Observing the Galápagos–EUC Interaction: Insights and Challenges

KRISTOPHER B. KARNAUSKAS

Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts

RAGHU MURTUGUDDE AND ANTONIO J. BUSALACCHI

Earth System Science Interdisciplinary Center, University of Maryland, College Park, College Park, Maryland

(Manuscript received 4 March 2010, in final form 28 July 2010)

ABSTRACT

Although sustained observations yield a description of the mean equatorial current system from the western Pacific to the eastern terminus of the Tropical Atmosphere Ocean (TAO) array, a comprehensive observational dataset suitable for describing the structure and pathways of the Equatorial Undercurrent (EUC) east of 95°W does not exist and therefore climate models are unconstrained in a region that plays a critical role in ocean–atmosphere coupling. Furthermore, ocean models suggest that the interaction between the EUC and the Galápagos Islands (~92°W) has a striking effect on the basic state and coupled variability of the tropical Pacific. To this end, the authors interpret historical measurements beginning with those made in conjunction with the discovery of the Pacific EUC in the 1950s, analyze velocity measurements from an equatorial TAO mooring at 85°W, and analyze a new dataset from archived shipboard ADCP measurements. Together, the observations yield a possible composite description of the EUC structure and pathways in the eastern equatorial Pacific that may be useful for model validation and guiding future observation.

1. Introduction

The Pacific Equatorial Undercurrent (EUC) is among the strongest and most coherent ocean currents in the world, with estimated peak climatological zonal velocity (zonal volume transport) exceeding 130 cm s^{-1} [40 Sv (1 Sv $\equiv 10^6$ m^3 s^{-1}) Johnson et al. 2002] and instantaneous measurements often exceeding 200 cm s^{-1}. The EUC also plays an important role in the equatorial Pacific and global climate system by relieving the zonal pressure gradient set up by the trade winds and surface ocean currents and transporting massive amounts of cold, nutrient- and carbon-rich water to the surface where their upwelling feeds the cold tongue, reinforces the zonal SST gradient, and plays an important role in global biogeochemical cycling (e.g., Feely et al. 2002). Because of sustained in situ platforms such as the Tropical Atmosphere Ocean (TAO) array (McPhaden et al. 1998) and quasi-regular research and maintenance cruises, we now have a well-resolved picture of the mean EUC from its emergence on the equator at ~150°E to the eastern terminus of the TAO array at 95°W (Johnson et al. 2002). The first topographic obstacle encountered by the EUC is the westernmost of the Galápagos Islands, Fernandina and Isabela. At the surface, Isabela extends from 1.06°S to 0.17°N. The Galápagos thus forms a 135.36-km-wide barrier to the EUC straddling the equator at 91.66°W. In the east-central Pacific, the EUC core is centered on ~0.25°S, and the 50 cm s^{-1} isopleths at 95°W span ~1°S to ~0.5°N (Johnson et al. 2002). Therefore, the Galápagos stands directly in the path of the EUC core, the meridional scale of which is the same order as that of Isabela.

Recent modeling suggests the interaction between the EUC and the Galápagos east of 95°W has a striking effect on the basic state of the tropical Pacific and influence on coupled ocean–atmosphere variability (Karnauskas et al. 2007, 2008), as well as nutrient availability, primary production, and CO_2 fluxes (Murtugudde 2008). Unfortunately, however, a dataset suitable for describing the real flow and thus validating model subsurface currents east of 95°W does not exist. There are presently three sources of direct current observations from which we can attempt to build a comparable depiction of the EUC east of the TAO array. 1) In the decades since the discovery of the

---

Corresponding author address: Kristopher B. Karnauskas, Woods Hole Oceanographic Institution, MS 23, Woods Hole, MA 02543.
E-mail: kk@whoi.edu

DOI: 10.1175/2010JPO4461.1

Pacific EUC in 1951–52 (Cromwell et al. 1954), oceanographers have returned to the equator in several expeditions aimed at observing the equatorial current system. A number of these expeditions resulted in velocity measurements, however sparsely distributed in space and time, of the EUC in the eastern equatorial Pacific: that is, near the Galápagos. These historical observations are reviewed in the following section. 2) For a short period of time in the early 1980s, a TAO mooring was actively recording subsurface velocity measurements east of the Galápagos at 0°, 85°W, which can be compared with TAO mooring locations west of the Galápagos (95°W, 110°W, etc.). 3) A potentially useful source of observations is global Joint Archive of Shipboard Acoustic Doppler Current Profiler (JASADCP) data. The JASADCP has previously been applied to equatorial current systems (e.g., Rowe et al. 2000; Marin et al. 2010; Perez et al. 2010), but it remains a relatively underutilized source of observations. These ADCP measurements, along with the aforementioned moored current measurements, are analyzed in section 3. This paper attempts to integrate all relevant observations toward a possible description of the EUC structure and pathways in the eastern equatorial Pacific, including its interaction with the Galápagos. In doing so, a hopeful outcome is to expose areas where further observations would be beneficial in understanding this key component of the equatorial and global climate system. Such a synthesis and comments are given in section 4.

2. Historical observations: 1952–93

The fate of the EUC upon approaching the Galápagos is not a new problem. The velocity measurements confirming the discovery of the EUC came in August 1952 on board the U.S. Fish and Wildlife Service research vessel *Hugh M. Smith* (Cromwell et al. 1954). Two months earlier, the *Hugh M. Smith* was in the eastern tropical Pacific supporting the Pacific Ocean Fishery Investigations in cooperation with the Scripps Institution of Oceanography Shellback expedition (Wooster and Cromwell 1958). According to Knauss (1960), measurements of dissolved oxygen concentration from hydrographic stations occupied by the *Horizon* during the Shellback expedition in May–August 1952 indicated the presence of the EUC to the north and south of the Galápagos at 91°W and on the equator at 85°W. In November 1955, the *Hugh M. Smith* returned to the equator along with the *Horizon* and *S. F. Baird* to support the Eastropic expedition during which velocity measurements were taken using free-floating parachute drogues. According to Knauss (1960), Cromwell and Knauss observed the EUC at 115° and 100°W, but not on the equator at 84°W. Three years later, in March–June 1958, the *Horizon* and *Hugh M. Smith* returned to the equator to support the Dolphin expedition. This time using a modified Roberts current meter, Knauss and King (1958) and Knauss (1960) reported a strong (120–150 cm s^{-1}) EUC on the equator from 140°W continuing unabated to 95°W. Between 140° and 95°W, the EUC core was observed to shoal from 100 m to a minimum of 52-m depth at 98°W. Between 95° and 92°W ($\sim$38 km west of the Galápagos Islands), the EUC core sloped downward and was reduced from over 100 to 62 cm s^{-1}. Just east of the Galápagos (89°W) and still on the equator, no EUC was found.

Again with the modified Roberts current meter (a newly designed current meter was lost on its first lowering), Knauss and the Swan Song expedition returned to the eastern equatorial Pacific aboard the *Argo* during September–December 1961. This expedition, reported in Knauss (1966), is especially important because it provided the first meridional sections of velocity both east and west of the Galápagos plus velocity profiles north and south of the Galápagos. The series of meridional sections of zonal velocity in Knauss (1966) show a 120-m-deep, 100 cm s^{-1} EUC core at 140°W, which shoals to 50 m and slows to 70 cm s^{-1} by 93°W. Two additional changes in the EUC begin to develop between 140° and 93°W: the EUC core shifts off the equator, to 0.5°S, and a deeper secondary lobe begins to develop north of the equator (to 1°N, below 100-m depth, eastward velocity $\sim$20 cm s^{-1}). A velocity profile taken just north of the Galápagos Islands (1°N, 90.75°W) is consistent with the development of the deeper northern lobe; eastward velocity $\sim$20 cm s^{-1} was observed throughout the 100–300-m layer. The corresponding profile due south of the Galápagos Islands shows no evidence of an eastward current. The meridional section taken at 87°W from 1°S to 1°N confirmed that the only eastward equatorial current surviving interaction with the Galápagos was the deeper and weaker northern lobe with 20 cm s^{-1} eastward velocity from 130- to 220-m depth. The fate of the main EUC core, which, west of the Galápagos at 93°W, was still >70 cm s^{-1} at 50-m depth and centered on 0.5°S, is still unknown.

Additional velocity measurements in the Galápagos region were made during the Equator expedition, February–March 1966, by towing current meters attached to a thermistor chain from the U.S.S. *Marysville* (Christensen 1971). Although the meridional transects of the Equator expedition were longer (4°S–4°N) than those of previous expeditions, the current meters were fixed at depths of 12, 75, 150, and 240 m. This is a potential limitation because we now know that (i) 75 m may only coincide with the depth of the EUC core at one location (perhaps 95°W); (ii) 150-m depth is perhaps a better target for the EUC core in the central Pacific (i.e., at the date line); and (iii) the readings at 240 m, which in this study were assumed to be approximately zero and used as a reference for the other depths, is actually in the heart of the deeper and weaker northern lobe observed by Knauss (1966). With these limitations in mind, the Christensen (1971) results can be interpreted to show the EUC to be (i) centered on ~0.5°S east of 95°W, (ii) shoaling to the east, (iii) in excess of 100 cm s^{-1} as far east as 92°W, and (iv) substantially reduced in spatial coherence and zonal velocity at 89°W (less than 30 cm s^{-1}; accuracy was estimated to be ±10 cm s^{-1}).

In 1967, the Eastern Tropical Pacific (EASTROPAC) expedition provided additional hydrographic stations east of the Galápagos occupied in January–April by the *Alaminos* and in June by the *Huayaipe*. From the *Alaminos* data, White (1969, 1973) noted that the EUC east of the Galápagos appeared to be split into two branches on either side of the equator based on the thermostad. From the *Huayaipe* data, Stevenson and Taft (1971) found a high-salinity core on the equator at 60-m depth at 82.5°W (>700 km east of the Galápagos), which was subsequently present at the same depth along the South American coast at 2°S. Stevenson and Taft (1971) also present velocity measurements taken with parachute drogues deployed at 15-, 75-, and 310-m depth from the *Thomas Washington* during the June 1969 Piquero expedition. The parachute drogues were deployed once at a single location (0.37°S, 84°W), and the 75-m drogue indicated an eastward velocity of 37 cm s^{-1}.

Lukas (1986) analyzed a compilation of all available hydrographic profiles through 1975 to describe the pathways of the EUC in the eastern equatorial Pacific. Although the oxygen tongue can be most readily traced around the north of the Galápagos, the mean path of the EUC based on the thermostad, isolated high-salinity core, and geostrophic currents appears to be south of the Galápagos, southeastward toward the coast of South America at 5°–7°S, and then southward along the coast of South America as the Peru–Chile Undercurrent (~50-m depth). Evidence of a deeper, weaker northern lobe can be seen in the zonal geostrophic velocity sections between 92° and 85°W. Calculations show that geostrophic velocities east of the Galápagos are much weaker than those west of the Galápagos.

The National Oceanic and Atmospheric Administration (NOAA) Equatorial Pacific Ocean Climate Studies (EPOCS) program in 1981 prompted velocity measurements using a new instrument called PEGASUS, a free-falling, acoustically tracked profiler. PEGASUS measures currents at each location twice (descending and ascending), and the absolute accuracy is thought to be on the order of 1 cm s^{-1}. In June 1981, the *Oceanographer* took PEGASUS velocity sections along 110°, 95°, and 85°W (Leetmaa 1982). At 110°W, the EUC core was 122 cm s^{-1}, with 70-m depth and centered on 0.3°S. Interestingly, by 95°W, the EUC could already be seen bifurcating into two cores (both 75 cm s^{-1}): one centered on 1°S at 50-m depth and one centered on the equator at 70-m depth. The 85°W section revealed two much-reduced but notable features: a 0–10 cm s^{-1} eastward velocity maximum centered on 1.5°S at 65-m depth and a 20 cm s^{-1} eastward velocity centered on 0.5°S at 275-m depth.

After roughly another decade, just as the ADCP was becoming standard instrumentation on research and naval vessels, the Iron Enrichment Experiment (IRONEX) II during November 1993 gave Steger et al. (1998) the opportunity to describe the physical circulation in the Galápagos Archipelago using data from hydrographic stations and ADCP mounted to the *Columbus Iselin*. The cruise plan for the *Iselin* was designed for a related field program (i.e., not necessarily optimized for measuring the physical circulation), but the observations were unprecedented for the region in terms of spatial and temporal resolution. The velocity measurements reported in Steger et al. (1998) showed an EUC core of 60–79 cm s^{-1} at ~75-m depth centered on 0.5°S at all transects from 94° to 92°W. As in Knauss (1966) and Leetmaa (1982), by 92°W a weaker and deeper northern lobe of the EUC was clearly branching off from the main core, below 100-m depth and centered between the equator and 0.5°N. At 91.75°W, eastward velocity in the main EUC core was still >40 cm s^{-1}, at 75-m depth, and centered on 0.5°S. In other words, the center of the EUC core was lined up with the latitudinal midpoint of the topographic barrier represented by Fernandina and Isabela, the shores of which were only 10 km away. Very strong meridional divergence away from the EUC core (southward stronger; exceeding 100 cm s^{-1}) was also observed at 91.75°W. The deeper, weaker northern lobe could not be observed at 91.75°W because that leg did not cross into the Northern Hemisphere. Finally, at 89°W, a meridionally wide, ~20 cm s^{-1} eastward signature in the Southern Hemisphere was evident at 50-m depth between 1.5° and 0.5°S, and the deep, weak northern lobe was found at 150-m depth centered on 0.5°N. The meridional velocity associated with both eastward velocity signatures was equatorward.

3. New analyses

a. *TAO mooring: 1981–82*

Between July 1981 and April 1983, a TAO mooring equipped with current meters deployed between the Galápagos and mainland Ecuador (0°, 85°W) collected ~12 months of subsurface current data. Gaps in velocity sampling occurred during September–October 1981 and April–October 1982. We analyze the middle period of

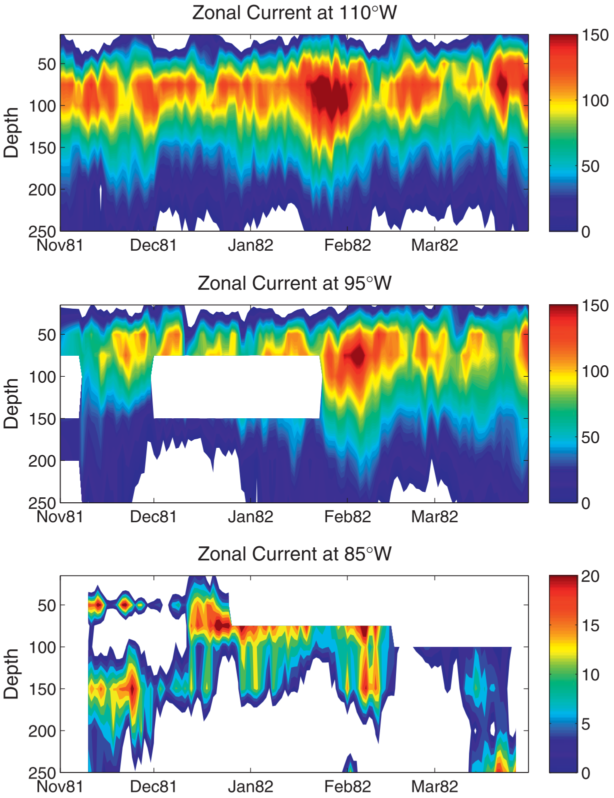

FIG. 1. Daily zonal velocity (cm s^{-1}) measured by TAO moorings on the equator at (top) 110°, (middle) 95°, and (bottom) 85°W from November 1981 through March 1982. Note that a different color scale is used for 85°W.

TABLE 1. List of all cruises archived by the JASADCP whose tracks passed within the region bounded by 4°S–3°N, 94.5°–84.5°W (black box in Fig. 3).

No.	Archive ID	R/V	Cruise begin	Cruise end
01[a]	00015	*Knorr*	22 Feb 1993	11 Apr 1993
02	00295	*Discoverer*	15 Oct 1992	19 Nov 1992
03	00324	*Columbus Iselin*	8 Nov 1993	22 Nov 1993
04	00573	*Ron Brown*	24 Jan 2001	8 Mar 2001
05	00604	*N. B. Palmer*	1 Oct 2002	17 Oct 2002
06[b]	00899	*Ron Brown*	22 Oct 2004	28 Nov 2004
07	01006	*Ron Brown*	10 Sep 2001	25 Oct 2001
08[b]	01007	*Ron Brown*	30 Oct 2001	2 Dec 2001
09	01008	*Ron Brown*	4 Oct 2005	20 Oct 2005
10[a,c]	01016	*Ka'imimoana*	31 Mar 2006	28 Apr 2006
11	01032	*Ron Brown*	27 Oct 2003	21 Nov 2003
12[a,c]	01202	*Ka'imimoana*	28 Mar 2007	27 Apr 2007
13[a]	01211	*Ka'imimoana*	6 Jun 2008	12 Jul 2008
14	01294	*Ron Brown*	3 Nov 2006	1 Dec 2006
15	01296	*Ron Brown*	11 Nov 2007	22 Nov 2007
16[a]	Pending	*Atlantis*	15 Mar 2010	14 Apr 2010

[a] Cruise occurred in the strong EUC season.

[b] Comparable cruises in terms of vessel, cruise track, and time of year.

[c] Comparable cruises in terms of vessel, cruise track, and time of year.

continuous data collection (November 1981–March 1982) because the first period was relatively short (<2 months) and the final period corresponded with a strong El Niño event (Firing et al. 1983). Shown in Fig. 1 are time–depth sections of daily averaged zonal velocity from two equatorial TAO moorings west of the Galápagos (110° and 95°W), and east of the Galápagos at 85°W. West of the Galápagos, the EUC core was found between 50- and 100-m depths. At 110°W (95°W), the mean maximum core velocity was 123 cm s^{-1} (100 cm s^{-1}), with standard deviation $\sigma = 19$ cm s^{-1} (23 cm s^{-1}). At 85°W, the mean maximum core velocity was substantially weaker (15 cm s^{-1}, $\sigma = 5$ cm s^{-1}). Interestingly, at 85°W there is evidence (e.g., November 1981 and February 1982) that there are at times two EUC-like structures: one at 50-m depth and one at 150 m or deeper. This observation is consistent with historical measurements, particularly Knauss (1966) and Leetmaa (1982), that found evidence of a deep and very weak lobe circumnavigating north of the Galápagos in addition to a stronger, shallower lobe branching south of the Galápagos. At other times (e.g., December 1981–January 1982), there is only a single eastward signature present within the range of depths sampled by the mooring. [Note that the deeper northern lobe observed by Leetmaa (1982) was centered at 275-m depth.] Also, the ambiguous and weak nature of the zonal velocity profiles at 0°, 85°W does not necessarily preclude the existence of the EUC at that longitude; even a minor latitudinal deflection of the EUC by the Galápagos or otherwise would prevent a fixed mooring from observing the EUC.

b. *Shipboard ADCP: 1992–2010*

The holdings of the JASADCP (E. Firing 1992) presently contain 16 cruises (Table 1) that sailed near the Galápagos Archipelago. The seasonal and spatial distributions of those cruises are shown in Figs. 2 and 3, respectively; also shown in Fig. 2 is an estimate of the mean seasonal cycle of EUC zonal current volume transport at 95°W (Johnson et al. 2002). We define a "strong EUC" season to be March–July as the season wherein EUC transport is appreciably stronger than the annual mean. Mapping the cruise histogram onto the EUC seasonal cycle yields 5 cruises from the strong EUC season and 11 cruises from the weak EUC season. Cruise tracks in Fig. 3 are color coded according to this seasonal definition. The pattern of sampling in the weak EUC season (blue tracks) is such that the 11 cruises were distributed rather evenly across the region, whereas in the strong EUC season (red tracks) sampling was primarily concentrated to the southwest and northwest of the archipelago. This is clearly driven by the route to Puerto Ayora, Isla Santa Cruz, from the 95°W line of the TAO array.

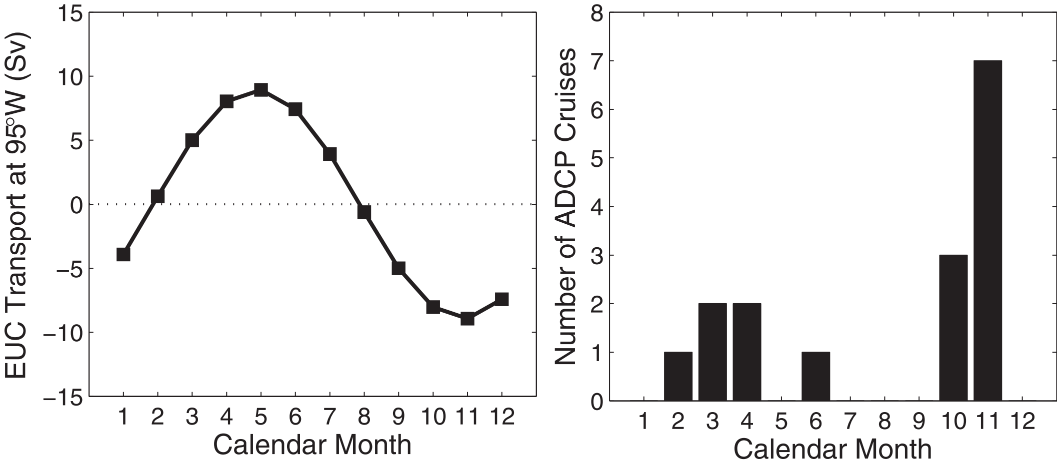

FIG. 2. (left) Estimated climatology of zonal current volume transport (Sv) for the EUC at 95°W (from Johnson et al. 2002; annual-mean value of 20.7 Sv removed). (right) Climatological distribution of ADCP cruises listed in Table 1. A strong EUC season is defined as March–July.

Horizontal currents from the five cruises during the strong EUC season, averaged through the 40–160-m-depth layer, are shown in Fig. 4. From this simple depiction, one can clearly identify a pronounced influence of the Galápagos on the EUC including strong ~50 cm s^{-1} flow topographically deflected north and south from the tips of Isabela. The broad eastward flow along 86°W (contributed by cruise 1) is either a separate, locally forced EUC-like flow, a direct extension of the central Pacific EUC with a link that is presently unresolved by available observations, a transient feature such as a Kelvin wave pulse as suggested by Kessler and McPhaden (1995) and Kessler (2006), or a superposition thereof. Indeed, ocean reanalysis products such as the Simple Ocean Data Assimilation (SODA; Carton and Giese 2008) indicate anomalously strong eastward subsurface flow in March 1993 relative to March climatology (not shown).

For each cruise in the weak EUC season, depth-averaged horizontal currents were gridded, averaged for overlapping tracks, and linearly interpolated onto a uniform 0.25° grid. The resulting field, shown in Fig. 5, provides a possible depiction of the subsurface flow east of the TAO array in the vicinity of the Galápagos for the weak EUC season. In this depiction, the EUC is observed to bifurcate between 95°W and the Galápagos; part of the flow circumnavigates Isabela to the north, whereas strong meridional divergence results in some of the flow turning to the south. East of Isabela, the northern branch appears to recirculate into the archipelago, whereas the southern branch turns eastward along ~3°S and southward [out of the southeastern corner of the analysis domain, consistent with the hydrographic analysis of Lukas (1986)]. Despite the uncertainties associated with gridding and interpolating measurements that are unevenly and sparsely distributed in space and time, which are likely to be large but unavoidable, the Galápagos appears to represent a considerable impediment to the eastward progression of the EUC. It is interesting to imagine how different the flow field would look if the Galápagos Islands formed just a few hundred kilometers north or south of their present position (i.e., out of the path of the EUC) and how differently the biodiversity and ecosystem dynamics of the Galápagos may have evolved as a result. Also, as noted in the introduction, some numerical modeling studies

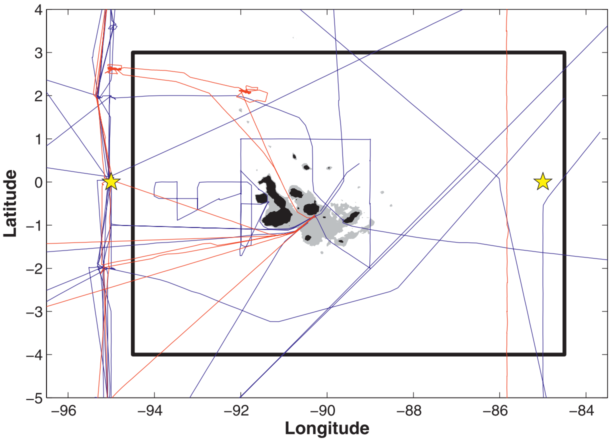

FIG. 3. Map of all 16 cruises archived by the JASADCP whose tracks passed within the region bounded by 4°S–3°N, 94.5°–84.5°W (black box). Red tracks correspond to the 5 cruises that occurred in the strong EUC season (March–July), and blue tracks correspond to the other 11 cruises. Yellow stars mark the locations of the 95° and 85°W TAO moorings whose measurements are shown in Fig. 1. The 500-m isobath is filled gray, and the emergent Galápagos Islands are shown in black.

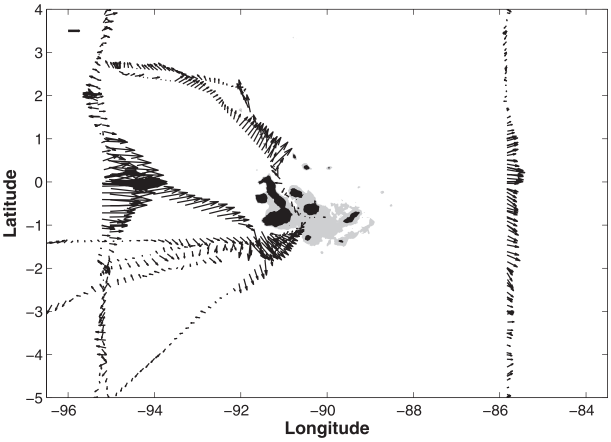

FIG. 4. Depth-averaged (40–160 m) horizontal currents for the five cruises that occurred in the strong EUC season. A 25 cm s^{-1} reference vector is provided in the top-left corner.

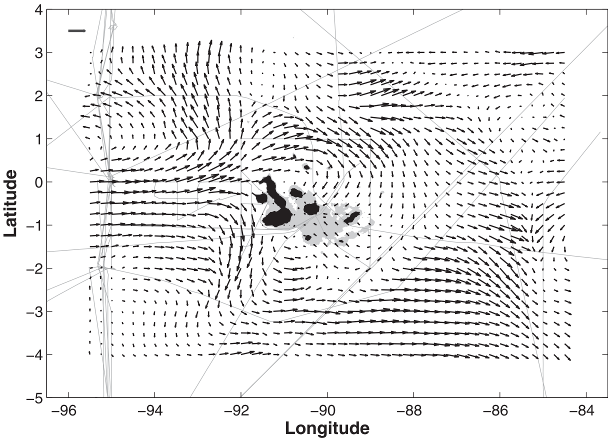

FIG. 5. Interpolated analysis of depth-averaged (40–160 m) horizontal currents for the 11 cruises that occurred in the weak EUC season. A 25 cm s^{-1} reference vector is provided in the top-left corner. Input cruise tracks are shown in gray.

have suggested this Galápagos–EUC interaction may have important large-scale climatic implications.

Two pairs of cruises that occurred at roughly the same time of year, with similar tracks and on the same vessel (Table 1), provide an opportunity to examine, in more detail, features of the subsurface flow and how much they might vary from year to year. Cruises 6 and 8 both occurred in November and had nearly identical cruise tracks (both were R/V *Ron Brown*), and cruises 10 and 12 both occurred in April and had very similar cruise tracks (both were R/V *Ka'imimoana*).

Shown in Fig. 6 is a comparison between cruises 6 and 8 of depth-averaged currents, zonal velocity along 95°W, and speed along a diagonal transect southeast of the Galápagos. In 2001 and 2004, the *Ron Brown* observed a well-defined EUC core in excess of 60 cm s^{-1} along 95°W centered between 50- and 100-m depths and a southeastward ribbon at roughly the same depth and 20–30 cm s^{-1} slower. Both the southern and northern Tsuchiya jets were also observed in both years. The southeastward ribbons found south of the Galápagos are very likely manifestations of the EUC, because their strength appears to correspond with the strength of the EUC at 95°W. Despite the EUC core at 95°W being overall stronger in cruise 8 (2001), the general structure of the EUC in both years appears quite similar.

Cruises 10 and 12 are juxtaposed in a similar manner in Fig. 7 and again provide some insight into the southward component of the EUC divergence upon the Galápagos. In addition, cruise 12 traveled from the 95°W line directly to the southwestern corner of Isabela, providing a continuous view of the EUC as it progresses from 95°W to the Galápagos (Fig. 8). Unfortunately, this transect also translated across the core of the EUC as it traveled along it. Nonetheless, the measurements reveal an EUC that is remarkably continuous, coherent, and strong (>100 cm s^{-1}) from 95° to 92.5°W. Because the cruises shown in Fig. 7 occurred in April, the EUC at 95°W is approximately twice as strong as that in the November cruises shown in the previous figure. Likewise, the southward flow along the western edge of Fernandina and Isabela is very strong (>60 cm s^{-1}). As in Fig. 6, both features are very clearly manifestations of the EUC, because the velocity downstream appears to correspond with the velocity upstream. Together with Fig. 6, these results imply some degree of steadiness to the flow of the EUC near the Galápagos, which bodes well for future attempts to measure the Galápagos–EUC interaction by means of more spatially complete sampling.

4. Synthesis and discussion

Given the lack of an existing comprehensive observational dataset for describing the structure and pathways of the EUC in the eastern equatorial Pacific, we have interpreted historical measurements, analyzed velocity measurements from TAO moorings, and analyzed a new dataset of shipboard ADCP measurements in the eastern equatorial Pacific. This effort was motivated in part to promote ocean and climate model validation in this critical region but also to establish the salient features of the real EUC east of where the TAO array leaves off and explore where and when further observational efforts could be targeted. The existing data by no means allow us to construct a complete and dynamically satisfying description of the Galápagos–EUC interaction including

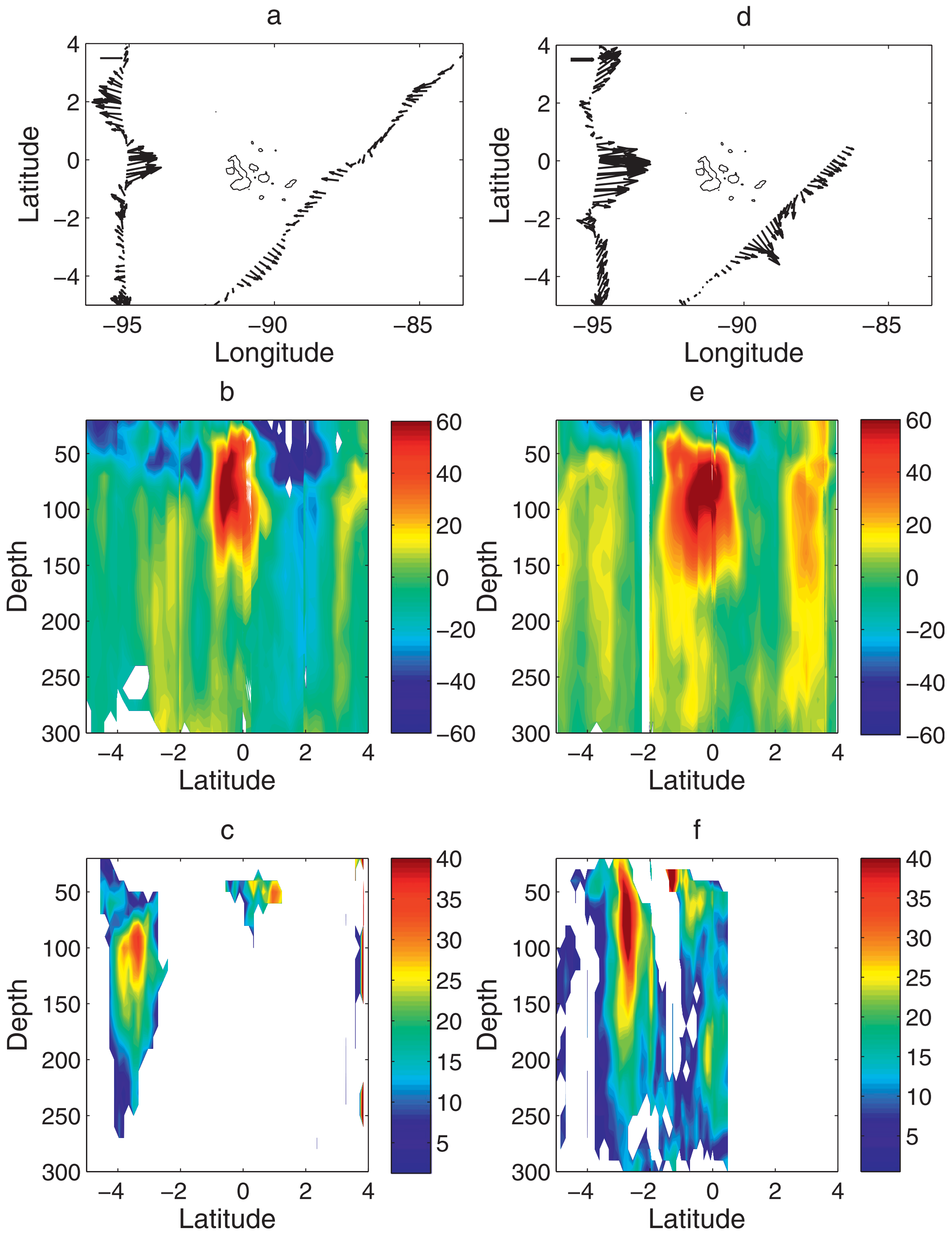

FIG. 6. (a) Tracks and depth-averaged (40–160 m) horizontal currents (50 cm s^{-1} reference vector provided), (b) zonal velocity (cm s^{-1}) along the 95°W transect, and (c) horizontal speed where $u > 0$ (cm s^{-1}) along the diagonal transect for cruise 6. (d)–(f) As in (a)–(c), but for cruise 8.

its subseasonal to interannual variations. However, in considering all of the presently available information, we offer the following description of the structure and pathways of the EUC in the eastern equatorial Pacific (Fig. 9):

- Between 95°W and the Galápagos, the EUC is observed to
  - be centered between the equator and 0.5°S;
  - transition from shoaling to deepening;
  - develop a tilt (downward and northward); and

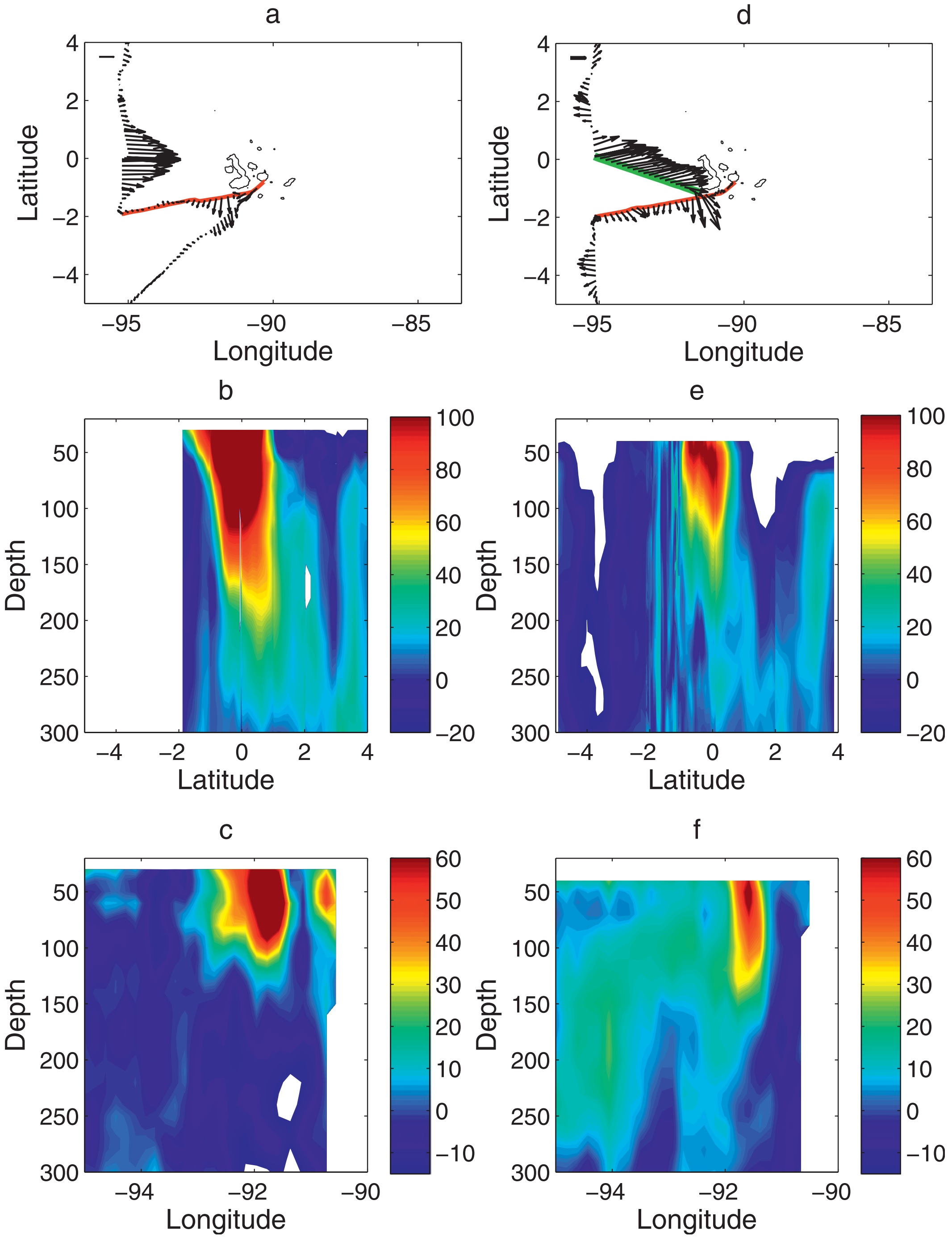

FIG. 7. (a) Tracks and depth-averaged (40–160 m) horizontal currents (50 cm s^{-1} reference vector provided), (b) zonal velocity (cm s^{-1}) along the 95°W transect, and (c) southward currents (cm s^{-1}) along the approximately zonal transect (highlighted red) for cruise 10. (d)–(f) As in (a)–(c), but for cruise 12, and (e) includes zonal velocity along the full cruise track from 4°N to 5°S, including the excursion from 95°W. Data from the green-highlighted transect of cruise 12 are shown in Fig. 8.

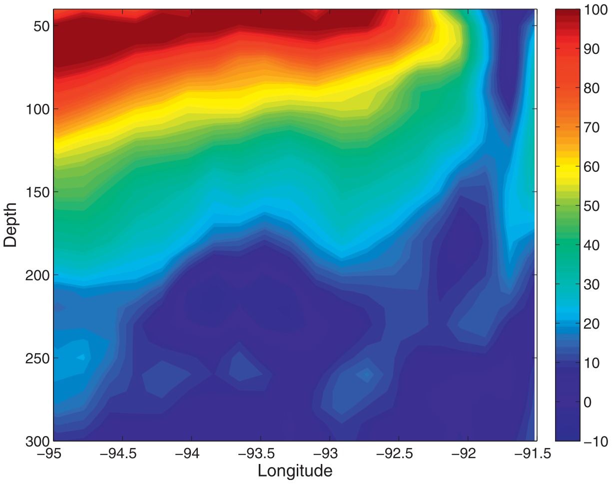

FIG. 8. Zonal velocity (cm s^{-1}) along the green-highlighted transect shown in Fig. 7d (cruise 12). Note that there is also an approximately 1° latitudinal translation along this longitudinal range.

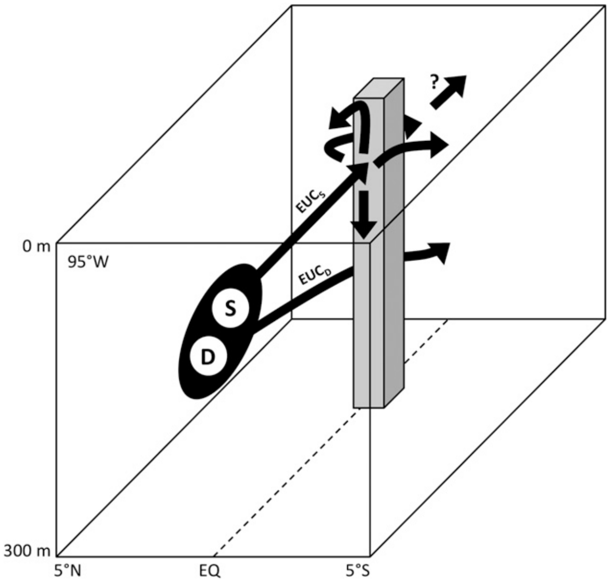

FIG. 9. Schematic illustration of the EUC structure and pathways in the eastern equatorial Pacific (east of the TAO array) from a synthesis of all available observations discussed in the present study.

  - bifurcate into a shallower/southern core (EUC_S) and deeper/northern core (EUC_D).
- EUC_S makes a direct impact on Fernandina and Isabela.
  - strong meridional divergence is observed within 50–100 km (<1°) of the islands:
    - some flow deflects southeastward toward the coast of Peru and
    - some flow circumnavigates Isabela to the north and returns equatorward into the central islands of the archipelago.
  - although vertical velocity is not measured directly, we find indirect observational evidence of significant vertical divergence (upwelling and downwelling):
    - high-resolution satellite observations of SST and chlorophyll indicate that maximum upwelling occurs within 50–100 km of the islands and is transported westward by the surface current (not shown) and
    - zonal temperature sections along the equator reported by Christensen (1971) and Taft and Jones (1973) indicate sharp and vertically symmetric isotherm spreading within 50–100 km of the islands.
- EUC_D, whose existence appears to be transient based on TAO measurements presented herein, remains intact but weakens considerably, continues to deepen (to 100–300 m), flows around the north of Isabela, and continues eastward.

The contribution of the new analyses presented in this paper primarily concerns the horizontal evolution and meridional divergences of the EUC. The extent to which this description depends on intraseasonal to interannual variability is beyond the limits of available observations. It is possible, for example, that pathways vary as TIWs modulate the meridional component of the EUC and as cross-equatorial winds modulate the southward translation of the EUC core. Although Lukas (1986) suggested the seasonal strength of the EUC affects the pathways in the east in a consistent manner, further ADCP measurements—particularly in boreal spring when the EUC is strong and available ADCP sampling limited—would be helpful for confirmation. The nature of EUC-like flow at ~85°W remains a challenging mystery. Despite the inherent complexity of island–flow interaction, repeat transects presented herein are encouraging for future efforts to understand the system through observation. Given the underlying importance of the eastern equatorial Pacific to coupled ocean–atmosphere variability, understanding this region remains a critical challenge to observationalists and modelers alike. To meet this challenge, future efforts crossing those lines will be needed.

Acknowledgments. Observational data gathered from a wide variety of sources were used in this paper. We acknowledge the NOAA/PMEL/TAO Project Office (available online at http://www.pmel.noaa.gov/tao/disdel/) for the moored velocity measurements shown in Fig. 1. Shipboard ADCP measurements were downloaded from the Joint Archive for Shipboard ADCP (JASADCP; available online at http://ilikai.soest.hawaii.edu/sadcp/), a collaboration of the NOAA/NODC and the Eric Firing ADCP Laboratory at the University of Hawaii. Data in the JASADCP are possible through the generous contributions of international scientists, scientific programs, and supportive agencies. Thanks especially to Dr. Jules Hummon for the timely processing of ADCP data from a very recent cruise (cruise 16). Thanks to Dr. Greg Johnson for providing the EUC transport estimates used in Fig. 2. High-resolution bathymetric data for the Galápagos region were compiled by Dr. William Chadwick, Oregon State University. We also thank Drs. Eric Firing, Mike McPhaden, Breck Owens, and Dan Fornari and two anonymous reviewers for many helpful suggestions for improving this manuscript. Karnauskas acknowledges the WHOI Penzance Endowed Fund in Support of Assistant Scientists.

REFERENCES

Carton, J. A., and B. S. Giese, 2008: A reanalysis of ocean climate using Simple Ocean Data Assimilation (SODA). *Mon. Wea. Rev.,* **136,** 2999–3017.

Christensen, N., Jr., 1971: Observations of the Cromwell Current near the Galápagos Islands. *Deep-Sea Res.,* **18,** 27–33.

Cromwell, T., R. B. Montgomery, and E. D. Stroup, 1954: Equatorial Undercurrent in Pacific Ocean revealed by new methods. *Science,* **119,** 648–649.

Feely, R. A., and Coauthors, 2002: Seasonal and interannual variability of CO_2 in the equatorial Pacific. *Deep-Sea Res. II,* **49** (13–14), 2443–2469.

Firing, E., 1992: Notes from Acoustic Doppler Current Profiler Workshop at the National Oceanographic Data Center, May 14–15, 1992. Unpublished manuscript. [Available online at http://ilikai.soest.hawaii.edu/sadcp/intro.html.]

——, R. Lukas, J. Sadler, and K. Wyrtki, 1983: Equatorial Undercurrent disappears during the 1982-83 El Niño. *Science,* **222,** 1121–1123.

Johnson, G. C., B. M. Sloyan, W. S. Kessler, and K. E. McTaggart, 2002: Direct measurements of upper ocean currents and water properties across the tropical Pacific Ocean during the 1990's. *Prog. Oceanogr.,* **52,** 31–61.

Karnauskas, K. B., R. Murtugudde, and A. J. Busalacchi, 2007: The effect of the Galápagos Islands on the equatorial Pacific cold tongue. *J. Phys. Oceanogr.,* **37,** 1266–1281.

——, ——, and ——, 2008: The effect of the Galápagos Islands on ENSO in forced ocean and hybrid coupled models. *J. Phys. Oceanogr.,* **38,** 2519–2534.

Kessler, W. S., 2006: The circulation of the eastern tropical Pacific: A review. *Prog. Oceanogr.,* **69,** 181–217.

——, and M. J. McPhaden, 1995: Oceanic equatorial waves and the 1991–93 El Niño. *J. Climate,* **8,** 1757–1774.

Knauss, J. A., 1960: Measurements of the Cromwell Current. *Deep-Sea Res.,* **6,** 265–285.

——, 1966: Further measurements and observations of the Cromwell Current. *J. Mar. Res.,* **24,** 205–240.

——, and J. E. King, 1958: Observations of the Pacific Equatorial Undercurrent. *Nature,* **182,** 601–602.

Leetmaa, A., 1982: Observations of near-equatorial flows in the eastern Pacific. *J. Mar. Res.,* **40** (Suppl.), 357–370.

Lukas, R., 1986: The termination of the Equatorial Undercurrent in the eastern Pacific. *Prog. Oceanogr.,* **16,** 63–90.

Marin, F., E. Kestenare, T. Delcroix, F. Durand, S. Cravatte, G. Eldin, and R. Bourdallé-Badie, 2010: Annual reversal of the Equatorial Intermediate Current in the Pacific: Observations and model diagnostics. *J. Phys. Oceanogr.,* **40,** 915–933.

McPhaden, M. J., and Coauthors, 1998: The Tropical Ocean Global Atmosphere observing system: A decade of progress. *J. Geophys. Res.,* **103** (C7), 14 169–14 240.

Murtugudde, R., 2008: Incredible shrinking iguana: Gaia on Galápagos. *Proc. Ocean Sciences Meeting,* Orlando, FL, Amer. Soc. Limnol. Oceanogr., 52.

Perez, R., M. F. Cronin, and W. S. Kessler, 2010: Tropical cells and a secondary circulation near the northern front of the equatorial Pacific cold tongue. *J. Phys. Oceanogr.,* **40,** 2091–2106.

Rowe, G. D., E. Firing, and G. C. Johnson, 2000: Pacific Equatorial Subsurface Countercurrent velocity, transport, and potential vorticity. *J. Phys. Oceanogr.,* **30,** 1172–1187.

Steger, J. M., C. A. Collins, and P. C. Chu, 1998: Circulation in the Archipielago de Colon (Galápagos Islands), Nov, 1993. *Deep-Sea Res. II,* **45,** 1093–1114.

Stevenson, M., and V. Taft, 1971: New evidence of the Equatorial Undercurrent east of the Galápagos Island. *J. Mar. Res.,* **29** (2), 103–115.

Taft, B. A., and J. H. Jones, 1973: Measurements of the Equatorial Undercurrent in the eastern Pacific. *Prog. Oceanogr.,* **6,** 47–110.

White, W. B., 1969: The Equatorial Undercurrent, the South Equatorial Countercurrent, and their extensions in the south Pacific Ocean east of the Galápagos Islands during Feb-Mar, 1967. Texas A&M University Department of Oceanography Tech. Rep. 69-4-T, 74 pp.

——, 1973: An oceanic wake in the Equatorial Undercurrent downstream from the Galápagos Archipelago. *J. Phys. Oceanogr.,* **3,** 156–161.

Wooster, W. S., and T. Cromwell, 1958: An oceanographic description of the eastern tropical Pacific. *Bull. Scripps Inst. Oceanogr.,* **7,** 169–281.