Chapter 1

The Galápagos Islands and Their Relation to Oceanographic Processes in the Tropical Pacific

FRANCISCO P. CHAVEZ and RICHARD C. BRUSCA

1. Introduction

Equatorial regions are characterized by significant interannual variability in oceanographic processes that are linked to changes in climate throughout the globe (Rassmusson and Wallace, 1983). Due in part to their role in global climate variability, equatorial regions—and particularly the equatorial Pacific—have received considerable attention from meteorologists and physical oceanographers during past decades. Recent measurements made during National Oceanographic and Atmospheric Administration (NOAA)-sponsored programs such as the Equatorial Pacific Ocean Climate Studies (EPOCS) and the Tropical Ocean Global Atmosphere (TOGA), as well as National Science Foundation (NSF)-sponsored programs such as Tropic Heat, have led to significant advances in our understanding of the oceanographic processes at work in the equatorial Pacific.

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The Galápagos Islands are located on the equator in the eastern equatorial Pacific. The Galápagos are the only oceanic islands on the equator in the eastern equatorial Pacific, with the nearest other truly equatorial islands being Christmas and Jarvis Islands which are approximately 5000 kilometers to the west of the Galápagos. The Galápagos are subject to the influence of several major current systems and their associated water masses, and provide an ideal location for observing the large-scale interannual ocean variability which characterizes the equatorial Pacific. Their location is particularly interesting since the amplitude of the interannual variability is greatest in a swath from 5°N to 5°S. This contribution focuses on oceanographic conditions in the Galápagos region that are determined primarily by basinwide equatorial processes. A short description of the geographic–tectonic setting of the islands is also provided. Following this we describe mean oceanographic conditions and their seasonal variability. It is the mean conditions that make the islands and their ecosystem biologically vulnerable to interannual variability. Mean is used instead of 'normal,' since 'normal' implies that variations are abnormal and as discussed in the final section interannual variability is an integral part of the Galápagos ecosystem.

2. Tectonic Setting

Two principal geotectonic features have shaped the Galápagos region. The first is the proximity of the islands to two major rift systems, or spreading centers. The Galápagos Islands are situated almost midway between the South American coast and the roughly north–south line of the East Pacific Rise. They lie about 1000 kilometers west of South America and about the same distance east of that point where the East Pacific Rise makes its northwest turn to approach the mouth of the Gulf of California. The Galápagos Spreading Center takes off eastward from this bend in the East Pacific Rise (forming a 'triple junction') and passes several hundred kilometers north of the Galápagos Islands. South of the Galápagos Spreading Center, crustal movement is about 3 centimeters/year southward. The relatively fast eastward spread from the East Pacific Rise (about 7 cm/year) results in a net east–southeast crustal movement in the Galápagos region of approximately 6–7 cm/year. This directional spread was first proposed by Wilson (1963) over 25 years ago, and confirmed by various studies in the late 1970s and early 1980s (e.g., Morgan, 1972; Anderson *et al.*, 1975).

The second feature is a theorized 'hotspot' deep in the mantle that supplies lava to and through the crustal plates as they move slowly along. Although the Hawaiian Islands have become the classic model of the hotspot phenomenon, Wilson's (1963) original work also noted the Galápagos as an example of the process. The concentration of recent volcanism in the western islands corroborates and identifies the locality of the Galápagos hotspot. Also corroborating the theory is the fact that older islands are found in line with the crustal drift direction, to the southeast. It has been suggested that the Carnegie and Cocos Ridges may also be remnant products of this hotspot mechanism (Morgan, 1971, 1972; Holden and Dietz, 1972). Current interpretation views the Carnegie Ridge and the Galápagos archipelago forming as the Nazca Plate passed over the Galápagos hotspot on its slow but inexorable journey southeastward, where it is eventually subducted under the South American Plate by the Cordilleran Trench system. The Cocos Ridge is seen as a remnant of former hotspot activity, coupled with past and present northeast crustal spread of the Cocos Plate away from the Galápagos Spreading Center, and eventual subduction under the Caribbean Plate at the Central America Trench. The Malpelo Ridge may be a fragmented remnant of the Cocos Ridge. Dalrymple and Cox (1968) analyzed lava samples from Cocos Island, on the flank of the Cocos Ridge about 500 kilometers from Costa Rica, and found them to be clearly oceanic in character. Bellon *et al.* (1983) radiometrically dated the Cocos Islands at 1.9–2.4 million years.

Hey and Vogt (1977) and Hey *et al.* (1977) reasoned that the 45,000 square kilometer Galápagos Platform, which sits at the crux of the Cocos and Carnegie Ridges, matches the exact physiographic pattern predicted by 25 million years of fixed mantle hotspot activity in which one plate is moving to the northeast and the other to the southeast.

Refinements in dating methods, particularly paleomagnetic and potassium–argon (K–Ar) radiometric methods, have led to a general agreement among geologists, at least for the time being, that the Galápagos Platform is no more than 10–15 million years old, while the oldest exposed land of the archipelago is on the order of 2.5–4.0 million years old (Cox and Dalrymple, 1966; McBirney and Williams, 1969; Bailey, 1976; Bow, 1979; Baitis and Lindstrom, 1980; Hall *et al.*, 1980; Cox, 1983; Hall, 1983; Simkin, 1984; Geist *et al.*, 1985). Many exposed parts of the islands are, of course, much younger than this, and volcanic activity continues today with infrequent eruptions reported from the western islands of Fernandina and Isabela. These dates are in conflict with Durham's (1963, 1966) earlier paleontological study in which he reported late Miocene (5–10 million years) invertebrates from Santa Cruz Island. However, to our knowledge, no one has addressed the possibility that the strata in question may represent an old (Miocene) uplifted area deposited in shallow water prior to the emergence of that portion of Santa Cruz. Emergence of shallow subtidal areas in the Galápagos in recent times has been documented by Glynn and Wellington (1983). Further, we now know that sea level fluctuations with vertical excursions up to 130 meters probably took place during the Pliocene/Pleistocene ice ages (e.g., Fairbridge, 1973; Vail and Mitchum, 1979). Virtual agreement now exists among geologists that the islands have never been any closer to the mainland than they currently are, being the products of ocean floor volcanism. Most biogeographic studies have supported this view (see Brusca 1987 for a review). Southeast drift is apparently moving the islands ever closer to the South American continent.

3. Mean Conditions and Their Seasonal Variations

3.1. Introduction

On average the eastern equatorial Pacific is characterized by sea surface temperatures (SST) which are abnormally cool for a tropical region. The region is dominated by a high pressure system which is centered over Easter Island. The Easter Island High is the largest southern hemisphere high-pressure system (Wyrtki, 1982) and from it the southeast trade winds flow toward the Indonesian Low. The anticyclonic wind system associated with the Easter Island High drives the Peru Current which flows to the northwest and the South Equatorial Current which flows westward (Figures 1 and 2). The meridional winds along the west coast of South America, which flow from south to north, are responsible for coastal upwelling. The zonal winds which flow from east to west along the equator generate equatorial upwelling. These winds are persistent annually and interannually so that coastal and equatorial upwelling are continuous throughout the annual cycle with only short interruptions. According to Wyrtki (1981), "upwelling in the equatorial Pacific Ocean manifests itself by a tongue of cool water stretching from the coast of Peru to the [international] dateline." The cool tongue of the equatorial Pacific is maintained primarily by equatorial upwelling but is also supported by horizontal advection of waters from the east.

There are well-defined surface water masses in the Eastern Tropical Pacific: 1) recently upwelled waters with salinities between 34.95 and 35.10 parts per thousand; these waters can be further subdivided into waters of costal upwelling and waters of equatorial upwelling, with the former being significantly cooler; 2) tropical surface waters (TSW) with lower salinities and warmer SST, which are separated from waters of equatorial upwelling by the Equatorial Front which extends from the coast of Ecuador to the Galápagos Islands and westward (Wooster, 1969); 3) Subtropical Surface Waters (SSW), which are offshore of the coastally upwelled waters and to the south of the equatorially upwelled waters (Figure 1), and have higher salinities (greater than 35.2) and warmer SST than the upwelled waters.

3.2. Hydrography, Nutrients, and Phytoplankton

The mean annual cycle of sea surface temperature (SST) for a station at Baltra, Galápagos indicates that that region has a strong austral or southern hemisphere character even though it is on the equator (Figure 3). Maximum temperatures are found during February, March, and April, and the coolest temperatures are during August and September. In northern Peru, and probably at the Galápagos, the annual austral summer warming is generated by a combination of local heating and a decrease in the export of heat associated with weaker trade winds (Chavez, 1987).

A strong east–west gradient in sea surface temperature is found along the equator with cooler temperatures to the east and warmer temperatures to the west (Figure 4). An east–west gradient is also evident subsurface, with a sloping thermocline (Sverdrup *et al.*, 1942; Barber and Chavez, 1983, 1986) which comes closer to the surface at the eastern terminus (Figure 5). This east–west basinwide tilt in the thermocline is maintained by the trade winds (Cane, 1983; Mangum and Hayes, 1984) (Figure 6). The east–west gradient in sea surface temperatures is a result of a combination of the east–west tilt in the thermocline, equatorial upwelling, and horizontal advection of water from the east. Around the Galápagos Islands the east–west gradient is reversed. Coolest temperatures are found on the western side and warmest temperatures are found on the eastern side of the islands. The cool temperatures on the western side are probably a result of topographically driven upwelling associated with the surfacing of the Equatorial Undercurrent

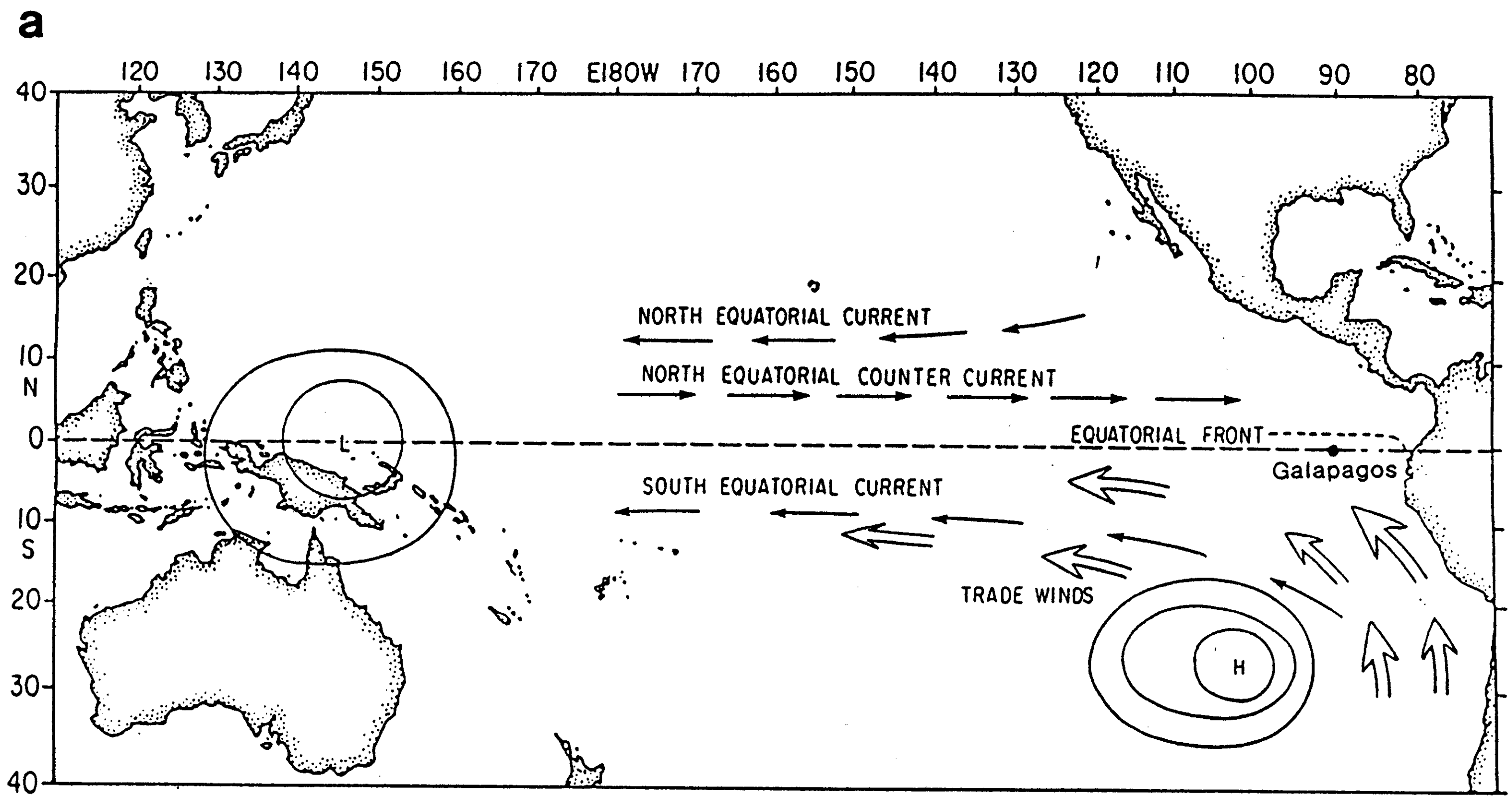

Figure 1. (a) Chart of the tropical Pacific showing the location of the major currents as well as the Easter Island High (H) and the Indonesian Low (L).

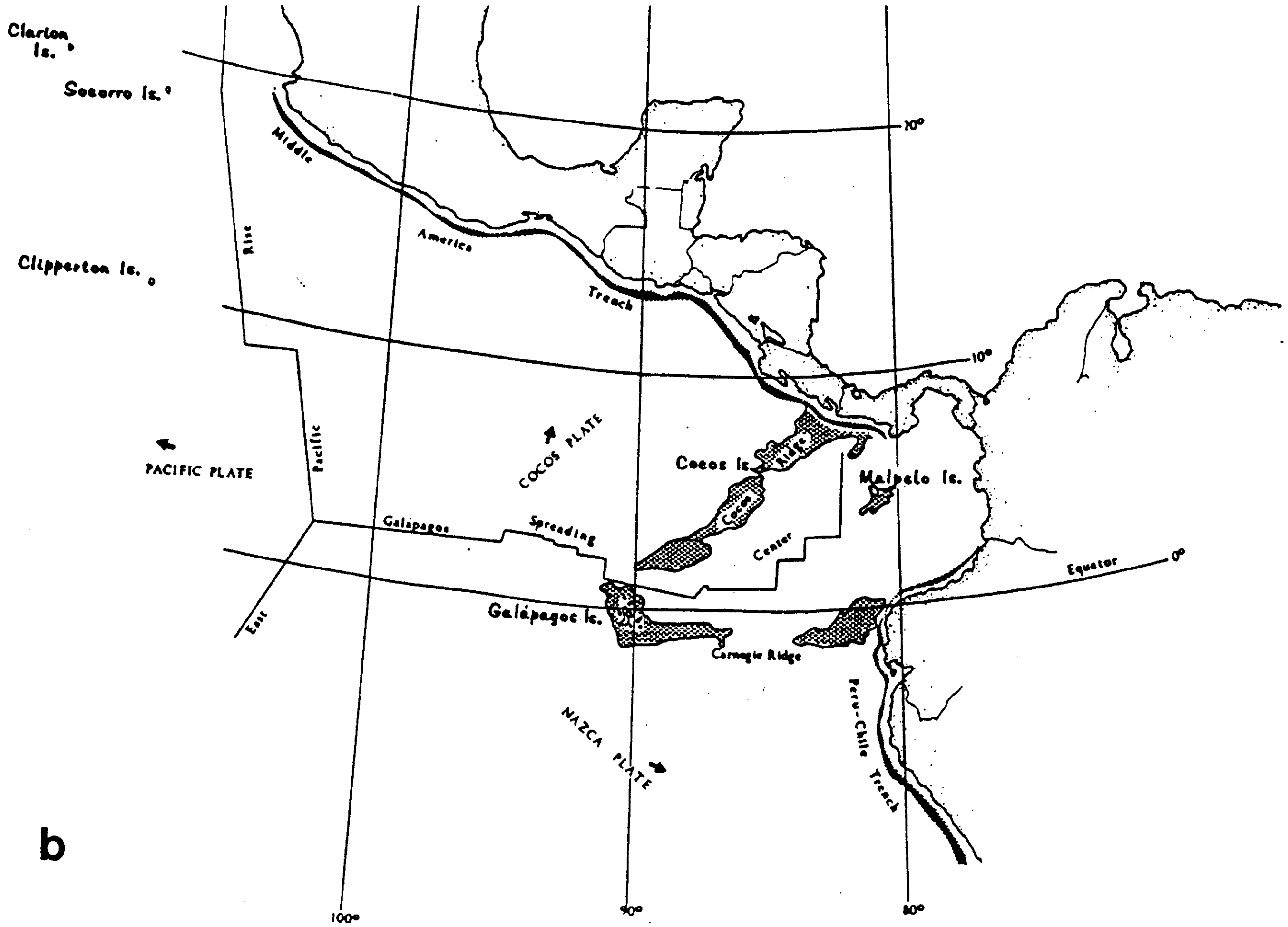

Figure 1. (b) Tectonic and geographic setting of the Galápagos Islands. Arrows indicate approximate direction of plate movements. Those portions of the Cocos and Carnegie Ridges above 1000 fathoms (1829 m) depth are stippled.

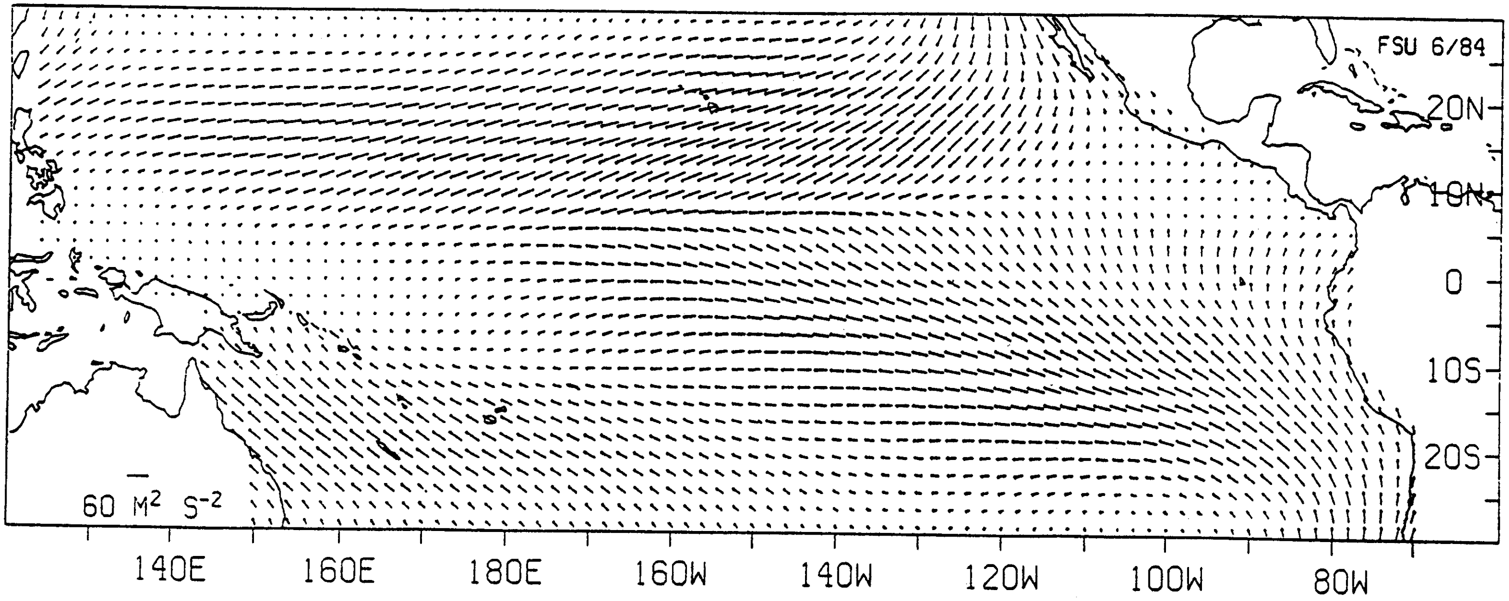

Figure 2. Twenty year mean (1961–1980) wind stress from the Florida State University ship wind analysis. The northeast and the southeast trades are clearly visible as is the wind stress minimum zone associated with the Intertropical Convergence Zone (ITCZ) around 10°N. The Galápagos are in a zone of weaker winds than to the south and west, and flow around the Islands is southerly. Data courtesy of Dr. James J. O'Brien.

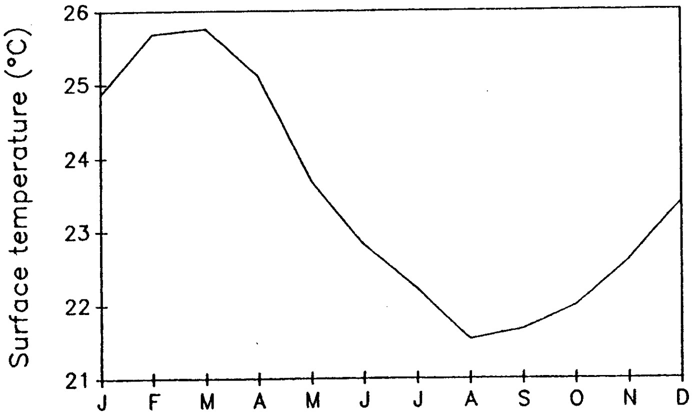

Figure 3. Twenty-two year mean (1960–1981) cycle of sea surface temperature taken from a pier at Isla Baltra, Galápagos. Although the Islands are on the equator, the cycle of sea surface temperature shows an austral or southern hemisphere character. Data courtesy of Dr. David Enfield.

(EUC). The east–west gradient found around the islands supports the notion that upwelling, rather than advection of waters from the east, is the primary mechanism for the cool sea surface temperatures along the equator.

Nitrate concentration at the surface, an index of ecosystem productivity, shows a similar pattern with highest values to the east (Figure 4). The sole exception to this pattern is found in and around the islands where concentrations are reduced. It is clear from the chlorophyll data that these low values are the result of uptake by phytoplankton. A sloping subsurface nutricline also shallows at the eastern boundary of the equatorial basin (Figure 5). Chlorophyll concentration, an index of phytoplankton biomass, shows a very different pattern with high levels in and around the islands and low and uniform levels to the east and west (Figure 4). A surprising observation is the lack of a gradient in chlorophyll to the west of the islands in the face of a substantial nutrient gradient. The high levels of phytoplankton biomass in and around the islands supports the hypothesis that phytoplankton require a certain proximity to land masses for bloom formation (Chavez, 1989).

There are conflicting reports on the seasonal variability in thermocline depth in the eastern equatorial Pacific (Meyers, 1979; Hayes and Halpern, 1984; Lukas, 1986). Lukas (1986) reported a deepening during January, February, and March, while Hayes and Halpern (1984) and Meyers (1979) reported that the deepening occurs from March to June. Observations along the coast of northern Peru seem to confirm that the deepening occurs in the March to June window (Chavez, 1987). The deepening of the thermocline has a duration of one-to-two months but varies each year in its timing. Seasonal subsurface variations in nutrients are similar to those in temperature (Chavez, 1987).

The meridional or north–south distribution of properties across the equator is very asymmetric, with warmer surface temperatures and lower nitrate concentrations to the north (Figure 7). The north–south asymmetry is evident from the coast of Peru to the dateline although it is more notable in the eastern Pacific. The Equatorial Front (EF) is the name given to the rather abrupt boundary between the cooler and more saline waters along the equator and the warmer, fresher tropical surface waters (TSW) to the north (Wooster, 1969). The EF also has a marked nutrient signature (Figure 7) with lower nutrients in the warmer water (Chavez,

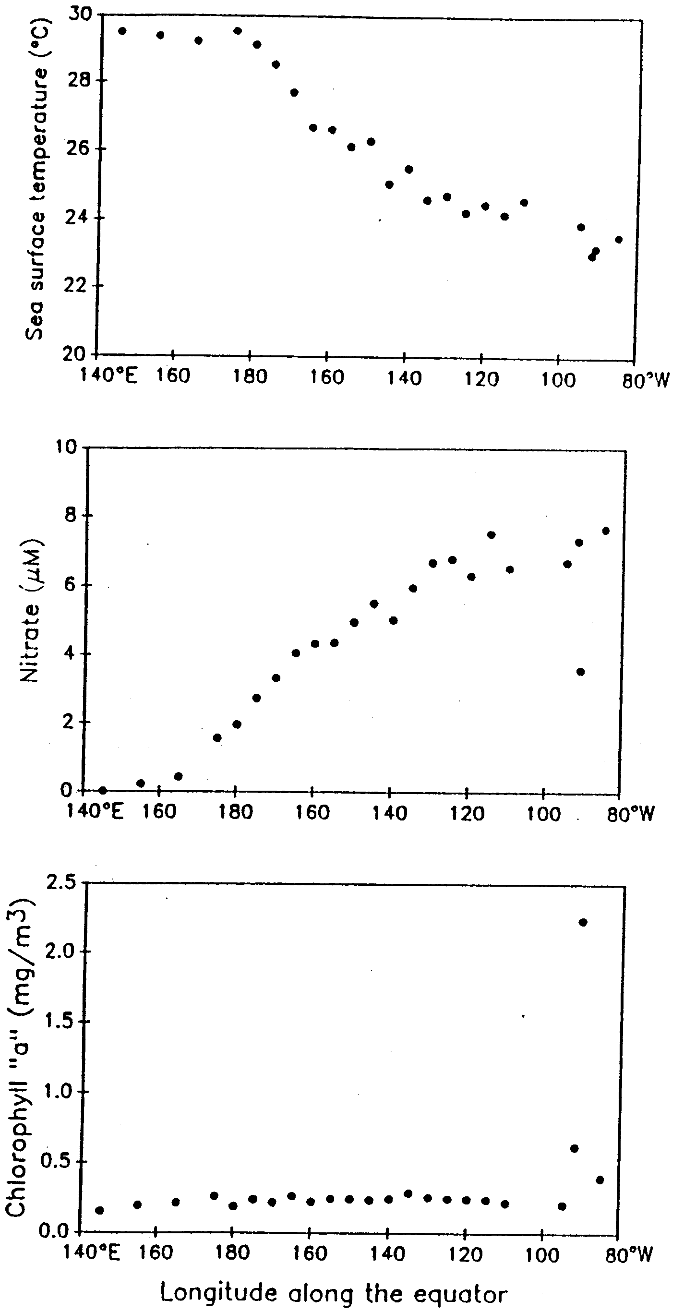

Figure 4. Means of surface temperature, surface nitrate, and surface chlorophyll from discrete observations along the equatorial Pacific on 40 cruises in 1980 and 1988. Measurements during the strong El Niño of 1982–83 were excluded from the calculations. The primary vehicles for the observations were NOAA ships working on the Equatorial Pacific Ocean Climate Studies (EPOCS) program. The lack of an east-west gradient chlorophyll despite gradients in temperature and nitrate is notable.

1987). The EF reaches its most southern extension at the western coast of South America where seasonally it may reach as far as 4°S. It then angles sharply northward, and at the Galápagos, where it is also known as the Galápagos Front, it is typically between the equator and 1°N. Further west it continues to angle slightly to the North and is found between 1°N and 3°N. The EF has a marked seasonal variation, with displacements to the north during the austral summer and to the south during winter and spring (Okuda *et al.*, 1983). During March, April, and May

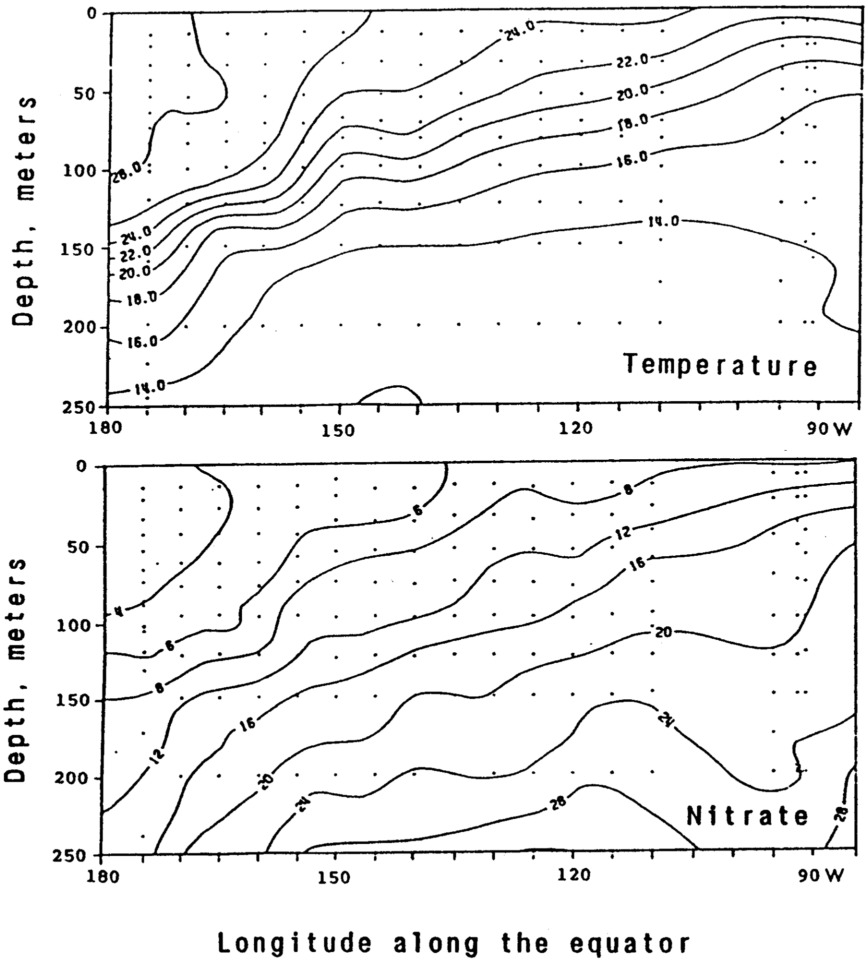

Figure 5. Mean profiles of temperature and nitrate along the equator. The east–west slope in the thermocline and nutricline is clear with cooler temperatures and higher nutrients closer to the surface at the eastern terminus.

the EF is to the north of the equator along 85°W but by June it has begun to migrate south and by November it is found around 2°S at which time it begins to return to the north (Chavez, 1987). The Islands extend from about 2°N to 2°S so that part of the Islands are immersed in the cool waters of the South Equatorial Current (SEC) and those which are north of the Equatorial Front (EF) are bathed by warmer waters and are much more tropical in nature.

3.3. Horizontal Currents

Reviews of ocean currents in the eastern and central tropical Pacific can be found in Sverdrup *et al.* (1942), Wyrtki (1966), Wooster (1970), and Wyrtki and Kilonsky (1984). The major surface current in the tropical Pacific is the South Equatorial Current (SEC) (Figure 1) which flows westward across the Pacific

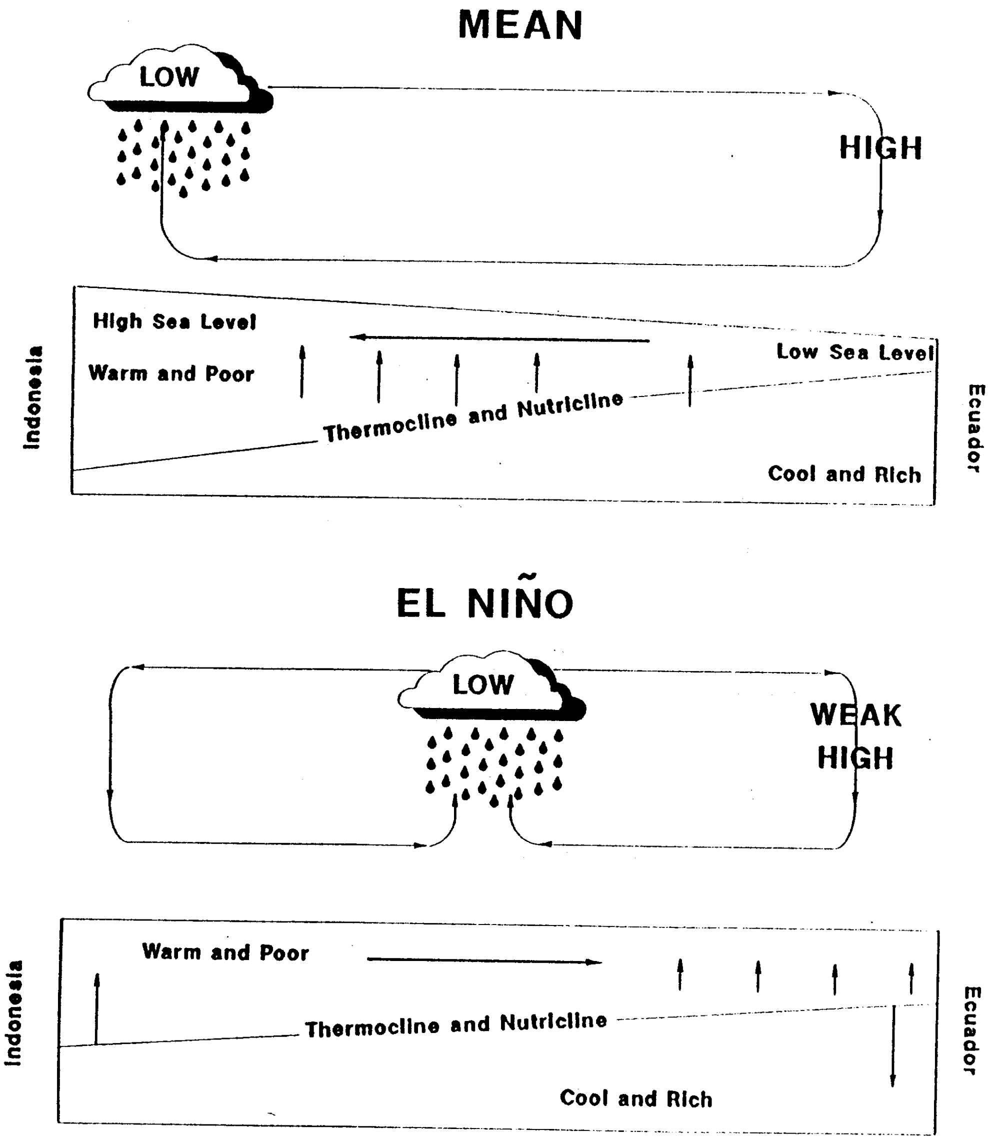

Figure 6. Oceanic and atmospheric conditions during the mean (above) and El Niño (below) states. During the mean, trade winds which blow from the Easter Island High to the Indonesian Low maintain a tilt in the thermocline and nutricline, drive equatorial upwelling, and pile up mass and heat in the western tropical Pacific. For reasons which are not well understood at present, westerly winds are generated in the western equatorial Pacific, as convective activity migrates eastward. The atmospheric forcing generates a series of oceanographic changes in the eastern equatorial Pacific; the most notable are higher sea level, a deeper thermocline and nutricline and abnormally warm sea surface temperatures. The oceanographic changes enhance the atmospheric effects so that these conditions remain in the eastern equatorial Pacific for 6 to 18 months. Less frequently than the El Niño condition there are extremely cool sea surface temperatures in the eastern Pacific associated with a higher than average Southern Oscillation Index (the difference between the Easter Island High and the Indonesian Low). This cool condition has been referred to as La Niña (Philander, 1985).

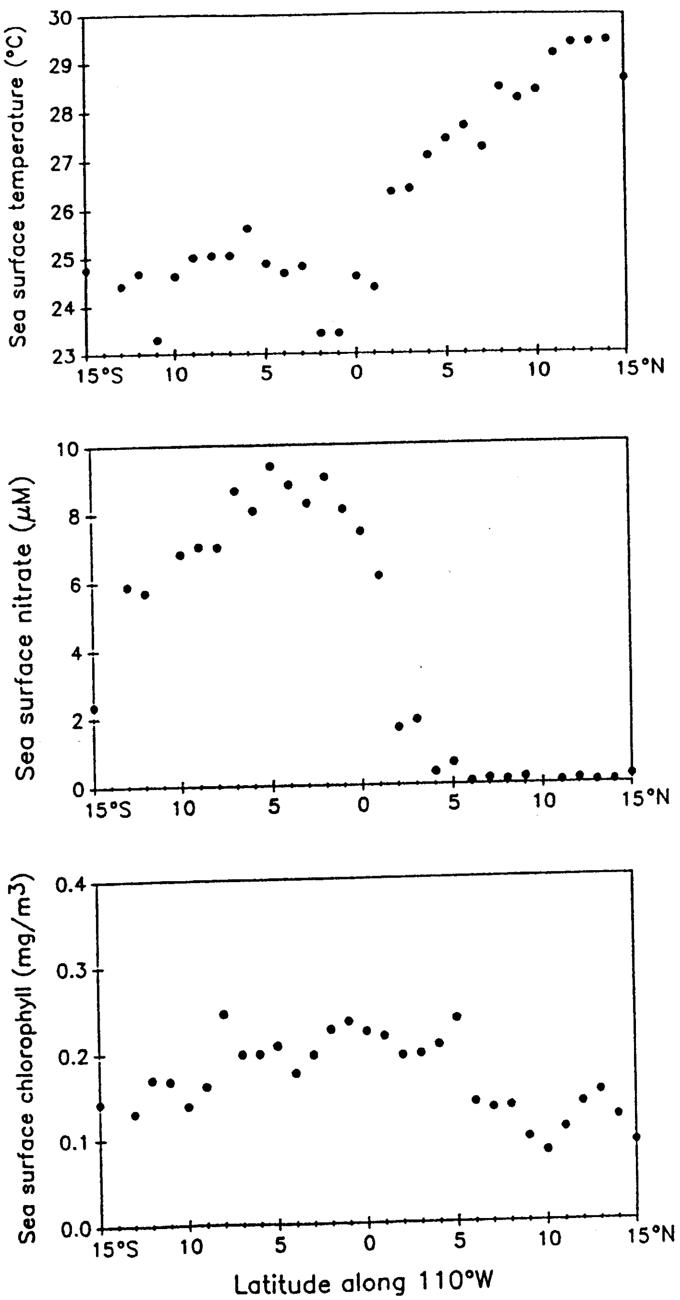

Figure 7. Means of surface temperature, surface nitrate, and surface chlorophyll from discrete observations along the 110 west meridian.

roughly between 5°N and 10°S with typical mean surface speeds of around 40 centimeters per second (Wyrtki, 1981), bathing the entire region of the Galápagos most of the year. The SEC is fed from the east by the Peru Current System (PCS). According to Wyrtki (1966), the PCS is composed of the Peru Coastal Current (PCC) and further offshore, the Peru Oceanic Current (POC), and these currents are usually separated by a weak and irregular flow to the southeast, the Peru Countercurrent (PC). The SEC is bounded to the north by the North Equatorial Countercurrent (NECC). The NECC has considerable seasonable variation, being most developed during August and September and weakest from February to April. During August and September the NECC reaches the South American continent while from February to April the current is difficult to detect past 120°W (Wyrtki, 1966). Mean flows in the core of the NECC are around 40 cm sec^{-1} (Wyrtki and Kilonsky, 1984). The South Equatorial Countercurrent (SECC) is much weaker than the NECC and has been observed occasionally around 10°S (Reid, 1959).

Temperature, nutrients, chlorophyll, and primary production along the equator are influenced by Long or Legeckis waves (Legeckis, 1977; Hansen and Paul, 1984; Chavez *et al.*, 1990). Theoretical studies (Philander, 1978) suggest that the Legeckis waves are generated by shear between the eastward flowing NECC and the westward flowing SEC. The waves are quite notable along the Equatorial Front in satellite sea surface temperature composites, have a scale of 1000 kilometers, and propagate westward at around 40 km per day (Legeckis, 1986).

Three major subsurface eastward flows have been identified in the equatorial region: the Equatorial Undercurrent (EUC) at the equator and the Northern and Southern Subsurface Countercurrents (NSCC and SSCC) at around 5°N and 5°S (Tsuchiya, 1985). Of these, the EUC is the most notable and of greatest consequence to the Galápagos. The EUC spans the entire equatorial Pacific and reaches maximum velocities in the core of over 100 cm sec^{-1} (2 knots) and mean speeds of around 80 cm sec^{-1} (Hayes *et al.*, 1987; Wyrtki and Kilonsky, 1984). In the eastern equatorial Pacific the EUC is strongest from March through May (Hayes and Halpern, 1984), and during this period it becomes evident in the hydrography and nutrient concentrations (Figure 8) to the east of the Galápagos (Lukas, 1986; Tsuchiya, 1985; Chavez, 1987; Pak and Zaneveld, 1973). Eastward surface flow is common along the equator during the March through May period and is probably associated with the surfacing of the EUC (Jones, 1969). The core of the EUC is commonly found in the thermocline so it is deepest in the west and shallows in the east (Wyrtki, 1981). At the Galápagos, the depth of the core of the EUC is approximately 60 m.

3.4. Upwelling

An excellent description of upwelling in the equatorial Pacific was given by Wyrtki (1981). An almost continuous westward surface wind flow, associated with the southeast and northeast trades, drives a poleward Ekman transport in both hemispheres, resulting in the upwelling of cool, nutrient-rich waters from below. Wyrtki (1981) suggested that water which is upwelled along the equator is recruited from 50 to 100 m depth, although geochemical observations (Broecker and Peng, 1982) and vertical velocities derived from current meter observations suggest that upwelling may be occurring down to 150 m.

Vertical velocities are very difficult to measure since they are on the order of 10^{-5}m sec^{-1}. Halpern *et al.* (1989) estimated that on time scales of months, vertical velocity in the equatorial Pacific between 165° and 90°W is around 2.5×10^{-5} m sec^{-1} (2 m day^{-1}), twice that reported by Wyrtki (1981). In addition, Halpern *et al.* (1989) suggested that upwelling is strongest around 140°W and decreases eastward. On time scales of days, upwelling rates of 3–5 m day^{-1} have been reported (Wyrtki and Eldin, 1982).

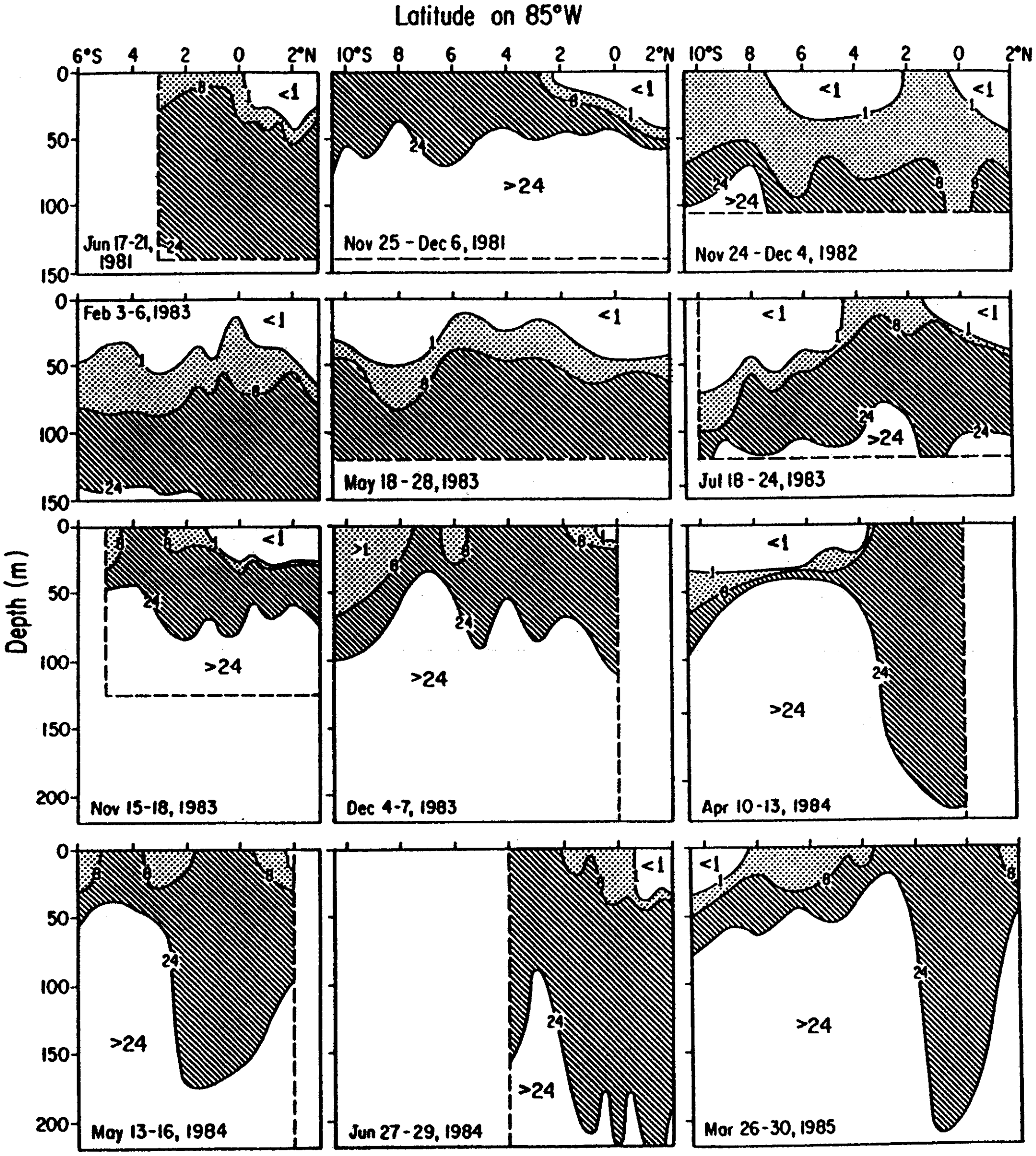

Figure 8. Twelve nitrate profiles along 85°W made between June 1981 and April 1985. The "nutricline" is defined here as the region with concentrations between 8 and 24 μm (hatched). The Equatorial Undercurrent (EUC) is recognized by a spreading of the nutricline, and during April 1984 and March 1985 it appears stronger and trapped along the equator. The contribution of the EUC is reduced during November and December. From November 1982 through July 1983, during El Niño, the nutricline is visibly deeper and the surficial nutrient rich equatorial zone disappears. The Equatorial Front (EF) is defined in these profiles by the northward transition between concentrations of nitrate that are less than 1 μM and greater than 1 μM. The Equatorial Front (EF) also varies seasonally and is further north during March, April, and May than in November and December. The EF disappeared during the 1982–83 El Niño.

The trade winds, which drive equatorial upwelling, are subject to sizeable seasonal variations. Wyrtki's (1981) estimate of upwelling, derived directly from the mean wind field, showed that upwelling is strongest between December and March and weakest from September to November. This result is counterintuitive because the southeast trades are strongest in August and September and weakest in February and March. The upwelling maximum, however, is driven primarily by northward Ekman transport which reaches a maximum in February as the northeast trades reach far south (Wyrtki, 1981).

Upwelling at the Galápagos has also been attributed to the surfacing of the Equatorial Undercurrent (EUC) as it collides with the westernmost islands, Islas Fernadina and Isabella. The EUC is a very fast subsurface eastward current which is "trapped" along the equator by the Coriolis effect. When the EUC reaches the Galápagos and collides with Isla Isabella Island, its flow becomes disorganized and further topographically driven upwelling may occur throughout the islands (Houvenaghel, 1984).

3.5. Sea Level

Low frequency variations in sea level reflect a variety of atmospheric and oceanic changes. In the equatorial Pacific, Wyrtki (1984) showed that nontidal sea level is associated with thermocline depth and dynamic height. As such there is a slope in sea level from the eastern equatorial ocean to the western equatorial ocean (Wyrtki, 1984). On average, sea level at the Galápagos is around 45 cm lower than sea level at the international dateline (Wyrtki, 1984).

Hayes and Halpern (1984) reported seasonal increases in sea level at the Galápagos on the order of 20 cm associated with a deepening of the thermocline and an increase in the strength of the Equatorial Undercurrent (EUC). The increases were observed between March and May. Smaller and more frequent oscillations in sea level, with periods of 40–60 days, are common in the tropics (Enfield *et al.*, 1987) and are linked to variations in the tropical wind fields (Madden and Julian, 1972).

Variations in sea level are also associated with changes in the nutricline (Chavez, 1987; Chavez, 1989). Data collected at the Galápagos during 1982 and 1983 (Kogelschatz *et al.*, 1985) show how sea level and nitrate concentration at 60 m, a depth from which upwelled water is recruited, are inversely related (Figure 9). In the March to June window, when the EUC is strongest and the thermocline and the nutricline are deeper, nutrient levels in the upwelling source water are lower and consequently biological production may be lower.

3.6. Climate

Local climate in the Galápagos reflects large-scale oceanographic and atmospheric conditions in the eastern tropical Pacific. The major low pressure zone affecting the Galápagos is the Intertropical Convergence Zone (ITCZ) which stretches from the coast of South America to Indonesia a few degrees north of the equator. The ITCZ is associated with a wind speed minimum and generally

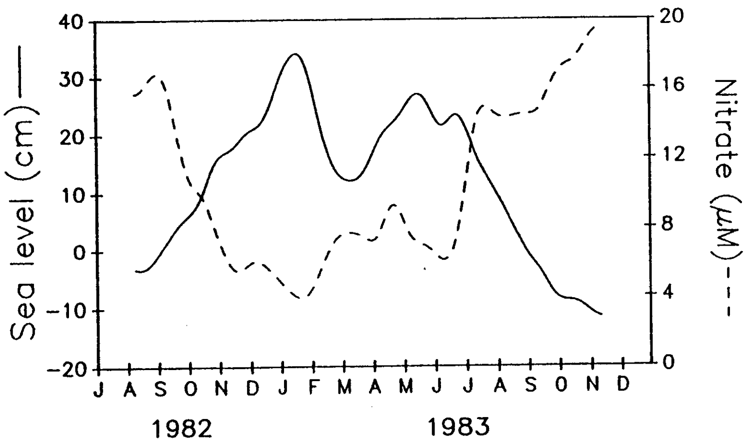

Figure 9. Relationship between sea level measured at a pier in Puerto Ayora, Galápagos, and nitrate at 60 m measured at a station offshore of Puerto Ayora (Kogelschatz *et al.*, 1985) during 1982 and 1983. The sea level was measured continuously and is courtesy of Dr. Klaus Wyrtki. Nitrate samples were collected three times a week with a small boat and is courtesy of Dr. R. T. Barber. The data has been smoothed with a normal filter in order to suppress periodicities of less than one week. The increase in sea level and the lower nitrate content of the 60 meter water are evident during the 1982–83 El Niño which lasted from September 1982 to July 1983 (Chavez *et al.*, 1984).

separates the northeast and the southeast trade winds (Rasmusson and Carpenter, 1982). Since the ITCZ is to the north of the Galápagos this puts the Islands within the regime of the southeast trades (Wooster and Hedgpeth, 1966). Trade wind speeds are in the order of 7 to 8 m $\sec^{-1}$ but at the Galápagos they are typically weaker than to the west. As a result of the locations of the Easter Island High and the ITCZ, the average wind direction around the Galápagos tends to be southerly (Figure 2). Further to the west along the equator the average wind direction has a more pronounced easterly component. The ITCZ exhibits a seasonal meridional migration reaching southern extremes in February and northern extremes in August. Precipitation patterns around the Galápagos Islands reflect the changes in the ITCZ, with highest rainfall from January to April (Robalino, 1985).

In general, the Galápagos climatic year may be divided into two seasons. A hot-wet period exists from about December to May and a cool-dry period (the "garua season") from about July to October. The Islands are probably best described as subtropical, although selected local areas would qualify as either tropical or warm-temperate based on their local thermal regime. Overall, the regime of the Galápagos rather closely resembles that of the northern Gulf of California or the northern Gulf of Mexico, two other regions generally regarded as subtropical.

4. Interannual Variability

4.1. Introduction

The waters of the South Equatorial Current are continually heated by the tropical sun and as a result both mass and heat tend to accumulate in the western tropical Pacific. The potential energy associated with increased mass and heat content is released periodically resulting in abnormally warm sea surface temperatures in the central and eastern tropical Pacific, and this phenomenon is known as El Niño. El Niño occurs aperiodically, once every three to eight years, and the magnitude of the anomalies varies significantly from event to event. The anomalies associated with El Niño persist in the eastern tropical Pacific for 6 to 18 months. The abnormally warm sea surface temperatures are associated with variations in the Eastern Island high and the Indonesian Low pressure systems which drive the southeast trades (Bjerknes, 1966). The seesaw in atmospheric pressure between the eastern and western Pacific is known as the Southern Oscillation (Walker, 1924). Although El Niño involves the entire tropical Pacific basin it is most notable along the coast of Peru where positive sea surface temperature (SST) anomalies of 10°C have been observed during these episodes.

Carrillo (1889) described a warm surface current which apparently came from the Gulf of Guayaquil and travelled southward up against the coast of northern Peru. The mariners of Paita called this current El Niño or "The Child" (Christ Child) since it appeared around Christmas. Schweigger (1945) showed there indeed is a weak and inoffensive current in northern Peru, which intensifies every year during the austral summer which he called the legitimate El Niño current (Chavez, 1987). As we shall see this current has little to do with the large scale oceanographic and meteorological events which are now known as El Niño. The "current" achieved notoriety as a result of the abnormally rainy and warm year of 1891. Carranza (1891), Eguiguren (1894), and Pezet (1896) suggested that the abnormal conditions in 1891 were the result of an unusually strong El Niño current. Later, Schott (1931) used the term El Niño for advection on a much larger scale. Schott (1931), who observed the 1925 El Niño, described a current that originated from around the Galápagos and reached the coast of Peru. Gunther (1936) and Mears (1943) referred to the El Niño current as responsible for the large scale oceanographic disturbances and their associated climatic repercussions. Thus, the name El Niño is today used to denote a complex set of processes that include more than just an intensification of a coastal current and advection of warm water from the north.

4.2. Hydrography, Nutrients, and Phytoplankton

Although El Niño appears as an amplification of the annual summer warming (Philander, 1985) it has a different origin. During El Niño, Kelvin waves forced by trade wind anomalies in the western equatorial Pacific raise sea level and deepen the thermocline and nutricline in the eastern tropical Pacific (Cane, 1983; Barber and Chavez, 1986; Enfield, 1988) (Figure 6). These anomalies are superimposed on the normal annual cycle so that there are significant warmings subsurface during the austral summer.

In addition to the rapid wave-propagated thermocline anomalies, there are slower advective disturbances during El Niño. The tropical surface waters (TSW) which normally are restricted to the north of 1°N are observed as far as 6°S as the Equatorial Front disappears. The Subtropical Surface Waters (SSW) impinge on the coast of South America associated with large scale changes in the South Pacific gyre (Wyrtki and Wenzel, 1984). Changes in the distribution of nitrate along 85°W prior to, during, and after the 1982–83 El Niño reflect some of the advective changes which occur during El Niño (Figure 8). Onset of the 1982–83 El Niño occurred in August 1982 around the Galápagos Islands and September 1982 at Paita, Peru (Chavez *et al.*, 1984). The nitrate section during November 1982 shows the depressed nutricline associated with the onset of El Niño. Soon afterward the fresher and nutrient poor tropical surface waters (TSW) from north of the Equatorial Front occupied the entire region. Anomalous conditions remained in the eastern tropical Pacific through May 1983, and partial recovery was observed in July 1983. By November 1983 conditions had returned to normal.

In the Galápagos anomalously high sea surface temperatures, enhanced fresh water input, reduced nutrient concentrations, deeper thermocline and nutricline, and lower levels of phytoplankton biomass and production were all observed during 1983 when compared to the cooler years of 1984 and 1985 (Figure 10).

4.3. Horizontal Currents

There are significant changes in circulation of the tropical Pacific during El Niño. The first advective effects are felt as Kelvin waves, generated in the western Pacific by westerly winds in this region, propagate along the equator from west to east (Harrison and Schopf, 1984; McPhaden *et al.*, 1988). Associated with the waves is an anomalous eastward current along the equator which may be on the order of 75 to 100 cm sec^{-1}. The duration of the anomalous currents is uncertain, however they probably continue as long as wind forcing in the western tropical Pacific is maintained.

During the 1982–83 El Niño there were significant changes in the position of the South Pacific gyre. The South Equatorial Current (SEC) was shifted southward so that its main flow was found between 10° and 20°S (Wyrtki, 1984). Observations by Hayes *et al.* (1987) showed that during the 1982–83 El Niño eastward flow was common along 95°N, just west of the Galápagos, as far as 6°S, with maximum current speeds of 60 cm sec^{-1}.

Transport by the NECC was enhanced significantly during 1982 and 1983 (Wyrtki and Kilonsky, 1984). Much of the redistribution of water from the western Pacific to the eastern Pacific may occur via the NECC. The flow described by Schott (1931) which appears to come from the Galápagos may be associated with the intensification of the NECC and result from the overflowing of water from the Panama basin. The Galápagos Islands are bathed by these warm, low salinity, and low nutrient waters during El Niño events (Figure 10).

Perhaps the most dramatic effect on currents during El Niño is the virtual disappearance of the EUC (Firing *et al.*, 1983). In the mean, the EUC is maintained by the sea level pressure gradient which is set up by the trade winds. When the trade winds relax and the excess water from the western Pacific is redistributed north, south and to the east the slope in sea level between eastern and western Pacific disappears (Wyrtki, 1984) (Figure 6) as does the EUC. Prior to direct observations of the disappearance of the EUC during El Niño it was believed that the redistribution of water from the western Pacific to the east occurred via this current.

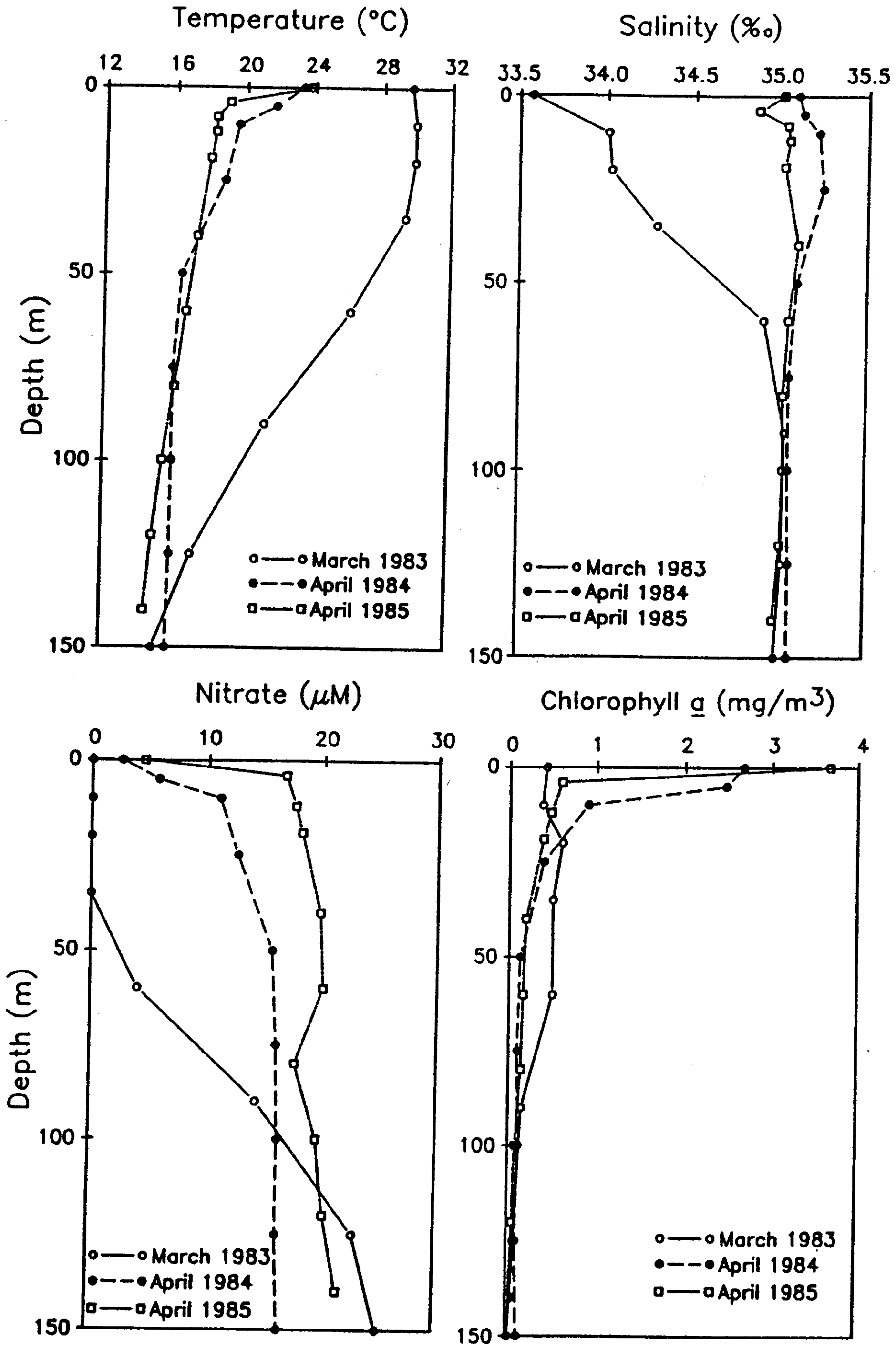

Figure 10. Vertical profiles of temperature, salinity, nitrate, and chlorophyll taken in the Bolivar Channel (0° 15′S, 91° 25′W) between Isla Isabella and Isla Fernadina Islands during March 1983, April 1984, and April 1985. The effects of El Niño are clearly visible during March 1983 with warmer sea surface temperature, lower surface nitrate, fresher surface water, lower surface chlorophyll, and deeper nutricline and thermocline. Data courtesy of Dr. R. T. Barber.

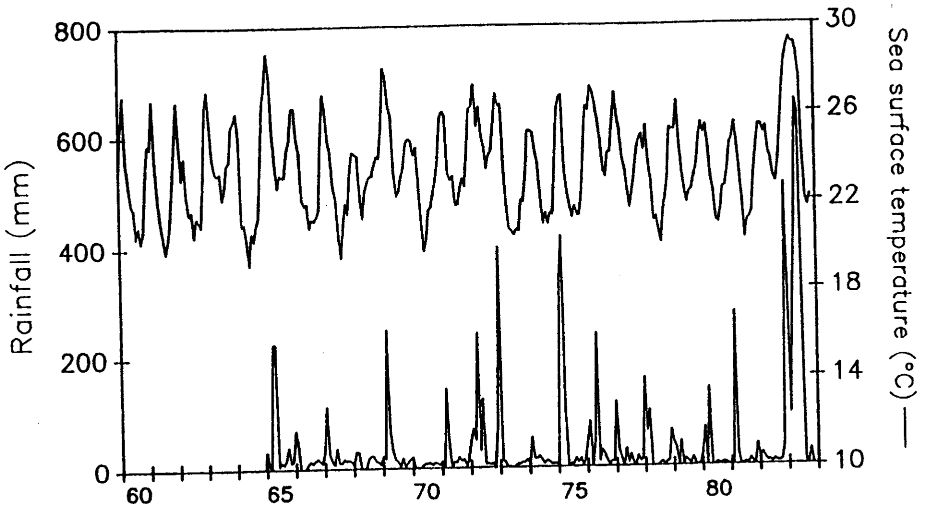

Figure 11. Time series of monthly sea surface temperature at Baltra, Galápagos, and precipitation at Puerto Ayora, Galápagos. The signal of the 1982–83 El Niño is prominent with large deviations in sea surface temperature and heavy precipitation.

4.4. Upwelling

Much the opposite of what was originally believed (Wooster and Guillen, 1974) the coastal winds of the southeastern tropical Pacific intensify during El Niño (Enfield, 1981; Enfield and Newberger, 1985; Bakun, 1987). Depending on the extent of the migration of the low pressure zone from the western tropical Pacific eastward (Gill and Rasmusson, 1983), upwelling is also probably maintained along the equator in the eastern Pacific. However in both coastal and equatorial systems the upwelling is of warm water as a result of a deeper thermocline. The southward migration of the ITCZ during El Niño contributes to reducing upwelling favorable winds along the equator.

4.5. Sea Level

Sea level is perhaps the best single feature that oceanographers have to follow the large scale changes which occur during El Niño. From propagating changes in sea level it has been possible to link events in the eastern equatorial Pacific with westerly winds in the western tropical Pacific (Wyrtki, 1975; Enfield *et al.*, 1983; Lukas *et al.*, 1984; Miller *et al.*, 1988). Theory shows that Kelvin waves excited by westerly winds in the western Pacific can propagate eastward at about 300 cm/sec along the equatorial waveguide deepening the thermocline and raising sea level (McCreary, 1976; Cane, 1983). Increases in sea level of 30 to 50 cm have been observed in the eastern tropical Pacific during El Niño with corresponding decreases in the western Pacific (Wyrtki, 1975; Wyrtki, 1984). In addition when the propagating disturbances reach the eastern boundary a portion of the energy propagates poleward; sea level increases associated with El Niño have been observed along the coast of the Americas from Alaska to Chile (Enfield and Allen, 1980).

The evolution of the 1982–83 El Niño at the Galápagos, in terms of sea level and nitrate at 60 meters, is shown in Figure 9. Wyrtki (1981) suggested that water upwelled along the equator comes from a depth of 50 to 100 meters, therefore nitrate concentration at 60 meters is a good proxy for the nitrate concentration of the upwelled water. Figure 9 shows that the concentration of nutrients in the upwelled source water along the equator is directly related to thermocline depth and sea level. The deepening of the thermocline and the nutricline in the eastern boundary during El Niño reduces the biological productivity of this region by lowering the level of nutrients in the upwelled water (Chavez and Barber, 1985).

4.6. Climate

Westerly winds in the western equatorial Pacific, generated in the lee of the Indonesian Low as it migrates eastward, are now believed to trigger the onset of El Niño (Cane, 1983; McPhaden *et al.*, 1988). The westerly winds are commonly associated with cyclone pairs on each side of the equator and intensive convective activity (Ramage, 1986). The oceanic response, in the form of warmer sea surface temperatures in the central and eastern Pacific, results in further atmospheric effects. The region of enhanced convective activity continues to migrate eastward and, as was the case during the 1982–83 event, may cross the entire Pacific and reach the Galápagos (Gill and Rasmusson, 1983). The ITCZ migrates south of its normal position as the Equatorial Front disappears (Rasmusson and Carpenter, 1982; Horel and Cornejo-Garrido, 1986). These changes bring enhanced precipitation to the Galápagos and the entire eastern tropical Pacific during El Niño (Figure 11).

5. Summary and Conclusions

1. The Galápagos Islands are located in the eastern equatorial Pacific, however the surrounding waters are considerably cooler and richer in nutrients than might be expected for a tropical region.
2. The cool and rich waters surrounding the Galápagos are a result of a combination of processes including:
   a. Trade winds, which blow primarily from east to west, set up a tilt in the thermocline and nutricline so that cool and rich waters are closer to the surface in the eastern terminus.
   b. The easterly component of the trade winds drives equatorial upwelling which "pumps" cool and rich water from around 50 to 100 meters to the surface.
   c. Horizontal advection of cool and rich waters by the Peru Current System.
   d. Local bathymetrically induced upwelling.
3. The seasonal cycle at the Galápagos has a distinct Southern Hemisphere character with warmer temperatures from February through April and cooler temperatures in August and September.
4. The Galápagos are located in a region where horizontal currents are particularly dynamic. The main current systems affecting the Galápagos are:

  a. The cool westward surface South Equatorial Current which bathes the Galápagos most of the year.
  b. The cool eastward subsurface Equatorial Undercurrent, which is "trapped" along the equator and is modified significantly by the Galápagos when it collides with Isla Isabella Island.
  c. The warm eastward surface North Equatorial Countercurrent which seasonally flows eastward north of the Galápagos.

5. The mean conditions described above are modified periodically, every three to eight years, by an ocean–atmosphere phenomenon known as the El Niño Southern Oscillation.
6. During El Niño years, the waters of the eastern equatorial Pacific are considerably warmer, sea level increases, and the major horizontal currents are modified as follows:
   a. The South Equatorial Current weakens considerably and is displaced southward. Eastward flow is found on occasion along the equator.
   b. The Equatorial Undercurrent weakens as the east–west slope in sea level is reduced.
   c. Transport of the North Equatorial Countercurrent increases considerably.

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