White Paper #3 – ENSO Research: The overarching science drivers and requirements for observations

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1. Introduction and history

ENSO is the largest interannual climate signal, with its coupled ocean-atmosphere core in the equatorial Pacific but producing global effects through atmospheric teleconnections. The unpredicted El Niño event of 1982-83 focused attention on this phenomenon and was the impetus for the original development of the tropical Pacific observing system (TPOS) and TAO array in the mid-1980s, under the Tropical Ocean/Global Atmosphere (TOGA) programmeme. ENSO has played two roles in stimulating the observational network and its modeling counterpart: it is a forecast problem with obvious practical benefits, and it is a laboratory for the study of tropical air-sea interaction, which informs the study of other phenomena in other ocean basins.

Before the 1960s, no mechanism had been proposed to connect the well-known SST anomalies known as El Niño on the Peruvian coast with winds and precipitation elsewhere in the basin. Bjerknes (1966) described the fundamental coupled interaction between surface winds and SST gradient, but the mechanism of eastern warming continued to be assumed local until Wyrtki (1975) showed that this signal must be remotely forced by wind anomalies in the west, and thus that ENSO was a basin-scale phenomenon. During the 1980s, models and theory (e.g., Anderson and McCreary, 1984) showed the essential role of equatorial Kelvin and Rossby waves in transmitting the signal across the Pacific, and an explosion of work in the late 1980s explained and fleshed out "delayed oscillator" ideas which established ENSO as a coupled oscillation with a distinct and explainable evolution (Zebiak and Cane, 1987; Battisti and Hirst, 1989; Schopf and Burgman, 2006; and Suarez and Schopf, 1988), although its genesis was (and remains) controversial.

At that time, observation of the subsurface ocean in the tropical Pacific was done primarily by XBTs deployed from merchant ships, producing at best monthly samples on a few meridional lines barely sufficient to detect the relatively slow Rossby waves (Kessler, 1990). Island sea level gauges added higher temporal resolution in a few places (Wyrtki, 1975 and 1981), but the absence of near-equatorial islands in the more than 7000km between the Line Islands (160°W) and the Galapagos (95°W) made it impossible to observe the Kelvin waves. Nevertheless, recognition of the role of these linear wind-driven waves gave some skill in using simple wave models and early GCMs to predict the evolution of El Niño events over a lead time of a few months (Zebiak and Cane, 1987). These models showed the strong role of ocean memory – mediated by equatorial wave propagation – in guiding the evolving climate of the tropics (Neelin, 1998). The early GCMs, however, proved unable to maintain a realistic mean background state or annual cycle, in either the ocean or atmosphere. The intense feedbacks of the tropical climate meant that small errors in modeling either fluid could quickly "run away" and required assimilated observations to control the background properties. The ad hoc parameterizations of processes that mixed and distributed surface fluxes into the interior ocean continued to require subsurface ocean observations to correct. The sense in the community that great progress was at hand if these needs could be met drove the unprecedented development of the TAO array in the late 1980s (Hayes et al., 1991; McPhaden et al., 1998 and 2010). The success of TAO in turn was a proof of concept for the creation of other basin-scale, multinational arrays (e.g., Argo).

ENSO has continued to propel much of the observational, modeling and theoretical progress of the past 30 years, but despite three decades of focused attention of the climate community, ENSO forecasting skill remains stubbornly slow to improve after the initial advances. In fact, while forecast skill for the full set of retrospective ENSO events has increased slightly, forecast skill for recent events has been lower than for the events prior to the turn of the century (Barnston et al., 2012). Coupled GCMs with far better resolution and more developed physical parameterizations than those of the 1980s have seen improvements in ENSO simulations (Wittenberg et al., 2006; Delworth et al. 2012), but have produced only modest progress in forecast skill (Davey et al., 2002; Turner et al., 2005). Strong hints of decadal or longer modulation of ENSO characteristics complicate the prediction problem, as have the emergence of what might be other "modes" of ENSO. These may be related to changes in the background state that alter the relation between upper ocean heat content and SST (McPhaden, 2012), or they may simply emerge at random from the stochastically-forced and/or chaotic ENSO system (Wittenberg, 2009; Newman et al., 2011ab; Stevenson et al., 2012; Wittenberg et al., 2014).

The overwhelming lesson of the past three decades of ENSO observation is its diversity, the ongoing succession of surprises in the expression of these events. The potential for future surprises in ENSO behavior is high. It appears that the relatively easy issues of wave-carried ocean memory are largely solved, but further advancement will entail diagnosing and explaining the mechanisms of air-sea heat and momentum exchange, in both fluids, which is unlikely to be accomplished by model experiments alone. This situation demands continued attention by the sustained observing system to the physical processes involved in tropical ocean-atmosphere interaction. As we look to the next decade and beyond, we can't predict the next surprises but we can expect that surprises will occur, and we must build a robust observing system that will be ready to detect and diagnose them. We take the point of view that the best way to prepare for new surprises is to observe the underlying physical processes, and thereby to teach models to represent these processes.

2. Unsolved problems of ENSO

2.1 The annual cycle

Winds, SST and zonal currents propagate west along the equator during the annual cycle, while thermocline depth propagates east (Yu and McPhaden, 1999). These facts have been interpreted from several points of view. Xie (1994) proposed a feedback based on wind speed and the resulting evaporative cooling, in which the ITCZ being north of the equator and resulting persistent southerlies are key (also see Mitchell and Wallace, 1992). Yu and McPhaden (1999), on the other hand, highlighted the role of oceanic Kelvin and Rossby waves. The pronounced one cycle per year variability in both ocean and atmosphere, despite the fact that the sun crosses the equator twice a year, indicates the important role of coupled processes, and it remains a non-trivial exercise for coupled models to reproduce the annual cycle. Many of the CMIP5 models either produce an annual cycle that is too strong, or exhibit a spurious semi-annual cycle. The latter may be linked to the double ITCZ still common in these models, which leads to a background state that is more symmetric about the equator than the very asymmetric observed state. Although some improvement to model simulations of the ITCZ can be achieved through increased resolution in the atmosphere and ocean, deficiencies in the ITCZ are seen even at the highest resolutions that can plausibly be used for multi-decadal integrations (Delworth et al., 2012), indicating that improved understanding and parameterizations are needed to improve ITCZ simulation for these long integrations.

Since ENSO appears largely phase-locked to the annual cycle, it is difficult to define, and impossible to prescribe, a "non-ENSO" climatology based on only a few decades of data. The observed phase locking of ENSO, and mechanisms that have been proposed to understand it, indicate a fundamental coupling between the annual cycle of insolation and the evolution of ENSO (Tziperman et al., 1994; Jin et al., 1994; Harrison and Vecchi, 1999; An and Wang, 2001; Spencer, 2004; Lengaigne et al., 2006; Vecchi, 2006; Lengaigne and Vecchi, 2009) – so improvements in the simulation of the mechanisms behind the mean-state and annual cycle are likely to yield improvements in the simulation and prediction of ENSO.

2.2 Low-frequency modulation

Although the basic mechanism of ENSO is contained in the tropical Pacific, there are strong suggestions that epochal changes of ENSO characteristics and predictability can be due to influences from outside, either internal or external to the ocean–atmosphere coupled system. To illustrate the range of possibilities, Trenberth and Hoar (1997) analyzed the abnormal warming during the 1990s and attributed it to anthropogenic global warming, while Gu and Philander (1997) suggested that these decadal changes are part of a natural variability of the mean thermocline in the tropical Pacific Ocean, resulting from a coupled tropical–extratropical interaction. Kirtman and Schopf (1998) also considered the decadal variability as natural, with its magnitude amplified by uncoupled atmospheric "noise". The epochal changes of ENSO have also been related to external factors such as volcanic emissions and solar variability (Mann et al., 2005). Long integrations of coupled GCMs, without any changes in external forcings, can generate multi-decadal epochs of extreme ENSO behavior (Wittenberg, 2009; Stevenson et al., 2012), which may not be predictable (Wittenberg et al., 2014). ENSO modulation, in turn, can affect the decadal-mean state of the tropical Pacific, by blurring and/or stirring the horizontal and vertical thermal gradients in the ocean (Schopf and Burgman, 2006; Ogata et al., 2013). The impact of decadal modulation of ENSO on the mean state of the Pacific combined with changes in observing systems, can affect our ability to detect and attribute changes to the mean-state of the tropical Pacific, reducing confidence in tests of hypotheses about the influence of radiative forcing on the state of the tropics (e.g., Vecchi et al., 2006, DiNezio et al., 2009, Karanauskas et al., 2009, Seager and Naik, 2012). The predictability of ENSO is modulated as well (Kirtman and Schopf, 1998; Karamperidou et al., 2014; Wittenberg et al., 2014).

One recent issue that has received considerable attention is the ‘pause’ or ‘hiatus’ in global mean surface temperature changes. Several theories have been put forward to explain the hiatus including variations in natural forcing agents (volcanoes, solar), additional heat uptake or redistribution in the ocean (Trenberth and Fasullo, 2012), and atmospheric teleconnections associated with on-going La Niña/negative PDO conditions in the Pacific (Kosaka and Xie, 2013). The accuracy, within which we need to be able to measure changes in ocean heat uptake, in order to explain the pause, challenges the current observing system.

Given the intrinsic modulation of ENSO, long, continuous climate records are needed to characterize ENSO and its sensitivity to external forcings. Observing systems have evolved significantly over the past 150 years, confounding the detection of secular changes in the background state and ENSO (Wittenberg, 2004; DiNezio et al., 2010). Paleo proxy records have been brought to bear on reconstructing past variations in the tropical Pacific mean state and ENSO (Li et al., 2011 and 2013; Emile-Geay et al., 2012ab; McGregor et al., 2013), but these reconstructions are still in their infancy.

2.3 ENSO Diversity - CP vs EP El Niños, or weak vs strong El Niños

The observational era has seen a succession of surprising manifestations of ENSO. The 1982-83 El Niño occurred at a different phase of the seasonal cycle to the accepted consensus description of Rasmussen and Carpenter (1982), which caused experts at the time to deny that it could be an El Niño. The 1986-87 El Niño lasted much longer than had been thought possible. The reappearance of El Niño conditions in early 1993, immediately after the more typical event of 1991-92, contradicted the then-current view that El Niño and La Niña events alternated. The El Niño of 1997-98 grew faster and stronger than could have been imagined before, and the prolonged La Niña conditions that followed have not been explained. In the past decade, the emergence of “Modoki” or Central Pacific El Niños (Ashok and Yamagata, 2009; Kug et al., 2009; Yeh et al., 2009; Takahashi et al., 2011) has confounded forecasters and also remains unexplained.

Gross features of the ENSO cycle can be seen back to the late 1800s in indices such as the Southern Oscillation Index; it is clear that ENSO is subject to decadal or longer apparently-natural modulation. This is expressed in periods of preferred sign of oscillation (e.g., no El Niños in the 1930s, few La Niñas in the 1990s), different phasing with the annual cycle, and different locations of peak anomalies (the occurrence of the "Modoki" or CP El Niños of the 2000s (section 2.3) after decades of peak anomalies near the coast of South America). It is not at all clear what aspects of the background conditions produce this spectrum of behavior. Indeed, both statistical models and coupled GCMs are capable of generating multi-decadal epochs of CP or EP El Niños -- even without changes in external forcings or predictable decadal variations in background climate (Newman et al., 2011b; Wittenberg et al., 2014).

Underlying much of the debate about the diversity of ENSO is continued uncertainty as to whether ENSO is a self-sustained quasi-cyclic oscillation, with irregularity due to "weather noise" (or internal nonlinearities), or if El Niño is a damped event-like phenomenon that requires external forcing as an essential "trigger". It is likely that ENSO exists in a spectrum spanning these states, and its location in the parameter regime may depend on the background state of the Pacific (Fedorov and Philander, 2000; Wittenberg, 2002).

Early theories for ENSO highlighted the role of oceanic equatorially-trapped waves in transmitting thermocline anomalies across the Pacific basin that, when coupled with the Bjerknes atmosphere-ocean feedback, produce quasi-regular oscillations (Battisti and Hirst, 1989; Suarez and Schopf, 1988). As coupled climate and seasonal forecast models were developed, the role of inherent atmospheric variability (e.g., westerly wind bursts) in amplifying individual modes was examined (e.g., Kessler and Kleeman, 2000; Lengaigne et al., 2004; Vecchi et al., 2006a; Gebbie et al., 2007; Zavala-Garay et al., 2008).

More recently, the apparent break in ENSO characteristics following the 1997-98 El Niño, followed by prolonged La Niña conditions and then a series of El Niño events that did not fit the previously-accepted picture has spawned considerable debate about ENSO diversity. There is evidence of more frequent occurrence of warming events that are focused in the central Pacific in the past decade, in contrast to warming events focused in the eastern part of the basin in preceding decades, which had been taken as “typical”. Some authors argue for the existence of physically-distinct modes of variability, positing the existence of the so-called ‘classical’, cold-tongue, or eastern-Pacific El Niño vs. the so-called central-Pacific, warm-pool El Niño or El Niño ‘Modoki’ mode (e.g. Ashok et al., 2007; Kao and Yu, 2009; Kug et al., 2009). This view sees different feedbacks operating in different events, with the CP El Niños tending to be dominated by the zonal advective feedback and the EP events by the Bjerknes or thermocline feedbacks (section 3.4). Model studies suggest that during the El Niño decay phase, EP events decay primarily due to poleward oceanic discharge of equatorial heat content (brought about by strong off-equatorial wind curl), while CP El Niños show a greater role for local surface heat flux damping (Kug et al., 2010; Ren and Jin, 2013; Singh and Delcroix, 2013). Others see these differences merely as manifestations of a continuous spectrum of variability (Giese and Ray, 2011; Newman et al., 2011b; Capotondi and Wittenberg, 2013; Johnson, 2013), arguing that the common view of different physical types is statistically biased by the two extreme events of 1982-83 and 1997-98 (e.g., Takahashi et al., 2011).

Observations and models have shown that the mechanisms in the eastern equatorial Pacific at the end phase of extreme El Niño events can be fundamentally different from those of more moderate El Niños (Vecchi and Harrison, 2006; Vecchi, 2006; Zhang and McPhaden, 2006; Lengaigne and Vecchi, 2009). Sustained and continuous observations documented the unusual coexistence of a very shallow thermocline with extremely warm SSTs in the eastern equatorial Pacific during the height of the 1997-98 El Niño; this was followed by an abrupt termination where the eastern equatorial Pacific SSTs cooled by almost 6°C in a matter of a week or two following the return of the easterlies (McPhaden, 1999; Harrison and Vecchi, 2001; Vecchi and Harrison, 2006; Vecchi, 2006; Zhang and McPhaden, 2006). The co-location of atmospheric and oceanic observations was crucial to understanding the termination of this event, and generalizing it to extreme El Niño events (Vecchi and Harrison, 2006; Vecchi, 2006; Lengaigne and Vecchi, 2009). Based on the understanding of the mechanisms inherent to the development and termination of extreme El Niño events, there is now a robust projection for an increase in these extreme El Niño events in the decades and century to come (Cai et al., 2014).

Observations by the sustained observing system can contribute to this discussion by diagnosing and quantifying the physical processes that distinguish the feedbacks, and by accurately describing low-frequency changes of the background. Long time series are needed, since understanding the interplay between El Niño and the background state is hampered by the limited duration of the satellite observations and sparse distribution of historical in situ data.

It is also noted that the ENSO cycle in the observational record is prominently skewed, with the cold phase being typically weaker and lasting longer than the warm phase (Kessler, 2002; Hanachi et al., 2003; An and Jin, 2004; Choi et al., 2013), and the spatial patterns of El Niño and La Niña not being mirror images of each other (Hoerling et al., 1997; Burgers and Stephenson, 1999). However, this asymmetry is not consistently represented in present-generation CGCMs. This may have larger significance than just for individual events, as Rodgers et al. (2004) connected the leading EOF pattern of tropical Pacific decadal variability with the El Niño-La Niña asymmetry (Rodgers et al., 2004; Schopf and Burgman, 2006; Ogata et al., 2013).

There is also considerable uncertainty on the physical mechanisms responsible for the asymmetry between El Niño and La Niña. Suggested mechanisms include the nonlinearity in oceanic vertical temperature advection in the eastern Pacific cold tongue (Hanachi et al., 2003; An and Jin, 2004), nonlinear rectification of the Madden-Julian Oscillation (Kessler and Kleeman, 2000), nonlinearities in the dependence of tropical deep convection on the underlying SST (Hoerling et al., 1997) and in the "biological thermostat" effect of phytoplankton in the upper ocean (Timmermann and Jin, 2002), and the positive skewness of the surface zonal wind anomalies in the western tropical Pacific that directly lead to the positive skewness of SST anomalies in the eastern tropical Pacific (Monahan, 2004). The reason for the last mechanism is that the anomalous wind field in the tropical western Pacific is dominated by westerly bursts, which would send down-welling Kelvin waves to the east and warm the SST there, thus, on average, making El Niño stronger than La Niña. A systematic investigation of these processes in a unified, quantitative framework is clearly needed, and there is no substitute for building long time series of winds, upper ocean thermal structure and currents, and surface variables indicating the turbulent and radiative fluxes that will be needed to disentangle these hypotheses.

Overall, the picture is of deep uncertainty about both the diversity of individual events and about the cycle as a whole. We argue that the path forward is to gain insight into the underlying physical processes as the way to resolve these uncertainties.

2.4 Response under ACC

Model forecasts

Estimating the response of ENSO to climate change presents a considerable challenge, both due to the separation of signal from noise and because of multiple, interacting ocean and atmosphere variability at all frequencies. One approach attempts to separate changes of the long-term climate of the tropical Pacific from long-term changes in the variability (e.g., Vecchi and Wittenberg, 2010; Collins et al., 2010; Watanabe and Wittenberg, 2012; Watanabe et al., 2012; Knutson et al., 2013).

Tropical Pacific SSTs have warmed over the period in which observations or reconstructions are available, but there is still debate over whether they have warmed preferentially in the east relative to the west or vice versa (e.g., DiNezio et al., 2010; Solomon and Newman, 2012). Theory suggests that the tropical trade winds should weaken as a result of the muted response of the hydrological cycle under warming (Held and Soden, 2006; Vecchi et al., 2006), although the role of SST pattern changes may also be implicated (Xie et al., 2010; Tokinaga et al., 2012). The apparent strengthening trend in the trade winds in the last two decades does not fit these theories (L'Heureux et al., 2013; Qiu and Chen, 2013), but evaluation of observed decadal and lower-frequency climate changes is confounded by changing observing systems (Tokinaga et al., 2012ab), and signal-to-noise issues in separating the mean from the variability in both observations and in models.

Future model projections of the mean equatorial climate indicate a peak in warming on the equator with a relatively uniform east-west pattern (Liu et al., 2005; Xie et al. 2010). However, considerable inter-model spread is found, so confidence in this conclusion is low. The ensemble-mean picture also indicates weakening trades, a shoaling and strengthening of the thermocline, a weakening of near-surface currents; but whether observed trends in these fields agree with this model ensemble-mean picture is still a matter of considerable debate (Tokinaga et al., 2012ab).

Future projections of ENSO variability are also still subject to much uncertainty. The recent IPCC AR5 concludes that "… natural modulations of the variance and spatial pattern of El Niño-Southern Oscillation are so large in models that confidence in any specific projected change in its variability in the 21st century remains low." The same conclusion was drawn in the AR4. That ENSO variability might significantly increase or decrease in either magnitude or frequency remains an open question.

For mean changes in the ocean, a 4-dimensional picture of the temperature of the upper levels (e.g. the top few hundred meters) is required to assess how heat is slowly penetrating the ocean, at what rates and in what locations. For mean changes in the atmosphere, the surface wind stresses and surface turbulent and radiative fluxes are required to diagnose and attribute the mean changes below the surface of the ocean.

For changes in ENSO variability, as elsewhere, detection is complicated by the large natural SST variability associated with different flavors of ENSO, the difficulty of separating trends in the mean from trends in ENSO characteristics, and because of SST variability unrelated to ENSO. As models are apparently not resolving these issues despite much work at many institutions, we advocate the documentation and study of changes in the processes and feedbacks in the ENSO cycle: the thermocline feedback, zonal advective feedback, mean current damping, the wind stress-upwelling-SST (Bjerknes) feedback, wind-evaporation-SST (WES) feedback, and the atmospheric damping of SST anomalies (see section 3.4 below). This diagnosis will require coherent information about monthly to seasonal variations in both atmosphere and ocean fields. These include 4-d estimates of ocean temperatures and velocities together with estimates of atmospheric turbulent and radiative fluxes.

The ENSO CO_2 signal and its observed changes

The equatorial oceans are the largest natural source of CO_2 to the atmosphere, contributing about 0.7 Pg C/yr (Takahashi et al., 2009; Wanninkhof et al., 2013); fed by equatorial upwelling, primarily in the eastern Pacific and Atlantic cold tongues (the Pacific is about 70% of the total tropical outgassing). For reference, 0.7 Pg C/yr is about 7% of total CO_2 emissions from anthropogenic sources in 2012 (LeQuere et al., 2013).

Three decades of sampling, mostly during TAO service cruises, have shown strong fluctuations of surface water CO_2 with the ENSO cycle. Tropical Pacific CO_2 emissions increase during La Niña events, and decrease during El Niños, with a magnitude of about ±0.1 Pg C/yr. This is attributed to upwelling transport changes, with stronger upwelling and shallower thermocline depths during La Niña providing a closer communication from the thermocline to the surface. The observed ENSO surface seawater CO_2 signal has a meridional scale of at least ±10° latitude.

Atmospheric pCO_2, by contrast, is well-mixed over broader regions and does not vary spatially nearly as much as the ocean values, thus the equatorial air-sea gradient depends more strongly on the ocean, so air-sea flux variability is driven by oceanic changes. However, the flux also depends on wind speed, which therefore also contributes to increasing CO_2 flux over the cold tongue during La Niña events.

This straightforward picture seemed to describe the observed variability of ocean surface pCO_2 through the El Niño event of 1997-98, with large pCO_2 drops occurring with all the El Niños since observations began in 1981. Since 1999, however, the level of surface water pCO_2 has stepped higher by about 20µatm, and the ENSO-timescale fluctuations are much less evident. As this occurred simultaneously with the apparent change in the physical manifestations of ENSO (e.g., the prolonged La Niña conditions of the 2000s, and largest El Niño SST anomalies observed further west than had been seen over the previous 20 years), it may reflect changes in the location and magnitude of upwelling. The important contribution of ENSO to atmospheric CO_2 variability is the subject of current research (see TPOS WP06).

2.5 ENSO predictability

ENSO has shown the highest predictability among identified climate modes in the Earth's climate system. That seasonal climate prediction is no longer a speculative practice is largely due to the predictability of ENSO and the quantification of ENSO's global impact (Barnston et al., 2003; Goddard et al., 2005). Present ENSO forecast models, despite their vast differences in complexity, exhibit comparable predictive skills, which seem to have plateaued at moderate level (Chen and Cane, 2008), although there are hints of progress (Stockdale et al., 2012). It remains to be seen how predictable ENSO really is and how much room there is for further improvement. To answer these questions, we need to know the underlying physics that produces predictability.

The long-range predictability of ENSO stems from ocean–atmosphere sensitivity in the tropics, the crucial role of the slowly-varying ocean, and the low-dimensional nature of this coupled system. Classic theories consider ENSO as a self-sustaining interannual fluctuation confined to the tropical Pacific, chaotic yet deterministic (Zebiak and Cane, 1987; Battist and Hirst, 1989;

Jin, 1997). Thus its predictability is largely limited by initial error growth, and the potential forecast lead time is likely to be on the order of years (Goswami and Shukla, 1991; Xue et al., 1997). Another strain of thought emphasizes the importance of atmospheric “noise” as triggers for ENSO events (Penland and Sardeshmukh, 1995; Moore and Kleeman, 1999; Thompson and Battisti, 2000). In such a scenario, ENSO is a highly damped oscillation sustained by stochastic forcing, and its predictability is limited more by noise than by initial errors, implying that ENSO events are essentially unpredictable at long lead times.

In principle, predictability can be estimated using twin-model experiments and perturbing the initial conditions, but the answer is model dependent, and existing ENSO models are not realistic enough for this purpose. Present estimates of ENSO predictability are mostly based on retrospective predictions over a relatively small number of events. With so few degrees of freedom, the statistical significance of such estimates is questionable. The uncertainty is worsened by the fact that ENSO predictability is time dependent (Balmaseda et al., 1995; Kirtman and Schopf, 1998). It has been shown that the predictive skill for ENSO varies significantly in the past one and a half centuries, especially at longer lead times (Chen et al., 2004; Tang et al., 2008). The predictability is high for periods dominated by strong and regular ENSO events, but low for periods with fewer and weaker events (Barnston, 2012).

Generally speaking, there are four factors that limit the current skill of ENSO prediction: inherent limits to predictability, gaps in observing systems, model flaws, and suboptimal use of observational data. As discussed above, there is considerable debate on the inherent limits to predictability, but increasing evidence suggests that our current level of predictive skill is still far from those limits and surely there is room for improvement (Chen et al., 2004; Chen and Cane, 2008). Our tasks are then to improve observing systems, models, and data assimilation methods. These call for a continuously sustained, optimally designed TPOS, and process studies that elucidate the physics of ENSO predictability and its low-frequency variability.

3. Processes involved in the above uncertainties

3.1 Equatorial upwelling and rapid atmospheric feedback – scales and fronts

The equatorial cold tongue complex is a region where strong upwelling occurs in the presence of vigorous turbulent mixing; the resulting intimate connection between the thermocline and the surface allows the interaction of basin-scale ocean dynamics and property transports with the equatorial atmosphere that responds sensitively to variations of SST. That sensitivity is demonstrated by the short spatial scales (100km or less) of wind response as southeasterly trade winds cross the SST front on or just north of the equator (Risien and Chelton, 2008). While satellite winds and SST detect the surface front on weekly timescales, SST variability is a convolution of surface fluxes, mixing and upwelling in a complex and time-dependent circulation cell whose dynamics are not well understood. The near-surface, near-equatorial circulation has posed a difficult problem for models, whose representations cannot even be evaluated because existing subsurface observations have been concentrated narrowly on the equator and do not adequately sample properties or currents in the ocean near-surface layer.

These phenomena include equatorial upwelling itself, which is the primary driver of communication between the thermocline and surface. Since the early studies of Cromwell

(1953), Knauss (1963), and Wyrtki (1981), we have known that upwelling transport into the upper layer of the east-central Pacific balances the Ekman transport across ±5° latitude, totaling about 30Sv, with a vertical velocity of a few meters/day (Weisberg and Qiao, 2000; Johnson et al., 2001; Meinen et al., 2001). If we assume that upwelling occurs across the east-central Pacific, and that vertical velocity has a Gaussian structure in latitude, its implied meridional e-folding scale is 50 to 150km. The divergence forcing this upwelling is quite shallow, perhaps 50m thick at most (Johnson et al., 2001). However, we have little information on the time-variability of upwelling. Although zonal pressure gradients in the upper equatorial ocean adjust to changing winds on about 10 day timescales (Cronin and Kessler, 2009), it is not clear that the meridional currents producing divergence and upwelling have the same timescale. Resolving this will require near-surface velocity observations spanning the equator.

Upwelling of cool thermocline water in the east is a key link in the Bjerknes feedback that establishes the mean state of the equatorial Pacific (section 3.4). By producing a zonal SST gradient, eastern upwelling suppresses atmospheric convection in the east and focuses it in the west, driving the trades and Walker Circulation, which is then a positive feedback for the easterlies that cause upwelling. If either upwelling decreases or the temperature of the water it draws from increases, that will tend to weaken the easterlies. This engenders a coupled chain reaction that amplifies the initial anomalies and pushes the system towards an El Niño state (see section 3.4).

The persistence of the sharp front bounding the cold tongue in the north, where strong poleward Ekman currents seem to cross the front, similarly implies a narrow, shallow, vertical circulation along the front. The front, and the tropical instability waves (TIW; section 3.g) that occur along it, are important as a source of heat to the equator from the warmer waters to the north, a meridional heat flux that is comparable in magnitude to that of upwelling (Bryden and Brady, 1989; Kessler et al., 1998). The front and TIW are more intense during La Niña periods and greatly weakened during El Niños, presumably because warming on the equator during El Niño weakens the meridional temperature gradient, and weaker easterlies weaken the shear of the zonal currents across the front.

Thus, processes acting on scales of 100km or less are key mechanisms by which the basin-wide changes in the ocean's vertical structure are communicated to the sensitive overlying atmosphere. While models can now simulate the large-scale ENSO-driven changes to the background vertical structure, especially those mediated by equatorial Kelvin and Rossby waves, models do not yet represent the actual mechanisms or scales by which SST evolution is controlled. Because of positive feedbacks (section 3.4), errors in representing these short-spatial-scale phenomena can grow and corrupt the overall model solutions.

An upper ocean heat budget estimate is a key part of the suite of diagnostics used to interpret changes of the ENSO cycle (Huang et al., 2010; Xue et al., 1997; "Monthly Ocean Briefing", NCEP/CPC). Such diagnostics are essential to understanding and predicting the evolution of ENSO events, yet our present capacity to close the heat budget is extremely limited. To provide an ongoing description of the interaction of upwelling, surface fluxes, horizontal advection and mixing, a credible heat balance should be enabled by the observing system. As we have seen diverse flavors of ENSO that embody different combinations of processes controlling SST (e.g. Kug et al., 2010; see section 2.3), it is essential – in the medium term at least – that the processes and local consequences of the vertical circulation be directly measured by the sustained observing system at a few representative locations spanning the equator, both for real-time diagnoses and to evaluate model simulations and drive their next generation.

3.2 Mechanisms by which subsurface ocean dynamics drive SST

Knowledge about the mechanisms through which ocean processes affect mixed-layer temperature and provide feedback to the atmosphere are critical to the understanding of ENSO and its decadal variation/modulation. High-frequency measurements of upper-ocean temperature, horizontal currents, and surface meteorological parameters by TAO/TRITON moorings have enabled a great growth of understanding on seasonal and interannual time scales (e.g., Wang and McPhaden, 1999, 2000, and 2001; Cronin and Kessler, 2002), making possible quantification of the roles of the terms of the heat balance on seasonal and interannual timescales (Wang and McPhaden, 1999, 2000, and 2001). Co-located mooring data at (0°, 110°W) was able to characterize the interplay of wind and solar insolation in modulating near-surface stratification and SST (Cronin and Kessler, 2002). However, significant knowledge gaps remain in several aspects:

(1) the contribution by vertical processes (vertical advection, entrainment, vertical mixing, and solar penetration through the water column) is inferred as a residual in observation-based analysis of mixed-layer temperature budget because these processes cannot be resolved by existing measurement techniques;

(2) the heat budget off the equator where there are no current meters is much less certain;

(3) the variation of the heat budget on decadal and longer time scales is not well documented;

(4) the vertical resolution of TAO sampling is too coarse to resolve the variations of mixed-layer depth and properties;

(5) salinity is known to vary on seasonal and interannual (and conceivably on decadal and longer) time scales (Singh and Delcroix, 2013); the relative lack of salinity measurements degrades the estimate of mixed-layer depth and indicates the dispersal of the large precipitation signal in the west Pacific warm pool. Formation of salinity barrier layers could provide yet another feedback that affects the intensity of ENSO events (Maes et al. 2002, and 2005; Maes and Belamari, 2011).

3.3 Atmospheric processes relevant for TPOS observations

The atmosphere is a strong driver of the ocean, and more so than elsewhere tropical oceans force the atmosphere with both local and remote responses. The Atmospheric Boundary layer (ABL) processes of this interaction span a broad spectrum of horizontal scales, with the dominant small scale processes related to convection, clouds and precipitation modulated by the large scale flow, which in turn depends on the small scales. In the vertical too, the free atmosphere and sub-thermocline ocean are connected through small scale processes in both planetary boundary layers. TPOS observations over the large scale of the tropical Pacific have revealed multi-year variability in the background state and ENSO. Of most relevance is the SST and its gradients, that modeling studies of Lindzen and Nigam (1987) suggest are responsible for observed features of the flow in the ABL. Other important observations are the large scale wind patterns, not only the zonal wind stress of relevance to ENSO, but also the cross equatorial flow that feeds into the convergence zones (e.g. ITCZ). These winds have also been a key reference standard for satellite wind products and their loss would open the door for spurious temporal changes in the combined satellite record.

For decades convection and related clouds and precipitation have remained a daunting challenge for observations and models of the atmosphere, because of their small scales and stochastic nature. Convection itself has a multi-scale character by being driven by low level convergence (dominant in the ITCZ, for example) and by heating from warm SST below. The latter places a premium on measurements of the sensible heat flux as it is the only component of the air-sea heat flux that directly heats the ABL. Evaporation is another, less effective, de-stabilizing flux. Perhaps the most promising prospect for a breakthrough are models that faithfully resolve both the processes and their interactions, but verification of having reached such a state in the tropics will require a series of observational programmes targeted at specific processes. These campaigns would include TPOS elements and utilize the whole of TPOS to set the large scale context.

Perhaps the most compelling argument for coincident and co-located ocean and ABL observations is to discover and diagnose significant correlations between atmospheric properties and the ocean mixed layer, along with their relation to background conditions. The recently observed correlation between small scale SST and near surface wind (Chelton et al., 2000) has important implications for the entrainment of free atmosphere air into the ABL. There may be other significant relationships to be found, and in some cases very long time histories of consistent high frequency observations may be needed to mitigate the statistical problem of sparse spatial sampling of TPOS, and diurnal variability. Discerning the fine details of these processes that connect the upper ocean and lower atmosphere will become more and more critical as forecast systems move toward true fully coupled data assimilation. Present practice of independent atmosphere and ocean assimilation can lead to incompatible initial atmosphere and ocean states, and hence a shock to the subsequent coupled integration. Instead, observations in the atmosphere should be allowed to influence the ocean state, and vice versa, based a priori on observed relationships. Observed air-sea fluxes would also become an integral part of the coupled assimilation/forecast system. Key constraints that could then be imposed within specified limits are conservation of heat and Ekman transports in the ABL that are of equal magnitude, but opposite direction to those in the ocean.

3.4 Large-scale feedbacks driving ENSO variability

Theoretical understanding of ENSO has significantly advanced over the past decades (see Wang and Picaut, 2004). The theoretical framework of the recharge oscillator (Jin, 1997) provides a widely accepted paradigm for ENSO. A linear analysis of the recharge oscillator SST equation provides a simple yet powerful way to evaluate the different mechanisms that amplify or damp ENSO growth.

Damping mechanisms include the thermal damping of SST anomalies by air-sea fluxes and the restoring effect of the mean state (i.e., the fact that advection of temperature anomalies by the climatological currents tend to reduce those anomalies). The Bjerknes feedback depends on the sensitivity of the atmospheric surface wind responses to ENSO SST anomalies. This atmospheric response to SST anomalies is here referred to as the atmospheric Bjerknes feedback and can be computed from observations. With the associated ocean response the coupling results in amplifying mechanisms through the so-called "ocean feedbacks": the zonal advective feedback, the thermocline feedback and the Ekman pumping feedback, further detailed below.

By focusing on the key processes affecting ENSO dynamics, evaluating these feedbacks from observations will accelerate progress in ENSO understanding and improve its representation in climate models. This evaluation requires coherent multi-decadal time series and is currently constructed from atmosphere and ocean reanalyses. In the tropical Pacific these reanalyses are strongly constrained by TAO in situ measurements which provide a uniquely coherent view of the relevant ocean and surface atmosphere variables over several decades. Evaluation of feedback processes can not only address the question of whether the characteristics of ENSO are changing in a changing climate but, by illuminating the underlying physical processes, also potentially improve the realism of predictions from seasonal to centennial-scale climate projections.

Bjerknes feedback: This is a positive feedback loop acting symmetrically in the ocean and atmosphere that controls the overall state of the tropical Pacific. It maintains the normal background state, but if perturbed can feed back to amplify the original perturbation, and thereby amplifies incipient El Niño or La Niña events. In normal conditions, surface easterlies force both a westward surface equatorial current and Ekman divergence that induces upwelling. The ocean zonal pressure gradient balances the westward wind stress, giving an upward slope of the thermocline towards the east, which means that a given upwelling velocity draws colder water in the east than in the central Pacific where the thermocline is deeper. The resulting zonal SST gradient focuses atmospheric convection in the west and subsidence in the east (the Walker circulation), which enhances the original easterlies in a positive feedback. While this system appears to be stable, the fact that it is maintained by positive feedbacks means that weakening any element weakens the entire system. This insight by Bjerknes (1966) was the first basin-scale theory of ENSO.

Zonal advective feedback: In normal conditions, a westward zonal current carries cool (upwelled) water westward, balanced in the mean by solar heating. If either the wind-driven current or the heating changes so to produce an initial warm anomaly, the winds – and thus currents – over and to the west of the anomaly are weakened. The resulting current anomalies carry warm water eastward, amplifying the original anomaly. It has been argued that the zonal advective mechanism is more effective than upwelling at changing SST in the central Pacific because the background zonal SST gradient is large but thermocline is deeper there so the Bjerknes feedback is less effective. This feedback appears have played a larger role since 2000.

Thermocline feedbacks: A deep-thermocline anomaly in the east Pacific will warm SST - even if upwelling itself remains strong - by reducing the background vertical temperature gradient that upwelling works on. Warm SST tends to produce further warming by either the Bjerknes or zonal advective feedbacks mentioned above, which will weaken the local winds and self-amplify.

SST/wind stress (Ekman) feedback: A weakening of the wind stress reduces upwelling velocity. Even if the background vertical temperature gradient is strong, this feedback anomalously warms SST as less cold water is pumped upwards. Those positive SST anomalies again act through Bjerknes or zonal advective feedbacks to the further weaken the wind stress.

Wind-evaporation-SST (WES) feedback: Warm SST anomalies induce not only dynamical effects as above but also – by changing wind speed – change the evaporation as well. Near the equator, reduced wind speeds due to a warm SST anomaly also decrease evaporation in a positive feedback. Like the Ekman feedback, the WES feedback can favor westward propagation of equatorial SST anomalies. However, the WES feedback acts somewhat differently for off-equatorial SST anomalies. A subtropical warm SST anomaly tends to induce a cyclonic surface wind, which (in the easterly trade wind regime) tends to reduce wind speeds on the equatorward flank of the SST anomaly – warming the surface by reducing evaporation and resulting in equatorward propagation of the SST anomaly. This feedback has been suggested to play a role in the triggering of ENSO events, by so-called “meridional modes” which propagate off-equatorial anomalies equatorward, where they can affect ENSO (Chiang and Vimont, 2004; Zhang et al., 2009; Dayan et al., 2013; Larson et al., 2013).

Heat flux damping: The heat flux feedback is defined as the regression coefficient between net surface heat fluxes and SST anomalies in the east Pacific. It is usually a negative feedback and is dominated by the shortwave and latent feedbacks. The shortwave feedback changes depending on the stability of the atmosphere. In unstable conditions, higher SST leads to an increase in convection, high clouds, and a decrease in surface shortwave flux: the shortwave feedback is negative in the convective regime. Under stable conditions, higher SST destabilizes the atmospheric boundary layer and prevents the formation of stratiform boundary layer clouds. This leads to an increase in shortwave flux at the surface and the associated feedback is positive in the subsident regime. This shortwave response to SST is, however, complex and non-local; it may be decomposed as the product of (1) the response of large-scale atmospheric dynamics to SST anomalies, (2) the response of clouds to changes in the large-scale circulation, and (3) the characteristics of the shortwave interception by clouds. Several studies have shown that the single largest source of model errors for ENSO in climate models comes from the misrepresentation of this shortwave feedback (e.g., Wittenberg et al., 2006), since it involves multiscale interactions among resolved large-scale motions and parameterized convection, cloudiness, and boundary layer processes. In situ platforms provide an essential component of the observing system, permitting cross-validation and calibration of satellite estimates of clouds and their impacts on the tropical Pacific mean state and ENSO. Estimates of this feedback are hampered by the sparcity of observations, especially of shortwave radiation, but the degree to which OAFlux is a quality product in the equatorial Pacific is mainly thanks to the in situ measurements of the TAO array (Cronin et al., 2006).

3.5 Diurnal cycle and penetration of surface fluxes into ocean

Observations of the ocean mixed layer near the equator show a large diurnal cycle of shear and stratification, both of which affect the vertical transmission of surface fluxes through the ocean.

During the night, with surface radiative cooling destabilizing the water column, the well-mixed layer deepens. As intense daytime solar heating produces shallow stratification, it traps wind-input momentum in a thin near-surface layer, perhaps 10m deep (Schudlich and Price, 1992). During a 7-month study at 2°N,140°W, a mean afternoon jet developed that was 12 cm/s faster in the direction of the wind at 5m than at 25m; this strong shear disappeared at night, despite the fact that the diurnal cycle of winds in the equatorial Pacific is weak (Cronin and Kessler, 2009).

The SST peak occurs in early afternoon, and then cooling begins while the surface is still being heated. One interpretation is that shear at the base of the afternoon mixed layer increases vertical turbulent mixing there, which deepens the sheared layer and hence deepens the penetration of diurnal heating. Later, even after surface heating has ended, the initially shallow stratification and shear continue to propagate downwards, as convection plus the residual shear at the base of the diurnal mixed layer increase vertical turbulent mixing and deepen the layer. This continues through the evening hours, transmitting the previously trapped momentum, heat and possibly freshwater downwards to the main thermocline (Danabasoglu et al., 2006). Strong turbulent dissipation has correspondingly been observed to extend to perhaps 80m depth in the evening, into the upper level of the equatorial undercurrent, before retreating to very shallow depths during the day (Lien et al. 2002), but the source of energy has yet to be partitioned between convection and shear.

The diurnal cycle, therefore, is a strong mediator of the relation between the primary ocean driver of surface heat flux (SST), and the primary upper ocean response (heat content). Further, non-linearity can rectify diurnal variability into the mean, and Bernie et al. (2008) found that diurnal coupling has profound impacts that include large scale variability in the tropics. In principle, models with very high vertical resolution could resolve diurnal mixing processes, but many of the mixing rules are based on unproven analogies with the atmosphere. Therefore, the uncertain results are not generally deemed to justify the substantial increase in computational costs. Alternatively, there are simple schemes (Zeng and Beljaars, 2005) that give an efficient diurnal cycle of SST, but not of shear or salinity stratification. The verification of such schemes is at present primarily indirect using remotely sensed SST.

Thus, it appears that much of the work of heat and momentum transmission to the thermocline in the equatorial Pacific is accomplished by the diurnal cycle. The magnitude and characteristics of the diurnal cycle is dependent on the local cloudiness, wind and precipitation, which vary regionally, seasonally, and with ENSO phase. As well, studies have shown sensitivity to the depth of solar shortwave penetration (e.g. Sweeney et al., 2005; Anderson et al., 2009). The overall picture is that mixing in this region is not a simple stirring of warm surface and colder subsurface waters, but acts through a specific set of downward-propagating dynamics; this implies that momentum transfer to the thermocline and equatorial undercurrent depends on diurnal processes. Since this transfer is key to the Bjerknes and zonal advective feedbacks (section 3.4), and model schemes are not directly verified, observation of the diurnal cycle of temperature, salinity and velocity from the surface to the thermocline should be part of the sustained observing system, at least at some representative locations, both for diagnostics of the above relationships and to spur model improvements that can be verified.

Interestingly, the equatorial Pacific can be sensitive to off-equatorial vertical mixing processes. That the equatorial Pacific background state can be strongly affected by off-equatorial processes – some of which are only crudely represented in models (e.g., the diurnal cycle) – is yet another motivation for an expanded in situ observing system, along with field campaigns to better constrain these dynamical and thermodynamic processes in models.

3.6 Recharge and discharge to subtropics (LLWBCs)

Low latitude western boundary currents (LLWBCs) in the Pacific (namely, the Mindanao Current in the north and the New Guinea and New Ireland Coastal Undercurrents in the south) are the western boundary pathways of the lower limbs of the shallow meridional overturning circulations that connect the tropical and subtropical Pacific Ocean (i.e., the subtropical cells). In the mean, they reinforce the interior geostrophic flow in the pycnocline, bringing colder pycnocline waters from the subtropics to the equator to balance the poleward transports of warmer surface waters by the Ekman currents. On interannual and longer time scales, however, the picture is very different. Satellite and in situ measurements, as well as ocean modeling and assimilation products, suggest that the variations of LLWBC volume transports tend to be anti-correlated to and partially compensate the more dominant variations of the interior transports (Kang and An, 1998; An and Kang, 2000). The causes for the different phasing of the LLWBCs and interior transport are related to two factors:

(1) Propagation of off-equatorial Rossby waves generated by central basin winds to the western boundary (Capotondi et al., 2004).

(2) Anomalous horizontal circulation in the western tropical Pacific due to variations in local Ekman pumping associated with the movement and the strength of the ITCZ and SPCZ (Lee and Fukumori, 2003).

Satellite altimeter data have inadequate resolution near coastlines to capture the complicated structure and tight gradients of the LLWBCs (100km or less), especially in the complex geometry of the Solomon Sea. Argo floats are also limited in sampling these narrow features, as they do not generally sample their cross-shore gradients. The representation of LLWBCs in modeling and assimilation products is dependent on their spatial resolution and the representation of the complicated geometry and bathymetry in these regions (Cheng et al., 2007).

Moreover, volume transports of the LLWBC are primarily a proxy to describe the role of these flows in regulating tropical upper-ocean heat content; the heat that they carry to the west Pacific warm pool is fundamental to the tropical climate evolution. Measurements of both the LLWBCs' transport and temperature are thus necessary to understand their role in ENSO and its decadal and longer variation/modulation; therefore, monitoring the LLWBCs should be an integral part of the ENSO observing system. The international Programmes “Northwestern Pacific Ocean Circulation and Climate Experiment” (NPOCE) and “Southwest Pacific Ocean Circulation and Climate Experiment” (SPICE) are designed to understand the roles of the LLWBCs in tropical Pacific Ocean and climate. However, these experiments are process-oriented. An integration of LLWBC measurements into a long-term monitoring system of the tropical Pacific is necessary to facilitate research on decadal and longer variation/modulation of ENSO.

3.7 Tropical instability waves

Tropical instability waves (TIWs) are an integral element of the coupled ocean-atmosphere system in the Pacific Ocean-atmosphere system. Signatures of the TIWs have been observed by satellites (in SST, SSS, SSH, wind and wind stress, precipitation, and ocean color) (e.g., Legeckis, 1977; Yoder, 1994; Xie et al., 1998; Chelton et al., 2000; Liu et al., 2000; Polito et al., 2001; Lee et al., 2012) and by subsurface ocean measurements (in temperature, salinity, currents, and surface meteorology) (e.g., Qiao and Weisberg, 1995; McPhaden, 1996; Halpern et al., 1998; Lyman et al., 2007). TIW meridional fluxes of heat, freshwater/salt, nutrients, and carbon are comparable to that of upwelling (Bryden and Brady, 1989). They provide a major mechanism of eddy-mean flow interaction in the tropical Pacific Ocean (e.g., Qiao and Weisberg, 1995). The vertical circulation of TIW also facilitates exchanges of heat, freshwater, momentum, and gases between the ocean and atmosphere (e.g., Feely et al., 1994; Xie et al., 1998).

Because of their relatively high frequencies (a dominant period of 17 days near the equator and 33 days off the equator in the Pacific; Lyman et al., 2007; Lee et al., 2012), TIW signals are aliased in Argo sampling (due to its typical 10-day profiling interval) and in the data of some satellites that have less frequent repeat times. On the other hand, the roughly 1500km zonal spacing of TAO mooring pickets is nearly one TIW wavelength, so it is not possible to diagnose TIW properties from the present moored array (but the moorings do resolve the front in detail as it passes (Cronin and Kessler, 2009)).

Since TIW are instabilities, their representation in atmospheric and ocean reanalysis products is hard to correct by assimilation. On the other hand, Vialard et al. (2003) present a more positive view, linking TIWs to the wind forcing. Recent advances in coupled ocean-atmosphere data assimilation (e.g., NOAA/NCEP's CFSR) has improved the representation of TIWs due to the combined use of ocean and atmosphere observations (Wen et al., 2012), demonstrating the utility of simultaneous, co-located, high-frequency measurements of the ocean and the surface meteorology. The representation of TIWs in coupled climate models are related to some model biases (e.g., the cold tongue; Wittenberg et al. (2006) and Delworth et al. (2012) in the context of GFDL's CM2.1 and CM2.5; Bill Large, personal communication in the context of NCAR's CCSM). Enhancing the ability of the Tropical Pacific Ocean Observing System to monitor TIWs would improve our understanding of the roles of TIWs in ENSO and the related impacts on marine biology and the carbon cycle.

4. Observations to resolve these processes

Section 3 above describes a wide variety of processes that contribute to ENSO evolution, some better-understood and becoming well-modeled, others that continue to require ongoing in situ observation to clarify basic facts and enable model advancement. In doing this, we take the viewpoint of future colleagues looking back at the present time: What will they wish we had been measuring in 2014?

4.1 Maintenance of climate time series

Long time series of climate-relevant variables are precious indicators of long-term change. These time series are the only means to document slow variations in the background fields that determine the characteristics of ENSO, and also underpin model bias correction. In situ measurements of geophysical quantities often suffer from poor statistics, and the few existing long time series uniquely reference ongoing data collection.

Through decades of effort, long time series of several climate variables are now available in the equatorial Pacific. Wyrtki (1974, and 1979) developed indices of surface currents from a few island sea level records, building time series back to 1950. These indices proved to be reasonable measures of seasonal and ENSO transport fluctuations when compared to those constructed from in situ temperature profiles (Taft and Kessler, 1991). Nevertheless, although the island sea levels are well-resolved temporally (able to average out tidal fluctuations), they are inherently limited to a small number of locations that in particular do not sample the equator between 160°W and the coast of South America.

Before the TAO array produced reliable and well-resolved temperature profiles across the tropical Pacific, wide use was made of XBT profiles deployed from three quasi-meridional merchant ship lines beginning in the mid-1970s (e.g., Rebert et al., 1985, Kessler, 1990; Picaut and Tournier, 1991). Beginning in the late 1980s and continuing to the present, several of these lines were converted to “high-resolution” lines under WOCE and then CLIVAR, carrying a dedicated observer and deploying XBTs more frequently, roughly every 1/4° (Roemmich and Cornuelle, 1990); data from these lines is adequate to make meaningful averages (for example of eddy properties (Roemmich and Gilson, 2001)). However, the XBT lines are limited to a few widely-separated tracks, and typically sample only once every few months.

The advent of TAO in the mid-1980s, and its completion in the early 1990s (Hayes et al., 1991; McPhaden, 1995), began the era of co-located surface atmospheric and subsurface ocean data, with high temporal resolution and basin-wide coverage. TAO also began the era of real-time and publicly-available data that is now taken for granted. Several sites have been occupied for 30 years, especially on the equator in the east and central Pacific. While the TAO array is described in detail in other white papers of this series, in the ENSO context we note the consistency of sampling over these decades, sampling that was originally designed – in the absence of credible model simulations – to meet the temporal and spatial spectral requirements of detecting the equatorial waves that were then key to progress on the ENSO cycle (Hayes and McPhaden, 1992; Kessler et al., 1996). In the presence of numerous sources of high-frequency signals that can produce aliasing in sparser sampling (e.g., TIWs (section 3.7), westerly wind bursts, as well as tides and internal waves), the highly-resolved sampling of moored measurements makes it possible to confidently extract unaliased low frequency signals. Indeed, one of the early results enabled by TAO’s growing time series was to describe the slowly-varying seasonal cycle in the subsurface eastern equatorial Pacific, and the lack of annual phase consistency between thermocline depth and SST (Gu et al., 1997).

We look forward to the lengthening of the Argo time series of temperature and salinity in the tropical Pacific. As Argo provides excellent zonal resolution that has heretofore been lacking, we expect to see the evolution of many signals – for example those associated with the off-equatorial Rossby waves whose timescales are well-matched to Argo sampling – with added detail and ability to relate them to the overlying winds.

In contrast to this history of carefully maximizing the information content of available data, the climate community has suffered several times from irretrievable losses from observing system changes without adequate documentation of the sampling characteristics of different instruments and techniques. First, the change from bucket to ship-intake SST measurements in the 1940s and 1950s added substantial uncertainty to reconstructions of time series spanning that period (Kaplan et al., 1998). Second, in the transition from broadscale XBT sampling to Argo early in the past decade, insufficient overlap for intercomparison again left a difficult-to-correct uncertainty (Lyman and Johnson, 2008; Wijffels et al., 2008). Third, in situ measurements of near surface winds were affected by a gradual increase in anemometer heights, as the ocean vessels on which they were mounted grew taller over the years (e.g., Wittenberg, 2004, and references therein). As we build time series for future generations, such mistakes must be avoided.

However, we are forced to watch another such mistake unfold today, as the transition of TAO from research lab management to operational status has decimated the array, with data return down below 40% and many moorings practically abandoned. If allowed to continue, this would produce serious gap in the climate record that our future colleagues will see as nothing short of tragic.

One of the most important fields for understanding the tropical Pacific climate and ENSO, is the surface wind stress. Unfortunately, the surface wind stress remains one of the most poorly observed quantities, especially since the 2009 loss of the NASA QuikSCAT satellite, which had for years measured surface wind stresses with unprecedented detail using the SeaWinds scatterometer. In the absence of QuikSCAT, the TAO moored array is one of the last remaining components measuring the all-important surface wind field. Scatterometers, such as ASCAT METOP-A and future instruments require in situ measurements for calibration and validation. The accuracy required in the equatorial region is particularly demanding, and this makes the long-term in situ sampling from the TAO array very important. Generation of a tropical Pacific climate record for future scientific use will critically depend on continuity of future wind-observing systems with ongoing TAO observations.

We are far from understanding either the natural or anthropogenic low-frequency variability of the tropical Pacific and its influence on ENSO characteristics. This variability depends on subtle changes of the underlying background conditions, whose source remains largely unknown. Progress in this area requires consistent long-term observation sufficient to detect small trends without aliasing, either by continuing existing systems, or after a well-understood and well-documented transition of observing techniques.

The difficult question of which existing time series have ongoing value and should be continued, vs. those that might be modified or abandoned, we leave for community discussion.

4.2 Ancillary measurements: shipboard sampling, embedded process studies

The ability to embed temporary process studies, and to build an ongoing suite of shipboard observations, is a significant side-benefit of servicing a large sustained array. The cruises that have maintained TAO have established a substantial database of CTD profiles and repeated ADCP transects. These have drawn an unprecedently clear picture of the zonal current structure and its seasonal and ENSO variation (Johnson et al., 2002). The regular presence of a research ship has enabled the CO_2 sampling discussed in section 2.4 above, which has documented a large CO_2 flux signal at ENSO and also longer timescales, though whether this is a natural decadal phenomena or anthropogenic signature is not known. These side-benefits have largely evaporated with the transition of TAO to operational status. Fewer CTD profiles are taken, the shipboard ADCP is neglected, and most ancillary measurements are not supported.

As our future colleagues look back from 2025, certainly they will have wanted ongoing surface ocean and atmospheric CO_2 sampling, which is the only means of measuring the ocean's role in recycling natural and anthropogenic carbon, and also serves to check climate model simulations (see TPOS WP06). Whether this sampling is done from ships (i.e., a few times/year, but extending to a wider range of latitudes), or more narrowly near the equator from moorings, remains an open question.

Shipboard ADCP sampling has already shown the ability to resolve the mean, annual cycles and ENSO variations of the zonal (but not meridional; Johnson et al., 2001) currents along a few longitudes, as mentioned above. As the ships traverse the tropical Pacific, they accumulate velocity data that fills in between the few moored velocity sites and improves the climatologies. We note that shipboard ADCP data requires careful processing, and this work at the University of Hawaii is presently unfunded. Research ships servicing the TAO array have been the principal means of deploying Argo floats in the tropical Pacific; with the transition to operations and loss of this opportunity, Argo coverage in the region will decrease unless other means of deployment are found.

Short-term process studies have been enabled by the TAO since its earliest days. The mooring hardware and software are designed to accommodate instrumentation added ad hoc, and the regular service cruises have provided platforms for many process studies (a short list would include TROPIC HEAT, EPOCS NECC, TIWE, JGOFS EqPac, TOGA-COARE, CEPEX, Nauru99, EPIC, NPOCE, SPICE). This facility has largely been a casualty of the transition to operational status, however, but the need and demand is high.

While some observations should be ongoing, other problems can only be attacked with intensive process studies that are necessarily short-term:

- Co-variability of the ocean mixed layer and lower atmosphere winds and precipitation. (Needs a ship with Doppler wind sampling).
- Turbulence measurements to diagnose momentum/property flux penetration into the thermocline and their relation with background currents/thermal structure. (Requires a dedicated cruise).
- Observe the 3-D evolution of the near-equatorial circulation cell (upwelling and the cold tongue front) under varying winds. (Process study embedded in a larger array)
- Clouds, convection, PBL

4.3 Vertical and temporal resolution of temperature sampling

Present TAO moorings typically sample SST and temperature at 11 depths down to 500m, with vertical resolution of 20 or 25m in the upper 100m, at 10-minute intervals. Argo sampling has much better vertical resolution (5m or less), and also measures well-calibrated salinity, but only every 10 days. These contrasting strengths will each be needed for different aspects of ENSO research.

It remains to be seen how well Argo sampling will resolve the ENSO-related fluctuations of the thermocline, which can only be determined by further study. However, as discussed in section 3.5 above, much of the important dynamics determining the injection of surface momentum and heat fluxes into the ocean occurs in the near-surface layer, which is at present poorly observed and poorly modeled. These dynamics are inherently high-frequency (diurnal), which also implies the need for a significant model development effort that will require observational guidance. Mixed-layer variability is also inherently local, especially in being dependent on the surface flux variability. The next generation of scientists will need us to have made progress in this crucial area. This need can be met by instrumenting the near-equatorial moorings proposed in section 4.d below (1° intervals to ±3° latitude, at a few longitudes) with thermistors at the same depths as the current meters (every 5m down to 50m). These moorings should also have a suite of surface flux measurements (section 4.5), enabling a complete diagnosis of the processes acting on and in the ocean, at several representative cross-equatorial sections.

4.4 Velocity

Ongoing ocean current profiles are made from moorings at five locations on the equator (110°W, 140°W, 170°W, 165°E and 147°E). Because the moorings are subsurface, their data is retrieved only when the mooring is recovered, so is not real-time, but velocity time series from these locations stretch back 20 years at least (though some of these are now failing under operational management). These current profiles are frequently used to validate models, since the velocity structure is a sensitive indicator of vertical momentum mixing. However, the upward-looking ADCPs presently deployed provide useful velocities only deeper than about 30m depth, because bubbles and irregular reflections from surface waves blur the signal (shipboard downward-looking ADCPs have a similar limitation). Thus existing velocity measurements do not adequately sample the ocean mixed layer.

We argued in section 3.1 above that enabling an ongoing upper layer heat balance diagnostic is the key to interpreting changes and mechanisms of ENSO evolution. As near-surface horizontal advection is one of the main processes contributing to SST change (section 3.4), and the model time-dependent velocities now used for this purpose are inconsistent across models and unreliable, real-time near-surface current sampling should be part of the sustained ENSO observing system.

The vertical limb of the equatorial circulation is more challenging to measure, and also much less dependable in models, as it depends on the meridional velocity that whose variability appears more complex than that of the zonal current. The sensitive interaction between downward mixing and upward advection is 0^{th}-order in all theories of ENSO, but its actual operation is very poorly understood. As the principal link through which basin-scale ocean dynamics and property transport communicates with the overlying atmosphere, these challenges must be faced. Observations of the full three-dimensional cell above the EUC core through several seasonal and ENSO cycles are the only means to improve and validate model representations. Therefore, current observations sufficient to estimate vertical velocity from horizontal divergence should be part of the sustained observing system for the next decade.

Since the divergence that drives upwelling occurs primarily in the upper 50m, is largely due to dv/dy, and is surface-intensified, an efficient and economical way to make these measurements would be to add or enhance surface moorings with shallow point current meters, every 5m depth down to 50m, at the equator and 1° intervals to ±3° latitude, at a few representative longitudes in the east-central Pacific.

4.5 Air-sea fluxes

The solar (shortwave) radiation is a standard surface flux measurement of TAO moorings, while downwelling longwave has been measured on a much more limited basis. These fluxes are the dominant ocean heating processes (100s of W/m^2) and hence essential for diurnal cycling, cloud-ocean feedbacks and the climate record, for example. They can be estimated from satellite radiation measurements of the top of atmosphere using radiative transfer equations given atmospheric composition and clouds (e.g. ISSCP-FD), but TAO observations have been critical to correcting biases in solar fluxes. Therefore, basin wide, continuous observations of both these flux components networks is essential to maintain consistency with future satellite estimates, understanding and modeling tropical ocean-atmosphere interaction, as well as to resolve the diurnal cycle.

Observations of surface precipitation have been much more sparse than called for by the science questions involved. In future they should be made whenever and wherever there are available platforms, because oversampling will never be an issue. Depending on location, tropical precipitation can be highly intermittent, can have a prominent diurnal cycle, can be the dominant branch of the hydrological cycle, and can play a critical role in ENSO cycles. Precipitation depends on numerous multi-scale processes, including convection, clouds, convergence, water vapor transport, so it is a powerful diagnostic. Therefore, demand will be for diurnally-resolving observations from all regimes: the high rainfall regions of the ITCZs and western warm pool; the regions of large ENSO related variance; the dry zones of precipitation minima. Such observations would provide key model validation metrics, because the multi-scale and multi-process nature of precipitation makes it difficult to tune or to get right for the wrong reasons. They also offer the prospect of discriminating between the disparate tropical precipitation data sets, including those inferred from satellite measurements and those produced from numerical weather prediction schemes. The range across products can approach a factor of two, so it is problematic to maintain a continuous climate record as the changing observing system (e.g. satellite sensors and algorithms), or data assimilation evolution introduce spurious signals. Although ocean salinity budgets offer limited hopes for constraints, there is no substitute for in situ observations. For some purposes very long time series will be needed to ameliorate the sparse spatial sampling, so the sooner more precipitation time series begin the better.

Turbulent fluxes of momentum, sensible heat and evaporation (latent heat) can be estimated from bulk formulae (see TPOS WP11 for an extensive discussion). The primary bulk parameters are SST, wind, air temperature and humidity the most important TPOS and surface current one of the secondary. They are observed frequently and broadly, hourly accuracy may not be within a factor of two, so direct measurements are needed to resolve the diurnal cycle, and to determine regional empirical bulk coefficients for tropical wind/wave/current conditions. The accuracy of bulk fluxes would then improve, especially when averaged over fluctuations in these conditions. In contrast, the situation for direct measurements of the turbulent fluxes is more like that of precipitation; measurements are difficult and, therefore sparse, yet long time series of frequent, accurate observations are needed to calibrate bulk estimates from either in situ or satellite based parameters, to reduce spurious signals in the climate record.

4.6 What determines the necessary location of in situ observations?

Tropical Pacific climate exhibits several different regimes in various parts of the basin, which undergo large changes during ENSO events. Characterizing each these regimes, such that each can be better understood and captured in models, should be a major goal of the Tropical Pacific observing system, but may not be well-sampled by broadscale arrays and will require special attention. These regimes include

> (1) the waters in a thin strip adjacent to the western coast of South America, where models tend to show warm SST biases, excessive oceanic thermal stratification, too little upwelling, and a deficit of stratus cloud;
>
> 2) the eastern equatorial Pacific cold tongue, where the thermocline is shallow, skies are mostly clear, and upwelling is intense;
>
> (3) the southeastern tropical Pacific, where models have too much stratus cloud and/or an unrealistically strong “double” ITCZ in boreal spring;
>
> (4) the LLWBCs, which are an important component in setting the water properties, depth, and intensity of the equatorial thermocline and equatorial undercurrent;
>
> (5) the northern ITCZ, which models often place too far poleward, and whose meridional shifts are critical to ENSO behavior and its interactions with global climate;
>
> (6) the west Pacific warm pool, a regime of atmospheric deep convection that helps to drive a global atmospheric circulation, and the source of the warm waters that spread across the tropical Pacific during El Niño;
>
> (7) the warm pool edge along the equator, a critical zone where complex feedbacks among stochastic westerly wind events, oceanic zonal advection, and possibly salinity barrier layers control the development of ENSO events, and which models usually place too far west.

5. Model-observation process studies and collaboration

5.1 Assessment of model representations of tropical Pacific climate

Coupled climate models continue to be developed with improved resolution, improved parameterisation of unresolved processes and addition of new processes. In addition, the coordination of model simulations and output (e.g. CMIP) mean than models now undergo greater scrutiny and comparison with the limited observational record. A useful evaluation of the current set of CMIP5 models is provided in Chapter 9 of the IPCC AR5 and is summarised here.

Some aspects of the mean climate of the tropical Pacific in models have improved since the previous generation (CMIP3). Cold SST biases in the west Pacific have generally been reduced, as have westerly biases in the zonal wind stress – although models are still not perfect in the west. Stubborn biases remain in all CMIP5 models. SSTs are generally too cold on the equator across a large area of the central Pacific resulting in a cold tongue that extends too far west (Zheng et al., 2012). SST biases are positive in the east against the coast of South America, linked to insufficient marine stratocumulus in models. The latter has been a subject of a coordinated observational and modeling programmeme (VOCALS - Wood et al., 2011). Biases remain in the thermocline depth and slope and in the structure of the equatorial current system. A persistent error, connected to those above, is the so-called "double ITCZ" problem – models have a tendency to produce an ITCZ in the Southern Hemisphere as well as the north. Also, the seasonal cycle of winds and SSTs in the east tends to be too strong and many models produce a spurious semi-annual cycle. All these biases are linked via coupled processes.

Some improvement is seen in CMPI5 representations of ENSO variability. Fewer models have a tendency for 2-yr ENSO in CMIP5 compared to CMIP3 (Guilyardi, 2006; Guilyardi et al., 2012b). Many models now simulate NINO3 SST variability somewhere in the observed frequency band. The spatial pattern of variability has also improved somewhat, with fewer models showing large excessive variability in NINO4. Some models are able to capture a diversity of ENSO events, including weak central Pacific events and strong east Pacific events (Kug et al., 2010; U.S. CLIVAR Project Office, 2013; Capotondi and Wittenberg, 2013).

However, precipitation variability in NINO4 is generally underestimated. These remaining errors in the NINO4 regions are probably due to the mean cold tongue extending too far west, pushing the sensitivity to feedbacks further west. In terms of simple metrics, the range of errors in the magnitude of variability is reduced in CMIP5, largely due to fewer very bad models. A significant advance has been in the evaluation of ENSO feedback processes in models that tend to show an underestimate of the negative thermal damping and positive bias in the zonal advective and thermocline feedback (Lloyd et al., 2012). Increasing atmospheric and oceanic resolution has also helped, by better resolving tropical convection, the Indonesian Throughflow, the Andes cordillera, and tropical instability waves (Delworth et al., 2012).

5.2 Reducing biases in models

Broadly speaking there are three ways in which observations are used to improve climate models; through the improvement of existing parameterisation schemes and in the development of new schemes, through the model assembly and ‘tuning’ procedure and through the identification and diagnosis of errors which are common to all models and the assessment of how those errors relate to uncertainties in predictions and projections.

5.3 Parameterization development and testing

Parameterisation schemes are self-contained components of models that represent physical or biological processes such as ocean mixing. Typically they are developed off-line from the complete model and are based on our understanding of the process combined with empirical relationships derived from observations or from high-resolution process models. A new development in parameterisation in recent years has been the incorporation of stochastic elements to these schemes. Parameterisation schemes that are important for simulating the tropical Pacific include atmospheric convection and clouds, the atmospheric boundary layer, ocean mixed layer processes and penetration of shortwave radiation through the water column, and ocean horizontal and vertical mixing and transport by unresolved eddies. Priorities for the improvement and development of schemes are listed in the following section.

5.4 Process studies targeted at particular model weaknesses where progress is likely

The following processes are currently either deficient or absent in the current generation of GCMs so are priority areas for research in both models and observations; they are where models require observational guidance to advance:

- Convection, in particular the diurnal cycle over land and ocean
- Organized convective features, e.g., the Madden-Julian Oscillation
- The diurnal cycle in the ocean mixed layer
- Low-level stratus clouds
- Tropical instability waves, their heat and momentum transport

5.5 Assembling and evaluating model performance

Model assembly and testing typically happens within each modeling center or within the community group when assembling a new version of a model. Each component, complete with new parameterisation schemes, is put together and initial experiments are performed. These test-experiments are compared with observations and previous versions of the model to prove 'fitness-for-purpose' and to show improvements. The priority-level given to different features of the model depends on the modeling group. For example, in building the HadGEM2 model, the Met Office concentrated a lot of effort into improving the climate of the tropical Pacific because of a focus on seasonal-decadal prediction (Martin et al., 2011). Test-versions of models usually require some improvement or tuning, either involving changing parameters within parameterisation schemes, or by revising the structure of the schemes. Here observations of 'processes' and 'emergent properties' are used.

Model intercomparison projects (MIPs): The exchange of model output between modeling groups has revolutionised climate science in recent years and now we have unprecedented knowledge of the performance of models and their response under enhanced greenhouse gases. Models are compared against climatologies of multiple variables and are also used in detection and attribution studies, which can be viewed as a sophisticated form of evaluation. Model evaluation is now an increasingly sophisticated exercise with evaluation exercises digging deeper and deeper into physical and biological processes. Many model errors persist (see Section 5.1 above) but are now diagnosed in a much better 'process-based' approaches, such as computing the BJ stability index (Jin et al., 2006), though these approaches could use further improvement (Guilyardi et al., 2009, 2012a; Graham et al., 2014).

Different observations are required in the three different stages of model improvement. Typically, detailed observations of processes, perhaps collected during dedicated field campaigns, are used to develop parameterisation schemes in (i) and may be used to test emergent processes in (ii). Normally, steps (ii) and (iii) require longer-term observations and typically gridded datasets are employed, perhaps with some gaps in-filled. Increasingly, analysis or re-analysis products are employed.

6. Conclusion and recommendations

We began by noting the societal and scientific importance of ENSO, and have surveyed here an astonishing amount of work by a large community over more than three decades. Although the bulk of this white paper has shown how much we still *don't* know, and how elusive the problems remain, in fact we've solved a lot of the easy problems and are closing in on the hard ones. These hard problems that observations can speak to are often those that fall below the spatial and temporal resolution of GCMs: interacting phenomena in the ocean mixed layer and atmospheric boundary layer – namely, the actual mechanisms that connect and couple the two fluids. We are confident that progress can be made, and that it will result in improved forecasts benefitting many millions. We believe that this progress will come from observing, diagnosing, understanding and teaching models to simulate the *physical processes* that underlie ocean-atmosphere coupling, and that this will have further benefits to much other science. The laboratory of ENSO will continue to illuminate the other tropical oceans.

We recommend:

a) Do not repeat the mistake of changing observational systems without adequate overlap, evaluation and intercomparison (section 4.1).

b) Focus moored observations where moorings' capabilities are needed: where rapid timescales dominate, and where co-located ocean and atmospheric observations are crucial. These are most importantly the near-surface boundary layers, and the near-equator. The moored array should be augmented to provide higher vertical resolution in the ocean mixed layer, with velocities, and to enhance sampling of the ABL.

c) Bring the TAO array back to the research community. The TPOS is not yet a mature system, and continues to serve comprehensive research goals, as well as goals we cannot yet specify; TAO is the backbone that supports almost everything we do. The research community has shown itself more competent at running these arrays than operational groups, and will provide for essential ancillary sampling and embedded process studies.

d) Foster a diverse-platform observing system because ENSO's rich multi-time and space scale variability and interactions requires comparably-diverse kinds of sampling.

e) Support Climate Process Teams to formulate and carry out process studies targeting model weaknesses.

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