# Integrated Boundary Current Observations in the Global Climate System

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## 1. Project Summary

For over 20 years the Consortium on the Ocean's Role in Climate (CORC) has focused on implementing new ocean observing technologies and systems. After identifying inadequately measured properties of the ocean circulation that are important to understanding and predicting climate variability, CORC investigators have developed cost-effective technology, methodology and infrastructure to implement observing systems to measure them. These systems have been put into operation to refine and demonstrate their abilities. Examples of past and ongoing projects are the High-Resolution Expendable Bathythermograph network operating from commercial ships, the Surface Velocity Program, the Argo network of profiling floats, the array of California Current glider transects, and moorings to capture high-frequency processes.

Motivated by national and international planning efforts, CORC is now focused on methods to observe boundary currents, both western boundary currents whose powerful circulation signatures affect global climate fluctuations and eastern boundary currents where the circulation affects local weather, ocean acidification, and valuable fisheries. The boundary current data streams are intended primarily for scientists developing societally valuable analyses and prediction products that are influenced by persistent ocean conditions i.e. ocean climate. Examples are developing models to predict seasonal temperature or precipitation anomalies over land, assessing and predicting trends in ocean productivity and fisheries, or planning coastal development in a changing climate.

More specifically, CORC is now developing regional observing systems in the California Current and the Solomon Sea and developing methods to merge these observations with global ocean climate observations like altimetry, winds, Argo profiles and the Surface Velocity Program. In and inshore of the California Current, changes in processes like alongshore currents from the north and south, upwelling, changes in stratification and mixing, and the frequency and strength of near-surface fronts have been implicated in large changes in the abundance of fish and their prey. CORC data is being used to look for relations between ecosystem properties and coastal circulation. The Western Boundary Current in the Solomon Sea is the main source of the Pacific's Equatorial Undercurrent. This makes it a central part of the shallow overturning circulation that influences central Pacific surface temperatures that drive the El Niño – Southern Oscillation (ENSO) fluctuations with global temperature and precipitation consequences. CORC observing systems are delivering data to test and improve methods of predicting ENSO and its decadal-variability relatives as well as ecosystems and local weather along the California coast. This delivery is done primarily through public web sites where data can be plotted or downloaded. CORC does not intend to operate these observing systems indefinitely and hopes to transition them to a program better suited to sustaining them.

CORC has identified circulation in mid-latitude western boundary currents (WBCs) as another type of inadequately observed components of the ocean climate system and is planning to address them with new methods. We are therefore exploring new ways of observing the transport processes of such WBCs with an eye toward sustaining measurements at a reasonable cost.

# 2. Scientific and Observing System Accomplishments

## A: Measurement of boundary current transport in the Solomon Sea

### Objective and approach

Our objective is to document the role of mass, heat and freshwater transport from the South Pacific through the Solomon Sea to the equator in predicting and understanding climate variability. Our approach uses underwater gliders launched from shore and Pressure Inverted Echo Sounders (PIES) to develop time series of the magnitude, structure and variability of these transports through the Solomon Sea, including the New Guinea Coastal Undercurrent (NGCUC) western boundary current. Ultimately these measurements should provide descriptions and indicators of transport processes that can improve predictions and models of the Pacific's climate variability.

Solomon Sea transport is important because (1) it is the main source for the Equatorial Undercurrent that is central to equatorial air-sea interaction, (2) it is a key unmeasured element of the shallow overturning circulation in the Pacirfic, which plays a key part in heat flow in the global climate, and (3) understanding how this transport impacts the equator should improve prediction of ENSO and decadal variability by providing data for (a) empirically based prediction and (b) testing and improving dynamical models used for forecasting.

Gliders are used to directly measure volume transport above 700 m and to infer the vertical structure of velocity, temperature and salinity from hydrography. The project began in 2007 with the initial goal of finding ways to reliably transit the Solomon Sea from shore to shore. Goals in 2008-2009 were to begin a transport time series and to reduce operational costs. By 2010 we were able to support 4 cruises a year, typically providing 8 crossings of the Sea per year. Added goals were (a) to understand boundary current variability and (b) to modifying sampling to make the data more useful for analysis. In 2011 a pair of PIES straddling the Solomon Sea began measuring the horizontally integrated flow at the pressure gauge depth. Mini-moorings were added in 2012 to provide hydrographic indicators of the integrated flow above that depth. A current goal is developing a stable, well-documented system to provide data sets and indicators to scientists predicting and modeling equatorial variability. If the climate utility of these data and indicators is demonstrated, the measurement of transports through the Solomon Sea could become a sustained observation that we would propose to continue.

Within the larger CORC program, the Solomon Sea effort is a pilot program for using gliders and PIES to effectively monitor the most climatically important transports of mass, heat and freshwater. These data also provide a basis for integrating boundary-current observations with global data like Argo and for combining dynamical models with observations using data assimilation. The 2009 COSC report on CORC noted that within a development effort, measuring at two sites, one quite remote, must be justified. In addition to the scientific and prediction interest of the Solomon Sea, the strength of the boundary current flow, its highly variable nature, the remoteness of operations, and the limited infrastructure in the Solomon Sea are all important problems to be solved that are not present in the California Current.

### Progress and achievements

Activities fall into three categories: technical improvements, collecting a time series of Solomon Sea transects, and analysis of the transport variability described by these data. Achievements as of August 2012 are**:**

***Technical***

In 2007-2009 techniques were developed to make repeated Solomon Sea transects with gliders launched and recovered near shore from small boats. The Solomon Sea area is challenging, with few facilities and regions that are not safe for unarmed visitors. Team member William Kessler of PMEL made many trips to the Solomon Islands and Papua New Guinea (PNG) to develop political connections, to find local people and facilities to help operations, and to tend the clearance process in both countries. Mr. Danny Kennedy of Gizo Island (Solomons) became invaluable by providing support facilities, providing boats, and completing deployments and recoveries on his own.

In these early cruises we discovered that the primary threats to successful transects were fish attacks and strong northward currents during El Niño. On several occasions gliders were upset in flight after which performance was degraded; recovery disclosed damage that was often identified as shark or billfish strikes. The glider components most prone to damage were strengthened to decrease performance degradation. Strong El Niño currents made transits from the Solomons to our landfall in PNG difficult, often halting progress completely. To combat this we increased the glider's ability to change their volume, thereby allowing (a) increased speeds to fight adverse currents and to better follow prescribed courses and (b) greater operating depths over which average currents are typically weaker.

A fundamental tradeoff in our approach is between reducing the interval between transits and the cost of many trips to the Solomon Sea. We are addressing this by shipping and preparing pairs of gliders, launching one immediately and "storing" one for later deployment. Sometimes the stored glider is held on land and then launched by Mr. Kennedy; other times it is deployed with the first but left to loiter before beginning its transit.

***Operational***

From 2007 through August 2012 we completed 40 transects of the Solomon Sea, missing only four planned transects because of damage to, or malfunction of, our gliders. Most transits crossed the Solomon Sea near 10$^{o}$S while some explored flow in the northern Sea. No gliders were lost, but one was damaged so badly as to be useful only for parts; two required heroic rescues with invaluable assistance of local residents. The transect frequency has increased from 3.5 per year in 2007-2008 to an average of 9 per year over 2009-2012. Four less cruises were completed than proposed. The number of losses was less than anticipated, but costs of maintenance and repairs were slightly greater.

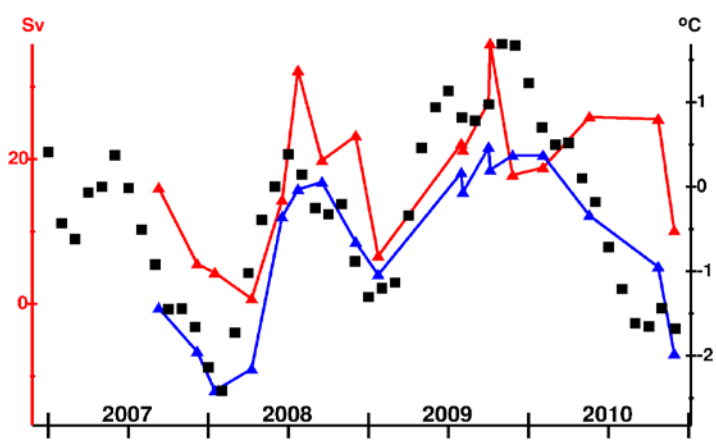


***Fig. 1.1*** *Time series of equatorward total transport above 700 m ( red), transport above 700 m of geostrophic velocity relative to 700 m (blue), and the Nino 3.4 SST index (squares). The higher total transport shows the effect of flow at 700 m. The correlation with ENSO is evident. The 2010 divergence of geostrophic and total transport is noteworthy.*

Fig. 1.1 shows a time series of equatorward transport through the

southern Solomon Sea through CY 2010 and its relation to ENSO. As COSC noted in its 2009 review, sampling was then apparently aliased. Figure 1 suggests that while the transports are noisy (± 3 Sv) the signals of interest are well described. Denser coverage since 2011 reduces eddy noise and allows determination of the timing and evolution of events. A transect takes 5-8 weeks so, as COSC noted, the sections are not synoptic. They are, however, taken much faster than the most energetic signals and the slow sections may be even more representative than the same number of synoptic sections because of time averaging during the transit.

Increased sampling frequency over time resulted from technical improvements and improved operational procedures. This was accompanied (a) by decreased operational cost per cruise enabled by greater use of local services and improved vehicle reliability and (b) by sampling arrays with more regular time intervals and more nearly repeated tracks that assist analysis.

Additional time resolution and horizontal integration of transports is obtained from a pair of PIES and mini-moorings deployed across the Solomon Sea. The first pair of PIES was deployed from locally chartered boats in February 2012, after suitably flat locations in the reef environment had been found on a reconnaissance mission with echosounders and lowered cameras. The mini-moorings were deployed in July 2012 during a French research cruise. These are small enough to be recoverable with local boats. PIES and mini-moorings carry acoustic modems, and the data can be downloaded via the CORC developed modem gliders, or from small local boats with an over-the-side modem (e.g. during glider deployment/recovery operations). First data from both PIES were acoustically retrieved during the mooring cruise in July, and first mooring data were just (October 2012) successfully retrieved acoustically on the eastern side using a small boat during a glider deployment mission (see figure 1.2)

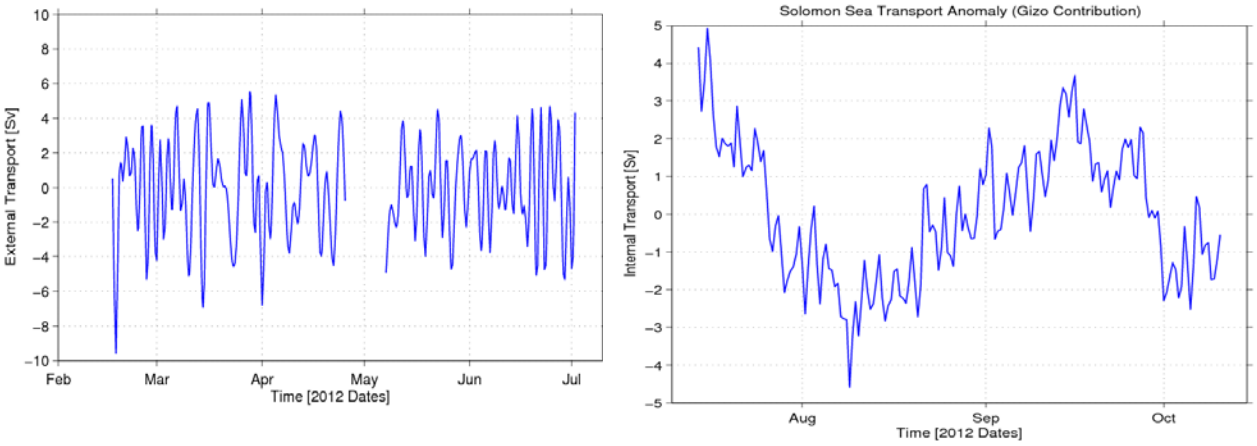


***Fig. 1.2*** *Transport timeseries [Sv] estimated from initial data downloaded from moorings and PIES. Left: 0-500m geostrophic transport from bottom pressure difference fluctuations across the Solomon Sea, in the 2-30day band (later longer periods can be analyzed when sensor drift can be better removed). Fluctuations of +/-4Sv can be seen. Right: 40-500m geostrophic transport from dynamic height determined at the eastern mooring (holding the western end fixed). Longer-period changes of +/-3Sv are found.*

***Scientific Results***

In December 2011 we completed an analysis of the data through 2010. The preliminary findings, based on only 3.5 years, are:

*Transport.* Over the 3.5 year time series, which included an El Niño and two La Niñas, the equatorward transport above 700 m averaged 15 Sv with fluctuations of ±15 Sv. This transport was moderately well correlated with ENSO (r=0.54 with the Nino 3.4 SST index). The strongest equatorward flow was during the 2009-2010 El Niño and flow was weakest during the two La Niñas.

*Vertical Structure of Variability.* The vertical profiles of cross-basin-averaged equatorward flow can be well described by two modes (EOFs) that describe two-layer flow. One layer spans 0-250 m depth and the other 300-700 m; tails of both modes contribute to flow over 200-300m. Interestingly, it is water in the 200-300-m zone that has the density of the Equatorial Undercurrent and is, therefore, capable of modulating air-sea interaction when upwelled. The shallow layer is well correlated with ENSO (r=0.94 with Nino 3.4) while the deep flow varies on similar time scales but is apparently unrelated to ENSO.

*Transport paths.* At the southern entrance to the Solomon Sea the NGCUC is prominent, carrying water from the Coral Sea along the PNG coast at depths below 300 m. At this southern entrance, a second concentrated flow is observed at mid-basin above 300 m. Confirmed by property analysis, farther north within the Solomon Sea, these two sources join into a western boundary current with deep flow coming from the Coral Sea and shallow flow coming directly from the South Equatorial Current by way of the mid-basin jet.

*Horizontal Structure of Variability.* Deep variability is focused in the western boundary current but shallow variability is distributed over the western two-thirds of the Solomon Sea. Across the Sea's southern entrance, the dominant mode of shallow variability is opposite flow perturbations in the mid-basin jet and along the PNG coast; the jet dominates during El Niño.

## Publications


Gourdeau, L., W.S. Kessler, R.E. Davis, J. Sherman, C. Maes and E. Kestenare, 2008. Zonal jets entering the Coral Sea. *J. Phys. Oceanogr.* 38, 715-725.

Davis, R.E., M.D. Ohman, B. Hodges, D.L. Rudnick, J.T. Sherman, 2008. Glider surveillance of physics and biology in the southern California Current. *Limnol. Oceanogr.* **53**, 2151-2168.

Checkley, D.M., Jr., R.E. Davis, A.W. Herman, G.A. Jackson, B. Beanlands, L.A. Regier, 2008. Assessing plankton and other particles in situ with the SOLOPC. *Limnol. Oceanogr*. **53**, 2123-2136.

Roemmich, D., G.C. Johnson, S. Riser, R. Davis, J. Gilson, W.B. Owens, S. Garzoli, C. Schmid, M. Ignaszewski, 2008. The Argo Program: Observing the Global Oceans with Profiling Floats. *Oceanoography.* **22**(2), 34-43.

Todd, R.E., D. L. Rudnick, and R.E. Davis, 2009. Monitoring the greater San Pedro Bay region using autonomous underwater gliders during fall 2006. *J. Geophys. Res.,* **114,** C06001

Simons, F.J., G. Nolet, P. Georgief, J.M. Babcock, L.A. Regier, R.E. Davis, 2009. On the potential of recording earthquakes for global seismic tomography by low-cost autonomous instruments in the ocean. *J. Geophys. Res.,* **114,** B05307.

Davis, R.E., 2010. On the coastal-upwelling overturning cell. *J. Mar. Res.,* **68**, 369-385.

Todd, R.E., D.L. Rudnick, M.R. Mazloff, R.E. Davis, and B.D. Cornuelle, 2011. Poleward flows in the southern California Current System: Glider observations and numerical simulation. *J. Geophys. Res.,* **116,** C02026

Todd, R.E., D.L. Rudnick, R.E. Davis, and M.D. Ohman, 2011. Underwater gliders reveal rapid arrival of El Niño effects off California's coast. *Geophys. Res Lett.*,. **38,** L03609

Todd, R.E., D.L Rudnick, M.R.. Mazloff, B.D. Cornuelle, and R.E. Davis, 2012. Thermohaline structure in the California Current System: observations and modeling of spice variance. *Geophys. Res.* **117,** C02008,

Davis, R.E., W.S. Kessler and J.T Sherman, 2012. Gliders measure western boundary current transport from the South Pacific to the equator. *J. Phys. Oceanogr.* in press

## B: Sustained observations in the California Current System

Eastern boundary currents are locations where global climate processes have profound regional and coastal impacts. Their sustained observation will enable analyses of the connection across these three scales, will enable understanding of how ocean climate variability governs carbon, acidification, ecosystem, and coastal climate, and ultimately lead to information for management and forecasting efforts.

CORC efforts in the California Current System (CCS) have the goal to develop and demonstrate methods and technologies for efficiently observing eastern boundary currents, and to initiate sustained boundary current observations at one location. An aim is to devise and disseminate products about these boundary current systems allowing descriptions, analyses, management, and predictability studies of climate change and impacts, and to facilitate the implementation of future sustained boundary current sites around the globe.

The choice of the CCS for developing the boundary current observation system was motivated initially by logistical convenience, but also by the societal relevance of climate fluctuations along the US west coast. Although not as strong as a western boundary current or likely to impact global atmospheric climate, the CCS is an example of the eastern boundary currents that in each ocean basin are home to large productive marine ecosystems that exhibit economically important responses to climate variation. Understanding and predictiing these ecosystem changes require observation and modeling to describe alongshore transport, overturning circulations, and responses to local air-sea interaction. The CORC observation and reanalysis system can provide a physical basis for effective ecosystem based management.

We are fortunate in southern California to have the 50-year California Cooperative Fisheries Investigation (CalCOFI) program, with its unique sustained measurements of physical, chemical, and biological variables in the SCB. The CalCOFI time series are special in their length, their spatial coverage, and their diversity in variables measured. CalCOFI has allowed a more thorough understanding of decadal variability than is possible in any other coastal region. CORC will enhance the sparse physical observations of CalCOFI and provide important complementary observations for interpreting the ecosystem changes observed by CalCOFI.

## Glider observations in the California Current System

### Objectives and approach

Two main objectives, one technical and one scientific, drive sustained glider observations in the California Current System (CCS). The technical objective is to demonstrate the utility of gliders in measuring a boundary current system in a logistically convenient location. The scientific objective is to quantify the regional effects of climate variability in a biologically productive eastern

boundary current system. Our approach involves the repeated deployment of Spray underwater gliders on a series of lines off the California coast. With the longest continuously occupied time series approaching 6 years in length, we believe we have addressed each of our primary objectives.

## Progress and achievements

***Technical and operational***

Our Southern California Glider Network (SCGN) is the longest running sustained glider network in the world, to our knowledge. We have established operations on CalCOFI lines 66.7 (Monterey Bay), 80.0 (Point Conception), and 90.0 (Data Point). Funding has come from a variety of sources, including state and private, with the support over the last few years being through CORC (lines 66.7 and 90.0) and the Southern California Coastal Ocean Observing System (SCCOOS, line 80.0). A reasonable metric of our performance is the number of operational glider-days /day, with the goal of having 3 glider-days /day in the SCGN (Figure 2.1). Lines 80.0 and 90.0 were started in late 2006, with line 66.7 initiated in late 2007. By late 2008, all three lines were being occupied continuously.

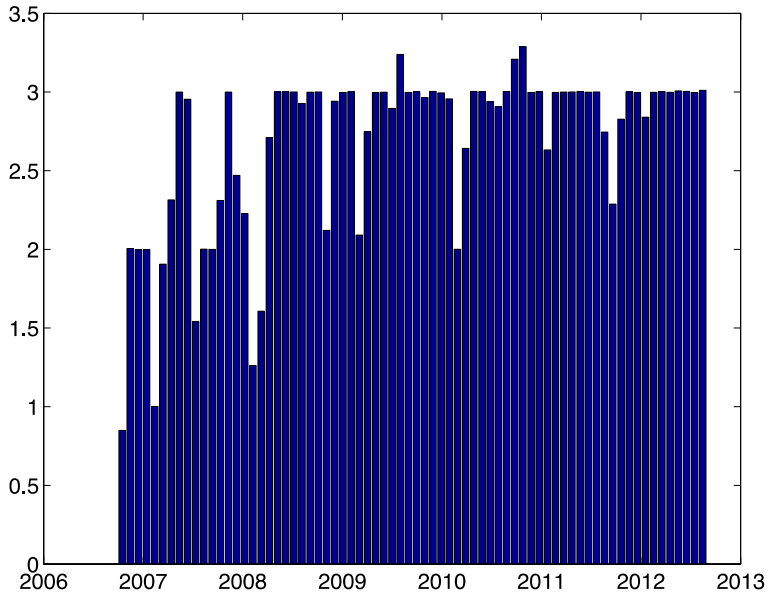


***Figure 2.1*** *Spray glider-days/day in the Southern California Glider Network, averaged in 30-day bins. Gliders have been sustained along three lines routinely since late 2008.*

Fluctuations in glider-days/day are caused by gaps in coverage or overlapping deployments on a line. Since 1 January 2009, coverage has been 97%, which is a fair bulk measure of operational success. To date, the SCGN has done a total of 57,000 dives, covering 128,000 km in 6200 glider-days.

The Spray glider fleet deployed in the CCS measures physical and biological variables at horizontal resolution of kilometers and temporal resolution of weeks. In this application, Spray dives between the surface and 500 m, completing a cycle in 3 hours, during which time it moves 3 km in the horizontal. Spray occupies lines 350-550 km long, completing one pass in about 3 weeks. Measured variables include pressure, temperature, salinity, depth-average and depth-dependent velocity, chlorophyll fluorescence for phytoplankton, and acoustic backscatter for zooplankton. Data is transferred to shore on surfacing, when piloting commands may be also be sent. Recoveries and

deployments are done from small boats, with a typical mission lasting about 100 days. We have pioneered the use of Acoustic Doppler Profilers (ADPs) on gliders. To our knowledge, we have by far the most extensive observations of depth dependent velocity and acoustic backscatter from gliders.

Glider data are distributed in real time for a variety of purposes. Perhaps the most important real-time application of glider data is to initialize ocean models. Data from SCGN are being used by modeling groups at the Naval Oceanographic Office (NAVO), the Jet Propulsion Laboratory (JPL), and by colleagues in CORC. The NAVO and JPL modeling efforts are for short term prediction, so they are delivered data several times per day. The CORC modeling effort focuses on the analysis of ocean state through 4DVAR methods. By virtue of the large number of profiles, glider data have a strong effect on assimilative predictions.

We believe the SCGN is a model for sustained glider operations along the US coast. Having proven the concept, the next step is to establish a national glider network. PI Rudnick is taking a leadership role in planning a national glider network through the US Integrated Ocean Observing System office. A workshop was held in August 2012, and a plan is being written with a goal of completion during the first quarter of 2013. Should a national glider network become a reality, it would add to the CORC legacy of being an initiator of sustained observing systems.

***Scientific***

*Alongshore flow.* As one of the goals of observing boundary current systems is quanitification of meridional transport, an initial target of analysis was alongshore flow (Davis et al., 2008; Todd et al., 2011b). Gliders measure depth-average velocity by dead reckoning. Glider velocity relative to the water is estimated from measurements of pressure and vehicle orientation. Differencing this displacement from the travel measured by GPS yields depth-average velocity. This depth-average velocity serves as a reference for vertical shear measured by ADP, or for geostrophic shear from density gradients. Gliders revealed a previously poorly known deep core of poleward flow in the CCS that was undetected by the traditional approach of assuming vanishing deep flow in geostrophic calculations. Alongshore flow is forced by annual fluctuations in wind along the coast. This annual set-up forces Rossby waves that propagate westward, eventually to form eddies that continue across the basin. These Rossby waves were definitively identified in the sustained glider observations.

*El Niño.* The El Niño/La Niña cycle is the climate variability most keenly felt along the coast of California. These fluctuations affect everything from fisheries to weather, making an El Niño the most obvious climate effect to the public in this region. Glider observations have proven to be especially useful for quantifying the local effects of El Niño (Todd et al., 2011a). A Hovmüller plot of temperature anomaly at 50 m on line 90.0 helps to understand the value of glider sampling (Figure 2.2). Fluctuations in the inshore 200 km, in the Southern California Bight (SCB), are in phase, and reflect the El Niño cycle. Offshore of 200 km, there is evidence of westward propagation. The gray dots show locations and times of glider profiles. The slope of the lines of dots indicate the gliders' relatively slow speed. Even so, it is apparent that the repeated section every 3 weeks are adequate for El Niño time scales. To form a SoCal Niño Index, we average temperature anomaly inshore of 200 km, and filter with a 3-month running mean (Figure 2.3). The SoCal Niño Index is remarkably correlated with the Oceanic Niño Index (Nino 3.4 filtered with a 3-month running mean). This immediate response implicates an atmospheric teleconnection between the CCS and the equator. The indices are just now crossing through zero on the increase. We plan to

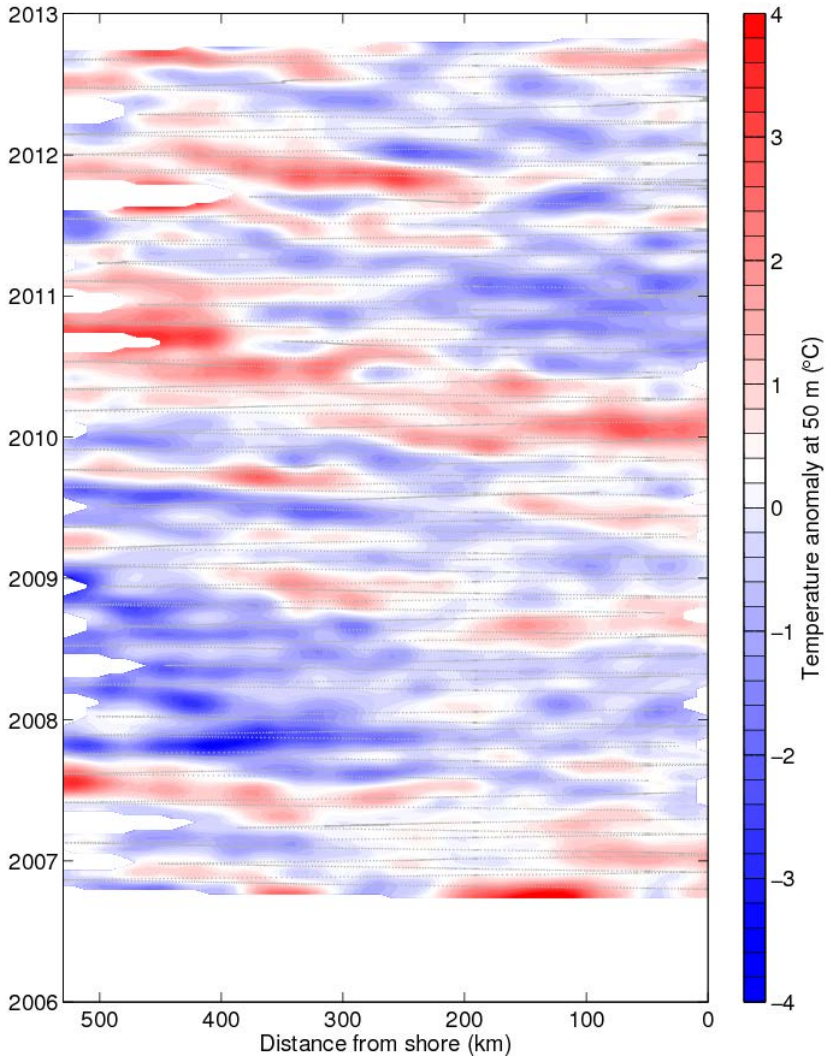


***Figure 2.2*** *Hovmüller plot of temperature anomaly at 50 m on line 90. Gray dots show the locations and times of glider profiles.*

update the SoCal Niño Index monthly and post it on the web, as the El Niño NCEP has predicted for this year develops.

*Glider data in the CORC reanalysis.* The value of sustained observations by gliders is fully realized through assimilation into models. The CORC reanalysis is now routinely assimilating glider data, and has been used to examine poleward flow in the CCS (Todd et al., 2011b) and thermohaline variability (Todd et al., 2012). The classic coastal circulation issue is to identify the source of water (important to the supply of nutrients through upwelling) and the destination of water (relevant to the dispersion of pollutants). Using temperature/salinity variability on an isopycnal, sometimes called "spice", we used the combination of glider data and the CORC reanalysis to identify the source of water in the SCB, and to deduce horizontal and vertical effective diffusivities. This sort of study is only possible through the complete CORC observation/modeling system.

*Ecosystems.* We have been collaborating with Sam McClatchie at NOAA Southwest Fisheries Science Center. Our contribution to a series of studies has been to use gliders to provide the physical background and bulk biological quantities to support more detailed measurements of organisms. The first of these studies examined the ecosystem surrounding a front that is nearly permanent on the offshore side of the SCB (McClatchie et al., 2012). Both physical and biological variables changed markedly across the front. The prevalence of icthyoplankton predators shoreward of the front made the offshore side safer for the commercially valuable sardine to spawn.

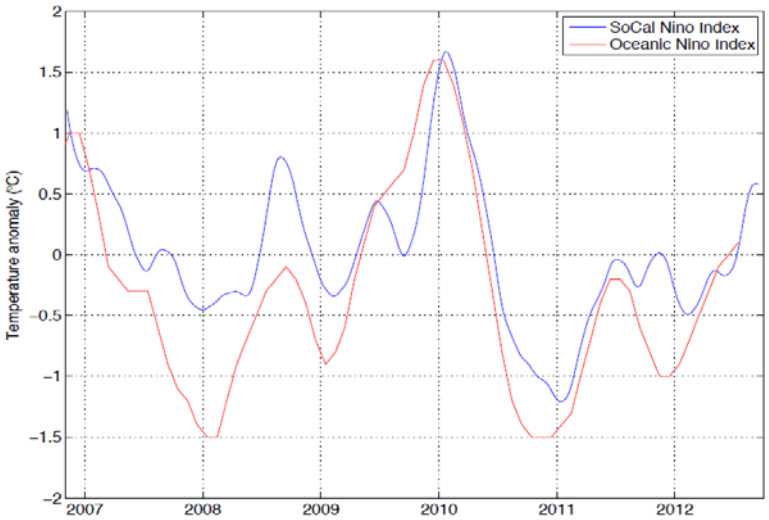


***Figure 2.3.*** *The SoCal Niño Index, temperature anomaly at 50 m on line 90, averaged over the inshore 200 km, and filtered with a 3-month running mean (blue), and the Oceanic Niño Index (red).*

*Water quality.* One of our early uses of gliders in the SCB was to identify an outfall plume over the shelf (Todd et al., 2009). Focused surveys and the regular line 90 observations showed evidence of fresh water from a sewage outfall. A value of gliders in a boundary current system is to resolve processes from climate scale down to shelf circulation. This dual use of the same observation system is a unique strength.

## References


Davis, R. E., M. D. Ohman, D. L. Rudnick, J. T. Sherman, and B. Hodges, 2008: Glider surveillance of physics and biology in the southern California Current system. *Limnology and Oceanography*, **53,** 2151-2168.

McClatchie, S., R. Cowen, K. Nieto, A. Greer, J. Y. Luo, C. Guigand, D. Demer, D. Griffith, and D. Rudnick, 2012: Resolution of fine biological structure including small narcomedusae across a front in the Southern California Bight. *Journal of Geophysical Research*, **117,** C04020, doi:10.1029/2011JC007565.

Todd, R. E., D. L. Rudnick, and R. E. Davis, 2009: Monitoring the greater San Pedro Bay region using autonomous underwater gliders during fall of 2006. *Journal of Geophysical Research*, **114,** C06001, doi:10.1029/2008JC005086.

Todd, R. E., D. L. Rudnick, R. E. Davis, and M. D. Ohman, 2011a: Underwater gliders reveal rapid arrival of El Niño effects off California's coast. *Geophysical Research Letters*, **38,** L03609, doi:10.1029/2010GL046376.

Todd, R. E., D. L. Rudnick, M. R. Mazloff, R. E. Davis, and B. D. Cornuelle, 2011b: Poleward flows in the southern California Current System: Glider observations and numerical simulation. *Journal of Geophysical Research*, **116,** C02026, doi:10.1029/2010JC006536.

Todd, R. E., D. L. Rudnick, M. R. Mazloff, B. D. Cornuelle, and R. E. Davis, 2012: Thermohaline structure in the California Current System: Observations and modeling of spice variance. *Journal of Geophysical Research*, **117,** C02008, doi:10.1029/2011JC007589.

## Integrating and high-frequency observations in the California Current System

### Objectives and approach

The objective is to develop and demonstrate cost-effective tools for documenting and understanding broad-scale and high-frequency impacts of climate variability in an eastern boundary current such as the CCS. We use a combination of moorings, inverted echosounders with pressure sensors (PIES), gliders, and acoustic communication technology.

The tools employed complement the glider observations outlined above in several ways. Horizontal transports over long distances can be determined with end-point observations instantaneously, without the need for mapping slower glider transects in space and time or assimilating them in state estimates. These horizontal integrals, as well as vertical temperature integrals from the PIES, are providing effective constraints on the state estimates and have already helped to improve the assimilation technology (see section 4). In addition, timeseries observations at fixed locations provide observations of high-frequency processes that are widely believed to be crucial in the response of the ecosystem, organisms, and fish to climate processes (impact of ocean acidification, upwelling variability, hypoxia, etc). Continuous observations at fixed locations or in integrating mode also lend themselves naturally to producing short-term products and indicators, while gliders with typically 3-week transects are ideal for more complete spatial descriptions on longer timescales.

The cost-effectiveness is being addressed in several ways. The deployment period of CORC subsurface moorings has been increased to over 2 years recently, PIES can remain deployed for 4 years. The modem gliders used for telemetering data from moorings and PIES are increasing their endurance via the new feature that allows “loitering” at 500m depth or below (resulting in prolonged battery life and reduced fouling), so that 1-year deployments for gliders seem feasible. Synergies with the CCE biogeochemical moorings are also being exploited now (the new CCE1 mooring will carry an acoustic modem to telemeter data from a new co-located CORC PIES and will collect dynamic height data for geostrophic transports). In some cases gliders may be usable as “virtual moorings” which is another approach being actively tested at present.

### Progress and achievements

We had originally hoped to have implemented, within 3 years, an integrated system that uses real-time in-situ observations, merges them with via assimilation among each other and with satellite altimetry and wind data, and routinely produces indices for the climate state and climate impacts of the California Current. A goal was also to establish a system which could serve as the nucleus for a west-coast wide observing system, and to which biogeochemical and ecosystem observations could be added easily. For reasons outlined below, the observational capability for this took longer to develop, but is in hand now and deployed. The modeling capabilities are still evolving toward the desired results (see section 4), but CORC has now started to produce indices about the CCS state and processes (see section 6). The specific achievements of the integrating and high-frequency observations are summarized in the following subsections.

***Technical***

A core component of the short-term data and product delivery was a new technology to use gliders for acoustic communication with subsurface platforms like moorings and PIES. This in the end took several years to develop to the point of routine operation, but the technology is now robust and data transfer capability is reliable with high degrees of success rates (see annual reports). Another new feature that was implemented is the capability for the gliders to "loiter" at depth, thus reducing battery drain and fouling. Only after these development efforts were completed could more gliders be fabricated with these new capabilities. Bottlenecks in glider production at SIO meant that the production then needed to be spread over several years. While the 6 modem gliders were eventually produced as originally envisaged and funded, two were lost during operation. Only one could be replaced with funding from the CORC coordination task. As a consequence, 5 modem gliders are now available to CORC as of summer 2012.

***Operational***

We have collected a 4 year long record of fixed-point data (density, dynamic height, bottom pressure, vertical traveltime) along line 90 using two deployments of the instruments (moorings, PIES). This has yielded enough data to design an efficient operational approach for capturing the variability of alongshore transport - see below for the correlation between satellite altimetry and the mooring transports. Telemetering mooring and PIES data with the modem-equipped gliders has been made routine and now being used operationally. Gliders are currently parked in "loitering" mode at mooring/PIES sites, and can be woken up to retrieve and telemeter data when needed/wanted.

At the time of writing, we have two moorings, 5 PIES, and 3 modem gliders in the water. As mentioned, the PIES have a 4-year endurance and are easy to deploy. The moorings are cost-effective sub-surface moorings, and the gliders are expected to approach a 1-year deployment length. Starting next week, we hope to be able to obtain daily to weekly data (depending on need) about isopycnal movements (for local upwelling state) and cross-shelf geostrophic transport referenced to the PIES bottom pressure (for the large-scale upwelling circulation).

We have started to generate indices from the high-frequency observations, which will be provided on the CORC website. One represents the alongshore transport of the main southward flowing part of the California Current, between 120° 30'W and 126° 15'W along line 90. These are the boundaries of the mean boundary current flow, as judged from glider sections on the inshore side, and from mean dynamic height on the offshore side. Another index shows the upwelling intensity in terms of isotherm depth at two comparable locations on line 90 and line 80, derived from the moorings there. This index is expected to reflect more realistically the actual in-situ upwelling activity, as opposed to atmospherically derived indices like the NOAA upwelling index. On line 80 we have verified that this is the case, on line 90 this is work in progress. The cross-shore geostrophic flow should be available soon with weekly resolution. A combined mooring-glider index for the occurrence of warm southern ("tropical") water in the CORC/CalCOFI area is also under construction. This origin of water has a strong influence on ecosystem properties and fish species encountered.

***Scientific***

*Alongshore transport:*

We have collected four years of geostrophic transport data for the main branch of the southward flowing California Current, between the edge of the inshore Undercurrent and an offshore minimum in dynamic height gradient, an approximately 700km long section. These are the first such data

which are referenced to a large depth (here 3500m) and in addition we measure the bottom pressure fluctuations there to assess barotropic components. We found that in the mean, the surface flow goes from southward to northward at 300m depth. Thus 300db is a better reference level, and 0-300m a better layer, for the California Current, than 500db which is often used. We also found that the deep pressure fluctuations add about 0.5Sv to the total transport variability. The mean transport of the CC is determined at 3.1Sv southward, and without the large anomalous positive event at the end of 2008 (see figure 1) it is 3.4Sv.

Once a long reference record of the transport is available, we can test to what extent satellite altimetry can capture the transport. Figure 2.4 shows the comparison between the best estimate from the moorings and bottom pressure versus a suitably scaled sea surface height difference over the same section. The skill is high ($R^2$=0.86), and at 60day timescales has an rms misfit of 0.22Sv, allowing future determinations of the southward transport from altimetry, with the scaling derived from our 4-year mooring/PIES record.

Planned work includes closer investigations of the strength and time variability deep flows, both below 300m and in the lower 1000-2000m, about which very little is known. The fully calibrated data for this will be in hand at the end of 2012.

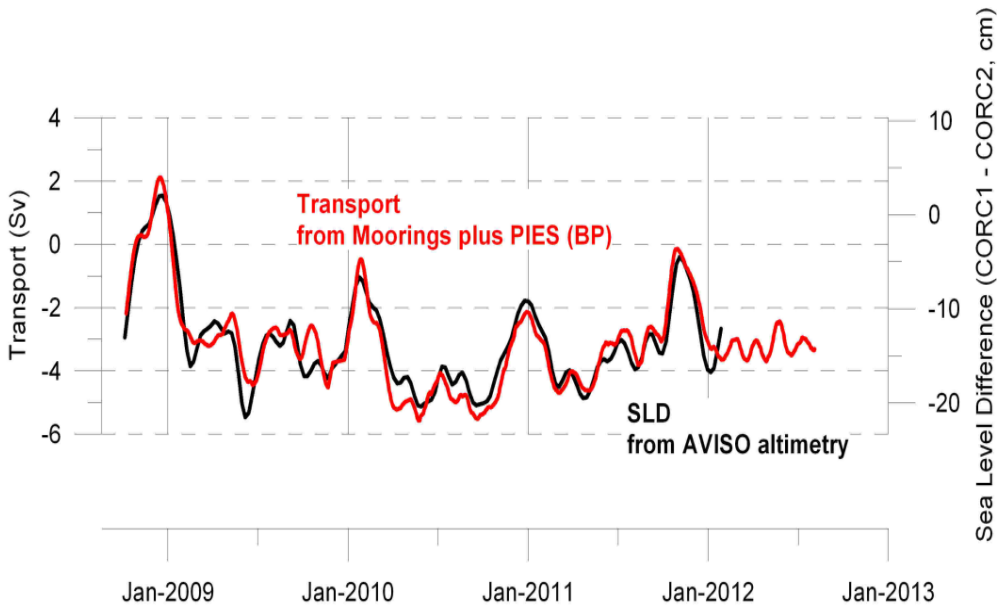


***Figure 2.4:*** *Total CC geostrophic transport from CORC moorings and PIES bottom pressure (red) and best-fit AVISO sea surface height difference between mooring locations.*

*Vertical heat content:*

The PIES instruments also measure vertical acoustic traveltime, which to first order is a measure of vertically integrated temperature. The five PIES we had deployed along line 90 show a lot of high-frequency variability, together with clear westward propagating anomalies (similar to the glider Hovmüller plots in fig.2.2). Here we only show (figure 2.5) a record from PIES2 which is also the new CORC4 mooring location. Over the available record a good correlation with the ENSO index is found, but we need longer timeseries to verify and study this correlation in more detail.

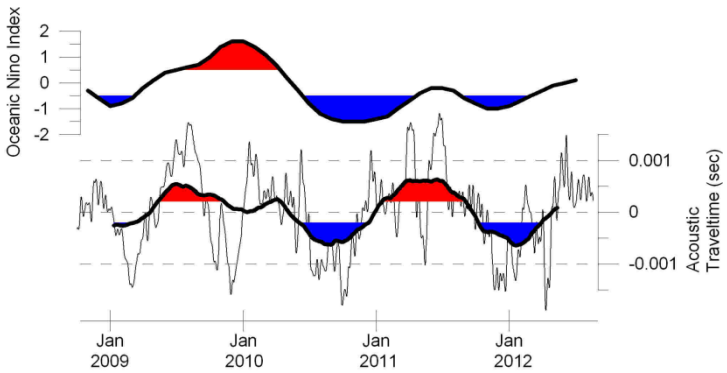


***Figure 2.5:*** *Oceanic Nino index and vertical acoustic traveltime from PIES2 instrument on line 90.*

*Mooring/PIES data in the CORC state estimates:*
The scientific collaboration with the modeling and assimilation partners within CORC has been productive. Initially, the state estimates did not well reproduce the alongshore transport of the California Current, probably because there were insufficient data to constrain this quantity. Insertion of the mooring and PIES data into the model has gradually improved the state estimate for the alongshore flow (see figure 4.1). For the vertical traveltime data a novel integral constraint was developed for the model (which actually uses the acoustic traveltime as input data). Similar work is planned for the mooring-derived transports (at the moment the model only uses the T and S from the moorings).

## Outlook

The new focus for routine observations is the cross-shore flow, upwelling variability, and temperature/heat content changes, since this is more directly related to applications for local climate, for ecosystem and fisheries, and for carbon/ocean acidification/hypoxia processes. Since summer 2012, the two CORC moorings and PIES on line 90 form a box with the CCE moorings on line 80, where also PIES have been deployed. This new configuration will allow determination of along-shore gradients of bottom pressure and dynamic height, from which we plan to estimate cross-shore transports and also provide one of the driving forces for the California Undercurrent (i.e. the alongshore bottom pressure gradient at the shelf slope).

The CORC high-frequency and integrating timeseries provide important physical variability and its relation to large-scale climate processes for regional applications in multiple disciplines. There is a natural synergy with the multi-disciplinary CCE moorings which NOAA OCO also partially supports. Merged products and indicators from both will provide information to the larger community about the physical drivers and their impacts. The combined use of these platforms, together with gliders collecting physical and biogeochemical data in section mode, can serve as a model or nucleus for an expanded network along the US west coast.

## References

Send, U., and S. Nam (2012): Relaxation from Upwelling: the effect on dissolved oxygen on the continental shelf. J. Geophys. Res. VOL. 117, C04024, doi:10.1029/2011JC007517

Nam, S., H.-J. Kim, and U. Send (2011): Amplification of hypoxic and acidic events by La Nina conditions on the continental shelf off California. Geophysical Research Letters. VOL. 38, L22602. doi:10.1029/2011GL049549

Send, U., L. Regier, and B. Jones (2012): Use of underwater gliders for acoustic data retrieval from subsurface oceanographic instrumentation and bi-directional communication in the deep ocean. J. Atmos. Ocean. Techn. In press

## C: Analysis of XBT, Argo, altimetry, and other datasets

### Objective and approach

XBT/Argo/altimetry data are analyzed to demonstrate the value and capabilities of the ocean observing system by synthesizing boundary current and interior ocean observations. Spatial domains include regions having CORC boundary current observations, and regions where additional boundary current observations may be implemented in the future – to understand needs and requirements. Objectives are to determine boundary current mean and time-varying transport in relation to the interior ocean and to close the time-varying mass, heat, and freshwater budgets for large ocean areas and ocean-spanning transects.

While many valuable goals have been articulated for inclusion of boundary current observations in the ocean observing system for climate, the evolution of the present system, which is very sparse in the boundary current regions, will be gradual and deliberate. It's unlikely that global boundary current observations can be implemented at the level recommended by OceanObs09. Rather, locations and system elements will be prioritized and implemented on the basis of cost-effectiveness and user benefits. For ocean/climate applications, the large role of western boundary currents in the mass, heat, and freshwater budgets of the oceans will be is a high priority. On an ocean-wide basis, estimation of the heat and freshwater transports requires closing the mass balance, which must include both the ocean interior and the equally large boundary current contributions. Cost effective observation techniques include Argo plus High Resolution XBT and glider transects, and it is important to understand the capabilities and limitations of these data, in combination with satellite altimetry, for constraining boundary current transport. This work focuses on statistical analyses of sustained datasets, and is a complement to CORC's ocean data assimilation modeling effort.

### Progress and achievements

***California Current system***

A broad spatial perspective of the Northeast Pacific, that includes both the California Current system and the eastern interior region was described (Auad et al., 2011) using Argo, High Resolution XBT, and CalCOFI data. The limitations of Argo coverage near the coast were illustrated, and the value of transect data (XBT, CalCOFI) was highlighted. New estimates were presented of the mean equatorward transport of the California Current (5 Sv) and the poleward California Undercurrent (2.5 Sv), of the time variations of heat and freshwater content caused by alongshore advection, and of the exchanges of coastal and interior ocean water masses.

***Solomon Sea***

Argo data in the ocean interior east of the Solomon Islands and in the Solomon Sea, provide basin-integrated estimates of the mean and time-varying transport of the of the South Pacific's shallow overturning circulation. Zilberman, Roemmich, and Gille (2012a) found that the ENSO fluctuations in the ocean interior transport (about 11 Sv per unit of Nino 3.4 index for annual mean values) were larger than those in the Solomon Sea (4 Sv per unit of Nino 3.4 index), and that the ocean interior and WBC ENSO fluctuations were oppositely phased. A comparison is made of the consistency of Argo-based and glider-based transport in the western boundary region. In this work, the ocean's

mean and time-varying mass and heat budgets are closed for the region north of 7.5°S, including the Indonesian Throughflow transport as a residual of geostrophic and Ekman flow across 7.5°S.

***Other western boundary currents***

In the future, CORC will implement boundary current observations in additional western boundary regions. Our emphasis remains on combing transect information (e.g. High Resolution XBT) in the western boundary region with spatially distributed Argo and altimetric height data in the ocean interior, in order to estimate mass and heat transport across full ocean basins. Analyses using multiple High Resolution XBT transects combined with Argo were carried out for the East Australian Current/SW Pacific region (Roemmich and Gilson, 2011 and Zilberman et al., 2012b) and for the Kuroshio/NW Pacific (Roemmich and Gilson, 2011, Douglass et al., 2010, Giglio et al., 2012). In general, regular high resolution transects across the boundary regions can be combined with broadscale Argo data in the ocean interiors to provide accurate estimates of basin-integrated mass, heat, and freshwater transport.

### Publications, 2010-2012


Roemmich, D. and Co-authors (2010). Integrating the ocean observing system: Mobile platforms. In *Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society (Vol. 1),* Venice, Italy, 21-25 September 2009, Hall, J., Harrison, D.E. & Stammer, D., Eds., ESA Publication WPP-306.

Goni, G., D. Roemmich & Co-Authors (2010). "The Ship Of Opportunity Program" in *Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society (Vol. 2),* Venice, Italy, 21-25 September 2009, Hall, J., Harrison D.E. & Stammer, D., Eds., ESA Publication WPP-306.

Douglass, E.M., D. Roemmich and D. Stammer, (2010) Interannual variability in North Pacific heat and freshwater budgets. *Deep-Sea Research II 57,* 1127-1140.

Auad, G., D. Roemmich, and J. Gilson, (2011) The California Current System in relation to the Northeast Pacific Ocean circulation. *Progress in Oceanography*, 91, 576-592.

Roemmich, D. and J. Gilson, (2011) Ocean circulation and the mass and heat budgets of large ocean regions: The synergies of High Resolution XBT transects, Argo, and satellite altimetry. *Invited presentation* at the First XBT Science Workshop, Melbourne Australia, July 2011. http://www.aoml.noaa.gov/phod/goos/meetings/2011/XSW/

Giglio, D., D. Roemmich and S.T. Gille, (2012) Wind-driven variability of the subtropical North Pacific Ocean. Accepted by the *Journal of Physical Oceanography*.

Zhang, X., B. Cornuelle, and D. Roemmich, (2012) Sensitivity of western boundary transport at the mean North Equatorial Current bifurcation latitude to wind forcing. Accepted by the *Journal of Physical Oceanography*.

Zilberman, N.V., D.H. Roemmich, and S.T. Gille, (2012a) The mean and the time-variability of the shallow meridional overturning circulation in the tropical South Pacific Ocean. Submitted to the *Journal of Climate*.

Zilberman, N., D. Roemmich, and S. Gille, (2012b) Meridional transport in the South Pacific Ocean: Assessing the mean state and SAM and ENSO related variability. *In preparation*.


## D: State estimates and assimilation

Technical innovation has been a central goal of the CORC project, both in observations and their optimal use in a state estimate. We have been developing a long-term, regional, eddy-permitting state estimate that is far different from other efforts for the US west coast (USWC). The long-term assimilations are advantageous since baroclinic ocean dynamics are slow, and thus it takes many days for the information from a local measurement to move very far from that observation. The longer the assimilation time, the more the model dynamical constraints can accumulate the

information in the observations. Short assimilation windows, even with 4D-Var, are hard to distinguish from Objective interpolation (OI).

Part of the work has involved checking the quality of the estimate, which is a challenge without a source of independent data for cross-validation. When doing 4D-Var, the closeness of fit of the state estimate to the observations is not a complete indication of quality because what matters is how the information is spread in space and time between observations by the model dynamics. One example of this is seen in the Todd et al. (2012) paper where salinity variance on isopycnals can be tracked in the model between glider lines. Another example is prediction, as suggested by reviewers at the mid-term COSC review, where the ocean state is forecast forward and compared to new observations not used in the estimate. This has been done as a check on a similar state estimate in the Gulf of Mexico, where there was a clear quantity of interest to forecast. The choice of metric for prediction in California is less obvious, but we can start with SSH, and we will be working on this. We can also compare the adjusted forcing to independent observations, such as those that Mark Bourassa offered to compare at the COSC meeting. We have yet to follow up on this, but we were spending time on improving aspects of the estimate and its components.

In addition to the innovative long-term state estimates, which are used to produce climate quality hindcasts with delays of 6-12 months, we are also starting to test and demonstrate ways to use more standard short-term assimilations for producing near real-time products.

## Objectives and approach

The data assimilation effort is essential in CORC since it is the only way to fully merge and exploit the in-situ data, altimetry, and forcing, thus providing maximum impact from the observations. By using dynamical constraints the information is accumulated over time. It can also provide a laboratory for tracing the influences on the features of interest (indices such as SSH, transport, or heat content) to suggest observing strategies. The longer the assimilation can be (which requires better model quality), the fewer observations are needed for a given level of information. A goal is to know how long the window can be, how close the estimate can get to the observations, and what needs to be done to improve the model. The resulting reanalysis also serves as a springboard for collaborative scientific analysis with the observers.

The assimilating models also are intended to make the connection between global, BC, and coastal domains. We have used the adjoint methodology to study the influence of global scale climate indices on local ocean regions and to examine what the effects of remote and local forcing are on the tropical pacific SST (Zhang, et al. 2011), a western boundary current (Zhang, et al. 2012, in press), and for the eastern boundary (Verdy, Mazloff, and Cornuelle, in prep.).

## Progress, achievements, and challenges

***Achievements:***

We have achieved the original goal of technology development to allow for regional assimilation at eddy-permitting resolution with long duration windows. This has included development of refined open boundary adjustment methods, better treatment of altimeter means and anomalies, and incorporation of new data types, including IES. Mesoscale eddies modulate much of the alongshore and cross-shore flows, and the model is now converging to reproduce the variability including eddy signals, see figures 4.1 and 4.2. We have developed complementary Ensemble Kalman Filter (EnKF) tools for the MITgcm and used them for some short-term experiments. We have compared

with ROMS runs by HaJoon Song for the same region, on short timescales, and compared and contrasted the ROMS vs MITgcm assimilation system, but not in a publication. We have tested our reanalysis heat flux adjustments against independent estimates using high-resolution cloud images.

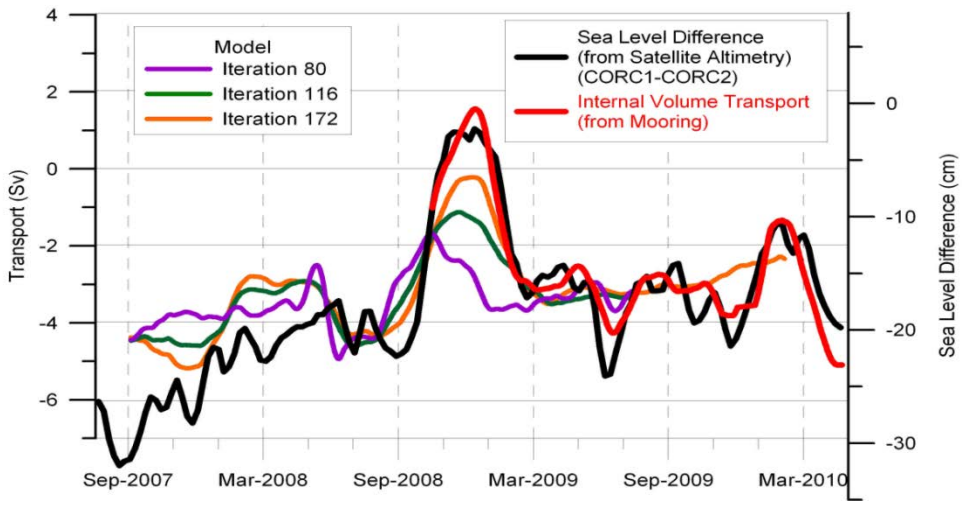


***Fig.4.1*** *California Current transport across line 90 from moorings (red), altimetry (black), and three iterations for the long-term adjoint state estimates.The mooring data start in October 2008, and the model clearly is converging to reproduce the large event in late 2008 due to an intense eddy or meander.The mooring data apparently help to constrain the transport on line 90 since prior to October 2008 the agreement with altimeter-derived transports is less good.*

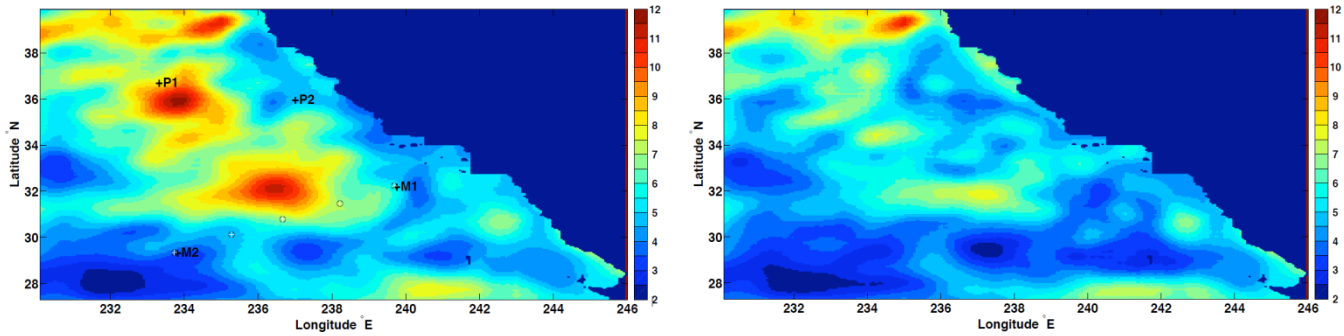


***Fig.4.2*** *Comparison of sea surface height from the adjoint model with AVISO altimeter measurements, expressed as RSM difference. Left is for the unconstrained run (iteration 0), right for iteration 172. The smaller differences in iteration 172 mean that eddy features are better reproduced after assimilating the CORC data.*

Not achieved yet is an operational near real-time assimilation system: at least two other groups offer real-time analysis and forecasts of aspects of the California current system, and therefore we focused on exploring new territory in regional assimilation by doing long-term re-analyses. We continue to do proof-of-concept runs with short assimilation windows, both with 4D-Var and EnKF, in order to demonstrate the options of generating near-realtime products. This is similar to the Gulf

of Mexico (GoM), where we have used the same machinery for near-real-time analysis and prediction of the Loop Current as participants (with other funding) in the Gulf of Mexico Pilot Prediction Program. Near-real-time operation in the CCS means using lower-quality and restricted ocean datasets and atmospheric estimates, and so has to be re-done later for a scientific reanalysis using the long-term adjoint runs. Computational constraints also mean using relatively short assimilation windows, meaning less value from the model dynamics and less accumulation of information from the observations.

***Challenges:***
Open boundary conditions were very challenging to get right, and we are still learning about them, especially the effects of restoring (sponge) layers at the boundary. To our knowledge, we are the only ones using this for eddy-resolving adjoint models. Running the eddy-permitting model for long periods means having to start with large horizontal eddy viscosities to suppress instabilities, and gradually reduce them as the state estimate improves. We are still trying to figure out how to best create the eddies that result from growing instabilities on the slowly-varying flows when they are suppressed by the viscosity. This may be the problem that limits the maximum duration of the state estimate.

In addition, representing the complex dynamics of the CCS via a limited number of key indices has presented a challenge. The significance of the CCS for the US has at least two components: climate effects and ecosystem effects. In the case of climate effects, SST or upper ocean heat content in regions would seem to be the important factor in the short term, while for ecosystems upwelling of nutrients, acidic water, and low-oxygen zones are also of interest. But small-scale structures, in particular small-scale fronts, jets, and eddies have come to great prominence recently as key drivers of productivity and connectivity between populations, so upper-ocean velocity structure is also important. We still believe that producing a reanalysis of the CCS with all variables at all points will allow researchers to put their observations in context, but we have also begun to produce some time series of heat content and upwelling indices.

***Impact of sampling noise on the state estimate (question from mid-term review):***
This question is regarding the small-scale features like internal waves that are present in the glider and mooring observations. We try to combat them by enforcing smoothness in our adjustments, so we don't try to fit every glider profile exactly. Likewise, the mooring observations are averaged over 6 hours to suppress some of the high-frequency content.

***Outputs:***
Main outputs to date are many iterations of the CCS state estimate, steady improvements in technology, collaborative papers analyzing glider observations with Rudnick and Todd, and papers exploring dynamical linkages in critical ocean regions.

We also started to to deliver indices. We have been making our entire state estimate available on the web, not just pictures of the SST or SSH, which are the most routine quantities. We have worked with NMFS SWFSC researchers to evaluate the model for some of their needs. Work is under way to improve the estimated surface currents to allow comparison to sardine egg distributions.

We are further starting to produce simple indices from the long-term assimilations (and providing them on the CORC website), designed to capture conditions of the CCS relevant for different users and applications. For example the location of the 14C isotherm is of interest since this is the minimum temperature needed for sardine spawning. The upper-layer heat content is expected to be

useful for both local climate impact (marine layer), for fisheries, and as a measure of upwelling. The area-averaged depth of isopycnals can be used as a different integrated measure of upwelling. Another form of index analysis is the structure of the annual cycle in the CCS, as seen in the CalCOFI dataset. One key question is what the quality of the state estimate is, which reflects on the quality of the indices.

## Outlook

***Future use of methodology:***

The long-term assimilation techniques are unique in boundary current applications and have the goal to deliver the highest quality reanalysis/hindcast of the boundary current state and conditions. Since it is continually evolving and improving, it would continue in a research mode, and regularly deliver updated products but with delays of 6-12 months. It can be compared to the climate-quality delayed-mode data processing of data sets like ARGO. The methodology will be published and disseminated freely to other groups around the world, to allow them to generate similar reanalyses.

The more short-term and near-realtime assimilations are less unique, since several groups are doing this kind of work for the California Current region. We know these other groups very well, exchanging students and postdocs with UCSC, in particular, and would collaborate more if resources allowed this. The goal for this work is to demonstrate what products and indices can be generated with the rich data set CORC is producing, and to determine the uncertainty in these more limited state estimates (e.g. by comparing with the full long-term assimilations). We plan to devise short-term products based on the recommended operational sampling in different locations (which results from CORC), which could then be migrated or executed by any of the other groups.

***Transition to operations:***

In addition to the methodology described above, we are producing a reanalysis product and indices for use by others, such as other modelers or fisheries scientists. Although our current computational resources are not adequate for the high-performance (long time window) methods to be practical for real time operational applications, increases in computing power have made it practical elsewhere, such as ECMWF, and we hope that time will ease this bottleneck. Given sufficient computing power and expertise, the methods and lessons from the long-term climate-quality state estimates are applicable for a number of ocean models, e.g. ROMS, which has apparantly been selected by NOS as the platform for a USWC modelling project.

Present partners and users are NOAA Fisheries, NOAA's USWC modeling effort, other USWC modellers, especially UW, OSU, JPL, and UCLA. In the future, we hope the larger regional climate, ecosystem, ocean carbon and ocean acidification communities will become interested in the climate-quality and near-realtime products and indices.

## Publications, 2010-2012


Zhang, X., B. Cornuelle, and D. Roemmich, (2012) Sensitivity of western boundary transport at the mean North Equatorial Current bifurcation latitude to wind forcing. Accepted by the *Journal of Physical Oceanography*. (also listed in XBT/ARGO section)

Zhang, X., B. Cornuelle, and D. Roemmich, (2011) Adjoint sensitivity of the Nino-3 surface temperature to wind forcing, *Journal of Climate, 24, 4480-4493. doi:* http://dx.doi.org/10.1175/2011JCLI3917.14

Todd, R. E., D. L. Rudnick, M. R. Mazloff, R. E. Davis, and B. D. Cornuelle, 2011b: Poleward flows in the southern California Current System: Glider observations and numerical simulation. *Journal of Geophysical Research*, **116,** C02026, doi:10.1029/2010JC006536.(also listed in glider section)

Todd, R. E., D. L. Rudnick, M. R. Mazloff, B. D. Cornuelle, and R. E. Davis, 2012: Thermohaline structure in the California Current System: Observations and modeling of spice variance. *Journal of Geophysical Research*, **117,** C02008, doi:10.1029/2011JC007589. (also listed in glider section)

## E: Development of Autonomous Deployment Pods for Drifters and Analysis of CalCOFI, Drifter and Altimetry Data for Climate Evolution Models

### Objectives

Our overall objective is to provide a novel synthesis of the mass transport through the southern limb of the California Current System and of the structure and variability, from intra-seasonal to decadal, of the near surface currents.

Understanding and being able to predict the state of the California Current System (CCS) on a variety of temporal and spatial scales is important because of the large impact of the three dimensional circulation patterns on the composition and distribution of fish feeding grounds and on the reproductive cycles and distribution of fish stocks of economical relevance to the nation. A second reason to study the CCS is the exploitation of a very large set of hydrographic and direct current observations accumulated through the CalCoFi program which dates back nearly 63 years which support, together with the observations made by CORC and others provided by the Global Ocean Observing System, the opportunity for a novel synthesis. The third important reason is the relationship between subducted SST anomalies in the southern CCS and the onset of El Nino events, a mechanism that deserves further studies.

Lagrangian observations of boundary current systems are important to document the mean structure of their surface expression and their short time variability (order of weeks) over extended areas that cannot be sampled with gridded altimetry products (time/space scale too short/small) or fixed installations at a few locations. One important rationale for developing new Lagrangian technologies to sample remote boundary current systems is the need to implement repeated deployments (time-series) in a reliable, sustainable, and cost-effective manner

The first specific objective is to synthesize drifter, altimeter, ADCP and hydrographic data to provide a complete historical perspective of the near surface circulation and transport from the surface to 500 m depth in the CCS to investigate the intra-seasonal to decadal circulation modes.

The second specific objective is to develop a new technology, an autonomously deploying drifter that parks at the ocean floor for long periods of times and surfaces at pre-set intervals. The application in mind is the implementation of Lagrangian time series in boundary currents with minimal use of ship time and skilled personnel.

### Approach

The approach to the first objective is to combine all available datasets in the CCS region to investigate the mean and time dependent geostrophic and ageostrophic circulation on time scales from intra-seasonal to decadal. The datasets include: CalCOFI hydrographic and ADCP data, satellite and re-analysis winds, historical SVP drifter data, CODE drifter data, satellite altimetry sea-level data, new deployment of drifters in the CCS near the coast where the coverage of

historical data is low. The idea is to produce maps of mean current and use EOF analyses to investigate the dominant modes of the variability. The results of the analyses can also be used to test the verity of CCS circulation models.

The approach to the second objective is to adapt existing deep-water underwater housing technologies and timed release systems into our SVP drifting buoy design, build and test several prototypes, and select the most successful design. The implementation of the developed technology consists of: 1) drifter releases in the CCS 2) implementation of a time series of Lagrangian observations in a remote area such as the Solomon Sea using VOS assets to demonstrate the viability of our approach. The logical transition of the technology is within programs such as the Global Drifter Program in troubled areas (i.e. the Somali Current System) and within specific boundary current systems monitoring arrays. This addresses some of the COSC concerns of seeing technologies emerging from CORC becoming part of the existing observing system (CORC's legacy).

## Progress and achievements

***Scientific results***

*Mean state of the CCS.* The analysis of the mean geostrophic and ageostrophic currents from drifter and altimetry data, eddy kinetic energy and the validation of four numerical models, HYCOM, NLOM, POP and ROMS, was completed in 2007. Four permanent meanders were identified in the CCS and are connected to a set of four slanted bands of zonal flow, also known as striations. ROMS is the model that bears the most accurate results in terms of circulation and eddy kinetic energy patterns and intensity. The ageostrophic currents from ROMS show large scale divergence patterns generally co-located with the observed meanders (Centurioni et al. 2008).

*Integrated analysis of CCS datasets*. The hydrographic data from 1949-2009, the SVP drifter data from 1985-2008, the satellite altimetry data from 1992-2008 and the ADCP data from CalCoFi ships were combined to compute comprehensive maps of the horizontal velocity along CalCoFi lines 77-93. These analysis produced time-mean horizontal maps of surface circulation in the southern portion of the CCS and vertical sections along the CalCoFi lines. The data on line 90 shows a significant ageostrophic velocity component normal to line 90 at depths shallower than 100 m. The spatial structure of the ageostrophic velocity cannot be entirely attributed to the wind-driven Ekman flow because the wind along line 90 does not have a spatial structure commensurate with the location of the spatial structure of the ageostrophic currents. The correlation between CODE derived geostrophic velocity observations (563 drifters) and altimetry derived currents is commensurate, at some locations, with that obtained with offshore SVP drifters. This will allow a precise assessment of where the flow is non-geostrophic vs where the altimetry dataset in unable to map the variability of the surface currents.

*Subducted SST anomalies in the eastern Pacific Ocean and onset of El Nino*. Warm STT anomalies located at the fringe of the CCS (115-135°W, 20-30°N) subduct and consequently depress the thermocline. These temperature disturbances, tracked by altimetry, propagate southward, reach the equator in 1.5 to 2.5 years and can contribute to the formation of El Nino by lowering the thermocline and consequently blocks the cooling of the equatorial surface water (Lee and Niiler, 2010), More details can be found at http://corcbrd.ucsd.edu/)

***Technical***

Several Bottom release Drifters (BRD) were designed, built and tested. They were built using

4000m pressure –resistant Benthos glass spheres and were fitted with a drogue of the appropriate size to preserve the 40:1 drag-area ratio so that they behave like regular SVP drifters. The drogue was contained in a plastic cone to prevent skating during the sinking phase and mud-suction. The first version of the BRD was fitted with a burn release mechanism, had no SST and drogue loss indicator. Four BRDs were tested at a depth of 100 m off point Loma, San Diego in July 2009. The first test at sea was set to release 24 hours after deployment. Out of the four drifters one deployed successfully to the surface, one was entangled in the recovery line, one flooded and one did not release (burn wire too long).

Eight Bottom Release Drifters (BRDs) were completed in March of 2010. Some essential aspects of the design revision include the ability to self-install from a standard pallet, maintain position and rest at ocean floor depths up to 4000 m, then deploy to the surface and operate as a standard Argos drifter with a drogue attached. On April 15, 2010 eight of these units were deployed in 2000 meters water depth near Monterey, CA and programmed to deploy periodically over a 4 month span. Deployments to the surface performed at a 75% success rate, and the longest-lived of the six successfully deployed units died on December 12, 2011. Drifter tracks can be seen at http://corcbrd.ucsd.edu/.

The third BRD generation is being built now (summer/fall 2012). Notable design changes include: 1) drogue presence detection capabilities integrated into the deep-sea evacuated glass sphere. This hardware operates identically to submergence sensors implemented on old-generation GDP drifters, but with the capability of deep-sea deployment;. 2) newly designed SIO resistor bridge and improved SST accuracy (now ±0.05°C, with 0.01°C resolution); 3) galvanic release mechanism; 4) In-house developed electronics: an MCU has been developed to significantly decrease the cost of the BRD systems. This controller paired with a galvanic release mechanism will decrease the cost of each drifter by $1K; 5) drogue improvement: materials selection for the drogue, which was addressed in spring 2011 both for GDP and CORC funded drifters will significantly improve the endurance and performance of the drogue; 6) size Improvement: the size of the system has been decrease by approximately 40%, resulting in a much more compact and reasonable deployment package.

***Operational***

Sets of 13 SVP surface drifters (drogued at 15 m depth) were obtained, prepared, and deployed on July 2009, November 2009, January 2010, and April 2010 from CalCoFi cruises. Three sets of 13 drifters each were deployed with the following funding cycle in August 2010, November 2012 and January 2011

The first year of deployments required close interaction with the CalCoFi marine technicians responsible for the actual deployments. Coordination with the CalCoFi technicians is an important milestone as they begun to view regular quarterly drifter deployments as one of their core cruise activities, ensuring future uninterrupted deployments. Unfortunately this activity was interrupted due to the lack of funding for the CORC CCS drifter activity.

BRD drifter releases are planned in the Solomon Sea to demonstrate the operability of the technology from VOS assets.

## Publications

Centurioni, L. R., J. C. Ohlmann, and P. P. Niiler (2008), Permanent Meanders in the California Current System, J Phys Oceanogr, 38(8), 1690–1710.

Lee, D.-K., and P. Niiler (2010), Influence of warm SST anomalies formed in the eastern Pacific subduction zone on recent El Nino events, J Mar Res, 68(3-4), 459-477.

## Summary Information:

a. Project deliverables serving the observing system's program deliverables
   - development of cost-effective techniques for routine observations of BCs
   - techniques for monitoring strong currents with gliders and measures of the utility of these measurements
   - time series of heat and mass transport through the Solomon Sea
   - enhanced technologies for BC monitoring
   - horizontally integrated currents and transports from moorings and PIES
   - glider sections allowing calculation of transport of various quantities, directly addressing CPO deliverables of Ocean Heat Content and Transport, and Ocean Carbon Uptake and Content
   - provision of enhanced, research-quality data sets of ocean currents corrected for the wind-induced velocity bias (slip) in the CC
   - SST in situ data for Cal/Val
   - provision of some data to the GTS (SST, and near-surface currents)
   - analysis of data and scientific interpretation of the results. Publication of findings in peer-reviewed journals
   - indicators summarizing the state of the California Current
   - analyses of broad-scale ocean heat and freshwater content and transport to identify sources and mechanisms of transport by the mean and time-varying ocean circulation
   - improvements to the technology for regional state estimation, technology test of regional adjoint-based state estimation with a long assimilation window
   - incorporation of additional data types into assimilations
   - incorporation the MITgcm biogeochemical package to include carbon cycling
   - short and long-term reanalysis of the CCS, including much of the CORC CCS observations.
   - time-continuous (but not yet real time), dynamically-consistent estimates of SSH, SST, currents, Ocean Heat Content and Transport, and atmospheric state.

b. Achievements
   - continuous occupation of two CC sections with gliders, one CC section with moorings/PIES, one SS section with gliders, with 100% data return
   - quarterly deployments of SVP drifters in the CCS
   - identified summarizing indicators of Solomon Sea heat and mass transports.
   - improvements in routine subsurface data retrieval via gliders, construction of modem gliders
   - improved design of the Bottom Release Drifter
   - identification of suitable sites for PIES in the SS
   - incorporated more observations into assimilations (IES in particular)
   - better model fits to observations in general and moorings in particular, including experiments with shorter assimilation windows

- Several publications, covering local effects of El Niño, poleward transport, thermohaline variance, and physical and biological processes in the CCS, analyses of broad-scale ocean heat and freshwater content and transport, and technology developments

c. Scientific advances made and/or facilitated through the project activities
   - We have proved the ability to combine our observations with an assimilating model to establish first estimates of ocean state in a BC.
   - Glider, mooring, and drifter data are now available for scientific analysis in regions of the CCS that were sparsely sampled before.
   - Impact of climate process on the CC regime is being studied with the CORC data set
   - Studies of climate variability in the BC feeding the equatorial undercurrent are now becoming feasible with the growing timeseries in the Solomon Sea.
   - The modem glider and BRD technology is available to the public upon request
   - The analysis by Auad et al provides a new perspective on the California Current System including the boundary current and the eastern limb of the North Pacific gyre, and the interactions of these flows.
   - The analysis by Zilberman et al combines the transport in the South Pacific low latitude western boundary current with that in the ocean interior to estimate the mean and interannual variability in the shallow meridional overturning circulation as well as in the source waters for the Indonesian Throughflow.
   - Analysis of spiciness data from the glider using the model.

d. Significance of these advances
   - We believe that the approach established in CORC is a prototype that can be replicated in other boundary current systems.
   - Our observations of the local effects of El Niño using gliders were the first of their kind.
   - Measurement of transports in a strong western boundary current with gliders is also a first
   - Deep mooring data provided insight for appropriate reference levels and CC depth extent
   - The tracking of tracers using the adjoint of a model verified with observations provides a new way of determining the source of waters that arrive in local regions.
   - The research provides new insight into the connection between continental shelf flows and the larger scale California Current located further offshore.
   - The continued repeated observations in the CC and SS will generate a data set that can be examined on longer “climate” time scales.
   - CORC analyses constitute original research that furthers our knowledge of ocean circulation and the heat and freshwater balance on climate scales.

e. Information jeopardized due to a lack of funding, lack of instrumentation, or inability to carry out the work
   - The funding is barely sufficient to keep the observations alive. Lack of reserves precludes replacing lost equipment, occasionally leading to gaps in time series. Also the inability to upgrade hardware degrade data quality.
   - Scientific analyses are essentially provided by the PIs as voluntary unfunded contributions. More in-depth exploitation of the results requires scientist support.
   - Analyses of the joint data sets and development of merged indicators, other than through the data assimilation, is not funded and therefore suffers delays.
   - More systematic and joint CORC-wide data management is not possible due to lack of funding, as well as routine work with OceanSITES for data dissemination.

f. Web sites for the program

- http://spray.ucsd.edu
- http://mooring.ucsd.edu/CORC
- http://corcbrd.ucsd.edu
- http://gdp.ucsd.edu/dashboard.html (password protected)
- http://sose.ucsd.edu/DATA/CORC/corc_stateestimation_welcome.html
- http://sccoos.org

g. Data Management

Glider data

- The data are not distributed on GTS, although we have established a conduit through NODC. We can begin distribution through GTS at any time.
- The real-time data reside on servers here at SIO. Plots of the data are publicly available in real time at spray.ucsd.edu and sccoos.org.
- The delayed mode data (after glider recovery) reside on the server sushi.ucsd.edu. They are available online through a password protected system. Data are QCed and available typically within a month of collection.
- The data are archived upon glider recovery at spray.ucsd.edu and sushi.ucsd.edu.
- We routinely use our public web sites to access plots of our data.

Mooring/PIES data

- Data not distributed on GTS since not in real-time at present
- Data are presently downloaded via gliders every few months. A realtime capability (daily download with gliders) exists now and will be demonstrated in the next months. Downloaded data are visualized on http://mooring.ucsd.edu/CORC. Data are intended to be distributed via OceanSITES ftp server, but this is not implemented yet.
- Delayed-mode data is on institutional computer with backup system, plots are provided on the website. Processed data will be made available through OceanSITES ftp servers up to most recent field operations but this is not implemented yet.
- Archival on institutional backup system happens daily; transfer of newly processed data to OceanSITES repository approx yearly (planned)
- Data plots are shown on http://mooring.ucsd.edu/CORC

The surface drifter data are available from http://www.aoml.noaa.gov/phod/dac/dacdata.php and details on SIO drifter's programs are available at http://gdp.ucsd.edu.

No data collection is carried out by the XBT/ARGO synthesis effort. The data collection questions are addressed in the XBT and Argo reports.

## *2.1. Outreach and Education*

CORC and the associated Scripps HR-XBT and drifter programs have made strong contributions to education by serving as a source of data for PhD and Master's theses and for research by post-doctoral investigators. For example, 8 completed PhD theses between 1996 and 2009 have used Scripps HR-XBT data as a primary dataset. In the present year, 3 postdocs and 1 graduate student were partially supported by CORC.

CORC is communicated to the public via various websites (see above).

Efforts to explain the societal utility of the Solomon Sea data are twofold. Globally, we rely on scientific papers and talks to expose the data and their potential uses to oceanographers,

climatologists and modelers who might use them for analysis of interannual-decadal prediction. Within the Solomon Sea the potential local uses of the same data are discussed with governmental and educational leaders in the region through a series of visits by co-investigator.

# 3. Publications and Reports

## *3.1. Publications by Principal Investigators*


Davis, R.E., 2010. On the coastal-upwelling overturning cell. *J. Mar. Res.*, **68**, 369-385.

Davis, R.E., W.S. Kessler and J.T Sherman, 2012. Gliders measure western boundary current transport from the South Pacific to the equator. *J. Phys. Oceanogr.* in press

McClatchie, S., R. Cowen, K. Nieto, A. Greer, J. Y. Luo, C. Guigand, D. Demer, D. Griffith, and D. Rudnick, 2012: Resolution of fine biological structure including small narcomedusae across a front in the Southern California Bight. *Journal of Geophysical Research*, **117,** C04020, doi:10.1029/2011JC007565.

Todd, R. E., D. L. Rudnick, and R. E. Davis, 2009: Monitoring the greater San Pedro Bay region using autonomous underwater gliders during fall of 2006. *Journal of Geophysical Research*, **114,** C06001, doi:10.1029/2008JC005086.

Todd, R. E., D. L. Rudnick, R. E. Davis, and M. D. Ohman, 2011a: Underwater gliders reveal rapid arrival of El Niño effects off California's coast. *Geophysical Research Letters*, **38,** L03609, doi:10.1029/2010GL046376.

Todd, R. E., D. L. Rudnick, M. R. Mazloff, R. E. Davis, and B. D. Cornuelle, 2011b: Poleward flows in the southern California Current System: Glider observations and numerical simulation. *Journal of Geophysical Research*, **116,** C02026, doi:10.1029/2010JC006536.

Todd, R. E., D. L. Rudnick, M. R. Mazloff, B. D. Cornuelle, and R. E. Davis, 2012: Thermohaline structure in the California Current System: Observations and modeling of spice variance. *Journal of Geophysical Research*, **117,** C02008, doi:10.1029/2011JC007589.

Send, U., and S. Nam (2012): Relaxation from Upwelling: the effect on dissolved oxygen on the continental shelf. J. Geophys. Res. VOL. 117, C04024, doi:10.1029/2011JC007517

Nam, S., H.-J. Kim, and U. Send (2011): Amplification of hypoxic and acidic events by La Nina conditions on the continental shelf off California. Geophysical Research Letters. VOL. 38, L22602. doi:10.1029/2011GL049549

Send, U., L. Regier, and B. Jones (2012): Use of underwater gliders for acoustic data retrieval from subsurface oceanographic instrumentation and bi-directional communication in the deep ocean. J. Atmos. Ocean. Techn. In press

Roemmich, D. and Co-authors (2010). Integrating the ocean observing system: Mobile platforms. In *Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society (Vol. 1)*, Venice, Italy, 21-25 September 2009, Hall, J., Harrison, D.E. & Stammer, D., Eds., ESA Publication WPP-306.

Goni, G., D. Roemmich & Co-Authors (2010). "The Ship Of Opportunity Program" in *Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society (Vol. 2)*, Venice, Italy, 21-25 September 2009, Hall, J., Harrison D.E. & Stammer, D., Eds., ESA Publication WPP-306.

Douglass, E.M., D. Roemmich and D. Stammer, (2010) Interannual variability in North Pacific heat and freshwater budgets. *Deep-Sea Research II 57*, 1127-1140.

Auad, G., D. Roemmich, and J. Gilson, (2011) The California Current System in relation to the Northeast Pacific Ocean circulation. *Progress in Oceanography*, 91, 576-592.

Roemmich, D. and J. Gilson, (2011) Ocean circulation and the mass and heat budgets of large ocean regions: The synergies of High Resolution XBT transects, Argo, and satellite altimetry. *Invited presentation* at the First XBT Science Workshop, Melbourne Australia, July 2011. http://www.aoml.noaa.gov/phod/goos/meetings/2011/XSW/

Giglio, D., D. Roemmich and S.T. Gille, (2012) Wind-driven variability of the subtropical North Pacific Ocean. Accepted by the *Journal of Physical Oceanography*.

Zhang, X., B. Cornuelle, and D. Roemmich, (2012) Sensitivity of western boundary transport at the mean North Equatorial Current bifurcation latitude to wind forcing. Accepted by the *Journal of Physical Oceanography*.

Zilberman, N.V., D.H. Roemmich, and S.T. Gille, (2012a) The mean and the time-variability of the shallow meridional overturning circulation in the tropical South Pacific Ocean. Submitted to the *Journal of Climate*.

Zilberman, N., D. Roemmich, and S. Gille, (2012b) Meridional transport in the South Pacific Ocean: Assessing the mean state and SAM and ENSO related variability. *In preparation*.

Zhang, X., B. Cornuelle, and D. Roemmich, (2012) Sensitivity of western boundary transport at the mean North Equatorial Current bifurcation latitude to wind forcing. Accepted by the *Journal of Physical Oceanography*. (also listed in XBT/ARGO section)

Zhang, X., B. Cornuelle, and D. Roemmich, (2011) Adjoint sensitivity of the Nino-3 surface temperature to wind forcing, *Journal of Climate, 24, 4480-4493. doi:* http://dx.doi.org/10.1175/2011JCLI3917.14

Centurioni, L. R., J. C. Ohlmann, and P. P. Niiler (2008), Permanent Meanders in the California Current System, J Phys Oceanogr, 38(8), 1690–1710.

Lee, D.-K., and P. Niiler (2010), Influence of warm SST anomalies formed in the eastern Pacific subduction zone on recent El Nino events, J Mar Res, 68(3-4), 459-477.