Integrated Boundary Current Observations in the Global Climate System

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1. Project Summary

Boundary currents (BC's) play a critical role in the climate system and in societal applications, since they carry a bulk of the ocean heat transport, are part of climate-controlling overturning circulations, exhibit the largest air-sea heat fluxes, and represent the most important coastal ecosystems and fisheries regions. In BC regimes the local responses and societal impacts from climate forcing are expected to be large (ocean acidification, health of the ecosystems, fisheries, recreation). Despite their importance, BC's around the world are not observed systematically, and this is one of the most critical gaps that were identified by the international community at the OceanObs09 conference in Venice.

The CORC project develops, demonstrates, and implements prototype BC observing systems that can fully monitor mass and heat transports and water properties of most boundary currents in a sustained and routine mode. CORC explores and exploits the complementarity of several technologies and techniques for which the PI's have expertise, and develops additional ones as needed. These include underwater gliders, moorings, inverted echosounders/bottom pressure sensors (PIES), XBT sections, surface drifters, data assimilating state estimation, together with ARGO and altimetry. New developments are routine subsurface data retrieval via gliders, bottom-released surface drifters, and improved data merging methods. CORC currently applies these developments in the southern California Current (CC) with ecosystem and fisheries relevance, and in the Solomon Sea (SS) where the highly variable flow impacts equatorial climate processes via the Undercurrent.

The supported activities include glider sections along 2 lines in the CC (typically every 3 weeks, physical/biological observations, upper 500m) and across the SS (every 6-8 weeks, physical, upper 700m), moorings (CC) and PIES (CC, SS) to provide high temporal resolution and to include deeper measurement, surface drifter releases in the CC, analyses to integrate boundary and interior observations, regional state estimates, and development of analysis methods and of technology.

The anticipated products and outcomes include:

- raw profile and binned section data from glider transects in the CC and SS
- mooring/PIES derived transport and high-frequency physical data
- long timeseries of currents and transports in the CC and SS
- in-situ cal/val data for satellite SST measurements
- indicators of the state and function of BCs in near-realtime
- state estimates and reanalysis of observations
- revised forcing products
- efficient BC observing techniques with quantification of performance
- assessment of physical climate forcing in BCs
- understanding how climate processes modulate BCs and how BCs impact climate
- published research.

The users/applications include climate modelers and forecasters (e.g. NAVO, JPL, SIO), disaster response (NOAA ERMA), ecosystem assessment efforts, fisheries researchers/managers, climate impact studies and mitigation, and the research community.

2. Scientific and Observing System Accomplishments

a) Technology Developments

CORC has made routine the glider-based data telemetry from subsurface moorings and bottom-mounted instruments such as PIES. After many improvements in the acoustic modem protocols which the gliders execute, and changes in the corresponding controller firmware, data downloads from both CORC moorings and the CORC inverted echosounder/bottom pressure sensors (PIES) are now highly successful. Figure a1 summarizes the typical data transfer rates and success rates. Communication is possible at ranges up to 7km horizontally and with instruments as deep as 4000m. A recent glider mission lasting 160 days captured 1.56 MB of error-free data. To acquire this volume, a total of 2.22 MB, including all retransmissions, were sent, a success rate of 70%. On average 57 kB of data were transferred in a day of acoustic communications.

Since then, work has focused on implementing improvements to the SPRAY glider's capabilities. The CORC modem gliders are now being upgraded with an "air sucker" that actively removes air bubbles from the hydraulics, and a new generation controller that allows more complicated missions. "Deep loitering" has been implemented, allowing gliders to be parked at depth for 24hrs (or more in future versions) between surfacing and acquiring/telemetering new data. This will greatly enhance the endurance of gliders on site, by saving power and reducing biofouling. One glider was recently lost, and we are using CORC funds to replace it. The currently planned glider construction will bring the total of fully capable/upgraded modem gliders for CORC to six.

Another task was the completion of the development of automated pop-up surface drifters. In January 2011 the Lagrangian Drifter Group of SIO has begun the in-house development of complete drifter systems. As a result, several new GDP style drifters were successfully built, tested and deployed as part of international research programs. Our development includes a PIC24 Micro Controller Unit (MCU) based controller. In order to accommodate the planned design changes and make the fabrication process more efficient (i.e. to take advantage of better pricing from combined bulk purchases) the construction of the Bottom Release Drifters (BRD,

Figure a2) has been deferred to the spring of 2012. The design changes include: 1) Drogue presence detection capabilities, which have been designed into the deep sea evacuated glass sphere. This hardware operates identically to submergence sensors implemented on GDP drifter, but with the capability of deep sea deployment; 2) Newly designed SIO bridge and improved SST accuracy (now ±0.05°C, with 0.01°C resolution); 3) Galvanic Release Mechanisms: An alternative release mechanism is being tested to improve reliability of the system; 4) In-house developed electronics: an MCU has been developed to significantly decrease the cost of future BRD systems. This controller paired with a galvanic release mechanism will decrease the cost of each drifter by $1K; 5) Drogue Improvement: materials selection for the drogue, which was addressed in spring 2011 both for GDP and CORC funded drifters will significantly improve the endurance and performance of the drogue; 6) Size Improvement: the size of the system has been decrease by approximately 40%, resulting in a much more compact and reasonable deployment package. Four electronic systems have been manufactured, and an additional six full systems are targeted for completion and deployment by 5/12. The information and plots from past deployments are available at http://corcbrd.ucsd.edu.

Both the BRD development and CORC drifter deployments in the CCS satisfy the requirements of the ocean observing system for climate to deliver observations of Sea Surface Temperature and Surface Currents, to identify significant patterns of climate variability and change. The BRD development is aimed at reducing the burden of logistics required to maintain SST and Lagrangian current measurements time-series.

b) Glider Measurements in the California Current System

Autonomous underwater gliders developed over the past several years offer the opportunity of sustaining fine resolution observations in boundary current systems. As used in the California Current System (CCS), the Spray gliders profile to 500 m or the ocean bottom, whichever is shallowest. The cycle from the surface to 500 m and back takes about 3 hours to complete, during which time Spray travels 3 km horizontally relative to the water. Spray position is measured by GPS at the beginning and end of each dive, allowing a dead reckoning estimation of depth average water velocity. Spray carries a pumped Sea-Bird CTD to measure pressure, temperature, and salinity, and a Seapoint fluorometer in the pumped stream. A SonTek acoustic Doppler profiler (ADP) measures depth dependent water velocity, and an estimate of zooplankton through acoustic backscatter. Data is transferred by the Iridium satellite system once per dive, when commands to the glider can also be sent. A typical deployment lasts about 3 months. Recoveries and deployments are done using a small boat.

The Southern California Glider Network (SCGN) is operated along the traditional CalCOFI lines. CORC supports line 90 off Dana Point, and line 66.7 off Monterey. The Southern California Coastal Ocean Observing System (SCCOOS) supports line 80 off Point Conception. Typical deployments oscillate offshore and onshore along the lines, as far as about 500 km offshore, taking about three weeks for one transit, and completing two round-trips before the glider is replaced.

Data are available in near real time through both http://spray.ucsd.edu and the SCCOOS web site http://SCCOOS.org. Data are pushed to modeling centers every 4 hours, including the Jet Propulsion Lab (JPL) and the Naval Oceanographic Office (NAVO). Importantly, the data are assimilated into the CORC regional model run by B. Cornuelle. Figure b1 gives a new example of what the assimilating model can do as an integrator of the CORC data.

We produce data products consisting of profiles of temperature, salinity, density, velocity, chlorophyll fluorescence, and acoustic backscatter on uniform grids for each glider transit along all lines. The resulting sections allow calculation of the transport of such quantities as heat, salt, phytoplankton, and zooplankton, directly addressing the Climate Program Office deliverables of Ocean Heat Content and Transport, and Ocean Carbon Uptake and Content. The past year has seen the completion of a series of studies using data from the SCGN, with two publications published, one in press, and one submitted. Topics covered include the following The first observation by gliders of the local effects of and El Niño was achieved in 2009-2010 (Todd et al., 2011a). Glider data was assimilated into the CORC model to address poleward flow in the CCS (Todd et al., 2011b). One of the outcomes of this work was the validation of the model's estimation of poleward flow. With confidence in the model's fidelity, a study of variance of thermohaline properties was completed (Todd et al., 2011c). Layers of strong thermohaline variability identified in glider observations were traced back in time through the model's adjoint. The fundamental result was the coincidence of these layers with traditionally defined water masses of distinct origins. Physical and biological processes occurring at a front in the CCS were studied using a combination of glider and ship data (McClatchie et al., 2011) This last publication is a collaboration with Sam McClatchie of NOAA Southwest Fisheries Science Center (SWFSC). We look forward to continuing to use CORC gliders to further the goals of SWFSC.

c) Mooring and PIES measurements in the California Current System

The two CORC moorings and five PIES have been in the water since their deployment in Dec'09. All are equipped with the acoustic modem hardware and data can be downloaded by gliders. Multiple glider missions have retrieved the data from these instruments every few months, and we currently have data in hand until October 2011. Data are displayed at http://mooring.ucsd.edu. Fully processed transports between the end-point moorings exist now until May 2011 (figure c1), and also the vertical mean structure has been updated (figure c2) showing that the southward CC flow extends to about 300m. During Mar-Nov 2010 (overlapping with but starting slightly earlier than the La Nina event) there seems to be a flow southward anomaly in the California Current, associated with higher sea level at the offshore mooring and lower sea level inshore. A lagged regression map (not shown) reveals that the positive sea level anomaly at the offshore mooring originated from farther north (subpolar region) whereas the negative anomaly at the inshore mooring is linked to changes in the equatorial region.

We have also found that the sea level difference (SLD) between the moorings (inshore minus offshore) is highly correlated with the mooring-derived geostrophic internal volume transport referenced to 3500 dbar and closest to the transport over the layer 0-300dbar (correlation R2=0.79), Figure c3. This is likely to allow calibration and fine-tuning of future and past transport observations from altimetry using the in-situ CORC mooring data.

Efforts are under way to merge the mooring/PIES data with the glider and other ancillary data (CalCOFI, ARGO, altimetry) in order to generate the most complete description of the structure and variability of the California Current. At present this is mainly being pursued with the data assimilation techniques (see section g), but in the future we will also explore more direct data-based approaches.

d) Surface drifter observations in the California Current

Drifter deployments continued in the CCS (subcontract to Dr. Carter Ohlmann, UCSB). A total 39 drifters were deployed as follow during FY11:

- CalCOFI-1008NH; 30 July – 18 August 2010; 13 drifters deployed
- CalCOFI-1011NH; 28 October – 15 November 2010; 13 drifters deployed
- CalCOFI-1101NH; 12 January – 5 February 2011; 13 drifters deployed

Note the Global Drifter Program contribution to CORC through airtime transmission costs. To date, with the cooperation of the Global Drifter Program (GDP) of CIMEC/AOML quarterly drifter deployments are continuing from the CALCOFI surveys (figure d1). This continuing observational effort will provide new insights into the connection between continental shelf flows and the larger scale California Current located further offshore. More importantly, the continued repeated quarterly releases of surface drifters from the same set of locations will ultimately result in a Lagrangian data set that will be examined on "climate" time scales. The increasing historical drifter dataset in the CCS now supports a robust estimate of the mean-state near-surface surface geostrophic flow, which can be used as an assimilation field (figure d2). Future plans include the analysis of ROMS 1km solutions for the Southern California Bight to compute relative dispersion quantities from the model trajectories to be compared with the corresponding quantity derived from drifters. The drifters' data are available from AOML (http://www.aoml.noaa.gov/phod/dac/dacdata.php) and details on SIO drifter's programs are available at http://gdp.ucsd.edu.

e) Boundary Current measurements in the Solomon Sea

In FY2011 we continued the time series of Solomon Sea (SS) transport above 700 m begun in 2007. Spray gliders with temperature and salinity sensors measure depth-averaged absolute to 700 m. An additional ten transects of the southern SS were completed with 100% data return. Each transect observes equatorward transport and its distribution by depth and density as well as the water column heat and freshwater content. By putting more than one glider in the water at a time, temporal coverage and robustness to equipment failures were increased and aliasing minimized. These observations are the only repeated indicator of the subsurface western boundary current in the tropical South Pacific.

A detailed analysis of the time series through CY 2010 was completed with the goal of developing specific products that can serve as indices of transport in the SS. The time series (Fig. e1) from 2007 to 2011 showed a typical equatorward transport of 15 Sv above 700 m varying from zero to 25 Sv in synchronism with the two La Niñas and one El Niño in the period. While short-term noise clouds the comparison some, there is no apparent time lag between Solomon Sea transport and ENSO indices like Nino 3.4 surface temperature or the Southern Oscillation Index. This suggests either an unexpectedly fast oceanic connection between the central Pacific and Solomon Sea or a local response to Solomon Sea winds that themselves respond to ENSO. Results will be published in Davis, Kessler and Shermaan (2012).

Remarkably, the vertical distribution of transport through the SS is like a two-layer flow (Fig. e2). The layer above 250 m depth is closely linked to ENSO; deeper flow behaves independently. Both the upper and lower layers are sources for the Equatorial Undercurrent. The transports and heat contents of the two layers have been tentatively identified as the best

indicators of equatorial transport through the Solomon Sea. We are now implementing streamlined procedures to report the indices in near real-time.

In order to provide more complete temporal sampling, we are now adding an end-point component across the Solomon Sea, starting with a PIES on each side. Figure e2 shows that bottom pressure measurements a depth of about 250m would be able to capture much of the variability of the flow that feeds the core of the Equatorial Undercurrent. In June 2011, surveys with echosounders and cameras were conducted on both sides of the Solomon Sea to locate suitable sites for PIES deployments (flat and sandy in depth range of interest) and this was successful. At the time of writing we are preparing the actual deployment of the PIES with acoustic modems during Jan/Feb'12.

f) Synthesis of High Resolution XBT, Argo, and other datasets

The Argo Program and the High Resolution XBT (HRX) Network provide the basin-scale and regional context for CORC observations in the California Current System (CCS) and the Solomon Sea low latitude western boundary current.

<u>California Current System:</u> Two repeating HRX transects span the CCS - off San Francisco and Los Angeles. These transects, including their basin-wide extension, have been used in studies of water mass formation, large-scale circulation and its interannual variability, transport of the CCS and of the Kuroshio, mesoscale eddies, sea surface height, and the heat budget of the North Pacific. With the Argo program now having provided 8 years of global coverage, the combined value of the HRX and Argo datasets is increased by having accurate estimates of heat storage and reference velocities for the 800 m XBT transects from Argo. Mass and heat budgets can be closed with unprecedented accuracy.

In Auad, Roemmich and Gilson (2011), new estimates are presented of the mean equatorward transport of the California Current (5 Sv) and the poleward California Undercurrent (2.5 Sv), of the time variations of heat and freshwater content caused by alongshore advection, and of the interactions of coastal and interior ocean water masses.

<u>Solomon Sea:</u> Argo data in the ocean interior east of the Solomon Islands and in the Solomon Sea, provide basin-integrated estimates of the mean and time-varying transport of the of the South Pacific's shallow overturning circulation. Zilberman, Roemmich, and Gille (2012, in preparation) show that the ENSO fluctuations in the ocean interior are larger than those in the Solomon Sea and out of phase with them. In this work, the ocean's mean and time-varying mass and heat budgets are closed for the region north of 7.5°S, including the Indonesian Throughflow transport as a residual of geostrophic and Ekman transports across 7.5°S.

HRX transect PX05 (Brisbane-Solomon Sea-Yokohama) crosses, from south to north, all of the tropical current systems in the western tropical South Pacific Ocean (see Figure f1). Hence, together with Argo it provides the regional context for the intensive CORC observations within the Solomon Sea.

g) Data Assimilation/State Estimates

The state estimation component of the CORC project uses modern methods to synthesize multiple observation types in a dynamically-consistent way. The goal is to use reliable dynamical constraints such as conservation of mass, heat, salt, and momentum to complement

the observing system and attempt to fill in the gaps in the coverage. State estimation projects have generally focused on the global ocean at resolutions such as 1 degree, and thus have difficulty in representing boundary currents. We are developing a prototype regional state estimate focused on the boundary current and its observing system, both as a proof of concept for other observing systems and as a way of increasing the information return from the observations. The main questions to be answered are: 1) What are the key features of the current, with relevance to both the gyre circulation, climate influences (such as ENSO), and local bio-geochemistry? 2) How accurately can the observation network resolve the key features of the current (e.g. transport, heat content, ecosystem-relevant variables such as upwelling or CO2)? 3) How can the observations be best arranged for maximum coverage of these features? And how consistent are these observations to one another? 4) Can the model reproduce the observed features (and over what time range?), and what is required in terms of forcing and boundary conditions to make that happen?

In addition to the science questions, many technical problems must be addressed, such as the treatment of open boundaries, the effects of the Boussinesq approximation in the model, and new data types, such as transport, IES, and averaged velocities from gliders.

Our primary method is adjoint-based state estimation, also called 4DVAR. This adjusts model initial conditions, boundary conditions, and forcing within predefined uncertainty bounds so that a forward run of the model matches the observations in a time range within observation (and model representational) error bounds. The longer the time range, the more difficult it is to match any particular set of observations, but more observations are available to determine the ocean state and the air-sea exchanges of heat, momentum, and fresh water which are consistent with the observations. The resulting dynamically-consistent synthesis provides a reanalysis of the observations, including SSH, surface temperature, surface currents, ocean heat content and transport. These can be used for bio-geochemical modeling, including carbon uptake and content and ecosystem analysis.

The California Current system (CCS) state estimate (CASE) was extended to include observations from the start of 2007 through July 2009, so that it could include the mooring T,S, bottom pressure, and round-trip travel time from the PIES. Using IES travel times directly avoids the errors made by converting to a "gravest empirical mode" amplitude using statistical methods. IES travel times were brought into the assimilation in 2011, and now both the IES travel times and the mooring observations have been included in many optimization cycles. Agreement of the model forward runs with the observations has improved by 20% to 30% as measured by variance. .

One area of experimentation has been to use shorter time ranges for 4DVAR. Subsets of the data have also been tried, using only AVISO mapped altimeter observations, for example, to check the compatibility of the model with the observations.The method can produce a model state that closely matches the SSH observations (Figure g1). Experiments over longer time ranges, such as a month, were also successful in adjusting the model.

Dan Rudnick and his student, Robert Todd, have done a new combined analysis of the glider results with the model 3D fields with a focus on spiciness variability. This has resulted in a published paper which will be discussed in the glider section.

MITgcm model runs using HYCOM boundary conditions have been made for the Solomon sea region and compared with the glider observations. Several versions have been run, using

different domains and resolutions, one example is shown in figure g2. The transports into and out of the Solomon Sea are roughly compatible with observations and expectations. The need to use realistic bathymetry in this region is a challenge to correctly modeling the circulation, given the juxtaposition of shallow, flat reefs with deep channels.

Summary Information:

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

b. Achievements during FY2011
   - continuous occupation of two CC sections with gliders, one CC section with moorings/PIES, one SS section with gliders, with 100% data return
   - quarterly deployments of SVP drifters in the CCS
   - identified summarizing indicators of Solomon Sea heat and mass transports.
   - improvements in routine subsurface data retrieval via gliders, construction of modem gliders
   - improved design of the Bottom Release Drifter
   - identification of suitable sites for PIES in the SS
   - incorporated more observations into assimilations (IES in particular)
   - better model fits to observations in general and moorings in particular, including experiments with shorter assimilation windows

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

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

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

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

f. Web sites for the program

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

g. Data Management

Glider data

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

Mooring/PIES data

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

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

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

2.1. Outreach and Education

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

CORC was presented to the next generation of researchers at the WCRP conference in Denver via a poster. It was also widely publicized by an oral presentation at the IUGG conference in Melbourne, in July 2011. CORC is communicated to the public via various websites (see above).

Efforts to explain the societal utility of the Solomon Sea data are twofold. Globally, we rely on scientific papers and talks to expose the data and their potential uses to oceanographers, climatologists and modelers who might use them for analysis of interannual-decadal prediction. Within the Solomon Sea the potential local uses of the same data are discussed with governmental and educational leaders in the region through a series of visits by co-investigator. Recent presentations were

“Gliders measure western boundary current transport from the South Pacific to the Equator.” San Francisco AGU, 7 December 2011 (Davis),

"Measuring the New Guinea Coastal Undercurrent with ocean gliders." Institute of Oceanology, Chinese Academy of Sciences, Qingdao, China, 24 Sep 2011 (Kessler),

"Measuring South Pacific western boundary currents with ocean gliders."

UW Bothell Environmental Science class, 19 May 2011 (Kessler); Central Washington University Environmental Science class, 4 Mar 2011 (Kessler).

"Glider measurements of Solomon Sea ocean currents." University of Papua New Guinea, 4 July 2011 (Kessler).

In June 2011, D.Rudnick participated in a joint workshop involving NOAA outreach personnel and the Ocean Discovery Institute (ODI). ODI is an educational organization involved in outreach to diverse urban communities, especially in the City Heights section of San Diego. In December 2011, ODI was awarded the Presidential Award for Excellence in Science, Mathematics and Engineering Mentoring by the White House.

In April 2011, D.Rudnick gave the keynote address at the Earth Day assembly at La Costa Canyon High School in Carlsbad, California. In a presentation titled "The ocean's role in climate change" he discussed the evidence for a warming ocean, Argo, El Niño and its local effects, and gliders.

3. Publications and Reports

3.1. Publications by Principal Investigators

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

Davis, R.R., W.S. Kessler and J.T. Sherman, 2010: Gliders measure western boundary current transport from the South Pacific to the Equator. J. Phys. Oceanogr., submitted..

Maximenko, N., R, Lumpkin and L. Centurioni, 2012, Ocean Surface Circulation, submitted for publication in ““Ocean Circulation and Climate”, edited by G. Siedler and J.W. Gould.

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

Send, U., L. Regier, and B. Jones (2011): Use of underwater gliders for acoustic data retrieval from subsurface oceanographic instrumentation and bi-directional communication in the deep ocean. J. Atmos. Ocean. Techn. submitted.

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

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

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Zilberman, N., D. Roemmich and S. Gille (2012) The mean and the time-variability of the shallow meridional overturning circulation in the tropical South Pacific Ocean. To be submitted to the *Journal of Physical Oceanography*.

4. Figures

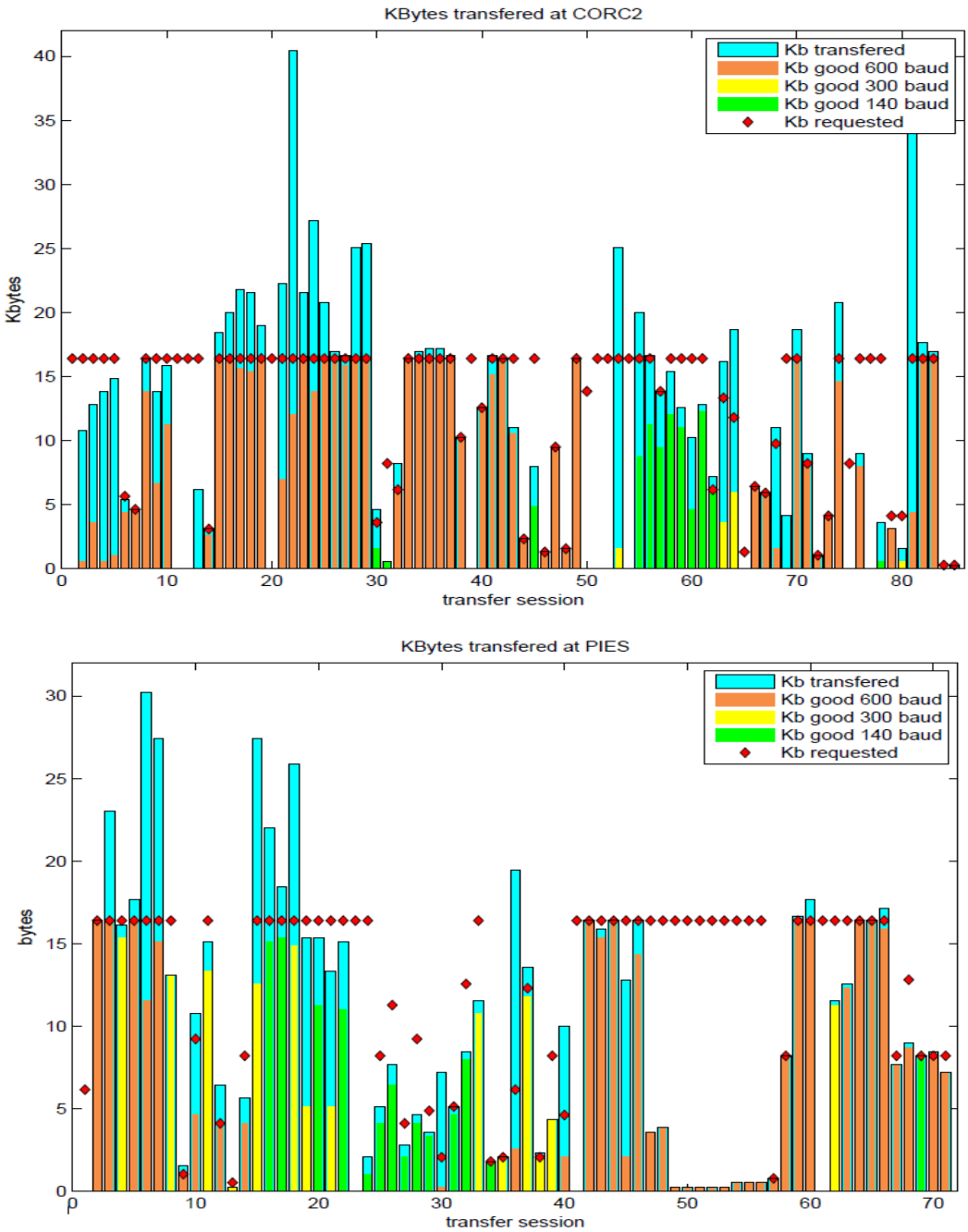


Fig. a1: *Diagram summarizing the data transfer success from a 160-day Spray glider mission, for the CORC2 mooring (top) and all the functioning PIES (bottom), each bar represents one dive. The red diamonds show the number of kbytes requested/sought during the dive. The overall height of the bar shows the number of Kbytes received, and green/yellow/brown show the amount of good data received (color coded by baud rate)*

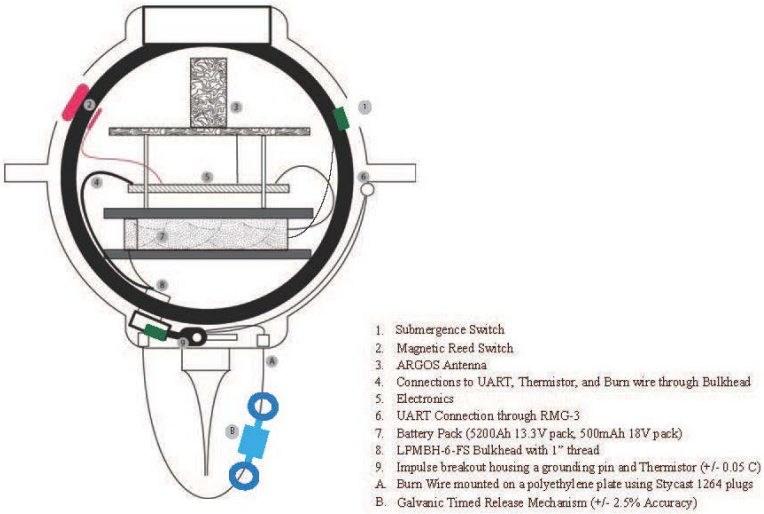


Figure a2: *Schematics of the new generation Bottom Release Drifter*

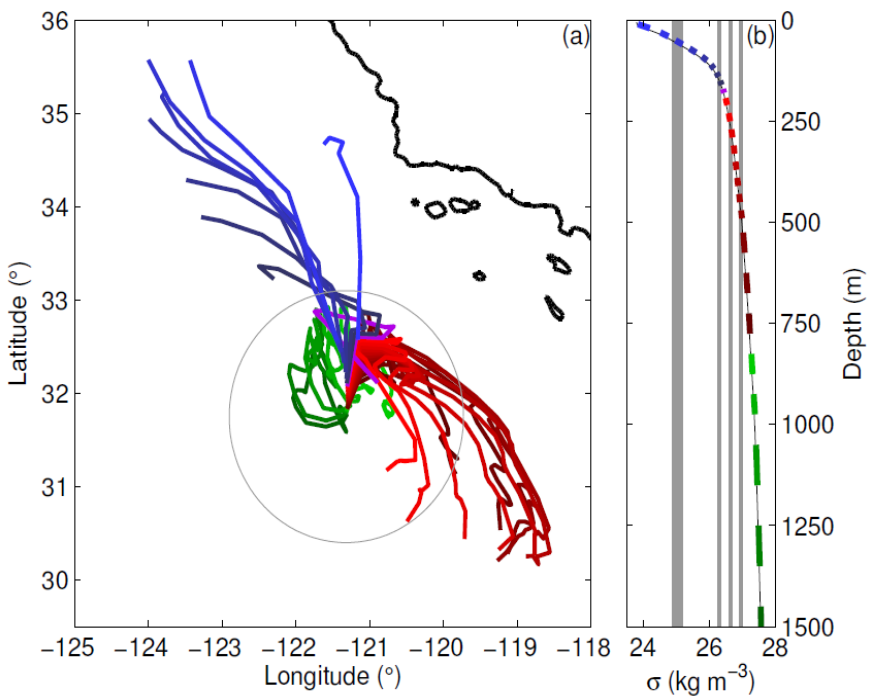


Figure b1: *Results from the CORC assimilating model's adjoint. (a) Paths of the centers of mass of fixed-depth tracers colored by depth range. The grey circle indicates the extent of the target region. (b) Mean potential density profile in the offshore target region at the end of the state estimate (black). Colored line segments denote the vertical ranges of the target regions for the 25 fixed-depth tracers. Colors correspond between panels a and b. Results show a northern source for waters shallower than 155 m, minimal movement at 175 m, a southern origin for 200-700 m, and little displacement deeper.*

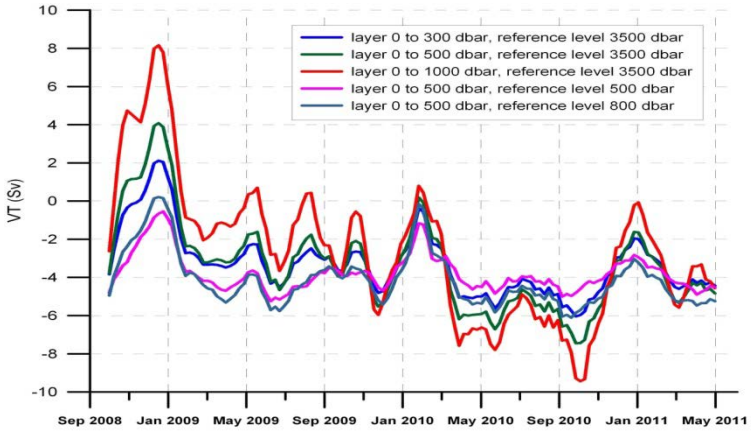


Figure c1: *Geostrophic transports between CORC moorings*

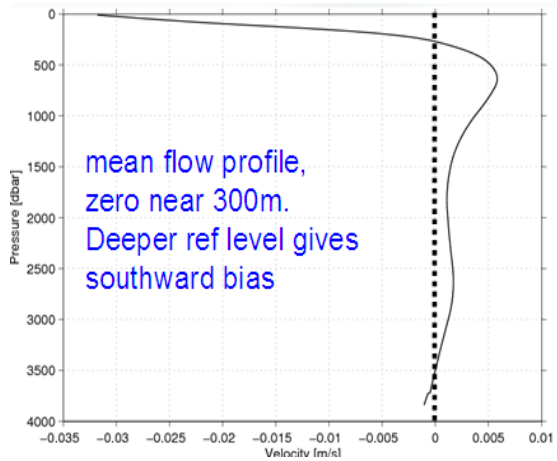


Figure c2 Mean geostrophic flow profile

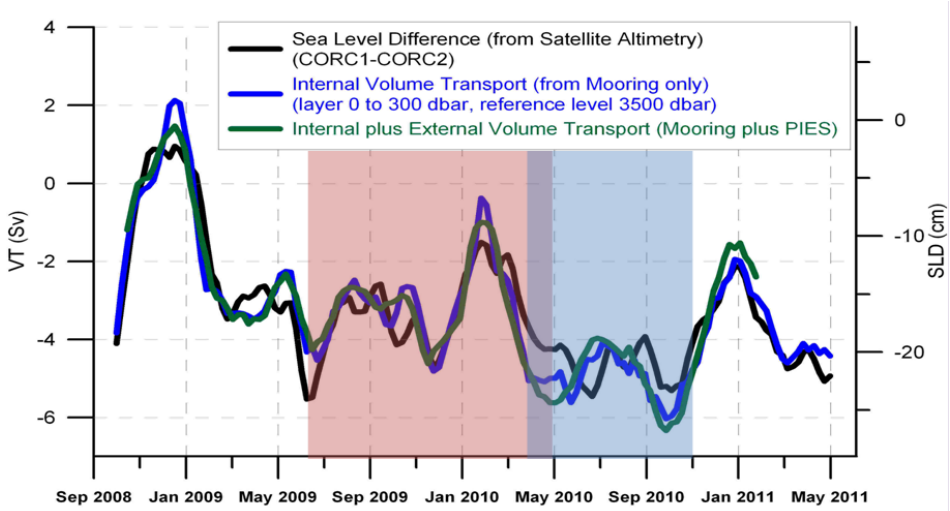
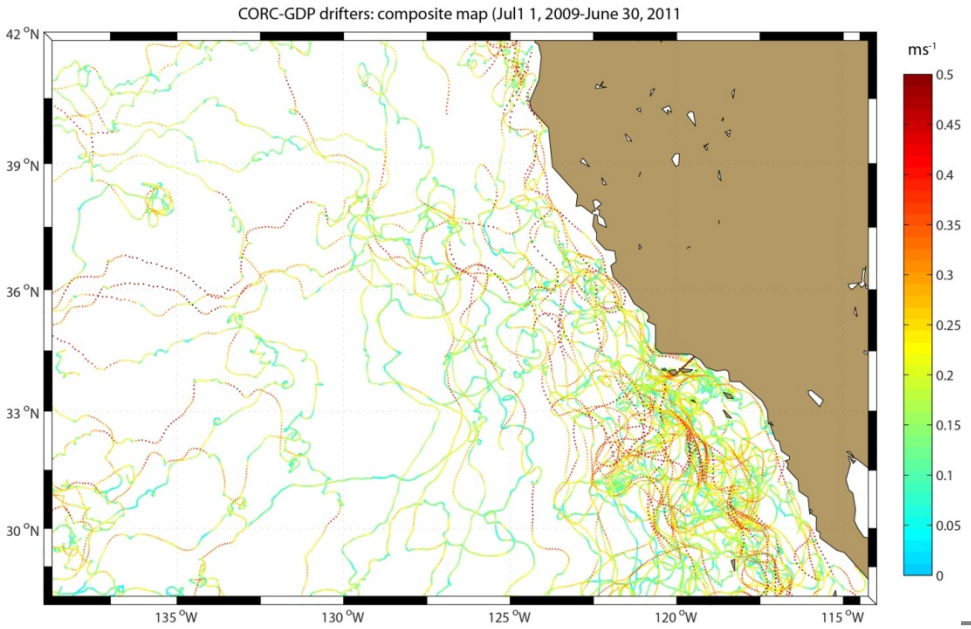


Figure c3: *Time series of volume transport from CORC moorings rel 3500db and rel bottom pressure data, and satellite altimetry-derived sea level difference (SLD). Red shading is 2009/10 El Nino, blue is a phase of increased equatorward flow.*

Figure d1: *position of the CORC funded drifters color-coded in accordance to the drifters' instantaneous speed. Tracks from 91 drifters are shown, which returned 35364 observations in the period July 1, 2009 through June 30, 2011.*



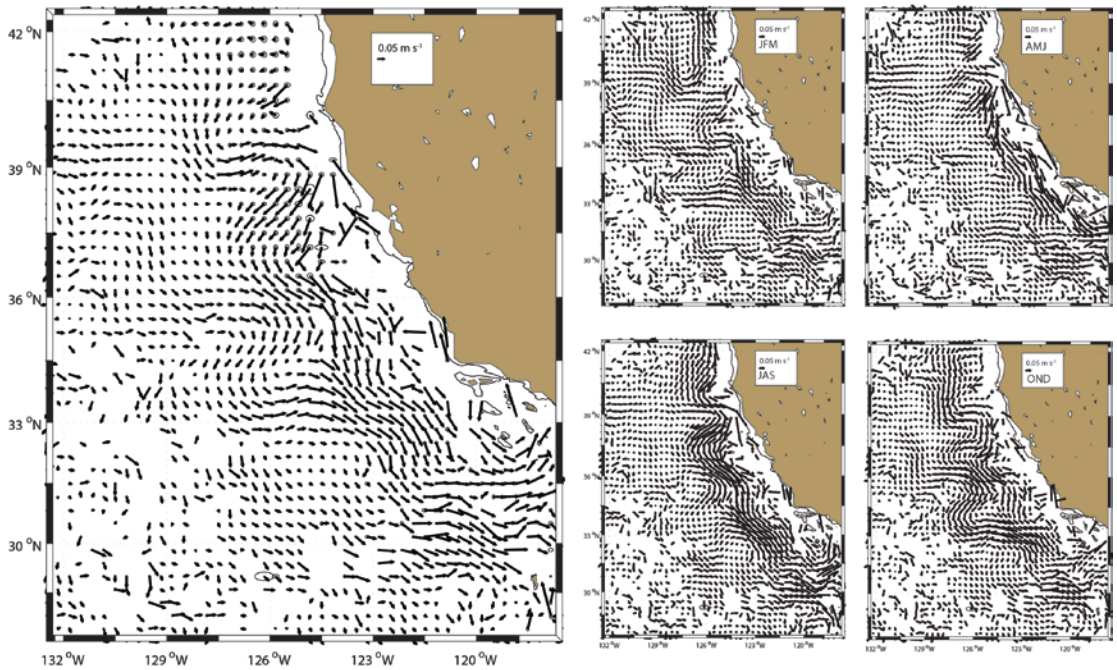


Figure d2: *Near-surface unbiased geostrophic velocity field. Year-long (left) and seasonal (four smaller panels on the right) ensemble-average between July 1992 and June 2011. Note the increase of the intensity of the currents in summer (JAS) and the larger extent of the meanders in fall (OND).*

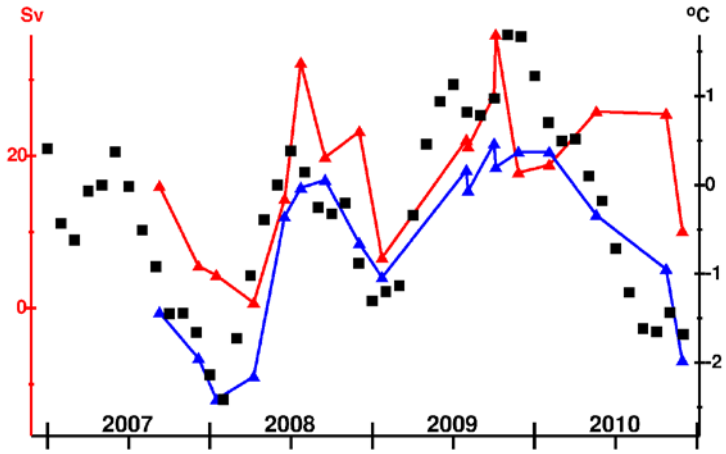


Fig. e1: *Time series through 2010 of equatorward transport through Solomon Sea. Red is absolute transport above 700 m. Blue is transport above 700 m of geostrophic shear referenced to 700 m. Black symbols are the anomaly of month-average NCEP Niño 3.4 SST showing how ENSO dominates transport variability, particularly of shallower currents.*

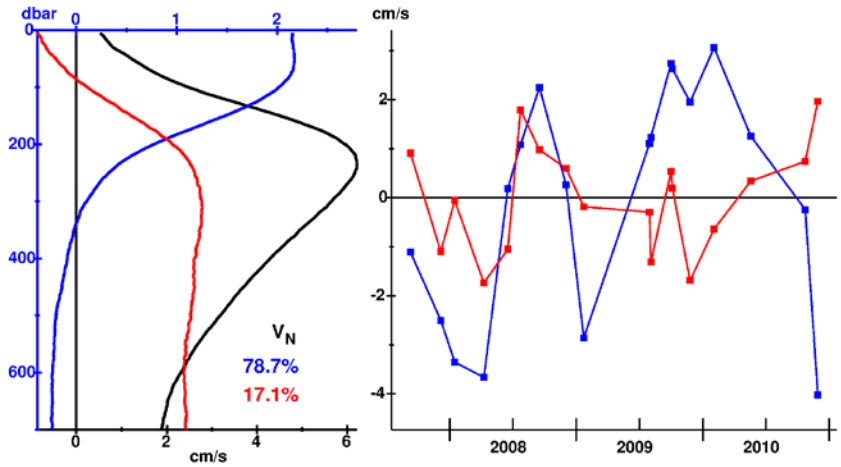


Fig. e2: *Properties of the cross-basin average of equatorward velocity $V_N(z)$. Left: Black is the mean profile of V_N; red and blue are EOFs explaining 79% and 17% of its variance. Right: EOF amplitudes (same color code); variability of EOF #1 (blue) is closely related to ENSO with minima in La Niñas (early 2008 and late 2010) and a maximum in the El Niño in late 2009.*

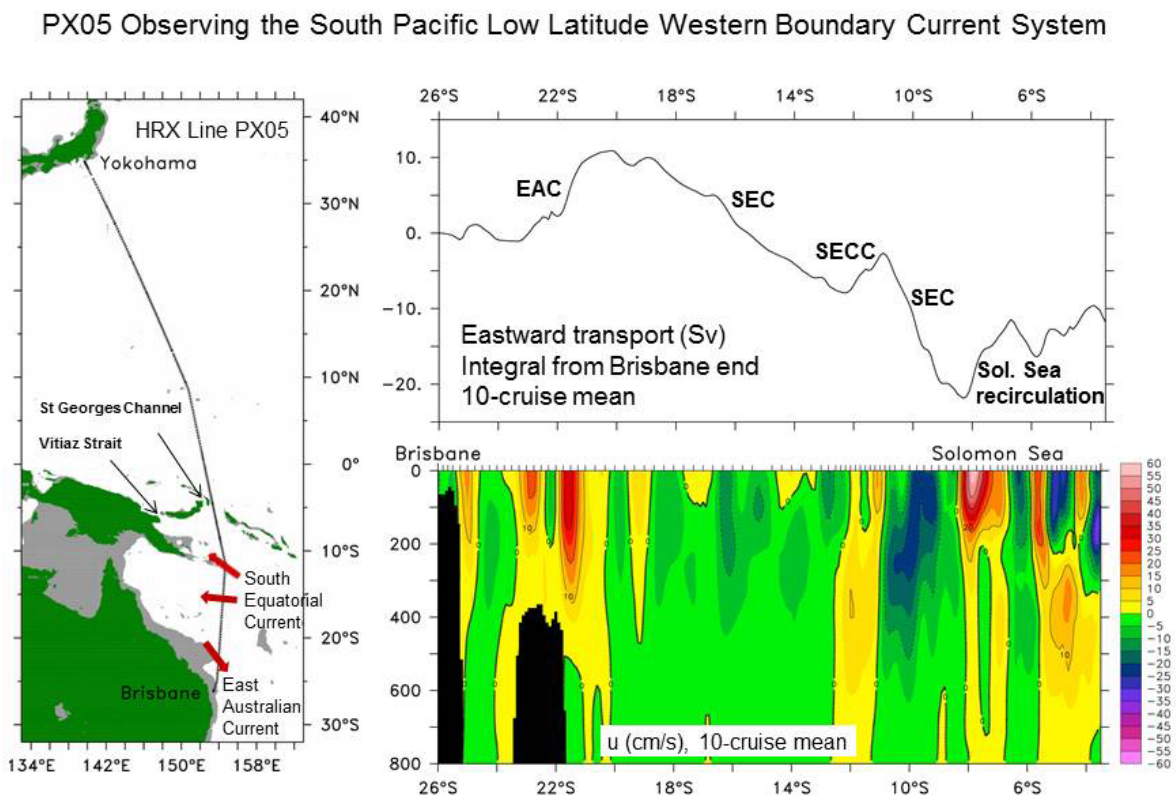


Figure f1: *PX05 crosses the East Australian Current (EAC), the southern and northern South Equatorial Current (SEC), South Equatorial Countercurrent (SECC), and a recirculation within the Solomon Sea. Passing close to New Ireland at 5°S, net transport to that latitude (-13 Sv) is the combined transport through Vitiaz Strait and St Georges Channel.*

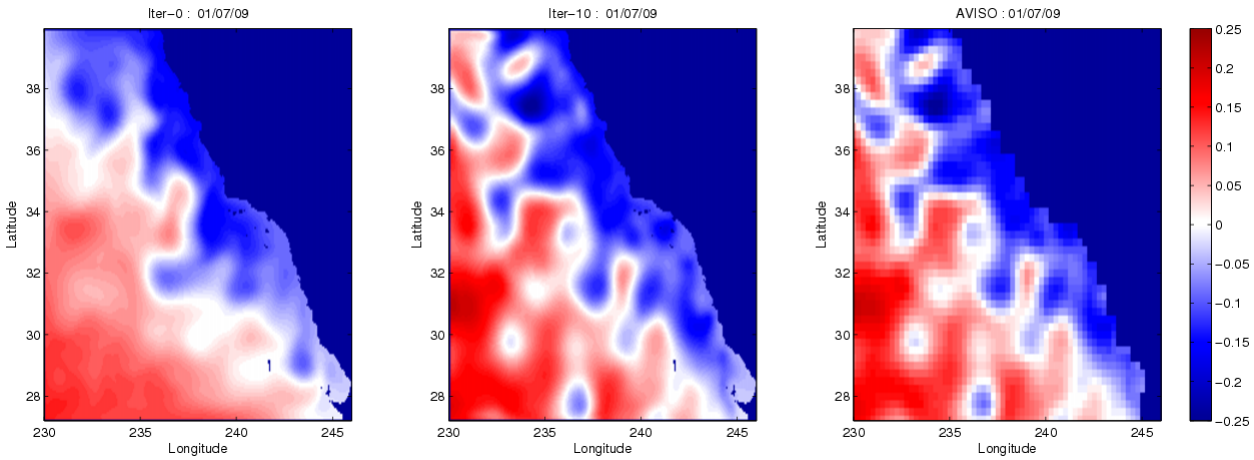


Figure g1: *All three panels are SSH (color scale in meters) for Jan. 7 2009. The left panel is the starting state of the model as determined by the longer assimilation. The center panel is the final model state after adjustment. The right panel is the mapped AVISO SSH.*

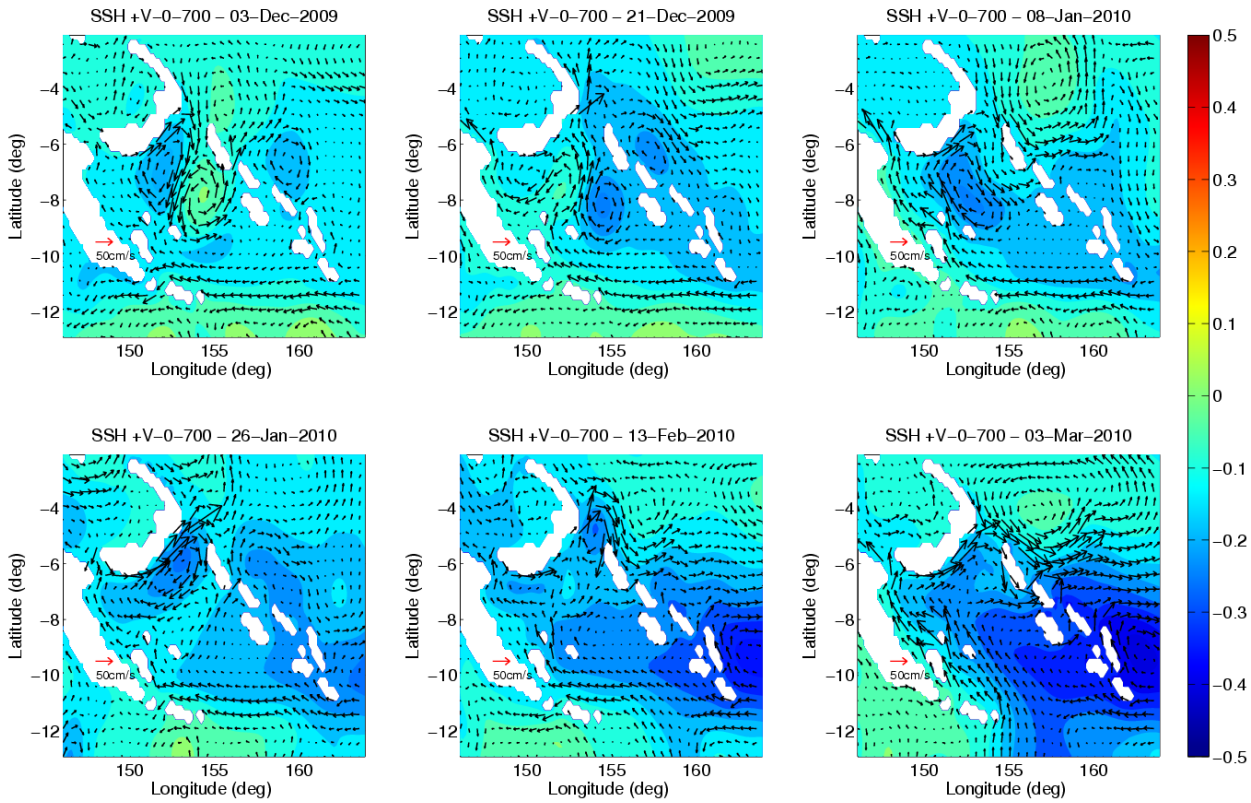


Figure g2: *Model SSH (color scale, -.5 to .5 m) and depth-averaged currents (0-700m) (arrows: scale arrow is 50 cm/s) for the Solomon Sea region shown every 18 days starting from Dec 3 2009.*