CORC

Uwe Send, Russ Davis, Daniel Rudnick, Dean Roemmich, and Bruce Cornuelle
Scripps Institution of Oceanography

Table of Contents

1. Project Summary 2
2. Scientific and Observing System Accomplishments 3
   2.1 Circulation Measurements in the California Current 3
   2.2 Measurement of western boundary current transport in the Solomon Sea 8
   2.3 XBT and ARGO analyses in support of western boundary current observations 12
   2.4 Data Assimilation tools for boundary current observing systems 14

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

2.1 Circulation Measurements in the California Current

Section observations with gliders

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 8 years in length, we believe we have addressed each of our primary objectives. Our observations contribute to the program deliverables: sea surface temperature and surface currents, ocean heat content and transport, and ocean carbon uptake and content.

The California Glider Network (CGN) 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 CGN (**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 97%, which is a fair bulk measure of operational success. The same 97% mark has been met over the past 12 months. To date, the SCGN has done a total of 77,000 dives, covering 175,000 km in 8400 glider-days.

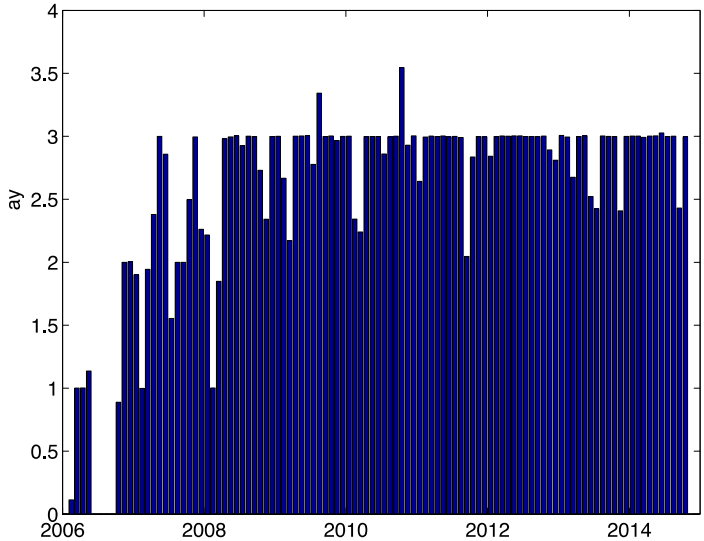

Fig. 1: *Spray glider-days/day in the California Glider Network, averaged in monthly bins. Gliders have been sustained along three lines routinely since late 2008.*

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 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.
Over the past year, we have worked on integrating two new sensors. First, we are beginning use of a dissolved oxygen sensor (Sea-Bird SBE63). The purpose of these measurements is to monitor the possible spread of hypoxia, and to keep track of one component of the carbonate system. We use a proxy relating temperature, salinity, and dissolved oxygen to infer more difficult to measure properties such as pH and aragonite saturation (Alin et al., 2012). Second, we are beginning a long-term process of replacing our obsolete Sontek Doppler profilers with newer, more capable Nortek units. As with any new sensors there have been growing pains with both the dissolved oxygen sensor and the Doppler profilers. We have worked closely with the manufacturers to diagnose and fix the problems, and we are well on our way to fully successful integration in the coming year.

El Niño. The El Niño/La Niña cycle is the climate variability most keenly felt along the coast of California. An El Niño threatened this year, but has abated to the point that temperatures along the equator are near normal. However, off California, the warming event has been significant. Our SoCal Niño Index is the glider-measured temperature anomaly at 50 m along CalCOFI line 90, averaged over the inshore 200 km (**Figure 2**) reveals a strong correlation with conditions at the equator measured by the Oceanic Niño Index. However, the two indices diverged during the past year. While the 50-m temperature anomaly is no warmer than during the moderate El Niño of 2009-10, the surface anomaly is the largest since 1997-98. We update the SoCal Niño Index monthly and post it on the SCCOOS website (http://www.sccoos.org/data/elnino/).

Climatology. In an effort to make the entire CGN data set accessible for scientific calculation, we have been working on a gridded climatology for each of the three lines. The product includes temperature, salinity, and velocity on a grid 10 m in the vertical by 5 km in the horizontal by 10 days in time. This climatology includes an annual cycle and the anomaly from this cycle. We are using this product to examine the unusually warm year with a goal of publication in the coming year. Graduate student Katherine Zaba is a key contributor to this project.

Publications in the past year have used glider data to address mixing in the California Current system (Johnston and Rudnick, 2014), to address the possibility of assessing primary production using gliders (Jacox et al., 2014), and have provided an overview of measurements in support of long term ecological research (Ohman et al., 2013). In addition, we participated in the planning workshop addressing the tropical Pacific observing system.(Rudnick et al., 2014).

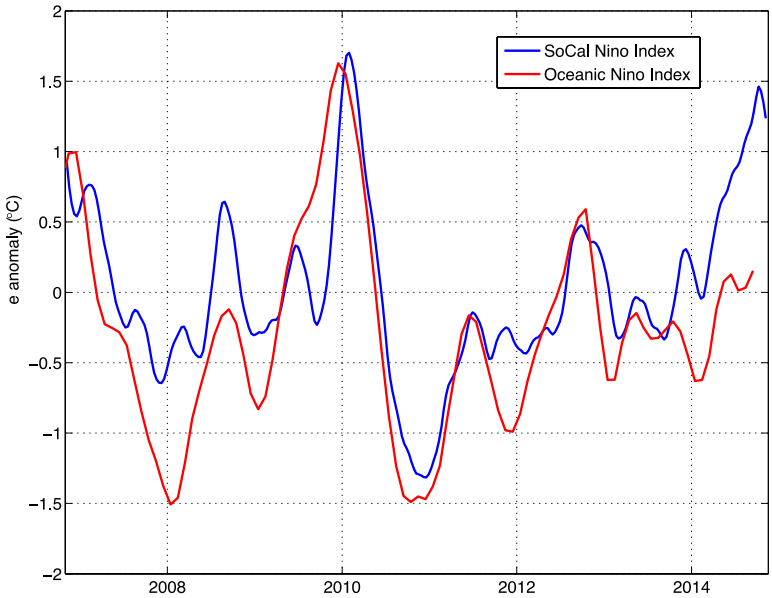

Fig. 2: *The SoCal Niño Index, temperature anomaly at 50 m on line 90, averaged over the inshore 200 km, and filtered with a 3-month running mean (blue), and the Oceanic Niño Index (red).*

Timeseries observations with moorings, PIES, and gliders

In the current phase we are focusing on the inner part of the California Current by combining observations at the sites CORC3 and CORC4, and CCE1 and CCE2 (map shown in previous reports). All sites have a PIES from which we mainly use the bottom pressure data at present to calculate absolute fluctuations of dynamic height (i.e. not referenced to some assumed level pressure surface). CORC4 has a dynamic height mooring (microcats measuring T/S throughout

the water column), and at CORC3 there is a glider in "virtual mooring mode" also allowing dynamic height calculations. Data from the PIES are retrieved via the gliders. At CCE2 (on the 800m isobath like CORC3) we also operate a glider in virtual mooring mode, since the CCE2 mooring does not cover the water column deep enough with T/S, and since the glider can do (once per week) a quick section to the coast and back to assess how much flow there is between the mooring and the coast. Both CCE moorings carry acoustic modems which routinely retrieve the data from the co-located PIES.

One goal is to diagnose the weekly total upwelling transport in the southern California Bight from cross-shelf geostrophic transports, similar to what Roemmich (1989) did with CalCOFI CTD data on multi-year timescales. First steps towards that are shown in **Figure 3**, using the dynamic height gradient between CORC3 and CCE2, where the density part ("internal transport") comes from the gliders parked there and the barotropic part from the bottom pressure using the PIES ("external transport"). We are trying to use the geostrophic cross-shelf transport from these along-shelf gradients as a measure for the upwelling. The only comparison for upwelling activity we have at present is the density at CCE2 itself. Figure 3 plots the cross-shelf transport together with the 15m density there. Even though the density at CCE2 enters the transport calculation, it does not dominate the time evolution of the transport obtained, and therefore we think the qualitative agreement is encouraging.

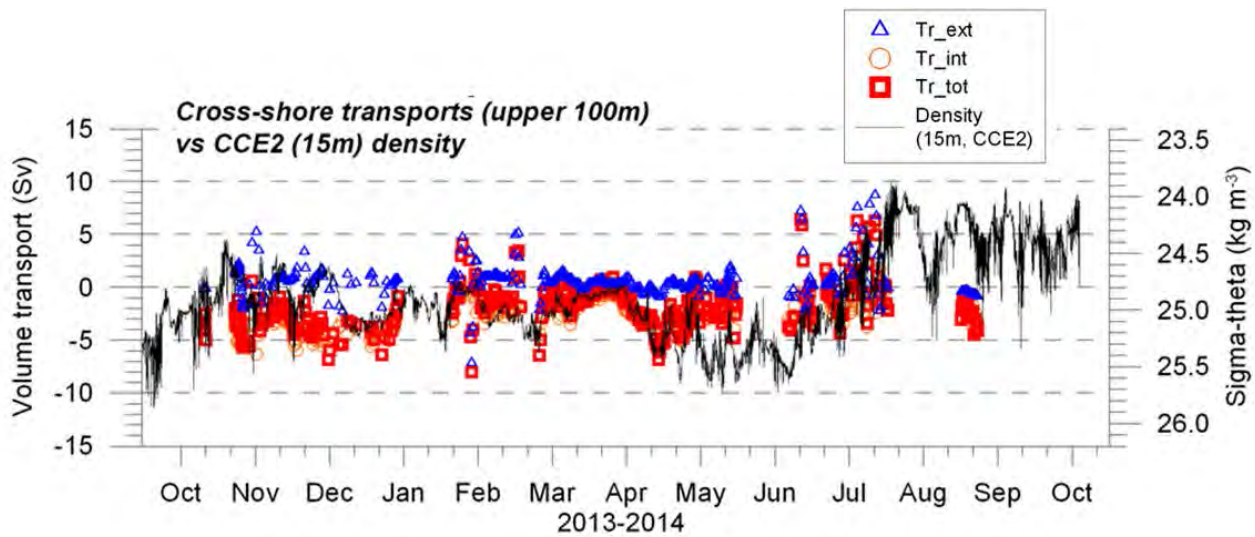

Fig. 3: *Cross-shelf geostrophic transport estimate between CORC3 and CCE2 (both on the 800m isobaths), showing the internal (circle), external (triangle), and total (square) contribution. Positive transport is offshore. Superimposed in black is the 15m density observed at CCE2 as a measure of upwelling. The sign is consistent since decreasing density in Jun-Aug means downwelling or onshore Ekman transport and thus offshore geostrophic flow.*

Figure 3 also reflects the extreme warming which occurred in the summer of 2014. We are in the process of analyzing the processes that led to the unusual warm and unproductive conditions in 2014. A first look at the winds seems to suggest that they were not anomalous, so it may not be an absence of upwelling itself. Various data sets (including CORC and CCE) show that the water was already anomalously warm and stratified at the beginning of the year, which could have led to upwelling just bringing warm water to the surface. The progressive vector diagram in **Figure**

4 of currents at CCE shows that a likely reason was anomalous northward currents already at the beginning of 2014.

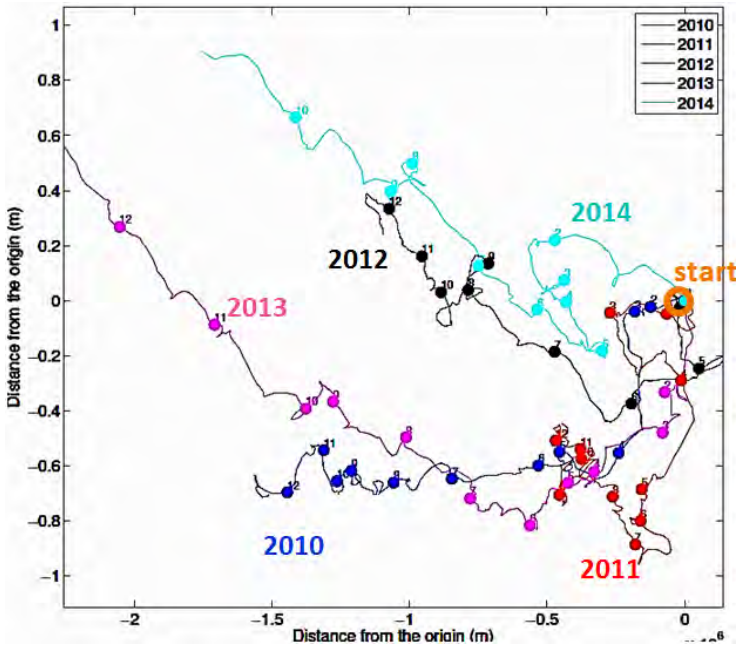

Fig. 4: *Progressive vector diagram (time integral of 2-D currents) at mooring CCE2 for the near-surface flow. Each pseudo-trajectory starts on Jan 1 of each year, and is plotted from a starting point marked with the orange circle. Each month is marked by a dot and labeled 1-12. Note that all years except 2014 have offshore our southward flow in the first half of the year, while 2014 has northward flow in those months.*

We are also in the process of analyzing the water properties of the California Undercurrent, which brings water of southern origin into the region and is believed to influence the ecosystem properties through upwelling of this water into the upper layer. A measure for the presence of this water is the spiciness, since at the same density the southern water has higher salinity and temperature than the surrounding water. **Figure 5** shows a timeseries of spiciness at site CCE2 together with the dynamic height between 500db and 200db (the layer of the undercurrent). Note that even though T and S enter both calculations, dynamic height depends on density variations

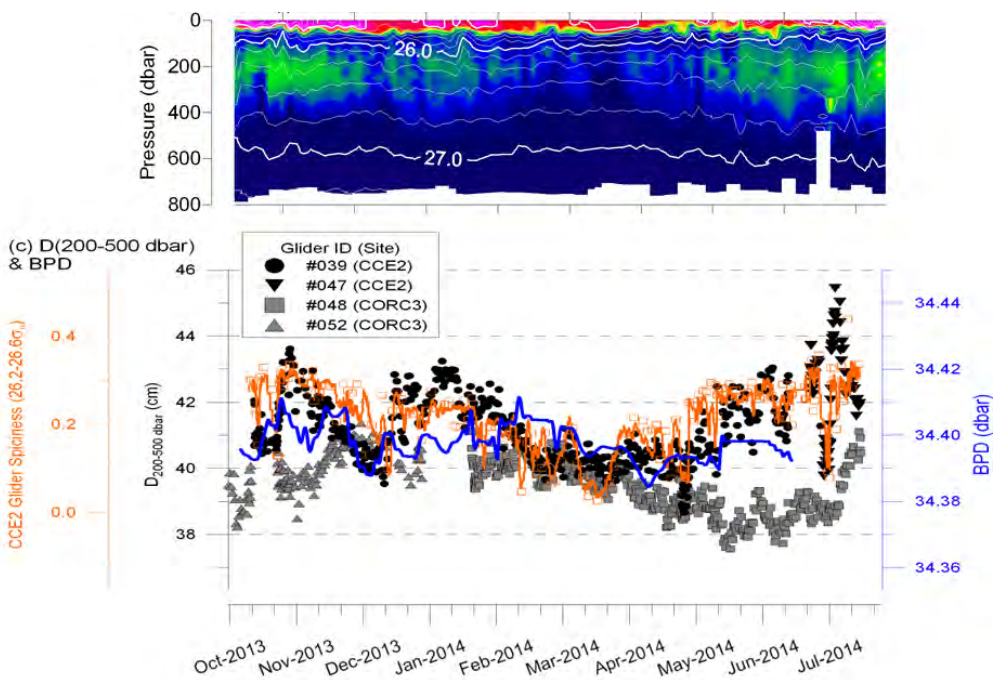

Fig. 5: *The upper panel shows spiciness at the CCE2 mooring in color and density as white lines. The 150-400m layer is the Undercurrent. Lower panel shows in orange the layer-average spiciness, and dark black symbols the 500-200db dynamic height at CCE2, which show similar time variability.*

while spiciness is orthogonal to it and not affected by density. Therefore the correlation visible in **Figure 5** is probably a dynamic connection which we will explore further. We also found that the vertical acoustic traveltime from the PIES is highly correlated with the 500-200db dynamic height and thus probably with spiciness of the Undercurrent water.

The above results contribute to the program objectives 'sea surface temperature and surface currents', 'ocean heat content and transport', 'ocean carbon uptake and content', and also to the societal challenge/cross-cutting theme of 'marine ecosystems in a changing climate'.

2.2 Measurement of western boundary current transport in the Solomon Sea

Broadly the deliverable of this task, which addresses the program's priorities, is an observational description of mass and heat transport in the western boundary current (WBC) of the South Pacific tropical gyre. The description is tuned to disclose the role of these transports in the global climate and its interannual-to-decadal regional variability, like ENSO. Because the subsurface WBC flow carries about a third of the return flow from equatorial upwelling, it is closely linked to equatorial SST and global climate. The observations elucidate the dynamics of equatorial SST variability in ENSO and its decadal relatives, hopefully improving their prediction.

Specific deliverables from this project are measurements of transport through the Solomon Sea using two technologies suitable for sustained observations: (a) repeated glider sections of velocity, temperature and salinity to 1000m depth and (b) T and S profiles, integrated sound speed, and pressure from a pair of mooring/PIES stations spanning the current. Both methods synergistically describe WBC transport toward the equator. The mooring/PIES stations continuously and directly measure integrated mass transport and also the local T and S variability at two sites. In addition, mass, heat and freshwater transports are found as path integrals of glider measurements that also describe internal structures. Monthly glider sections are aliased by eddies that mask signals of sub-seasonal period but are seen clearly by the mooring/PIES stations.

Another deliverable is technical improvement of technologies for sustained and affordable measurement of WBCs. These critical elements of the global ocean's climate dynamics will need to be measured to maximize understanding and prediction skill of both global change of the state of the ocean and regional climate variability. CORC technical improvements will help make such measurements practical and affordable.

Gliders completed 13 sections of T, S and velocity across the Solomon Sea in FY2014. The profiling depth was extended from 700m to 1000m to increase the depth of measured geostrophic shear and transport. This also increased the typical glider operating range so that four sections can now be completed in a single mission. Consequently, although we completed only 5 missions (less than our target of 6 per year) we measured more sections than the target of 12. This was accomplished despite a serious operating anomaly when Spray SN53 ceased diving below 50-100m; its safety drop weight had been released prematurely by a leak-induced short circuit. Skillful piloting by J. Sherman, favorable currents, and fortuitous skillful and helpful work by residents of Woodlark Island, PNG, led to recovering the glider. As a result of excellent care and shipping arranged by co-investigator W. Kessler of PMEL, SN 53 returned to SIO in

excellent condition without any CORC personnel travelling to the South Pacific. **Figure 6** shows some of the local people who recovered SN 53.

Fig. 6: *John Kelebi, who found and recovered Spray SN 53, in front of his home on Woodlark Island, PNG. In yellow are employees of Kula Gold Mining Company whose services were essential to getting the glider ready for its journey home.*

Conversion of raw glider data into quantitative transport measurements depends on knowing the glider's velocity through the water. For a clean glider, this is accurately done from compass, measured vertical velocity, and the glide slope inferred from measured pitch and the known angle of attack between the glide slope and the pitch. After weeks of fouling, drag and angle of attack grow; occasional fish-bite damage can induce turning tendencies that cause an average sideways slip velocity. We have completed a set of programs to reliably and quickly find and correct for these effects and have used them to "calibrate" transports for all 54 delayed-mode CORC cross-Solomon-Sea sections (several missions devoted to exploration of the northern "exit" of Solomon Sea were not included). The transport time series is shown in **Figure 7**.

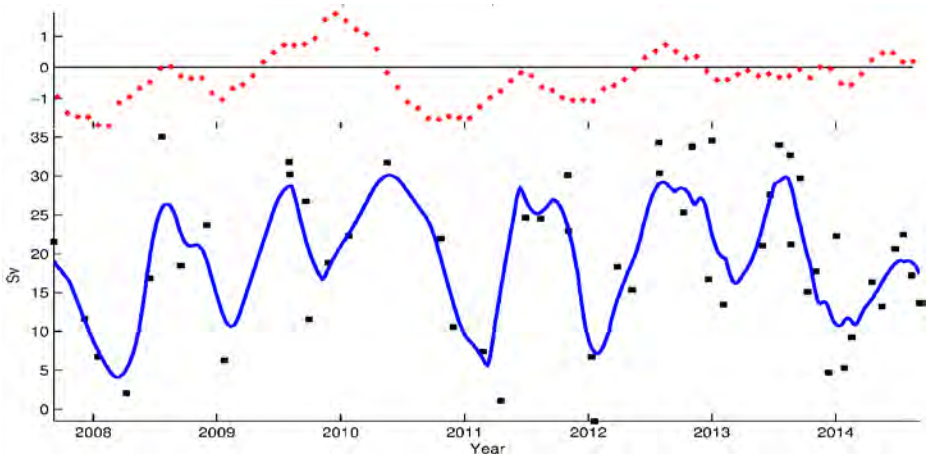

Fig. 7: *Equatorward transport through the Solomon Sea (black squares) and the monthly Niño 3.4 SST index (red dots). The blue line is a 3-month running mean of the time series made by connecting those points with straight lines.*

The effort and cost to sustain glider sampling of WBCs has been steadily decreased through the projects history as the sampling frequency has increased. Key cost factors are (a) vehicle reliability, (b) speed made good in typical currents, and (c) cost of vehicle preparation,

deployment and recovery in the field. Reliability was treated first; the biggest step was invention of an "air sucker" that removes gas from the hydraulic fluid, preventing vapor-lock of the pump. This year's increase of dive depth to 1000m generally reduces the average current seen by the glider and extends range, allowing one mission to complete four sections rather than two. Travel time and expenses to the South Pacific are substantial, so training Solomon Island residents to recover and deploy prepared gliders has substantially reduced operating cost. Preparing two gliders in one trip, and delaying one deployment has increased the time between air-travel. The delay before deployment is limited by air accumulation in the hydraulic fluid that exceeds the air-sucker's removal ability during deployment. We are now testing a procedure to continuously remove this air during storage so that gliders can be reliably deployed longer after preparation, thereby increasing the interval between trips to prepare the gliders for deployment.

As explained above, the glider measurements are complemented by the mini-mooring/PIES on both sides of the Solomon Sea, each equipped with acoustic modems. In the past year we had one more opportunity to acoustically download the data during a research cruise on the RV 'l'Atalante' in March 2014. At that time we found that the modem in the mooring on the Solomon Islands side had stopped acquiring data soon after the previous data download from local ships in May 2013 (the data are however stored inside the microcats themselves). As expected from the modem firmware bug detected in 2013, the PIES modem on the Papua New Guinea (PNG) side was found dead. In May 2014 we heard that the small French research vessel 'Alis" stationed in New Caledonia would be making a transit leg through the Solomon Sea in early September and would be passing very near our PNG PIES. With the help of W.Kessler's contact in PNG we got permission to recover and redeploy a PIES off Misima Island during that transit leg, and the French colleagues were willing to add a day to the trip for our work. With extreme difficulty we managed to ship 2 PIES and equipment in time to the remote island in PNG where the cruise started, and two members of our team joined the transit leg. They successfully recovered the PIES whose modem had stopped, deployed a new PIES (again lowering it with a camera and acoustic release to avoid landing on coral reef), and acoustically retrieved data from the co-located small mooring.

This data recovery allowed us to fill the early gaps in the first year of data, and to extend all data except for the Solomon Islands mooring, to two years in length. **Figure 8** shows a preliminary update of the mooring/PIES transport for the first year, together with updated glider transports. It also gives the individual contributions of the barotropic (PIES) and baroclinic (microcat) parts. These more complete measurements further corroborate the earlier results that more extreme transport variability occurs and on even shorter timescales than the gliders can observe – the range is 50Sv, and changes of 20Sv are observed over a few weeks.

Figure 9 presents the full timeseries of nearly 2 years length of the transport derived from the bottom pressure differences alone, together with the individual contribution of the fluctuations on the Gizo (Solomon Islands) and Misima (PNG) side. The Gizo side seems to contribute more long-period changes, while the Misima side has higher-frequency variability. The minimum and maximum observed may be part of an annual cycle – the range (30Sv) and phase (minimum in the early months of the year) are broadly consistent with the glider timeseries.

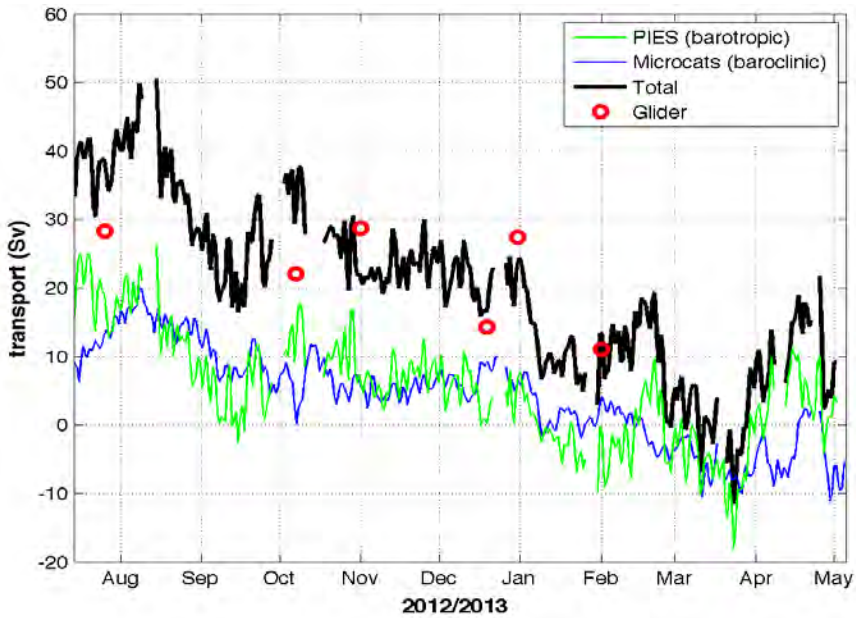

Fig. 8: *Preliminary 0-500m transports from PIES and moorings for the first deployment year, based on the data recovered in September 2014. The black line shows the total transport, blue is the microcat, green is the PIES contribution. An arbitrary offset in the green and black line has been applied to match the time-mean profile from the glider data. Glider transport estimates are shown in red.*

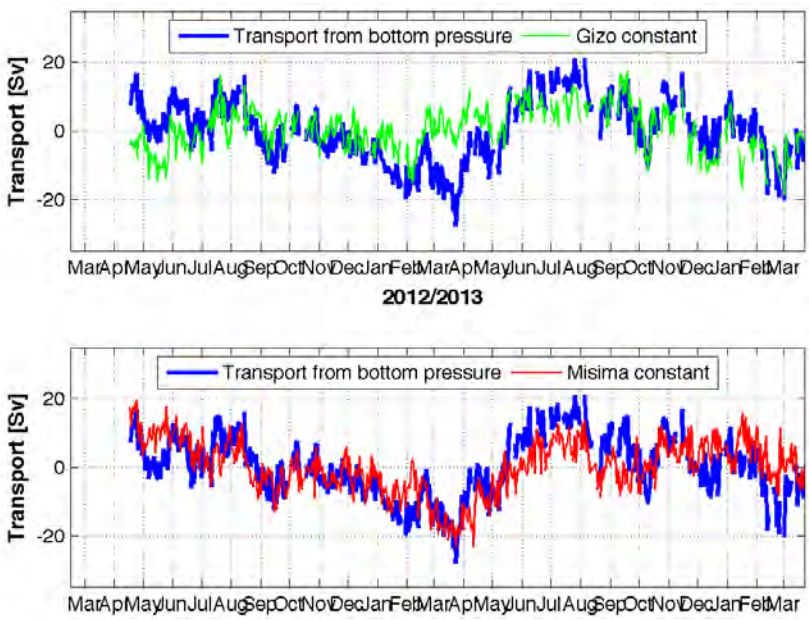

Fig. 9: *Transport anomaly timeseries derived from only the PIES (bottom pressure differences) for the upper 500m layer, blue. The green and red curves show the transport changes if one side is held constant at a time. The range and phase of what could be an annual cycle is consistent with that observed by the gliders.*

The scientific advances made as a result of the CORC sustained observations are a description of the mean and seasonal to interannual variability in the Solomon Sea circulation and its heat transport. We believe this description will lead to an assessment of the role of WBC transport on ENSO, on related variability, and on the quasi-mean state of the ocean. Specific findings are:

- Equatorward 0-700m transport varies over 0-25 Sv on seasonal time scales. Variations are correlated with the ENSO cycle indices like Niño 3.4 SST. The two El Niños in the record corresponded to strong equatorward flow while flow nearly vanished during two La Niñas.
- Mean equatorward flow peaks near 250 m depth where $\sigma_\theta \approx 25.5$ matches the Equatorial Under-Current. Transport variability is dominated by two modes describing independent layers separated in depth by a transition zone around 150m. The annual cycle and signals correlated with ENSO are strongest in the upper-layer mode.

- Sudden changes in transport can occur over 1-2 weeks, and much of the short-period variability comes from the barotropic component on the PNG side.
- Deeper flow enters the Solomon Sea as a WBC and moves equatorward along the western boundary. Entering upper layer flow and its variability are focused in a mid-basin in a jet marked by high salinity. This branch soon joins the deeper one to form a WBC from the surface to at least 0-700 m. Kessler and Cravatte (2013b) trace the source of deep branch to Coral Sea and find shallow mid-basin jet's origin near the Tasman Front northeast of New Zealand.
- In the 7+ year record the annual cycle of transport emerges from eddy noise (see **Fig. 7**). The annual maximum is in July and minimum in February. The time-lagged covariance of transport is well described by an annual cycle, a cosine of frequency anywhere near one cycle per three years and white noise. The variance of noise and the annual cycle are comparable, explaining why frequent sampling is required to clearly see semi-annual variability. The variance of interannual variability is half that of each of the other components.
- Solomon Sea transport variability lagged ENSO indices by roughly a season for the two positive and two negative interannual peaks in our record. This lag may indicate a response to central Pacific winds as in a "delayed oscillator" model. It implies that Solomon Sea mass transport is not a short-term predictor of ENSO but is a major part of the recharge/discharge of mass on the equator that characterizes the climate of the Pacific.

2.3 XBT and ARGO analyses in support of western boundary current observations

This work, combining XBT, Argo profiles and trajectories, and satellite altimetry contributes directly to NOAA/Climate Observation Division Program Deliverables including : ***Ocean Heat Content and Transport; Sea Surface Temperature and Surface Currents.*** During FY14, work continued on a case study of the East Australian Current (EAC) near Brisbane. Zilberman et al (2014, In preparation) provides the mean and time varying geostrophic volume transport of the EAC and its tight recirculation. Argo trajectory data shows a significantly weaker EAC and recirculation transport than a 2000 m reference level calculation (**Fig. 10**). The HR-XBT data provides a much greater density of profiles than Argo across the boundary current, including many profiles in depths less than 1000 m where Argo floats are typically not found due to grounding problems. 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. Both the line-mode (HR-XBT) and the area-mode (Argo) of sampling are essential for the integrated ocean observing system.

The scientific advance made by this work is demonstration of the capability of the present ocean observing system for quantitative description of the ocean's western boundary currents, and hence, in combination with ocean interior transport, for closing the mass balance of the upper ocean circulation. The boundary currents have been identified (OceanObs'99, OceanObs'09) as an under-observed but critical component of ocean circulation and transport. In order to improve on boundary current estimation, we must first understand the capabilities and limitations of present integrated observations. Following the EAC case study, we will undertake similar efforts in all 5 subtropical western boundary currents.

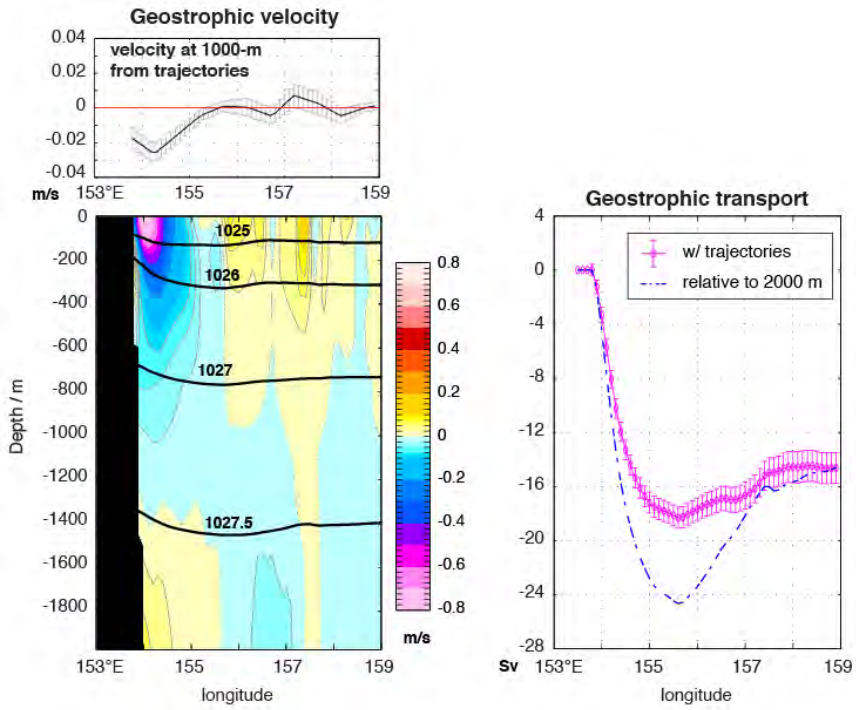

Figure 10: *Mean absolute velocity (left) and transport integral (right), 0 – 2000 m for the EAC, 2004 – 2012. Shear from XBT and Argo profiles is combined with Argo trajectory data providing reference velocities at 1000 m. From Zilberman et al (2014, In preparation)*

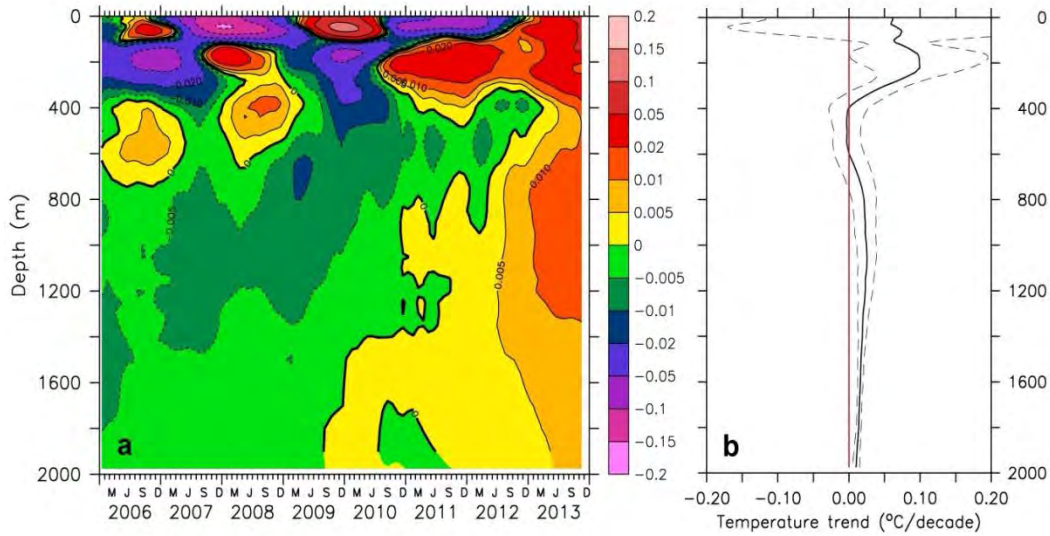

Figure 11: *(Left) Globally-averaged temperature anomaly (°C) versus depth from Argo data, 2006 – 2013, 12-month running mean. (Right) Temperature trend (°C year^{-1}) versus depth, zonally-averaged, with 95% confidence interval. Data from Roemmich et al (2014, Submitted to Nature Climate Change).*

Additional work, including participation in the IPCC 5th Assessment Report, and a new analysis of global ocean heat gain during the Argo era, contributes directly to the NOAA/Climate Observation Division Program Deliverable: ***Ocean Heat Content and Transport***. D. Roemmich was a Lead Author of Chapter 3 (Ocean Observations) from Working Group I of IPCC AR5. The significance of this element of the IPCC assessment is in providing the community consensus on multi-decadal climate change in the oceans, including temperature and ocean heat content, salinity and freshwater content, and ocean circulation and transport. The increasing heat content of the global ocean is among the best-documented and most compelling lines of evidence in the entire climate system.

In the new analysis, (Roemmich et al, 2014, "Unabated planetary warming and its anatomy since 2006", Submitted to *Nature Climate Change*), **Figure 11**, we find that steady ocean heat gain occurred over the period 2006 – 2013. The significance of the work is to show that (i) in contrast to the surface temperature "hiatus", ocean heat content has continued to increase without interruption, (ii) the depth and spatial distribution of the warming signal is well-determined in the 8-year period having homogeneous global coverage by the Argo array. Almost all of the heat gain during 2006 – 2013 occurred in the extratropical Southern Hemisphere ocean, and the heat gain was equally distributed between the surface layer (0 – 500 m) and intermediate depths (500 – 2000 m). The hemispheric asymmetry in heat gain is consistent with the asymmetry in radiative forcing together with the larger area of the Southern Hemisphere ocean. By observing the patterns and rate of global ocean warming, other complementary observing systems (sea level, greenhouse gas concentrations, earth radiation balance) and coupled climate models are challenged to demonstrate their consistency with the observations and to better understand the recent patterns.

2.4 Data Assimilation tools for boundary current observing systems

This effort focuses on the California Current system, assimilating CORC and other data.
The sub-project deliverables are: Improved CCS state from assimilations, including atmospheric state, eddies, and cross-shelf transports; Integrated index of CCS upwelling in terms of isopycnal displacements on and between glider/mooring lines (directly from observations and from assimilations); 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); Related indexes of heat and mass transport of the northward-flowing currents, especially the CUC; Scientific examination of the sensitivity of SSH and transport to atmospheric forcing, using the adjoint. These address the program's priorities with a regional model-based analysis and synthesis of data in the California Current region to provide information for science, fisheries management, and the general public on all of the listed priorities: Sea surface temperature and surface currents; Ocean heat content and transport; Air-sea exchanges of heat, momentum, and freshwater; Sea level; and Ocean carbon uptake and content.

The main scientific advances of this task are identified by bolding in the narrative.

The long-term assimilation, which covers 2007-2010, now uses an enhanced version of the NOAA GFDL "Biology Light Iron Nutrient and Gas" model (BLING). Work on this continues under separate funding, with the enhanced BLING model available as part of the MITgcm for use in the shorter-term assimilations to estimate, for example, carbon and oxygen in the California Current System (CCS) region. This effort targets all five of the priorities listed above, and all five deliverables.

For example, the long-term state estimate (LTSE) has been used to refine measures of the California Undercurrent (CUC) to produce a CUC index time series, as an indicator of this generally warm and salty poleward flow, which affects heat content and transport as well as ecosystems. The CUC index will be evaluated for usefulness as a measure of the state of the undercurrent. The CUC velocity was found to be correlated along the coast, and the correlations were used to help determine the region chosen for the index. **Figures 12 and 13** show the definition of the region and the CUC index time series for the LTSE, respectively. Strong events are episodic, superposed on a seasonal cycle that generally has the CUC stronger in winter. The same definition of the CUC has been calculated from the ongoing short-term state estimates (not shown). **One of the conclusions of the study, which is in preparation for publication, is that the CUC is a dynamically-driven current which does not only transport the high-salinity water mass. Comparing undercurrent and spiciness (anomalous salinity on constant density surfaces) shows many periods where the two are not aligned, suggesting that time-varying wind forcing can modulate these currents without regard to water masses.**

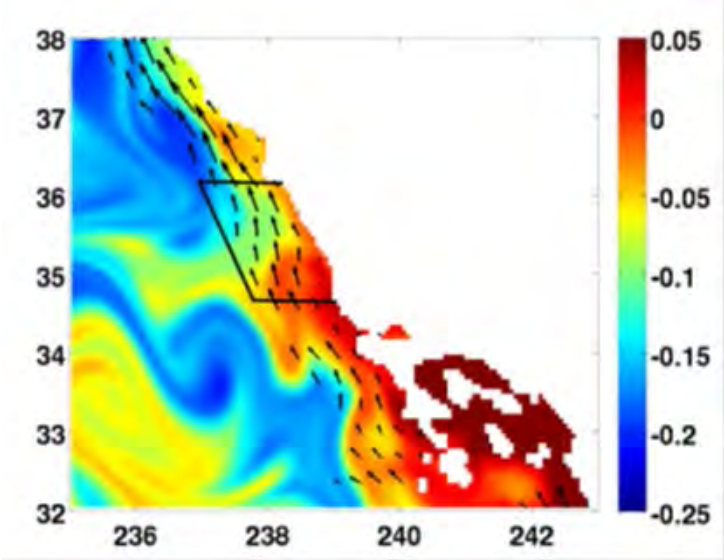

Figure 12: *Model domain with spiciness (shown in color) and velocity vectors (shown as arrows) at 420 m depth for a 5 day average centered on Aug 10, 2007. The domain used for computing the undercurrent index is shown as the black box extending from 34.35 N to 36.75 N. The index is*

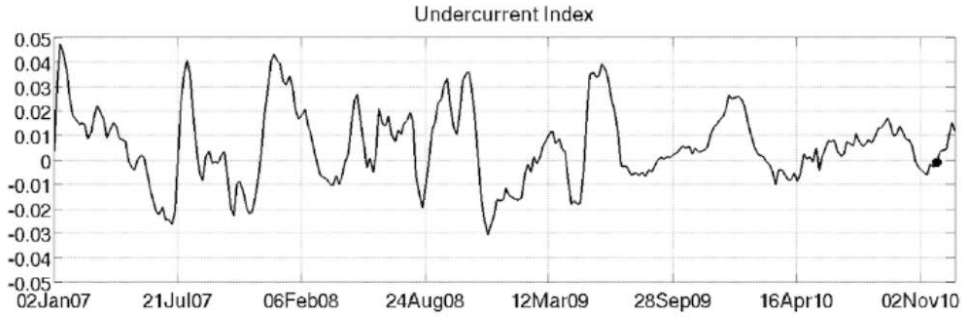

Figure 13: *Magnitude of the undercurrent index computed every 5 days from Jan 02, 2007 until Dec. 27, 2010. The undercurrent index is computed as the area-mean alongshore velocity from 34.35 N to 36.75 N from -300 m depth to -600 m depth.*

Focusing on sea level, both long- and short-term state estimates produce dynamic ocean topography (DOT), which is strongly constrained by the CORC observations. The DOT can be subtracted from the altimeter SSH to produce estimated corrections to the reference geoid (**Figure 14**), which is thought to have root-mean-square (RMS) errors of 10cm or more at scales shorter than about 100km. We construct improved estimates of the geoid by subtracting the LTSE time-mean dynamic ocean topography from the time-mean observed SSH. These are objectively mapped to a smooth field using prior estimates of the magnitude and length scales of the geoid errors. A paper describing this work has recently been accepted in GRL. **The geoid errors have been reduced from about 10 cm RMS to 6 cm RMS, verified by testing against independent observations, including altimeters with long repeat periods. This geoid correction will be extended to the ongoing short-term state estimates to allow the altimeter data to supply more information to the state estimate and will provide a better reference for other altimeter users.**

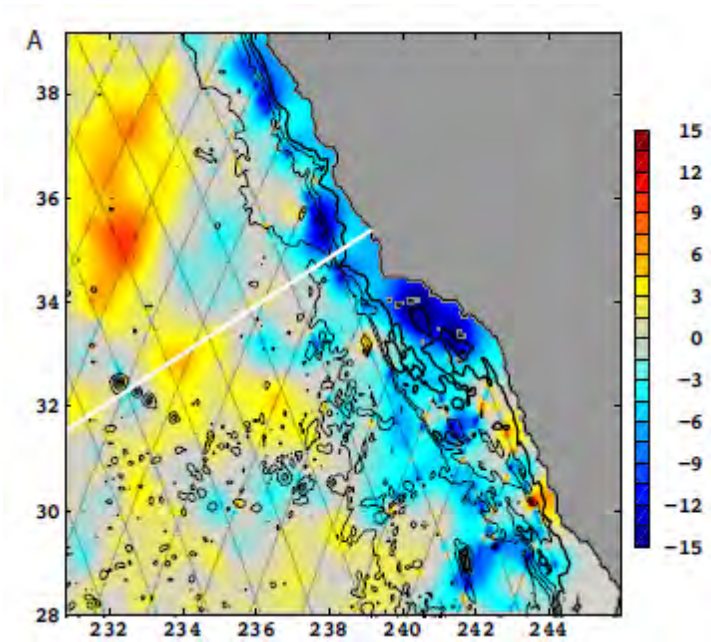

Figure 14: *The geoid correction field (in cm) from the state estimate. The bathymetry is contoured in black with a 1000m contour interval, and the CalCOFI line 75 is shown in white.*

In parallel to the long-term state estimate (LTSE) effort, we are producing sequential short-term state estimates (STSE) of one month duration, now covering from late 2010 to mid-2014. The shorter windows allow a better match to observations, at much lower computational cost than LTSE, but allow jumps in the state estimate at each month boundary. The shorter time period also gives more control to the model initial conditions, so adjustments to the forcing are not well-determined. Although the ability to distinguish between the time-mean satellite sea surface height (SSH) and the anomalies is reduced, with some satellites having no repeats in the time window, the adjustment of the geoid is expected to ameliorate the situation to some extent.

Short-term state estimates have been made from 2010, before the end of the LTSE, through mid-2014, and are continuing to be updated as observations come into final form for assimilation. The technology of these estimates has been examined and improved by adjusting the

uncertainties used for the observations and for the controls, as well as perturbing model parameters such as viscosities. There is a trade-off with pushing to near-real-time when some of the observations may change, or more observations may become available, requiring re-running of the analysis, which can take several weeks. The present analysis is mostly determined by the most plentiful observations: Spray glider data, Hi-resolution XBTs, Argo, and satellite SSH. Satellite SST is also used, but with reduced weight because of the model uncertainty in the surface mixed layer.

As specified in the workplan, we have evaluated the quality of the monthly estimates by calculating the weighted root-mean-square (RMS) errors with respect to observations for both hindcasts and forecasts. The forecasts extended for a month starting from the end of each one-month estimate and used climatological forcing and boundary conditions. Forecasts are a form of cross-validation of the state estimates, since they compare against independent (unused) observations. This is analogous to the cross-validation of linear and non-linear regression estimates, which are created on a training dataset and then tested on withheld data. Forecasts can also provide information which may be useful for user communities. On the other hand, in a strongly wind-driven system like the CCS, the skill of the forecast can be low when the winds deviate significantly from climatology. We calculated RMS differences with respect to AVISO-mapped SSH as well as AVISO monthly climatology and assimilated global HYCOM/NCODA (https://hycom.org/dataserver/glb-analysis) as alternative analysis estimates for the region. **Figure 15** shows an example of the hindcast and forecast differences for Nov-Dec 2013. The hindcast is for November (before the dashed vertical line) and the forecast is for December. The STSE dynamically-consistent hindcast has similar misfit with AVISO as the HYCOM/NCODA analysis which allows sequential jumps in model state and therefore can more closely fit the observations. **The forecasts using the MITgcm from HYCOM initialization (black line) and from the STSE (red line) both have lower misfits than persistence (keeping the initial state fixed) (blue line), showing that the model dynamics are supplying useful information.** The green line shows the RMS misfit with AVISO monthly climatology, which is a measure of the variability. Note that the RMS misfit is about 3-4 cm averaged over the region, showing that the signal is not large.

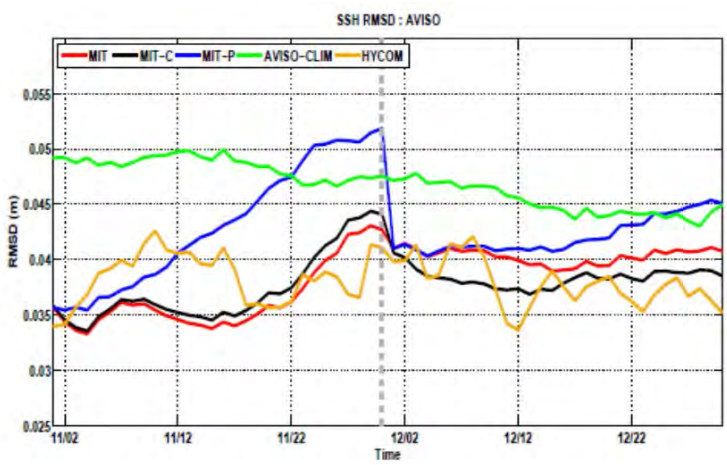

Figure 15: *Hindcast and forecast RMS misfits with respect to the AVISO daily analysis for Nov-Dec 2013. The hindcast is for November (before the dashed grey vertical line) and the forecast is for December 2013. The STSE hindcast and forecast RMS misfit is shown as the red line. The RMS misfit with AVISO for the HYCOM/NCODA analysis is shown by the gold line. The forecasts using the MITgcm from HYCOM initialization are shown by the black line. They are started from HYCOM on Nov 1 and again on Dec 1. The blue line shows the persistence forecast keeping the MITgcm starting state from Nov 1 and again for Dec 1. The green line shows the RMS misfit with AVISO monthly climatology, which is a measure of the variability.*

Because the variability of the SSH in the domain is relatively small (3-5 cm RMS) and the altimeter noise is in the 3 cm range, the signal-to-noise ratio of the measurements is not high. Most of the time, the errors for the full model forecasts are lower than the errors calculated by assuming persistence of the initial conditions. We have evaluated the effect of assimilation window length on forecast performance in a limited way, and have remained with one-month assimilation window durations, but we may revisit this in the future.

We did not improve the model technology for the open boundary conditions (OBC) in this cycle, since they are not as important for the two month window as for the multi-year windows, but improved OBC controls remains a goal of the project.

The STSE extended the upwelling/heat content indices to 2014, with the example of isotherm depths integrated over the Southern California Bight shown in **Figure 16** with both hindcasts and forecasts. **It is clear that especially the winters of the last three years become increasingly warm, with deepening isopycnal depths, and January 2014 shows the deepest isotherm depth seen. For the summers, 2014 shows much deeper isotherms than other years. The agreement between forecasts and hindcasts (which are overlaid here, distinguished by line color) during the times without strong forcing variability is the cross-validation of the state estimate against independent observations.** The undercurrent index and other measures (not shown) have been calculated from these estimates as described in the deliverables.

In summary, all deliverables have all been addressed, although the adjoint calculations require more work to complete the analysis of the influence of wind on the CCS, including the CUC.

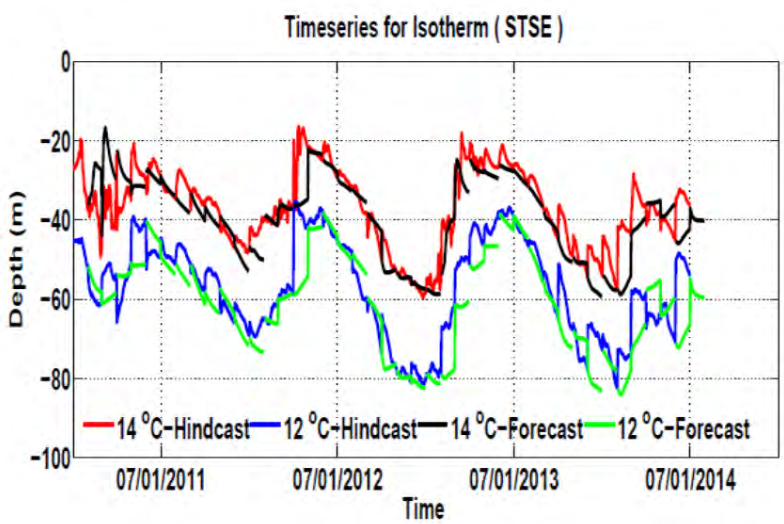

Figure 16: *Isotherm depths in meters integrated over the Southern California Bight for the 12 and 14 degree isotherms. Both hindcasts (blue and red lines for 12 and 14 degrees, respectively) and forecasts (green and black lines for 12 and 14 degrees, respectively) are shown. Note the annual tick marks are placed in summer (July 1).*

Summary CORC Achievements and Data Dissemination

The following is a collection of the primary achievements of CORC during FY2014:

- Successful observation of the remarkable warm event in the southern California Current with gliders and moorings, with initial hypotheses for the causes
- First indications that real-time (approx. weekly) estimates of the large-scale cross-shelf transport are possible for diagnosing the upwelling circulation
- Dynamic connection between the California Undercurrent water properties and dynamic height
- 97% continuous glider coverage on 3 sections in the California Current
- Gliders completed 13 T, S and velocity sections across the Solomon Sea, extending time series of western boundary current heat and mass transport to 7+ years so that the seasonal cycle and connections to ENSO are clear.
- Continuous transport time series through the Solomon Sea are now available from the endpoint moorings/gliders for the first year, revealing extreme changes on very short timescales; baroclinic transports in hand for 2 years
- The 7-year glider time series from the Solomon Sea has been quality controlled, velocity has been corrected for glider drag and slip, and sections of T, S and velocity are archived and available on the web.
- Technical advances for the Solomon Sea have: (a) increased Solomon Sea glider range and doubled the number of sections possible per mission; (b) extended sampling to 1000m depth; (c) increased time resolution of transport estimates; and (d) reduced the cost of sustaining the time series.
- Combination of the East Australia boundary current region with the ocean interior for basin-wide estimation of mean and time-varying volume and heat transport and meridional overturning circulations.
- Updated California Current state estimate, which also shows that warming occurred in winter as well as summer over the past 3 years.
- Real-time distribution of all California Current glider data to a fully public server and to GTS.

Impediments/Information jeopardized

The continued reduced funding level coupled with the IDC increase at SIO four years ago means that we cannot devote the desired effort to data processing and analysis, quality control, dissemination, and websites. We also have trouble replacing lost or worn equipment. We have managed to maintain the observations due to efficiencies developed, leveraging/sharing with other programs, and since we got better at doing things cost-effectively. But it is difficult to sustain this, and try new methods and technologies, while developing the products and users that are expected from NOAA projects in general, in addition to publishing the results.

Websites for CORC activities

We are in the process of setting up a CORC-specific website where analyses and products from CORC as a whole will be made available publicly, publications will be listed, and links to quality-controlled data will be provided. In the meantime, the following websites, which are method-specific, provide access to CORC activities and data:

1) Graphic displays of all active Spray glider deployments can be seen at http://spray.ucsd.edu
2) Time series specific information and data are shown at http://mooring.ucsd.edu/CORC
3) The complete set of California Current glider missions are at http://www.sccoos.org/data/spray/?r=0
4) Real-time numerical data can be accessed at http://coastwatch.pfeg.noaa.gov/erddap/tabledap/scrippsGliders.subset a site run by NOAA SWFSC
5) http://sose.ucsd.edu/CASE/ is the website for the state estimation efforts which also serves results

Dissemination of CORC data

Real-time glider data are stored and disseminated via the servers and site above, they also go to the GTS. Acoustically telemetered moorings/PIES data are stored on the server geo.ucsd.edu. Delayed-mode data from recovered gliders are available on sushi.ucsd.edu and disseminated via the websites above, data from recovered moorings/PIES reside on geo.ucsd.edu and are displayed on the mooring.ucsd.edu website (data download will be available through the future website). The State Estimate data can be accessed via sose.ucsd.edu/CASE/. Archiving at present happens on the institutional servers only. We have successfully retrieved our own data from our sites. There is no mechanism at present to track downloads and use of our data. We direct users of the data to acknowledge support of COD.

3. Outreach and Education

With the flurry of action related to El Niño this past year, we participated in a press release from Scripps https://scripps.ucsd.edu/news/el-niño-shaping-southern-california

Undergraduate student Nicholas Delfino is employed to do quality control of glider profiles. Nicholas has been working on a complete archive of Spray glider sections for browsing on the web. Nicholas majors in Mechanical and Aerospace Engineering with an expected date of graduation in 2016.

Graduate student Katherine Zaba 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. She is currently addressing the very warm event of the past year using this climatology.

Graduate Student Arachporn Anutaliya is processing and analyzing the Solomon Sea mooring and PIES data, and participates in field activities. The California Current CORC cruises always take several students along for training and exposure to ocean observation at sea.

Graduate student Xue Fan just defended her dissertation about eddy analyses using moorings and gliders, and one future application is expected to be the California Current regime using CORC and CCE data.

D. Giglio completed her PhD dissertation in November 2014 (Advisor: D. Roemmich), titled "Large-scale ocean circulation, dynamics, and air-sea exchanges: Argo observations of the mean and time-varying ocean."

Former Post-doctoral Investigator N. Zilberman (now Project Scientist) has the primary responsibility for "Syntheses of XBT and Argo data for boundary current estimation".

Post-doctoral Investigator F. Gasparin is carrying out the analyses of ocean observations in the tropical Pacific Ocean, including improved requirements for sustained ocean observations (e.g. Roemmich et al., 2014).

4. Publications and Reports

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.

Ganachaud, A., S. Cravatte, A. Melet, A. Schiller, N. Holbrook, B. Sloyan, M. Widlansky, M. Bowen, J. Verron, P. Wiles, K. Ridgway, P. Sutton, J. Sprintall, C. Steinberg, G. Brassington, W. Cai, R. Davis, F. Gasparin, L. Gourdeau, T. Hasegawa, W. Kessler, C. Maes, K. Takahashi, K. Richards, and U. Send (2014): The Southwest Pacific Ocean and Climate Experiment (SPICE). *J. Geophys. Res.*, doi: 10.1002/2013JC009678.

Jacox, M. G., C. A. Edwards, M. Kahru, D. L. Rudnick, and R. M. Kudela, 2014: The potential for improving remote primary productivity estimates through subsurface chlorophyll and irradiance measurement. *Deep Sea Research Part II: Topical Studies in Oceanography***,** in press.

Johnston, T. M. S. and D. L. Rudnick, 2014: Mixing estimates in the California Current System from sustained observations by underwater gliders. *Deep Sea Research Part II: Topical Studies in Oceanography***,** in press.

Kessler, W.S. and S. Cravatte, 2013a: ENSO and short-term variability of the South Equatorial Current entering the Coral Sea. *J. Phys. Oceanogr.*, **43**, 956-969.

Kessler, W.S. and S. Cravatte, 2013b: Mean circulation of the Coral Sea. *J. Geophys. Res.-Oceans*, **118**, 1-26, doi:10.1002/2013JC009117.

Kim, S.Y., G. Gopalakrishnan, and A. Ponte, 2014: Interpretation of coastal wind transfer functions with momentum balances derived from idealized numerical model simulations. *Ocean Dynamics*, in press 2014.

Mazloff, M, S. Gille, and B. Cornuelle, 2014: Improving the Geoid: Combining Altimetry and Mean Dynamic Topography in the California Coastal Ocean. *Geophysical Research Letters*, in press 2014.

Ohman, M. D., D. L. Rudnick, A. Chekalyuk, R. E. Davis, R. A. Feely, M. Kahru, H.-J. Kim, M. R. Landry, T. R. Martz, C. L. Sabine, and U. Send, 2013: Autonomous ocean measurements in the California Current Ecosystem. *Oceanography*, **26,** 18-25, doi:10.5670/oceanog.2013.41.

Rudnick, D. L., C. Meinig, K. Ando, S. Riser, U. Send, and T. Suga, 2014: Emerging technology. *Report of the Tropical Pacific Observing System 2020 Workshop (TPOS 2020), Volume II - White Papers*, 299-319.