TPOS2020: An integrated observing system for 2020 and beyond
(Response to NRC Decadal Survey in Earth Science and Applications from Space)

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Introduction

We are writing on behalf of TPOS 2020 (http://tpos2020.org/), a focused project to guide development of an international coordinated and supported sustainable observing system for the Tropical Pacific Ocean for 2020 and beyond. TPOS 2020 aims to achieve a significant change in all elements that contribute to the Tropical Pacific Observing System (TPOS), aiming for greater and continued efficiency, greater effectiveness for all stakeholders, enhanced robustness and sustainability, and improved governance, coordination and supporting arrangements. The core in situ element of the current TPOS has existed in basically the same form about 20 years, with about 70 moored buoys collecting surface meteorological and ocean measurements, even as many valuable new types of observations have become available (e.g., from satellites and autonomous in situ platforms, such as floats). The goal of TPOS2020 is to optimize and integrate the observing system in the Pacific to make the best use of the measurements and limited resources. The TPOS 2020 design will emphasize integrated observing approaches, but also multi-purpose and multi-use systems. The design is being informed by multiple science communities, spanning the ocean, climate, atmospheric, and biogeochemistry communities.

Responding to this RFI is particularly relevant to our mission, because we seek to develop an integrated observing system for the tropical Pacific that meets the needs "across the spectrum of basic research, applied research, applications, and/or operations in the coming decade". Some of the choices being deliberated for the future TPOS are tightly intertwined with the parallel choices being deliberated for the future satellite earth observing system. Our intent here is to communicate the role of existing and future satellite measurements in the future TPOS.

The existing TAO (Tropical Atmosphere-Ocean) mooring array was developed to provide real-time information on winds, sea surface temperature, subsurface ocean temperature, sea level, and ocean velocity (McPhaden et al., 1998) to improve understanding of and our ability to model ENSO. When the array was designed in the 1980s, there was no other reliable way to produce large-scale, synoptic maps of winds or thermocline depth. Some of these variables are now routinely measured or inferred from satellites, and atmosphere and oceanic research and operational endeavors, such as weather and seasonal forecasting, now rely heavily on these satellite measurements.

The in situ measurements from the TAO array are now being used differently than they were when the array was designed. End users needing mapped fields of surface winds, sea surface temperature (SST), or sea surface height (SSH) often turn to satellite or assimilation products, rather than the relatively sparsely distributed mooring data. Satellite scatterometers, altimeters, and radiometers are thus now a core part of the observing system. In situ data still has important uses, typically providing superior temporal sampling, ground truth, and calibration/validation data for the satellites, and measurements of essential ocean variables that cannot be measured remotely (e.g., surface humidity, subsurface temperature, salinity, velocity, etc.). The new design is still under discussion, but there is likely to be more emphasis on having in situ sampling in different dynamical regimes (e.g., within the Intertropical Convergence Zone) and on more detailed measurements of relatively small-scale physical processes (like surface boundary layers and the equatorial upwelling zone in the eastern Pacific), and less emphasis on having a grid of moorings that can be used to map the surface wind field. The design of the future TPOS is likely to shift toward doing a better job of fulfilling these new and emerging needs while relying more heavily on the continued existence of satellite scatterometer, altimeter, and radiometer data for monitoring the large-scale variability.

We are still far from understanding the phenomena we are trying to predict (such as ENSO), with models encountering systematic errors sometimes as large as the signals they are trying to model. Climate models need to be greatly improved to capture ENSO variability, a phenomenon with huge societal and economic impacts. There is a pressing need for observations (in situ and satellite) that will help improve understanding and lead to better parameterizations and models of key processes. TPOS 2020 will base its design on an integrated observing system with in situ measurements supporting satellites and vice versa; and ocean, atmosphere and climate models supporting both. TPOS 2020 will seek strength, robustness, sustainability and dependability through a design that has a measure of redundancy in all elements of the observing system. Diversity in observing approaches mitigates the possibility of systematic instrument or measuring error harming climate records and forecasts. In situ and satellite systems working together in the field and in operations is a fundamental design element. An integrated system (models, satellites and in situ) is likely to be able to deliver more relevant data and products for society; each on their own can only deliver part of the solution.

So, a first point we wish to emphasize is that ***maintaining and improving the space-time sampling of vector winds, SSH, SSS and SST is a key challenge for Earth System Science across the spectrum of basic research, applied research, applications, and/or operations in the coming decades.*** Basic and applied research, applications, and operations depend on measurements from satellite scatterometers, altimeters, and radiometers (e.g., for ENSO research and forecasting). New capabilities for satellite measurement of other ocean and atmospheric boundary layer properties, such as ocean currents, near-surface humidity, the carbon cycle, and biogeochemistry would also be of great value.

Need for improved satellite wind measurements

Satellite scatterometers have proven valuable for improving understanding of ocean dynamics and for operational applications. The oceanic response to wind forcing is sensitive to the curl of the wind stress, which varies on relatively small spatial scales (e.g., Kessler, 2002), and operational forecast centers rely on wind speed and direction from scatterometers for marine forecasts and warnings (e.g., Atlas et al., 2001; Isaksen and Janssen, 2004; von Ahn et al., 2006; Chelton et al., 2006; Brennan et al., 2009). The western tropical Pacific has exhibited some of the world's largest rates of sea level change since the modern satellite altimetry record began in 1993, and these changes are believed to be largely attributable to low-frequency changes in the wind field associated with the Pacific Decadal Oscillation/Interdecadal Pacific Oscillation (Palanisamy et al., 2015). Understanding the interannual to decadal timescale changes in the tropical Pacific and the world oceans, and separating effects of internal climate-system variability and anthropogenic influences, will require improved wind measurements that can reduce biases due to systematic measurement and sampling errors.

Biases in winds, even if small, can have profound effects on seasonal prediction systems where often the winds are assumed to be without error. The resulting subsurface imbalances impact both short- and long-term predictions. Biases in the winds have an equally profound effect on our understanding of the dynamics of low-frequency variability in the tropical oceans.

An advantage of satellite wind measurements is the high spatial resolution over most of the ice-free global ocean and the relatively continuous operation of satellites. The relatively more uniform and dense spatial sampling of satellite wind observations compared with in situ observations allows estimation of the divergence and wind stress curl fields, both of which are dynamically important for ocean and atmospheric circulation. Buoy wind measurements, in contrast, are sparsely distributed and prone to prolonged data outages. Among the advantages of buoy wind measurements are the ability to sample at a much higher temporal resolution, to obtain other meteorological and oceanographic measurements (particularly subsurface ocean measurements), and the ability to measure winds more accurately, particularly in rain. Buoys also help improve satellite observations by providing independent measurements critical to the calibration and validation of many satellite measurements (e.g., Freilich and Dunbar 1999). While temporal sampling is generally good for buoy wind observations, the geographically sparse distribution of moorings is too coarse to study many air-sea interaction and ocean dynamics problems.

Satellite scatterometers measure the microwave backscatter cross-section, which is then converted to an estimate of the winds 10-m above the sea surface using a geophysical model function (GMF). Scatterometer winds suffer from several systematic problems, including measurement or geophysical model function errors in rain, high winds, and low winds. In addition, scatterometer satellites tend to be placed in sun-synchronous orbits to reduce sun-glint errors, which leads to sampling errors from inadequate sampling of relatively substantial and ubiquitous diurnal (daily-period) and semi-diurnal (half-day-period) wind variability. All of these error sources are especially prominent in the tropical Pacific.

Winds estimated in raining conditions from scatterometers suffer from systematic measurement biases and random errors from the effect of rain on atmospheric transmissivity and surface roughness (e.g., Portabella and Stoffelen 2001; Stiles and Yueh 2002; Weissman et al., 2002; Weissman et al. 2012). This rain contamination of the scatterometer radar backscatter is more apparent for Ku-band scatterometers such as QuikSCAT, RapidScat, and OSCAT than for scatterometers operating in C-band, such as ASCAT. Progress has been made in reducing rain-induced uncertainties of Ku-band scatterometer retrieved winds through improvements in the retrieval algorithm which converts raw backscatter measurements to vector winds (Ricciardulli and Wentz, 2015) and through enhanced processing techniques (Stiles and Dunbar 2010; Fore et al. 2014). Even so, retrieved winds from Ku-band scatterometers still exhibit substantial uncertainties in raining conditions (e.g., Fore et al. 2014; O'Neill et al. 2015). Additionally, while C-band wind retrievals in rain are generally of better quality than Ku-band retrievals, rain-induced uncertainties are nonetheless elevated relative to those in rain-free conditions (e.g., Portabella et al. 2012; O'Neill et al. 2015).

The effects of rain on scatterometer measurements are especially troubling in the tropical Pacific, and are a source of wind errors on both synoptic timescales and longer timescales. To understand this, we have analyzed wind measurements from three past and present scatterometers (ASCAT-A and ASCAT-B, SeaWinds on QuikSCAT) and the WindSat polarimetric radiometer and have compared them against

wind measurements from the TAO mooring array. We examined two different versions of the QuikSCAT data, one produced by Remote Sensing Systems (RSS) and one produced by JPL. (An extended version of this analysis is available here:
ftp://ftp.coas.oregonstate.edu/pub/loneill/oneill_report_final_07082014.pdf).

Buoy locations are shown in Fig. 1, with the percentage of QuikSCAT data that was rain flagged over a 10-year period shown in color. The buoy locations span the full range of rain frequencies, which provides a rigorous evaluation of the performance of the satellite wind measuring capabilities in rain.

Comparisons were made only when a buoy observation was within ±30 minutes and ±25 km of a satellite observation. In rain-free conditions, all satellite datasets perform similarly, with RMS wind speed differences between 0.96 and 1.09 m/s, mean wind speed differences between −0.04 and 0.16 m/s, and RMS direction differences between 16.6° and 19.2°. Performance in raining conditions clearly separates the four satellite datasets. Overall, compared to the buoy winds, ASCAT- A performs most favorably in rain using all wind speed and direction metrics. WindSat has slightly worse agreement with the buoys than the other three satellites. The RSS QuikSCAT performs worst in the metrics of RMS and mean wind speed differences, although it performs among the best in rain-free conditions. There is a marked difference between the JPL and RSS QuikSCAT datasets, which shows the large improvement of wind measurements in rain in the JPL dataset. However, there is still a significant wind speed bias in rain in the JPL QuikSCAT dataset. Fore et al. (2014) has shown that this bias has a dependence on rain rate, particularly for rain rates between about 2 and 10 mm/hr.

The accuracy of scatterometer winds in rain can have a surprisingly large impact on measured wind variance on time scales less than 5 days. There is a significant discrepancy between satellite and buoy estimates of temporal wind variability on time scales less than 5 days due to accuracy and sampling limitations of the satellite measurements, particularly associated with rain accompanying ephemeral tropical convection. On timescales greater than 5 days, the ASCAT-A and RSS and JPL QuikSCAT datasets provide better estimates of the lower frequency wind variability compared to the buoys, although the possibility exists that there could be small but important biases in rainy regions associated with systematic covariability of rain and wind in precipitating systems.

Fig. 1 provides a succinct illustration of the potential for systematic wind errors associated with rainfall: over vast regions of the tropical Pacific, about 25% of the QuikSCAT measurements are flagged as being potentially invalid due to rain. If these measurements are excluded, we risk substantial sampling biases resulting from covariability of rain and wind in tropical deep-convection systems. If the measurements are used with retrieval algorithms attempting to deal with the rain effects, we risk including systematic measurement errors (biases) from covariability of rain intensity and wind speed errors (Fore et al., 2014).

Innovative solutions for wind measurements in the presence of rain fall, such as from a dual-band scatterometer, could reduce the measurement errors in rain and the exclusion of rainy conditions. ***Continuation of the climate record of ocean vector winds, and improved capabilities for measurement of winds, is a key challenge that must be met to allow continued progress in understanding and prediction of seasonal to interannual variability in the climate system.***

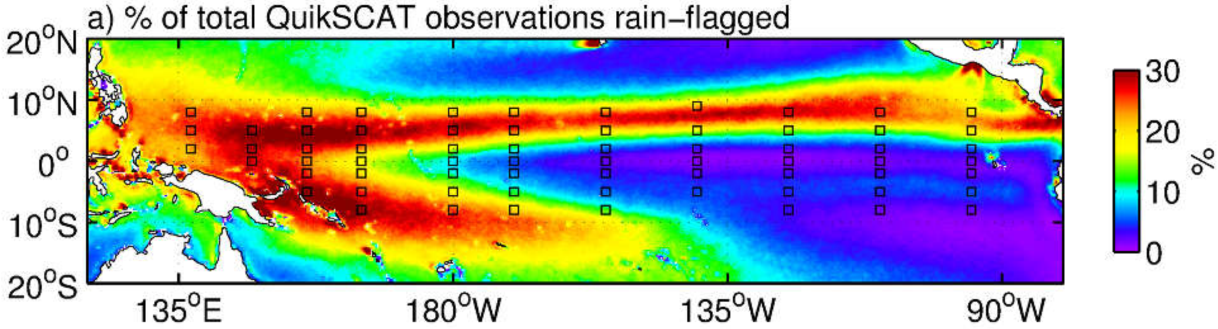

Figure 1: Map of the QuikSCAT rain-flag frequency over the 10-year period August 1999- July 2009. Over much of the tropical Pacific, about 25% of the QuikSCAT measurements are flagged as being potentially invalid due to rain, which can contribute to problematic wind biases.

On societal benefits and linking space-based observations with other observations to increase the value of data for addressing key scientific questions and societal needs

Improving understanding, monitoring and prediction of ocean, atmosphere and climate variability on scales from those of weather prediction to those of climate and climate change is of clear value to society. Improved predictions of hurricane activity on monthly scales, and weather variability (including fresh water availability and fisheries impacts), and the observations needed to test and improve climate modeling of ENSO, the largest and most influential interannual signal in the Earth system. Scientific understanding of interannual variability, including ENSO, does not yet allow efficient and effective predictions. There is some evidence that progress has slowed in recent decades, not accelerated as one might have expected. In part, this is because of the complexity of the issues being tackled, but this simply means we must deliver more sophisticated, integrated observational approaches that will unlock the mystery of processes that are currently holding back progress. TPOS 2020 is designing for 2020 and beyond, and this means anticipating where observations will add maximum value. As one example, remote measurements of salinity or perhaps ocean currents hold great potential for improving understanding of the ocean boundary layer.

TPOS 2020 is basing its design on an integrated observing system with in situ measurements supporting satellite measurements and vice versa; and ocean, atmosphere and climate models supporting both, including through extending the reach into gaps in space and extrapolating information in time. TPOS 2020 will seek strength, robustness, sustainability and dependability through a design that has a measure of redundancy in all elements of the observing system. Diversity in observing approaches mitigates the possibility of systematic instrument or measuring error harming climate records and/or leading to poor analyses and forecasts. In situ and satellite systems working together in the field and in operations is a fundamental design element. An integrated system (models, satellites and in situ) is likely to be able to deliver more relevant data and products for society; each on their own can only deliver part of the solution.

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