White Paper #8a – Regional applications of observations in the eastern Pacific: Western South America

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1. Introduction

El Niño is the main source of climate variability in the tropical Pacific ocean and it is particularly dramatic along the western coast of South America, where monthly sea surface temperature anomalies during the peak of the 1982-83 and 1997-98 events have been on the order of 9°C. The local warming favors a southward displacement of the ITCZ, which results in dramatic increase in rainfall on the coasts of northern Peru, Ecuador, producing significant losses in infrastructure and economical activities associated with flooding. Also, the tropicalization of the coastal upwelling environment of Peru and Chile produces disruptive effects on the ecosystem and associated fisheries. Decadal variability in the equatorial Pacific is closely linked to variability along western South America. Recent manifestations include the abrupt warming around 1976 throughout the eastern Pacific, which was followed by a cool period since the late 1990s. Similar to El Niño, this variability also impacts climate along the coast and the marine ecosystems. The dynamics of this variability, however, is poorly understood at present. A similar issue is related to climate change, and its potential influence associated with equatorial dynamics and local air-sea interactions along the coast. These relationships are not well understood at present.

Key needs in the region are the enhancement of subsurface monitoring in the far eastern equatorial Pacific and along the coast of South America, and the reduction of long-standing biases in the mean and the variability in climate models in the eastern Pacific, guided by process understanding, to provide reliable climate forecasts on intraseasonal to decadal scales, and climate change projections for the eastern Pacific and its feedbacks and impacts on global climate.

2. Applications of ocean observations

Scientific applications:

- Improve the understanding of critical processes in the equatorial eastern Pacific that will lead to the improvement in the understanding and modeling of ENSO, decadal variability and climate change in this region. This is particularly important in the light of long-standing errors in the eastern Pacific in climate models and the associated challenges in representing ENSO diversity. Key processes are ocean temperature advection, turbulent ocean mixing, dissipation and dispersion oceanic equatorial waves, atmospheric convection in the ITCZ and convectively-coupled wave-like atmospheric disturbances, meridional ocean-atmosphere coupled mechanisms, and the role of the wind mountain gaps between the Caribbean and Pacific in equatorial ocean-atmosphere dynamics.
- Monitoring of CO_2, pH, chlorophyll and oxygen, and associated oceanic transports and air-sea fluxes in the near-equatorial eastern Pacific and coastal zone in order to improve the understanding of large marine ecosystems dynamics in the context of climate variability and change.

Operational applications:

- Near real-time monitoring of intraseasonal equatorial Kelvin wave propagation across the basin and along the coasts of western South America (e.g. SST, sea level and thermocline depth). This information, together with forecasts from international centers, feeds the analysis that national institutions make for the assessment of local potential effects of ENSO-related anomalies in the eastern Pacific.
- Monitoring of upper ocean water masses (temperature, salinity, and other tracers) in the eastern Pacific on monthly to seasonal timescales to attribute causality of climatic anomalies (e.g. associated with the southward displacement of the equatorial front or shutdown of coastal upwelling) to water transports (horizontal advection) or more local processes (mixing, vertical advection, cloudiness). Continuity and quality control of long term series by regional institutions and buoys (TAO and Stratus) are prioritary for assessing decadal variability.
- Near real-time monitoring of coastal and eastern Pacific winds (i.e. local forcing of coastal ocean conditions) on meteorologically synoptic timescales. In addition to the equatorial zonal winds and the southeasterly trades, northerly gap winds in the far-eastern Pacific are also important.
- Real-time diurnal-cycle-resolving observations in the ocean subsurface thermal structure, sea surface temperature and 3D atmosphere structure (wind, temperature), with emphasis on the eastern tropical Pacific, for assimilation and validation of operational seasonal forecast model systems.
- Near real-time monitoring of intraseasonal atmospheric equatorially propagating disturbances (e.g. MJO or convectively coupled Kelvin waves) for medium-range weather forecasting for western South America and forecasting potential forcing of equatorial ocean Kelvin waves. In addition to remote sensing (e.g. OLR), in situ daily profiling of atmospheric variables along the equator will be valuable, particularly in the eastern Pacific where convective coupling is generally weak.
- Near real time and long term monitoring of surface-ocean and coastal waves for assimilation (and validation) into operational wave forecast and warning systems. Long term monitoring is also needed for a climatologically characterization of surface waves and their extremes for planning in the coastal and offshore (i.e. navigation, fishing and oil/gas offshore activities) regions.
- Monitoring of ocean biogeochemical variables on seasonal timescales to identify environmental changes for marine ecosystems management and associated fisheries. These will be the basis for medium and long term adaptation strategies and international coordinated efforts.
- Near real-time monitoring of precipitation, both *in situ* and through high resolution 3D remote sensing (e.g. Global Precipitation Mission), in the eastern Pacific, including western South America, is needed for assessment of ENSO-related impacts and potentially for assimilation into forecast systems and their validation. Both types of data should be considered complementary and inter-dependent.

3. Scientific questions/main drivers

3.1 Role of the eastern Pacific in ENSO Diversity

Great progress in El Niño research has been made under the TOGA program and it is believed that an understanding of the essential mechanisms has been achieved (e.g. Wallace et al., 1998;

Neelin et al., 1998). However, in the recent decade there has been renewed interest in understanding the differences among individual ENSO events. As noted by Wallace et al. (1998): "Descriptions based on a single index do not do justice to the complexity of the climate variability over the equatorial Pacific", and Trenberth and Stepaniak (2001) proposed that at least two indices should be used for describing ENSO evolution. This extra degree of freedom and, particularly, the associated effect on the longitudinal position of the maximum SST anomalies has been the focus of recent work (e.g. Larkin and Harrison, 2005; Ashok et al., 2007; Kug et al., 2009). This approach is particularly relevant considering that the recent decade appears to have experienced a larger relative frequency of El Niño events with their SST maxima located in the central Pacific (e.g. Kug et al., 2009; Lee and McPhaden, 2010), although it is unclear whether this reflects a long-term trend (Ray and Giese, 2012).

A different interpretation of the record suggests that the extraordinary El Niño events of 1982-83 and 1997-98 corresponded to a nonlinear ENSO regime, different from all the other El Niño events (Takahashi et al., 2011; Dommenget et al., 2012; Takahashi and Dewitte, 2014). In addition to their generally large magnitude, these events featured disproportionally large SST anomalies in the Niño 1+2 regions (Takahashi et al., 2011) and a different temporal evolution to the “canonical” El Niño, which precluded the recognition of the onset of the 1982-83 event at that time (Wallace et al., 1998). However, only two extraordinary events have been observed in modern times, and only the 1997-98 event was measured comprehensively by the TAO array. Furthermore, despite their similarities, these two events presented some substantial differences between them, so that the observational constraints on some subtle aspects of their common dynamics are not tight (Takahashi and Dewitte, 2014).

A way of gaining some insight into what made these events different is to analyze simulations by models that reproduce some of the key observed features and verifying the relevant mechanisms with observations. For instance, an analysis of the GFDL CM2.1 model, which reproduces in detail many aspects of both observed extraordinary events, indicates that atmospheric and oceanic non-linearities are at the heart of the existence of the two El Niño regimes (Takahashi and Dewitte, 2014). Two types of nonlinear processes are considered the leading potential sources of asymmetries in El Niño/La Niña.

Firstly, it has been proposed that positive nonlinear ocean advection in the eastern Pacific enhances El Niño and reduces La Niña, particularly through vertical advection (Jin et al., 2003; An and Jin, 2004) and this idea has been used to devise simple mathematical models that reproduce burst-like El Niño events (An and Jin, 2004; Timmermann et al., 2003). However, newer reanalysis products indicate that this vertical nonlinear advection is actually negative, but that the zonal nonlinear advection makes up for this and produces a net positive nonlinear advection (Su et al., 2010). These analyses are all based on reanalysis products that provide a complete 4D depiction of the state variables yet, if observed data is not assimilated into them; the result would be dependent on underlying the ocean general circulation models. The discrepancy in the sign in nonlinear vertical advection among reanalysis products can be traced to the sign of the equatorial vertical velocity anomalies in the Pacific east of 95W (Su et al., 2010), but this variable is not directly measured (and therefore is not assimilated into the reanalysis) so the contribution of this process to ENSO asymmetry and regimes remains an open question.

The other key nonlinearity is related to the existence of a threshold SST above which atmospheric deep convection is active (e.g. Graham and Barnett, 1987). This nonlinearity has been formulated in a variety of ways in ENSO models, where it accounts for a nonlinear response of surface wind stress to SST anomalies (e.g. Zebiak, 1986). This can explain not only the asymmetry between El Niño and La Niña (Dommenget et al., 2012; Choi et al., 2013) but, if the threshold is substantially above the climatological values, this can explain the existence of two different El Niño regimes, with one of them corresponding to the extraordinary events (Takahashi et al., 2011; Takahashi and Dewitte, 2013). However, observational evidence of the latter is limited to the sampling of only two events. Empirically, the response of convection to SST anomalies is known to depend on the basic atmospheric state (Zebiak, 1986; Xiang et al., 2013), yet the nature of this dependence and how the changes on long time-scales will influence the convective feedback on ENSO is not straightforward.

It has been proposed that decadal changes in the air-sea coupling in the eastern Pacific (Choi et al., 2010) and westward shift in the mean equatorial Pacific atmospheric low-level convergence (Xiang et al., 2013) resulted in the observed changes in ENSO characteristics, i.e. with reduced variability in the eastern Pacific in the recent decade, leading to an ENSO SST pattern maximizing in the central Pacific. On longer timescales, Vecchi and Soden (2007a) showed that climate change effects on tropical convection through SST could be non-local, i.e. changes in the tropical SST pattern can also have an effect comparable to the changes in local SST. On the other hand, climate model projections show that increased atmospheric moisture associated with warming will lead to larger precipitation anomalies during El Niño, even if the related SST variability does not change (Power et al., 2013).

Although El Niño research has adopted the ENSO paradigm, El Niño events local to the far eastern Pacific, characterized by coastal warming and heavy rainfall in northern Peru and Ecuador as they were initially identified (Carrillo, 1891; Carranza, 1893; Murphy, 1926), can be substantial and not strongly linked to the basin-scale mode (e.g. Deser and Wallace, 1987). For example, the El Niño event in 1925 (Murphy, 1926) had very strong impacts associated with heavy rainfall along the coasts of Peru and Ecuador due to a southward displacement of the ITCZ like has not been seen ever since, while the central Pacific was anomalously cool (Takahashi et al 2014). Meridional ocean-atmosphere dynamics in the eastern Pacific appear to have played a role at least as important as the well-known zonal processes (i.e. equatorial zonal winds and oceanic waves, etc.). Additionally, meridional processes originating in the southeast Pacific associated with surface winds and heat ocean-atmosphere exchange could penetrate into the equatorial eastern Pacific and affect ENSO (Toniazzo, 2010; Zhang et al., 2014ab), similarly to the air-sea coupled process already documented for the Northern subtropical Pacific (Chiang and Vimont, 2004, Vimont et al., 2003).

3.2 The equatorial Kelvin wave in the eastern Pacific

The equatorial Kelvin wave is a salient feature of the tropical Pacific dynamics at a variety of timescales (from intraseasonal to interannual) because it transfers rapidly (in a few months) and efficiently the variability from the western Pacific to the eastern Pacific. For this reason, the equatorial Kelvin wave is also inherently tied to the ENSO dynamics through its effect on both the zonally averaged heat content in the equatorial Pacific and the advection processes, acting both as a trigger and a time-integrator for ENSO. It is also the main oceanic conduit by which the South American west coast is impacted by the tropical climate due to the coast behaving as an extension of the equatorial wave guide. Although variations in sea level, thermocline and current in the equatorial Pacific can be interpreted to a large extent from linear theory, due to the anisotropy for the mean state (thermocline, SST, currents), a number of processes have the potential to modify the characteristics of the equatorial Kelvin wave (flux, phase speed, amplitude, vertical structure).

TAO data have been key for documenting/monitoring the variability in current and thermocline depth associated to the intraseasonal to interannual Kelvin wave (McPhaden and Taft, 1988; Kessler et al., 1995; Johnson and McPhaden, 1993; Kessler and McPhaden, 1995ab; McPhaden et al., 1998). However, progress in our understanding of the role of the Kelvin wave on ENSO dynamics has been permitted by the satellite altimetric data that provides the sufficient horizontal resolution for an estimated separation into Rossby and Kelvin waves (Perigaud and Dewitte, 1996; Boulanger and Menkes, 1995; Boulanger and Fu, 1996), allowing for testing ENSO theories (see Neelin et al. (1998) for a review) that confers to the reflections of equatorial waves on the meridional boundaries a key role. Sea level anomalies has been also shown to be a good proxy of anomalous heat content in the equatorial band (Meinen and McPhaden, 2000), which determines to a larger extent the evolution and amplitude of ENSO (Jin, 1997). Although the interannual Kelvin wave has a clear signature on SST and is well observed through altimetric data, the intraseasonal Kelvin wave has its largest influence on subsurface temperature (in the vicinity of the thermocline) with a weak signature on SST (Mosquera et al., 2014) and is less easily diagnosed from weekly satellite data due to its stronger dissipation.

Because the thermocline slopes from west to east, the vertical structure of the equatorial waves is not homogeneous in space (Dewitte et al., 1999), which implies that the Kelvin wave may experience a change in amplitude, phase speed, vertical and meridional structure as it reaches the eastern Pacific (Dewitte et al., 2003) or a strong dispersion through scattering of energy (Busalacchi and Cane, 1988; Dewitte et al., 1999). At intraseasonal timescales, the equatorial Kelvin wave can be also impacted by Tropical Instability Waves (TIW) (Giese and Harrison, 1999) that produces mixing (Luther and Johnson, 1990). In return, the Kelvin wave can also affect the instability conditions (if the mean flow is weak) on which the TIWs depends. The Kelvin wave can also partially reflect as Rossby waves which may subsequently trigger TIWs (Allen et al., 1995). The scattering of energy of the Kelvin wave has been studied previously mainly theoretically (Busalacchi and Cane, 1988; Giese and Harrison, 1990). Dewitte et al. (1999) using a multimode ocean model suggested that modal dispersion could explain the large eastward increase in the contribution of the higher-order baroclinic modes to zonal currents and sea level in the eastern Pacific (east of 120°W) at interannual timescales, implying a change in dynamical regime in the eastern Pacific compared to free non-dispersive low-order propagating wave dynamics as in the central Pacific, Such modal dispersion process remains largely undocumented from observations although satellite data reveals an eastward change of the dominant frequency (from ~60 days^{-1} to ~120 days^{-1}) of the intraseasonal Kelvin wave (Cravatte et al., 2003) suggestive of energy scattering of the long waves.

The motivation for better understanding the dissipation process of the equatorial Kelvin at intraseasonal timescales arises also from the observations that the recent decades have been characterized by a relatively steeper mean thermocline, favorable for the of wave energy in the central Pacific. Recent El Niño events (i.e. Central Pacific events) are characterized by an increased variance of the intraseasonal Kelvin wave activity in the central Pacific (Gushchina and Dewitte, 2012; Mosquera et al., 2014) at their peak phase, suggesting that the intraseasonal Kelvin wave may be linked to Central Pacific El Niño dynamics. So far the study of the intraseasonal equatorial Kelvin wave and its role on ENSO has been somewhat limited to its potential in triggering a local Bjerknes feedback prior to the development of ENSO (Lengaigne et al., 2004; Kessler and Kleeman, 2000; Kleeman et al., 2003), which applies to extreme El Niño events. Intraseasonal Kelvin wave activity is linked to the MJO activity that favors the development of Westerly Wind Bursts. In previous studies (Hendon et al., 2007; McPhaden et al., 2007; Lengaigne et al., 2004), MJO (and associated intraseasonal Kelvin wave) activity was shown to be anomalously active prior to the development of El Niño (6 to 7 month ahead the peak phase). However, as mentioned earlier, extreme El Niño events are very few over the instrumental record (2 events, 1982/83 and 1997/98), so that such relationship may apply mostly for Eastern Pacific events although Bergman et al. (2001) indicate that the MJO was abnormally inactive prior to the 1982/83 El Niño.

The “stochastic” nature of the intraseasonal Kelvin wave and its tied relationship to ENSO calls for monitoring parameters that allows for its derivation/estimation. Whereas, within the assumption that the ocean reduces to a unique active surface layer, satellite data do provide estimate of the amplitude and evolution of the intraseasonal equatorial Kelvin wave, they have not been used to understand the processes that impact its propagating characteristics, because the latter depends largely on the vertical structure variability of currents and temperature. The TAO array has provided such information so far. However, it is not clear to which extent the available information can be used for inferring the characteristics of the equatorial Kelvin wave in the far eastern Pacific and its dispersion due to the rather coarse vertical resolution of the existing array and lack of data east of 95W.

Long wave dissipation has been modeled by a Rayleigh friction in most simple model studies and a wide range of estimates of the time decay for such effective friction have been used (from 6 months to 30 months). The rather wide range of values reflects that the decay time scales of equatorial waves are frequency dependent. Upper ocean wave dissipation has been studied in the frame of linear theory assuming that the vertically propagating variability through the thermocline accounts for the loss of energy that has a surface expression onto sea level (Kessler and McPhaden, 1993; Dewitte and Reverdin, 2000). Such process is hardly detectable from available observations because of the paucity of the data below the thermocline and the relatively low vertical resolution. The study of such process would also greatly benefit from the implementation of high-vertical resolution thermal profiling in the eastern Pacific where the annual and interannual Rossby wave is detectable below the thermocline. Dissipation can be accounted for by non-linear processes that are potentially at work in the eastern Pacific due to the strong vertical current shear associated to the equatorial undercurrent (EUC), the sharp SST front north of the equator associated to the cold tongue and a driver of TIW activity, the maximum zonal gradient of the thermocline (located ~120°W) potentially producing modal dispersion of the waves (Mosquera et al., 2014), and local-air sea interactions. Wave damping in the eastern Pacific will result in all cases from the accumulation of warmer water (weaker stratification) where the Kelvin waves are damped. So far the study of these processes has been mostly based on the experimentation with ocean models confronted to TAO observations (Cravatte et al., 2006; Benestad, 1997; Mosquera et al., 2014). The better understanding of these processes (that are resolution-dependent) would require high-vertical resolution and high-frequency measurements (microstructure, internal waves) which have been only available in the past from dedicated cruises (3 main experiments in the eastern Pacific since 1979) and now from the Argo data (although the equatorial divergence does not ease the dense sampling of such processes). The modeling community would greatly benefit from such measurements in order to develop useful parameterizations of diapycnal fluxes in the equatorial upwelling region and to improve the realism of the mean vertical stratification of the eastern equatorial Pacific as simulated in current generation CGCMs (Figure 3.1).

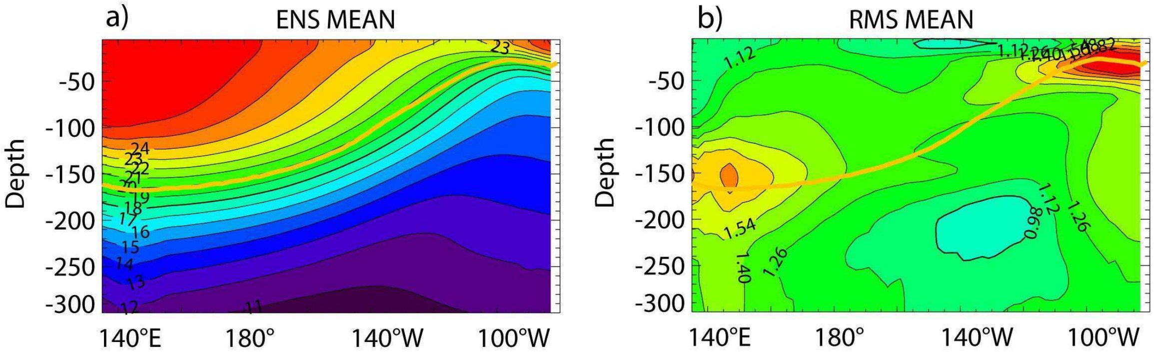


Figure 3.1 - (a) Ensemble mean (15 CMIP3 models) of vertical temperature and (b) the dispersion (RMS) among models. The ensemble mean thermocline depth is overplotted (orange thick line).

3.3 The thermocline feedback in the eastern Pacific

The magnitude and interaction of the mechanisms by which the thermocline fluctuations connects to the SST in the eastern pacific (called “thermocline feedback” in ENSO studies) remain largely unknown and depend on the complex of processes that connects the thermocline to the surface. These processes are parametrized as a whole in intermediate complexity coupled model. In the OGCMs, also parametrized into the mixing terms, they are highly dependent on both horizontal and vertical resolution. Due to the large dispersion in the representation of the thermocline in current generation coupled models in the eastern tropical Pacific (cf. Figure 1), there is a large uncertainty on how these models can predict the change in ENSO statistics. The thermocline feedback in the eastern Pacific is crucially influential on the evolution of ENSO and determines its stability (An and Jin, 2001). Quantifying its “strength” requires estimating the details of the heat budget in the eastern Pacific in the upper ~50m since it implicitly accounts for various processes, including vertical diffusion/entrainment and linear vertical advection. So far the thermocline feedback in the eastern Pacific has not been explicitly estimated observationally although it is a key parameter for ENSO dynamics. Current estimate relies on oceanic reanalysis in which TAO data have been assimilated and consists in either the estimate of the regression coefficient between SST and thermocline depth anomalies or the derivation of ad-hoc parametrizations (Zebiak and Cane, 1987). There is also indication of a marked zonal variation of the thermocline feedback within the eastern Pacific region (e.g. Niño 3 region), particularly with a sharp decrease east of the Galapagos Island associated with the higher SST there.

There have been some speculations concerning a possible connection between the cold tongue and the upwelling off Peru, which would imply a relation between the thermocline feedback and the Peru upwelling, although a model experiment suggests otherwise (Kessler et al. 1998). In order to refine our understanding of such process and to validate the ocean models in this region, observations of upwelling in full three dimensional context are necessary, which the TAO data have allowed so far, although the current design of the network (i.e. low meridional resolution) have limitations for inferring the 3-D circulation of the “tropical cells” (McCreary and Lu, 1994) or details of the ramification of the EUC east of the Galapagos Islands (Montes et al., 2010). New instrumentation (e.g. gliders and Argo floats) and high-resolution oceanic model could help documenting the meridional variability of the circulation in the eastern Pacific and its role in modulating the equatorial stratification, which can provide guidance for adapting the TAO mooring array spacing.

3.4 Coastal dynamical and biogeochemical processes

The carbon, nitrogen and oxygen cycles are closely related in the Peru-Chile upwelling system (PCUS) (Lam et al., 2009). Coastal upwelling and the relatively shallow position of the thermocline allow an efficient upward advection of nutrients from the nutrient/CO_2-rich subsurface waters, releasing CO_2 during the active upwelling and triggering strong phytoplankton growth when upwelling relaxes. The large productive area associated to this Eastern Boundary Upwelling System, overlaps to some extent with the southeastern Pacific oxygen minimum zone (OMZ) that impinges the continental margin (Pennington et al., 2006; Helly and Levin, 2004). Due to the predominant oxygen-deficiency in the subsurface waters and the high concentrations of organic matter, high rates of anaerobic ammonium oxidation and water column denitrification occur in the water column, causing that this region be one of the most important areas of Nitrogen loss in the global ocean (Lam et al., 2009). Over the shelf and upper slope, the main oxygen sources are the Peru–Chile undercurrent, which is mainly fed by the eastward equatorial subsurface currents (Montes et al., 2011), and the turbulent diffusion from the surface; while the main sink is the oxygen consumption by the high respiratory demand of the particulate organic matter settling from surface waters (Codispoti et al., 1989; Fossing, 1990; Pennington et al., 2006; Schunk et al., 2013).

This general pattern exhibits latitudinal and mesoscale variations along the PCUS, associated with the distance to the Equator, the position of upwelling cells relative to the south Pacific anticyclone, and the extension of the continental shelf, among other factors. ENSO-driven impacts vary in intensity as well, and local and regional forcing gain in importance nearshore and poleward.

The classical description of biogeochemical impacts associated with El Niño involves the disruption of coastal upwelling-related fertilization of surface waters due to the deepening of the thermocline, associated with the intensification of the poleward undercurrent and the propagation of coastal trapped waves from the Equator from the early phases of the events (Huyer et al., 1991; Morales et al, 1999, Gutiérrez et al., 2008). The same process ventilates the subsurface waters, while the reduction of primary productivity results in lesser oxygen consumption in the water column, leading to a net oxygenation of the system. In addition, coastal trapped waves propagating during non-El Niño conditions also trigger shallow subsurface oxygenation episodes (Gutiérrez et al., 2008). So far, the El Niño impacts on the nutrient cycles have not been quantified, but certainly the subsurface oxygenation and the decreased productivity should modify the nutrient ratios in the upwelling source waters, while in parallel diminish the export production to the seafloor and offshore, as well as the release rates of nitrous oxide and CO_2 to the atmosphere.

On the other hand, in the eastern tropical Pacific, a different seasonal upwelling mechanism occurs along the central American coast from December through March, where wind jets cross the physiographic gaps of central America existing at the Gulf of Tehuantepec, Gulf of Papagayo and the Isthmus of Panama (Chelton et al., 2000) producing oceanic upwelling due to Ekman pumping, increasing the subsurface oxygen and nutrient availability and producing a surface chlorophyll bloom as was observed in the Colombian Pacific Ocean (Rodríguez-Rubio and Stuardo, 2002; Rodríguez-Rubio et al., 2003). This particular process, and its relationship with the wind field and ocean and coastal currents, is also influenced by the ENSO and is involved in ocean-atmosphere feedbacks (Chiang and Vimont, 2004; Xie et al., 2005).

Understanding the coupling between physical and biogeochemical processes along the west coast of South America has major practical consequences. The PCUS is the most productive in the world (e.g., Alheit and Bernal, 1993; Chavez et al., 2008) and supports the large fishing industry of Chile and Peru. According to the hypothesis of the “optimal environmental window” (Cury and Roy, 1989), both La Niña-like conditions (stronger mixing and advection) and El Niño-like conditions (weaker upwelling) would be negative for small pelagic fish larval recruitment. But if El Niño signature changes towards a dominance of Central Pacific El Niños (Yeh et al., 2009), the net effect would be more complex to predict. Paleoceanographic records evidence multi-decadal changes in oxygenation, productivity and fish production along the Peru-Chile coast, associated to past warmer or cooler periods. During the Little Ice Age (ca. 1500 – 1800 AD), an overall reduction of fish productivity off central Peru occurred while the OMZ weakened, with little effect off northern Chile. By the mid- to late nineteenth century, a period of more frequent El Niño events (Ortlieb, 2000; Gergis and Fowler, 2009) was associated to a reduction of anchovy and increase of sardines off central Peru, with lower effect off northern Chile (Gutiérrez et al., 2009; Valdés et al., 2008), suggesting a poleward displacement of the anchovy population nucleus. Using projected surface winds from regional numerical downscaling (Fuenzalida et al., 2007). Aiken et al. (2011) studied larval dispersion and meridional connectivity off central Chile under intensified favorable upwelling winds, suggesting a potential reorganization of coastal communities at the end of this century. Moreover, Yáñez et al. (2013) found large discrepancies in the anchovy landings in northern Chile under different climate scenarios through the XXI century. For instance, by 2050 the annual landing would increase (~4%) or decrease (~20%) if a cooling or warming condition is verified in northern Chile, respectively.

3.5 Convective processes in the eastern Pacific and ENSO

The atmospheric circulation in the deep tropics is strongly tied to moist convection. In the eastern Pacific, the latter is primarily organized by the ITCZ, that features a zonal band of convective systems to the north of the equator and that constitutes the regional component of the upward branch of the Hadley circulation. Seasonally, the latitude of the eastern Pacific ITCZ varies, approximately in synchrony with the highest SST (e.g. Mitchell and Wallace, 1992), although the two should be viewed as part of strongly coupled system (e.g. Xie and Philander, 1994; Takahashi and Battisti, 2007ab) seasonally driven by insolation. On interannual timescales, variability in precipitation in this region is dominated by ENSO and can also be characterized as meridional displacements of the ITCZ according to the SST anomalies, but also providing nonlinear feedbacks into the ENSO system (Lloyd et al., 2012; Dommenget et al., 2012; Takahashi and Dewitte, 2014). With future climate change, the increase in atmospheric moisture content could lead to an intensification of the precipitation rates in rainy regions such as the ITCZ (Held and Soden, 2006), although the climate models indicate also a southward displacement of the ITCZ (IPCC WG1, 2013). Recently, analyses of global climate models indicate that, with future climate change, El Niño would produce stronger rainfall anomalies even if the SST statistics were unchanged (Power et al., 2013; Cai et al., 2014). Also, climate change scenarios indicate that future changes in upwelling-favorable winds off Peru are strongly linked to the changes in precipitation (Belmadani et al., 2013).

However, the climate model deficiencies are large in the eastern Pacific and calls for considering these results with caution. In particular, global climate models suffer from the so-called “double ITCZ syndrome”, which results in strong positive rainfall biases in the southeastern Pacific and appears to be associated with the frequency of deep convective events in the atmospheric models (Bellucci et al., 2010). The problem persists even in the end-of-the-line CMIP5 models (IPCC WG1, 2013). On the other hand, observations of the eastern Pacific ITCZ are lacking and its basic structure is not well known. Satellite based measurements indicate that the vertical structure convective heating is maximum in the mid-upper troposphere (Schumacher et al., 2004), but Reanalysis products indicate that the ascent is shallow (Back and Bretherton, 2006), consistent with the direct observations of a strong shallow overturning circulation in this region (Zhang et al., 2004). The vertical structure of the latent heating is of particular importance to ENSO since it has substantial influence on the surface wind response that is key for the Bjerknes feedback (Nigam et al., 2000; Nigam and Chung, 2000; Wu, 2003).

Given the uncertainties in reanalysis and remote sensing, observational estimates of profiles of latent heating, which can be obtained from radiosonde networks, or vertical velocity, which can be directly measured with wind-profiling radars (e.g. Gage et al., 1991) are required. In the case of the latter, however, these are restricted to equatorial islands (e.g. Galapagos and Christmas islands), so would only measure the ITCZ during strong El Niño events. On the other hand, field campaigns like EPIC (Raymond et al. 2004) would provide invaluable information, but the determination of the mean vertical velocity profiles would require a field campaign design with several radiosounding stations around the ITCZ over periods long enough to average out the high-frequency variability.

Additionally, warm conditions in the eastern Pacific may allow equatorial weather systems such as the Madden-Julian Oscillations and convectively coupled Kelvin waves to propagate farther into the east (Straub and Kiladis, 2001), thus providing an enhancement of stochastic forcing of ENSO (e.g. Jin et al., 2007). It is necessary to carry out observational verification of this process and the characterization of the dynamics of these systems in order to improve ENSO representation. Continuous wind and thermodynamic profiling from equatorial islands would allow observing these systems even when the convective signal is weak, particularly over the equatorial cold tongue, which would be useful for monitoring and forecasting purposes.

3.6 Decadal variability and climate change in the tropical-south Pacific

Since Nitta and Yamada (1989) and Trenberth (1990) noticed the presence of interdecadal fluctuations in the observed climate records, their importance has increased dramatically dramatically due in part to the difficulty to separate their regional manifestation from climate change of anthropogenic origin. Certainly, all the different interdecadal climate modes defined since the 1990s are the result of internal climate variability, in which the ocean plays a key role. In the Tropical-South Pacific region the most important interdecadal mode is the Interdecadal Pacific Oscillation (IPO; e.g., Power et al., 1999), or the ENSO-like interdecadal variability (Zhang et al., 1997), that resembles the typical ENSO pattern but with a broader latitudinal scale in the eastern Pacific (e.g., Garreaud and Battisti, 1999). The interdecadal variability along the west coast of South America was first recognized in fisheries fluctuations in Peru (Pauly and Tsukayama, 1987), Chile (Yanez, 1991) and Colombia (Díaz-Ochoa *et al*., 2004). However, there is a few studies based on observed atmospheric and oceanic in Perú and Chile (Montecinos et al., 2003), and recently in Colombia (Rodriguez-Rubio, 2013).

Clarke and Lebedev (1999) showed that decadal and longer changes of the thermocline depth off California are mainly driven by low-frequency strengthening and weakening of the equatorial Pacific trade winds. They suggested that this mechanism should be responsible for decadal and longer fluctuations along the western coast of the Americas. Accordingly, Pizarro and Montecinos (2004) found that the thermocline depth and SST anomalies off Ecuador, Peru and Chile, which are positively correlated at interdecadal timescales, change along with the equatorial wind anomalies. Specifically, their estimation of the thermocline depth in the eastern tropical Pacific, which is proportional to the integral of the zonal wind stress along the equatorial Pacific (Clarke and Lebedev, 1999), presents similar evolution and amplitude in comparison with the observed thermocline along the western coast of South America.

On the basis of multivariate analysis of the SST-sea level pressure (SLP) coupled interdecadal variability in the tropical South Pacific region, Montecinos and Pizarro (2005) compared three mechanisms explaining SST variability along the western coast of South America: the equatorial wind driven mechanism of Clarke and Lebedev (1999), the advection mechanism of White and Cayan (1998), and the local upwelling mechanism of Tourre et al. (2001). According to their results, positive (negative) SST interdecadal anomalies in the eastern equatorial Pacific and along the western coast of South America are explained by westerly (easterly) equatorial wind stress anomalies that would force deeper (shallower) thermocline depths in the region, while south of 30°S the local northerly (southerly) alongshore wind stress anomalies reinforce the positive (negative) SST anomalies driven remotely, through coastal upwelling fluctuations. These results were derived from the analysis of numerical simulations of the interface elevation anomalies with a reduced gravity model forced by observed wind stress (Montecinos et al., 2007). Also, these authors shown that, in the eastern equatorial Pacific, interface elevation anomalies are negatively correlated with SST at interdecadal timescales.

As a result of the external forcing, the global mean surface temperature exhibits positive trends (warming) since the beginning of the XX century, with an interruption from 1940s to 1970s (e.g., Vose et al., 2012). Natural forcing, in particular the increased solar radiation, can explain most of the warming in the first part of the XX century (e.g., Stott et al., 2000; Meehl et al., 2004; 2009a), while anthropogenic forcing appears to be responsible for the warming observed since late 1970s (e.g., Hegerl et al., 2007; Meehl et al., 2009a). The expected surface warming in the tropics is not uniform (Meehl et al., 2007). The IPCC projections for the XXI century show local minimum warming in the Southeastern tropical Pacific, the South tropical Atlantic, and the North tropical Atlantic (e.g., Vecchi and Soden, 2007a; Leloup and Clement, 2009). In particular, Leloup and Clement (2009) suggest the increasing efficiency of latent heat flux as responsible for the minimum warming, yet it would not be applicable in areas where the projected wind speed increases, as the southeastern Pacific (Garreaud and Falvey, 2009). On the other hand, most model simulations suggest that the response of tropical Pacific to radiative forcing would resemble an El Niño-like warming pattern (e.g., Held and Soden, 2006; Vecchi and Soden, 2007b), although a La Niña-like cooling pattern could also be expected theoretically (Clement et al., 1996; An and Im, 2013). So far, the observational evidences are ambiguous (e.g., Vecchi et al., 2008).

In the context of the global anthropogenic warming, observational evidence shows a noticeable cooling trend in the Southeastern Pacific since late 1970s (Trenberth et al., 2007; Falvey and Garreaud, 2009; Schulz et al., 2011; Gutiérrez et al., 2011a) in contrast with warming immediately inland. Vargas et al. (2007) and Gutierrez et al. (2011b) have extended back in time the evidence of the coastal cooling since late XIX century based on paleo-temperature estimations from sediments at 23°S and 14°S, respectively. According to Gutierrez et al. (2011b), the cooling trend increases since 1950s despite the interdecadal variability present in the region (e.g., Garreaud and Battisti, 1999; Montecinos et al., 2003). This negative sea and air surface temperature trends in the Southeastern Pacific, from tropics to mid-latitudes, is not simulated by coupled global models (Falvey and Garreaud, 2009). On which degree the observed cooling trend is related with the intensification of the Eastern Pacific OMZ (Stramma et al., 2010) is still an open question. Although in the latest years there have been reports of sulphidic events reaching the surface waters off the Central Peruvian coast (Schunk et al., 2013; G. Lavik, pers. comm.), so far there is not a conclusive result on existing long-term trends for the subsurface oxygenation along the Peru-Chile coast.

A plausible factor for explaining the cooling trend is an intensification of the alongshore wind stress and the associated coastal upwelling enhancement. The coastal winds could be increasing due to an intensification of the South Pacific subtropical anticyclone (Falvey and Garreaud, 2009), increasing land-sea pressure gradient due to the land warming (Bakun, 1990; Narayan et al., 2010) or the increasing land-sea thermal contrast due to reduced mean low-cloud cover (Vargas et al., 2007). In climate change models, the increase in the winds off central Chile is associated with changes in the anticyclone, but changes off Peru, on which models do not agree, is associated with changes in the oceanic rainfall distribution (Belmadani et al., 2013). The remote response of the coastal thermocline to enhanced zonal equatorial Pacific wind stress at low frequency timescales (Pizarro and Montecinos, 2004; Montecinos et al., 2007) or the increase occurrence of Central Pacific El Niño in the recent decades (Dewitte et al., 2012) are other sources of cooling. Also, changes in the northward advection of subantarctic water have been argued to explain observed cooling (and freshening) trend during the 1990s (e.g., Schneider et al., 2007). On the other hand, local processes such as an increase in cloudiness associated with cold advection or low level stability (Klein and Hartmann, 1993; Takahashi, 2005) or enhanced evaporation associated with subsidence (Takahashi and Battisti, 2007; Xie et al., 2010) could also play a role. To this respect, Schulz et al. (2011) shown that, for northern Chile, the cloudiness exhibited a strong decrease since the 1970s.

On a broader scale, away from the coast of South America, decadal variability in the southeast Pacific has been characterized in terms of local ocean-atmosphere interactions involving SST, cloudiness, wind speed, and evaporation (Clement et al., 2009; Okumura, 2013). Due to the meridional asymmetry of the eastern Pacific climate relative to the equator, this southeastern Pacific variability can influence the equatorial Pacific more easily than the north Pacific and can therefore lead to further teleconnections through changes in the equatorial convection and through the oceanic equatorial waveguide (Okumura, 2013; Zhang et al., 2014ab). Although ocean dynamics in the southeast Pacific itself do not appear to be important for this mechanism, characterizing and monitoring the changes in the ocean thermal structure will be necessary for modeling and prediction efforts on decadal timescales.

Monitoring the eastern equatorial Pacific on decadal timescales is also important in terms of global climate change, as has been suggested in relation to the reduced global warming rate of the last two decades. The model experiments of Kosaka and Xie (2013) suggest that one important process behind this was the intensification of the eastern Pacific cold tongue. An observational confirmation of the mechanism would require adequate data for a heat budget calculation over decadal timescales, but in this region upwelling and mixing are key processes and their estimation would require knowledge of vertical velocities and turbulence, which are not standard variables.

3.7 Seasonal and intraseasonal prediction

The history of physically based seasonal climate forecasts is relatively short and strongly linked to the ability to predict sea surface temperatures (SST) in the El Niño region. The first physically based model forecast of equatorial Pacific Ocean temperatures was produced only in the mid-1980s (Cane et al., 1986). The growing ability to predict El Niño led to a cascade of efforts for developing and improving the seasonal climate forecasts and attempting to make those useful to society (Goddard et al., 2011). El Niño is the overall dominant influence in regional climate variability worldwide, though other modes of sea surface temperature variability can be more important in some regions (Folland et al., 1991).

On the other hand, although many operational climate models were able to predict an El Niño event in 1997, they all underestimated its magnitude (Barnston et al., 1999; Landsea and Knaff, 2000). This issue is particularly notorious in the prediction of the eastern Pacific SST anomalies, which were the largest during this event, as they were in 1982-1983 (e.g. Takahashi et al., 2011), and even the most recent climate models can not hindcast this correctly, as shown in Figure 3.2 for the NOAA CFS v2 model. In this model, it is interesting that not only the Niño 1+2 hindcasts for the 1982-1983 and 1997-1998 events were underestimated by the ensemble mean by a half, with none of the members predicting the right amplitude, but forecast of the central Pacific 2009-2010 event (Lee and McPhaden, 2010) called for the same magnitude in Niño 1+2 as for the extreme eastern Pacific ones. Thus, the CFS v2 forecast did not distinguish among the very different spatial patterns of these events, despite assimilating data from TAO TRITON, satellite, etc. Although unpredictable westerly wind bursts could have played a role degrading the forecasts (e.g. Lengaigne et al., 2004), this model failed to maintain the warm conditions in the eastern Pacific even when the event was underway. Other GCMs (not shown) share a similar problem in their hindcasts. This suggests that either the model physics are inadequate, resulting in errors in the mean state and feedback processes, and/or important measurements are missing for initialization. Considering that recent research into El Niño suggests that the extreme events are qualitatively different from the others, possibly corresponding to a different dynamical regime (Takahashi et al., 2011; Takahashi and Dewitte, 2014), then the sampling by the TAO array of the subsurface ocean dynamics and surface meteorology, limited to only one extreme El Niño (1997-98), may not be enough to adequately identify all of the relevant mechanisms. In any case, enhanced observations in the far eastern Pacific are likely to be necessary to improve prediction in this region.

On intraseasonal timescales, the monitoring of equatorial Kelvin waves is a key source of predictability of coastal conditions due to their finite travel time to the South America of two or three months. These waves can impact the coastal sea surface temperature and trigger heavy rainfall, as was the case of the wave pulse forced in December 2001 (McPhaden, 2004) that, even though it did not trigger a large-scale El Niño, resulted in warning and flooding in northern Peru in March 2002 (Takahashi, 2004). Additionally, the modulation of the subsurface environment affects the coastal marine ecosystem (Echevin et al., 2014). On the other hand, coastal winds also play an important role in modulation the coastal conditions on intraseasonal timescales (Dewitte et al., 2011).

With respect to decadal variability, several studies have suggested that the south Pacific can be considered an important component of the system in the tropical Pacific, although the mechanisms are diverse, e.g. tropical/subtropical interactions (Giese et al., 2002, Luo et al., 2003), equatorial/coastal wave dynamics (Power and Colman, 2006; Montecinos et al., 2005 and 2007) or thermodynamic ocean response to stochastic forcing (Okumura, 2013). However, studies of decadal Pacific predictability have focused mainly in the northern and equatorial regions due to a large extent to the lack of long-term data in the south Pacific (e.g. Meehl et al., 2010). Monitoring decadal variability in the southeast Pacific is a key need for improving understanding and predictive capacities over these timescales.

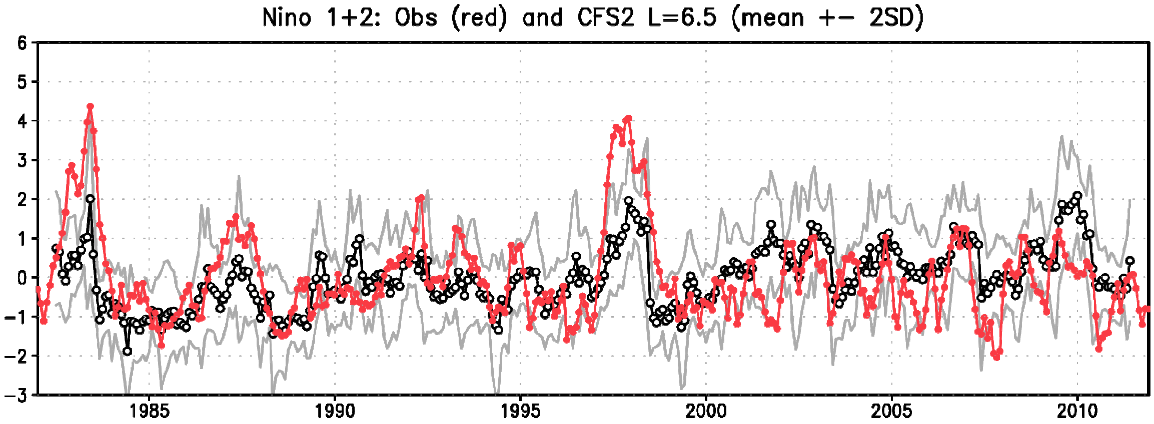


Figure 3.2 - Observed Niño 1+2 SST anomaly (red) and NOAA CFS2 6.5-lead forecast ensemble mean (black) and ensemble spread (2 standard deviations, grey).

3.8 Extreme surface waves climate and the long-term variability

The extreme surface wave climate is of paramount importance for: (i) off-shore and coastal engineering design, (ii) ship design and maritime transportation, or (iii) analysis of coastal processes. Monitoring such events and identifying the synoptic patterns that produce extreme waves is necessary to understand the wave climate for a specific location. Thus, a characterization of these weather patterns may allow the study of the relationships between the magnitude and occurrence of extreme wave events and the climate system (Izaguirre et al., 2012).

Alterations in wave climate are also often related to climate pattern variability. This variability as well as long-term trends has been an issue of research in recent years around the world but in the region of Latin America an understanding of wave climate and its variability is scant (Reguero et al., 2013). On the other hand, a strong correlation between the significant wave height and the Southern Oscillation Index (SOI), and both directional components of the wave energy flux and the SOI shows that the El Niño-Southern Oscillation (ENSO) variability has a strong influence on the wave climate of the Pacific (Hemer et al., 2011), however the ENSO influence in the wave climate on the eastern tropical and south Pacific is not well know. Furthermore, model-based projections indicate that the western coast of South America would be among the regions with largest relative increase in significant wave heights with climate change (Hemer et al., 2013).

Hence, an integrated network of surface wave measurements in the eastern Pacific is needed to monitor extreme wave events, perform the analyses of the effects of climate variability in this region and validate the wave models that are commonly used for short-term forecasting and climate scenarios.

3.9 Regional impacts and applications

In terms of impacts, western South America experiences different and even opposing influences from El Niño, depending on the geographical location and the seasonality of the associated SST anomalies. For instance, there is a direct effect of the coastal warming on the occurrence of rainfall along the western tropical coast of South America as a result of the local destabilization of the lower atmosphere and larger moisture content, particularly during the seasonally warm months (Horel and Cornejo-Garrido, 1986; Goldberg et al., 1987; Poveda and Mesa, 1997; Takahashi, 2004). On the other hand, anomalous warming in the central equatorial Pacific in austral summer tends to reduce rainfall in the tropical Andes (Aceituno, 1988; Poveda and Mesa, 2000; Lagos et al., 2007; Lavado and Espinoza, 2013; Takahashi et al., 2014). For instance, cool central Pacific conditions were present during the 1925 El Niño and this is believed to have enhanced substantially the rainfall along the coast of Peru and Ecuador (Takahashi et al 2014). In the austral winter, rainfall maxima changes latitudinal in central Chile associated with teleconnection effects from the central Pacific (Aceituno, 1988; Montecinos and Aceituno, 2003).

Thus, the differences in warming and cooling patterns along the equator associated with ENSO diversity have very important practical consequences for impacts in western South America, as it implies different behavior, even opposed, among El Niño regions. Although a single-mode view of ENSO implied that these two types of effects were expected to occur simultaneously, after the 1997-1998 El Niño the coast of South America has experienced atypically low SST variability and, hence, the coastal impacts of ENSO have been small. In Peru, this prompted the official committee for El Niño forecast (ENFEN) to define an operational index based on Niño 1+2 (ENFEN, 2012) to establish the presence of El Niño or La Niña in the eastern Pacific, while simultaneously considering more conventional ENSO indices such as SOI or NOAA's ONI in order to monitor the central Pacific El Niño/La Niña and its teleconnection effects. Using this index, in mid-2012, ENFEN were able to announce El Niño conditions in the eastern Pacific to Peruvian users (ENFEN, 2012b), while the international community was still expecting to see whether the central Pacific would warm.

During and after El Niño 1997-1998, the increasing access to web based products and the real time monitoring with TAO, determined a significant change in the way of Western South America countries monitor ENSO. The comprehensive monitoring done by National institutions and local scientists in the region to El Niño 1997-1998, combined with coastal observation networks along the coast, research cruises and weather stations in the continental areas, lead to different ways to estimate impacts and further evolution of the SST (Zambrano, 2000). In the framework of the ERFEN program (Programa para el Estudio Regional del Fenómeno El Niño en el Pacífico Sudeste) under the Permanent Commission for the South Pacific (CPPS), the western South America countries (Colombia, Ecuador, Peru, Chile) have implemented specialized groups for the assessment and forecasting of ENSO-related ocean-atmosphere conditions and potential impacts, which are then integrated into a regional assessment. ENFEN in Peru is an example of one of such national groups, which directly analyzes TAO/TRITON data, ocean reanalysis, global climate model forecasts and even a linear shallow water model forced by observational wind products (Mosquera, 2009) for intraseasonal prediction of coastal conditions. Similarly, in Ecuador, due to the urgency to provide advice to decision makers, in 1997, INOCAR developed a very simple model to foresee the SST evolution based on a spectral correlation model using the strong and linear relationship between sea level anomalies, the depth of thermocline and consequently SST anomalies in the Ecuadorian sea. This model was able to represent fairly well the SST anomalies and predict the potential trends months ahead (Martínez et al., 2000). The information provided contributed with the analysis and climate forecasts at moments where the seasonal forecast was not implemented in most of the countries in the region.

Regional Climate Outlook Forums are an innovative concept developed and supported as part of the WMO Climate Information and Prediction Services (CLIPS) project in partnership with the National Meteorological and Hydrological Services (NMHSs), regional climate institutions and other agencies. The RCOFs have completed about 12 years of successful operation in different sub-regions of Africa, in parts of South America and in the Andean region. Regional Climate Outlook Forums in various forms and sizes are now in operation serving more than 10 sub-regions around the world, and concerted efforts are being made to extend the concept to several other regions. Despite the challenges of resources and human and infrastructural capacities, some of the RCOFs have achieved remarkable progress in regional networking and user liaison, and have contributed substantially to capacity-building and user awareness (Martínez et al., 2010).

National and regional capacities are varied, but are certainly inadequate to face the task alone. Built into the RCOF process is a regional networking of the climate service providers and stakeholders including user sector representatives. Participating countries recognize the potential of climate prediction and seasonal forecasting as a powerful development tool to help populations and decision-makers face the challenges posed by climatic variability and change. In parallel, NMHSs and some decision-makers have come to realize the potential benefits to be gained and have played larger roles in the processes. Ownership now lies largely with national and regional players, but there is a continuing need for support at all levels to ensure that the momentum gained to date is maintained (Goddard et al, 2011). For all this process, data provided by TAO and satellite derived data are key to provide suitable predictors for regional expert assessments and statistical models which could be for some seasons and transition periods more accurate and useful than numerical prediction (Martinez et al, 2011).

Regional Climate Outlook Forums bring together national, regional and international climate experts, on an operational basis, to produce regional climate outlooks based on input from NMHSs, regional institutions, Regional Climate Centers (RCCs), Global Producing Centers of long-range forecasts (GPCs) and other climate prediction centers. Through interaction with sectoral users, extension agencies and policy makers, RCOFs assess the likely implications of the outlooks on the most pertinent socio-economic sectors in the given region and explore the ways in which these outlooks may be used. Regional Climate Outlook Forums also review impediments to the use of climate information and the experiences and successful lessons regarding applications of past RCOF products in an effort to enhance sector-specific applications. In many cases the RCOFs are followed up by national forums to develop detailed national-scale climate outlooks and risk information including warnings for communication to decision-makers and the public at large.

Since 2003, the International Research Centre on El Niño (CIIFEN), with WMO sponsorship, assumed the coordination of the Climate Outlook Forum for Western South America (WCSACOF). The seasonal forecast for the region is produced monthly as a result of a consensus discussion, conducted by e-mail, among all the NMHSs. All the members share a common methodology and several parameters have been agreed upon and are being refined from year to year. This consensus forecast is widely disseminated by e-mail to more than 15 000 users across Central and South America and contacts on other continents. This approach has increased the understanding of the climate information management process, and the organizations have established a regional/national basis for early warning and risk management systems (Martínez, 2009).

However, although the coordination and dissemination mechanisms have being strengthened in the past few years, an outstanding remaining limitation is the scarcity of international-level scientists working in the far-eastern Pacific research that is necessary for improving the quality of the information produced, but which involves substantial challenges that have baffled the international scientific community for long and that are also not priority issues for countries away from this region. Collaborative participation of the eastern far-Pacific countries in TPOS activities in this region is a key way by which their scientific capabilities can be enhanced.

4. Data requirements

- High zonal (dx = 500km), meridional (dy = 200km), vertical (dz = 10m) and temporal (dt = 1 day) resolution subsurface temperature measurements are needed between 110°W and the coast of South America within 10° of the equator in order to characterize the propagation, modal dispersion and effective dissipation of Kelvin waves and to characterize the vertical gradients of the shallow thermocline and its vertical displacements.
- Continuity of the TAO array surface meteorology and subsurface temperature measurements in the equatorial (8°S, 5°S, 2°S, Eq, 2°N, 5°N, 8°N) eastern Pacific (125°W, 110°W, 95°W). The preservation of long and homogeneous records is necessary for the characterization of decadal variability and climate change.
- Coastally-trapped wave monitoring requires a coordinated network of sea level and subsurface temperature and current measurements along the coast of South (and Central) America, approximately every 5° latitude on a daily timescale. High vertical resolution (dz=5m in the upper 100 m) would be needed due to the shallow thermocline.
- Alongshore coastal wind measurements are necessary in order to assess the local forcing of the ocean. The strong diurnal cycle would need to be adequately sampled and alongshore variability associated with local topography needs to be considered.
- Vertical velocity estimates in the equatorial eastern Pacific (near 90°W) are necessary to estimate vertical thermal advection, which is a key component of the heat budget in this region. This is needed also for estimating the thermocline ENSO feedback and to quantify the nonlinear advection ENSO feedback. The estimates would need to resolve the intraseasonal timescales observed in Kelvin and tropical instability waves. Vertical resolution should match that of the temperature measurements (dz = 10m in the upper 200m) with a precision on the order of 1cm/day.
- Zonal velocities associated with the equatorial current system near 95°W (8°S-2°N) are important to assess the transport of water properties towards the coast of South America and for monitoring the contribution to zonal advection associated with ENSO and the equatorial Kelvin wave. Intraseasonal timescales should be resolved.
- Surface heat flux measurements on the eastern Pacific TAO/TRITON buoys and at locations along the coastal upwelling region on intraseasonal to decadal timescales are necessary for the upper ocean heat budget as a tool for determining feedback mechanisms and validating coupled models.
- Estimations of subsurface vertical turbulent heat fluxes on equatorial eastern Pacific buoys (e.g. 110°W, 95°W) are necessary for closing the heat budget, for estimating the thermocline ENSO feedback and to validate numerical ocean models.
- Long-term measurements of surface winds and heat fluxes and upper ocean vertical thermal structure in the data-sparse southeast Pacific (e.g. Stratus buoy) are needed to characterize the meridional dynamics that can influence the equatorial Pacific and the decadal variability in this region.
- Periodic measurements of dissolved oxygen, pH, PAR, surface chlorophyll-a, turbidity, nitrates, phosphates and silicates in the eastern equatorial Pacific and along the coasts are necessary for monitoring the effect of biogeochemical variability on seasonal to decadal timescales.

- Measurements of surface air-sea gas fluxes in equatorial and coastal regions.
- Wind stress fields resolving the diurnal cycle over the tropical Pacific are needed to adequately characterize atmospheric component of ENSO and decadal variability.
- Characterization of the atmospheric vertical velocity and/or latent heating profiles in the ITCZ on monthly timescales in the eastern Pacific are necessary to validate models for the atmospheric role of ENSO, particularly during strong El Niño.
- Hourly precipitation rates on the TAO/TRITON array and coastal locations to provide ground truth to remote sensing products (e.g. Global Precipitation Mission) and to validate models.
- Diurnal cycle-resolving profiles of equatorial atmospheric temperature, humidity, height and winds for the study of boundary layer processes, equatorial convectively coupled waves and the ITCZ.
- Hourly and long-term measurement of surface wave characteristics (significant height, period, and directional spectrum) that impact the western coast of South America to characterize their dynamics (sea and swell) and their variability on intraseasonal to decadal timescales.

5. Observational strategies

- Near real-time daily subsurface temperature data along the equatorial waveguide is key to monitor the propagation of equatorial Kelvin waves into the far eastern Pacific in support of intraseasonal forecasts for coastal conditions in western South America. TAO/TRITON is an essential source of data for Equatorial Ocean monitoring and is key for providing long-term continuous records, but has some limitations:

    a) It only extends to 95°W to the east, so it cannot observe the propagation and dispersion of Kelvin waves as the thermocline becomes shallower and then deeper towards the coast.

    b) The system requires constant maintenance and is therefore vulnerable to funding limitations: 9 out of 10 buoys in the far-eastern equatorial Pacific (110°W-95°W, 5°S-5°N) stopped reporting subsurface temperature data between March and August 2012 when maintenance was suspended (Figure 5.1), and the completeness of the 100 m-depth temperature data was below 40% in the 2012-2013 period for 7 out of these 9 buoys (Figure 5.2).

    c) Even though TOA/TRITON contains a relatively large number of buoys, it does not have redundant measurements, particularly in the eastern Pacific where strong zonal and meridional gradients in the circulation exist and the data from different latitudes are needed to separate Kelvin and Rossby modes.

    d) Vertical resolution in the far-eastern Pacific (95°W) is too low (approx. dz = 20m for 0-140m) for thermocline displacements and Kelvin wave dispersion. Need approximately 10m down to a 200m depth.

- Some possible strategies for strengthening the subsurface physical and biogeochemical observing system in the far-eastern equatorial Pacific are:

    a) Establish partnerships with regional institutions to maintain the existing easternmost buoys (110°W, 95°W).

    b) Add an additional buoy line at 85°W (10°S-10°N), equipped with physical and biogeochemical sensors. However, high exposure to vandalism would make the sustainability challenging.

c) Deploy Iridium-equipped ARGO drifters equipped with biogeochemical sensors (oxygen, pH) in the region 95°W-80°W, 10°S-10°N with high meridional resolution (2°) and sampling rate of at least one profile every 3 days per drifter.

d) Operate gliders equipped with biogeochemical sensors in a continuous monitoring mode in the region 95°W-80°W, 10°S-10°N. However, the required dense spatial and temporal sampling, the need for permanent human resources, and the large size of the region, would be limiting considerations for this approach.

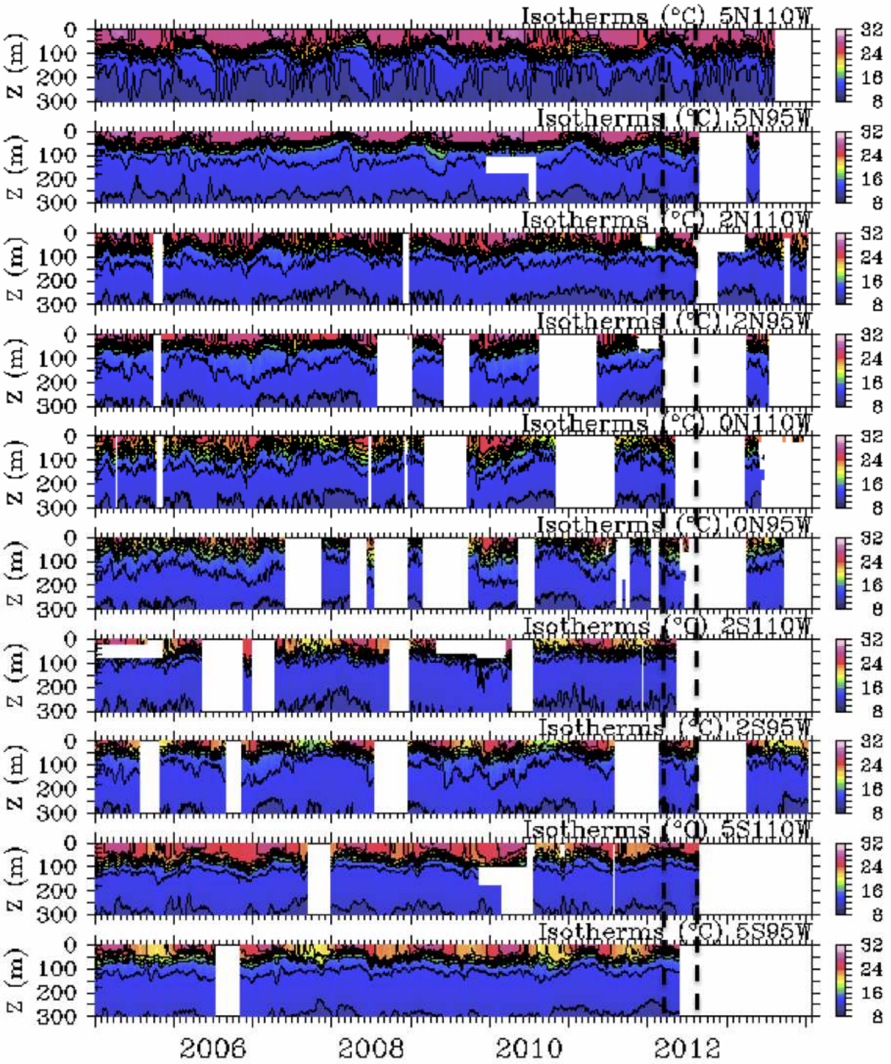


Figure 5.1 - 5-day mean TAO subsurface temperature measurements in the far-eastern equatorial Pacific (110W-95W, 5S-5N). Dashed lines indicate March and August 2012 (from http://www.pmel.noaa.gov/tao).

- TOPEX/JASON data does provide adequate meridional resolution, but meridional structures of different vertical modes present subtle differences on sea level, so this should be considered complementary to the buoys. Additionally, the temporal resolution is too low for adequate monitoring of intraseasonal Kelvin waves.
- ALTIKA will provide high-resolution sea level that could be used for coastal wave propagation.

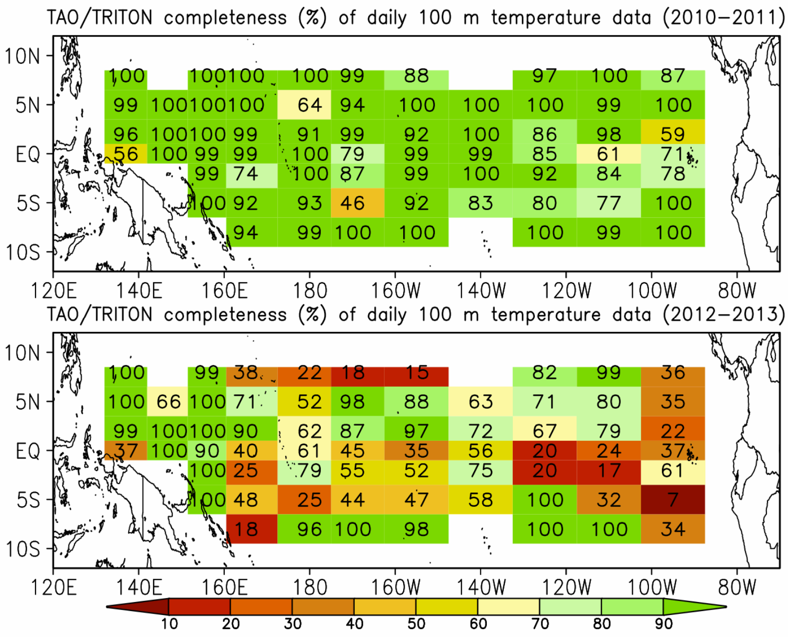
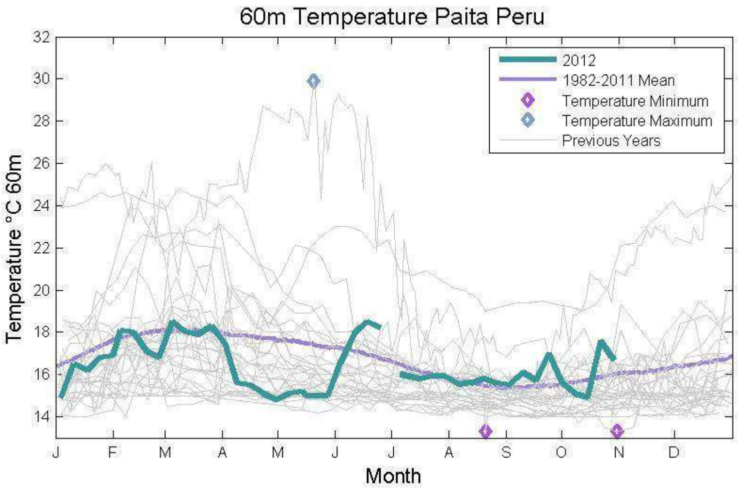


Figure 5.2 - Completeness (%) of daily 100 m-depth temperature TAO/TRITON data for the 2010-2011 (top) and 2012-2013 (bottom) periods (data from http://www.pmel.noaa.gov/tao/data_deliv/deliv.html).

- Along the coast of South America, high-frequency subsurface temperature and salinity, surface meteorology and air-sea fluxes measurements are also needed for near real-time monitoring and research. Given the strong problem of vandalism, surface buoys are not recommended. Some options are:

  a) Oil drilling platforms near the equatorial coasts (excellent opportunity for thermodynamic profiling although measurements of currents could be compromised by the platforms themselves).

  b) Small islands that disturb minimally the air-flow (corrections could be estimated with a modeling approach).



Climatology Minimum on Aug-20-82, Oct-30-10, =13.3 °C ; Maximum on May-19-83, =29.9 °C

2012 YTD Minimum on Apr-28, =14.8 °C ; Maximum on Mar-03, Jun-16, =18.5 °C

Monterey Bay Aquarium Research Institute: http://www.mbari.org *Updated:21-Nov-2012*
Contact: reiko[at]mbari.org

Figure 5.3 - Weekly 60 m-depth temperature off the coast of Paita, Peru (5S) maintained by MBARI from 1982 to the present (from: http://www.mbari.org/bog/Projects/Peru/peruhome.htm).

c) Shallow subsurface moorings with data collected weekly using small crafts or connected with cables to the coast.
d) Continuous operation of gliders near the coasts (an advantage is that they could be withdrawn when fishing activities pose a risk)
e) Near-coastal (0-100 m) periodic CTD measurements using very small crafts (a cheap approach been proven reliable by the continuous weekly measurements supported by MBARI off Paita (5S) since 1982 to date, see Figure 5.3).

6. Data and Information delivery

The dissemination system for TAO/TRITON through the PMEL website is excellent, although it could use some improvements. The quick-view figure feature should be treated as a data delivery component for real-time applications and it would be useful to allow for more customization (interpolation options, contouring, averaging) and more explicit warnings in case of buoy problems.

It is highly desirable that other real-time components of the monitoring system, e.g. Argo drifter data, satellite data, and the regional observations (e.g. sea level, coastal temperature, etc.) are available in a similar fashion, ideally through a single integrated portal and common file formats (e.g. NetCDF), even if each observing subcomponent maintains particularities in their data processing. Data quality and other metadata should be easily accessible and common standards and protocols should be implemented.

7. Potential synergies and opportunities with countries in western South America

- Since 2003, the SE Pacific countries (Colombia, Ecuador, Peru and Chile), established the GOOS Regional Alliance for the South Eastern Pacific (GRASP). It has a Strategic Plan which could be updated and discussed in line with the TPOS new challenges and objectives. http://www.grasp.cpps-int.org/
- Considering the annual efforts that SE Pacific countries develop to conduct regional cruises each year (since 1997), this cooperation mechanism could be a good opportunity as support of TPOS, particularly for buoys maintenance, and as platforms for addressing critical gaps in research. http://www.cpps-int.org/index.php/el-nino-y-la-oscilacion-del-sur/erfen/crucero-regional.html
- The potential interaction and coordination between Global and regional programs requires a considerable effort, time and resources mobilization. Regional organizations such as CPPS (http://www.cpps-int.org/index.php/el-nino-y-la-oscilacion-del-sur/erfen/crucero-regional.html) and CIIFEN could make a significant contribution to hasten cooperation mechanisms with TAO-TRITON, integrate and exchange data and enhance the TPOS.
- Since 2001 to 2009, relevant efforts of IOC-UNESCO were developed in the region to enhance the ocean data exchange and evolve the traditional observing systems to near real time systems. These efforts are still ongoing, but not well connected with the research community at regional and global scale.
- Galapagos Islands (Ecuador), Hormigas Island (Peru) and oil drilling platforms, are strategic places to concentrate observations and multipurpose platforms. In addition, there is increasing interest of local and international organizations to enhance ocean and atmosphere observation systems that can be taken as an opportunity for the new design of TPOS.
- SE Pacific countries have increased their near real time gauges and coastal stations.

However the data exchange is still limited as well as ocean modeling for operational and research purposes. Potential tradeoffs could be explored to get a better and more collaborative TPOS which involves to SE Pacific countries.

8. General Recommendations

- Explore bilateral or regional cooperation mechanisms for ship employment as contribution to TPOS, particularly for the maintenance of TAO buoys and/or other components of the observational system.
- Define a road map for a high level cooperation mechanism between TAO/TRITON and GRASP.
- Ensure the continuity of the TAO array into the far eastern Pacific equatorial waveguide (to 95°W) and implement high-density ARGO monitoring farther to the east with comparable latitudinal resolution to characterize intraseasonal Kelvin wave propagation across the zonal thermocline gradients.
- Promote and support a sustained real-time coastal network of sea level, SST, and wind measurements based on national systems to be incorporated into TPOS.
- Promote and support a network of sustained coastal measurements of subsurface temperature, currents, biogeochemistry, and surface heat/momentum/gas fluxes. The data should be made available as part of TPOS at least monthly.
- Include biogeochemical sensors in the eastern Pacific TAO buoys and Argo drifters.
- Explore synergies between SE Pacific region scientific networks with GEWEX.
- Organize an international meeting in SE Pacific region with the support of International agencies, IOC, WMO and JCOMM to define the road map to the enhancement of TPOS in the Eastern Pacific region including the presence of financial institutions. Explore bilateral or regional cooperation mechanisms for ship employment as contribution to TPOS, particularly for the maintenance of TAO buoys and/or other components of the observational system.

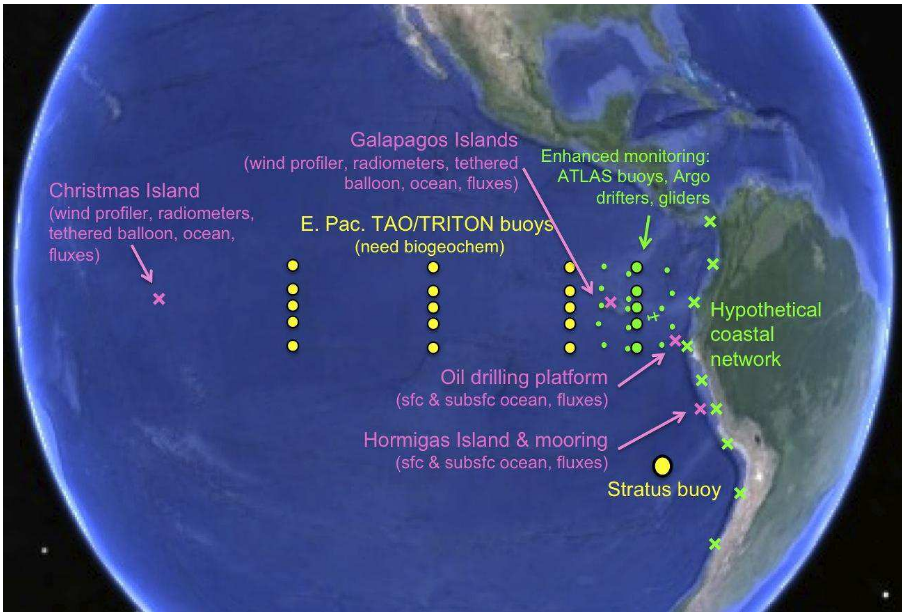


Figure 8.1 - Potential components of the enhanced observing system in the far-eastern Pacific for addressing needs of western South America.

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