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Editorial

Introduction: A review of eastern tropical Pacific oceanography

The eastern tropical Pacific Ocean – the region west of Central and South America, between the tip of the Baja California Peninsula on the north and Peru on the south, and as far west as Hawaii (Fig. 1) – was sporadically explored by scientists from the early 19th through the mid-20th centuries. In the 1950s, scientists from Scripps Institution of Oceanography began a systematic study of the region, motivated by the burgeoning tuna fishery then based in San Diego. A young scientist named Klaus Wyrtki came to Scripps in 1961, after working in Indonesia during the 1950s and learning "the importance of past data and the importance of variability" (Wyrtki, 2002). Wyrtki compiled and synthesized the data and results of the Scripps researchers and published several summary papers on the oceanography of the eastern tropical Pacific (Wyrtki, 1964, 1965a,b, 1966, 1967). These reviews have been invaluable to researchers studying the oceanography and resources of the region. They give a broad summary of regional oceanography that has remained accurate and useful, even though based on limited observations.

Scientific progress in the field and in the laboratory since 1967 has greatly increased knowledge and understanding of the eastern tropical Pacific, and the world's oceans in general. Observations from oceanographic and fisheries research ships and from ships of opportunity have added data points. Oceanographic data have been compiled into publicly available databases. New instruments such as Acoustic Doppler Current Profilers, satellite-tracked drifter buoys, and networks of moored buoys have provided new types of data. Satellite sensors have produced views of spatial and temporal patterns that could never be seen from ships or shipboard data. High-resolution coupled ocean–atmosphere models allow hypothesis-testing experiments that are impossible in the field. Although much of Wyrtki's description of eastern tropical Pacific oceanography remains valid today, there are physical and biological phenomena that were not understood or even known by 1960s oceanographers, e.g.: mesoscale eddies, tropical instability waves (Willett et al., 2006, this volume) and interdecadal variability (Mestas-Nuñez and Miller, 2006, this volume).

This volume consists of a series of related articles, each reviewing an aspect of the oceanography of the eastern tropical Pacific Ocean. This review volume brings up to date Wyrtki's reviews in two ways: (1) new observations and tools have enhanced our understanding of features covered by Wyrtki, and (2) aspects of the oceanography of the region covered briefly or not at all by Wyrtki, are covered here. The physical or biological topic covered by one paper will be related to topics covered by other papers in the volume. We emphasize oceanographic patterns of spatial and temporal variability, relationships between atmospheric forcing and ocean dynamics, physical–biological interactions, and linkages between temporal variability at seasonal, interannual, and longer time scales.

1. Extent of the eastern tropical Pacific

For this review, the eastern tropical Pacific Ocean is centered on the eastern Pacific warm pool off SW Mexico and Central America (Fig. 1), and encompasses the equatorial cold tongue and the equatorial current system to the west of the Galapagos Islands. Eastern boundary currents – the California Current in the north and

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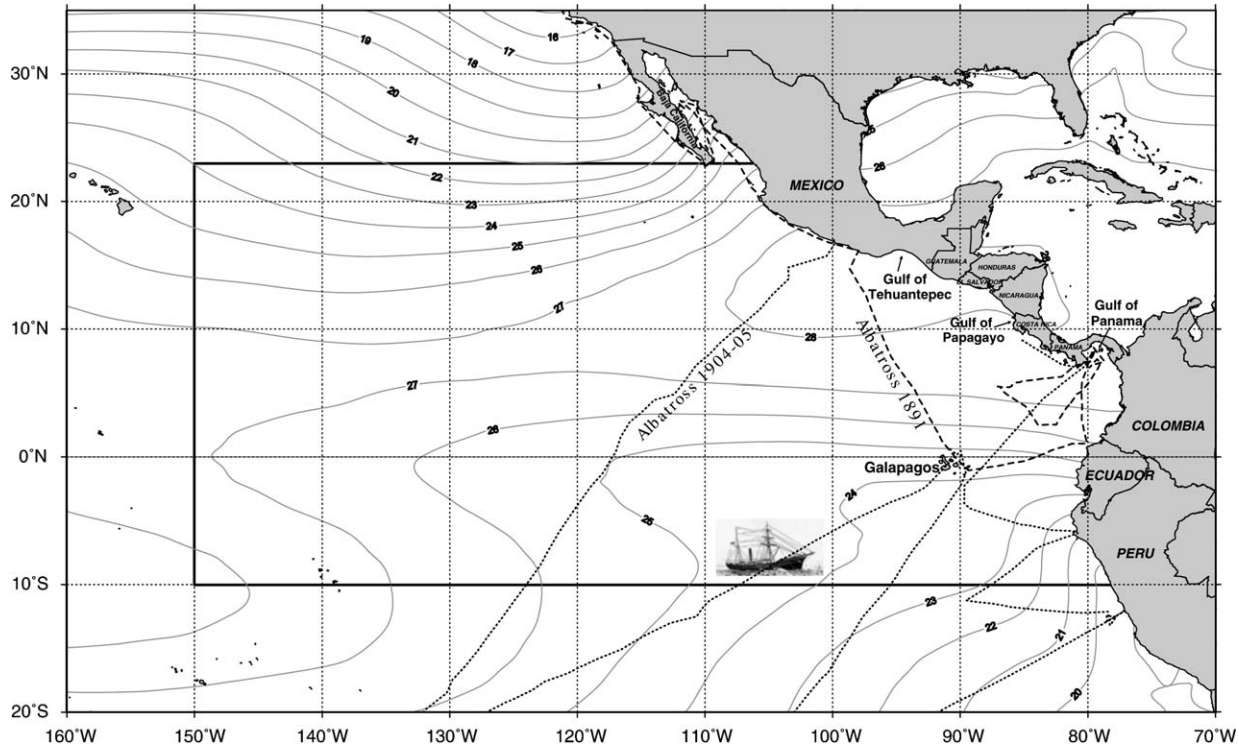

Fig. 1. Base map of the eastern tropical Pacific Ocean. Contours are mean sea surface temperature (Shea et al., 1992). The rectangle marks the general limits of this review volume. Also shown are cruise tracks of early Albatross Expeditions.

the Peru Current in the south – are important ''boundary conditions'' for the region and their influence will be covered in the review. The physical oceanography of these eastern boundary current regions has recently been reviewed by Hickey (1998) and Strub et al. (1998), respectively. We use the name ''Peru Current'' for the eastern boundary current at the southeastern corner of our study area, while recognizing that some would consider the Peru Current as the equatorward segment of a larger Peru–Chile or Humboldt Current System and, at the same time, circumventing the debate over nomenclature begun by Schott (1937) and Wüst (1936).

This review will focus on open-ocean patterns, dynamics, and processes. Many of these open-ocean phenomena are influenced by coastal boundaries and processes, although the continental shelf is very narrow over most of this region (Fig. 3). Badan-Dangon (1998) and Herguera (2006) review the oceanography of the coastal shelf and slope region of the eastern tropical Pacific.

The oceanic eastern tropical Pacific region as defined here consists of two subregions that are distinct in many ways. The eastern Pacific warm pool and the equatorial cold tongue are hydrographically and dynamically different. In his ''Ecological Geography of the Sea'', Longhurst (1998) separates the region into two provinces: the North Pacific Equatorial Countercurrent Province (warm pool) and the Pacific Equatorial Divergence Province (cold tongue). We will review differences between these subregions, but also similarities and interrelationships.

2. History

Research in the Pacific during the 18th and 19th centuries consisted of observations and collections made by individual scientists or ''naturalists'' aboard global voyages of exploration and discovery. These voyages often had political, military and economic objectives, with science being a secondary or even incidental activity. A pattern that was often repeated during this early period of exploration was set by James Cook, who skirted but missed the eastern tropical Pacific during his three global voyages of 1768–1780. Cook, however,

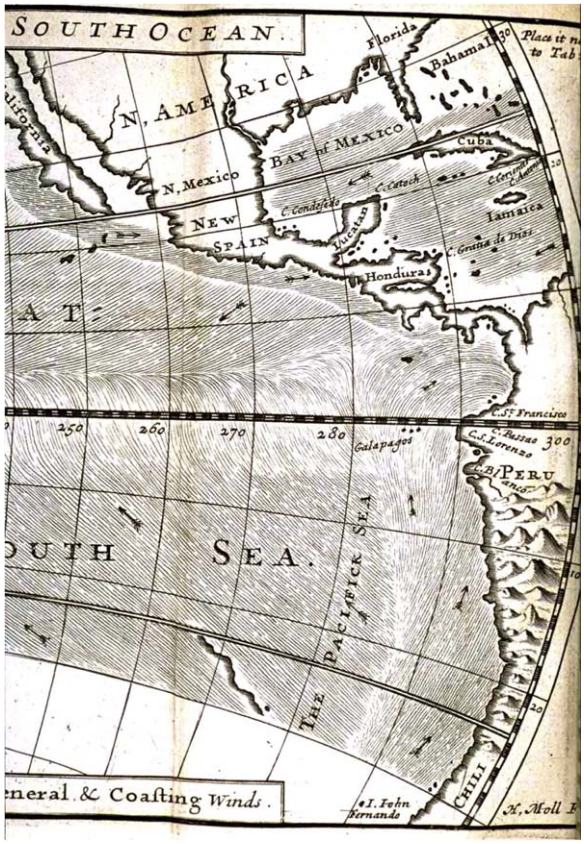

Fig. 2. Detail from William Dampier's "View of the General and Coasting Trade-Winds in the Great South Ocean" 1697. The text along the bottom edge reads "Note that the Arrows among the Lines show the Course of these General and Coasting Winds". The "streamlines" appear to delineate an Intertropical Convergence Zone along 5°N.

did read reports by the English "Pirate and Hydrographer"[1] William Dampier, who kept meticulous and copious notes on hydrography, meteorology and biology and tried to fit his observations into a logical framework (Preston and Preston, 2004). "A Discourse of Trade-Winds, Breezes, Storms, Seasons of the Year, Tides and Currents of the Torrid Zone throughout the World" (Fig. 2) was published in 1699 as a supplement to his best-selling book "A New Voyage Around the World", which included observations along the coast between Peru and Baja California and at the Galapagos.

One of the first voyages that explicitly set out to make methodical scientific observations and produced significant scientific results in the eastern tropical Pacific was a Spanish exploratory expedition, under Captain Alessandro Malaspina, that collected hydrographic, meteorological and biological data along the coast from Callao to Acapulco and at the Galapagos in 1791 and then crossed the Pacific to Guam in 1792 (Brand, 1967; Porrua, 2000). Alexander von Humboldt made temperature measurements and collected botanical specimens between Callao and Acapulco in 1802–1804, described the cold eastern boundary current off Peru that has borne his name, and apparently was the first to describe El Niño temperature anomalies in coastal waters (Kortum, 2002). Everyone knows that Charles Darwin made important observations of terrestrial fauna on the Galapagos when *HMS Beagle* visited there in 1835, but hydrographic sampling in island waters was also done by Captain Robert FitzRoy. Captains Beechey and Belcher continued FitzRoy's hydrographic efforts as *HMS Sulphur* surveyed the coast of Central America several times during 1836–1842 (Ruggles, 1967). The *HMS Herald* carried a naturalist on the North Pacific Survey of 1845–1851 and spent some time along the

[1] Inscription on Dampier's portrait in London's National Portrait Gallery (Preston and Preston, 2004).

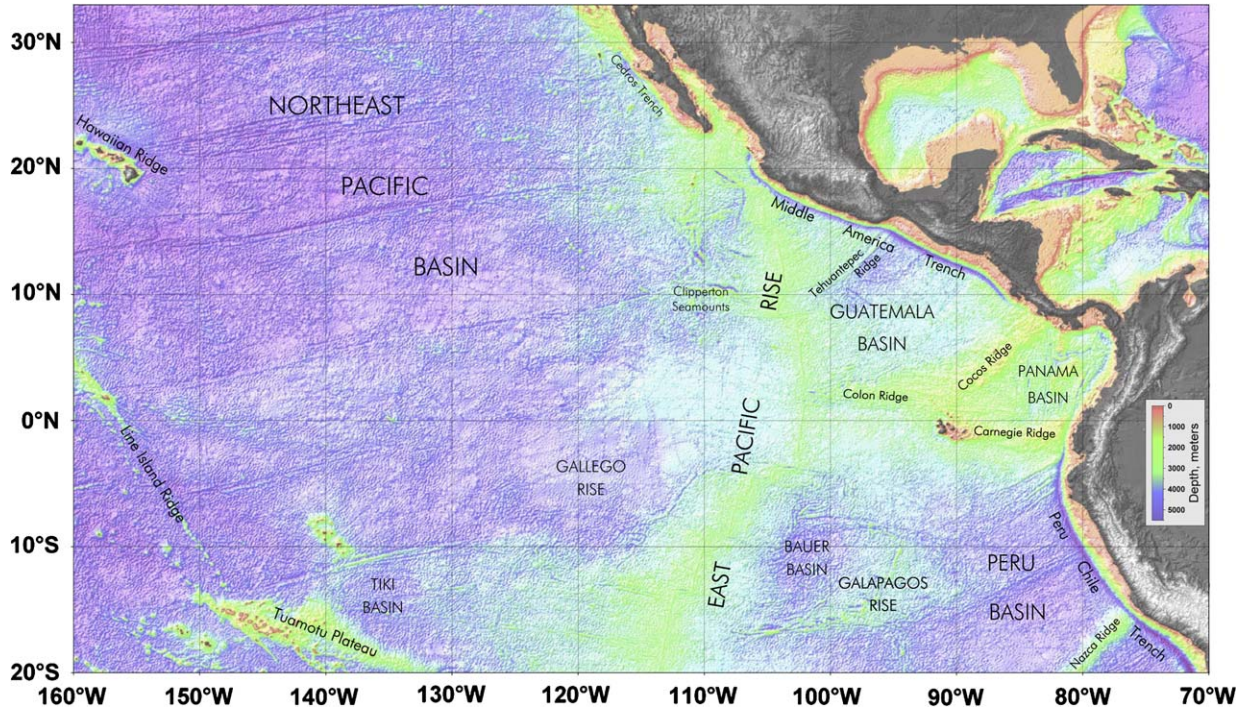

Fig. 3. Bathymetry and topography of the eastern tropical Pacific region (data from Lindquist et al., 2004; bathymetry based on Smith and Sandwell, 1997).

coasts of Peru, Ecuador, and Central America (Samson, 1998). The United States Exploring Expedition of 1838–1842 and the North Pacific Exploring Expedition of 1853–1856 both missed the eastern tropical Pacific. The Italian naval vessel *Vettor Pisani* collected soundings, bottom samples, hydrographic measurements, and faunal samples in the region in 1883–1884 (della Croce, 2002).

The United States Navy, and later the Coast and Geodetic Survey, surveyed and charted the Pacific coast from California to northern Peru beginning in 1872. Open ocean hydrography and soundings were also carried out, but only along navigational and potential cable routes to Hawaii and the Far East, north of the eastern tropical Pacific (Bertrand, 1967). Louis Agassiz collected shallow-water biological samples from the US Coast Survey Steamer *Hassler* at the Galapagos and along the coast from Peru to California in 1871–1872.

The *Challenger*, on the first global expedition with primarily oceanographic research objectives, had its original cruise plan altered to sail south from Hawaii to Fiji, then east to Valparaiso, thereby missing the eastern tropical Pacific in 1875 (Hedgepeth, 1971). Zoologist Alexander Agassiz used the US Fish Commission's *Albatross* for oceanographic research in the eastern tropical Pacific region in 1891 and 1904–1905 (Fig. 1), with the explicit purpose of filling the gap left by the *Challenger*. The Albatross Expeditions to the eastern tropical Pacific were the first modern oceanographic expeditions in the region: they were supported by both public and private funds, systematic sampling was carried out, and multiple scientists with specific research objectives participated.

During the first half of the twentieth century, after the 1904–1905 *Albatross* Expedition, most of the research conducted in the eastern tropical Pacific was by scientists employed by private institutions. The expeditions were often sponsored by wealthy benefactors who furnished their own yachts for the cruise. The opening of the Panama Canal in 1914 facilitated the use of small ships based in the Atlantic. Denmark's Carlsberg Foundation conducted two *Dana* Expeditions (1920–1922 and 1928–1930) that collected hydrographic and plankton samples in the region as part of a global investigation of eel spawning (Wolff, 2002). The first description of the extreme oxygen minimum zone in the eastern tropical Pacific was based on *Dana* stations in the Gulf of Panama (Schmidt, 1925). William Beebe of the New York Zoological Society conducted biological sampling with nets and dredges during the 1920s and 1930s and published popular accounts of two expeditions

in the region: (''Galápagos: World's End'' (Beebe, 1924) and ''The *Arcturus* Adventure'' (Beebe, 1926)). The Allan Hancock Pacific Expeditions were sponsored by the Hancock Foundation of USC: scientists aboard *Veleros I–III* collected fauna along the coast in the eastern tropical Pacific and at the Galapagos between 1922 and 1941 (Aleem, 2002).

The general lack of information ''within the triangle bounded by the North American coast and lines from Hawaiian Islands to San Francisco and to Panama'' was decried in Resolution No. 16 of the Fifth Pan-Pacific Science Congress, held in Vancouver in 1928 (Hedgepeth, 1971). The dearth of modern oceanographic research in the eastern tropical Pacific continued until after World War II. At that time, research throughout the world's oceans was stimulated by postwar funding and by the need for scientific advancement, at first by the United States and later by other countries, as recovery allowed. Research in the region from the 1950s onward is listed on-line (see below). A few highlights are mentioned here.

The Scripps Tuna Oceanography Research program (STOR, 1957–1973) was undertaken by the Scripps Institution of Oceanography, funded largely by the US Bureau of Commercial Fisheries, to sample the eastern tropical Pacific and learn how the oceanography of the region affected fishery resources. STOR was inspired primarily by the valuable fisheries of the region, but also by the recent discovery of the equatorial undercurrent, and the growing realization of the importance of the El Niño phenomenon. Seminal papers describing the circulation, dynamics and water properties of the region came out of this project during the late 1950s and 1960s (see Kessler, 2006, this volume; Fiedler and Talley, 2006, this volume). Several cruises in the eastern tropical Pacific during this period were part of the International Geophysical Year of 1957–1958. This program marked the beginning of a period of international, multi-ship programs that continues to this day.

The culmination of STOR and other research efforts at institutions on the US west coast in the 1960s arose from an ambitious Eastern Pacific Oceanic Conference (EPOC) proposal in 1960: the Cooperative Effort Towards Understanding of the Oceanography of the Eastern Tropical Pacific Ocean (EASTROPAC) under the direction of Warren Wooster of SIO and then of Alan Longhurst of the Bureau of Commercial Fisheries (Longhurst, 1972). This field survey program for physical, chemical, and biological oceanography and some meteorology conducted comprehensive sampling of the region that dominates physical and biological datasets to this day (2811 STD casts, 2673 bottle casts, 2488 XBT drops, 1346 MBT drops, 4141 plankton tows, and 849 micronekton hauls). Scientists and ships from the United States, Mexico, Ecuador, Peru, and Chile conducted sampling in seven two-month cruise periods from February 1967 through March 1968. The EASTROPAC Atlas and related information are available on-line (http://swfsc.nmfs.noaa.gov/PRD/atlas/).

The Equatorial Pacific Ocean Climate Studies (EPOCS) was initiated by NOAA in 1979 to investigate the role of the tropical Pacific Ocean in influencing large-scale interannual climate fluctuations. The goal of EPOCS was an improved understanding of the El Niño-Southern Oscillation (ENSO) phenomena leading to the development of predictive models. An array of moored buoys known as TOGA-TAO spanning the tropical Pacific was installed as part of EPOCS.

Most of the bathythermograph data available for the eastern tropical Pacific were collected by ''ships of opportunity'' or ''volunteer observing ships'', rather than by research ships. Institutions contributing MBT and XBT data include the US Navy, US Coast Guard, American Tunaboat Association, Canadian Navy, Australian Navy, New Zealand Royal Navy, British Navy, Peruvian Navy, Hydrographic Oceanographic Service of Ecuador, French Office de la Recherche Scientific et Technique Outre-mer (ORSTOM), and commercial and merchant ships of many countries.

A Mexican program known as DOMO surveyed the region of the Costa Rica Dome on four cruises between February 1979 and August 1982. Published results are primarily studies of the plankton net samples. Since the late 1980s, Mexican expeditions have investigated the gyres generated by the Tehuantepec wind jet (Willett et al., 2006, this volume).

The Southwest Fisheries Science Center of the US National Marine Fisheries Service has conducted research in the eastern tropical Pacific since 1979 to monitor trends in the abundance of dolphin populations. Oceanographic sampling was conducted during 1986–1990, 1992, 1998–2000, and 2003 to study habitat variability. This and other sampling programs are continuing at the time of this review. A list of oceanographic cruises, expeditions, and programs in the eastern tropical Pacific Ocean is available on-line (http://swfsc.nmfs.noaa.gov/PRD/ETPac/ETPacCruises.pdf).

Note. The authors of papers in this review volume, when discussing a topic outside the subject of their review, often refer only to the relevant review paper in this volume, rather than to the original references. Therefore, citations to accompanying review papers such as "(Kessler, 2006, this volume)" should be understood to mean "(Kessler, 2006, this volume, and references therein)".

3. Dedication

We dedicate this volume to Professor Klaus Wyrtki, for the diligence and vision of his early review of eastern tropical Pacific oceanography and for his original research in the tropical Pacific in general. We also acknowledge the early work of Richard Fleming, Harald Sverdrup, Robert Reid, Townsend Cromwell, Warren Wooster, John Knauss, Gunnar Roden, Edward Bennett, and others who provided the scientific basis for Wyrtki's review, and also Alan Longhurst, Maurice Blackburn, Mizuki Tsuchiya and the other scientists of EASTROPAC who completed a unique survey of this important region of the global ocean.

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