White Paper #7 - A Tropical Pacific Observing System (TPOS) in relation to biological productivity and living resources

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1. Introduction

The tropical Pacific Ocean is remarkable for a variety of reasons. It is the most variable region of the oceans on interannual to centennial time scales (McPhaden et al., 2006; Chavez et al., 2011) and this ocean variability influences climate globally (Rasmussen and Wallace, 1983). It is also the largest natural source of carbon dioxide to the atmosphere, supplying up to 1 petagram (Pg) of carbon annually to the atmosphere (Feely et al., 2002; Chavez et al., 1999). Changes in primary production (PP) in the tropical Pacific dominate global anomalies in PP, resulting in decreases of an order of 3 Pg carbon per year during the large 1997-98 El Niño to increases of 2 Pg per year during La Niña (Chavez et al., 2011; Messie and Chavez, 2012); this interannual variability is on the same order as that observed globally by terrestrial primary producers (Field et al., 1998; Zhao and Running, 2010). The southeastern tropical Pacific supports the largest single species fishery in the world, the Peruvian anchoveta (*Engraulis ringens*) (Chavez et al., 2008). The western and central Pacific Ocean support 60% of global commercial catches of tuna that contributes up to 40% of national Gross Domestic Product (GDP) for countries in the region (order of 7 billion US dollars annually). These and other living marine resources fluctuate dramatically from the resulting physical variability (Barber and Chavez, 1983; Chavez et al., 2008; Williams and Terawasi, 2013). Given the importance of the region in driving global climate variability and the significance of resources throughout the region, it is of great value to society to have a well-designed and sustained observing system that provides a wide variety of information on the state of this large ocean ecosystem. This overview focuses on how a tropical Pacific observing system (TPOS) can support science and management of ocean ecosystems. Given that the existing TPOS is currently returning a reduced amount of information and the real prospects of continued declines we reconsider requirements for biologists, and recommend improvements given emerging technologies.

2. Biological dynamics

Dynamics in ocean physics in the tropical Pacific Ocean can be directly tied to variations in biological production regionally and globally (Figure 1; Chavez et al., 2011; Messie and Chavez, 2012, 2013). ENSO to multi-decadal variations with multiple nomenclatures, permeate through to biological productivity and living marine resources. In the following sections we discuss processes, features and variations that impact biology at: 1) the interannual to centennial time scales; 2) the local or regional scale; and 3) the global scale.

The interannual to centennial time scales **–**The El Niño and La Niña cycle, often combined with their atmospheric counterpart the Southern Oscillation, and referred to as ENSO are presently the dominant mode of ocean variability in the tropical Pacific and globally (Philander, 1990; McPhaden et al., 2006; Desser et al., 2010; Messie and Chavez, 2011). The theory behind ENSO and its impact on biology are relatively well developed (Philander, 1990; McPhaden et al., 2006; Barber and Chavez, 1983). At the core are basin-scale changes in the depth of the thermocline (and nutricline, the region that separates nutrient poor waters at the surface to nutrient rich waters at depth) that are initiated in the western equatorial Pacific by anomalous winds. Atmospheric teleconnections propagate additional changes in ocean conditions. The character of ENSO varies from event to event and perhaps even on decadal to multi-decadal time scales (Takahashi et al., 2011); the past decades have seen the emergence or prominence of ENSO Modoki (Modoki is Japanese for like but not the same) or central Pacific ENSO (Figure 2.1).

Interest in decadal to multi-decadal variations was first spurred by the observations that some important fish populations vary dramatically over these time scales; as a result an additional family of recurring climatic phenomena have been identified over the past several decades (Mantua et al., 1997; Chavez et al., 2003; DiLorenzo et al., 2008). Those that are particularly germane to the Pacific include the multi-decadal Pacific Decadal Oscillation (Mantua et al., 1997), also referred to as the Interdecadal Pacific Oscillation (Power et al., 1999) or the El Viejo/La Vieja cycle (Chavez et al., 2003), and the decadal North Pacific Gyre Oscillation (DiLorenzo et al., 2008), which appears related to Modoki (Messie and Chavez, 2011). Robust theory behind these fluctuations is still emerging but their improved understanding and prediction lies at the core of a new TPOS.

Centennial variability in the tropical Pacific associated with changes from the medieval warm period (900-1300) to the Little Ice Age (LIA, 1400-1800) to the present warm period has been elucidated from paleo (cores in anoxic sediments, corals, etc.) proxies (Newton et al., 2006; Gutierrez et al., 2009; Sachs et al., 2009; Conroy et al., 2010; Mann et al., 2010; Chavez et al., 2011). The general picture that emerges is that during the LIA the Walker circulation in the atmosphere was shutdown in the tropical Pacific as a result of a southward migration of the mean position of the InterTropical Convergence Zone (ITCZ) across the equator (Sachs et al, 2009). This resulted in a flattening of the equatorial thermocline (normally deep in the west, shallow in the east and as a result the typical surface nutrient enrichment, anoxic conditions and abundant populations of anchoveta along the coast of Peru disappeared during LIA but returned with a bang after 1820 (Gutierrez et al., 2009).

Human activities have changed the concentration of elements in the atmosphere with potential impacts on temperature, climate and biological productivity. Human activities on living marine resources are more direct, through exploitation. Humans are also altering water quality in the oceans, most notably by the absorption of carbon dioxide derived from the burning of fossil resulting in so-called ocean acidification. Recent declines in subsurface oxygen concentrations may also be tied to a warmer planet (Stramma et al., 2007). Here we refer to these declines collectively as global change since climate change includes the natural variations described above. Global change presents an emerging challenge to the sustainable management of living marine resources in the ocean, and robust information is essential to ensure future sustainability. Climate, water quality and harvest affect stocks of living marine resources, populations of non-target, dependent species and the ecosystem. To provide relevant advice we need an improved understanding of oceanic ecosystems and better information to parameterise the models that forecast the impacts of global change (Nicol et al., 2013).

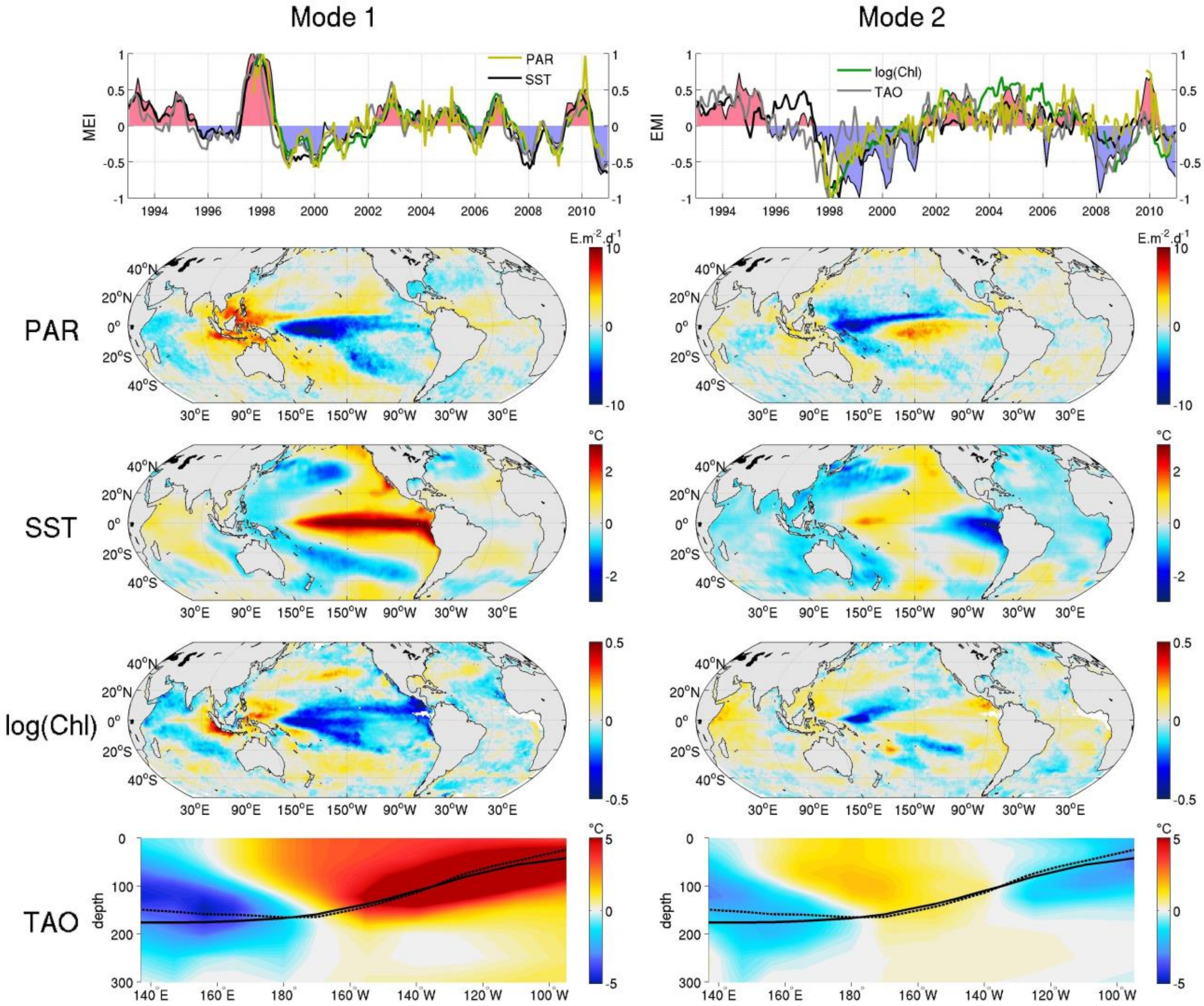

Figure 2.1 - Time series (top) of the Multivariate ENSO Index (MEI, left) and the ENSO Modoki Index (EMI, right) (shaded) together with the first (left) and second (right) principal components of global fields of Photosynthetically Active Radiation (PAR, equivalent to precipitation/cloudiness), Sea Surface Temperature (SST) and Chlorophyll (Chl). Also included are principal component time series (one, left and three, right) for equatorial TAO temperatures. Below the time series are the spatial distributions of the Empirical Orthogonal Functions (EOFs) of the first (left) and second (right) modes. The variations in the atmosphere (PAR), ocean (SST, TAO temperature), and atmosphere are synchronous across the two modes (and the ENSO indices) showing that they are intimately related. Figures redrawn from Chavez et al., 2011; Messie and Chavez, 2012; and Messie and Chavez, 2013.

The regional scale -There are well-known processes and features that influence and are diagnostic of biological productivity and its variability in the tropical Pacific. The dominant is thermocline dynamics (Cane, 1983; Barber and Chavez, 1983). This dynamic is directly linked to the atmosphere via the trade winds, which drive the accumulation of heat and water in the western Pacific raising the thermocline in the east and deepening it in the west (Philander, 1990). Since the thermocline and nutricline are linked, high levels of nutrients and carbon dioxide reach the surface in the east but are kept at depth in the west creating a east (more productive)/west (less productive) gradient in biological productivity (Barber and Chavez, 1983; Chavez et al., 1999). Surprisingly tuna populations thrive in the so-called oligotrophic warm pool (Lehodey et al., 1997); episodic enhanced productivity in the lee of islands or close to the western boundary may support these populations but further research is required. Periodically this east-west dynamic is perturbed by the phenomena described above. During El Niño (and El Viejo) the thermocline and nutricline are deepened in the east while rising in the west Barber and Chavez, 1983). The thermocline dynamics and the trades set up the western Pacific warm pool and the eastern/central Pacific cold tongue whose size and character are also modulated by climate (Chavez et al., 1999). A perplexing feature of the cold tongue is the reduced biological productivity relative to the input of macro nutrients such as nitrate leading a condition referred to as high nitrate/nutrient low chlorophyll (HNLC). This condition could also be referred to as high CO_2 low chlorophyll (HCLC) since the reduced biological productivity can be directly linked to the large natural source of CO_2 to the atmosphere. The favored hypothesis is that the HNLC condition is a result of iron deficiency (Martin et al., 1996) associated with weak input from the atmosphere. Periodically the Equatorial Undercurrent (EUC) delivers increased levels of iron to the cold tongue, resulting in large and unusual blooms of phytoplankton (Chavez et al., 1999; Ryan et al., 2002). It is hypothesized that during these times the EUC recruits this iron from the continental shelves in the New Guinea region, a behavior that may also be climate modulated. The front that sets up between these the warm pool and cold tongue, as well as other fronts between warm and cold features such as the North Equatorial Counter Current (NECC) and the South Equatorial Current (SEC), the so-called Equatorial Front (EF) are locations of enhanced biological activity. Along the EF Tropical Instability Waves are generated creating spectacular features that are clearly visible from space.

The global scale – Fast moving waves (Kelvin, 200 km per day) generated by the westerly wind anomalies in the western Pacific propagate thermocline anomalies from the western to the eastern Pacific ocean. Upon reaching the eastern Pacific these waves propagate poleward expanding the tropical dynamics to higher latitudes. A complex set of slower travelling waves (Rossby, Yanai, etc.) propagate back towards the western Pacific. In the atmosphere, teleconnections change the intensity and position of low and high pressure systems globally. These oceanic and atmospheric processes result in global biological impacts of tropical variability.

<u>THE USER COMMUNITY AND HOW THEY USE THE EXISTING TPOS</u>

The user community is broad from managers to scientists. These include:

1) Scientists are interested in:

- Primary production
- Zooplankton
- Fish
- Large Marine Vertebrates

2) Industry interested in:

- The harvest of living marine and terrestrial resources

3) Managers interested in:

- Regulation of harvest of living marine and terrestrial resources
- Conservation of marine life
- Ocean health

3. TPOS user examples

Remote Sensing

Remote sensing of ocean color from space began in 1978 with the successful launch of NASA's Coastal Zone Color Scanner (CZCS). Since then multiple ocean color sensors have been launched (e.g., MODIS, SeaWiFS, MERIS, HICO, VIIRS) and still more are planned for the near future by various space agencies. The significance of ocean color sensors is the ability to provide a continuous, global view of near surface ocean bio-optical properties to the Earth science community, from which chlorophyll-a (chl-a), inorganic and organic matter, colored dissolved organic matter, primary production, phytoplankton functional types, and other biological variables are derived. While remotely sensed ocean color data are informative of biological activity on the ocean surface, what is happening subsurface, and the physical or chemical mechanisms responsible for the biological responses remains unclear. Thus, in situ observations are necessary in coincidence with satellite data to fill in the gaps and to validate ocean color estimates.

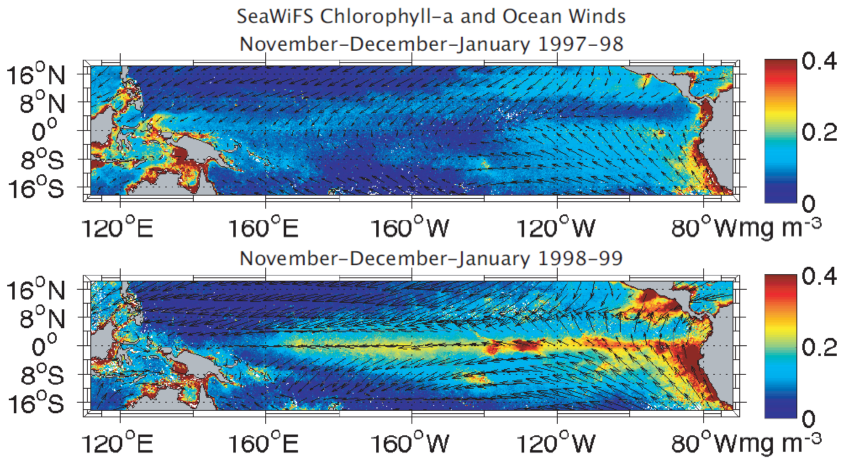

Figure 3.1 - November-December-January (NDJ) averaged SeaWiFS chl-a in the equatorial Pacific Ocean for the (top) 1997-98 El Niño and (bottom) 1998-99 La Niña overlaid with Cross-Calibrated Multi-Platform (CCMP) ocean surface wind vectors.

For a short duration in the late 1990s, biological and chemical sensors (i.e., continuous pCO_2 analyzers, three biospherical irradiance meters, nitrate analyzers, and PAR sensors) were added by MBARI to several TAO buoys that permitted researchers to directly and continuously monitor biological productivity improving our understanding of biophysical coupling from interannual (ENSO events) to intra-seasonal (tropical instability waves) timescales (e.g., Chavez et al., 1998; Chavez et al., 1999; Strutton et al., 2001). Taking advantage of the spatial coverage of satellite sensors, past studies have illustrated a decrease (increase) in near surface phytoplankton biomass and productivity in the eastern Pacific during El Niño (transition and La Niña) events in association with weakened or possibly reversed (enhanced) trade winds (Figures 2.1 and 3.1). The vertical dimension of TAO data, such as the 20°C isotherm depth and depth profiles of temperature and zonal currents, allows monitoring subsurface variations that contribute to understanding the surface biological observations.

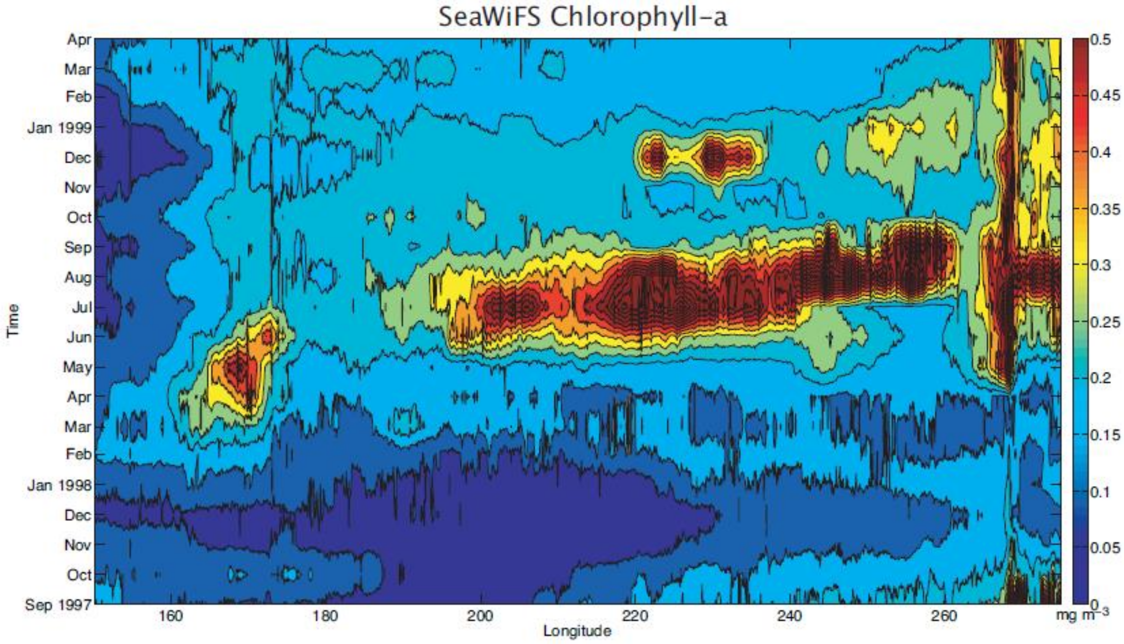

Figure 3.2 - 2°N–2°S averaged SeaWiFS chl-a (mg m^{-3}) in the equatorial Pacific Ocean from September 1997 – April 1999, showing the 1997-98 El Niño, 1998 transition (or recovery), and 1998-99 La Niña.

The depth of the 20°C isotherm is generally used as a proxy for the thermocline and nutricline, whereas maximum eastward velocities are used as proxies for the Equatorial Undercurrent, which is an important nutrient source for the equatorial Pacific. TAO data has shown that the thermocline and nutricline deepen (shoal) and the EUC is suppressed (enhanced) in the eastern Pacific during El Niño (La Niña), both of which decrease (increase) the flux of nutrients to the euphotic zone reducing (increasing) phytoplankton biomass and productivity observed at the surface by satellites (Figures. 3.1-3.3). The scenarios provided above are classic examples of the biophysical response to El Niño and La Niña events. However, the frequency and intensity of ENSO events are highly variable, eliciting different physical and thereby biological responses. Such variability has led to the idea of two flavors of El Niño: the classic, Eastern Pacific (EP) El Niño with surface anomalies spreading from the South American coast to the central basin and the Central Pacific (CP) El Niño (Kao and Yu, 2009), otherwise known as the dateline El Niño

(Larkin and Harrison, 2005), El Niño Modoki (Ashok et al., 2007), or warm-pool El Niño (Kug et al., 2009), with anomalies restricted to the central basin. TAO data in concert with satellite observations are extremely important to our understanding of how biology, the physical environment, and their coupling will respond to ENSO variability in the equatorial Pacific. Numerous scientific articles have illustrated the need for such coincident observations including, but not limited to: Chavez et al., 1998 and 1999; Gierach et al., 2012 and 2013; Messié et al., 2006; Messié and Chavez, 2012 and 2013; Radenac et al., 2001, 2012, and 2013; Ryan et al., 2002 and 2006; Strutton et al., 2001; Turk et al., 2001 and 2011; Wilson and Adamec, 2001.

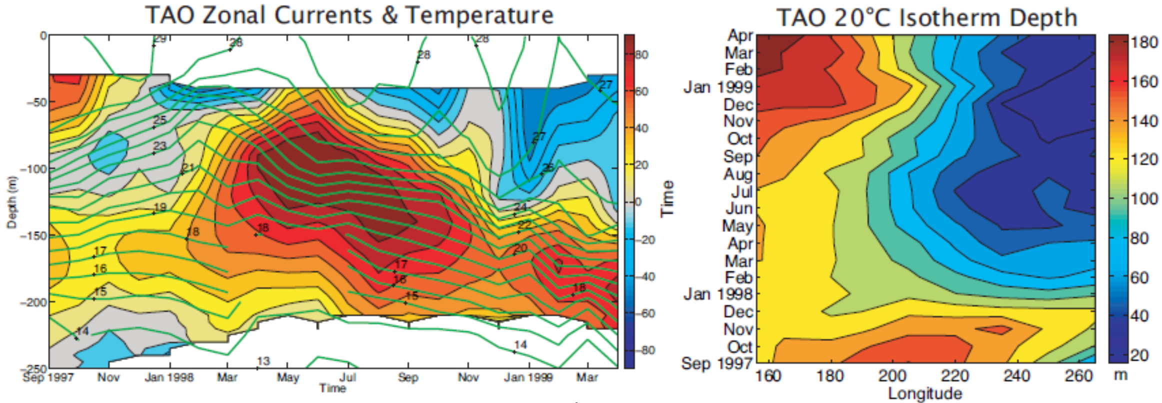

Figure 3.3 - (left) Subsurface zonal currents (cm s^{-1}) and temperature (°C; green contours) from the TAO array at 0°N, 165°E, and (right) 2°N–2°S averaged TAO array 20° isotherm depth (m) in the equatorial Pacific Ocean from September 1997 – April 1999, showing the 1997-98 El Niño, 1998 transition (or recovery), and 1998-99 La Niña.

Existing TPOS observations of the physical and biological/biogeochemical environment have been extremely important in the validation of past and present satellite observations, as well as filling in information about subsurface conditions that are incapable from satellite. However, improvements are necessary to the existing TPOS framework to usher in the next era of satellite observations and further our understanding of the ocean processes/dynamics in the Pacific. Upcoming satellite missions, including the NASA Pre-Aerosol, Cloud and ocean Ecosystem (PACE) mission, will usher in a new era in ocean color. PACE will address outstanding ocean science questions, such as separating absorbing components, assessing ocean particle abundances and living carbon stocks, nutrient stressors, and phytoplankton functional groups. Such problems have been difficult to address given limited capabilities of earlier satellite sensors (e.g., CZCS, SeaWiFS, MODIS, VIIRS), but PACE proposes advanced global remote sensing capabilities, such as hyperspectral imaging with extended spectral coverage. TPOS should incorporate instruments that can provide calibration/validation capabilities and help explore the refined science goals/questions of PACE (e.g., hyperspectral measurements of down-welling irradiance and upwelling radiances, and phytoplankton composition) and other future satellite missions. Overall, the future TPOS framework should continue and expand upon key physical observations, incorporate biological and biogeochemical observations at multiple sites for continuous duration, and provide observations with gap-free temporal resolution.

The Peruvian anchoveta fishery

Fishing is an important activity for Perú, since it generates order of 2 billion dollars annually, with interesting perspectives for growth. However, this activity is affected in a recurring manner by climate variations that disrupt the dynamics of marine living resources that support it (Figure 5), in particular the abundance of anchoveta (*Engraulis ringens*) (Barber and Chavez, 1983). This species supports harvests on the order of 5 to 6 million tons per year which is primarily used to produce fish meal and oil, utilized in a variety of ways by humans. More recently the anchoveta has started to be consumed directly. El Niño events of varying intensities not only affect the fishing industry but also the climate throughout the country and therefore the entire Peruvian economy. Extreme rainfall in northern and central Peru cause floods and destroy services including transportation. Large El Niño events like 1982/83 and 1997/98 caused losses of the order of 3 to 4 billion dollars.

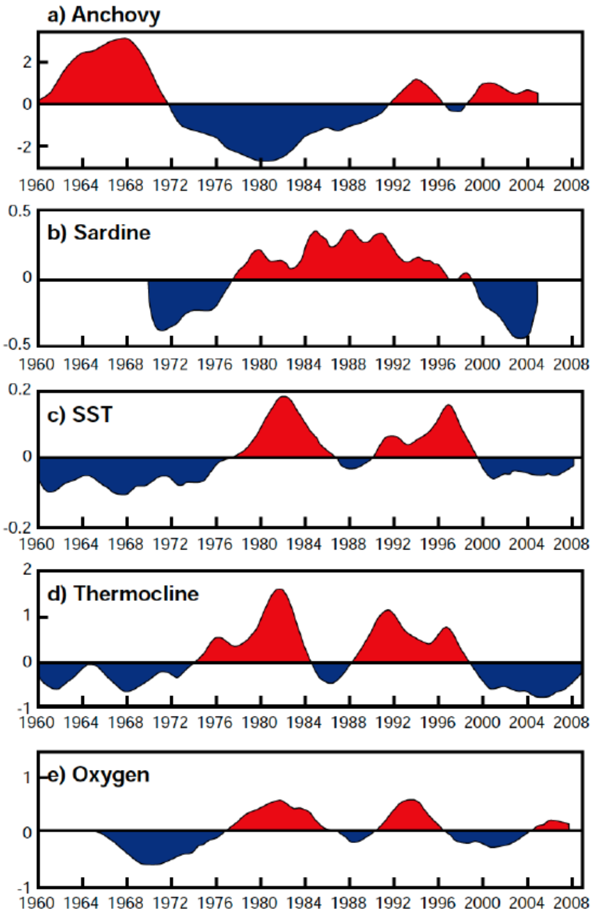

Figure 3.4 - Time series of anomalies in fish catch (anchoveta and sardine) compared to anomalies in a series of environmental variables (Empirical Orthogonal Function of sea surface temperature (SST) in the Peru domain, depth of the 15°C isotherm close to the coast of Peru and surface oxygen off Peru). There is clear alignment of the positive anomalies in the sardine catch with the positive anomalies in the environmental parameters for about 20 years. The negative anchoveta catch anomalies are of the same length but begin and end earlier (Figure by Purca, S., IMARPE).

The tight coupling between ocean variability and the biological processes of the species that support the fishing industry have driven the Instituto del Mar del Peru (IMARPE) to develop an observation strategy geared at monitoring for El Niño. The strategy seeks to observe climate driven changes in real time to provide scientific and technical information for fisheries management and other government activities. The ability to provide real time information to the managers improved dramatically in the 1990s when information from the TAO array was provided over the internet. This information has not only led to a better understanding of these climatic phenomena but also to better forecasts. On a monthly to seasonal basis IMARPE utilizes TAO data to schedule their field activities. Given Peru's location at the eastern terminus of the Pacific basin the TAO data provides timely information regarding the arrival of down-welling Kelvin waves since these can be forecast and followed 8 to 10 weeks prior to their arrival to the Peruvian coastal ocean. The waves affect the not only the availability of anchoveta but also that of the jack mackerel (*Trachurus murphyi*), the horse mackerel (*Scomber japonicus*) and the jumbo squid (*Dosidicus gigas*). Eastern Pacific TAO buoys provide information about the Equatorial Undercurrent, an important ventilator of the anoxic waters off Peru. This ventilation regulates the abundance and distribution of the hake (*Merluccius gayi peruanus*). The real time TAO data is also used by a consortium of western South American countries (Colombia, Ecuador, Peru and Chile), under an organization called de Estudio Regional del Fenómeno El Niño (ERFEN), which supports a wide variety of government activities, including disaster preparedness. On longer time scales the variability of anchovies and sardines can be directly related to variations in the large scale physical environment (Figure 3.4).

Tuna and the Pacific

Tunas and billfishes are particularly valuable (Collette et al., 2011), with worldwide ex-vessel values approaching $9 billion in the 1990s, exceeded only by the value of the world's small pelagic and demersal fisheries (Sumaila et al., 2007) (see Figure 3.5).

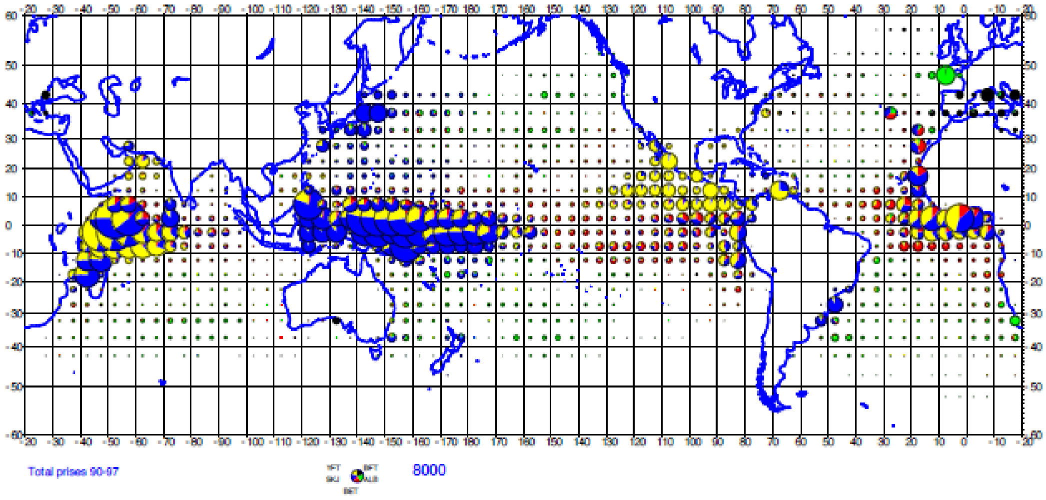

Figure 3.5 - Total global tuna (skipjack, yellowfin, bigeye, albacore and Bluefin) catch from 1990-97. Evident are the large tropical concentrations (Figure by Fonteneau, A.).

WCPO tuna fisheries were worth about $4 billion in 2007 (Reid 2007; Parris 2010a). Tuna fisheries comprised about 11% of the GDP of the region’s 22 island nations in 1999, and half of total export value (Gillett et al. 2001). Moreover, Pacific Island Countries and Territories (PICTs) typically derive 5-8% of wage employment from tuna fisheries and related industries. As noted by Gillett et al. (2001), “for people of the Pacific, tuna is not only a key resource but often *the* key resource.”

Despite being regarded as a low productivity region, the equatorial warm pool region in the western Pacific Ocean supports the world’s largest tuna fishery (50-60% of global catches). Tuna fisheries are central to socio-economic security in many PICTs, providing income and employment. The western equatorial region of the Pacific around Papua New Guinea/the Solomons Islands is a key region driving physical features and productivity within the warm pool region and these processes have impacts across the whole Pacific basin, particularly in association with ENSO. Although central to ecosystem productivity, the dynamics of the western warm pool region are poorly understood and satellite imagery and ocean models currently are not able to capture physical and biological processes in the area effectively. This has flow-on implications for understanding the impacts of climate variability and change on tuna populations. Fisheries oceanographers seek an improved understanding of the circulation and dynamics of water masses in western warm pool region and their coupling to the biogeochemistry of the water column.

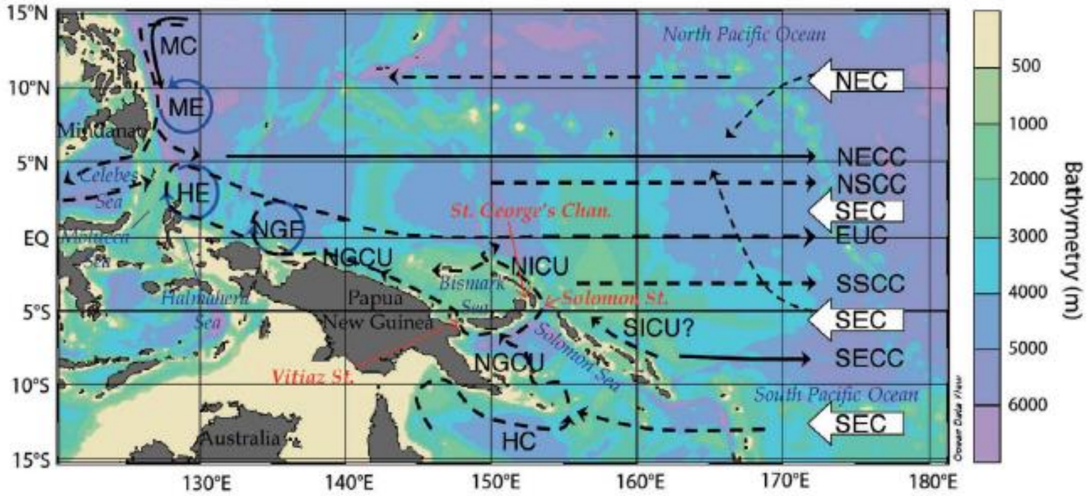

Figure 3.6 - Schematic map of major currents in the equatorial western Pacific region (Grenier et al., 2011).

The physical oceanography of the western equatorial Pacific Ocean is dominated by a number of major ocean currents including the North Equatorial Current (NEC), the South Equatorial Current (SEC) and the sub-surface Equatorial Under-Current (EUC; Figure 3.6). The NEC and SEC are driven by prevailing easterly trade winds, and as water moves from the eastern to the western Pacific, a thick layer of warm water (>29°C) known as the warm pool is formed (Lehodey et al., 2011; Figure 3.7). The thermal stratification of the warm pool delimits subsurface nutrients from the surface, resulting in the warm pool being largely nutrient depleted. As both the NEC and SEC encounter islands, and eventually the western edge of the basin, they bifurcate into a number of currents some of which, particularly the New Guinea Coastal Undercurrent (NGCUC) and the Mindano Current contribute to the warm pool and EUC (Ganachaud et al., 2011). Along the equatorial Pacific, the EUC transports water eastward from north of Papua New Guinea (PNG) to the coast of South America where it upwells into the SEC.

Water transported by the EUC is considered to contribute significantly to equatorial thermocline waters and is suspected to modulate ENSO. The EUC is the primary source of upwelled biologically available iron in the photic layer and variability of biological productivity in the region is driven by variability in this iron supply (Ryan et al. 2006). Iron is thought to derive mainly from the NGCUC and is potentially determined by sedimental release along the continental slope north of PNG and hydrothermally.

Oceanic fisheries and particularly tuna fisheries in the western and central Pacific are intimately linked to the western Pacific warm pool. Close to 60% of global tuna catches in 2009 were caught in the western and central Pacific Ocean, around 95% of which were caught in the EEZs of countries situated in the warm pool region (Lehodey et al., 2011). Distributions of tuna follow inter-annual variability in the warm pool associated with ENSO which lead to large fluctuations in catches within country EEZs (Figure 3.7). Variation in productivity associated with ENSO also has flow-on effects on tuna abundances (Lehodey et al., 2011), which then flow-through to neighboring fisheries including Australian fisheries. The distribution of such large tuna populations in a region largely considered as oligotrophic appears to be a paradigm and the physical and biological processes that support such large tuna populations in the region are not well understood.

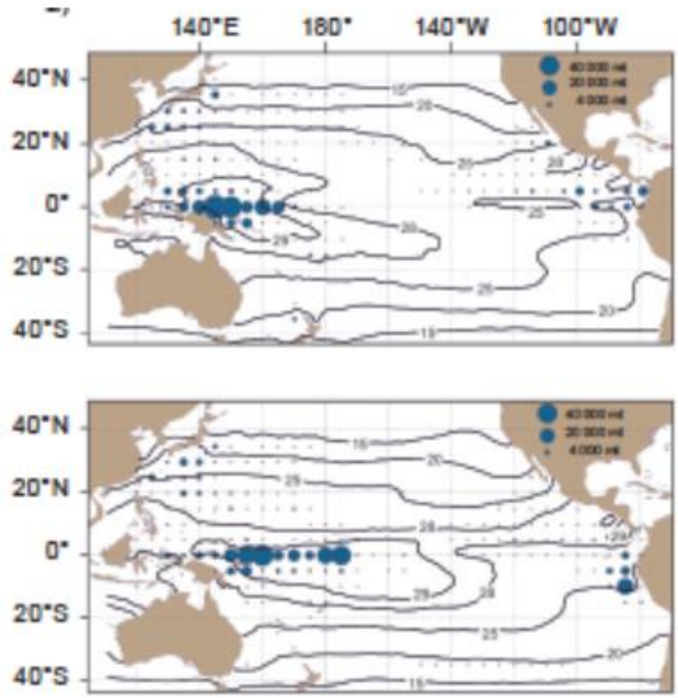

Figure 3.7 - Catches of skipjack tuna and mean sea surface temperatures during a La Niña (top) and El Niño (bottom). The 29°C contour depicts the area of the warm pool (taken from Lehodey et al., 2011).

Tropical tuna fisheries provide a vital contribution to the development goals of PICTs, with many depending heavily on the benefits derived from these fisheries. License fees from distant water fishing nations operating in the region contribute as much as 40% of government revenue and domestic tuna fishing fleets and local fish processing can account for up to 20% of national gross domestic product. Tuna resources provide an important source of jobs and opportunities to earn income and there are active plans to domesticate more of the benefits associated with tuna resources, increasing local job opportunities (Bell et al., 2011).

Given the importance of tuna to countries in the region, there is a need to understand the physical and biological processes that support tuna populations and the impacts of both short and longer-term variability in these. Satellite imagery does not fully capture the physical and biological processes driving productivity as many of the processes occur below the ocean surface layer and the present state of ocean models do not fill this void which requires *in situ* observations (Le Borgne et al. 2011). The ability to provide robust projections of ecosystems and their influence on tuna populations is therefore limited and recent assessment of the vulnerability of oceanic fisheries to climate change have highlighted these limitations (Lehodey et al., 2011). Improved observations and models and, in association, improved projections of tuna stocks, are required by regional fisheries management organizations and agencies to assess the socio-economic implications of changes in tuna catches and adjust preliminary recommended adaptations (Bell et al., 2011b) to minimize any risks and maximize opportunities.

Key features of uncertainty that could be resolved by an improved observing array include:

1. circulation in the far western Pacific, including the EUC origins, which has flow-on effects for understanding the climate of the equatorial Pacific, and in turn, global climate.
2. transport and distributions of trace metals and macro and micro-nutrients, particularly coupling of water mass dynamics and biogeochemistry

with this understanding, gained from improved observations, the fisheries oceanographers can then begin to determine the;

3. coupling of food webs supporting tuna populations to the biogeochemistry of the western warm pool region and in particular transfer of energy from nutrients to plankton to zooplankton to nekton
4. composition and structure of food webs supporting tuna populations, particularly estimates of the relative abundance of key functional groups in the food web of the western warm pool region

Ecosystem Modeling

Information collected by the physical TPOS has been of great value for validation of the emerging next generation ecosystem models (Figure 3.8). These models are now being used to develop operational models for tuna management for example (Figure 3.9). What is currently missing is validation information for chemistry and biology. Even a limited amount of such information would serve to greatly improve our existing models.

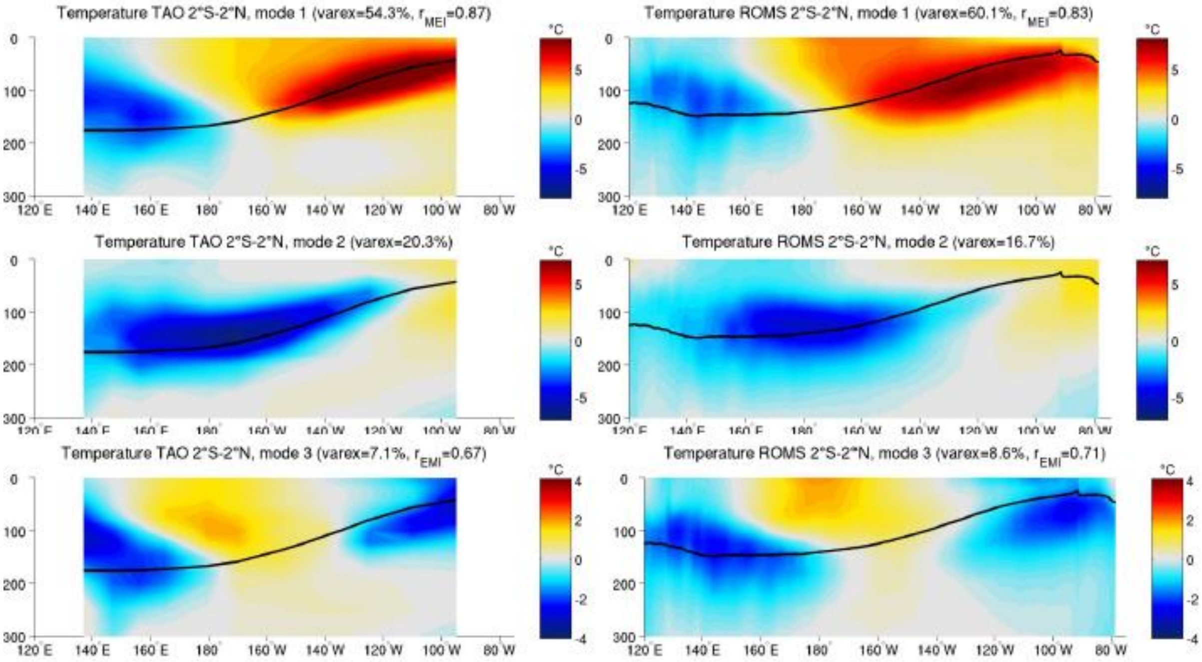

Figure 3.8 - Comparison of data from the TPOS and the output of a coupled physical-biological model. Shown are the first 3 EOFs of temperature (left – data; right –model).

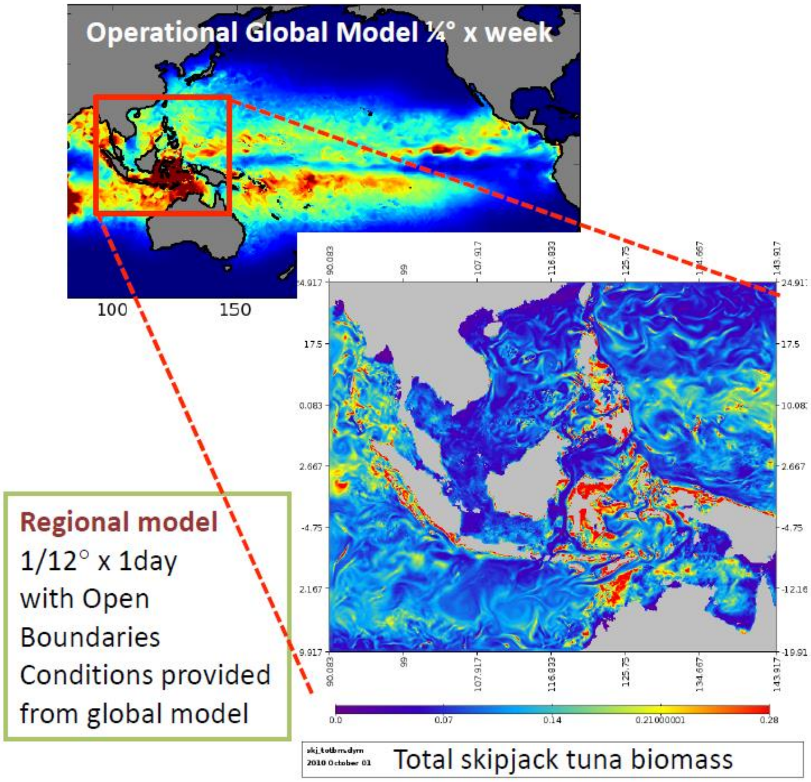

Figure 3.9 - Example of a coupled global and regional model utilized for real time management of tuna stocks in the western Pacific.

4. A biological TPOS – requirements and how to achieve them

The biological and fisheries community routinely utilizes existing physical information (i.e., surface winds, and currents, temperature and salinity with depth) from the present TPOS. Ideally and in the future this information would be daily to weekly gap-free temporal resolution over the entire tropical Pacific with order of 5-10 degree latitude spatial resolution, higher in some areas. A future TPOS would also benefit greatly by the addition of vertically distributed bio-optical, chemical, and ecological observations at a subset of locations to: 1) validate satellite measurements; 2) initialize and validate ecosystem models; and 3) be extrapolated over the entire tropical Pacific using physical *in situ* observations, remote sensing and modeling. In the following sections we assume that physical observations, including those from remote sensing (winds, sea level, SST, salinity, ocean color) will be available at about the resolution described above and focus on the measurements and locations that might be augmented with bio-optical, chemical and ecological sensors and samplers. We build on the biogeochemistry white paper. We try to avoid specifying a particular platform unless it is felt that there are no other options.

A biological TPOS for 2020 should support both operational (what is ready) and evolving/needed technologies (important information but not presently ready for operations). The use by the biology and fisheries communities is as follows:

1) Utilize information provided by the in situ physical and remote sensing observing system to: a) Determine the state of the tropical Pacific and direction of change (e.g. warming or cooling); b) Assimilate information into numerical models with embedded ecosystems to produce nowcasts and forecasts; c) Use the information in statistical models that predict biological fields.
2) At strategic locations augment the physical TPOS with biogeochemical and ecological measurements to calibrate/validate: a) remote sensing products; b) Ecosystem models; c) Statistical models that utilize the physical information to predict biological fields. The payoff for these is great likely improving estimates from physics alone by 50-100%.
3) Implement a technology development effort to develop critical sensors and systems (i.e. iron, eDNA, etc,) that can be added to the TPOS; this requires that the TPOS be designed/implemented with expansion capabilities.

The desired outputs:

1) Remote sensing calibration/validation of ocean color
2) Concentrations of chemical elements (nutrients) that drive primary production or determine the distribution of animals (e.g. oxygen)
3) Rates of primary production and the composition of the primary producers
4) The growth and distribution of forage species (zooplankton to small pelagic fish)
5) The growth and distribution of large marine vertebrates (living marine resources to endangered charismatic species)

How might these be achieved?

1) Vertically distributed hyperspectral measurements of down-welling irradiance and upwelling radiances at order of 20 locations in the tropical Pacific.

2) Vertically distributed concentrations of oxygen, nitrate and pH at order of 40 locations in the tropical Pacific. Investment in autonomous sensors for iron.
3) Vertically distributed concentration of chlorophyll and samples for the analysis of: a) Triple isotopes of oxygen; b) Composition of the primary producers (and the entire food web via environmental DNA) at order of 20 locations in the tropical Pacific.
4) Acoustic estimates of forage species biomass from fixed and moving platforms.
5) Tracking of tagged large marine vertebrates.
6) Regional and basin-wide ecosystem models.

What platforms could be instrumented to supply these data?

1) Ships – important to consider this part of a TPOS. Certain biological and biogeochemical measurements can only be made from these platforms.
2) Moorings – bio-optics, nutrients, carbon, samples, acoustics
3) Argo floats – bio-optics, nutrients, carbon
4) Gliders (profiling and wave – other ASVs)/Long Range AUVs – bio-optics, nutrients, carbon, samples, acoustics
5) Large Marine Vertebrates – tags, T, S

There is a requirement for broad-scale TPOS information for biology and biogeochemistry. This broad-scale coverage can be achieved by collection of data from a subset of the physical TPOS and development of basin-wide and regional relations/models that link physics with biogeochemistry and biology. The regional focus would include:

1) The eastern to central Pacific cold tongue, where biological productivity is enhanced and variability is greatest.
2) The eastern boundary where the production of small pelagic fish is enhanced. The boundary regions in general are regions of enhanced production of living marine resources.
3) The western Pacific oligotrophic warm pool where the chlorophyll maximum is deepest, requiring subsurface measurements for accurate estimates of primary production. Tuna populations are enhanced in this region as well.
4) The region north or on the Equatorial Front.

5. Conclusions/recommendations

There are clear needs for biogeochemical and biological information from the tropical Pacific across a wide variety of time and space scales. The requirements are diverse and include:

1) The physical state and direction of change. Multi-decadal variations with strong ecological imprints are particularly challenging.
2) The biogeochemical state and direction of change.
3) The ecological state and direction of change.
4) The synthesis of information for decision making purposes regarding biology and biogeochemistry.

The recommendations are:

1) Have adequate physical information to: a) Determine the state of the Tropical Pacific Ocean; b) Assimilate into numerical models with embedded ecosystems and utilize model simulations; c) Develop algorithms that predict biological fields.
2) At strategic locations augment the physical TPOS with biogeochemical and ecological measurements to calibrate/validate: a) remote sensing products; b) Ecosystem models; c) Algorithms that utilize the physical information to predict biological fields.
3) Implement a technology development effort to develop critical sensors and systems (i.e. iron, eDNA, etc,) that can be added to the TPOS; this requires that the TPOS be designed/implemented with expansion capabilities.

References

Ashok, K., Behera, S.K., Rao, S.A., Weng, H., and Yamagata, T. (2007): El Niño Modoki and its possible teleconnection, J. Geophys. Res., 112, C11007, (doi:10.1029/2006JC003798).

Bell, J.D., Reid, C., Batty, M.J., Allison, E.H., Lehodey, P., Rodwell, L., Pickering, T.D., Gillett, R., Johnson, J.E., Hobday, A.J., and Demmke, A. (2011): Implications of climate change for contributions by fisheries and aquaculture to Pacific Island economies and communities. pp. 733–801 in Bell, J.D., Johnson, J.E., and Hobday, A.J. (editors): Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Secretariat of the Pacific Community. Available for download at www.spc.int.

Chavez, F.P., Strutton, P.G., and McPhaden, M.J. (1998): Biological-physical coupling in the central equatorial Pacific during the onset of the 1997-98 El Niño, Geophys. Res. Lett., 25, pp. 3543-3546.

Chavez, F.P., Strutton, P.G., Friederich, G.E., Feely, R.A., Feldman, G.C., Foley, D.G., and McPhaden, M.J. (1999): Biological and chemical response of the equatorial Pacific Ocean to the 1997-98 El Niño, Science, 286, (doi:10.1126/science.286.5447.2126).

Chavez, F., Messié, P.M., and Pennington, J.T. (2011): Marine primary production in relation to climate variability and change. Annual Review of Marine Science, 3; pp. 227–60, (doi:10.1146/annurev.marine. 010908.163917).

Gierach, M. M., Lee, T., Turk, D., and McPhaden, M.J. (2012): Biological response to the 1997-98 and 2009-10 El Niño events in the equatorial Pacific Ocean. Geophys. Res. Lett., 39, L10602, (doi:10.10.29/2012GL051103).

Gierach, M. M., Messié, M., Lee, T., Karnauskas, K.B., and Radenac, M.H. (2013): Biophysical Responses near Equatorial Islands in the Western Equatorial Pacific Ocean during El Niño/La Niña Transitions. Geophys. Res. Lett., (doi:10.1002/2013GL057828).

Grenier, M., Cravatte, S., Blanke, B., Menkes, C., Koch-Larrouy, A., Durand, F., Melet, A., and Jeandel, C. (2011): From the western boundary currents to the Pacific Equatorial Undercurrent – Modeled pathways and water mass evolutions. Journal of Geophysical Research: Oceans, Vol. 116.

Kao, H.-Y., and Yu, J.Y. (2009): Contrasting eastern-Pacific and central- Pacific types of ENSO, J. Clim., 22, pp. 615–632, (doi:10.1175/ 2008JCLI2309.1).

Kug, J.-S., Jin, F.F., and An, S.I. (2009): Two types of El Niño events - Cold tongue El Niño and warm pool El Niño, J. Clim., 22, pp.1499–1515, (doi:10.1175/2008JCLI2624.1).

Larkin, N. K., and Harrison, D.E. (2005): Global seasonal temperature and precipitation anomalies during El Niño autumn and winter, Geophys. Res. Lett., 32, L16705, (doi:10.1029/2005GL022860).

Le Borgne, R., Allain, V., Griffiths, S.P., Matear, R.J., McKinnon, A.D., Richardson, A.J., and Young, J.W. (2011): Vulnerability of open ocean food webs in the tropical Pacific to climate change. pp. 189 – 249 in Bell, J.D., Johnson, J.E., and Hobday, A.J. (editors): Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Secretariat of the Pacific Community. Available for download at www.spc.int.

Lehodey, P., Hampton, J., Brill, R.W., Nicol, S., Senina, I., Calmettes, B., Pörtner, H., Bopp, L., Ilyina, T., Bell, J.D., and Sibert, J. (2011): Vulnerability of oceanic fisheries in the tropical Pacific to climate change. pp. 433 – 492 in Bell, J.D., Johnson, J.E., and Hobday, A.J. (editors): Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Secretariat of the Pacific Community. Available for download at www.spc.int.

Lehodey, P., Hampton, J., Brill, R.W., Nicol, S., Senina, I., Calmettes, B., Pörtner, H.O., Bopp, L., Ilyina,,T., Bell, J.D., and Sibert, J. (2011): Vulnerability of oceanic fisheries in the tropical Pacific to climate change. pp. 433-492 in Bell, J.D., Johnson, J.E., and Hobday, A.J. (editors): Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Secretariat of the Pacific Community. Available for download at www.spc.int.

McPhaden, M.J. (1993): TOGA-TAO and the 1991-93 El Niño Southern Oscillation Event, Oceanography, 6(2), pp. 36-44.

McPhaden, M.J. (1999): Genesis and Evolution of the 1997-98 El Niño, Science, 283, pp. 950-954.

McPhaden, M.J., Busalacchi, A.J., and Anderson, D.L.T. (2010): A TOGA Retrospective, Oceanography, 23, pp. 86-103.

Messié, M., Radenac, M.H., Lefevre, J., and Marchesiello, P. (2006): Chlorophyll blooms in the western Pacific at the end of the 1997-1998 El Niño: The role of the Kiribati Islands. Geophys. Res. Lett., 33, L14601, (doi:10.1029/2006GL026033).

Messié, M., and Chavez, F.P. (2012): A global analysis of ENSO synchrony - The oceans' biological response to physical forcing, J. Geophys. Res., 117, C09001, (doi:10.1029/2012JC007938).

Messié, M., and Chavez, F.P. (2013): Physical-biological synchrony in the global ocean associated with recent variability in the central and western equatorial Pacific, J. Geophys. Res. Oceans, 118, pp. 3782–3794, (doi:10.1002/jgrc.20278).

Nicol, S. J., Allain, V., Pilling, G.M., Polovina, J., Coll, M., Bell, J.D., Dalzell, P., Sharples, P., Olson, R., Griffiths, S., Dambacher, J.M., Young, J., Lewis, A., Hampton, J., Molina, J.J., Hoyle, S., Briand, K., Bax, N., Lehodey, P., and Williams, P. (2013): An ocean observation system for monitoring the affects of climate change on the ecology and sustainability of pelagic fisheries in the Pacific Ocean. Climatic Change; (doi:10.1007/s10584-012-0598-y).

Radenac, M.H. (2001): Modeled and observed impacts of the 1997-1998 El Nino on nitrate and new production in the equatorial Pacific, J. Geophys. Res., 106, pp. 26879-26898.

Radenac M.H., Léger, F., Singh, A., and Delcroix, T. (2012): Sea surface chlorophyll signature in the tropical Pacific during Eastern and Central Pacific ENSO events, Journal of Geophysical Research, 117, C04007, (doi:10.1029/2011JC007841).

Radenac M.H., Messié, M., Léger, F., and Bosc, C. (2013): Oligotrophic and non-oligotrophic waters in the equatorial Pacific warm pool as observed from space, Remote Sensing of Environment, 134, pp. 224-233, (doi:10.1016/j.rse.2013.03.007).

Ryan, J.P., Polito, P.S., Strutton, P.G., and Chavez, F.P. (2002): Unusual large-scale phytoplankton blooms in the equatorial Pacific. Prog. Oceanogr., 55, pp. 263-285.

Ryan, J.P., Ueki, I., Chao, Y., Zhang, H., Polito, P.S., and Chavez, F.P. (2006): Western Pacific modulation of large phytoplankton blooms in the central and eastern equatorial Pacific. J. Geophys. Res., 111, G02013, (doi:10.1029/2005JG000084).

Strutton, P.G., Ryan, J.P., Chavez, F.P. (2001): Enhanced chlorophyll associated with tropical instability waves in the equatorial Pacific, Geophys. Res. Lett., 28, pp. 2005-2008.

Turk, D., McPhaden, M.J., Lewis, M.R., and Busalacchi, A.J. (2001): Remotely-sensed biological production in the Tropical Pacific during 1992-1999. Science, 293, pp. 471-474.

Turk, D., Meinen, C.S., Antoine, D., McPhaden, M.J., and Lewis, M.R. (2011): Implications of changing El Niño patterns for biological dynamics in the equatorial Pacific Ocean. Geophys. Res. Lett., 38, L23603, (doi: 10.1029/2011GL049674).

Weng, K. C., Glazier, E., Nicol, S.J., and Hobday, A.J. (in review): Fishery Management, Development and Food Security in the Western and Central Pacific in the Context of Climate Change. Deep Sea Research II.

Wilson, C., and Adamec, D. (2001): Correlations between surface chlorophyll and sea surface height in the tropical Pacific during the 1997-1999 El Niño - Southern Oscillation event. J. Geophys. Res., 106, 31, pp. 175-188.