal
31520 Ramonville St Agne
France
Tel: +33 5 61 39 47 82
Fax: +33 5 61 75 10 14
Email: kstroker@jcommops.org

Luis VASQUEZ
Instituto del Mar del Peru
Esq Gamarra y Gral Valle S/N
CALLAO
LIMA
PO Box 22
Peru
Email: lvasquez@imarpe.gob.pe

Dr Xiao XIANJUN
Research Scientist
Chinese Meteorological Administration, Beijing Climate Center
China
Email: xiaoxj@cma.gov.cn

Dr Yih YANG
Taiwan Ocean Research Institute (TORI)
No.219, Sec.1, Dongfang Rd., Qieding Dist
852 Kaohsiung City
TAIWAN
China
Email: yy@narlabs.org.tw

Appendix 4. TPOS 2020 Project Terms of Reference

The TPOS 2020 Workshop and Review has recommended the creation of a TPOS 2020 Project to achieve the major change from a loosely coordinated set of ocean observing activities in the tropical Pacific to a systematic, sustained TPOS by 2020.

The Project will:

- Achieve a significant change for sustained observing and leave a legacy for GOOS of a robust, efficient and effective contribution in the tropical Pacific.
- Focus on the tropical Pacific Ocean but embrace partnerships with the meteorological and adjacent coastal/regional ocean communities, as appropriate.
- Embrace contributions from multiple agencies and countries through a coordinated portfolio of resources and high-level oversight of the scientific and technical design, sub-projects and interfaces to the user community.
- Operate within the context of the Framework for Ocean Observation and build on existing activities while at the same leading needed change.

The TPOS 2020 Project will be autonomous and self-supporting but will coordinate with relevant existing intergovernmental bodies through the GOOS Steering Committee.

The overarching goals of the Project are:

- To refine and adjust the TPOS to monitor, observe and predict the state of ENSO and advance scientific understanding of its causes.

- To determine the most efficient and effective method for sustained observations to support prediction systems for ocean, weather and climate services of high societal and economic utility, including underpinning research.

- To advance and refine the knowledge of the predictability horizon of the tropical Pacific variability (physical and biogeochemical), as well as its impacts in global climate.

- To determine how interannual to multidecadal variability and human activities impact the relation between marine biogeochemistry and biology to carbon budgets, food security and biodiversity.

A resources panel/forum broadly representative of the sponsors of TPOS 2020 will be responsible for coordinating the variety of resources needed for the Project to succeed and support a TPOS 2020 Project.

TPOS 2020 Steering Committee Terms of Reference

The Steering Committee will:

- Provide scientific and technical oversight for the planning, system design, and implementation of the TPOS.
- Assess the evolving set of requirements through dialogue with relevant users and stakeholders.

- Coordinate a set of (pilot) projects designed to test and evaluate options, which initially may include:
    - Studies of potential broad-scale sampling strategies.
    - Investigation of potential sustained requirements for air-sea interaction and circulations and interactions in the upper ocean.
    - Studies of potential approaches in the tropical Pacific boundary current regions and the equatorial wave guide.
- Assess potential technology options for delivering a more effective and efficient TPOS; Coordinate with other relevant scientific/expert panels and bodies, including those responsible for GOOS information systems and services.
- Together with the Resources Forum, manage communication and reporting.

The TPOS 2020 Project will report to the GOOS SC.

It will meet at least once per year but may meet more frequently if required.

The membership of the Steering Committee shall not exceed 10 (or 12) and should include expertise broadly representative of the scientific and technical elements of the observing system, as well as expertise in the use and application of TPOS products.

TPOS 2020 Resource Forum (TRF) Terms of Reference

The TPOS Resources Forum will:

1. Facilitate and coordinate the provision of resources by member institutions required to advance TPOS 2020 activities based on recommendations from, and in consultation with, the TPOS Steering Committee (TSC, figure 1).

2. Promote and encourage contributions from institutions in non-participating countries and expand membership of the TRF as necessary.

3. Facilitate and coordinate resources that may be applied to the system, including ship time for developing and maintaining the TPOS, necessary research, and deployment of TPOS observing platforms.

4. Explore the potential for international resources from Official Development Assistance (ODA) agencies to develop and sustain the TPOS.

5. Explore bilateral and multi-lateral partnerships (e.g., PANGEA Framework resource sharing) as a means to complement national resources.

6. Coordinate with the CLIVAR Pacific Panel, Indian Ocean Observing System (IndOOS) Resources Forum (IRF), Pacific Islands GOOS, DBCP TAO Implementation Panel (TIP), PIRATA Resources Board and other relevant resourcing bodies.

The TRF will meet initially to monitor and consider the rationale of the TPOS 2020 (January 27-30, 2014) Workshop Report and Recommendations; consider support of recommended activities from the TPOS Steering Committee; come to consensus on its Terms of Reference; decide how the TRF conducts its business; and assess current interests and contributions to TPOS 2020.

It is expected that TPOS 2020 resources will support a range of relevant research activities that address the goals of TPOS 2020, including support for existing observing systems; development and testing of new observing technologies; evaluation of new observing strategies for relevant research and forecasting; and other topics.

The outcome of the TRF will be to deliver a sustainable system beyond 2020 for satisfying the Scientific Requirements identified by the TPOS 2020 Steering Committee (TSC) and Task Teams (TT), as well as the Operational Requirements of Member National Meteorological and Hydrological Services (NMHS).

Membership of the TPOS 2020 Resources Forum (TRF)

TRF members will be high-level representatives of Institutions in their respective countries that have a stake in the development of TPOS 2020 and have authority to deploy resources. Members will report at the TRF annual meetings on the actions taken by their Nation/Institution during the past year to advance the implementation of TPOS 2020.

The TPOS 2020 Steering Committee will identify one of its Members to serve as Convenor for the annual TRF Meetings. The Convenor will assemble and consolidate recommendations for the TRF to consider, assess the status of Semi-Annual Implementation Report Cards, and communicate with TRF members and the TPOS Project Office (TPO, as described in the TPOS 2020 Workshop Recommendations) out-of-session to facilitate with the coordination of resources. The Convenor will also prepare an annual report to the TPOS Executive Board on the TRF's recommendations and decisions. Administrative support for TRF activities (e.g., logistics and arrangements for meetings) will be provided by the TPO.

The TRF will elect from its members a Chair who will serve in that capacity for two sessions. An individual shall serve no more than two consecutive terms as Chair. The Chair will work with the Convenor and TPO to prepare the agenda for annual meetings and will lead the meetings toward decisions and actions to support TPOS 2020 during the following year.

Proposed Resource Forum Participants:

1. Integrated Marine Observing System (IMOS), Australia
2. Comité Oceanográfico Nacional/ Servicio Hidrográfico y Oceanográfico de la Armada, Chile (TBC)
3. Second Institute of Oceanography (SIO), China
4. Institut de Recherche pour le Développement (IRD), France
5. Meteorological, Climatological and Geophysical Agency (BMKG)/ Agency for the Assessment and Application of Technology (BPPT), Indonesia
6. Japan Marine-Earth Science and Technology Center (JAMSTEC)
7. Korea Institute for Ocean Science and Technology (KIOST)
8. Peru Instituto del Mar (IMARPE)
9. Taiwan Ocean Research Institute (TORI)

10. UNESCO Intergovernmental Oceanographic Commission (IOC) TBC
11. National Oceanic and Atmospheric Administration (NOAA), USA
12. WCRP/IOC/GOOS Ocean Observations Panel for Climate (OOPC)

Appendix 5. Proposed TPOS 2020 Project Task Team Descriptions

1. Task Team on evaluating and improving the Broadscale Observing System

The tropical Pacific ocean circulation and density field has structure and variability on many space and time scales. “Broadscale” sampling has as its goal to observe and quantify the processes that control the monthly mean and longer time scale structure and variability. Its outcome includes the provision of information to efficiently constrain ocean state estimates of seasonal-to-interannual/decadal forecasting systems. Different spatial resolution is needed in different regions, as determined by the local gradients of the density, current, and biogeochemical variable fields. Temporal resolution needs also depend upon the region and variable of interest; in and near the equatorial waveguide, much higher time resolution of temperature, salinity, carbon system variables and currents are needed than in many extra-equatorial areas. For some variables and in some regions, the spatial scales that we wish to observe are well known; in others, it will be necessary to plan for an evolving sampling strategy as new information is gained.

The initial “ENSO observing system” in the tropical Pacific depended upon a combination of repeat XBT tracks (some with ship-borne ADCPs), surface drifters, island tide gauges, the sparse TAO mooring array and some repeat hydrography; satellite oceanography was in its infancy at the beginning of this system. Considerable technological progress has been made since then. Satellite ocean observing is now an established technology: the Argo profiling float array is a proven source of temperature, salinity, and float displacement observations, and air-sea carbon flux observations are proven. New autonomous technologies such as gliders and wavegliders have been developed and also need to be considered in the future TPOS 2020 observing strategy. The GCOS Climate Monitoring Principles for the evolution of observing system elements comprise an important set of guidelines for the transition from the present into the TPOS 2020.

The major objective of this Task Team is to identify needs of the broadscale observations in the tropical Pacific and to recommend a feasible configuration of the broadscale observing suite.

Some specific questions that must be addressed are:

- What will be the data ‘synthesis’ strategy for integrating the full multivariate suite of observations into a coherent view of the region?
- What are the unique capabilities of the ‘legacy’ ENSO observing system elements, and what are the enhancements that have been made over the past decade that should be continued in TPOS 2020?
- What enhancements/modifications to the legacy observing element efforts should be sought?
- What enhancements to the existing Argo profiling float array are needed?
- What should be the initial broadscale strategy for carbon system observations? For other biogeochemical observations? For fisheries observations?

These questions should be addressed while considering how feasible new observation platforms and sensors are for the broadscale sampling and what mitigation efforts/options are needed to ensure robustness of the observing system.

The broadscale strategy must be developed jointly with the strategies of the other Task Teams to ensure that the TPOS 2020 will be as fully integrated as possible and will make best use of both observing system platforms and deployment assets as feasible.

This Task Team should have connections to:

- Argo Steering Team
- CLIVAR Pacific Panel
- GODAE OceanView Task Teams for Observing System Evaluation (OSEval) and Marine Ecosystems Analysis and Prediction (MEAP)
- International Ocean Carbon Coordination Project (IOCCP)
- OOPC
- JCOMM Observations Coordination Group

2. Task Team on air-sea interaction: diurnal variability, air-sea fluxes, and near-surface dynamics.

Background

Improved monitoring, understanding, parameterization, modelling and initialization of air-sea interaction has been identified as a key application area for TPOS 2020. Progress in simulating and initializing air-sea interaction is expected in the coming years in view of the imminent use of fully coupled ocean-atmosphere-wave models for seamless forecasts (from days to decades), and the ongoing development of coupled data assimilation for earth-system reanalyses and forecast initialization. The observing capabilities of TPOS 2020 should evolve accordingly. Many essential state variables are now derived from a combination of satellite and in situ data. Thus supporting the observational needs of these synthesis activities is essential (e.g., GHRSST for SST). Thus satellite calibration/algorithm development and validation requirements along with product synthesis pathways need to be imbedded in the new TPOS 2020 design.

In addition, improved understanding is leading to new requirements. For instance the importance of the diurnal cycle (amplitude, phase) in modulating air-sea exchange is now apparent. However, observations of the rectification of the diurnal cycle via its impact on the ocean mixing and atmospheric convection, while limited, are now recognised to be needed over a larger set of spatial and seasonal regimes. The parameterization of fluxes (and boundary layer processes) under different regimes (stable/unstable boundary layer, sea wave state dependency, etc.) also need dedicated observations.

The observational needs regarding improved monitoring and modelling of air-sea interaction are likely to have two components: sustained detailed observations and process studies. It is the role of this Task Team to identify which requirements are best met via a sustained observing effort (> 5 years), and which can be addressed with specific short-term process campaigns.

The TPOS 2020 whitepapers have indentified some requirements and identified questions for discussion. For instance, in a future TPOS, should all buoys have velocity, salinity, temperature and meteorological state variables measured hourly? Higher vertical resolution is needed in the upper ocean – what are the exact needs? How many sites for direct measurements of flux, eddy correlation, are needed? Is tying these specialised measurements to sites permanently the right strategy, or should they be moved around to cover different regimes?

The capabilities of present and near-horizon technologies should be taking into account when designing future configurations. The design of broadscale subsurface observing is being considered by another Task Team, as are the needs around the circulation in the western, eastern, and equatorial boundary layers.

Terms of Reference

Starting with guidance from the TPOS whitepapers and other available reports, and taking into account both existing and near horizon capabilities:

- Formulate a practical observing strategy and technical sampling requirement to ensure comprehensive air-sea fluxes can be estimated at hourly or better resolution across a set of key ocean and climate regimes in the tropical Pacific, covering the full suite of state variables to estimate heat, moisture, and momentum exchanges using bulk formula.

- Specify requirements that allow the resolution of diurnal processes in the ocean mixed layer across these sites.

- Identify a subset of regimes where direct eddy-correlation approaches are needed to improve bulk flux algorithms in both the atmospheric and ocean boundary layers.

- Liaise with existing and developing ocean satellite science teams on efficiently meeting their present and future requirements for improved state variable and flux algorithms, calibration, and validation needs, including for sea level, sea state, surface temperature, surface salinity, currents, mass, vector wind speed, wind stress, etc.

- Engage biogeochemical and ecosystem experts to ensure the needs of key gas exchange calculations are met.

- Liaise with the TPOS Task Teams on broadscale and boundary observing to maximize logistical and scientific synergies.

- Carry out a risk analysis of the proposed approach (e.g., dependency on a single satellite mission or communications systems or ship time) and suggest possible mitigation strategies (e.g., some redundancy).

3. Task Team for eastern, western and equatorial boundary regions (BRTT)

The western and eastern boundary regions of the tropical Pacific Ocean are the primary conduits of tropical-subtropical interaction, and the leaky western boundary also facilitates exchange between the Pacific and Indian Oceans through the complex Indonesian archipelago (Maritime Continent). These regions thus play crucial roles in ocean dynamics and climate variability on both regional and global scales, and need to be adequately covered by the TPOS. The general objectives of the BRTT are:

- To advocate for sustained monitoring of the boundary regions as an integral part of the TPOS, in support of regional and global climate prediction, as well as process studies that lead to improved understanding and forecasting.
- To identify key variables of the boundary observation system that are required for climate, ecosystem, risk management, and fishery applications, making synergistic use of in-situ and high-resolution satellite measurements.
- To establish the observational sites of the highest priority, decide on the variables to be observed in terms of priority and readiness of technology, and determine the time and space scales that must be resolved.
- To foster interaction and collaboration between the TPOS and other international programs that have an observational focus on the tropical Pacific boundary regions, such as NPOCE, SPICE and CLIVAR ITF TT.
- To explore potential opportunities to collaborate with regional institutions for the implementation and maintenance of TPOS and its national components, and to evolve process-oriented boundary measurements towards a sustained system.

4. Task Team for modelling and assimilation

Background

The Workshop identified inadequacies in model and data assimilation as major limiting factors for effective use of TPOS observations and the accuracy of related products, including both the analysis of the ocean state and the predictive skill of coupled model forecasts. Inadequacies could be model errors of atmospheric or oceanographic origin that interact with and have impacts across the entire system, or could be related to data assimilation methodologies. Experience with atmospheric reanalyses and weather forecast systems clearly indicates that greater information can be extracted from observations as the models and assimilation systems improve. This appears to be also the case for coupled sub-seasonal to longer-range dynamical model forecasts, including ENSO forecasts. Further, just as multi-model forecasts for sub-seasonal and seasonal time scales have led to greater forecast reliability, so too multi-model analyses will lead to greater reliability and quantification of analysis errors. In summary, the “route to impact” for the TPOS is inextricably linked to efficacy of modelling and assimilation systems.

In recent years there have been a number of internationally coordinated efforts on evaluation of model and ocean analyses and reanalyses, including through intercomparisons, as well as observing system experiments (OSEs) using a variety of systems. Given the remarks above about the criticality of such efforts for achieving scientific and societal impact, the TPOS needs to embed such activities in the overall design and evolution of the system. The results from these efforts will assist in the identification of model errors, areas of large uncertainty where model/reanalyses diverge, and observational needs for relevant parameterizations. In addition, further coordinated observing system experiments may be needed to assist the design of future observing system, beyond TPOS 2020. Such activities should involve (ocean and coupled) model and forecast system developers and TPOS observationalists.

TPOS observational requirements should go hand in hand with the evolution of the forecasting systems. As model resolution increases, the observational needs for forecast initialization, parameterization and verification changes. For TPOS 2020, the typical ocean resolution would range from about 1° x ½° for climate applications (likely finer by 2020) to 1/12 of degree (or higher) for global medium-range ocean forecasting. The vertical resolution of the upper ocean is already about 1 m but is limited around the depth of the thermocline. Choices need to be made between model resolution and complexity of the assimilation system. The increased model resolution and complexity of the forecasting system (coupled ocean-atmosphere-wave models for the medium range) has also implications on the requirements for initialization.

Terms of Reference

- To develop strategies for coordinated modelling and assimilation activities for designing and planning the future TPOS observing systems, such as those proposed by the other task teams.
- To contribute modelling and data assimilation insights into the identification of observational requirements.
- To provide guidance on the assessment of the influence of modelling and assimilation, including through systematic continuous evaluation (metrics and process-oriented diagnostics), OSEs, and OSSEs, of the TPOS and its design, especially using the multi-model approach.
- As appropriate, recommend strategies for initialization for the efficient use of TPOS information.

http://www.ioc-goos-oopc.org