CORC

Uwe Send, Bruce Cornuelle, Russ Davis, Dean Roemmich, Daniel Rudnick
Scripps Institution of Oceanography, La Jolla, CA

Table of Contents

Project Overview 1
MEASUREMENT OF BOUNDARY CURRENT TRANSPORT IN THE SOLOMON SEA 3
1. Task Summary 3
2. Scientific and Observing System Accomplishments 4
3. Outreach and Education 8
SUSTAINED OBSERVATIONS IN THE CALIFORNIA CURRENT SYSTEM 10
1. Task Summary 10
A. Glider observations in the California Current System 10
A2. Scientific and Observing System Accomplishments 11
A3. Outreach and Education 15
B. Integrating and high-frequency observations in the California Current System 15
B2. Scientific and Observing System Accomplishments 16
B3. Outreach and Education 20
SYNTHESIS OF XBT AND ARGO DATA FOR BOUNDARY CURRENT ESTIMATION .. 21
1. Task Summary 21
2. Scientific and Observing System Accomplishments 21
3. Education 22
DATA ASSIMILATION TOOLS FOR THE BOUNDARY CURRENT OBSERVING SYSTEMS 23
1. Task Summary 23
2. Scientific and Observing System Accomplishments 23
3. Education 27
SUMMARY OF THE CORC APPROACH 28
PUBLICATIONS BY THE CORC PROJECT 29

Project Overview

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, and Argo profiles. 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.

MEASUREMENT OF BOUNDARY CURRENT TRANSPORT IN THE SOLOMON SEA

Russ E Davis[1], William J. Kessler[2] and Uwe Send[1]
[1]CIMEC, Scripps Institution of Oceanography, San Diego, California
[2]NOAA Pacific Marine Environmental Laboratory, Seattle, Washington

1. Task Summary

The Solomon Sea component of CORC is developing cost-effective methods for sustained measurement of the characteristics of strong western boundary currents that are most important to climate dynamics; these characteristics are integrated measures of the transport of mass, heat, salt and potential vorticity between different regions in the general circulation.

To describe climate, long observation records are required. The strength of boundary currents challenges conventional moored approaches and ship cost precludes regular use of research vessels. Our approach is to use autonomous underwater gliders that are launched from small boats near shore, small moorings outside the current itself and bottom mounted pressure gauges with inverted echo sounders (PIES). From a 2007 pilot glider-crossing of the Solomon Sea we have improved glider technology and operational methods while completing 50 Solomon Sea crossings. A single glider was lost as the operational cost of a section was reduced to less than one day's ship time. During 2011 we developed a simple end-point approach with moorings and PIES, suitable for rugged bathymetry and remote logistics, to complement the glider sections with high time-resolution data. These were implemented in 2012 and the first data were retrieved by small boats in 2013. New developments continue as we enable expanded global boundary current observations within limited budgets.

Our techniques of observing western boundary currents are proven by regular observation of transport through the Solomon Sea. This flow carries water from the subtropical South Pacific to the equator and is a central, and largely unmeasured, element of ocean circulation. Our interest in this remote current is its impact on predicting air-sea interaction in the equatorial zone, most notably on El Niño – Southern Oscillation (ENSO) and related decadal climate variations. ENSO is the clearest example of the ocean's role in climate and its effect on predicting climate variability that strongly impacts human activity. Potentially predictable impacts include: precipitation-drought patterns that modulate agriculture, wildland fire and the water supply, particularly in the western and southern US; the global frequency and regional distribution of tropical storms that impact public safety, property loss and emergency response; the frequency and typical strength of cold-season storms, particularly along the Pacific coast from the US to South America where rain and coastal flooding are key; and ocean ecosystem variation along the west coast that influences fishing, its regulation and conservation.

Today's models of ENSO, which focus on equatorial dynamics, provide useful prediction skill a few months in advance. Extending prediction range to years is a goal that will require including influences from the extratropics. Transport through the Solomon Sea is the primary source for the Equatorial Undercurrent (EUC) that upwells along the equator, modulating sea-surface temperature and air-sea interaction that affect the global atmosphere. The widely speculated

effect of the EUC's source on climate predictability has not yet been proven. Our scientific goal is to provide time series of this source's transport so its importance to prediction can be assessed by researchers and developers of operational prediction methods.

While our scientific goal requires decadal time series, the data are of immediate use to researchers, local policy makers, and maritime activity. Realtime glider data are plotted at spray.ucsd.edu, can be downloaded with an available password, and are delivered regularly to US agencies/programs (e.g US Navy for operational forecasts/planning and research); additional connections are invited. Delayed-mode data are archived locally and can be downloaded (with a password). IOOS is establishing archival and regular distribution of all glider data. Mooring/PIES data from the Solomon Sea will be gathered only for a 2-year demonstration period. Nonetheless, once processed they will be made available to modelers, SPICE collaborators, and any other researchers interested in them. In a sustained operation, this could become a routine product to complement the glider data. There are now no known operational users for delayed-mode Solomon Sea data.

2. Scientific and Observing System Accomplishments

Scientific results

Davis, Kessler and Sherman (2012) presented analysis of transport through the Solomon Sea based on glider observations through 2010. The major findings were

- Equatorward transport above 700 m varies between 0 and 25 Sv on seasonal time scales. Its variations are correlated with ENSO as measured by indices like Niño 3.4 SST and the Southern Oscillation Index. The single El Niño in the record brought strong equatorward flow while two La Niñas reduced transport near to zero. These fluctuations were larger than expected from model simulations, especially for these moderate events, raising questions about our understanding of subtropical-equatorial exchange during ENSO.
- Mean equatorward flow peaks near 250 m where the potential density of 25.5 matches the EUC's. Transport variability is well described as two independently varying "layers" separated by a transition zone between 75 and 250 m where the two layers blend together. The EUC-source waters at 250 m are mainly in the lower layer, but this layer's variability is weak so both modes contribute comparably to its variability.
- The upper-layer mode is well correlated with ENSO. Deeper flow enters the Solomon Sea from the west (the Coral Sea off Australia) and follows the western boundary as it moves equatorward. Surprisingly, upper layer flow into the Solomon Sea and its variability are focused in a mid-basin jet marked by high salinity indicating a subtropical origin. No cause of the lower-layer variability presents itself.

These results, which need confirmation through much more than one ENSO cycle, show that transport of the EUC's Solomon Sea source has comparable variability from two origins: shallow transport that varies with ENSO and the deeper layer whose driver is unknown.

Operational activity

Deliverable: "Six glider cruises across the Solomon Sea in FY13 with reports of depth-average velocity above 700 m and profiles of temperature and salinity across the SS available as data files and graphical descriptions on spray.ucsd.edu ." Our five glider deployments completed falls one short of this, but the 12 completed sections match what was expected from 6 cruises. Three trans-Pacific trips, some for two-people, were required yet the total cost per section (vehicle and instrument preparation, shipping and travel, and field operations) was less than $20K. There were no operational mishaps and the data quality is good. Data from all cruises finished before September 2013 have been quality-controlled, corrected for flight dynamics changes, and are available for distribution.

The complete glider record is depicted in Figure 1 as time series of directly measured transport and relative geostrophic transport from glider-measured density. Our archive now includes 24 cruises and 50 sections covering 35,000 km (near the global circumference). One glider was lost and another needed rescue recovery.

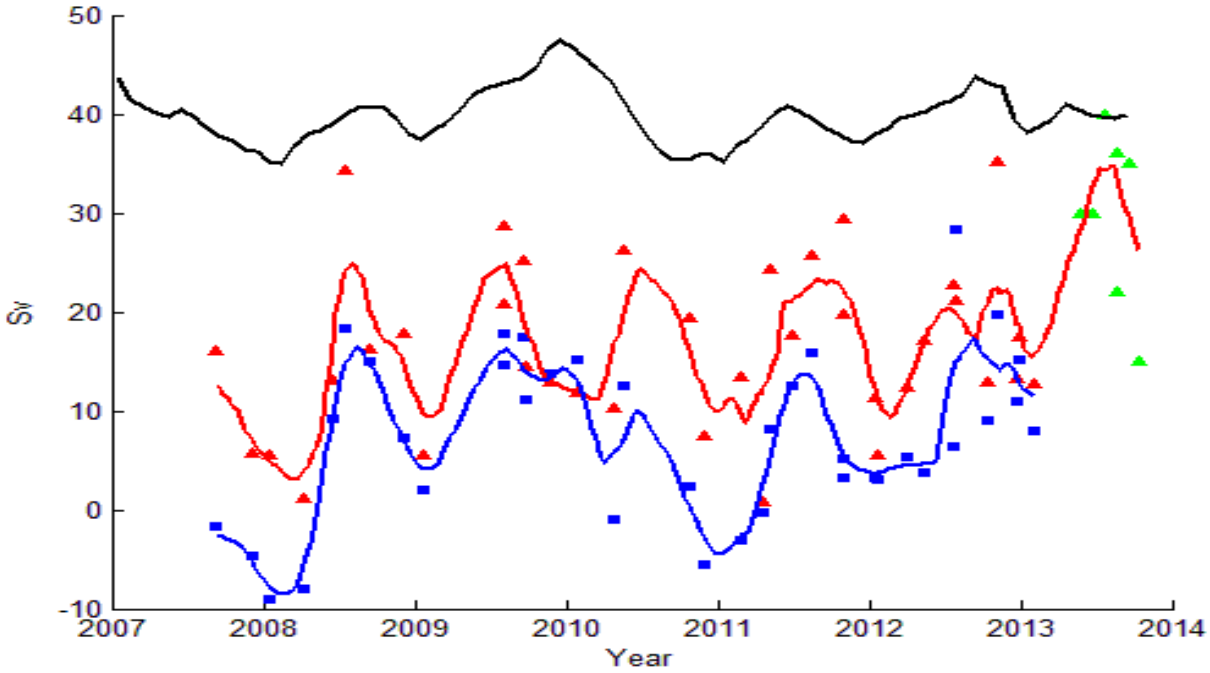


Figure 1. *Equatorward Solomon Sea transport above 700 m from: (red) absolute velocity from glider motion; (blue) geostrophic relative flow referenced to 700 m from glider profiles. Symbols are transports from single cross-basin sections; green triangles are realtime data without QC. Solid lines are outputs of a 3-month running mean filters applied to the interpolated series. The black line is the Nino 3.4 monthly anomaly from its seasonal cycle (arbitrarily scaling).*

Deliverable: "Operation of moorings and PIES across the Solomon Sea and analyses of acoustically downloaded data." Two PIES were deployed across the Solomon Sea in February 2012 and two simple moorings added in July 2012. In May 2013, Kessler used local boats to visit the PIES/mooring locations and acoustically download most of their data. Technical problems with a modem on one PIES led to data gaps which we can close after instrument

recovery. The moorings allow the calculation of geostrophic transports (as a function of depth to 500 m) through the Solomon Sea relative to 320m; the PIES measure the pressure gradient fluctuations at 320 m. Only the mean pressure difference at 320 m is unknown. The mean vertical profile of the transport looks very similar between the 10 months of mooring data and 2½ years of glider data (figure 2, left), thus we adjusted the mean PIES pressure gradient to bring the two profiles into approximate agreement. The resulting total transport for 0-500 m is shown in figure 2 (right) in black, with the total glider transports superimposed as red circles. Joint analysis of the glider and mooring/PIES data is in progress and will be presented at the AGU/ASLO Ocean Sciences Meeting in February 2014.

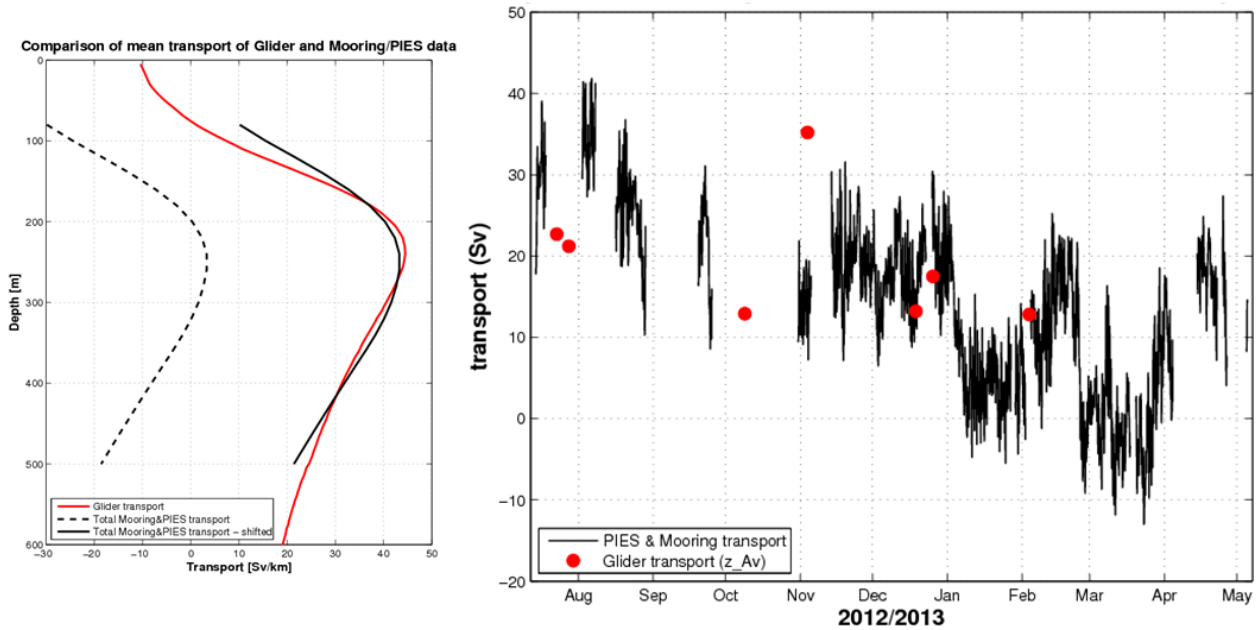


Figure 2. *Mean profile of transport through the Solomon Sea from mooring/PIES data (left). Timeseries of 0-500m transport from moorings/PIES in black and 0-700m from gliders in red (right).*

Figs. 1 and 2 show remarkably rapid variation of basin-wide transport. Glider transport from depth-average velocity and relative geostrophic flow both show several examples of transport changes of O(15 Sv) over a month or two. Similarly, the mooring/PIES data show several 10 to 15 Sv changes over 10-20 days. These changes are noise to the seasonal variability of interest. Correlation of the two independent glider measurements and the changes in the mooring/PIESs data argue that this noise is, in fact, ocean variability not instrumental.

The 2009 El Niño is evident in both glider series but is clearest in the relative transport because. this is dominated by the upper layer that is well correlated with ENSO. Transport to the EUC occurs in the lower layer and the O(10) Sv difference between the absolute and relative-geostrophic transports reflects a flow of O(4 cm/s) at the relative flow's reference level, which is in the lower layer. This is why direct velocity measurements are important in the Solomon Sea boundary current.

When filtered, both glider series show a clear seasonal cycle that was not detected in the first 2½ years of record. This shows how extending record length not only raises the precision of measurements but can disclose new processes. As our record approaches a decade in length, we can begin to see how the quasi-annual variability is modulated by ENSO and as the record grows longer we will be able to examine what is now just a hint of slower variability. Proponents of a subtropical influence on equatorial air-sea interaction expect it to be on decadal periods.

Technical developments

Deliverable: "Technology modifications of SS gliders to improve data quality and reduce the cost of maintaining the transport time series. A technical report of our technical improvements is planned for FY14." Maintaining the glider time series of trans-basin sections roughly every month has depended on technical and methodological advances in two general areas: (a) minimizing cost by providing training and technology so Solomon Islanders can deploy and recover gliders in our absence and (b) improving glider performance to get more data from a cruise and avoid failures. New techniques (including tests that the glider carries out itself) were developed to enable locals to check-out gliders before deployment. This allows us to deploy six gliders a year with only three trans-Pacific trips. Reliability improvements used post-cruise forensics to target modifications to eliminate systemic weak points. The most important was adding a small pump to remove gas from the hydraulic system to avoid vapor-lock of the buoyancy pump. This is key to "remote" preparation for launches and "delayed" deployments.

Major glider improvements introduced this year were:

- "Delayed" deployments provide a way to start multiple missions at minimum effort in order to improve control of the mission schedule and control cost. Two gliders are deployed simultaneously and one begins its mission immediately. The other goes into "sleep" mode for a month or more before beginning its mission. A "sleeping" glider rests at depth using little energy and occasionally surfaces for communication. No drag-producing biofouling has been observed from resting at depth.
- The Spray buoyancy system was modified to pump 100 cc more oil for buoyancy. This raises velocity 20% and increases operating depth from 700 to 1000 m. The small speed increase greatly reduces the time to transit adverse currents that otherwise might nearly halt progress. Greater operating depth gives more time in weak currents and reduces the rate at which biofouling adds vehicle drag. Extra pumping increases energy use and reduces duration, but duration was already determined by biofouling and simulations suggest that added performance in adverse currents will actually increase range.
- As a result of extra buoyancy control, beginning May 2013 all cruises are scheduled for two round-trips (four transits) of the Solomon Sea. The first two such cruises were just completed after making four transits each. This ability promises to nearly halve the cost of a section.

The technical developments for the mooring/glider complement are being validated now with the first data in hand. We took care to design this component to be cost-effective by using small hardware that can be handled by local boats, can remain in the water for 2 years (moorings) and 4 years (PIES), and carry acoustic modems for data retrieval from small boats. We are in the process of assessing the quality of the data. The richness of the information provided in the time

domain is demonstrated by Figure 2. First indications suggest that this is a feasible, low-cost approach for the integrated mass transports in this and other western boundary current regions.

Another development area was the glider data system. Stated FY13 and FY14 goals were:

- to improve the data system to process delayed mode data more quickly with lower human effort, to document the system while making it transportable to other operators, and
- to develop products for dissemination that will allow others to integrate our results into their research and prediction studies.

We have adopted the initial quality control procedures developed by Rudnick and used in CORC California Current work. We built a system based on wide-spread MatLab to support the special analyses needed for accurate transport measurements, including the novel techniques to estimate glider-speed as vehicle drag changes. This is operational and is speeding delayed-mode processing. Its regular use is still leading to improvements through code revision.

Data management

Product dissemination will need the faster data processing now available. Developing useful indices of Solomon Sea transport will require describing its climate impacts and subtropical influences to equatorial air-sea interaction. Simple plots like Figs. 1 and 2 are not adequate and research is required to develop more useful products. This is still planned for FY14.

The glider data flow begins with satellite reports received at Scripps, added to a realtime archive on three local servers and delivered to requesting operational and research users. Plots of profiles and velocities are made publically available at spray.ucsd.edu and the data can be downloaded from sushi.ucsd.edu with an available password. Soon the IOOS Glider Data Assembly Center will distribute these data over the Global Telecommunications System (GTS), make them publically available and archive them centrally. More complete data is collected when a glider is recovered. This is archived on sushi.ucsd.edu , backed up to three local servers and quality controlled. The complete glider data set is re-archived approximately monthly. Quality controlled delayed-mode data can be downloaded (with available password) from sushi.ucsd.edu. At this writing (20 October), the most recent observation recovered from the delayed-mode online archive was taken 16 September 2013 and had not been quality controlled.

The mooring and PIES data are only fully available after instrument recovery. After processing and quality control these data will be made available via project websites. The preliminary acoustically downloaded data is not an operational product yet so there is no plan for dissemination. If implemented in a sustained fashion, acoustically retrieved data (even using gliders) could become an operational product.

3. Outreach and Education

Development of the ocean observing system is a fascinating technological accomplishment of surprising public interest. Davis (2011), published in a lay maritime history magazine, sought to capture the history of how a network of ocean innovators brought a global system into being.

Fig. 3. *The people of Manus Island, PNG examine a Spray glider recovered in their waters. Maintaining diplomacy and cooperation with local residents through education is time-consuming but rewarding. (Photo courtesy of WS Kessler).*

Co-investigator William Kessler has made the program's most important contributions to outreach and education; this is described in more detail in Kessler's complementary report. Our operations occur near coasts, populations, and economic activity (fishing), making them conspicuous to the local people and sensitive for the governments of Papua New Guinea and the Solomon Islands. Kessler meets regularly with provincial and tribal leaders encouraging them to accept gliders, PIES and moorings in fishing areas. A side benefit is visible beneficial representation of the United States in regions where Americans are not often seen. Relations with the governments require ongoing maintenance. Both governments are wary of foreign researchers, and insist that the findings be shared (beyond sending copies of data and published articles) and that their people receive some benefit, typically by contributing to their educational systems and by training local personnel. To this end, Kessler regularly lectures at schools, colleges and churches throughout both counties and meets with stakeholders, local government officials, and the Solomon Islands Meteorological Service where he lectures to their personnel on results from the project. He also maintains a close connection with students and faculty at the University of Papua New Guinea, involves them in science and technology and provides us very helpful contacts for field work. An example of this benefit occurred during the recovery of a sick glider north of Manus Island. Our contacts explained that we needed to visit the island to request permission from the local chief. The resulting visit is depicted in Figure 3.

The PIES measurements provide excellent information on tidal variability and analyses for local tidal information are promised to local partners. We have finished these analyses and they will be delivered in the near future. The Solomon Sea project also is providing an excellent opportunity for training students and young researchers in the US. Project Scientist M.Lankhorst has participated in several trips to the Solomon Sea for field work, and first-year student J.Koelling at SIO is carrying out some of the mooring/PIES analyses and will present a paper about the glider comparisons at the Hawaii ASLO/AGU meeting in Feb'13.

SUSTAINED OBSERVATIONS IN THE CALIFORNIA CURRENT SYSTEM

Daniel Rudnick and Uwe Send

1. Task Summary

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 predicting 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.

A. Glider observations in the California Current System

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 7 years in length, we believe we have addressed each of our primary objectives

A2. Scientific and Observing System Accomplishments

.

Technical and operational.

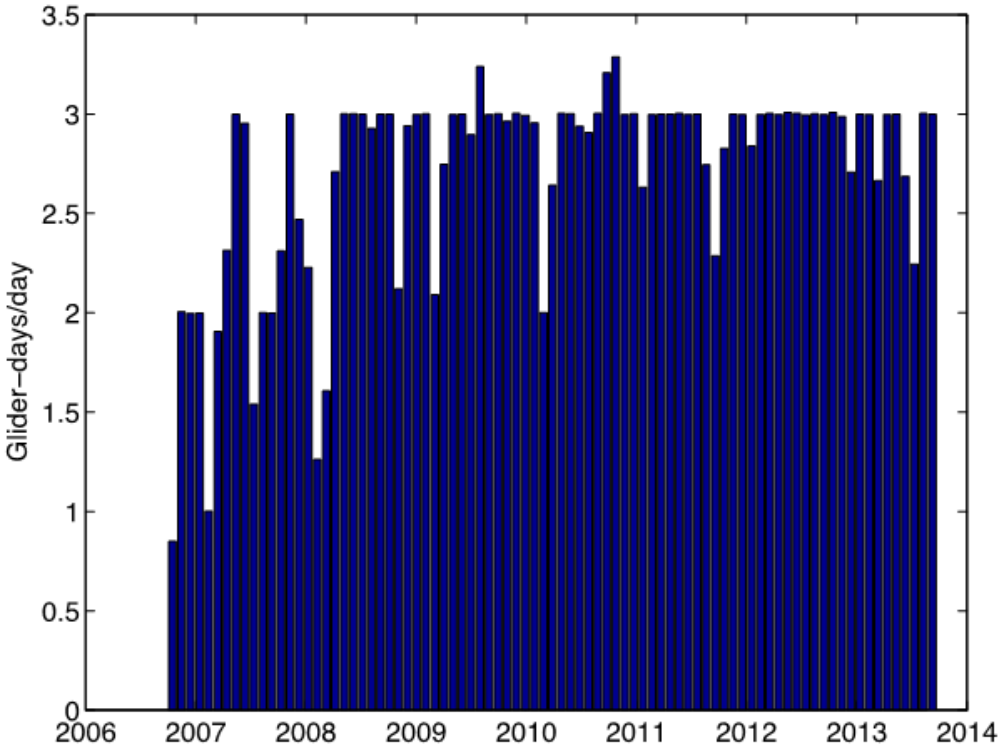


Figure 1. *Spray glider-days/day in the Southern California Glider Network, averaged in 30-day bins. Gliders have been sustained along three lines routinely since late 2008.*

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 (Dana 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 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. Fluctuations in glider-days/day are caused by gaps in coverage or overlapping deployments on a line. Since 1 January 2009, coverage has been 7%, which is a fair bulk measure of operational success. To date, the SCGN has done a total of 67,000 dives, covering 149,000 km in 7200 glider-days.

The Spray glider fleet deployed in the CCS measure 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), and at UCLA and UCSC, in addition to our group here in CORC. The NAVO, UCLA, and UCSC modeling efforts are for short term prediction, so they are delivered data at a regular 4-hour interval. 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 last 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.

A significant challenge with respect to instrumentation arose this year. The manufacturer of our ADPs, Sontek, informed us that they would no longer support our instruments nor sell new units to us, as they were terminating the product line. We have started working with the manufacturer Nortek, and the first of these new AD2CPs is currently deployed. Results so far are promising, but the need to replace our pool of Doppler current profilers poses a significant challenge in terms of time and funds.

Scientific

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). 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 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. We are updating the SoCal Niño Index monthly and posting it on the SCCOOS website (http://www.sccoos.org/data/elnino/).

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.

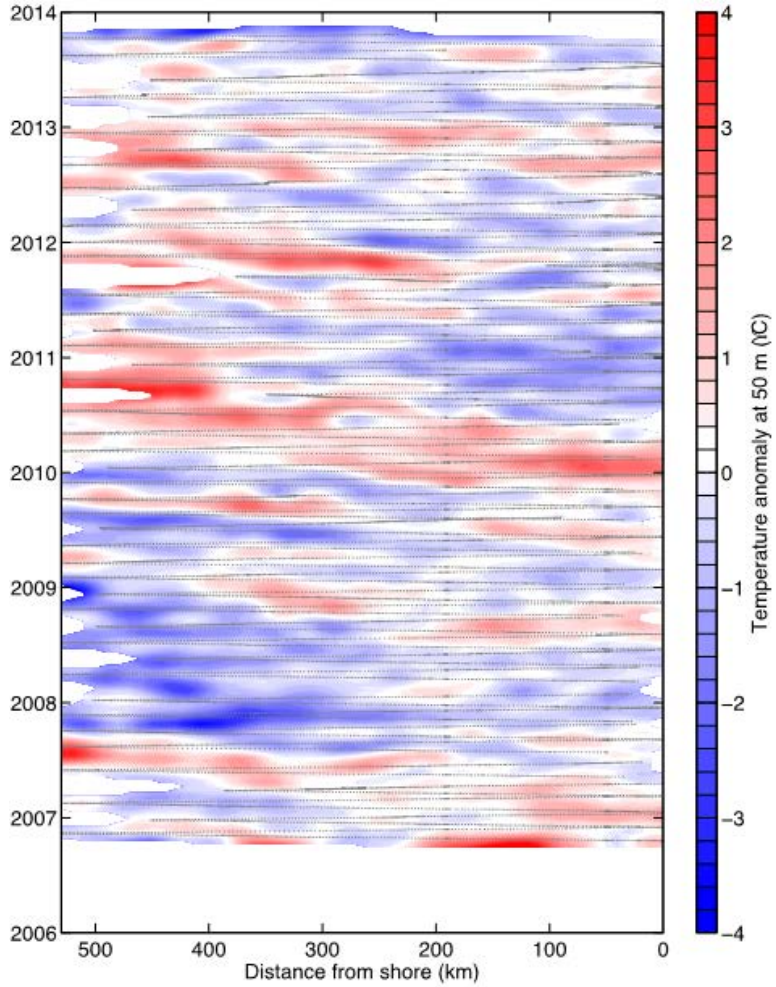


Figure 2. *Hovmüller plot of temperature anomaly at 50 m on line 90. Gray dots show the locations and times of glider profiles.*

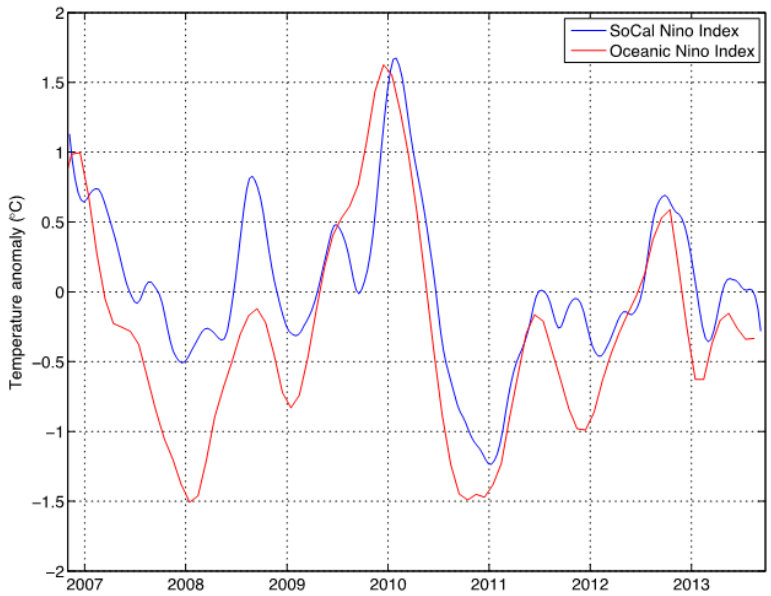


Figure 3. *The SoCal Niño Index, temperature anomaly at 50 m on line 90, averaged over the inshore 200 km, and filtered with a 3-month running mean (blue), and the Oceanic Niño Index (red).*

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).

Data Distribution

All data are distributed in real time through a variety of methods. In the following, we address the specific questions asked by COD.

a. The data are not yet available on GTS, but they will be within the next few months. We have been working on a route to GTS through an IOOS Data Assembly Center. The idea is that we will push data to the DAC, the DAC will forward the data to NDBC, then NDBC will make BUFR files and put the data on GTS. Part of this effort has been to create a CF-compliant netcdf format for glider profiles. We can already make these files, and we will soon begin forwarding them to the DAC.
b. The real time data reside on sushi.ucsd.edu, a password-protected server. We have provided accounts to anyone who has asked, and we currently support over 30 data users. The IOOS DAC will provide unrestricted public access within the coming year.
c. Delayed-mode quality controlled data are available on sushi.ucsd.edu. All these data are available to our registered users. The most recently quality-controlled data were collected in September 2013.
d. Data are archived at the conclusion of each glider mission, roughly every 4 months.
e. We have two web sites at which plots of real time and archived data can be freely accessed: spray.ucsd.edu, and www.sccoos.org/data/spray/?r=0. Data files are available through an ftp server at sushi.ucsd.edu.
f. We use the same server as all our users, that is sushi.ucsd.edu. We access the data several times per day, and we are certain it works.
g. We are in the process of documenting our data management plan, which has been developed over the past several years in parallel with the glider deployments.

Users of our data include the following:

a. The most voracious users of our data are modelers, with 4 groups currently using our data in both real time and delayed mode. NAVO receives our data directly by email in TESAC KKYY format for the purpose of short-term forecasts. The SCCOOS modeling effort run by UCLA and Remote Sensing Solutions gets our data by an ftp push. The CeNCOOS modeling effort run by UCSC has direct access to our server. Our model at CORC makes hindcasts of ocean state, and is beginning to make forecasts through data on our server.
b. The Orange County Sanitation District uses our data for their annual report on ocean conditions in the region of their outfall. This reporting is a requirement for all dischargers in our region.
c. The Southern California Coastal Water Research Project (SCCWRP) is a public agency formed to support research on water quality. SCCWRP was established largely in response to permit requirements for local dischargers. SCCWRP uses our data in support of these requirements.
d. Several research scientists at academic institutions are using our data for a variety of purposes.

e. Scientists at NOAA Southwest Fisheries Science Center have an interest in our data for the purpose of defining indices useful for the management of pelagic species.

A3. Outreach and Education

Underwater glider technology continues to be popular with the media as it combines robotics and oceanography. Scripps observing technology, including Spray underwater gliders and SOLO floats, was covered in an article in the San Diego Union-Tribune in September. Following are a few links to the story and photos: http://www.utsandiego.com/news/2013/sep/15/environment-scripps-gadgets-science-argo/, http://www.utsandiego.com/news/2013/sep/16/technology-oceanography-scripps-gadgets-hp/#&panel1-3, http://www.utsandiego.com/photos/2013/sep/14/1105483/, http://www.utsandiego.com/photos/2013/sep/13/1105056/.

Undergraduate student Adrian Castillo is employed to do quality control of glider profiles. Adrian has been the primary QC person for Spray glider data over the past two years. Adrian is working on a web site on Spray with an intended target of an educated public, such as his fellow undergraduate students. Adrian will complete a double major in Earth Sciences and Applied Mathematics this year, and he is considering graduate school.

Graduate student Katherine Zaba just started in our group a few months ago. Katherine is working on a climatology of the California glider data. The goal is to produce a climatology for each of the three gliders lines on evenly spaced grids in time, depth, and along section distance. This effort is inspired by the Argo climatologies produced by several groups.

B. Integrating and high-frequency observations in the California Current System

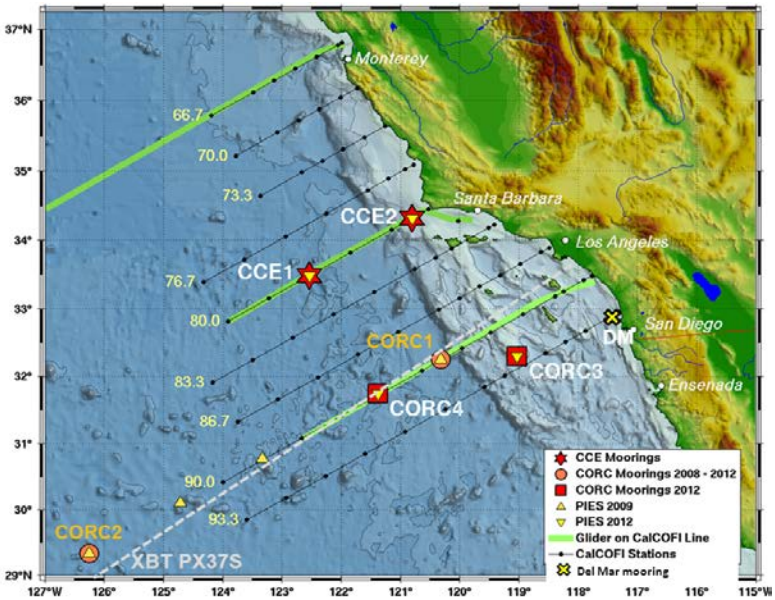
The objective is to develop and demonstrate cost-effective tools for documenting and understanding broad-scale and high-frequency impacts of climate variability in an eastern boundary current such as the CCS. We use a combination of moorings, inverted echosounders with pressure sensors (PIES), gliders, 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. 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 carries an acoustic modem to telemeter data from a new co-located CORC PIES and will collect dynamic height data for geostrophic transports). We have also started to experiment with gliders as “virtual moorings”, e.g. to complement the CCE1 mooring which does not have sufficient vertical T/S sampling, or to replace the CORC3 mooring which was fished away recently.

B2. Scientific and Observing System Accomplishments

We had originally hoped to have implemented by now 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. 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. Much progress has been made for producing indices about the CCS state and processes. The specific achievements of the integrating and high-frequency observations are summarized in the following subsections.



Technical

We still maintain a fleet of 5 modem gliders for CORC, with typically 2 in the water at any one time. We also usually have two subsurface moorings deployed on line 90 (CORC3 and CORC4) which form a rectangle with the separately funded moorings CCE1 and CCE2 on line 80. CORC PIES are deployed at all four sites in order to provide bottom pressure information to complement dynamic height data collected at those sites, and all PIES and moorings have acoustic modems for remote data transfer (for the PIES near CCE1 and CCE2, both the surface buoys of those moorings now carry modems to retrieve the data, and also gliders can recover the data). At the CCE2 site, we started to operate a CORC glider in March 2013, which holds station at CCE2 to the extent possible to collect T/S

profiles for dynamic height calculations (and water mass indexing, see below), and once per week does a round-trip to the coast to capture the flow between the coast and the CCE2 mooring site. In November 2013 we will also start the same with a glider at the CORC3 site. See figure 4 for an overview of these locations.

Operational

From the first CORC phase we have in hand 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, between CORC1 and CORC2). This has yielded enough data to design an efficient operational approach for capturing the variability of alongshore transport - see below for updated analyses of the correlation between satellite altimetry and the mooring transports.

At the time of writing, the intention was to have two moorings, 4 PIES, and 2 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. On October 17, 2013, approximately one year after deployment, CORC3 was cut off by fishing activity near Cortez Bank, and the upper 200m of the mooring started drifting. This segment with 5 microcats was recovered during a 2-day emergency rescue cruise with R/V "R.G. Sproul" on October 24. The lower part of the mooring with 3 more microcats, two acoustic releases, the controller and modem, apparently got caught around the anchor after release, we will need to dredge for those in 2014. In the meantime, we will use a glider to keep station at site CORC3 to collect T/S profile data and interrogate the PIES there. This will serve as a test for replacing two CORC-like moorings with station-keeping gliders.

We continue to work towards the improvement of various indices/indicators (see below) in order to generate them routinely and make them available via the CORC website.

Scientific

Deep alongshore transport

The 4 years of data from the first CORC phase, having been quality-controlled and fully processed, provide a unique view into the variability of the deep circulation in this eastern boundary regime. Such information has not been available to date. Figure 5 shows the internal (baroclinic, referenced to 3500m) transports in the top panel, and the total transports referenced to the bottom pressure from the PIES, for the Pacific Deep Water layer, below 2500m. There are significant

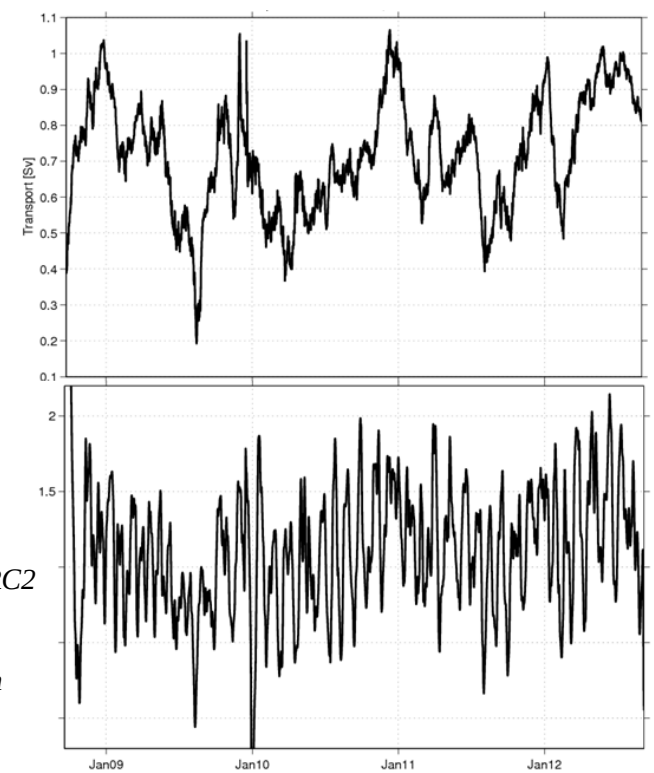


Figure 5: *Pacific Deep Water layer (2500-3500m) transport from the CORC1 and CORC2 moorings/PIES. Top panel shows only the baroclinic transport relative to 3500db, the bottom panel has higher-frequency part from the bottom pressure added.*

transport changes on several timescales. This deep transport is also relevant for the upper layer California Current (CC), since it sets the "reference level" velocity at the bottom of the CC layer which essentially is a barotropic offset/addition for the CC transport.

Upper-layer alongshore transport

In the FY12 report we had shown that the altimeter sea surface height difference from AVISO can give a very good representation of the total transport between the CORC moorings. That was done with the delayed-mode AVISO product and special filtering applied by P.Niiler's group at the time. We have been working to do the same with the realtime AVISO product which is available with minimum delay. Figure 6 shows the current state of this work. With some filtering, we can bring the delayed-mode and real-time AVISO to agreement now on the timescales of interest (blue and green curve). They still do not agree quite as well as the previous product (black) but we are quite confident we can develop and apply the same processing to these AVISO products. The result is expected to be a real-time product for the CC transport, derived from AVISO, calibrated and validated with nearly 4 years of CORC data.

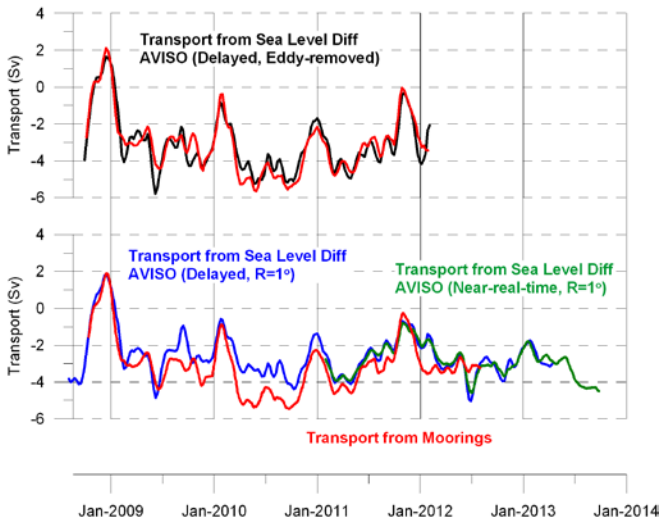


Figure 6: *Transport of the California Current between the CORC1 and CORC2 moorings (red), and various scaled SSH differences between these locations from AVISO altimetry (black with original filter on delayed-mode data, blue 1° filter on the same, and green blue 1° filter on near-realtime AVISO product).*

Advection of southern water masses

We are working along several lines to document and understand the water mass variability which results from advection of southern, more subtropical water via the California Undercurrent. This water normally is found at depths between 150 and 250m but can spread vertically and laterally, and the Undercurrent can be more or less pronounced. Due to its different characteristics (high salinity, high nutrient, low oxygen) it is believed to have important controls on the oxygen/pH variability in the upwelling regime, to affect euphotic zone productivity, and influence habitat conditions for marine fishes. A good measure for water of southern origin is spiciness π (high temperature and high salinity; orthogonal to density in the T-S diagram). Another measure is distance in the T/S diagram to the typical properties to the south and to the north, which allows us to generate an index between -1 (completely northern water) and 1 (completely southern water). We have started to analyze spiciness and this North/South index more systematically from moorings and gliders in the CORC region. A goal is to relate these to dynamical processes and forcing.

One core of the undercurrent passes moorings CORC3 and CCE2, while another one is found more inshore on line 90 (and probably merges with the offshore core by the time it reaches CCE2). However, the signature reaches as far as the old CORC1 mooring. At CCE2, we have

started to use the glider parked there since March 2013 (with weekly transects to the coast), to analyze the spiciness of water from the undercurrent. Figure 7 shows the variability of water from the south as the yellow-red colors in the 100-300m depth range, using the glider there. A more continuous record, but only as deep as 75m depth, can be obtained from the CCE2 mooring, shown in figure 8. There the spiciness is compared with the along-shelf difference of acoustic traveltime from the CORC PIES at CORC3 and CCE2 (we use this as a proxy for dynamic height differences at present). There seems to be a correlation, and we are in the process of analyzing this further to learn about the indicators and forcing of these Undercurrent waters.

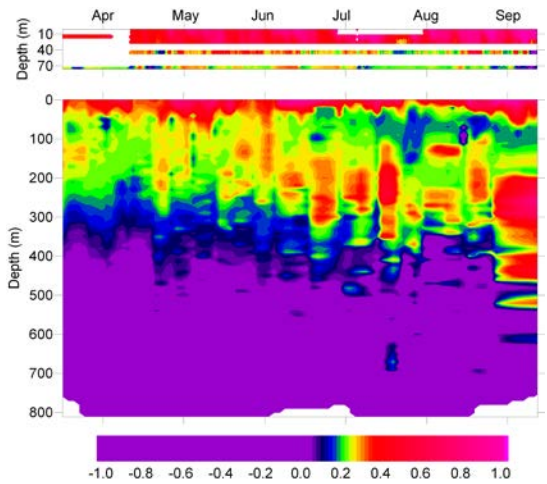


Figure 7: *Spiciness at CCE2 during 7 months in 2013 from a CORC modem glider (bottom panel) and from the few upper mooring sensors (top). Yellow/red colors below 100m show southern water masses.*

We are also relationship between the presence of Undercurrent water at CORC1 and the flow observed between CORC1 and CORC2. Figure 9 shows the north/south index of water between 150m and 250m depth (where the Undercurrent is found) on mooring CORC1 in red, together with different measures of the flow (geostrophic flow at that depth and of the upper 500m from the moorings, and the flow diagnosed from altimetry). Especially at low frequency, a relationship is visible, and we hope this can be developed into an index of southern water presence as well.

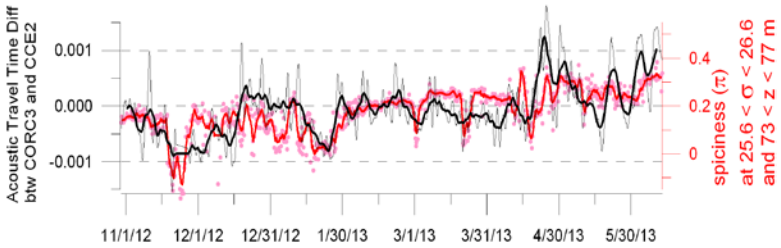


Figure 8: *Spiciness at the 75m CCE2 sensor (red) and alongshore PIES traveltime difference between CCE2 and CORC3.*

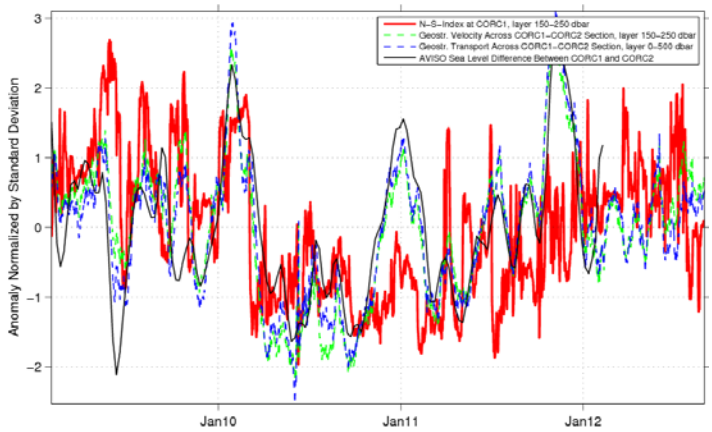


Figure 9: *North/South water mass index at mooring CORC1 (red) in the 150-250m layer, and various estimates of the flow through the CORC1-COR2 section (green: geostrophic velocity in the same layer between CORC1 and CORC2; blue: same but upper 500m layer; black: altimeter difference between the mooring locations).*

Upwelling event indicators
As shown in the CCE mooring Progress Report, we are working on upwelling indicators based on wind stress observations along the coast and based on high-frequency observations with moorings and PIES in the CORC/CCE region. To save space, we will not reproduce the figures and results here. But we continue to analyze wind, mooring, and PIES data, in conjunction with model results and glider sections, to determine the most suitable descriptors of upwelling events based on the real-time data being collected, in order to derive routine products for use by researchers, agencies, and the fishing community.

Data Management
Mooring data are presently not collected in real-time (only with large delays when downloaded by gliders) and thus do not get sent to the GTS. PIES data are not made available on the GTS. Data downloaded acoustically from moorings and PIES reside on an institutional server, which is connected to a backup system. Mooring data are shown in graphical form online when they are available.

Delayed-mode data from moorings and PIES reside on an institutional server, which is connected to a backup system. Subsets of the data are plotted on the CORC website. The project is finishing processing of all mooring and PIES data recovered in 2012 or earlier, and will provide these via a publicly accessible server with a proper data report once this is complete (status Oct. 2013: PIES processing complete, mooring salinities being re-processed due to spurious drifts in some datasets). The backup of the institutional server is run daily.

The website for the program is http://mooring.ucsd.edu/projects/corc/corc_data.html. We are in the process of documenting our data management plan, which has been developed over the past several years.

B3. Outreach and Education

One young scientist and one graduate student are being trained via work on the CORC mooring program and data. Wherever possible, we invite students to participate in CORC cruises. In our teaching, and during visits of prospective students, CORC is used as a demonstration of exciting and relevant technology and research. Many potential new students contact us as a result of their interest in the CORC mooring program as explained on our websites.

The CORC mooring effort will be presented at the ASLO/Ocean Sciences Conference in Honolulu in February 2014.

SYNTHESIS OF XBT AND ARGO DATA FOR BOUNDARY CURRENT ESTIMATION

Dean Roemmich

1. Task Summary

The objective of this work is estimate the volume and heat transport of western boundary currents systems by combining High Resolution XBT, Argo, satellite altimetry and other datasets, and to relate the boundary current transports to those of the ocean interior. The combination of boundary current and interior transport reveals the strength and depth-dependence of meridional overturning circulations that are key elements of the ocean/climate system. Mean transports and their time variability are estimated for understanding the ocean's roles in the climate system and in sustaining marine ecosystems, and for assessing the adequacy of the ocean observing system for these goals. Present work is focused on boundary currents of the southwestern Pacific, with planned work to include the western boundary currents of all five subtropical gyres.

2. Scientific and Observing System Accomplishments

Syntheses of XBT and Argo data: For this sub-program the deliverables are analyses of geostrophic velocity and transport in ocean boundary currents, and their combination with interior flows. These contribute directly to several NOAA/Climate Observation Division Program Deliverables, specifically: ***Ocean Heat Content and Transport; Sea Surface Temperature and Surface Currents; Sea Level.***

2.1 Scientific highlight – Synthesis of XBT and Argo data

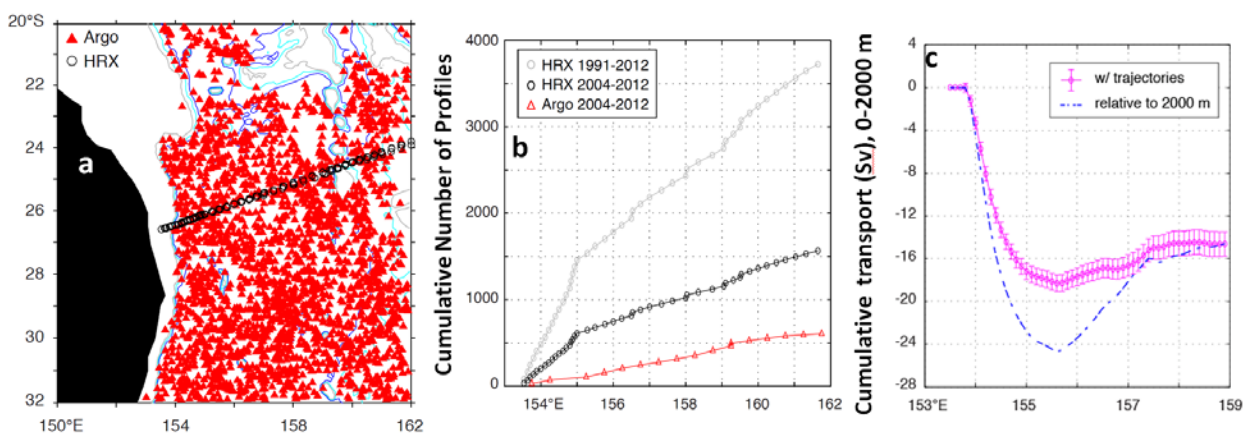


Figure 1: (a) Location of all Argo profiles in the EAC region, 2004-2012, compared with profiles from a single year (2010) with 4 HR-XBT transects. (b) Cumulative number of HR-XBT profiles for 2004-2012 (black), and for 1991-2012 (gray), compared with Argo profiles within 1.5-degrees of latitude of the HR-XBT track. (c) Cumulative geostrophic transport, 0-2000 m with standard error, for the combined HR-XBT and Argo data (including trajectory-based reference velocity).

The spatial sampling characteristics of High Resolution XBT and Argo data in the East Australian Current (EAC) region near Brisbane are illustrated in Fig 1. While Argo is efficient at broadscale areal coverage, it does not provide sufficiently dense sampling to resolve the energetic, temporally and spatially varying EAC. The HR-XBT network provides the necessary spatial resolution along the sampled routes, and is thus strongly complementary to Argo. For example, in a 3° latitude range east of Brisbane, between the shelf break and the offshore edge of the EAC at 155°E, about 100 Argo profiles are found since 2004. This compares with 1500 XBT profiles along the HR-XBT line PX-30 since 1991, including 700 during the Argo era since 2004. As a consequence the EAC shear in the upper 800 m is much better resolved by the XBT transects. Moreover, there are many XBT profiles shoreward of the 1000 m isobath, where significant transport occurs and where Argo floats are not found due to grounding problems. However, the HR-XBT data do not extend below 800 m, nor do the 4 cruises per year provide adequate resolution of the time domain. Our work (Zilberman et al, in progress) also uses Argo and altimetric height, projected onto subsurface density, 0-800 m and 800-2000 m, both to correct temporal aliasing of mean fields and for resolving time variability of the EAC transport as well as its tight recirculation. Moreover, Argo trajectory data provide a reference velocity for absolute transport estimation. In turn, the boundary current region is combined with the ocean interior for basin-wide estimation of mean and time-varying volume and heat transport and meridional overturning circulations. The line-mode (HR-XBT) and the area-mode (Argo) of sampling are both essential for the integrated ocean observing system, with these and satellite altimetric height each providing complementary coverage of spatial, depth, and temporal domains.

3. Education

Post-doctoral Investigator N. Zilberman is partially supported to carry out the analyses of XBT and Argo datasets for boundary current estimation.

DATA ASSIMILATION TOOLS FOR THE BOUNDARY CURRENT OBSERVING SYSTEMS

Bruce Cornuelle

1. Task Summary

The goal of the CCS assimilation effort is to develop new methods that enable a synthesis of the observations to use the information they produce to the fullest. This is done by using models to enforce kinematic and dynamical constraints, such as conservation of mass, heat, salt, and momentum, together with consistency with observations, to produce hindcasts, nowcasts, and forecasts that will be useful for diagnosis of the CCS physical system and ecosystem. There are two parts to the effort, long-term state estimates, which extend over 4 years and are to be extended further, use the balance constraints to adjust surface forcing as well as model initial conditions and boundary conditions, providing improved flux estimates for the CCS, as listed in the Program Deliverables. The long-term estimates are supplemented by more nimble short-term estimates that will extend to near-real time, and provide more up-to-date reanalysis of the observations for use in diagnosing questions like sea lion mortality. The model reanalysis and the adjoint of the model allow the tracing of dynamical influences for the CCS, quantifying the effects of local and remote forcing.

2. Scientific and Observing System Accomplishments

2.1 Long-term state estimation using CORC observations:

This focuses on the continuation of the long-term assimilation, which is currently 4 years but should be extended (or moved) to reach 2012 or 2013. Using other funding, the state estimate was extended to the MITgcm Biogeochemical (BGC) model package, and now the Biogeochemistry with Light, Iron, Nutrients and Gases (BLING) model has been added and tested in forward runs. For this sub-program the deliverables are analyses of ocean state in the CCS region and model-based analysis of internal and external connections through adjoint sensitivity analysis. These contribute directly to several NOAA/Climate Observation Division Program Deliverables, specifically: ***Ocean Heat Content and Transport; Sea Surface Temperature and Surface Currents; Sea Level, Ocean Carbon Uptake and Content.***

The long-term state estimate produces estimates of air-sea interaction every two days throughout the 4-year duration, including heat, momentum, freshwater, and now CO2 fluxes, as shown in Figure 1. These can be examined annually, seasonally, or interannually to understand the balances in the CCS. The reanalysis is a complete ocean state, providing estimates of surface temperature and velocity (average surface velocity shown in figure 2), heat content, isotherm and isopycnal displacement (figure 3), sea surface height (SSH) , and subsurface pressure gradients. These are mentioned as deliverables 4 and 5 in the workplan (Improved CCS state from assimilations, including atmospheric state, eddies, and cross-shelf transports; Integrated index of CC upwelling in terms of isopycnal displacements on and between glider/mooring lines (directly from observations and from assimilations)) and are available on the website. One of the goals of the state estimation is to estimate varying along-shore and cross-shore transports, which are important for the climate and for ecosystems. Northward surface current, averaged within a box

that extends along the entire coast out to 1.5 degrees offshore (figure 2), is an indicator of when the warmer and saltier undercurrent surfaces, and is a prototype diagnostic for surface transport of heat, nutrients, and larvae. This addresses another deliverable: Related indexes of heat and mass transport of the northward-flowing currents, motivated by the interest in finding physical changes influencing the recent increase in Sea Lion mortality, among other phenomena. The deliverable: North-south pressure gradients at ~100m as a diagnostic index of the CC shallow upwelling overturning cell (geostrophic return flow balancing the Ekman offshore transport) has been calculated for the 4-year LTSE. The 100m pressure behaves similarly to surface pressure, having an annual cycle, but with strong inter-annual variability (not shown). A submitted paper on Calcofi climatology includes a figure that shows the annual cycle of the offshore temperature and salinity gradients, indicating less seasonality in those diagnostics. The deliverable: Model estimate of CC alongshore wind stress and upwelling, in comparison with above indices and with alongshore surface flow estimates has been addressed by the estimates, and an estimated curl was shown in Todd, et al. 2011, but comparison with indices remains to be done. Along-shore surface flows have been calculated from the state estimate, while the accepted paper on HFR flows (Kim, et al. 2013) shows progress from the observational side.

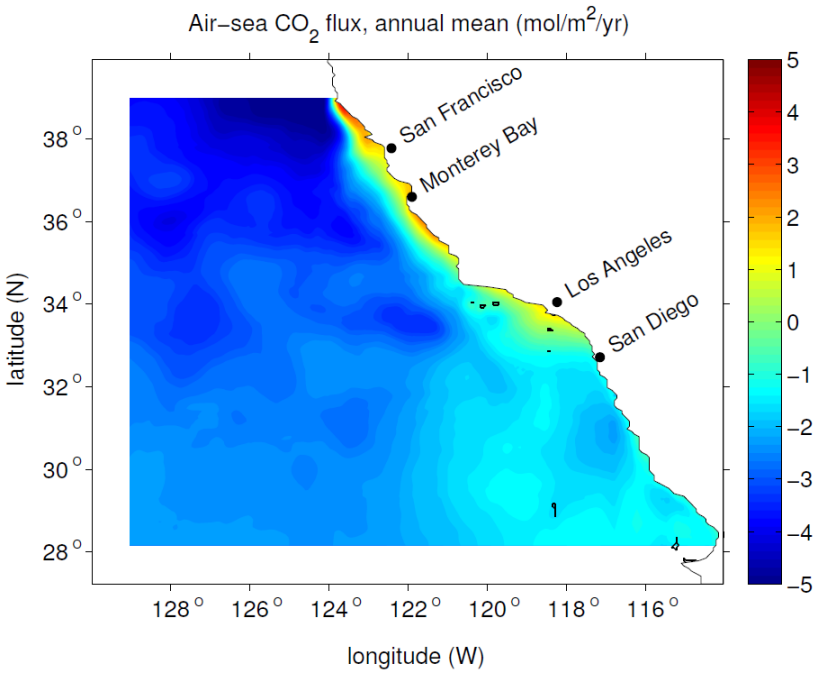


***Figure 1**: The four-year mean of air-sea CO2 flux as estimated by the model using an optimized state including the CORC observations.*

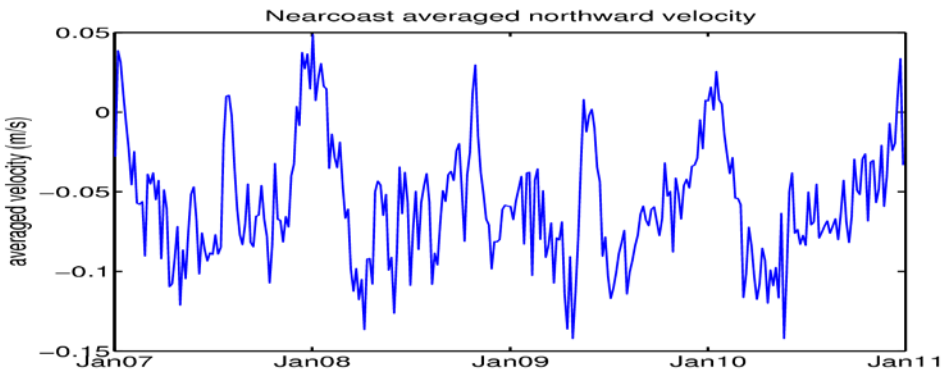


***Figure 2:** Time series of average northward surface velocity (m/s) near and inside of the continental slope for the four-year LTSE. This shows the northward undercurrent surfacing during the winter.*

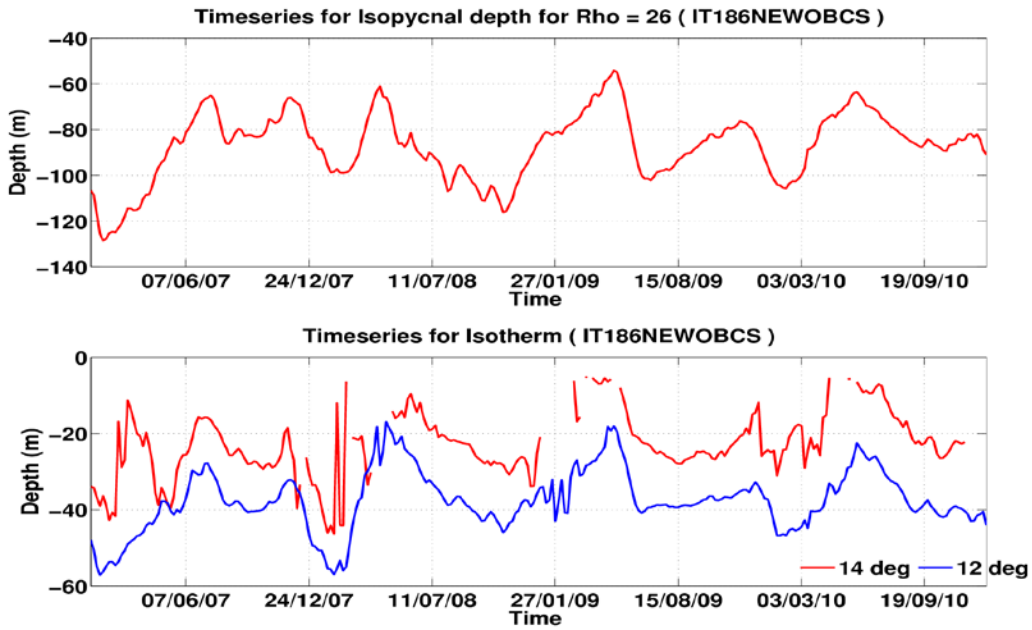


Figure 3: *Upwelling indices for the 4-year state estimate. The upper panel shows a time series of the depth of the potential density sigma = 26 isopycnal averaged over the Southern California Bight region (defined here as the region within 150 km of the coast between CalCOFI line 95 in the south and line 80 in the north). The lower panel shows time series of the averaged depth of the 12 degree (blue) and 14 degree (red) isotherm for the same region. The water is upwelled during the spring and summer, and downwelled in the winter. Interannual variability is clear.*

The state estimates are tested by comparison with observations, and against independent observations through forecasts, as shown in figures 5 and 6, which also involve comparisons to the short-term state estimate.

The recently accepted paper by Verdy et al. (2013) is an example of the adjoint analysis, diagnosing the influences on SSH at the coast, as the first step in understanding the controls on the transport, and detailing the effects of Coastally-Trapped Waves (CTW) and other physics. The paper by Kim, et al. (2013) is an analysis of similar influences in the High-Frequency Radar observations, examining the propagation of signals in along-coast surface velocity. These address the deliverable: Scientific examination of the sensitivity of SSH and transport to atmospheric forcing, using the adjoint**.**

2.2 Short-term state estimation using CORC observations: In parallel to the long-term state estimate (LTSE) effort, short-term state estimates (STSE) of one month duration have been made, both overlapping with the LTSE for comparison, as promisedbeginning in January 2012 in anticipation of the expansion of the LTSE. These shorter windows allow a better match to observations, at lower computational cost, but the discontinuities between windows amount to some loss of information compared to a single, long window. The monthly STSE fit the observations primarily by adjusting the initial temperature and salinity, whereas atmospheric forcing and open boundary conditions play a dominant role in adjusting the LTSE. These STSE window lengths are still 3 to 18 times longer than other state estimates for the California Current System. STSEs have been completed through March 2013, although not all CORC observations

are available at the most recent times. . These contribute directly to several NOAA/Climate Observation Division Program Deliverables, specifically: ***Ocean Heat Content and Transport; Sea Surface Temperature and Surface Currents;*** and ***Sea Level.***

Figure 3 shows upwelling indices for the 4-year state estimate (LTSE), and figure 4 shows the same indices for the sequence of one-month (STSE) estimates (solid) and their monthly forecasts (dashed). The forecasts show agreement with the hindcasts except in times of strong wind-driven transitions which are not represented in the climatological forcing used in the forecasts.

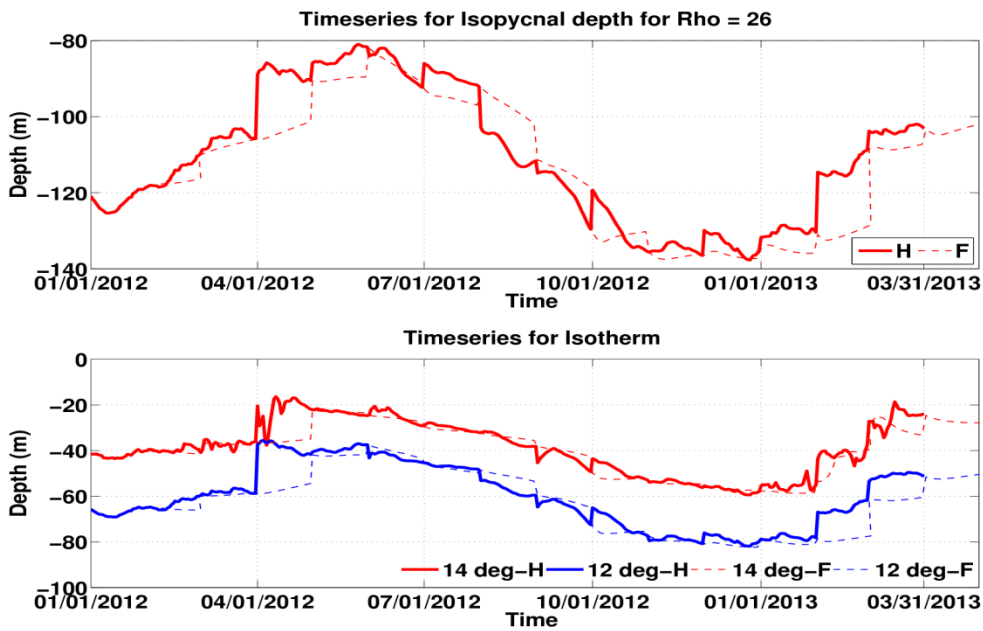


Figure 4: *Upwelling indices for the series of one month short-term state estimates from Jan 1 2012 through the end of April 2013. As in figure 2, the upper panel shows a time series of the depth of the potential density sigma = 26 isopycnal averaged over the same Southern California Bight region as the previous figure. The lower panel shows time series of the depth of the 12 degree (blue) and 14 degree (red) isotherm for the same region. Each monthly state estimate is used to forecast forward 30 days using climatological forcing and boundary conditions, and the upwelling indices from the forecast state estimate are shown as dashed lines. As with the LTSE, the annual cycle is clear, and interannual variability is hinted at.*

As stated in the workplan, we have compared the new STSE with the existing LTSE by calculating both hindcast and forecast weighted root-mean-square differences (RMSD) with respect to observations. Figure 5 shows how the STSE can fit the observations more closely than the LTSE, while figure 6 shows SSH forecasts for three months starting from the optimized state at the end of the same one month (Dec 2010) STSE and of the four-year LTSE. Both forecasts showed smaller RMSD (meaning better skill) with respect to AVISO gridded SSH than persistence of initial conditions for most of the three month forecast period. This is a test of the state estimate against independent observations, and shows that it performs well. Similar performance statistics are computed for the CORC observations, including glider and mooring profiles of temperature and salinity (not shown).

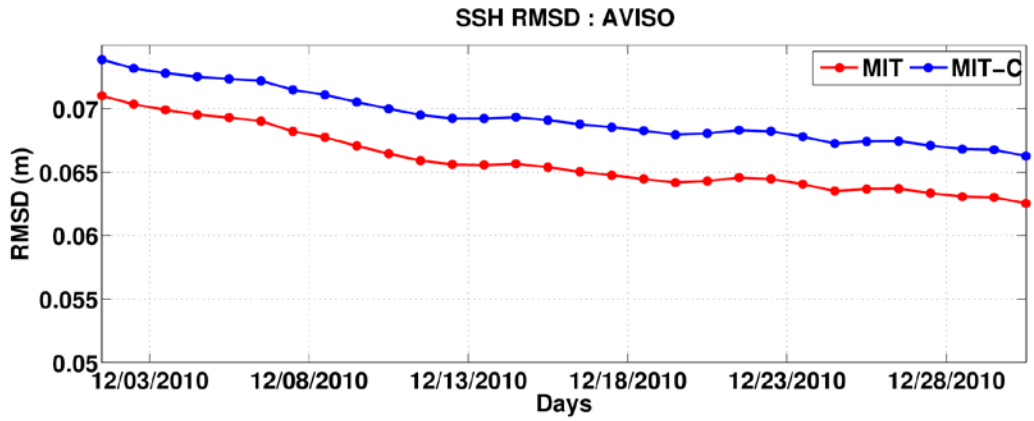


Figure 5: *Time series of root-mean-square difference (RMSD) between the model state estimates and the AVISO mapped product, averaged over the entire model region for December 2010, the final month of the current long-term state estimate. The blue line is the RMSD for the LTSE, while the red line is the RMSD after that state has been improved by the 1 month fit to SSH, SST, CORC, Argo, XBT, and pinniped observations*

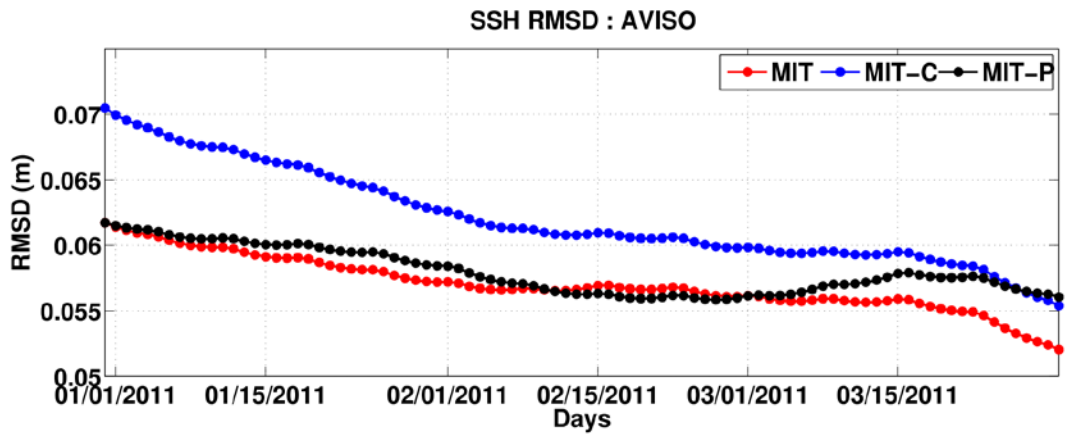


Figure 6: *Time series of root-mean-square difference (RMSD) between forecast model state estimates and the AVISO mapped product, averaged over the entire model region for January 1 2011 through the end of March 2011. The blue line is the RMSD for a forecast from the LTSE, while the red line is the RMSD for the forecast from the STSE, meaning the LTSE state improved by a 1 month fit to SSH, SST, CORC, Argo, XBT, and pinniped observations. The black line is a persistence forecast from the optimized 1 month state, for comparison. The 1-month optimized state forecast is better than persistence or the LTSE, cross-validating the state estimate against the independent (future) observations.*

2.3 Synergies with other components

The CCS state estimation is meant to be an optimal representation of the CORC observations, combined with other observations and with a model enforcing dynamical balances. The state estimate uses the same balances to adjust surface forcing to be consistent with the observed heat content and upwelling. As the observing system becomes mature, observing system experiments can be done by withholding certain observations and examining the impact on the estimates and forecasts.

3. Education

Post-doctoral Investigator G. Gopalakrishnan was partially supported to do the short-term state estimation, and has now transitioned to Project Scientist.

SUMMARY OF THE CORC APPROACH

The CORC effort in ocean climate observations is a response to the community consensus and recommendation from OceanObs09 that extending the ocean observing system to boundary currents is of the highest priority. Most methods used for sustained observations are unsuitable for boundary currents and most methods used to observe boundary currents are not sustainable. Therefore CORC's goal is to develop and prove methods for sustained observation of these currents including those that are narrow and strong and those that are highly productive and biogeochemically climate-sensitive. This is being approached with a hierarchy of tasks including (a) developing ways to sustainably measure the transport of western boundary currents, (b) developing methods to observe physical, biogeochemical, and ecosystem processes in boundary currents, (c) linking the boundary current observations to the global large-scale observing system, and (d) merging the boundary current observations into state estimates. All components build on and extend technologies and techniques developed under CORC in the past.

Dean Roemmich is examining global ocean data with an eye toward selecting boundary currents that are of highest climate priority and feasibility for early addition to the ocean observing system. His task helps to relate CORC observations to Argo and hi-res VOS XBT sections . If sustainable observing methods are proven, the results of this work will be central to selecting boundary-current sites important to both physical climate and its impact on biogeochemistry and ecosystem science and management.

Russ Davis leads the western boundary current transport project which includes Uwe Send and William Kessler of PMEL. This group is using gliders and end-point moorings and pressure gauges sited on both sides of the current to measure transport through the Solomon Sea from the subtropical South Pacific to the equator. Raising the quality and reliability of techniques for strong-current measurements, while reducing their cost, is the technical goal. The scientific objective is understanding Solomon-Sea transport into the Equatorial Undercurrent in relation to ENSO, and decadal climatic variability of air-sea interaction along the equator. Technical success would make sustained western boundary current observations feasible.

Rudnick and Send are developing and demonstrating sustainable observing approaches for process, event, and climate impacts on eastern boundary current ecosystems, fisheries, carbon dynamics, and ocean acidification. The combination of gliders and moorings merges the important aspects of permanent presence, spatial coverage, high temporal resolution, multi-variable observations, and real-time data access. This has already established a showcase infrastructure which is becoming increasingly important for characterizing and understanding/modeling the habitat conditions affecting marine life, including commercial and recreational species on the west coast.

Cornuelle is developing methods for an effective use of boundary current observations to provide useful ocean climate products from scattered observations. The model state estimate has recently been extended with a biogeochemical package, allowing additional state estimates of carbon, ocean acidification, and ecosystem quantities. As such its main application and demonstration to date is for the eastern boundary current application on the US west coast.

CORC's goal and intended legacy is to define and hand off to NOAA an efficient and sustainable implementation for eastern and western boundary current observations, which can be either extended (e.g. US West Coast) or replicated in other global locations (such as mid-latitude western boundary currents).

PUBLICATIONS BY THE CORC PROJECT

Davis, R.E., 2012. It takes a network to build an ocean observing system. *Mains'l Haul*, **48** (3,4), 18-31.

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.*, **42**, 2001-2013.

Hristova, H., W.S. Kessler, J.C. McWilliams and J. Molemaker, 2014: Eddy distribution in the Coral and Solomon Seas. In preparation

Ganachaud, A., M. Bowen, G. Brassington, W. Cai, S. Cravatte, R. Davis, L. Gourdeau, T. Hasegawa, K. Hill, N. Holbrook, W. Kessler , C. Maes, A. Melet, B. Qiu, K. Ridgway, D. Roemmich, A. Schiller, U. Send, B. Sloyan, J. Sprintall, C. Steinberg, P. Sutton, J. Verron, M. Widlansky and P. Wiles, 2013: Southwest Pacific Ocean circulation and climate experiment (SPICE), *CLIVAR Exchanges*, **18**(61), 16-23.

Ganachaud, A. et al., 2014: Ocean circulation of the southwest Pacific: new insights from the Southwest Pacific Ocean and Climate Experiment (SPICE). Davis, Kessler and Send are co-authors. In preparation

Kessler, W.S,. and S. Cravatte, 2012: ENSO and short-term variability of the South Equatorial Current entering the Coral Sea. *J. Phys. Oceanogr.*, **43**, 956-969.

Kim, Sung Yong, Eric J. Terrill, Bruce D. Cornuelle, Burt Jones, Libe Washburn, Mark A. Moline, Jeffrey D. Paduan, Newell Garfield, John L. Largier, Greg Crawford, and P. Michael Kosro, 2013: Poleward propagating subinertial alongshore surface currents off the U.S. West Coast. *Journal of Geophysical Research*, accepted.

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.

Verdy, Ariane, Matthew R. Mazloff, Bruce D. Cornuelle, Sung Yong Kim, 2013: Wind-driven sea level variability on the California coast: an adjoint sensitivity analysis. *Journal of Physical Oceanography*, accepted.

Send, U., L. Regier, and B. Jones, 2013: Use of underwater gliders for acoustic data retrieval from subsurface oceanographic instrumentation and bi-directional communication in the deep ocean. *J. Atmos. Ocean. Techn.* 30(5). doi: 10.1175/JTECH-D-11-00169.1

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. *Journal of Geophysical Research*, **116,** C02026, doi:10.1029/2010JC006536.

Todd, R.E., D.L. Rudnick, R.E. Davis and M.D. Ohman, 2011: Underwater gliders reveal rapid arrival of El Nino effects off California's coast. Geophys. Res. Lett., **38**, doi:10.1029/2010gl046376

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.

Zilberman, N.V., D.H. Roemmich, and S.T. Gille, 2012 The mean and the time-variability of the shallow meridional overturning circulation in the tropical South Pacific Ocean. Journal of Climate, 26, 4069 - 4087. doi: 10.1175/JCLI-D-12-00120.1