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A review of eastern tropical Pacific oceanography: Summary

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Abstract

The collection of articles in this volume reviewing eastern tropical Pacific oceanography is briefly summarized, and updated references are given. The region is an unusual biological environment as a consequence of physical characteristics and patterns of forcing – including a strong and shallow thermocline, the ITCZ and coastal wind jets, equatorial upwelling, the Costa Rica Dome, eastern boundary and equatorial current systems, low iron input, inadequate ventilation of subthermocline waters, and dominance of ENSO-scale temporal variability. Remaining unanswered questions are presented.

Keywords: Eastern tropical Pacific; Review; Physical and biological patterns

1. Introduction

This review of eastern tropical Pacific oceanography has shown major advances in some fields since Klaus Wyrtki's reviews of the 1960s, such as studies of mesoscale processes and analyses of temporal variability. On the other hand, many of his conclusions about hydrography and circulation (Wyrtki, 1965, 1966, 1967) are still relevant. Here, we will summarize the scientific content of this review, with emphasis on why this area is special as a physical environment for the development of distinct biological communities. We will also point out some recent publications illustrating the rapid progress in some fields of study of the region, and add some thoughts about future directions. The original aim of the volume was to establish an up-to-date review of our knowledge of the eastern tropical Pacific, so that the singular characteristics of the region, its interactions with the global ocean, and the imminent effects of global warming could be put in perspective.

Although we strived to make this collection of review articles as complete as possible within our focus on the oceanic pelagos, some important subjects were admittedly left out (such as turtles and impacts on the benthos). Readers will surely recognize other omissions. Also missing from the collection is a review of regional

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fisheries oceanography, which could not be delivered in time to be included in this volume. It will be made available online, and may be published in a later number of Progress in Oceanography.

A causal approach will be followed in this summary, starting with the atmospheric forcing patterns, following with the ocean physics as represented by hydrography, circulation and mesocale features, then the lower trophic levels represented by primary productivity and zooplankton, and ending with the distribution of higher organisms and fisheries (although the chapter on the latter subject is not included in the collection). This approach is applied in turn to each of the most outstanding physical/ecological features or provinces of the eastern tropical Pacific. First the mean or average status is described, and then the seasonal, interannual and decadal variability will be considered.

2. Highlights/why is the eastern tropical Pacific special?

The eastern tropical Pacific presents unique environmental characteristics for plankton, as well as for higher organisms. These characteristics are rooted in physical oceanographic features whose behavior depends on the space–time variability patterns of the solar and atmospheric forcing agents, both within and outside of the region (Amador et al., 2006).

Direct effects of the solar and atmospheric forcings operate through air–sea exchange of heat and moisture and through the injection of momentum (for Ekman transport) and turbulent kinetic energy (for vertical mixing). The direct effects are most evident in the distributions of sea surface temperature (SST), sea surface salinity (SSS), the depth and strength of the thermocline, and the depth of the surface mixed layer (Fiedler and Talley, 2006). Ekman pumping generates coastal and open-sea upwelling, as well as fronts, eddies and meanders (Willett et al., 2006). More indirect effects operate through dynamical processes like geostrophic balance and Rossby and Kelvin waves, all of which involve the topography of the thermocline (Kessler, 2006). Instability of the currents can also generate eddies and meanders.

The wind field, in particular, has a very important role by shaping the topography of the thermocline through Ekman pumping, and by producing vertical mixing. The wind stress field is dominated by the trade winds and their area of convergence, the Intertropical Convergence Zone (ITCZ). The trade winds are the eastern and equatorial limbs of the anticyclonic flow around the subtropical, sea level high-pressure systems in both hemispheres (Amador et al., 2006). The facts that the ITCZ is always in the northern hemisphere and that it oscillates seasonally between $\sim$5°N (in winter) and $\sim$10°N (in summer) have profound consequences for the oceanography of the eastern tropical Pacific.

The convergence of the trade winds on the ITCZ occurs a good distance from the American continent, leaving a "shadow" zone to the west of Mexico and Central America where the wind is comparatively weak. As a consequence of diminished evaporation and vertical mixing in the presence of strong surface heat input, the thermocline is shallow and strong in this area, and sea surface temperature is higher than elsewhere in the region (Fiedler and Talley, 2006). This zone is the eastern Pacific warm pool, or simply "warm pool" hereinafter, which constitutes an open-ocean biogeographic province with a distinct biological community.

While primary production in the eastern tropical Pacific as a whole is iron-limited, surface waters of the warm pool are also devoid of nitrate due to the strong stratification, and thus dominated by picoplankton (Pennington et al., 2006). Zoogeographic studies have shown a distinct assemblage of zooplankton species here, some of which are adapted to the subthermocline oxygen minimum and are capable of successfully utilizing the suboxic environment (Fernández-Álamo and Färber-Lorda, 2006). A distinct and prevalent association between specific seabirds, yellowfin tuna, and certain dolphin species is also characteristic of the warm pool region (Ballance et al., 2006).

In stark contrast from the physical point of view is the equatorial cold tongue, an open-ocean upwelling region caused by divergent Ekman transport beneath the southeast trade winds. The basin-wide west-to-east upward tilt of the equatorial thermocline, also created by the trades, makes subthermocline water with high nutrient concentration available for upwelling (Pennington et al., 2006). Although upwelling brings nutrients into the surface waters, iron-limitation results in high nitrate-low chlorophyll conditions. Iron limitation also results in (1) an important microbial loop in the food web, consisting of picoplankton, bacteria, and microzooplankton (Fernández-Álamo and Färber-Lorda, 2006), and (2), along with the warming of upwelled water, a globally important source of atmospheric CO_2.

Less dramatic but just as important is the lifting of the thermocline below the ITCZ at ~10°N, caused by Ekman transport divergence across the ITCZ (the zonal winds south of the ITCZ are weaker than to the north). It gives rise to the North Equatorial Countercurrent (NECC) that has an associated band of high near-surface nitrate concentration and increased production (Kessler, 2006; Pennington et al., 2006). This countercurrent or 10°N thermocline ridge bisects the warm pool and is a significant physical feature for a great many apex predators, including members of the tuna–dolphin–seabird assemblage so characteristic of the eastern tropical Pacific in general (Ballance et al., 2006).

The Costa Rica Dome is another open-ocean upwelling region with great biological significance. It is caused by a seasonally changing combination of interconnected features: coastal jets and eddies, the ITCZ, and geostrophic balance at the eastern extreme of the 10°N thermocline ridge (Kessler, 2006). Primary and secondary production are relatively high at the Dome; the density of two species of cetaceans is greatly increased here, although no seabird species are known to associate with this feature (Ballance et al., 2006); and it seems to support tuna and other fisheries, such as jumbo squid (Ichii et al., 2002).

The most important coastal upwelling zone in the eastern tropical Pacific is found off Peru (Kessler, 2006; Pennington et al., 2006), caused in text-book fashion by the predominantly alongshore, equatorward trade winds. The low SST signature of the coastal upwelling process merges with that of the equatorial cold tongue, just as the Peru Current joins the South Equatorial Current (SEC). The productive Peruvian Coastal Upwelling system has supported the largest fishery in the world, but is particularly susceptible to interannual variability caused by the El Niño-Southern Oscillation (ENSO, see Section 3.2).

The equivalent upwelling and eastern boundary current in the northern hemisphere are the upwelling off the western USA and NW Mexico and the California Current (Pennington et al., 2006). Although not in the eastern tropical Pacific, the California Current is an important input and boundary condition for the region; however, the transition of the California Current to the North Equatorial Current is not completely understood nor adequately sampled (Kessler, 2006).

The atmosphere of the eastern tropical Pacific boasts three examples of the rare condition of a narrow wind jet blowing from land to sea: the Tehuantepec Jet, the Papagayo Jet and the Panama Jet (Amador et al., 2006). Although they are intermittent and occur only from November to April, their effect is detectable in mean distributions of SST and clorophyll (Chl). In satellite images, their effect shows as cool, productive areas (streaks in individual images, wide areas in average) interrupting the warm, low-productivity warm pool (Willett et al., 2006; Pennington et al., 2006). Although they induce divergence (and therefore thermocline lifting) on their left-hand-side, the SST and Chl anomalies are due to intense vertical mixing below the axis of the wind jet (Willett et al., 2006). In fact, these are probably the only areas of the eastern tropical Pacific where surface mixing is more important than upwelling in enriching the surface, mixing made possible by the extreme wind speeds and the shallowness of the thermocline/nutricline. The high-chlorophyll anomalies are then advected and spread out over a wide area in the gulfs and to the west by the mesoscale structures generated by the jets, especially by the anticyclonic eddies. Secondary productivity is also increased due to the wind jets (Fernández-Álamo and Färber-Lorda, 2006).

Although most notable in the warm pool, the shallow and strong thermocline is a characteristic of the entire eastern tropical Pacific; it is perhaps the feature that most contributes to the uniqueness of the region. Its strength indicates that the exchange of properties (e.g. dissolved oxygen and nutrients) between the surface waters and the subthermocline layers is very weak. Indeed, one of the most striking hydrographic characteristics of the eastern tropical Pacific is the pronounced Oxygen Minimum Layer (OML), with lower oxygen concentration than most other low oxygen areas in the world ocean and which can be as close as a few tens of meters from the surface (Fiedler and Talley, 2006). The combination of the shallow thermocline and pronounced oxygen minimum determine the vertical distribution and movements of zooplankton: some species are adapted to living in the OML, while others concentrate in the photic zone above the OML (Fernández-Álamo and Färber-Lorda, 2006). The OML affects the metabolism and distribution of both planktonic and benthic organisms, and the vertical fluxes of carbon to the benthos in the area. The presence of the OML indicates that ventilation by subthermocline currents is very weak; the only eastward subsurface currents in the equatorial current system are the Equatorial Undercurrent and the Tsuchiya Jets, found between 100 and 350 m depth at ~5° of latitude north and south (Kessler, 2006).

3. Temporal variability

3.1. Seasonal

As the solar heating maximum shifts seasonally between the Southern and the Northern hemispheres, the atmospheric variables (winds, clouds, precipitation, evaporation, etc.) follow. Of prime importance for the oceanography of the eastern tropical Pacific is the seasonal meridional migration of the ITCZ, which reaches its southernmost position during the boreal winter. During this season, the NE trades intensify and cold air masses are frequently displaced south to produce the Tehuantepec, Papagayo and Panama jets (Amador et al., 2006).

The seasonal cycle of the wind forcing translates into changes in the topography of the pycnocline, and hence in the equatorial circulation system. The seasonal response of the thermocline to the seasonal wind variability (trades, ITCZ and jets) can be interpreted as Rossby waves that cause a southwestward-propagating perturbation of the thermocline depth. This accounts for the seasonal variability of the NECC and its thermocline ridge, the Tehuantepec Bowl and the Costa Rica Dome (Kessler, 2006).

In the eastern tropical Pacific, the NECC flow is weak or absent in spring. At that season, the California Current provides most of the input to the NEC, after skirting the Tehuantepec Bowl (Kessler, 2006). The latter is at its strongest and closest to the continent in winter and spring.

The seasonal variability of the warm pool is large in extension but low in SST amplitude, especially along the thermal equator (Fiedler and Talley, 2006; Wang and Fiedler, 2006). The seasonal variation of SST (which shows two peaks) is not controlled only by local heat fluxes, and ocean advection seems to play an important role as well (Wang and Fiedler, 2006). The seasonal changes in biology are not well documented but are generally small (Pennington et al., 2006). Located within the warm pool, the areas affected by the wind jets in winter (Gulfs of Tehuantepec, Papagayo and Panama) do have a seasonal cycle, becoming cool and very productive during the season of the jets (Pennington et al., 2006). There is some evidence that zooplankton biomass also increases during winter off Central America (Fernández-Álamo and Färber-Lorda, 2006).

The Costa Rica Dome exhibits large seasonal variations in extent, being small and close to the American continent in February–March and extending to the west up to 600 km in summer–fall (Kessler, 2006; Fiedler and Talley, 2006). However, its SST and productivity do not change greatly through the year (Pennington et al., 2006). This is because when the Papagayo jet weakens in May, convergence of the trade winds in the ITCZ provides compensating wind stress curl (Kessler, 2006).

The equatorial cold tongue region, with its shallow but relatively weak pycnocline, has a moderate seasonal variability: it is coldest and most productive in September, when upwelling is strongest (Pennington et al., 2006). The seasonal cycle is decidedly annual, despite the biannual passage of the sun at the spring and fall equinoxes. Phytoplankton and zooplanton biomasses are largest in summer and autumn (Fernández-Álamo and Färber-Lorda, 2006; Pennington et al., 2006). Winds and precipitation in the region between the equator and 10°N are strongly influenced by the annual cycle of cold tongue SST (Amador et al., 2006).

Peruvian coastal upwelling is strongly seasonal, and appears to reach even below the thermocline (Kessler, 2006). The highest levels of chlorophyll and primary production occur during the austral summer and fall, and highest zooplankton biomass during fall (Pennington et al., 2006). Both are out of phase with the seasonal upwelling winds that peak in winter.

3.2. El Niño-Southern Oscillation, ENSO

The temporal variability of the eastern tropical Pacific is dominated by the ENSO time-scale (Fiedler and Talley, 2006). As most of the physical effects of El Niño (La Niña) involve a deepening (shoaling) of the thermocline and nutricline, the effect on primary productivity (Pennington et al., 2006) is mainly negative (positive). Diminished primary productivity and the deepened thermocline during El Niño have detrimental effects on the survival, reproduction and distribution of higher trophic level organisms (Ballance et al., 2006). In the equatorial and coastal upwelling areas, zooplankton volume diminishes under El Niño conditions (Fernández-Álamo and Färber-Lorda, 2006). This can cause birds and cetaceans to die or fail to reproduce as their normal prey become unavailable. Of course, the negative effect of El Niño on fisheries is well documented, especially in Peru where the anchoveta fishery crashes during El Niño. However, the deepening of the upper boundary of the minimum oxygen layer and the warming of the surface waters during El Niño seem to benefit some benthic species. In some localities zooplankton might increase during El Niño; changes in species composition can also occur.

As the zonal tilt of the equatorial thermocline flattens at the peak of El Niño, the EUC weakens or disappears, while the NECC strengthens (Kessler, 2006). Although upwelling in the cold tongue, the Costa Rica Dome and off Peru continues (or increases), the upwelled water comes from the thickened warm and nutrient-poor upper layer; therefore the productivity in these areas diminishes considerably (Pennington et al., 2006). The same happens in the mixing areas of the Central American wind jets.

As the eastward-travelling, downwelling, equatorial Kelvin waves become coastally trapped perturbations that travel poleward against the coasts of South and North America, the thermocline thickens near the coast (Kessler, 2006), and poleward invasions of Tropical Surface Waters and tropical species of plankton and fishes occur (Fiedler and Talley, 2006; Fernández-Álamo and Färber-Lorda, 2006); these are more marked in areas of strong meridional gradients of properties. In the eastern tropical Pacific the SST increase during El Niño occurs not only because of oceanic advection but teleconnections and local feedback processes appear to be very important as well.

Since the trapped waves of El Niño are non-linear and downwelling-only, a net poleward intrusion occurs (Kessler, 2006), and return to normal conditions is affected by local processes, unless La Niña starts soon enough to hasten the process. In most cases the return to normal physical and ecological conditions takes place within months (Pennington et al., 2006).

Although the interannual variability of the warm pool is comparable to the seasonal variability, and it is related to El Niño events due to direct oceanic connection to the equator, both the physical and biological effects of ENSO are less pronounced than in the equatorial and upwelling zones (Fiedler and Talley, 2006; Wang and Fiedler, 2006; Pennington et al., 2006).

3.3. Interdecadal

Although the origin of the interdecadal variabilty is still under debate (Mestas-Nuñez and Miller, 2006), its physical and biological consequences are well documented, especially in the North Pacific. The overall effects resemble a mild and prolonged ENSO, with higher SST, deeper thermocline and decreased productivity during the warm phase (El Niño) than during the cool phase (La Niña). From the physical point of view there is a significant difference in pattern between ENSO and the leading interdecadal mode of variability or the Pacific Decadal Oscillation (PDO): the PDO SST maxima are displaced north and south of the equator with larger amplitudes in the northern branch near the coast of North America (Mestas-Nuñez and Miller, 2006).

The changes in the ecological fabric are detectable up to the top trophic levels (Pennington et al., 2006; Fernández-Álamo and Färber-Lorda, 2006, Ballance et al., 2006, Fiedler and Talley, 2006), especially in commercial fisheries (sardine, anchovy, salmon, etc.) because of the long and accurate records. The changes from one regime to another can be quite rapid, as occurred in the 1976–1977 shift from cool anchovy-dominated to warm sardine-dominated conditions (Chavez et al., 2003). Another regime shift seems to have occurred in the late 1990s (Mestas-Nuñez and Miller, 2006).

The interdecadal variability of the eastern tropical Pacific is less well documented than that in the North Pacific, especially its biological effects. The most affected areas, as with ENSO, are the highly productive cold tongue and the coastal upwelling areas of Peru and Mexico (Pennington et al., 2006). Long-term studies off Peru show a decline of zooplankton biomass in 20 years (1964–1987), most pronounced after the 1974 El Niño (Fernández-Álamo and Färber-Lorda, 2006). In contrast, the warm pool seems to be much less affected, although this should be carefully examined as more biological data become available for that region.

4. Updates

As inevitably happens with reviews, advances have been made since the articles were accepted. In order to bring this review volume somewhat up to date, brief additions are offered below.

Understanding of air–sea interaction and atmospheric forcing over the open ocean is being greatly extended by the East Pacific Investigation of Climate Processes in the Coupled Ocean-Atmosphere System (EPIC, Wijesekera et al., 2005; http://www.atmos.washington.edu/gcg/EPIC/). Long-term changes in hurricane intensity associated with ocean warming have been suggested by Webster et al. (2005), although there is considerably uncertainty in the hurricane database (Landsea, 2005).

Direct observations of a surface poleward current off SW Mexico (Lavín et al., 2006) give three-dimensionality to Wyrtki's (1965, 1966) description of the surface currents in the area, but leave questions about relationships to the California Current and the Costa Rica Coastal Current. At the mesoscale, Zamudio et al. (2006) used satellite altimetry and results from the Naval Research Laboratory Layered Ocean Model (NLOM) to show that coastally trapped waves (CTWs) of equatorial origin play an important role in the generation and development of eddies, by inducing barotropic and baroclinic instabilities in the coastal poleward current. Those instabilities can generate eddies southeast of the Gulf of Tehuantepec and strengthen previously present ones. They also argue that the ENSO modulation of the number and strength of eddies is due to larger numbers of CTWs during El Niño than during La Niña. The offshore transport of mass and nutrients from the Gulf of Tehuantepec was addressed in numerical models by Samuelsen and O'Brien (in press), who find that the largest transport occurs during the eddy season.

Forcing of ENSO events continues to be explored and debated, both in the Pacific (Eisenman et al., 2005) and globally (Tourre and White, 2005). Temporal variability with scales longer than ENSO (interdecadal and climate change) continues to be a rapidly evolving field of investigation. The predominant area is the search for mechanisms of interdecadal variability with further support presented for those that originate in the tropics (Vimont, 2005; An et al., 2005), extratropics (Tourre et al., 2005; Yeh and Kirtman, 2006), and those that involve interactions between the tropical and extratropical North Pacific (D'Arrigo et al., 2005; Lohmann and Latif, 2005; Schneider and Cornuelle, 2005; Yeh and Kirtman, 2006). Resolution of long-term changes in ENSO variability is improving (Rein et al., 2005).

Spatial and temporal patterns of productivity are being elucidated by lengthening times series of data from SeaWiFS and other sensors (Waliser et al., 2005) and explained by coupled physical-biogeochemical modeling (Jiang and Chai, 2005; Radenac et al., 2005). The biological effects of ENSO and multidecadal variability have been reviewed by Chavez (2005). Understanding of distribution and habitat use by top predators (including birds and mammals) is being advanced by the concept of biological ''hot spots'' (Sydeman et al., in press).

5. Outstanding questions

Continued research is needed to address unanswered questions about this globally important region. Some of these questions are:

What are the interconnections in the eastern extreme of the equatorial current system?

What are the relative contributions to the SEC by equatorial upwelling, the Peru Current, the EUC and the Tsuchiya jets?

What happens to the branch of the California Current that flows southeast parallel to the Mexican coast?

Is the poleward current off SW Mexico different from the Costa Rica Coastal Current? If so, what are the mechanisms that give rise to it?

Why does the chlorophyll signature of the anticyclonic Tehuantepec and Papagayo eddies persist for so long after the initial mixing-induced bloom and its wrap-around on the eddies' periphery? Is frictional spin-down causing upwelling (Palacios and Bograd, 2005)?

Are these eddies important biological hot spots that carry substantial amounts of nutrients and organisms to the ocean interior? How much water and nutrients do they transport, and how does the ecosystem evolve?

How does the shallow OML affect zooplankton and higher organisms living in the epipelagic or surface layer?

Is the lack of evidence for multidecadal variability and climate change in the eastern tropical Pacific due to inadequate data or simply because there is little energy at these time scales in this region?

Have long-lived (K-selected) birds and cetaceans evolved to survive ENSO-scale variability, and how might this affect vulnerability to lower-amplitude interdecadal variability and climate change?

How does the eastern tropical Pacific support such a diverse community of seabirds and cetaceans, and why is it the region of highest abundance for so many pan-tropical species in these groups?

6. Concluding remarks

The understanding of spatial and temporal patterns of eastern tropical Pacific oceanography, and the effects of this variability on biological production and ecosystems, has clearly advanced over the last 40 years. Important contributions have been made by scientists, institutions and governments in the region, as well as by others with economic interests in the region or simply with an appreciation of the central role of the eastern tropical Pacific in the global ocean-atmosphere system. Unanswered questions remain, along with opportunities based on new sampling technologies and on continuing time series. We hope this review will need to be updated in the not too distant future.

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