ABSTRACT

SWEET, WILLIAM VANDERVEER. Mechanisms of Variability within the Upper Ocean of the Galápagos Archipelago. (Under the co-direction of John M. Morrison & Lian Xie).

Five hydrographic surveys (March 2005, November 2005, June 2006, November 2006, and May 2007) and four continuous moored time series document changes of the surface-layer properties within the Galápagos Archipelago from 2005 to 2007. The March 2005, November 2005, and June 2006 surveys are used to describe the annual cycle within the archipelago. Changes include those of the sea surface temperature (SST), which cools in the Garúa season (June – November) when the southeast trades and South Equatorial Current (SEC) strengthen and the Equatorial Undercurrent (EUC) is weaker and deeper. Opposite conditions occur in the wet season (December – May). Sea surface salinity (SSS) freshens in the wet season from local rainfall as the Inter-tropical Convergence Zone (ITCZ) nears and in the late Garúa season from influxes of the North Equatorial Countercurrent (NECC). The SSS is high in the latter half of the wet season when the EUC strengthens and flows near the surface. The SSS is normally higher west of Isabela where the EUC collides/upwells and when advected from the Cold Tongue westward by the SEC into the archipelago. Surface chlorophyll a (Chl a) concentrations are highest where the thermocline (20°C isotherm) is shallowest.

In the fall (boreal) of 2005, the effects of tropical instability waves (TIW) appear as oscillations within the SST, meridional current ($V_y$), and the depth of the thermocline in the eastern equatorial Pacific. Meridional advections of the equatorial front (EF) by the TIW are observed in the SST at 0°, 110°W. At 0°, 95°W, the SST changes concurrently to changes of the thermocline depth. Within the Galápagos Archipelago, a strong 3-wave succession of ~15-day period TIW in Sep and Oct 2005 registered a large subsurface (5-m) temperature and water level response at four moorings. Upwelling speeds of ~5.0 m d$^{-1}$ are estimated for the central archipelago during the TIW, dropping temperatures by ~7°C within a week. A significant biological response to the TIW is observed throughout the archipelago. Coincident with coldest temperatures, the Chl a
increased across the archipelago by 25 – 40% above its 2004 – 2006 mean and nearly 25% above its 1998 – 2007 mean. The much larger Chl a concentrations near/within the archipelago as compared to 95° and 110°W implicate an iron-enriched upwelling within the island platform.

Effects from the El Niño Southern Oscillation (ENSO) produce significant variations within the surface-layer properties of the Galápagos Archipelago during the last two hydrographic surveys that occurred November 2006 and May 2007. The 2005 – 2007 ENSO cycle is indexed by the SST anomalies within the Niño Region 3.4. The water-column response is quantified through comparison to the results from the November 2005 and June 2006 surveys, which occurred during similar times of the year but very different by the ENSO cycle. Downwelling Kelvin waves promoting the warm 2006/07 El Niño and an upwelling Kelvin wave promoting the cool 2007/08 La Niña cause significant variations within the archipelago. During the ENSO-warm surveys, the survey-mean thermocline depth deepens between 10 and 25 m, which results in a >2°C rise in the SST. The SSS and water-mass classification remain relatively unchanged. Mean Chl a concentrations decline by >0.2 mg m⁻³, or a >15% drop from the respective 1998 – 2007 monthly mean.
Mechanisms of Variability within the Upper Ocean of the Galápagos Archipelago

by
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A dissertation submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the Degree of
Doctor of Philosophy

Marine, Earth and Atmospheric Sciences

Raleigh, North Carolina

2008

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BIOGRAPHY

William Sweet was raised in a family that encouraged exploration of the mind, body, and soul. Years spent in the backyard creek led to his fascination with water and its creatures. An undergraduate degree in physics exposed many wonders associated with the earth’s processes. An influential conversation in 1993 with his astronomy professor at UNC Chapel Hill directed him to the marine sciences. His awakening occurred during the summer of 1994 at NCSU where he met his future academic adviser studying remotely sensed data and participated on a couple field cruises to deploy and recover experimental trawl-proof instrument housings. It was under the hot sun and rolling waves that he realized he belonged in the field to study first hand the marine environment. He spent the next 10 years as an operational field scientist involved with numerous mooring and survey projects. His experiences include work on the Carolina’s Ocean Margins Program (OMP), the Joint Global Oceanographic Flux Survey (JGOFS) in the Ross Sea of Antarctica, and the Carolina-based CaroCOOPS and CORMP components of the Integrated Ocean Observing System. Another field endeavor sampled and documented a series of physical forces that sequenced prior to a large fish kill in the Neuse River Estuary and was the topic for his Master’s degree in 2000. He jumped at the chance to participate in a biophysical investigation of the Galápagos Archipelago for his Ph.D. program in 2005. Here, he made some lifelong memories and friends deploying moorings and surveying the archipelago with a boatload of high-tech gear, buoys, hot sauce and rice.
ACKNOWLEDGEMENTS

I would like to thank the many former and current faculty and staff of NCSU’s Department of Marine, Earth and Atmospheric Sciences, who have afforded me many opportunities to work and study. I would especially like to thank my co-adviser, John Morrison, for the many once-in-a-lifetime opportunities (from Antarctica to the Galápagos) that he has been involved and shared with me. Also, I thank my committee for their insightful conversations and comments, which have helped clear my focus and reveal many wonderful biophysical complexities. Lastly, I thank my family who has lead by example and my wife, Whitney, who has made my time in school an unforgettable experience full of colorful memories.
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Project Overview

The following work is part of the *Connectivity and Upwelling Dynamics in the Galápagos Marine Reserve* project, a cooperative program by the University of North Carolina at Wilmington (UNCW), North Carolina State University (NCSU), the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC), the Charles Darwin Research Station (CDRS), and the Galápagos National Park Service (GNP). The program is researching variability that occurs within the upper ocean and its effects upon the biodiversity of the Galápagos. While considerable effort is given to studying the biodiversity and ecology of the Galápagos, little systematic effort has gone into studying the oceanographic setting. No complete understanding of biological variability in the ocean will be forthcoming without complementary knowledge of the physical processes acting upon it. One of the focuses of the program is to better understand the spatial and temporal presence of Equatorial Undercurrent (EUC) filaments as they propagate across and upwell within the Galápagos Archipelago. Quite probably these features are the most important physical process supplying nutrients to the surface and stimulating the archipelago’s very high local primary production that feeds its extreme biodiversity.

The following three manuscripts describe mechanisms causing annual to inter-annual variability within the upper ocean of the Galápagos Archipelago. The findings are based on *in-situ* observations collected during the 2005 – 2007 field campaign as well as a suite of complimentary moored and remotely-sensed data. Specifically, the dissertation documents the upper ocean variability that occurs 1) annually as the seasons change and those changes that are superimposed and driven by 2) tropical instability waves (TIW) and 3) the El Niño Southern Oscillation (ENSO). These results compliment the other concurrent geochemical, surface plankton, and circulation modeling components of the NASA-funded program, which aims to provide an integrated understanding of the ecology and enhance the predictive capabilities for management of the newly formed Galápagos Marine Reserve (GMR).
Chapter 1

Water Mass Seasonal Variability in the Galápagos Archipelago

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Published in

Deep-Sea Research I
Oceanographic Research Papers
doi: 10.1016/j.dsr.2007.09.009
Water mass seasonal variability in the Galápagos Archipelago

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Abstract

Three hydrographic surveys were conducted within the Galápagos Archipelago during 2005–2006. The surveys captured the surface properties (<80 m) near the extremes and midpoint of the annual cycle of the mean sea surface temperature (SST) and winds. A cooler SST occurs in boreal summer and fall as the southeast trades strengthen. Current data at 110°W show that this coincides with the Equatorial Undercurrent (EUC) becoming weaker and deeper below a strengthening westward South Equatorial Current (SEC). Opposite conditions are generally found in the spring. Meanwhile, the sea surface salinity (SSS) freshens in late winter/spring when the archipelago receives large rainfalls as the Intertropical Convergence Zone (ITCZ) shifts southward, or in late fall when receiving large influxes from the North Equatorial Countercurrent (NECC). As a result, Tropical Surface Waters (TSW) with salinity ($S$) $\leq 34$ fill the archipelago from the late fall through early spring. The SSS becomes saltiest in late spring/early summer as the EUC strengthens, resulting in Equatorial Surface Waters (ESW), $S$ > 34, throughout the archipelago. Equatorial Surface Waters are present west of Isabela, where the EUC upwells as it interacts with the Galápagos platform. They also are found east of the archipelago in the cold tongue, which extends westward from South America, and therefore may be advected by the SEC into the archipelago. The upwelling west of Isabela creates a consistently shallow 20°C isotherm (thermocline), which remains elevated across the archipelago. Linear extrapolation of the thermocline depth along the equator from 110 to 95°W gives a good approximation of the thermocline depth within the archipelago from 92 to 89°W.

Keywords: Galápagos; Eastern Pacific; Equatorial Undercurrent; Upwelling; Water masses

1. Introduction

The Galápagos Archipelago (Fig. 1) lies within the eastern Pacific, near the Equatorial Front (EF), the divide separating the warm and low-salinity ($S$ $\leq 34$) Tropical Surface Waters (TSW) in the north and the colder and saltier ($S$ > 34) Equatorial Surface Waters (ESW) of the east Pacific cold tongue to the south (Wyrkki, 1966; Fiedler and Talley, 2006). The core of the eastward-flowing Equatorial Undercurrent (EUC) rises within the equatorial thermocline (Wyrkki and Kilonsky, 1984), feeding the Ekman divergence of the cold tongue with high salinity ($S$~35.2) Subtropical Underwater (STUW). When the EUC runs into
and through the Galápagos platform, it further upwells from their topographic blockage (Houvenaghel, 1978; Eden and Timmermann, 2004). At the surface, the westward-flowing South Equatorial Current (SEC) flows weakly across the archipelago to depths between 20 and 50 m (Knauss, 1960), before splitting into northward and southward lobes west of Isabela (Kessler, 2006). Along the equator, the SEC is variable due to momentum and mass exchange with the underlying EUC (Wyrtki and Kilonsky, 1984). The upwelled waters of the EUC supply the majority of the SEC’s volume (Wyrtki, 1966, 1981), which also receives inputs from the eastward North Equatorial Countercurrent (NECC) to the north (Kessler, 2006) and equatorial and coastal upwelling of thermocline waters to the east.

The strength and depth of the EUC affect the water properties within the archipelago. In the central Pacific, Wyrtki and Kilonsky (1984) observed the EUC core near the 20°C isotherm (thermocline). At 125°, 110°, and 95°W, Johnson et al. (2002) reported a 15-year mean of the EUC core between the 17 and 20°C isotherms along the equator at ~80, 60, and 40 m, respectively, with eastward surface currents. At 92°W, Steger et al. (1998) noted the EUC within the 14–20°C isotherms and driving an eastward surface current during a November survey. At this time, the EUC had upwelled much of its volume before splitting north and south around Isabela, where it continued beneath the ~30-m deep thermocline across the archipelago.

A strong seasonal variability affects the archipelago (Houvenaghel, 1984). During the dry, Garúa season (May–November), the Intertropical Convergence Zone (ITCZ) is well north of the equator, the SE trades strengthen, and the sea surface temperature (SST) decreases. Garúa, the Spanish word for mist, forms when warm air masses move over a much cooler SST causing moisture to condense out of the atmosphere. During the hot, wet season (December–April) when locally heavy rainfalls are possible, the ITCZ nears the equator, the SE trades subside, the SST warms from both reduced Ekman divergence and evaporative cooling (Xie, 1994). Yu and McPhaden (1999) and Johnson et al. (2002) have quantified the annual response within the eastern Pacific. Observations at 110° and 95°W indicate maximum southeasterly winds, shallowest thermocline and strongest SEC in early fall and opposite conditions in mid/late spring. In mid
spring, the EUC is strongest (speed and transport), shallowest, and has highest salinity ($S \sim 35.2$), which becomes weakest, deepest, and freshest ($S \sim 34.9$) towards late fall. The SST is $> 3^\circ C$ higher in early spring than in early fall. The sea surface salinity (SSS) is generally freshest, in phase with the warmest SST, but becomes saltiest towards late spring from enhanced transport within the EUC/thermocline and from the northward migration of the ITCZ. By late fall, the SSS freshens throughout the eastern, equatorial Pacific as the NECC strengthens and increasingly feeds the SEC (Kessler, 2006).

Other mechanisms affecting the water masses around the archipelago include the strong interannual variations of the El Niño/Southern Oscillation (ENSO) cycle that may increase the SST by $>1^\circ C$, leave the SSS relatively unchanged, depress the thermocline, and reduce the SEC and EUC during the warm phase (El Niño). The opposite conditions are brought about during the cool La Niña (Johnson et al., 2002; Fiedler and Talley, 2006). In addition, shearing of the major zonal currents can create tropical instability waves (TIW), which meridionally distort the EF by advecting warm waters to the south and cool waters to the north (Philander, 1978; Willett et al., 2006).

In March 1998, Ecuador created the Galápagos Marine Reserve (GMR) in order to help preserve its unique and juxtaposed warm- and cold-water ecosystems (Bustamante et al., 1999). Amazingly enough, little to no systematic studies have been made of the oceanographic regime of the GMR. A few studies have quantified surface plankton around the archipelago, noting highest concentrations west of Isabela (Feldman, 1986; Feldman et al., 1984). A detailed physical description of the water masses incident upon the archipelago is lacking, and essential if GMR managers are to better predict the ecosystem response to an environmental stress. The primary focus of this paper is the identification of the seasonal characteristics of the archipelago’s surface waters made during three hydrographic surveys between 2005 and 2006.

2. Data

The data presented here were collected during a study of key ecological processes that affect the biodiversity within the archipelago. These cruises were a cooperative effort by the University of North Carolina Wilmington (UNCW), North Carolina State University (NCSU), the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC), the Charles Darwin Research Station (CDRS), and the Galápagos National Park Service (GNP). Additional papers will discuss the biochemical and planktonic properties of the archipelago and a circulation modeling effort.

Data were collected during three surveys (Fig. 1) conducted March 17–28, 2005 (March 2005), November 22–December 3, 2005 (November 2005) and June 26–July 4, 2006 (June 2006) on the patrol launch of the Galápagos National Park Service, the M/N Sierra Negra. Surface data included underway measurements of salinity, temperature, and fluorescence with a Seabird Electronics SBE 19 + (CTD) and a WetLab BB2F fluorometer averaged over 30-min intervals. Vertical profiles to approximately 80 m were made at each station with an identical system, deployed by hand in the 2005 surveys and by a small winch during the 2006 survey. Temperature-salinity (TS) diagrams of the CTD data averaged every 2 m show the water-mass types of Wyrtki (1966). For this study, although, if the SSS is $>34$ the water mass will be considered ESW, and if it is $<34$ it will be considered TSW, regardless of the SST.

Wind and SST data were obtained from the Physical Oceanography Distribution Active Archive Center’s (PO.DAAC) Ocean Earth Science Information Partner (ESIP) Tool (POET). Mean 8-day infrared imagery of SST from the MODIS Aqua sensor (4-km resolution) close in time to each survey period provided large-scale views ($5^\circ N–5^\circ S$, 95–80 W) of the region. Mean monthly Reynolds/NCEP (NCEP) SST ($1^\circ$) and its anomaly from a 25-year mean and a monthly mean of daily winds (0.25”) from NASA’s microwave scatterometer (QSCAT) were averaged between 2°N and 2°S and between 92 and 88 W. The ENSO SST anomalies from Niño region 3.4 ($5^\circ N–5^\circ S$, 170–120 W) were obtained from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center. Ocean current (110 W) and temperature (110 and 95 W) profiles from the Tropical Atmosphere Ocean (TAO) array along the equator.
assisted in the interpretation of the EUC and thermocline.

3. Results

The three surveys March 2005, November 2005, and June 2006 occurred during a mid-wet, a late-Garúa, and an early-Garúa season, respectively. The annual cycle of the monthly mean (Fig. 2a) reveals minimum winds and maximum SST in the winter/spring and opposite conditions in the summer/fall. Fig. 2b shows the SST anomaly (−0.4, −0.5, and 1.2 °C) and the ENSO SST anomaly (0.4, −0.5, and 0.3 °C) for the three cruises. Table 1 shows the mean of the daily values for each survey period of the depth (speed) of the EUC at its core and the thermocline depth at 110°W, the depth (temperature) of the upper surface of the EUC at 110°W, the depth of the thermocline at 95°W, and the thermocline depth at 110 and 95°W linearly extrapolated to 92°W. Also shown is a mean thermocline depth from CTD profiles for each survey computed from stations within ±0.5° of the equator between 89 and 92°W.

![Fig. 2. 2002–2006 monthly mean (92–88°W, 2°N–2°S) of (a) meridional wind (QSCAT) and SST (NCEP) and (b) SST (NCEP) and ENSO (Niño region 3.4) anomaly.](image-url)

Table 1

<table>
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<th>(1) EUC core, m (velocity, cm/s)</th>
<th>(2) Thermocline, m (velocity, cm/s)</th>
<th>(3) EUC surface, m (temperature, °C)</th>
<th>(4) Thermocline (m)</th>
<th>(5) Predicted thermocline (m)</th>
<th>(6) CTD thermocline (m)</th>
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<td>March 2005</td>
<td>83 (155)</td>
<td>76 (147)</td>
<td>&lt;10 (25.62)</td>
<td>30</td>
<td>21</td>
<td>16</td>
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<tr>
<td>November 2005</td>
<td>87 (85)</td>
<td>45 (7)</td>
<td>45 (20.04)</td>
<td>20</td>
<td>15</td>
<td>23</td>
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<tr>
<td>June 2006</td>
<td>67 (146)</td>
<td>62 (138)</td>
<td>&lt;0 (24.12)</td>
<td>45</td>
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3.1. March 17–28, 2005 survey

The mean SST is high (∼25 °C) and the winds light (∼2 m/s), both typical of the wet season and near their annual extremes (Fig. 2a). It should be noted that torrential downpours inundated the island of Santa Cruz for 2 days prior to the survey. Further observations of regionally heavy rainfall were recorded by the Tropical Rainfall Measuring Mission (TRMM) satellite available at http://www.remss.com. The SST during this survey was close to the climatological mean (∼0.4 °C) at the end of the weak 2004–2005 El Niño (Fig. 2b). The EUC at 110°W is quite strong (155 cm/s), has its core just below the thermocline, and drives an eastward flow near surface at 110°W (Table 1). The thermocline shoals to 30 m at 95°W, ∼20 m at 92°W, and within the archipelago is <20 m.

A large-scale view of the SST for the eastern Pacific (Fig. 3a) shows very warm water from 85 to
92°W covering the archipelago and separating cooler regions of equatorial upwelling to the west and cold tongue waters eastward towards South America. Within the archipelago the SST is warmest (>26 °C) north and south and coolest (<20 °C) west of Isabela (Fig. 3b). Cool temperatures (<19 °C) exist centrally across a NW/SE span at the 20-m depth (Fig. 3c), warmer to the north and coldest (<17 °C) west of Isabela. The thermocline is near the surface west of Isabela and reflects the NW/SE span of cool water at the 20-m depth across the archipelago (Fig. 3d). Vertical temperature profiles along 91.8°W (Fig. 3e) reveal a lifting of the isotherms >16 °C south of ~1°N, while along 0.3°N (Fig. 3f), all isotherms have a downward gradient heading east across the archipelago.

Higher salinity at the surface and 20 m (Fig. 4a and b) generally corresponds to lower temperatures ($r^2 = 0.47$ and 0.61). Freshest waters ($S < 33$) are found towards the north and south, with the highest

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**Fig. 4.** March 2005 survey of (a) SSS, (b) 20-m salinity, (c) salinity at 91.8°W, (d) salinity at 0.3°N, and (e) TS diagram.
salinity ($S > 34.9$) found west of Isabela and within a surface plume in the east. A transect along 91.8°W (Fig. 4c) reveals high salinity ($S > 34.9$) shoaling to 10 m west of Isabela to ~0.5°N, where a strong meridional gradient exists heading north. The transect along 0.3°N (Fig. 4d) shows the fresher waters north of Isabela and higher salinity in the east that are part of the surface plume. The TS diagram in Fig. 4e shows warm TSW and the ESW found west of Isabela and to the east in the salty (SSS $> 34.9$) surface plume.

3.2. November 22–December 3, 2005 survey

The mean SST is low (~23 °C) and the SE trades are of intermediate strength (~4 m/s), reflecting a shift from the Guara to the wet season (Fig. 2a). The mean SST is ~0.5 °C below the climatological

![Figure 5](image-url)
mean during the transition, which is also reflected in the ENSO anomaly (Fig. 2b). The EUC at 110°W is relatively weak (87 cm/s), and its core is ~40 m below the thermocline. Above the thermocline, westward flow of the SEC is observed (Table 1). The thermocline shoals to the east, reaching ~20 m at 95°W, and remains approximately at this depth across the archipelago.

The EF crosses the archipelago (Fig. 5a), with the SST (Fig. 5b) warmer (>24°C) to the north and cooler (<22°C) to the south. The near surfacing of the thermocline west of Isabela is quite obvious in the SST (Fig. 5b), while Fig. 5c shows cooler waters (<20°C) south of the equator at 20 m. The depth of the thermocline (Fig. 5d) is shallow over the cooler waters found at 20 m, and deepens north of the equator. A transect at 91.8°W (Fig. 5e) shows a strong lateral gradient within the EF, increasing ~4°C to the north. A transect at 0.3°N (Fig. 5f) shows the thermocline slightly

![Fig. 6. November 2005 survey of (a) SSS, (b) 20-m salinity, (c) salinity at 91.8°W, (d) salinity at 0.3°N, and (e) TS diagram.](image-url)
shallower in the west nearing the cooler upwelling region.

Higher salinity at the surface and 20 m (Fig. 6a and b) generally corresponds to lower temperatures ($r^2 = 0.46$ and 0.83, respectively). Highest SSS ($S \approx 34.6$) is west of Isabela, freshening to $S < 33$ towards the east and across the EF. The vertical sections at 91.8°W and 0.3°N (Fig. 6c and d) show upwelling of waters with $S > 34.6$ west of Isabela and strong gradients north and east across the EF, where the SSS freshens. TSW cover much of the archipelago, with SST $\approx 24$ °C and SSS $< 34$ (Fig. 6e), while pockets of ESW are found west of Isabela and south, where SSS is $> 34$ (Fig. 6a).

3.3. June 26–July 4, 2006 survey

The mean SST (Fig. 2a) is relatively low ($\approx 24$ °C) and the SE trades are strong ($\approx 5$ m/s), both close to their seasonal peaks respective to the Garúa season.

Fig. 7. June 2006 survey of (a) MODIS 8-day mean (26 June–3 July) SST, (b) CTD SST, (c) 20-m temperature, (d) thermocline depth, and (e) temperature at 90.8°W.
The SST is significantly (+1.2°C) above its climatological mean (Fig. 2). The EUC at 110°W (Table 1) has a strong core velocity (146 cm/s) near the thermocline (62 m). This results in an eastward flow near the surface at 110° W. Heading east, the thermocline shoals to ~45 m at 95° W and remains close to this depth across the archipelago.

The archipelago lies within the cold tongue, which reaches to the coastal upwelling zone off of the coast of South America (Fig. 7a). The SST (Fig. 7b) is highest (> 25°C) northeast, cooler towards the southwest, and coldest (<21°C) within the upwelling zone west of Isabela. At 20 m, the structure is quite similar to that of the SST (Fig. 7c), as the thermocline (Fig. 7d) is very deep (> 50 m), except slightly shallower in the central archipelago and where it nearly surfaces west of Isabela. Unfortunately, because of mechanical problems, numerous stations were not sampled, prohibiting direct comparison to the transects at 91.8° W and 0.3° N shown for the other two surveys; a substitute transect composed of stations near 90.8° W (Fig. 7c) shows a deep thermocline that shoals slightly from north to south.

The salinities at the surface and 20 m are nearly identical (Fig. 8a and b) due to a mixed-layer depth > 20 m, as discussed above by the deep thermocline depth. Higher salinity correlates with lower temperatures ($r^2 = 0.73$ and 0.65, respectively). Freshest waters ($S \approx 34$) are found towards the northeast and steadily increase to the southwest, reaching a maximum ($S \approx 35.2$) west of Isabela. The 90.8° W transect (Fig. 8c) shows a vertically homogeneous water column south of the equator with high salinity ($S > 34.9$) that lessens slightly at the surface towards the north. The TS diagram reflects the high salinity throughout the archipelago (Fig. 8d), indicating that the surface waters of the archipelago are dominated by a mixed layer of ESW.

![Fig. 8. June 2006 survey of (a) SSS, (b) 20-m salinity, (c) salinity at 90.8° W, and (d) TS diagram.](image-url)
3.4 Biological response

The mean surface chlorophyll a (Chl a) values over the archipelago are 0.92 ± 0.70 mg/m³ for March 2005, 0.98 ± 0.59 mg/m³ for November 2005, and 1.16 ± 1.06 mg/m³ for June 2006. No statistical differences were found between Chl a levels within the ESW and TSW around the archipelago, although values were usually highest within the ESW west of Isabela. Schaeffer et al. (in review) report generally higher Chl a within low SST, high SSS, and high, but a slightly reduced, surface nitrate. The relationship presented here (Fig. 9) compares the thermocline depth to surface Chl a values for the three surveys (exponential decay fit, with \( r^2 = 0.21, 0.18, \) and 0.24). Although yielding statistically insignificant correlations, the relationships illustrate the tendency for increased Chl a over a shallow thermocline, a factor that helps explain Chl a levels in the eastern equatorial Pacific and the archipelago (Palacios, 2002).

4. Discussion

The results of the present study provide snapshots of the surface water (>80 m) properties over the archipelago during the hot and calm extremes of the wet season (~December–April), the cooler and windier conditions of the Garúa (~May–November), and conditions transitioning between the two. The observed responses largely reflect the annual cycle of the eastern equatorial Pacific (Yu and McPhaden, 1999; Johnson et al., 2002); they may also be modified by the ENSO cycle (Fiedler and Talley, 2006).

The March 2005 survey occurred near the peak of the wet season but may still be affected by the later stages of the weak 2004–2005 El Niño, which ended the month prior. The March 2005 survey featured large rainfalls as a result of the close proximity of the ITCZ, resulting in TSW in the central portion of the archipelago (Fig. 4a). The EUC is strong and shallow, with its core near the thermocline (Table 1), which shoals to the east, nearly surfacing west of Isabela (Fig. 3b, d, and e). Within the archipelago, the thermocline is ~20-m deep and is indicative of eastward flow of the EUC, or at least reflects the distribution of its upwelling. ESW with a SSS ~35.2 west of Isabela (Fig. 4a) define the maximum value of the EUC (Fig. 4e), but S > 34.9 appears more suggestive of the EUC’s presence within the archipelago (Fig. 4c). Fig. 4a reveals a large, shallow plume of ESW with SSS > 34.9 in the TS diagram (Fig. 4e). This feature is indicative of upwelling that has occurred somewhere towards South America, with the upwelled waters being advected westward with the SEC into the eastern portion of the archipelago. This idea is supported in Fig. 4d, where both the surface and 80-m depth are shown to have S > 34.9 at ~89.5°W.

The November 2005 survey occurred during a transition from the Garúa to the wet season. Conditions are intermediate in terms of the annual cycle (Fig. 2a) and cool with regards to ENSO (~0.5°C). As the SE trades are still moderately strong, surface currents are of the westward SEC at 110°W. Beneath the thermocline, a relatively weak and deep EUC core is observed (Table 1). With stronger winds during this seasonal transition period, there is a greater evaporative cooling (Xie, 1994) and Ekman divergence, which produce a regionally pronounced cold tongue and EF that crosses the archipelago (Fig. 5a). ESW are found west of Isabela, where the EUC upwells and raises the SSS; ESW are also found south of Isabela, more so where the thermocline is shallow. The remainder of the archipelago is covered by TSW (Fig. 6e) that originate in the fresher NECC, which is strongly developed during this time of year (Kessler, 2006). Salinity > 34.9 in the TS diagram (Fig. 6e) is the EUC, which consistently maintains a depth > 30 m across the archipelago (Fig. 6e and d). The reduced SSS west of Isabela and across the archipelago as
compared to March 2005 is indicative of a less vigorous EUC, which is deeper and upwells less, but is also fresher because of a reduced transport within the thermocline during the late fall (Johnson et al., 2002). It should be noted that the SST recorded by the TRMM satellite revealed limited TIW activity (Legeckis, 1977), though substantially less than the seasonal maximum of September–October 2005. Because of this, it is possible that some of the mean values reported here could be slightly aliased by the physical processes of the ~20-day periodicity associated with TIW activity along the equator (Halpern et al., 1988).

The June 2006 survey is interesting in that its winds (5 m/s) are the highest, while its SST has a value between those of the other surveys (Fig. 2a); yet both quantities are near their annual maximum and minimum, respectively, typical of the Garúa season. The reason may be related to the forthcoming 2006–2007 El Niño that diminishes the ensuing annual cycles. Already, the mean SST is significantly (+1.2°C) above climatology in the archipelago (Fig. 2b). The EUC characteristics at 110° are similar to those of March 2005, when it had a strong core velocity centered near the thermocline. Different is the tilt of the thermocline during June 2006 (March 2005), whose depth of 67 m (83 m) at 110°W shoals to only 45 m (30 m) at 95°W, where it remains centrally throughout the archipelago, except west of Isabela. It is assumed that the eastward EUC flows above the thermocline within the archipelago, similar to the March 2005 survey. The SSS maximum of ~35.2 west of Isabela (Fig. 8a) is of the EUC (Fig. 7d). The strong signature of the ESW within the TS diagram reflects the salt content of the eastward-flowing EUC as well as the SEC flowing above it, which would be composed largely of the same EUC/thermocline waters upwelled somewhere east of the archipelago and warmed slightly at the surface.

5. Conclusions

Surface water properties of the Galápagos Archipelago reflect the degree that TSW and ESW are formed within and delivered to the archipelago. Tropical Surface Waters (SSS < 34) form when rainfall locally increases as the ITCZ nears, or when largely diluted by the relatively fresh waters of the NECC. Tropical Surface Waters partially covered the archipelago during March 2005 from large rain inputs and substantially during the November 2005 survey from large inputs of NECC waters. Equatorial Surface Waters (SSS > 34) will emerge when the EUC is strongly developed to the west, the thermocline/EUC upwells locally by topographic blockage of the EUC, or within the cold tongue to the east, which advects west within the SEC into the archipelago. Conversely, ESW may be more prevalent when the sources of fresher water are removed, i.e., when the ITCZ/rainfall migrates northward or in the spring when the NECC is weak (Kessler, 2006). Equatorial Surface Waters were present because of a combination of all these processes in June 2006, as well as in the March 2005 survey, but large rainfalls introduced TSW to the central archipelago during this survey. The results of this project are unique to the Galápagos but largely follow with the annual hydrography and circulation patterns for the eastern equatorial Pacific (Yu and McPhaden, 1999; Johnson et al., 2002; Fiedler and Talley, 2006; Kessler, 2006). The ENSO cycle and TIW activity are both capable of modifying the annual cycle of the surface properties within the archipelago; however, further work needs to be performed in order to better quantify locally these responses.

Upwelling was observed consistently west of Isabela, attributed to the topographic blockage of the EUC. In addition, a relatively shallow thermocline is maintained centrally within the archipelago, usually south of the equator. Linear extrapolation of the thermocline depth along the equator from 110 to 95°W gives a good approximation of the thermocline depth within the archipelago from 92 to 89°W. Without direct current measurements, distinguishing the EUC flow path is difficult, although the thermocline is a good indicator of its thermal influence and locations of its upwelling. Fluctuations that occur have consequences in both the vertical and horizontal. Vertical thermocline fluctuations deliver nutrients (iron) that influence the primary production at the surface (Palacios, 2002), while horizontal thermocline fluctuations are important to recruitment and the maintenance of cold-water and productive environments, such as those in the western archipelago associated with highest fish endemism (Edgar et al., 2004). There is difficulty attributing Chl a concentrations about the archipelago to any of the measured physical parameters, although higher Chl a values were measured over shallow thermoclines. The difficulty may stem from the uncoupling between the SEC and its Chl a expression and between the EUC and its nutrient supply (Palacios, 2004).
Acknowledgments

This project was supported by NASA’s Biodiversity and Ecological Forecasting grant NNG04GL98G, Counterpart US-AID no. 518-A-00-03-00152-00 to the Charles Darwin Research Station and UK Darwin Initiative project no. 14-048. We would like to thank the Galápagos National Park (GNP) Marine Resources Head Mario Piu, the GNP Science Coordinator Eduardo Espinola Merlen, the captain and crew of the M/N Sierra Negra, and the scientific dive team from CDRS, Marianna Vera, Marco Tosca, Julio Delgado, Natalia Tirado, Roberto Pepolas, and Diego Ruiz. Lastly, we thank William Kessler and two anonymous reviewers for their constructive comments.

References


Chapter 2

Tropical Instability Wave Interactions within the Galápagos Archipelago

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Submitted for Publication

Deep-Sea Research I
Oceanographic Research Papers
Chapter 2

Tropical Instability Wave Interactions within the Galápagos Archipelago

Abstract

In the boreal fall of 2005, the effects of tropical instability waves (TIW) appear as oscillations within the sea surface temperature (SST), meridional current ($V_y$), and thermocline ($20^\circ$C) in the eastern equatorial Pacific. The $V_y$ oscillations of the equatorial front (EF) by the TIW are observed in the SST at $0^\circ$, $110^\circ$W, but not at $0^\circ$, $95^\circ$W, where the SST changes concurrently to changes in the thermocline depth. Within the Galápagos Archipelago, a strong 3-wave succession of TIW in Sep and Oct 2005 registered large 15-day period oscillations in temperature and water level time series recorded at a 5-m depth at four mooring locations. Upwelling speeds of ~5.0 m day$^{-1}$ are estimated for the central archipelago during the TIW, dropping temperatures by ~7$^\circ$C within a week. A significant biological response to the TIW is observed throughout the archipelago. Coincident with coldest temperatures, the chlorophyll $a$ (Chl $a$) increased across the archipelago by 25 – 40% above its 2004 – 2006 mean and nearly 25% above its 1998 – 2007 mean. The much larger Chl $a$ levels near/within the archipelago as compared to $95^\circ$ and $110^\circ$W implicate that the island platform itself further iron-enriched the upwelling waters.

Introduction

Tropical instability waves (TIW) are westward-propagating oscillations common July – February during non-El Niño conditions (Contreras 2002). In the eastern Pacific, TIW are readily observed in the sea surface temperature (SST) along the Equatorial Front (EF) (Legeckis 1977). In-situ measurements further refine TIW as oscillations with periods of 15-23 (~17) days detectable ±2° of the equator and of 28-35 (~33) days found ~5°N (Lyman et al. 2007). The ~17-day TIW has strong meridional current ($V_y$) oscillations that result from the shearing of the northern branch of the westward South Equatorial Current.
(SECN) and the eastward Equatorial Undercurrent (EUC) just north of the equator (Luther and Johnson 1990; Qiao and Weisberg 1995). Prior studies (Halpern et al. 1988; Qiao and Weisberg 1995; Lyman et al. 2007) along the equator between ~150° and 95°W contribute to the following description of the ~17-day TIW. Oscillations of the $V_y$ occur mainly ±1° of the equator and are strongest within the surface layer and decrease rapidly towards the EUC/thermocline (20° isotherm). The vertical penetration of the oscillation decreases to the west as does the wave period. The $V_y$ at the equator are associated with oscillations within the subsurface temperature between ~2°S and 2°N. Downwelling (upwelling) occurs north (south) of the equator when $V_y$ is northward, and the opposite conditions occur when $V_y$ is southward. The off-equator temperature response lags the $V_y$ at the equator by ~90° and is opposite across its latitudinal scale.

Within the high-nutrient, low-chlorophyll (HNLC) conditions of the iron-limited, equatorial Pacific (Martin et al. 1991), upwelling supplies the surface waters with iron-saturated waters from the EUC core (Barber et al. 1996). Upwelling within 17- and 33-day TIW can reach speeds >10 m day$^{-1}$ (Kennan and Flament 2000; Weisberg and Qiao 2000; Menkes et al. 2006), contributing to areas with elevated primary production and chlorophyll $a$ (Chl $a$) values an order of magnitude greater than the ~0.2 µg l$^{-1}$ baseline for the equatorial Pacific (Murray et al. 1994; Foley et al. 1997; Strutton et al. 2001). These rate changes also affect the zooplankton and higher tropic levels as well (Murray et al. 1994; Roman et al. 1995; Menkes et al. 2002). The heightened biological processes have been observed most often in regions of strong $V_y$ and SST gradients making convergent (Yoder et al. 1994; Chavez et al. 1999; Kennan and Flamment 2000) and divergent (Strutton et al. 2001) zones of the TIW. There is some doubt as to whether there is an annual mean stimulus to the Chl $a$ concentrations by TIW. Gorgues et al. (2005) actually estimates that there is a net 10% decrease in Chl $a$ near the equator where the meridional advection of TIW are ~5 times greater than their vertical advection, diluting the upwelled inputs with the oligotrophic waters from north of the EF.

Long-term concentrations of Chl $a$ in the equatorial Pacific are consistently higher near the Galápagos Archipelago (Fig. 1), reaching highest concentrations to the west of Isabela where the EUC further iron enriches by collision and topographic upwelling of the
EUC with the island platform (Feldman 1986; Gordon et al. 1998; Steger et al. 1998; Palacios 2002). Surface levels of Chl $a$ diminish eastwards across the archipelago (Lindley and Barber 1998) because the SECN is iron limited when it enters the archipelago (Gordon et al. 1998). There are “hot spots” with high Chl $a$ concentrations often near north and south-facing sides of the individual islands (Schaeffer et al. Accepted) and/or in areas with a shallow thermocline (Palacios 2002; Sweet et al. 2007). Inter-annual changes of the El Niño Southern Oscillation (ENSO) can alter the spatial patterns of EUC upwelling and Chl $a$ concentrations throughout the archipelago, as happened at the climax of 1982-83 El Niño (Feldman et al. 1984). Annually, the Chl $a$ increases within the archipelago when the cold tongue magnifies in the latter half of the year (Palacios 2004). Short-period (<10 min) and intense (0.3 m s$^{-1}$) upwelling can cause large (9°C) temperature variability along island walls that enhance larval recruitment of benthic invertebrates, but are too short to affect surface biomass (Whitman and Smith 2003).

Quantifying the mechanisms responsible for the observed phytoplankton biomass in the Galápagos is important since it feeds the archipelago’s biodiversity. Current assessments of the underwater communities are providing baseline information used to create complex mass-balance tropic models (Okey et al. 2004) to improve the predictive efforts by managers of the Galápagos Marine Reserve (GMR) under changing environmental conditions. In this study, we utilize remote and in-situ observations to assess the vertical pumping associated with the ~17-day TIW from 110°W east into the Galápagos Archipelago. Specifically, the study highlights the passage of three prominent TIW from Aug 28 and Oct 13, 2005 and the biological response they create near and within the archipelago.

Data

Data used in this study include time series of water level (WL) and temperature collected by Yellow Springs Incorporated (YSI) 6600EDS sondes. The sondes were fastened within the top float of rigid, taut-wire, subsurface (~5 m) moorings deployed in 60-m deep waters near 4 islands within the archipelago (Fig. 1). Hourly temperature and WL (Santiago and Isabela only) data are presented from Aug to Dec 2005 period, highlighting
the three successive TIW from Aug 28 to Oct 13, 2005 that created large temperature oscillations. The YSI WL (temperature) sensors have a resolution of 0.001 m (0.01°C) and accuracy of ±0.02 m (±0.15°C). Hourly data has been lowpass filtered (half power period = 38 hours), and unless otherwise stated, the presented data has been bandpass filtered (10- and 40-day period passed) to highlight TIW dynamics. Additional time series include daily ocean currents, thermocline depth, SST and dynamic height (DH) data from the Tropical Atmosphere Ocean (TAO) array along the equator at 110° and 95°W. The TAO data were similarly bandpass filtered. Power spectrum density (PSD) estimates of the time series were performed using the multitapering MATLAB function PMTM with the time bandwidth parameter NW set to two (Mathworks 2007). Standard 95% confidence intervals for the spectra were computed using the chi-squared approach and all peaks referred to in the text achieve the 95% level.

Wind and SST data were obtained from the Physical Oceanography Distribution Active Archive Center’s (PO.DAAC) Ocean Earth Science Information Partner (ESIP) Tool (POET). Mean monthly Reynolds/NCEP (NCEP) SST (1°) and its anomaly from a 25-year mean (Reynolds et al. 2002) and a monthly mean of daily winds (0.25°) from NASA’s microwave scatterometer (QSCAT) were averaged between 2°N and 2°S and between 92° and 88°W to provide a climatological setting for the Galápagos. Mean 8-day, longitudinal vs. time SST (NCEP) anomalies were averaged between 1° and 2°N. This data was bandpass filtered zonally (444-km and 2220-km cutoff) from 150° to 90°W to produce a time vs. longitude plot (Hovmoller diagram) to quantify the TIW propagation. The ENSO SST anomalies from Niño region 3.4 (5°N-5°S, 170°-120°W) were obtained from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center.

In addition, 3-day mean snapshots of the SST (0.25° resolution) were obtained from the Advanced Microwave Scanning Radiometer (AMSR-E) satellite to provide a clear image of the TIW features. Eight-day composites of Chl a (0.1° resolution) from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) were obtained from Giovanni. Mean Chl a is presented for zones that cover the archipelago and encompass certain YSI sensors, including a northern (2°-0.5°N, 91.5°-89.5°W), western (0.5°N-1°S, 92.7°-91.2°W), and a central
(0.5°N-1°S, 91.2°-89.7°W) zone. In addition, Chl $a$ is computed within a 1° box around the TAO buoy locations on the equator (i.e., 0.5°N-0.5°S, 95.5°-94.5°W). The Chl $a$ values are temporally centered in their 8-day composites, and the values have been averaged for 1998 – 2007 (10-yr) and 2004 – 2006 (3-yr) periods to provide long-term means. Water-column profiles in the archipelago were obtained by the Argo project.

**Results**

The annual cycle of the monthly mean (92°-88°W, 2°N-2°S) of SST and meridional winds ($V_y$) is shown in Fig. 2. Mean $V_y$ winds are maximum (~6 m s$^{-1}$) and the SST is minimum (~22°C) in the boreal summer/fall. Opposite conditions generally occur in the winter/spring. Also shown in Fig. 2 is the SST anomaly of the El Niño Southern Oscillation (ENSO) within region 3.4 (5°N-5°S, 170°-120°W). The 5-year ENSO SST anomaly shows a few El Niño events and the absence of any cool La Niña events. A mild El Niño ended in early 2005, and the region continued to cool throughout 2005, reaching a -0.8° anomaly by the year’s end (although not classified as a La Niña). Warming occurs at the start of 2006 and becomes a classified El Niño by August 2006.

The SST images (Fig. 3a) show the EF stretching from the South American coast across the archipelago and into the central equatorial Pacific where the TIW oscillations become accentuated. Time series from Jun 2005 through Feb 2006 show oscillations ±4° of the equator in the SST (http://www.remss.com) and ocean color (http://oceancolor.gsfc.nasa.gov). The SST oscillations are most notable Sep through Nov 2005 near the Galápagos, and this study focuses primarily on that period. A Hovmoller diagram (not shown) of the SST anomaly indicate westward TIW with a ~48 km day$^{-1}$ phase speed and a range of wavelengths from 900 to 1400 km and periods of 19 to 29 days in Sep and Oct 2005.

Oscillations of $V_y$ along the equator are most notable from Sep through Nov 2005 at 110°W (Fig. 3b) and from Nov 2005 to Jan 2006 at 140°W (not shown). The $V_y$ oscillations are most intense (~0.75 m s$^{-1}$) near the surface and diminish below a 75-m depth. The mean depth (temperature) separating the SECN from the EUC beneath is ~40 m (20°C) at 110°W during the period of high TIW activity. The PSD of the 30-m $V_y$ for Jun 2005 – Mar 2006
peaks at ~20.5 days at 110°W and ~16.5 days at 140°W (Fig. 4a). In-situ measurements at 0°, 110°W show the water column response to the TIW V_y oscillations (Fig. 5). Data gaps occurred when some of the in-situ sensors stopped reporting. Northward (southward) V_y oscillations lag by ~5 days the upwelling (downwelling) of the thermocline, which changes by ~40 m, or ~3.5 m day^{-1}. Concurrent to the thermocline rise (fall) is a ~9 dyn-cm increase (decrease) in the DH of the upper 500 m of the water column. The changes in the SST decrease (increase) ~3°C nearly simultaneous with the northward (southward) V_y oscillations. The mean Chl a at 0°, 110°W steadily decreases from ~0.4 ug l^{-1} in August, which is a remnant of the large-scale equatorial bloom (Ryan et al. 2006) and oscillates ± 0.06 µg l^{-1} in Oct 2005 close to its 3-yr and 10-yr means of 0.23 and 0.25 µg l^{-1}, respectively.

At 0°, 95°W, the TIW produce a series of 14 to 17 (~16) day oscillations in the SST, highlighted by the 16-day peak in the PSD for Jun 2005 – Mar 2006 (Fig. 4b). The SST changes are concurrent to the thermocline/DH oscillations (Fig. 6a). For example, from Sep 23 – Oct 1, 2005, the SST drops from ~24°C to 19°C. The thermocline (unfiltered daily values, not shown) upwells from 40 (25) to 15 (0) m, or ~3.1 m day^{-1}, lowering the DH by ~4 dyn-cm. During the TIW, the daily SST was often <20°C indicating that the thermocline had surfaced. However, the mean adjustment from the bandpass data shows the thermocline below the surface during these periods (Fig. 6a). Oscillations of the daily values of the 18°C isotherm at this location confirm upwelling of ~25 m over the same period (not shown).

Within the Galápagos Archipelago, the TIW produce a series of 14 to 17 (~15) day temperature oscillations of ~7°C at Santiago, >5°C at Genovesa, and >3°C at Wolf (Fig. 6b). These series are nearly concurrent to one another but lag Isabela and the SST at 95°W by ~2.5 days. The WL also oscillates and is quite pronounced at Santiago, reaching ~50 cm and lead changes in its temperature by ~3 days in Sep 2005. The magnitude of the WL change may be aliased by buoy motions induced by the TIW currents. The PSD of WL at Santiago during the Jun to Dec 2005 period has a peak at ~15.1 days (Fig. 4b). West of Isabela the oscillations are less, but interestingly, the lowpass temperature drops on Aug 28 from mean values of ~19°C to < 16°C until ~Oct 13 (Fig. 6a). The temperature oscillations
at Isabela are largely concurrent to those of the SST at 95°W. The WL oscillates <6 cm and leads the temperature by ~4 days in Sep 2005, but often the two signal are fairly concurrent. The PSD of WL at Isabela has a peak at ~13.5 days for Jun to Dec 2005 period, though it is less pronounced than Santiago (Fig. 4b).

Three temperature and salinity profiles (Figs. 7a, b) were made during the passage of the TIW in Sep 2005 by Argo drifters in the archipelago near Santiago and Wolf (Fig. 1). Two profiles captured water-column conditions slightly south (Sep 8) and north (Sep 11) of the EF near the warm peak of a TIW (Fig. 6b). The Sep 8 (Sep 11) profile indicates a deep layer below ~50 m (30 m) with a temperature <16°C (16°) and salinity of ~35.05 (34.95) that mixes into a ~20-m (10-m) thick surface layer with a temperature of 21°C (25°) and a salinity of 34.6 (33.8). Lowpass temperatures similar to the Sep 8 (Sep 11) profile are reported at Santiago (Wolf and Genovesa) in Fig. 6b. A later profile occurred on Sep 18 near Santiago and the very close to the Sep 8 profile. The Sep 18 profile was south of the EF like the Sep 8 profile, but it happened during the subsequent cold peak of the TIW. The Sep 18 profile indicates upwelling of the deeper layer to ~20 m and whose SST of ~17°C is also reported at Santiago (Fig. 6b). Upwelling rates are estimated by the vertical excursion of the pre (post) isotherm structure of the Sep 8 and 11 (Sep 18) profiles as determined by the 7-day drop in temperature at each YSI location between the warm (Sep 11) and the cold (Sep 18) peak of the TIW. The lowpass temperature change (mean isotherm excursion, upwelling rate) at a 5-m depth at Santiago is ~24° to 17°C (35 m, ~5.0 m day⁻¹), at Genovesa ~25° to 19°C (25 m, ~3.5 m day⁻¹), and at Wolf ~25.4° to 22.4°C (20 m, ~2.9 m day⁻¹). Upwelling rates near Isabela are not estimated since the temperature series (Fig. 6a) are much below the range reported in the Argo profiles.

Large increases of Chl a are observed near/within the archipelago coincident with the cold peaks of the TIW (Figs. 6b, 7c). Table 1 gives the mean of the SeaWiFS Chl a values within the Aug 28 to Oct 13, 2005 (1.5-month) period when three prominent TIW passed over the archipelago. Also listed are the 3-yr and 10-yr means to compare the TIW-related contribution to the long-term Chl a levels. Highest Chl a (~1.03 µg l⁻¹) occurs in two distinct peaks within the western zone, whose 1.5-month average of 0.71 µg l⁻¹ is a 31% (0%) increase over its 3-yr (10-yr) mean. In the central zone, Chl a increases in each of its
three peaks to ~0.72 µg l\(^{-1}\) in early Oct 2005, and its 1.5-month mean of 0.55 µg l\(^{-1}\) is a 41% (32%) increase over its 3-yr (10-yr) mean. In the northern zone, Chl \(a\) initially rises to ~0.5 µg l\(^{-1}\) at the start of Sep 2005 and declines; its 1.5-month mean of 0.35 µg l\(^{-1}\) is a 25% (24%) increase over its 3-yr (10-yr) mean. At 95°W, the increase of Chl \(a\) happens later and it oscillates less, rising to ~0.4 µg l\(^{-1}\) in early Oct 2005; its 1.5-month mean of 0.33 µg l\(^{-1}\) is a 28% (16%) increase over its 3-yr (10-yr) mean.

**Discussion**

The relatively cold ENSO conditions in the latter half of 2005 (Fig. 2) favor a pronounced TIW season (Contreras 2002), as was observed in the eastern equatorial Pacific starting in late Aug 2005. Images of the SST show large undulations of the EF that repeatedly cross over the Galápagos Archipelago (Fig 3a). The TIW propagate westward at ~48 km day\(^{-1}\) as quantified by a Hovmoller diagram of the SST, which may contain features of both the ~17 and ~33-day oscillations (Lyman *et al.* 2007) and may explain the range of computed periods (~19 to 29 days) and wavelengths (~900 to 1400 km). Of more interest to this study are the in-situ measurements of the TIW, such as the strong (0.75 m s\(^{-1}\)) meridional currents (Fig. 3b) and their prominent ~20.5 (~16.5) day oscillations at 0°, 110°W (140°) in Fig. 4a, which are very similar to past studies (Halpern *et al.* 1988; Qiao and Weisberg 1995; Lyman *et al.* 2007).

It is evident that TIW-induced flows result in a combination of vertical and meridional responses. At 0°, 110°W, the SST signal is largely regulated by and concurrent to the \(V_y\) oscillations, both of which lag ~5 days (~90°) the ~3.5 m day\(^{-1}\) upwelling (downwelling) of the thermocline (Fig. 5). Such a response is typical for an area exposed to large meridional oscillations of the EF, and is analogous to the 90° phase lag of SST to the sea surface height (SSH) observed in satellite data of TIW (Polito *et al.* 2001; Pezzi *et al.* 2006). The relationship describes a forced response from a geostrophic \(V_y\) anomaly that advects the SST gradient north and south. However, at 95°W, the SST and thermocline oscillate with no apparent lag between signals (Fig. 6a). Thus, the SST signal is not controlled by meridional oscillations of the SST gradient, but by vertical pumping that decreases (increases) the SST when the thermocline is shallower (deeper).
Within the Galápagos Archipelago, the remote SST images do not resolve the TIW motions, but the in-situ measurements do and indicate the presence of both a meridional and vertical response. The oscillations of the 5-m temperature signal at Isabela (Fig. 6a) are nearly concurrent to the SST 95°W, though are much colder (~15°C) and indicative of the EUC. The WL signal at Isabela occasionally leads its temperature signal, and sometimes is nearly concurrent. The phase changes between the signals might reflect the meridional motion of the EUC that cause a topographic shift in its upwelling intensity. Within the interior of the archipelago (Fig. 6b), the ~15-day swings in temperature are largest (~7°C) centrally near Santiago and are slightly diminished at Genovesa and Wolf. The WL oscillations at Santiago lead the temperature and unlike at 95°W, affirm the presence of the north/south oscillations of the SST gradient (EF) within the archipelago.

It was fortuitous that a number of Argo profiles occurred near the moored sensors at Wolf and Santiago during the passage of the TIW (Fig. 1). The profiles establish the water-column conditions before and after the passage of a TIW and help determine the extent of localized upwelling that occurred. The Argos profiled slightly north (Sep 11) and south (Sep 8) of the EF near a warm peak of a TIW and south of the EF (Sep 18) during a subsequent cold peak at a location close to the Sep 8 profile (Figs. 7a, b). Maximum upwelling speeds of ~5.0 m day\(^{-1}\) are estimated near Santiago during passage of the TIW. The upwelling estimates from isotherm excursions are only approximate since there is uncertainty of the contribution to the vertical profile by \(V_y\) advections. It is clear, though, from the isohaline structure of the Sep-18 profile that the deep layer with salinity (temperature) of ~35 (16°C) has upwelled from ~50 m to ~18 m, and that this water is attributable to the EUC (Sweet et al. 2007).

Large Chl \(a\) peaks are observed within the archipelago coincident with the cold-water peaks of the TIW that passed between August 28 and Oct 13, 2005 (Fig. 7c). The zones to illustrate the SeaWiFS data are somewhat arbitrary, but the spatial response of the Chl \(a\) further supports localized TIW upwelling (Table 1). For instance, in the northern archipelago there exists a stronger stratification, warmer temperatures (Wolf lowpass data >21°C), and weaker oscillations from the TIW (Fig. 6b). The smaller Chl \(a\) response in the northern zone is a result of a less vigorous upwelling supplying less iron needed for surface
production. Any southward meridional advection of Chl $a$ from the north during the TIW oscillations could not have caused the much greater Chl $a$ response in the central zone. Also, the Chl $a$ response in the western zone is similar to the central zone, but is ~0.3 µg l$^{-1}$ greater. This trend also occurs under normal flow conditions, stimulated by the topographic upwelling of iron by the EUC west of Isabela (Feldman 1986; Palacios 2002). Normal during high TIW activity are strong southeasterly trade winds and the presence of the westward SECN, which would inhibit an eastward advection of high Chl $a$ into the central archipelago from the west of Isabela.

The 10-yr (1998 – 2007) mean concentration of Chl $a$ increases from 110°W to the archipelago near the equator, as does the 1.5-month (Aug 28 – Oct 13, 2005) mean during the passage of the TIW. The long-term trend is attributed to the eastward rise of the thermocline/EUC that feeds the surface divergence in the cold tongue and its high Chl $a$ levels. The short-term trend during the TIW simply accentuates the likelihood and frequency of surface exposure to the EUC/thermocline towards the east under comparable upwelling conditions (>3 m d$^{-1}$). However, the disproportionate Chl $a$ response within the archipelago when compared to 95°W distinguishes the importance of upwelling that occurs specifically within the bounds of the archipelago platform. For instance, at 95°W the daily SST and sea surface salinity (SSS, not shown) on Sep 8 and 18 are 21°C and 34.6 and 18.7°C and 35.0, respectively. These values are nearly identical to the Argo profiles (Figs. 7a, b) and lowpass temperatures at Santiago for the same days (Fig. 6b). The argument could be made that surface waters at 95°W and Santiago are largely of the same water mass, whose temperature (<20°C) and salinity (~35) on Sep 18 are characteristic of the EUC surface (~20°C) at 110°W. Yet the Chl $a$ response is remarkably different, and substantially higher along the western and within the central zones of the archipelago (Fig. 7c). It is supposed that the vertical pumping of the TIW upwelled waters of the EUC to the surface in both locations, but the iron enhancement from the archipelago spurred a greater Chl $a$ response.
Conclusions

Critical to the ecology of the Galápagos Archipelago is the upwelling of the EUC west of Isabela (Steger et al. 1998) and along the other interior islands that promotes areas of consistently high Chl $a$ (Feldman 1986; Palacios 2002; Schaeffer et al. Accepted) and regions of unique biodiversity (Edgar et al. 2004). A range of physical mechanisms affect the thermocline/EUC depth, upwelling of nutrients, and the surface chlorophyll (Chl $a$) in the eastern equatorial Pacific. Large-scale, inter-annual effects of the ENSO cycle can alter equatorial upwelling processes (Chavez et al. 1999; Ryan et al. 2006) and the EUC and SECN flow patterns affecting the Chl $a$ distribution about the archipelago (Feldman et al. 1984). An annual increase in the Chl $a$ around the archipelago has been documented by monthly climotologies during boreal fall (Palacios 2004) attributed to strengthened wind-driven currents and equatorial upwelling (Yu and McPhaden 1999; Johnson et al. 2002). The energetic conditions diagnosed above for the boreal fall also spawn TIW, whose intra-annual presence increase regional upwelling and contribute to elevated surface Chl $a$ near the archipelago. It is very likely that the monthly (Feldman 1986) and annual (Palacios 2004) signal of the Chl $a$ pattern in the archipelago contain the pulsing response inherent to the TIW.

This study focuses on a series TIW along the equator within the eastern equatorial Pacific in 2005 that directly impacted the Galápagos. To our knowledge, these are the first documented observations of the passage of TIW and their effects within the archipelago, and our findings indicate that the contribution to the Chl $a$ is substantial. The heightened Chl $a$ values reflect not only greater mean concentrations, but also a widespread distribution throughout the archipelago (http://oceancolor.gsfc.nasa.gov). The TIW may be fundamental to the ecology of the Galápagos, with its rhythmic pumping and pulses of high Chl that wash across the archipelago from a primary production that is more spatially equalized than might otherwise occur.

Acknowledgements

This project was supported by NASA’s Biodiversity and Ecological Forecasting grant NNG04GL98G, Counterpart US-AID No. 518-A-00-03-00152-00 to the Charles
Darwin Research Station and UK Darwin Initiative Project No. 14-048. We would like to thank the Galápagos National Park (GNP) Marine Resources Head Mario Piu, the GNP Science Coordinator Eduardo Espinoza, the GNP Science Consultant Godfrey Merlen, the captain and crew of the *M/N Sierra Negra*, and the scientific dive team from CDRS, Marianna Vera, Marco Tosca, Julio Delgado, Natalia Tirado, Roberto Pepolas, and Diego Ruiz.

Tropical Atmosphere Ocean (TAO) data were obtained from the TAO Project NOAA/PMEL (http://www.pmel.noaa.gov/tao). AMSR-E images are produced by Remote Sensing Systems and sponsored by the NASA Earth Science REASoN DISCOVER Project and the AMSR-E Science Team; data are available at www.remss.com. The Reynolds/NCEP SST anomalies and SeaWinds for Quickscat ocean wind data were obtained through the online PO.DAAC Ocean ESIP Tool (POET) at the Physical Oceanography Distributed Active Archive Center (PO.DAAC), NASA Jet Propulsion Laboratory (http://podaac.jpl.nasa.gov/). The ocean color (Chl *a*) data were acquired using the GES-DISC Interactive Online Visualization and Analysis Infrastructure (Giovanni) as part of the NASA's Goddard Earth Sciences (GES) Data and Information Services Center (DISC). The ENSO SST anomalies were obtained from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (http://www.cpc.noaa.gov). The Argo data were collected and made freely available by the International Argo Project (http://www.argo.ucsd.edu).

**References**


Table 1: SeaWiFS mean Chl $a$ concentrations. Shown for the Aug 18 – Oct 13, 2005 TIW period, 3-yr (2004 – 2006) and 10-yr (1998 – 2007) periods at 95°W (0.5°N-0.5°S, 95.5°-94.5°W) and the western (0.5°N-1°S, 92.7°-91.2°W), central (0.5°N-1°S, 91.2°-89.7°W), and northern (2°-0.5°N, 91.5°-89.5°W) zones covering the Galápagos Archipelago. Also the percent increase during the TIW over the 3- and 10-yr means in these zones.

<table>
<thead>
<tr>
<th>Zone</th>
<th>95W</th>
<th>W. Zone</th>
<th>C. Zone</th>
<th>N. Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chl a [ug l$^{-1}$] TIW period</td>
<td>0.33</td>
<td>0.71</td>
<td>0.55</td>
<td>0.35</td>
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<td>Chl a [ug l$^{-1}$] 3-yr (10-yr)</td>
<td>0.26 (0.29)</td>
<td>0.54 (0.71)</td>
<td>0.39 (0.42)</td>
<td>0.28 (0.29)</td>
</tr>
<tr>
<td>TIW % inc 3-yr (10-yr)</td>
<td>28 (16)</td>
<td>31 (0)</td>
<td>41 (32)</td>
<td>25 (24)</td>
</tr>
</tbody>
</table>
Figure 1: Bathymetry [m] of the Galápagos Archipelago, time series locations, and Argo profile locations
Figure 2: 2002 – 2006 monthly mean (92-88°W, 2°N-2°S) of meridional wind (QSCAT) and SST (NCEP) and ENSO (Niño region 3.4) SST anomaly
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110W Vy, Thermocline Depth, SST and Chl a

Figure 5: 0°, 110°W time series of thermocline depth (TZ), SST, and 30-m V_y and mean Chl a (SeaWiFS) within a 1° grid.
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Figure 7: Argo profiles of (a) temp and (b) salinity and (c) mean Chl a (SeaWiFS) for the northern, central and western archipelago zones and 0°, 95°W
Chapter 3

El Niño Southern Oscillation Related Water Mass Variability in the Galápagos Archipelago

Abstract

Hydrographic surveys and moored time series from 2006 – 2007 show the interannual effects of the El Niño Southern Oscillation (ENSO) upon the surface-layer properties within the Galápagos Archipelago. The ENSO cycle is indexed by the sea surface temperature (SST) anomalies occurring within the Niño Region 3.4, and the water-column response is quantified through comparison to the results of Sweet et al. (2007) who describe the upper ocean properties during similar times on the annual cycle but very different on the ENSO cycle. Downwelling Kelvin waves promoting the warm 2006/07 El Niño and upwelling Kelvin waves promoting the cool 2007/08 La Niña cause significant variations within the archipelago. The survey-mean thermocline depth (20°C isotherm) deepens between 10 and 25 m, resulting in >2°C rise of the SST during the periods with warmest ENSO indexes. The sea surface salinity and water-mass classification remain relatively unchanged. Mean chlorophyll a (Chl a) concentrations declined by >0.2 mg m⁻³, or nearly a >15% drop in surface concentrations computed for the 1998 – 2007 period during the El Niño episodes.

Introduction

The El Niño-Southern Oscillation (ENSO) is a coupled oceanic-atmospheric phenomenon that has an inter-annual (3-7 yr) period. The oceanic component of the ENSO signal superimposes upon the annual signal of the eastern equatorial Pacific (Yu and McPhaden 1998; Johnson et al. 2002). The effects of ENSO appear in sea surface temperatures (SST) and sea level pressures (SLP), and they occur across the Pacific basin (Rasmusson and Wallace 1983). During the warm El Niño phase, the eastern tropical
Pacific is characterized by equatorial positive SST and negative SLP anomalies, while the western tropical Pacific is marked by off-equatorial negative SST and positive SLP anomalies. The opposite conditions occur during the cool La Niña phase (Wang and Fiedler 2006). Fluctuating SLP and wind-stress anomalies can trigger oceanic waves (i.e., Kelvin and Rossby) along the equator, which transfer energy between the western, central, and eastern Pacific basins (Wang 2001). Dependent upon the wave nature, they can cause significant oscillations of the thermocline (20°C isotherm) as they propagate. The resultant thermocline depth anomalies modify the over-lying SST, affecting the regional values that index the ENSO cycle.

Prior studies have documented ENSO-related changes of the thermocline depth, zonal current structure, and the surface water-mass composition within the eastern equatorial Pacific. During the warm El Niño phase, the south equatorial current (SEC) and the Equatorial Undercurrent (EUC) diminish in strength during their respective annual cycle (Johnson et al. 2002). Also, the thermocline in the eastern Pacific sinks tens of meters as does the EUC core (Johnson et al. 2002). In addition, a decreased Ekman divergence and evaporation (Xie 1994) and eastward migration of the warm SST pool contribute to a reduced upwelling and warming of the SST by >1°C (Fieldler and Talley 2006). The opposite response generally occurs during the cool La Niña phase. The sea surface salinity (SSS) remains relatively constant during the ENSO phases, with only slight increases attributed to a slight change within the SEC (Fieldler and Talley 2006). During El Niño (La Niña), the SEC becomes ~0.2 fresher (saltier) as the upwelling within the equatorial cold tongue and EUC is suppressed (heightened). Locally, the SSS may adjust to rainfall patterns that result from the meridional migration of the Inter-tropical Convergence Zone (ITCZ).

The SST oscillations associated with ENSO can be extreme within the SE trade wind-driven Cold Tongue (CT) region and the Galápagos Archipelago (Feldman 1984). The CT extends northwestward from Peru to the middle of the Pacific Ocean along the equator. The equatorial front (EF) is northern divide of the CT, often bisects the archipelago, and distinguishes two distinct water masses (Wyrtki 1966). Tropical Surface Waters (TSW) form north of the EF and are warm (>24°C), fresh (S<34), and nutrient-poor. Equatorial Surface Waters (ESW) form within the CT region and are cold (<24°C), salty (S>34), and
nutrient-rich since they derive from upwelling processes. As such, the migration of the EF strongly regulates the spatial distribution of surface chlorophyll concentrations around the Galápagos Archipelago (Palacios 2004). ENSO-related SST changes indicate variability of the thermocline depth and upwelling intensity, both which can have extreme ecological consequences in the archipelago (Fielder 2002). The extent of the response is dependent upon the magnitude and duration of the deepening of the thermocline/nutricline. Severe cases can result in a decreased primary production that ultimately affects the survival, reproduction, and distribution of higher trophic level organisms (Barber and Chavez 1983, 1986; Valle et al. 1987).

Surprisingly, there have been and currently are few in-situ observations to document the ENSO-related water mass variability within the Galápagos Archipelago. Such an assessment will assist ecological modeling efforts (Okey et al. 2004; Vargas et al. 2007) to predict the marine-system ENSO variability and help the managers better manage the resources within the recently established Galápagos Marine Reserve (GMR). The objective of this study is to ascertain the water-mass variability that results from ENSO-related processes and affects the upper ocean (>100 m) within the Galápagos Archipelago. Hydrographic data sets collected November 2006 (Nov06) and May 2007 (May07) and moored temperature time series (Apr 2006 – Jun 2007) are utilized. Specifically, the Nov06 and May07 surveys are compared to similar surveys performed Nov05 and Jun06 (Sweet et al. 2007), respectively, whose properties describe the annual signal in the archipelago under a very different cycle of ENSO. Data is presented that shows the development of the warm-water anomalies of the Nov06 survey associated with the 2006/07 El Niño. The situation reverses by the time of the May07 survey, which was anomalously cool prior to the La Niña of 2007/08. Changes associated with the different ENSO phases are emphasized in the SST, SSS, thermocline depth, the chlorophyll a (Chl a), and the surface water mass types. These results are in support of a concurrent biological investigation studying the ENSO-related variability of plankton distributions within the archipelago.
Data

The study was part of the *Connectivity and Upwelling Dynamics in the Galápagos Marine Reserve* project, a cooperative effort by the University of North Carolina Wilmington (UNCW), North Carolina State University (NCSU), the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC), the Charles Darwin Research Station (CDRS), and the Galápagos National Park Service (GNP). Two surveys were conducted November 14-23, 2006 (Nov06) and May 17-27, 2007 (May07) on the Galápagos National Park Service’s *M/N Sierra Negra*. Vertical profiles measurements of salinity (S), temperature (T) with a Seabird Electronics SBE 19+ (CTD) and fluorescence with a WetLab BB2F fluorometer were made to ~80 m at each station (Fig. 1) and averaged into 2-m depth bins. Temperature-salinity (TS) diagrams are shown in the manuscript to quantify water-mass types similar to Wyrtki (1966), but solely based upon SSS and not the SST. If the SSS is >34, the water mass will be considered ESW; if the SSS is <34, it will be considered TSW.

Hourly temperature measurements were collected by Yellow Springs Incorporated (YSI) 6600EDS sondes. The sondes were fastened within the top float of rigid, taut-wire, subsurface moorings deployed in 60-m deep waters near three islands within the archipelago (triangles; Fig. 1). The YSI temperature sensors have a resolution of 0.01°C and accuracy of ±0.15°C. The daily temperature data were lowpass filtered with a cosine-tapered filter (half power period = 38 days) for the period of Apr 2006 – Jun 2007. Additional daily, 5-day, and monthly mean profile and time-series data of wind, ocean current, thermocline depth, and temperature profiles were obtained from the Tropical Atmosphere Ocean (TAO) array along the equator (147°E to 95°W). These data were also lowpass filtered with the same filter as the YSI data. The zonal current measurements at 0°, 110°W help establish the spatial relationship between the EUC and thermocline. Unfortunately, the preferable measurements with an acoustic Doppler current profiler (ADCP) were not available during the period of the May07 survey. Therefore, fixed-depth single points currents were utilized, whose values were fit with a third-order polynomial to interpolate the values of the zonal speeds at the EUC core and thermocline.
Mean 8-day SST from the MODIS Aqua sensor (4-km resolution) for each survey period is shown for 5°N-5°S, 100°-80°W. Mean monthly Reynolds/NCEP (NCEP) SST (1° spatial resolution) and SST anomaly based on a 25-year mean and a monthly mean of daily winds (0.25° spatial resolution) from NASA’s microwave scatterometer (QSCAT) were averaged for the area 2°N - 2°S, 92° - 88°W. The ENSO cycle is indexed by SST anomalies within the Niño region 3.4 (5°N-5°S, 170°-120°W). Sea surface height (SSH) anomalies are a merged data from the Jason-1, Envisat, and GFO satellites, produced by Ssalto/Duacs and distributed by Aviso (http://las.aviso.oceanobs.com). Time versus longitude plots (Hovmoller diagrams) of the zonal wind, thermocline, and SSH anomalies are shown to determine wave properties along the equator.

**Results**

The annual cycle of the monthly mean winds and SST (Fig. 2a) is characterized by minimum strength of the SE trade (meridional component) winds and maximum SST during the wet season (Dec-May). The opposite occurs during the Garúa season (June-Nov). The Nov06 survey occurred during the transition from the Garúa to the wet season of the annual cycle, while the May07 survey occurred during the wet-to-Garúa transition. During the Garúa season, the ITCZ is well north of the equator, the SE trades strengthen, and the sea surface temperature (SST) decreases. Garúa, the Spanish word for mist, forms when warm air masses move over a much cooler SST, causing moisture to condense out of the atmosphere. During the wet season locally heavy rainfalls are possible as the ITCZ nears the equator, and the SST warms as the SE trades subside reducing the Ekman divergence and evaporative cooling (Xie 1994). The phase and magnitude of the respective minimum and maximums in the mean SST and winds are modulated by ENSO-phase changes. Anomalies of the SST within the archipelago and for ENSO in the Niño 3.4 region are shown in Fig. 2b.

*Background Conditions: The 2006/07 El Niño and the 2007 La Niña*

The El Niño of 2006/07 was statistically recognized Aug 2006 within the Niño 3.4 region. Two downwelling Kelvin waves, described here and referred to as DK1 and DK2,
cross the equatorial Pacific in the latter half of 2006. These waves establish and intensify the El Niño event (Harkert et al. 2007). Satellite observations of anomalously high SSH (>0.2 m) in the Hovmoller diagrams (Fig. 3) show that the waves initiate close to ~160°E during the months of Aug and Oct 2006, respectively. These periods coincide with strong westerly wind anomalies at the same location (Fig. 4a). The waves traverse the basin (160°E to 80°W) in ~2.5 months, which equates to a speed of ~2.4 m s⁻¹, which is similar to past observations (Kessler et al. 1995). The eastward-propagating surface convergence along the equator results in a simultaneous depression of the thermocline as the waves propagate (Fig. 4b). The Kelvin waves have a progressively greater amplitude and influence upon the water column to the east. The thermocline is depressed ~50 m by late Nov 2006 near 110°W (Fig. 4b). Figure 5a shows the actual arrival time at each TAO location, with the DK1 cresting at 95°W in early Oct 2006 and the DK2 in Jan 2007. The YSI sensors in the archipelago capture the subsequent transit of the Kelvin waves through the archipelago. The DK1 crests in ~late Oct 2006 at Isabela and DK2 in early Feb 2007 (Fig. 5b). At the time of the Nov06 survey, the anomalies of the thermocline are >10 m and of the water-column temperature are ~1°C, both of which are greater in the central equatorial Pacific (Figs. 6a, b).

In late Dec 2006, the westerly wind anomalies at ~160°E diminish and become easterly (Fig. 4a). The easterly forcing causes a divergence along the equator and the thermocline depth anomaly indicates a shoaling at nearly the same time (Fig. 4b). The SSH (Fig. 3) shows the disturbance as a negative (~0.10 m) anomaly at ~170°E. The negative SSH anomaly propagates eastward across the basin in ~2.5 months, arriving the archipelago in ~Feb 2007. The zonal current (Vₓ) derived from the SSH (not shown) also has a negative anomaly (~0.60 m s⁻¹), which indicates that the wave is an upwelling Kelvin wave (Delcroix et al. 1994). McPhaden (2007) observed that the easterly wind anomaly in Dec 2006 is related to the Madden-Julian Oscillation (MJO) and triggers the upwelling Kelvin wave (referred to UK1). The El Niño of 2006/07 officially terminates in Feb 2007. The TAO data capture the progressive cooling as UK1 passes (Fig. 5a). At 95°W, the temperature starts dropping in late Jan 2007, falling by ~7°C to 18°C by Mar 2006. The temperature
drops >3°C within the archipelago, first at Wolf in early Feb 2007 and then in mid Feb 2007 at Santiago (Fig. 5b). By the time of the May07 survey, a thermocline anomaly of -10 m and cooler than normal (-1°C) temperatures (Figs. 6a, b) exist. The La Niña was not officially classified until Aug 2007 by the ENSO Niño 3.4 index.

**November 14-23, 2006 Survey**

The mean SST is ~25°C and the SE trades have a ~4 m s⁻¹ mean within the archipelago during the survey; both are transitioning in response to the shift from the Garúa to the wet season (Fig. 2a). The mean SST is ~1.3°C above its long-term mean (Fig. 2b), which is also reflected by an ENSO anomaly of ~1.1°C (Fig. 2b). The daily mean depth and speed of the EUC core at 110°W is 100 m and 1.4 m s⁻¹ during the Nov06 survey (Table 1). Also at 110°W, the depth of the thermocline and the speed of the EUC there is 80 m and 1.11 m s⁻¹. The depth and temperature of the upper surface of the EUC during the Nov06 survey is 25 m and 23.5°C at 110°W. At 95°W, the depth of the thermocline is 33 m, where it is throughout the archipelago as computed from CTD profiles within ±0.5° of the equator between 89° and 92°W.

Surface temperatures >24°C cover much of the eastern equatorial Pacific (Fig. 7a), with a patch of cooler waters (<23°C) stretching west from Isabela (Fig. 7b). At a 20-m depth, the temperatures cool to ~19°C west of Isabela (Fig. 7c), where the thermocline is ~20 m below the surface (Fig. 7d). A transect at 91.8°W (Fig. 1 and Fig. 7e) shows that the thermal stratification between the 18° and 24°C isotherms is ~0.2 °C m⁻¹ (~0.12 °C m⁻¹) north (south) of the equator where the isotherms are more convergent (divergent), respectively. A transect at 0.3°N (Fig 1. and Fig. 7f) highlights the very strong vertical thermal gradient (~0.4 °C m⁻¹) between the 18° and 24°C isotherms in the eastern archipelago. The thermocline remains close to a 40-m depth along this transect.

The SSS within the archipelago increases from the northeast (33.7) to the southwest, reaching highest concentrations (~34.6) to the west of Isabela (Figs. 8a, b). The salinity at 20 m has a similar pattern, with concentrations of 35.2 to the west of Isabela. Linear regression between the salinity and temperature at the surface and 20 m within the
archipelago (not shown) has r² values of 0.75 and 0.95, respectively. The vertical sections at 91.8°W and 0.3°N (Figs. 8c, d) show lifting of the ~34.9 isohaline west of Isabela, and fresher SSS (<33.7) to the north and in the east, where strong salinity stratification is observed. TSW cover much of the archipelago, with SST >24°C and SSS <34 (Fig. 8e), while pockets of ESW are found primarily west of Isabela. The TS diagram indicate a common water mass at depths >50 m, converging at a salinity >35 and a temperature <18°C (Fig. 8f).

The Chl a concentration at the surface is relatively low and constant, ranging from 0.3 mg m⁻³ in the north to highest values of 0.9 mg m⁻³ south of Santa Cruz (Fig 1 and Fig. 9a). The mean surface Chl a computed from all sampled stations is 0.6 ±0.3 mg m⁻³ for the Nov06 survey. Vertical profiles of Chl a at 91.8°W and 0.3°N (Figs. 9b, c) reveal a slightly different scenario. The Chl a has a subsurface peak located near the thermocline (shown in Figs. 7e, f) that reaches >1.5 mg m⁻³ west of Isabela, but is >0.9 mg m⁻³ throughout much of the archipelago.

**May 17-27, 2007 Survey**

The mean SST (Fig. 2a) is quite low (<22°C), and the SE trades are mild (~3 m s⁻¹) but increasing in strength. The SST is significantly below (-2.3°C) its 25-yr climatological mean (Fig. 2b). The daily mean depth and speed of the EUC core at 110°W is 70 m and 1.20 m s⁻¹ during the May07 survey (Table 1). The depth of the thermocline and the speed of the EUC there is 50 m and 1.03 m s⁻¹, respectively. The depth and temperature of the upper surface of the EUC during the May07 survey is 15 m and 23.8°C. At 95°W, the depth of the thermocline is 30 m, and it is 17 m within the archipelago as computed from CTD profiles within ±0.5° of the equator between 89° and 92°W.

The archipelago has a ~21°C SST and lies within the CT, which stretches from the coastal upwelling zone off the coast of South America (Fig. 10a). Within the archipelago, the SST (Fig. 10b) is coolest <18°C west of Isabela. The temperature at 20-m resembles the pattern of the SST, only a couple degrees cooler (Fig. 10c). The thermocline is <20 m from the surface over the southern half of the archipelago and surfaces west of Isabela (Fig. 10d).
The transect at 91.8°W (Fig. 10e) shows a weak thermal stratification (0.05 °C m⁻¹) between the 16° and 20° isotherms, which are divergent south of ~0.8°N latitude. North of this latitude, a much stronger thermal stratification exists (~0.27 °C m⁻¹). A transect at 0.3°N (Fig. 9f) shows a strong downward tilt of the 16° and 18°C isotherms east across the archipelago.

The salinity at the surface and 20 m are nearly identical throughout the archipelago (Figs. 11a, b) with salinity >34.9. Highest salinity >35.1 is found west of Isabela. The linear regression of salinity and temperature at the surface and 20 m have an r² value of 0.18 and 0.02, respectively (not shown). The vertical profiles at 91.8°W and 0.3°N show that the salinity is well-mixed vertically, highest (>35) south of the equator (Fig. 11c) and in the eastern archipelago (Fig. 11d). During this survey, the water mass is entirely ESW (Fig. 11e) and its ~35 salinity is vertically homogeneous throughout the 100-m depth profiles (Fig. 11f).

The surface Chl a concentration is relatively high, consistently above 1.0 mg m⁻³ throughout the archipelago and peaking at >10 mg m⁻³ west of Isabela (Fig. 12a). The mean surface Chl a computed from all sampled stations is 1.4 ±1.4 mg m⁻³ for the May07 survey. High subsurface concentrations (>1 mg m⁻³) occur throughout the water column in the western archipelago (Figs. 12b) and it is extremely high near Isabela. Interesting, the Chl a has a strong eastward zonal gradient (Fig. 12c) similar to the isotherm distribution (Fig. 10f).

Survey Comparison

Table 2 summarizes how surface properties respond to anomalies of the archipelago’s SST and that of ENSO in the Niño 3.4 region. Parameters shown are the archipelago’s mean SST, SSS, depth of the thermocline, and Chl a for the Nov06 and May07 surveys and for the Nov05 and Jun06 surveys (Sweet et al. 2007). The four surveys allow a comparison of the ENSO-related variability (i.e., Nov05 vs. Nov06 and Jun06 vs. May07) since they are closely timed in terms of the annual cycle. It can be seen that the SST anomalies for ENSO region 3.4 and in the archipelago are quite different. The ENSO conditions during the Nov05 survey are anomalously cool at -0.8°C (-0.5° in archipelago) and they are anomalously warm at 1.2°C (1.1° in archipelago) during the Nov06 survey,
which occurred at the height of the 2006/07 El Niño. The Jun06 survey had a 0.3°C ENSO anomaly and occurred immediately prior to the 2006/07 El Niño. On the contrary, the May07 survey had a -0.1°C ENSO anomaly and occurred at the start of a dramatic cooling that eventually develops into the 2007/08 La Niña. The extent of the ENSO-related variability is better diagnosed by the SST anomalies within the archipelago, which were 1.2°C during the Jun06 survey and -2.3°C during the May07 survey.

**Discussion**

Two significant downwelling Kelvin waves, DK1 and DK2, initiate near 160°E in Aug and Oct 2006 (Fig. 3) in response to strong westerly wind anomalies (Fig. 4a). The waves establish and intensify the 2006/07 El Niño by re-locating the warm SST pool eastward across the Pacific. The wave action depresses the thermocline, whose anomaly becomes eastward intensified (Fig. 4b). The downwelling raises the SST within the archipelago as the waves cross and head towards the South American continent. During the Nov06 survey, the lingering effects from DK1 and approaching DK2 create a deeper than normal thermocline depth (>10 m) and warmer than normal SST (>1°C) within the Galápagos Archipelago (Figs. 6a, b). The anomalies are much greater (thermocline >40 m and SST >4°C) during Nov 2006 between 140° and 110°W, where the conditions are dominated by the DK2 presence.

Surprisingly, the EUC is strong (1.37 m s⁻¹) at 110°W and extends to within 25 m of the surface during the Nov06 survey (Table 1). At the 80-m deep thermocline, the EUC speed is ~80 percent of the core speed. These results differ substantially from the Nov05 survey (Sweet *et al.* 2007), when the EUC was much weaker at its core (~0.87 m s⁻¹), and it was only ~8% of its core speed at the depth of the 45-m deep thermocline (0.07 m s⁻¹). As explained by Johnson *et al.* (2002), the EUC transport and speed is least in the latter half of the year. During these times, the SE trades, the SEC, and the Ekman transport are greater, which results in a shallower thermocline and a reduced EUC volume due to shearing losses with the SEC. Results during the Nov05 survey follow this trend. Close inspection of the data (www.pmel.noaa.gov/tao) at 110°W in 2006 reveals that the thermocline depth fluctuates considerably (>80 m) as the Kelvin waves pass. As the thermocline depth
deepens, the EUC becomes stronger and higher in the water column. Simultaneously, the deepening thermocline acts to increase the dynamic height along the equator and lower the positive meridional pressure gradient that is responsible for the geostrophic SEC (Kessler 2006). The Nov06 survey occurred during a period of increasingly deep thermocline depths at 110°W. The daily zonal flows of the EUC used to compute the survey mean are affected by the presence of DK2 and are an anomaly when compared to the longer period.

Temperatures at Isabela (Fig. 5b) show that the Nov06 survey occurs subsequent the crest of DK1. There are strong thermal and salinity gradients throughout the archipelago (Figs. 7e, f and Figs. 8c, d). The 34.9 isohaline is elevated and the thermocline is divergent south of ~0.5°N west of Isabela, which indicates upwelling within the EUC above its core (Kessler 2006). The result of the upwelling EUC is to lower the water column temperatures west of Isabela in an otherwise very warm surface state (>25°C) established by the El Niño (Figs. 7a-c). Accordingly, the highest SSS >35 located west of Isabela (Fig. 8b) establishes the limited presence of ESW masses in an otherwise TSW-dominated setting (Fig. 8e). The relatively fresh surface waters within the archipelago during the survey originate within the North Equatorial Countercurrent (NECC), which is strong and extends nearly to the South American coast (http://las.aviso.oceanobs.com), and largely supplied the SEC (Kessler 2006). Mean concentrations of Chl a are relatively low, highest subsurface near the thermocline and the presence of the EUC (Figs. 9b, c).

In late Dec 2006, the westerly wind anomalies at ~160°E become easterly (Fig. 4a), which contribute to the demise of the El Niño (McPhaden 2007). An upwelling Kelvin wave (UK1) spawns from the area and propagates eastward across the Pacific (Fig. 3). The effects of DK1 set into motion a ~5-month shoaling of the thermocline (Fig. 4b), which is maintained by easterly wind anomalies east of the dateline (Fig. 4a). The change in thermocline depth is amplified in the east (i.e., ~40 m at 110°W) where the vertical thermal gradient becomes increasingly stronger. The upwelling wave, UK1, enters the archipelago ~Feb 2007 (Figs. 3 and 4b). Though the temperature response is not as sharp or as intense as the 6°C drop at 95°W in Feb 2007 (Figs. 4a, b), the temperatures within the archipelago continue to cool after the passage of UK1. By the time of the May07 survey, the mean SST
is much colder than normal (-2.3°C) throughout the archipelago (Figs. 2a, b) and is nearly a 5-year low even though not classified yet as a La Niña.

Data for the EUC at 110°W during the May07 survey are similar to the Jun06 survey. Both follow the trends normal for the annual signal. The strength and depth (1.20 m s⁻¹, 70 m) of the EUC core during the May07 survey (Table 1) are similar to the Jun06 survey (1.46 m s⁻¹, 46 m) as shown in Sweet et al. (2007). Similar too is the speed of the EUC, which is ~85% (95%) the core strength at the thermocline during the May07 (Jun06) survey. The EUC extends nearly to the surface during both surveys, and did so for ~3 months prior both surveys. The difference between the surveys is that the thermocline depth is shallower during the May07 survey, >10 m shallower at 110° and 95°W, and >25 m shallower throughout the archipelago.

During the May07 survey of the archipelago, the divergence of the 16° and 20° isotherms (Fig. 10e) and the high salinity (>35) co-located within this region (Fig. 11c) illustrates the likely position of the EUC. Further evidence, although somewhat anecdotal, are from shipboard observations of in-situ profiler deployments that verify a strong and near-surface EUC throughout much of the archipelago. The thermocline (and thus EUC) has upwelled and is near the surface throughout most of the archipelago (Fig. 10d), but less so in the northern archipelago (Fig. 10e). As such, the SST within the archipelago is cold (Fig. 10b) from the EUC entering from the west and from upwelled CT waters entering in the east (Fig. 10a). Further evidence of the EUC is the vertically high salinity (>35) throughout the archipelago (Figs. 11a, c, d) that results in a water mass entirely of ESW (Fig. 11e). This survey has the highest concentration (1.4 mg m⁻³) of surface Chl a (Table 2), with extreme (>10 mg m⁻³) values west of Isabela (Fig. 12a). The high surface concentrations of Chl a reflect a strong, near-surface, upwelling EUC presence throughout the archipelago, which supplies additional iron necessary for growth (Gordon et al. 1998).

Table 2 summarizes the changes in the archipelago’s mean SST, SSS, Chl a, and thermocline depth affected by changes promoted by changing ENSO conditions. The SSS changes little in the archipelago (~0.2) over the ENSO cycle (i.e., Nov05 vs. Nov06 and Jun06 vs. May07). The SSS is expectedly higher during the May07 survey, but it is also higher during the Nov06 survey, which is different than the 0.2 decrease normal for the
eastern equatorial Pacific during El Niño events. The SST, however, undergoes a substantial adjustment during the warm phases of ENSO. The SST is >2°C during the Jun06 and Nov06 surveys, resulting from the >10-m deepening of the thermocline. Also significant is that the mean surface Chl \(a\) concentration are much less when the ENSO SST anomaly is warmer and the thermocline is deeper. The Chl \(a\) concentrations are \(\sim 0.2\) and \(\sim 0.4\) mg m\(^{-3}\) less during the warm Jun06 and Nov06 surveys, respectively. However, the location-specific correlation between Chl \(a\) and thermocline depth (Fig. 12) is statistically insignificant (\(r^2 \sim 0.2\)) and similar to the results of Sweet \textit{et al.} (2007). The relationship (Fig. 13) shows that higher Chl \(a\) concentrations tend to be co-located over shallower thermoclines.

We note that our sampling strategy lacks the sufficient spatial and temporal coverage to accurately determine the synoptic variability of the Chl \(a\) concentration across the archipelago from ENSO-phase changes. However, our results are verified by similar trends within a spatial average (2°N-2°S, 92°-88°W) of the SeaWiFS data. Comparison to the 1998 – 2007 mean Chl \(a\) over the 2-month periods of Nov/Dec and May/Jun show that a >15% decrease (increase) from the mean occurred during the warm (cool) ENSO phases of the Jun06 and Nov06 (Nov05 and May07) surveys.

**Conclusions**

Our sampling program captures and documents the effects of the 2006/07 El Niño and those directly prior the 2007/08 La Niña within the Galápagos Archipelago. The results show that the archipelago is particularly sensitive to and affected by the series of Kelvin waves spawned during the 2006/07 ENSO cycle. The downwelling Kelvin waves that promote El Niño conditions and upwelling ones that promote La Niña conditions can create prolonged conditions within the archipelago that are quite different from those diagnosed from the annual signal (Sweet \textit{et al.} 2007). The depth of the thermocline can differ between 10 and 25 m from ENSO conditioning, resulting in a >2°C change in the sea surface temperatures. While the sea surface salinity and water-mass classification remain relatively unchanged, the chlorophyll \(a\) can dramatically fluctuate by >0.2 mg m\(^{-3}\) in surface concentrations (Table 2), or nearly a >15% mean change from ENSO-related processes.
Our results here show that the trends of the annual cycle are still present (Sweet et al. 2007), but that its timing and intensity are modified by ENSO-related Kelvin waves and changes in the zonal currents strength and influences. Observations from the TAO array (140°, 125°, 110°, and 95°W) during the 2005 – 2007 period show that the ENSO-related anomalies increase progressively eastward. Our moored time series extend the equatorial measurements of the TAO array eastward into the Galápagos Marine Reserve (GMR), a dynamic epicenter to regional forcing that is of global importance. To date, the moorings have captured significant variability in thermocline pumping from tropical instability waves (TIW; Sweet et al. In Review) and ENSO-related Kelvin wave activity. The associated changes in upwelling intensity and its distribution is of importance to the GMR managers since the process supplies nutrients to the phytoplankton, which feeds the archipelago’s biodiversity. It is recommended that the mooring array be maintained and expanded to continue observing the mechanisms causing widespread variability within the Galápagos Archipelago.

Acknowledgements

This project was supported by NASA’s Biodiversity and Ecological Forecasting grant NNG04GL98G, Counterpart US-AID No. 518-A-00-03-00152-00 to the Charles Darwin Research Station and UK Darwin Initiative Project No. 14-048. We would like to thank the Galápagos National Park (GNP) Marine Resources Head Mario Piu, the GNP Science Coordinator Eduardo Espinoza, the GNP Science Consultant Godfrey Merlen, the captain and crew of the M/N Sierra Negra, and the scientific dive team from CDRS, Marianna Vera, Marco Tosca, Julio Delgado, Natalia Tirado, Roberto Pepolas, and Diego Ruiz.

The author(s) wish to acknowledge use of the altimeter data, made available from the Duacs (Developing Use of Altimetry for Climate Studies) program, which is affiliated with a segment of the French Space Agency (Cnes) segment called Ssalto (Segment Sol ALTimétrie et Orbitographie). The Tropical Atmosphere Ocean (TAO) data were obtained from the TAO Project NOAA/PMEL (http://www.pmel.noaa.gov/tao). The Reynolds/NCEP SST and Quickscat ocean wind data were obtained through the online PO.DAAC Ocean
ESIP Tool (POET) at the Physical Oceanography Distributed Active Archive Center (PO.DAAC), NASA Jet Propulsion Laboratory (http://podaac.jpl.nasa.gov/poet). Satellite ocean color (Chl $a$) data were acquired using the GES-DISC Interactive Online Visualization and Analysis Infrastructure (Giovanni) as part of the NASA's Goddard Earth Sciences (GES) Data and Information Services Center (DISC). The ENSO SST anomalies were obtained from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (http://www.cpc.noaa.gov).

References

Johnson, G.C., Sloyan, B.M., Kessler, W.S., McTaggart, K.E., 2002. Direct measurements of upper ocean current and water properties across the tropical Pacific during the 1990s.


Table 1: EUC characteristics and thermocline depths. Shown are the survey mean of daily values at 110°W of (1) EUC depth (velocity) at its core, (2) the depth (EUC velocity) of the thermocline, (3) the depth (temperature) at the surface of the EUC, (4) thermocline depth at 95°W, and (5) mean thermocline depth from CTD profiles ±0.5° of the equator.

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<td>3. <strong>EUC surf</strong> (temp)</td>
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**Nov06**

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<td>May07</td>
<td>70 m</td>
<td>50 m</td>
<td>15 m</td>
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* ± 0.5 degree of equator
Table 2: Surface ocean properties in the archipelago. Shown for the Nov05, Jun06, Nov06, and May07 surveys are the (1) SST anomaly in the archipelago and Niño region 3.4 and the mean and standard deviation (stdev) of the (2) SST, (3) SSS, (4) thermocline depth, and (5) Chl $a$ from CTD profiles of the archipelago survey.

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<tr>
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<th>Nov06</th>
<th>May07</th>
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<td>1. Anomaly* [$^\circ$C] SST (ENSO)</td>
<td>-0.5 (-0.8)</td>
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<td>-2.3 (-0.1)</td>
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<td>2. SST [$^\circ$C] mean (stdev)</td>
<td>23.0 (1.1)</td>
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<td>3. SSS mean (stdev)</td>
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<td>4. Thermo. Dep. [m] mean (stdev)</td>
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<td>35 (10)</td>
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<td>5. Chl $a$ [mg m$^{-3}$] mean (stdev)</td>
<td>1.0 (0.7)</td>
<td>1.2 (1.1)</td>
<td>0.6 (0.3)</td>
<td>1.4 (1.4)</td>
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* SST [$2^\circ$N-2$^\circ$S, 92$^\circ$-88$^\circ$W], ENSO [$5^\circ$N-5$^\circ$S, 170$^\circ$-120$^\circ$W]
Figure 1: Bathymetry [m] of the Galápagos Archipelago, sampling stations, and presented vertical profiles at 91.8°W and 0.3°N
Figure 2: 2002 – 2007 monthly mean (92°-88°W, 2°N-2°S) of (a) meridional wind (QSCAT) and SST (NCEP) and (b) SST (NCEP) and ENSO (Niño region 3.4) anomaly with surveys marked.
Figure 3: Longitude versus time (Hovmoller diagram) of altimeter-derived sea surface height anomaly along the equator with dashed lines indicating downwelling Kelvin (DK) and upwelling Kelvin (UK) waves (note: time increases on the y-axis)
Figure 4: Longitude versus time (Hovmoller diagram) between 2°S and 2°N from TAO Array of 5-day mean (a) zonal wind and (b) thermocline depth anomalies (note: time decreases on the y-axis)
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Figure 6: November 2006 and May 2007 anomalies from a 30-year mean of the (a) thermocline depth [m] where increases (>0) equate to a deeper depth and (b) subsurface temperature [°C]
Figure 7: Nov06 temperature [°C] survey of (a) MODIS 8-day mean (25 Nov - 2 Dec) SST, (b) CTD SST, (c) 20-m temperature, (d) thermocline depth, and temperature profiles along (e) 91.8°W and (f) 0.3°N
Figure 8: Nov06 survey of (a) SSS, (b) 20-m salinity, (c) salinity along 91.8°W, (d) salinity along 0.3°N, and TS diagrams of (e) 2-m CTD values and (f) vertical profiles
Figure 9: Nov06 survey of Chl $a$ [mg m$^{-3}$] of (a) surface concentrations and profiles along (b) 91.8$^\circ$W and (c) 0.3$^\circ$N
Figure 10: May07 temperature [°C] survey of (a) MODIS 8-day mean (25 Nov - 2 Dec) SST, (b) CTD SST, (c) 20-m temperature, (d) thermocline depth, and temperature profiles along (e) 91.8°W and (f) 0.3°N
Figure 11: May07 survey of (a) SSS, (b) 20-m salinity, (c) salinity along 91.8°W, (d) salinity along 0.3°N, and TS diagrams of (e) 2-m CTD values and (f) vertical profiles.
Figure 12: May07 survey of Chl a [mg m\(^{-3}\)] of (a) surface concentrations and profiles along (b) 91.8°W and (c) 0.3°N.
Figure 13: Depth of thermocline [m] vs. Chl a [mg m$^{-3}$] for the Nov05, Jun06, Nov06, and May07 surveys
Concluding Marks

Classification of the surface-water masses provides a mean description of the geochemical properties of the water and its potential to stimulate the surface primary production that feeds the biodiversity of the Galápagos Archipelago. The significance of this type of delineation is highlighted by the recent work of Schaeffer et al. (2008) who show a strong positive correlation between salinity and nitrate concentrations and a negative correlation between temperature and chlorophyll a (Chl a) surface concentrations in the archipelago. Warm nutrient-poor tropical surface waters (TSW) and cool nutrient-rich equatorial surface waters (ESW) exist in the archipelago and their ranges vary in time and space. This project defines TSW where the sea surface salinity (SSS) is <34 and ESW where the SSS is >34.

As the Inter-tropical Convergence Zone (ITCZ) nears the archipelago during the wet season (December – May), TSW form locally as rainfall dilutes the surface. The TSW masses will also emerge and cover much of the central and northern archipelago when the relatively fresh North Equatorial Countercurrent (NECC) strengthens and its waters become a greater source of the South Equatorial Current (SEC) during the latter half of the Garúa season (June – November). The cycles of the SEC and NECC are considerably stronger during the Garúa season, closely following the SE trade winds. On the other hand, ESW form locally where upwelling occurs from the collision of the Equatorial Undercurrent (EUC) against the island platform. The ESW will also emerge during the Garúa season when strengthened SE trades enhance upwelling within the Cold Tongue, whose waters advect westward with the SEC into the archipelago. Lastly, ESW are most prevalent during the latter half of the wet season and the early Garúa season when the SE trades are weak and the SEC is usually absent within and west of the archipelago along the equator. In response, the EUC volume and transport increases and its eastward momentum will extend to the surface. During these periods, the EUC surface temperature is warmer, but its salinity is still ~35, and its influence is widely apparent throughout the upper water column in the archipelago.
Quantifying the mechanisms causing variability in the upper ocean allows for a deeper understanding of ecological setting by identifying processes critical to the archipelago’s niche habitats. Modifications to the annual cycle occur from the interannual forcing of the El Niño Southern Oscillation (ENSO), which alters the timing and intensity of the annual cycle. Much of the variability in the archipelago stems from Kelvin-wave activity (and possible Rossby waves) that are spawned during the ENSO cycle. The Kelvin waves modify the synoptic-scale thermocline depth along the equator, which affects the SEC and EUC strength and presence and the archipelago’s water masses. However, the most noticeable changes occur directly from the depression of the thermocline within the archipelago that results in a reduced delivery (upwelling) of sub-thermocline nutrients to the surface layer. Changes in the salinity structure were not apparent during this study, and thus the water-mass classification normal for the annual cycle remained relatively unaffected. Although salinity was unchanged, temperature changes were significant. During the study a thermocline depression of 10 to 25 m occurred during the ENSO-warm surveys that resulted in the sea surface temperature (SST) warming by >2°C and a reduction of the surface Chl a by >15% within the archipelago.

Previously undocumented within the archipelago are the interactions of and variability from tropical instability waves (TIW). During the ENSO-cool period between August and October of 2005, TIW appeared within the eastern equatorial Pacific and created large subsurface temperature oscillations at four instrumented moorings within the archipelago. Shearing between the northern branch of the SEC and the EUC has previously been recognized as the mechanism generating TIW with periods between 15 and 25 (<20) days along the equator. The in-situ effects from the TIW are readily apparent along the TAO array as strong meridional currents ($V_y$) that have a <20-day period oscillation. Cross-equatorial pumping of the thermocline is associated with the oscillations. Downwelling (upwelling) occurs within ~2° north (south) of the equator when $V_y$ is northward. The opposite occurs when $V_y$ is southward. The SST along the equator at a location such as 0°, 110°W may change from the vertical pumping, but its signal is more responsive to the $V_y$ advections of the equatorial front (EF). The opposite occurs at 0°, 95°W, where the SST changes concurrently to the pumping of the thermocline (i.e., SST warms as the thermocline
The SST signal at 0°, 95°W had a period of ~16 days, which was significant between June 2005 and March 2006. Within the archipelago, the moored water level and temperature measurements showed a clear ~15-day periodicity between June and December 2005. During a strong 3-wave succession between August 28 and October 13, 2005, large (~7°C) temperature oscillations occurred within the central archipelago. Argo drifters made several profiles that captured a warm-to-cold succession over a half TIW wavelength. The profiles indicate upwelling of ~5 m day\(^{-1}\) as computed through the vertical displacement of both the isohaline and isothermal structures. In addition to the formation of ESW from the TIW pumping, a significant biological response occurred throughout the archipelago. Coincident with coldest temperatures, SeaWiFS measurements reveal that the Chl \(a\) increased across the archipelago by 25 – 40% above the 2004 – 2006 mean and nearly 25% above the 1998 – 2007 mean. The much larger Chl \(a\) levels within the archipelago as compared to 95° and 110°W implicate that the island platform itself further iron-enriched the upwelling waters.

To date, our sampling program has captured and documented changes in the archipelago of the annual cycle as well as the variability from the 2006/07 El Niño and those directly prior to the 2007/08 La Niña. In addition, it has revealed a strong presence of TIW, which were previously unrecognized in the archipelago. Our moored time series extend the equatorial measurements of the TAO array eastward into the Galápagos Marine Reserve (GMR), and our results indicate that the GMR is a dynamic epicenter to regional forcing. The associated changes in upwelling intensity and its distribution are of importance to the GMR managers especially in the face of global change. Upwelling supplies nutrients to the phytoplankton that sustains the archipelago’s amazing biodiversity, which is of global importance.