Integrated Boundary Current Observations in the Global Climate System

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1. Abstract

An integrated boundary current observing system is being developed and initially implemented in the California Current. It uses a mix of gliders, moorings, inverted echosounders with pressure sensors (PIES), XBT sections, surface drifters, and data assimilation. The gliders are now able to acoustically retrieve the data from subsurface moorings and bottom-mounted PIES and to telemeter them to shore. Gliders and moorings are starting to reveal the spatial, temporal, and depth structure of the California Current and of its time variability. XBT and ARGO analyses help to connect the boundary current to the interior circulation. Automated bottom-released surface drifters are now functioning are starting to be used. Data assimilation is producing first results. The CORC project is thus entering a more routine and quasi-operational phase.

2. Project Summary

The current national and international Ocean Observing System for Climate consists of several components, none of which are designed for capturing the concentrated circulation systems found in boundary currents. This is one of the most important gaps that were identified and agreed on by the international community and agencies at the OceanObs09 conference in Venice. Boundary currents play a critical role in the climate system and for societal applications, since they carry a bulk of the ocean heat transport, have the largest air-sea heat fluxes, and represent the most important coastal ecosystems and fisheries regions. Therefore, additional approaches and sustained observing infrastructure are needed for studying and monitoring western and eastern boundary currents.

The CORC project develops, demonstrates, and implements a system that can fully monitor the intensity (mass and heat transports) and other properties of most boundary currents in a sustained and routine mode, delivering indicators about the state of those regimes in near-realtime. CORC explores and exploits the complementarity of several technologies and techniques for which the P.I.'s possess a large pool of expertise, and which were partly developed in prior CORC phases. These include

- *underwater gliders:* upper-layer distributions of heat, currents, and some biological parameters every few weeks
- *end-point moorings:* dynamic height differences, and thus mass transports, throughout the water column with high temporal resolution (horizontal integral)
- *inverted echosounders/bottom pressure (PIES):* 2 vertical integrals (e.g. dynamic height and heat content) at each location along a section with high temporal resolution.
- *XBT sections:* cost-effective upper-layer sections of heat and currents; historical comparisons
- *Surface drifters:* Ekman flow and eddy activity
- *data assimilation:* state estimate of heat and flow distributions, merged from all the data types, plus satellite altimetry and forcing fields (wind) and large-scale information.

Additionally underwater telemetry is being developed for the PIES and (subsurface) moorings using gliders equipped with acoustic modems as "data shuttles" to the surface.

Much of the OceanObs09 Community White Paper about a boundary current observing system is based on CORC insights and contributions from CORC investigators. The user community includes climate modelers and forecasters, ecosystem assessment efforts, fisheries management, and climate impact studies and mitigation. A data management and public distribution system for boundary currents is currently lacking as well, and the representation in and strong connection of CORC with OceanSITES may offer a way to start building public data access, for research users, agencies, and policy makers.

The CORC observing system is being implemented and demonstrated initially in the California Current which has large climate and socio-economic relevance and does not have a routine monitoring system. Concentration on CalCOFI line 90 in southern California assures synergy with other programs, and coincides approximately with the high resolution XBT line PX31. First results reveal important northward flow cores, large variability in transports, and barotropic flows. The modem shuttle gliders have started to deliver quasi-daily data from the subsurface moorings.

Parallel to the California Current implementation, technological and methodological developments continue, and implementation of the system in a climatically highly relevant western boundary current is planned. The initial choice is in the low-latitude western Pacific, where a western boundary current feeds the Equatorial Undercurrent through the Solomon Sea. This has huge potential climate impact by modulating the equatorial conditions for El Nino through upwelling of this water along the equator. Initial exploration with gliders has revealed dominating eddy variability and large vertical extent in the flow there, which requires addition of integrating techniques and drifters.

3. Accomplishments

3.1. Task A: Glider Operations in Boundary Current Observing Systems *(Russ E. Davis, D.L. Rudnick, U.Send)*

This task is aimed at exploiting underwater gliders to observe and monitor boundary currents that have an impact on the global climate system. The effort has two venues: (1) as part of the integrated development of techniques for monitoring boundary currents, gliders are operated in the California Current to observe the seasonal and interannual variability of the California Current System; and (2) with an eye toward using this system to observe the climatically crucial transports from the Pacific's South Equatorial Current to the equatorial Pacific, a continuous series of transport transects is being made across the Solomon Sea.

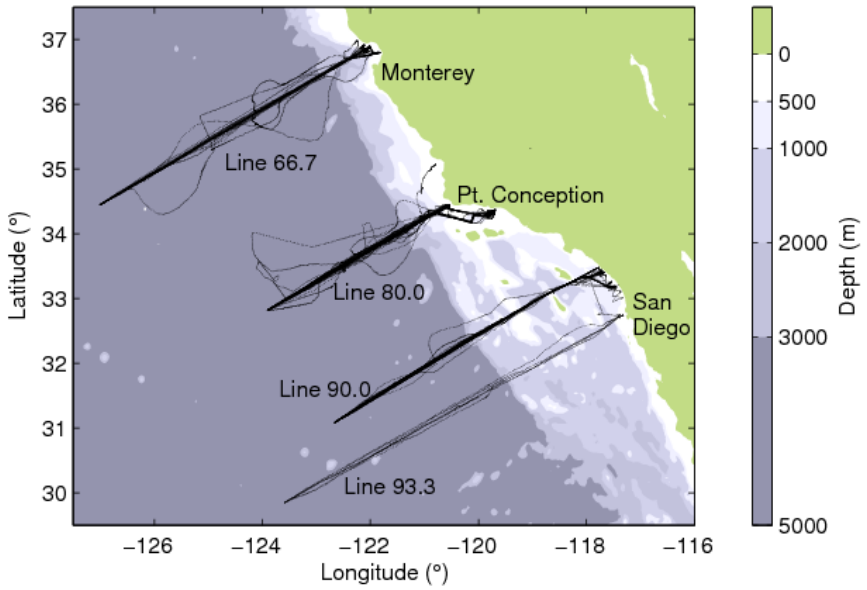


Figure A-1: *Glider sampling along CalCOFI survey lines. CORC gliders continuously observe the length of Lines 66.7 and 90 while Line 80 is continuously observed under separate funding. Spray gliders sample T, S, absolute velocity, acoustic backscatter, and chlorophyll fluorescence.*

Gliders are central to the observing technology being developed to make sustained observations of boundary currents. By repeating transects across the current, they measure the temperature and salinity associated with changing mass and heat transports and other variables, such as oxygen, nutrients, chlorophyll fluorescence and acoustic backscatter, that are descriptors of physical climate impacts on the current's ecosystems. Gliders are also fitted with acoustic modems to match those mounted on Pressure and Inverted Echo Sounders (PIES) and moorings (as described in Task B) to relay data from subsurface instrumentation.

<u>California Current.</u>

Figure A-1 shows the network of CalCOFI Lines. Gliders have been operated under CORC on Lines 90 or 93 since April 2005. Biological sensors were added in October 2006 when sampling on Line 80 was begun under separate funding. Sampling on Line 66.7 began in April 2007 and became continuous in April 2008.

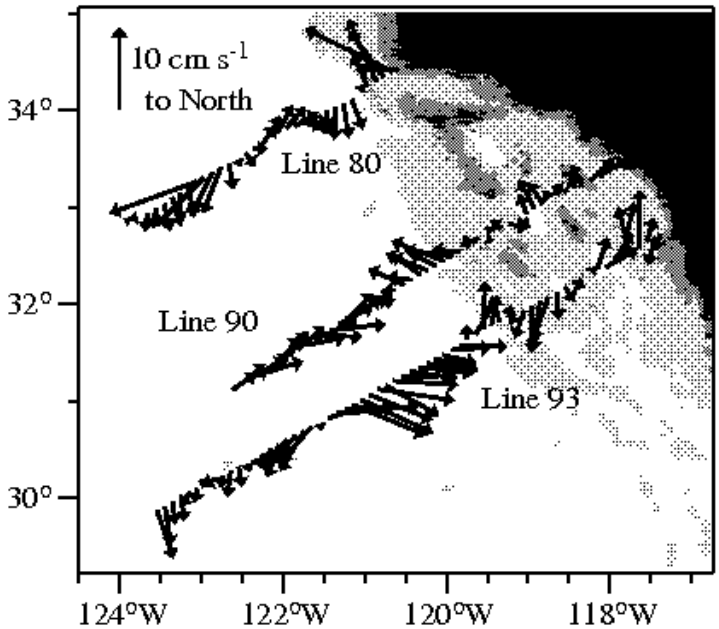


Figure A-2: *Annual average of the depth-average velocity from the surface to 500 m depth from about 3 years of glider data.*

Two types of Spray gliders are operated in the California Current System (CCS). ADP-Sprays are fitted with Seabird CTDs, 750 kHz Acoustic Doppler Profilers (ADP) that are calibrated for backscatter, and Seapoint Chlorophyll Fluorometers, also regularly calibrated with chlorophyll-a solutions. This sensor suite observes (1) absolute velocity profiles by combining vehicle set and drift with the ADP velocity shear, and through geostrophic calculations, (2) chlorophyll fluorescence, which serves as an indicator of the lowest trophic level affected directly by physical forcing, and (3) acoustic backscatter, which serves as an indicator of zooplankton and forage-fish that prey on phytoplankton and are prey for commercially valuable fish. Under other funding, a nitrate sensor is being installed on gliders to better observe the bottom-up physical forcing of phytoplankton through availability of nutrients. In Transponder-Sprays the ADP is replaced by a Benthos acoustic modem matched to transponders on moorings and PIEs.

A preliminary analysis of data on CalCOFI Lines 80, 90 and 93 appeared in *Limnology and Oceanography*[1]. The length of the record available when this analysis was completed was insufficient to clearly define even an annual signal but some aspects of the flow were clear. First, the California Undercurrent is frequently the big signal over the first 100 km from shore and its seasonality is more complex than a simple appearance of the Davidson Current in winter. Second, poleward flow is typical of the entire CCS below 250 m. Third, the eddies in the CCS are frequently powerful (0 to 500-m average velocities of 30 cm/s), sometimes remain trapped in a location for many months, and are a major organizing feature for the phytoplankton and zooplankton. Statistical descriptions of some of these features are shown in figures A-2 and A-3.

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

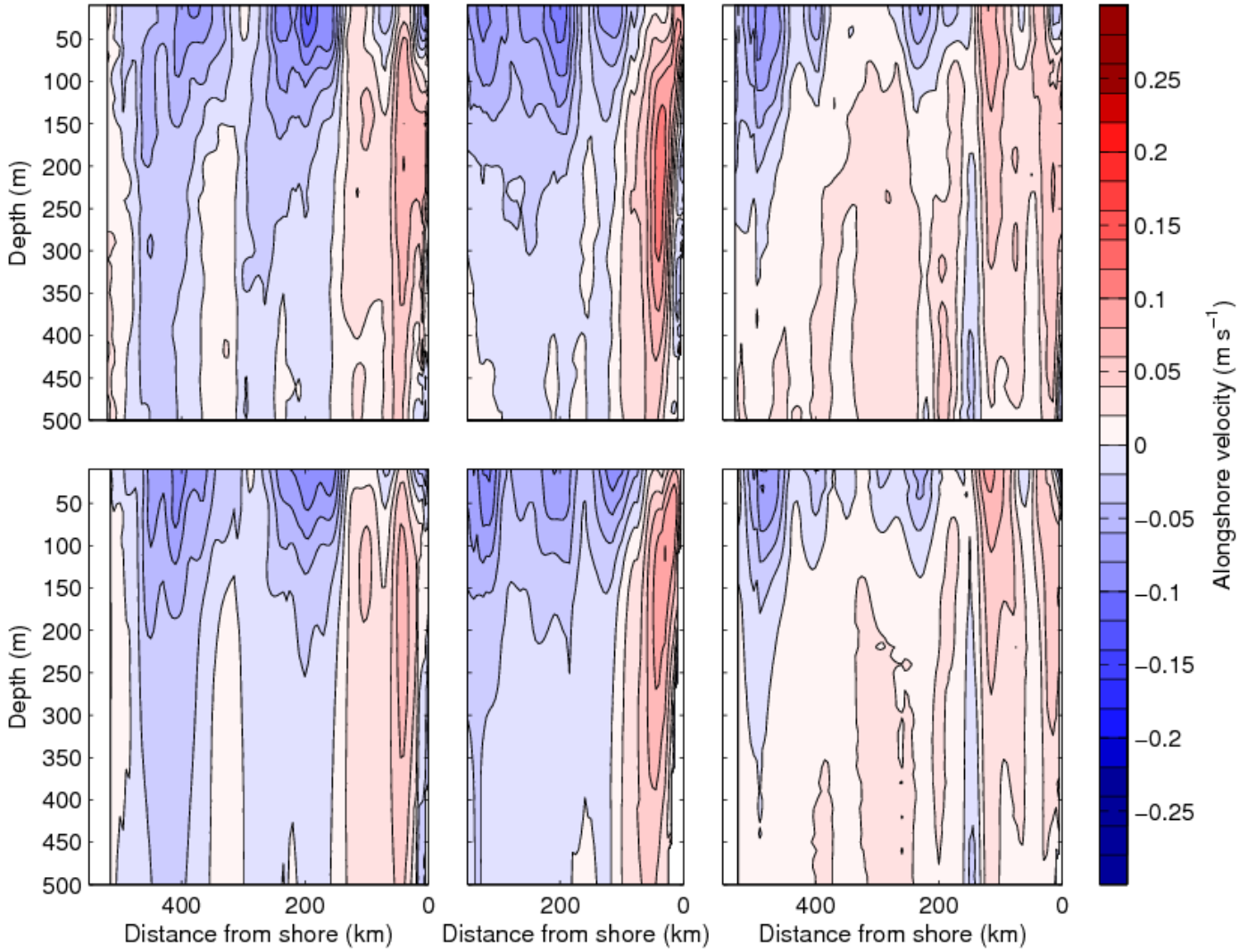


Figure A-3: *Sections along Lines 66.7 (left), 80 (middle) and 93 (right) of mean poleward flow (cm/s) based on ADP measurements (top) and geostrophic shear referenced by measured depth-averaged flow(bottom) (in m/s). The averages include all glider sections until Jan 2010. The California Current is the shallow fresh equatorward flow largely above 200 m that is apparently split into two branches. Near the continental slope, the depth-intensified poleward flow at all depths is the California Undercurrent of warm, salty water. On line 90 there is also poleward flow farther offshore.*

Although the depth average flow in is still affected by eddy variability, the nearshore Undercurrent and a second, weaker poleward flow is evident near 120^0W on Line 90 and near 122^0W on Line 80. These flows are nearly undetectable in relative geostrophic flow referenced to 500 m, explaining why the extent of poleward flow has been underestimated in earlier work based on hydrography

Figure A-3 shows offshore sections of mean velocity computed from ADP data and geostrophic shear referenced by the depth-average velocity measured directly from the set and drift of the glider. This shows that both the poleward flows seen in depth average flow (figure A-2) are manifestations of largely subsurface undercurrents.

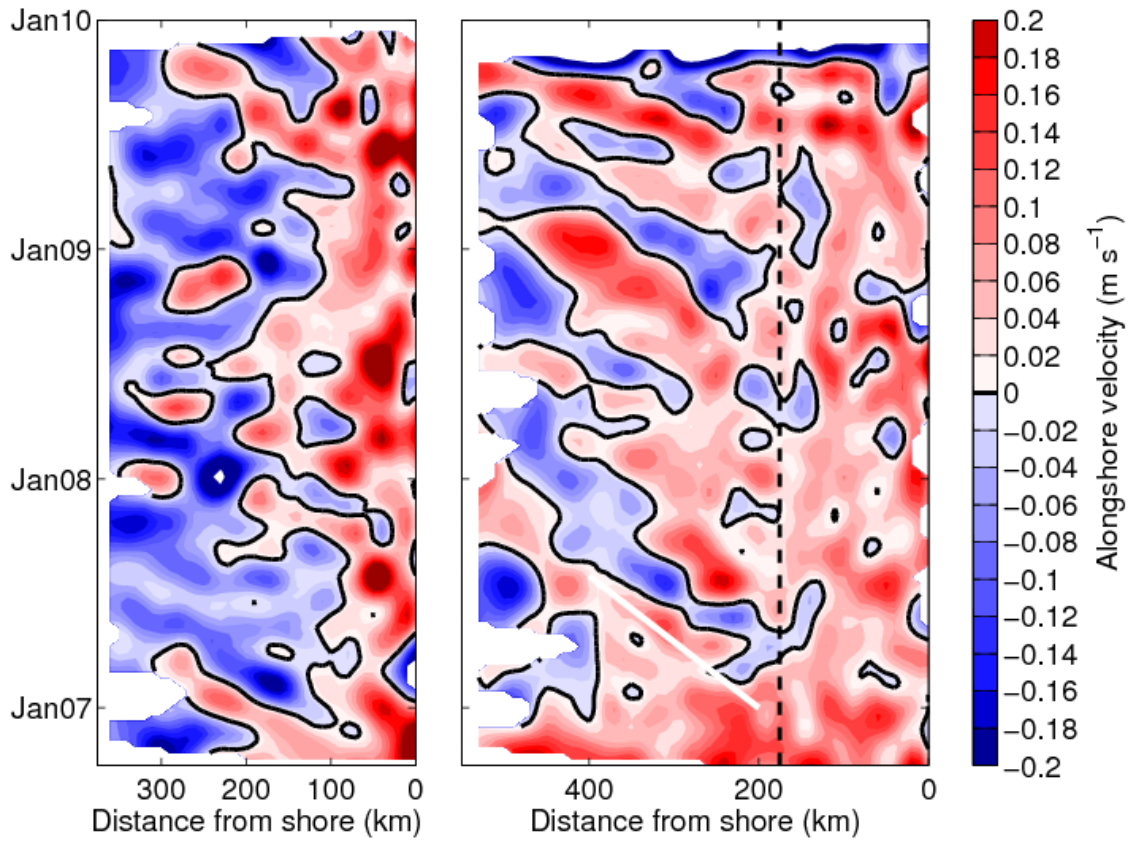


Figure A-4: *Hovmueller diagram of depth-averaged alongshore flow on line 80 (left) and line 90 (right). The dashed lone indicates the location of Santa Rosa Ridge. Westward propogation is visible on line 90 west of the ridge.*

Figure A-4 shows the variability of the depth-averaged alongshore flow as Hovmueller diagrams on lines 80 and 90.

Our depth-averaged velocity sections often show large changes in the flow distribution from one transect to another, highlighting the fast timescales in the boundary current regime. After averaging all the available transects, a patterns emerges, which is equal to the depth integral of figure A-3. As expected, the main undercurrent cores are located against the continental slopes (3000m-1000m isobaths), but there are indications of more offshore flow cores. Cumulative transport calculations show that on lines 90 and 80 the gliders miss much of the more offshore southward flow of the California Current, which should be typically 4 Sv or more. At line 66 it seems that the glider section captures more of the main equatorward California Current. More discussion on the offshore extent of the California Current and its sampling will be found in later sections.

Further analysis of the glider observations in comparison with the modeling will be given in the report of Task E further below.

<u>Solomon Sea.</u>

There are two basic mechanisms by which conditions outside the equatorial zone might impact sea-surface temperature along the equator and, consequently, impact global atmospheric climate variability. While these mechanisms are potentially active in the ENSO cycle, the case for them playing a central role in decadal climate variability is even stronger. In one mechanism proposed by Gu and Philander,[2] air-sea interaction in the subtropics can change the temperature and/or salinity properties of subtropical surface waters. These anomalies are then subducted in the shallow overturning cell and flow below the surface back to the equator. There they upwell and their anomalous properties produce anomalous air-sea fluxes. McPhadden and Zhang[3] have suggested that a more direct and faster mechanism may be variability of the transport of the subtropical cell.

Because the western boundary current in the Solomon Sea is the subtropical cell's putative link between the South Equatorial Current and the Equatorial Undercurrent that feeds upwelling and modulates SST, CORC includes an exploration of transport through the Solomon Sea using underwater gliders. The goals are to find a suitable section through which to measure the equatorward transport and to begin a time series of these transports. The project is collaborative between Scripps, William Kessler of PMEL, and Alex Ganachaud of the IRD laboratory in Noumea, New Caledonia.

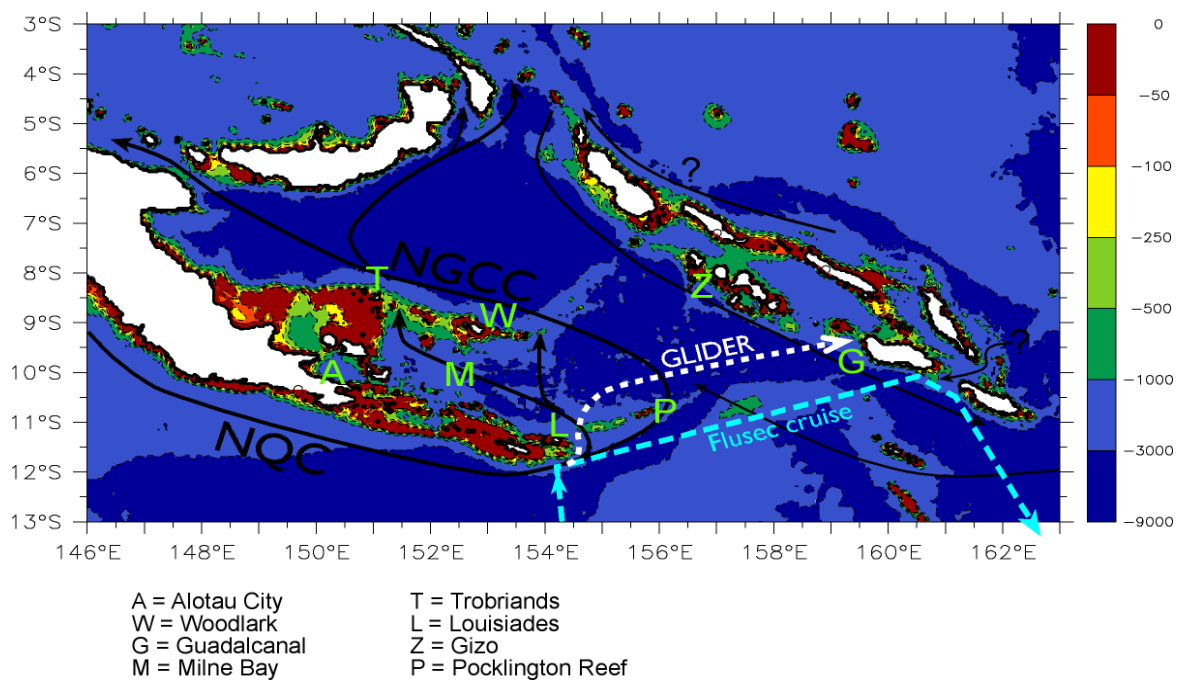


Figure A-5: *Bathymetry of the Solomon Sea and its main transport paths. The South Equatorial Current is the source for both the North Queensland Current (NQC) and the path from the east southeast that becomes the New Guinea Coastal Current (NGCC) in the Solomon Sea. Nominal path for our first glider operation and a 2007 cruise mounted by IRD are shown. The western end of all transport sections to date is Rossel Island at the tip of the Louisiades Archipelego. The eastern end of our sections is either Honiara on Guadalcanal or on the island of Gizo.*

[2] Gu, D., and S.G.H. Philander, 1997. Interdecadal climate fluctuations that depend on exchanges between the tropics and extratropics. *Science*, **275**, 805-807.
[3] McPhadden, M.J., and D. Zhang, 2002. Slowdown of the meridional overturning circulation in the upper Pacific Ocean. *Nature*, **415**, 603-608.

Figure A-5 depicts the Solomon Sea, some of the place names used here, and the main currents that carry water toward the equator. The main transport path toward the equator is shown notionally as a New Guinea Coastal Current that leaves the Solomon Sea by both of two exist on the east and west sides of the island New Britain.

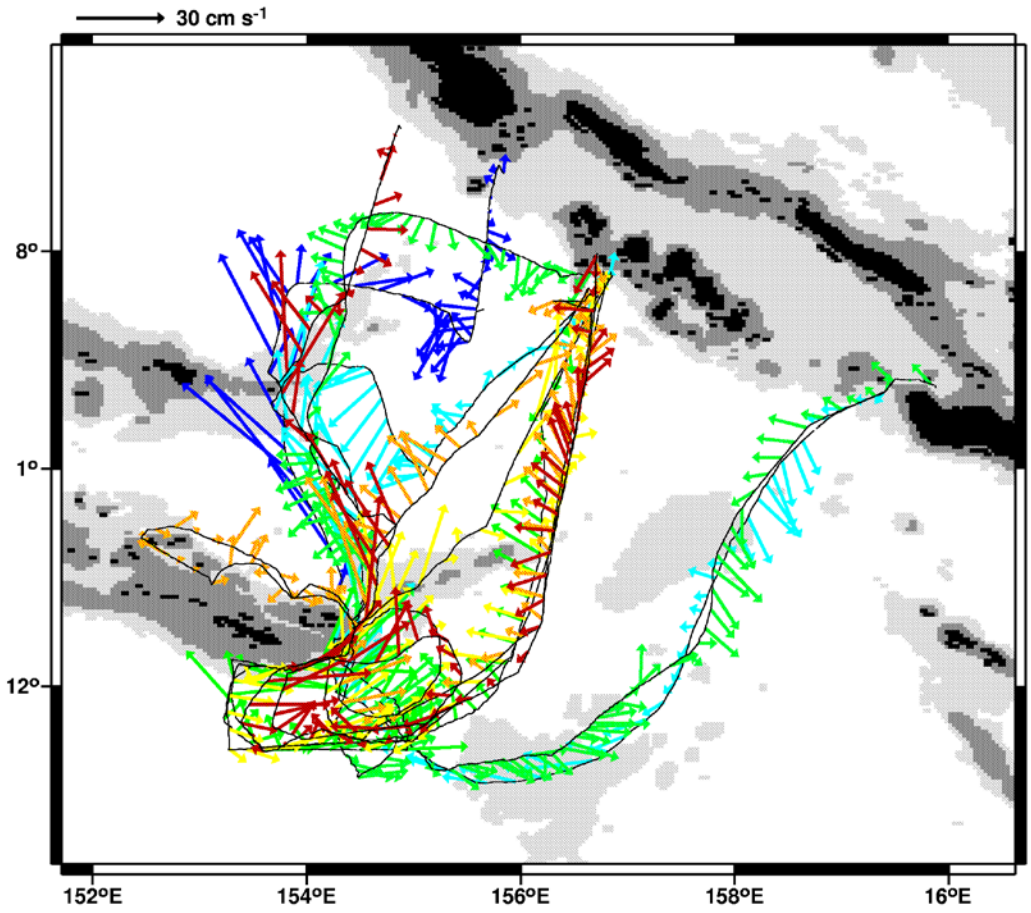


Figure A-6: *The seven Solomon Sea glider cruises completed between late 2007 and late 2009. The glider tracks are shown as black lines and depth-average water velocity is shown as colored vectors. The most occupied section is between Gizo in the Solomon Islands and Rossel Island at the eastern tip of New Guinea. Each transit of the Solomon Sea takes a month or more and most cruises involve a roundtrip from the Solomons to New Guinea and back.*

Figure A-6 shows all the glider cruises completed in the two years between late 2007 and late 2009. A total of seven approximately 100-day cruises have been completed. These show substantial cruise-to-cruise variability both in the basin interior and in the western boundary current. The most unusual circulation was seen in the February-June 2008 cruise during La Nina conditions in the western tropical Pacific. In rough agreement with the Sverdrup transport of the anomalous winds, the South Equatorial Current and the flow into the Solomon Sea were weak. This made glider progress so slow that we barely completed the cruise before power was exhausted.

Transports observed over two years are plotted in Fig. A-7. Transport is the double integral with depth and distance along the measured section of the velocity normal to the section and headed toward the equator

$$Q(X) = \int_0^X dx \int_{-H}^0 dz\, u(z,x)\,.$$

The x integral begins at Rossel Island, each section's western terminus, and ends at the Solomon Islands. Transits in both directions are included. Transport integrals are computed from measured depth-average velocity typically spanning the upper 500-700 m.

Interpretation of figure A-7 requires care because the sections are far from straight so the distances to the same point along two sections are quite different. In all sections, transport associated with the strong western boundary current is apparent and reasonably constant while interior transport varies markedly, so much so that the net transports from early 2008 essentially vanished. Without knowing the seasonality of the Solomon Sea transport it is dangerous to ascribe causes, but we suspect this anomaly was a consequence of the La Nina winds in the western tropical Pacific at that time. A desire to separate seasonal and anomalous transport motivates continuation of the regular transport transects to put the first two year's data in the context of the annual cycle and other forcing events.

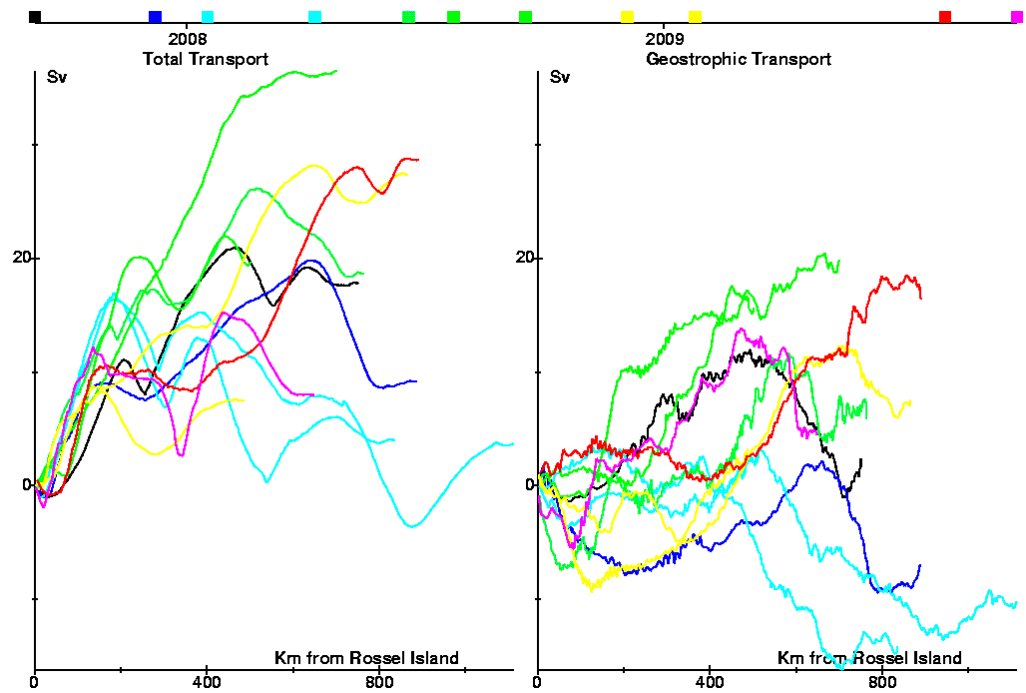


Figure A-7: *Volume transport Q(X) (in Sv) integrated from Rossel Island on the western boundary. Transport is based on measured depth-average to 600 m of measured velocity (left) and of the geostrophic shear relative to 600 m (right). The value for the largest distance plotted for each curve is the net equatorward transport. Colors refer to cruises at times indicated in the timeline above. The lowest transports are from the first half of 2008 during La Nina conditions. The largest transport variations appear to be in the ocean interior rather than in the western boundary current.*

Time variation of total transport (boundary current and interior) through the Solomon sea is substantial, as is shown in Fig.A-8. This figure shows both the measured transport for each Solomon Sea crossing and also the transport carried by the geostrophic shear relative to 600 m. The

two curves differ by the transport associated with extending upwards the velocity at 600 m, which is substantial. The figure shows apparently strong seasonal cycles that are fairly similar between the measured and geostrophic-shear transports – several years of data will be needed to define the seasonal cycle and the non-seasonal variations associated with ENSO and other climate phenomena. The difference between measured and geostrophic shear transports – which appears as barotropic flow to our observations – is rather more constant than the shear-related transport.

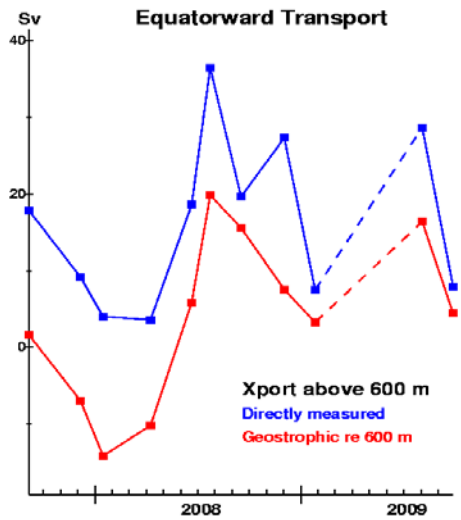


Figure A-8: *Time series of transport: measured transport above 600 m depth (blue); transport above 600 m from geostrophic shear relative to the same depth (red). The distance between the curves, the transport by the measured velocity at 600 m, appears to decline through the two years. Although obscured by the gap in early 2009, it appears that both transports have an non-seasonal minimum in early 2008, presumably in response to La Nina winds during that time.*

There are two notable features in Fig. A-8. First, the minimum equatorward transport occurring in early 2008 appears to deepen the seasonal minimum at that time of year. This is believed to be a result of La Nina winds in the western tropical Pacific at th
at time. Second, there is a 6-month gap in measurements early in 2009 that resulted from failure (but not loss) of the glider scheduled to continue the time series during March-June 2009. The cause of malfunction was a compute initialization problem for which a fix had been retrofitted into all gliders beginning just after this unit was shipped.

The Solomon Sea glider operations are the advanced surveillance effort for a potentially much larger effort to gather more comprehensive and highly resolved measurements of transport variability in the Solomon. Toward this end, in Fall 2009 we dispatched two gliders across the Solomon Sea, with one scheduled to explore waters off the coastline northwest of Rossel Island. One of the promising techniques for monitoring strong boundary currents uses end-point moorings and bottom measurements between these moorings. The flow near Rossel Island is strong in the mean and highly turbulent (vertical motions dramatically impact glider flight) and is, therefore, probably not a good mooring site. Our measurements show that the region northwest of Rossel was quite benign when we visited it and may be a much better mooring site.

Acoustic Modem gliders.

A fundamental to our boundary-current technology is using subsurface instrumentation that can survive strong currents as well as bottom-mounted instruments. To regularly return data from these instruments, underwater gliders have been equipped with acoustic modems to interrogate the subsurface instruments and relay the data through Iridium. For these applications we are still using Benthos 887 acoustic modems operating at 8-12 kHz. In the past CORC years we have had

problems with unsatisfactory performance of these modems which needed urgent addressing in the period reported here.

Intensive interactions with Benthos have finally lead to a marked improvement in reliability and data throughput. Firstly, Benthos had introduced a new Generation 4 of their modem electronics which have a number of technical improvements over the Generation 3 model which were previously installed in our Spray glider and the deployed instruments. We modified our software and hardware installations to allow use of the newer version. Then a Benthos engineer spent a few days at SIO to work with us, conducting tests with Spray gliders in the lab, and simulating the type of signal and data volume used, with transmission delays and signal-to-noise reduction corresponding to the long ranges we are operating under. During that visit, several problems were found in the Benthos firmware and in the way we were using the modems in the gliders. A few weeks after correcting all these issues, a Generation 4 test modem was deployed in 3000m depth off San Diego together with Benthos engineers, and communication with it was successfully executed over distances of up to 5km. This lead us to assemble a new glider with the new modem and electronics. Tests with this gave satisfactory results, and it was commanded to head for the CORC moorings in late November 2009.

After redeployment of the CORC moorings and PIES (see Task B) also with new Generation 4 modems, this glider successfully transferred data from mooring CORC1 and PIES P1 on a routine basis. From mid-December (deployment) until end of January, approximately 3860 temperature and conductivity values, and 2000 pressure values were acoustically recovered from the CORC1 mooring and the telemetered to shore by the glider. During the same time, the glider transmitted approximately 1100 pressure and traveltime measurements from the PIES.

The following figures demonstrate the success with glider data telemetry as it stands now.

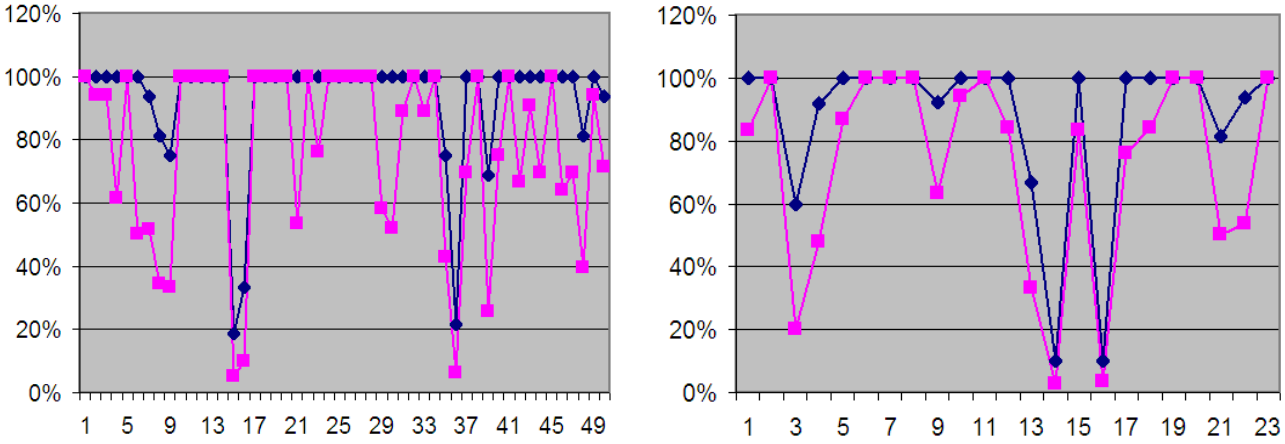


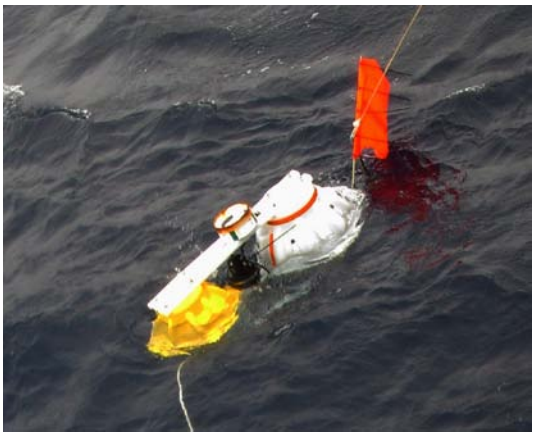
Figure A-9: *Success rates of transmitting data from the microcat mooring (left) and from the PIES on the seafloor (right). For each contact made with a modem, the percentage shows how many of the transmitted bytes of data were received and were correct. The purple graphs count all re-tries, the blue one just counts the attempted bytes during one session regardless of re-tries.*

Overall, for the mooring, 93% of the bytes transmitted were received correctly (77% if re-tries are counted). For the PIES these values are 87% and 72%. This means that once contact is made, data can be transferred with a success rate of around 90%.

3.2. Task B: Moorings and PIES in Boundary Current Observing Systems *(U.Send)*

This task has the goal to provide the end-point mooring and inverted echosounder (PIES) components of the boundary current observing system. The high-light during the reporting period was the first recovery of moorings and PIES that had been deployed in the California Current (on CalCOFI line 90) in September 2008, and redeployment of newly constructed ones with the Generation 4 modems and with a planned increased deployment period of 2 years. This cruise took place during 12-20 December 2009. It recovered and redeployed the two CORC moorings, and recovered 5 PIES and redeployed 6. Also one additional modem glider was launched near mooring CORC2. All recovered 29 microcats and 5 PIES had worked well and delivered full data sets, see below for preliminary analyses. Some fotos of the main hardware components which were deployed are shown in the following figures.

Figure B-1: *Top float (left) of a CORC mooring, with radio&satellite transmitters and a flasher on the top, and an inductive microcat (wrapped in copper foil). The microcat is connected to the inductive telemetry loop, which uses the mooring wire to allow communication between all microcats and the controller shown on the right (yellow). The controller cage shown above is at 3700m depth in the mooring, and passes the microcat data to the acoustic modem in the same cage (black pressure case). The red hydraulic hose is the by-pass of the mooring wire inductive loop, to connect the mooring above and below the controller cage.*



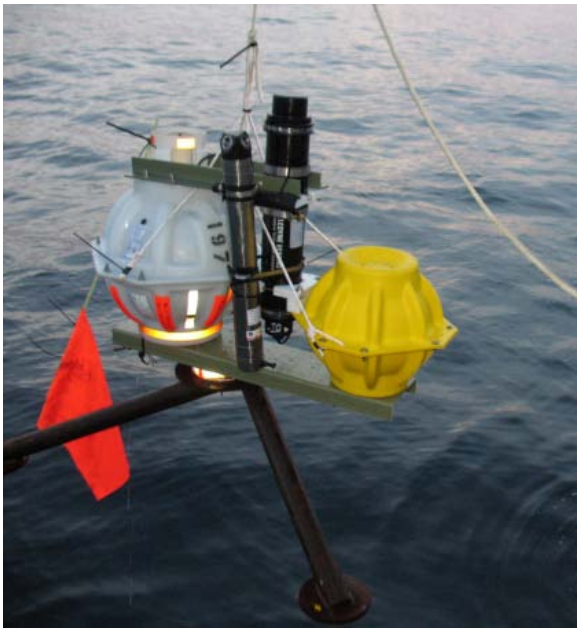


Figure B-2: *A released PIES with modem floating at the surface prior to recovery (left), and a new PIES (white) with modem (black) and Aquadopp current meter (silver) being launched. The yellow sphere is an additional floatation element.*

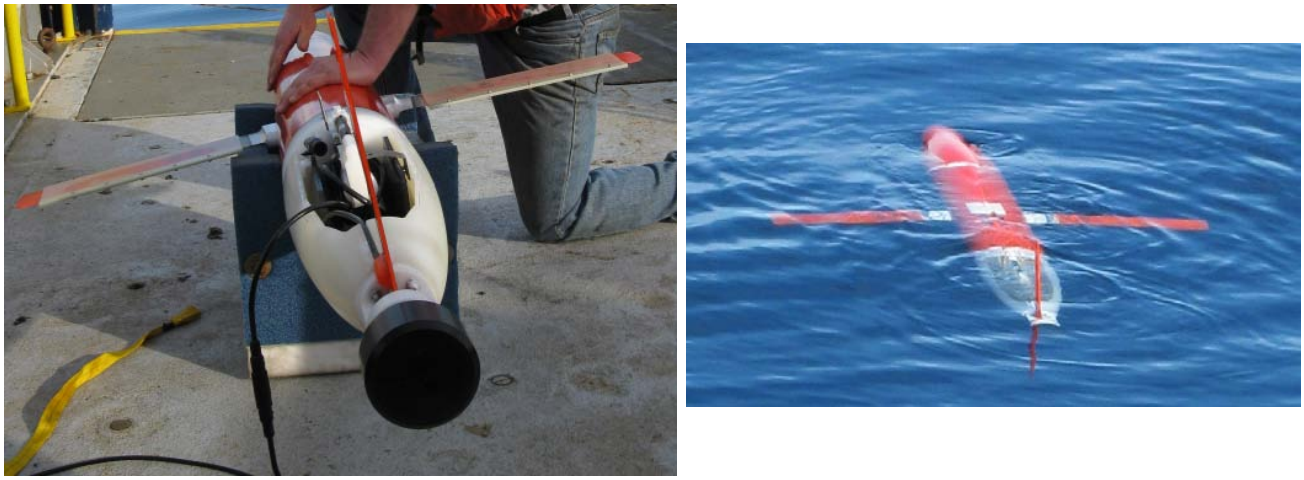


Figure B-3: *A modem Spray glider being prepared for deployment (left), clearly showing the modem transducer mounted on the back of the glider. Spray glider at the surface after deployment (right).*

Careful re-evaluations of the mooring placement and section length came to the conclusion that the previous mooring locations were optimal, based on the available information. This was concluded from ARGO/XBT analyses such as in Task C, and from maps of the mean surface flow derived from altimeter and surface drifter data. The current design with a mooring separation of approximately 700km and a total distance from shore of close to 950km is believed to capture what usually would be called the California Current, i.e. the enhanced flow near the eastern boundary, all the way out to a minimum in alongshore flow.

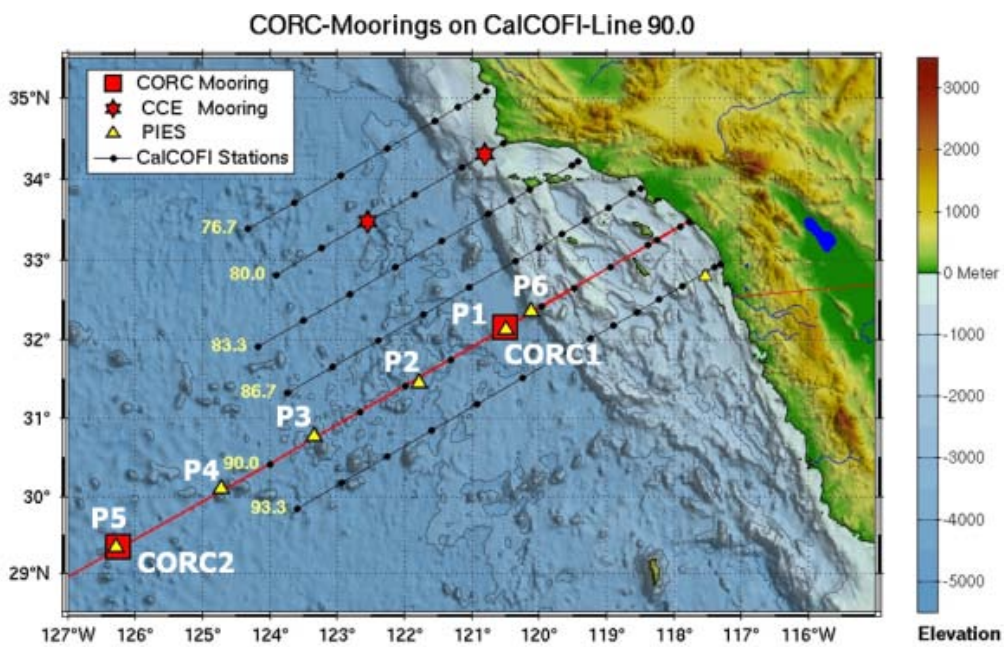
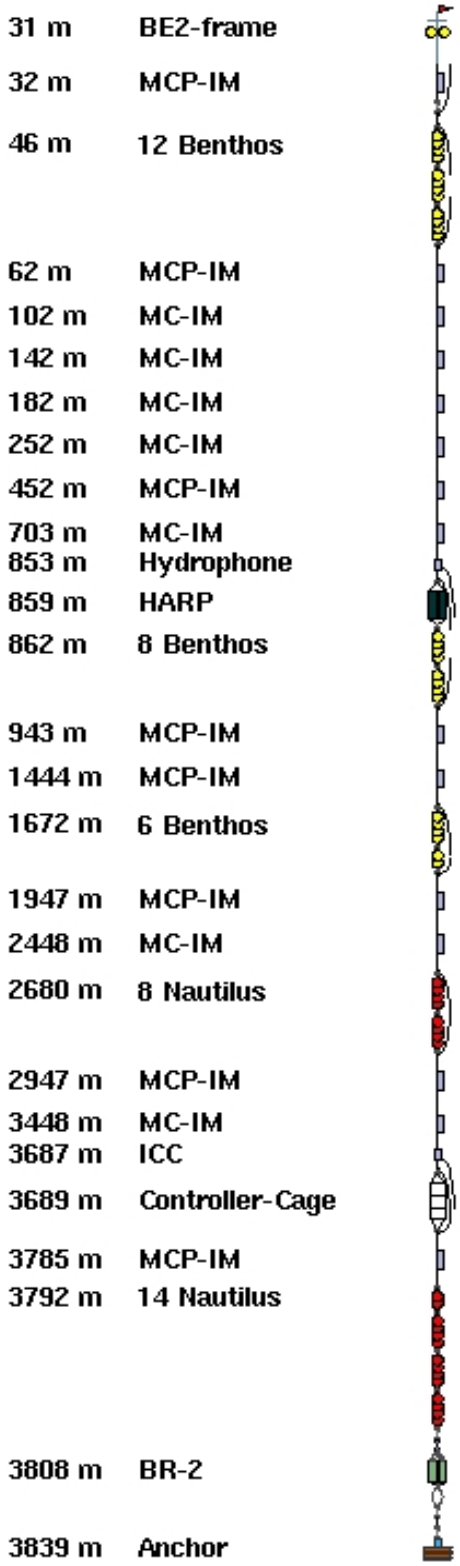


Figure B-4: *Placement of moorings CORC1 and CORC2, and PIES P1-P6 along CalCOFI line 90, as deployed in December 2009.*



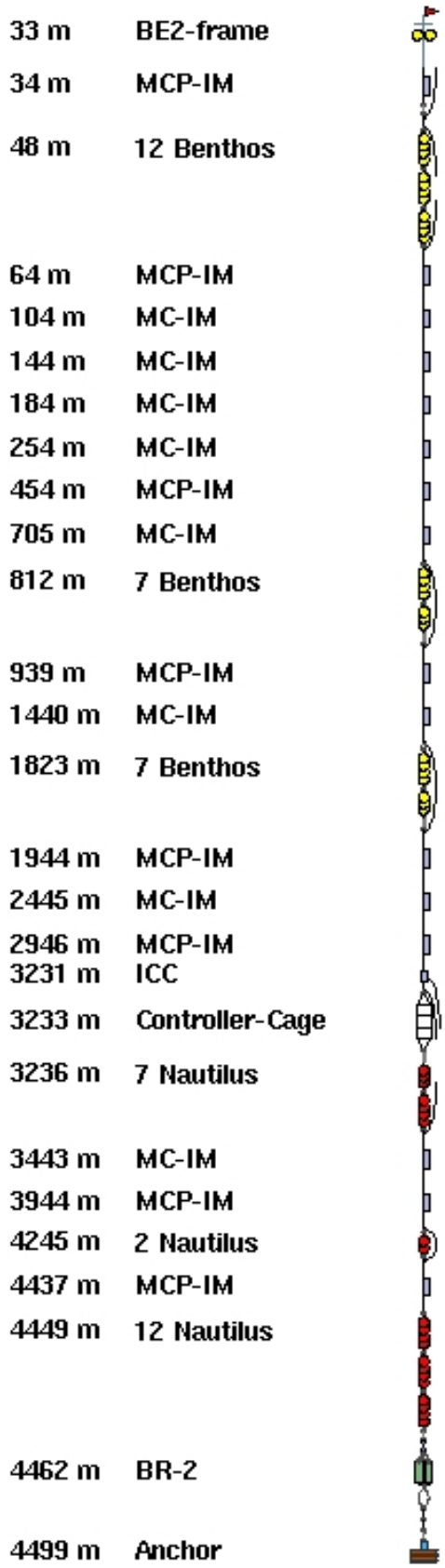


Figure B-5: *Design of the two endpoint moorings as now deployed on line 90 (see figure B-4), with 15 microcats (MC-IM and MC-IMP) each.*

With the extremely careful sensor calibrations for the microcats carried out on board (attaching them to a CTD rosette, and calibrating the CTD conductivity sensor with bottle samples and salinometry analyses), first transport calculations could be carried out from the recovered data. Figure B-6 shows some complete timeseries from the first deployment (Sep'08-Dec'09) of the horizontally integrated transport of the California Current between the two CORC moorings, with some surprising new results. The red line represents what is traditionally done when calculating the California Current transport from e.g. XBT or CTD data – the geostrophic flow is referenced to 500m, and the layer considered is also 500m deep. With our new data we can for the first time use a deeper, probably more realistic reference level, e.g. 3500m as in the magenta curve. We can see that the flow is likely to be weaker southward (or more northward) then. One can also see more dramatic transport variations, with excursions of up to 10Sv and complete transport reversals. If one considers a thicker layer, e.g. 1000m, the flow becomes even more northward, meaning that in the 500-1000m layer there probably is predominantly northward flow.

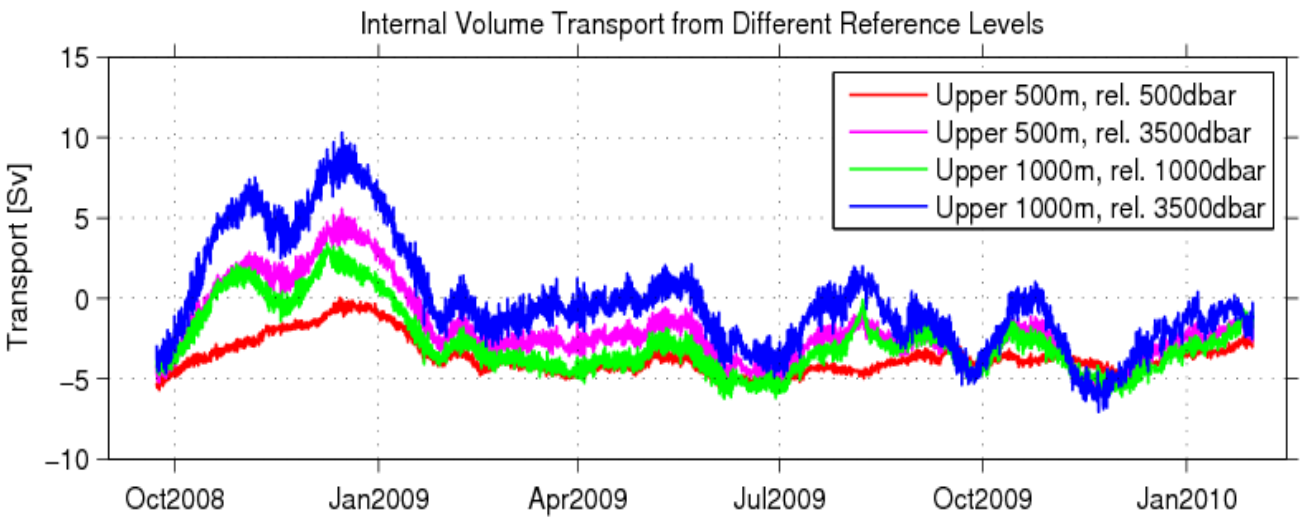


Figure B-6: *Geostrophic transport between the two CORC moorings, for the 0-500m and 0-1000m layers, referenced to 500/1000db and to 3500db. Negative means southward flow.*

The next step is to use the bottom pressure measurements from the PIES at the two mooring locations to also calculate the horizontal pressure gradient fluctuations <u>at the reference level</u>. With this, the flow fluctuations can be made absolute (though not the mean flow, since the leveling of the pressure sensors is unknown and thus the mean pressure gradient between them). Figure B-7 shows the first data that exist to determine the geostrophic flow fluctuations at the reference level and thus barotropic transport changes which are usually unknown/unmeasurable. We see in that figure that the barotropic flow adds transport variations of another +/- 3Sv to the previously estimated transports (taken over the upper 500m). This somewhat surprising result means that flow fluctuations exist at the seafloor in 3500-4000m depth, which contribute to the upper layer transport of the California Current.

Note that the timeseries shown in figures B-6 and B-7 extend beyond the date of mooring recovery in mid-December 2009. Those additional data are first estimates of transports using the real-time data recovered from the newly deployed moorings with the acoustic modem gliders. They are preliminary at present, since only CORC1 mooring data are available so far (but this mooring contributes the most to the dynamic height gradients and thus transports).

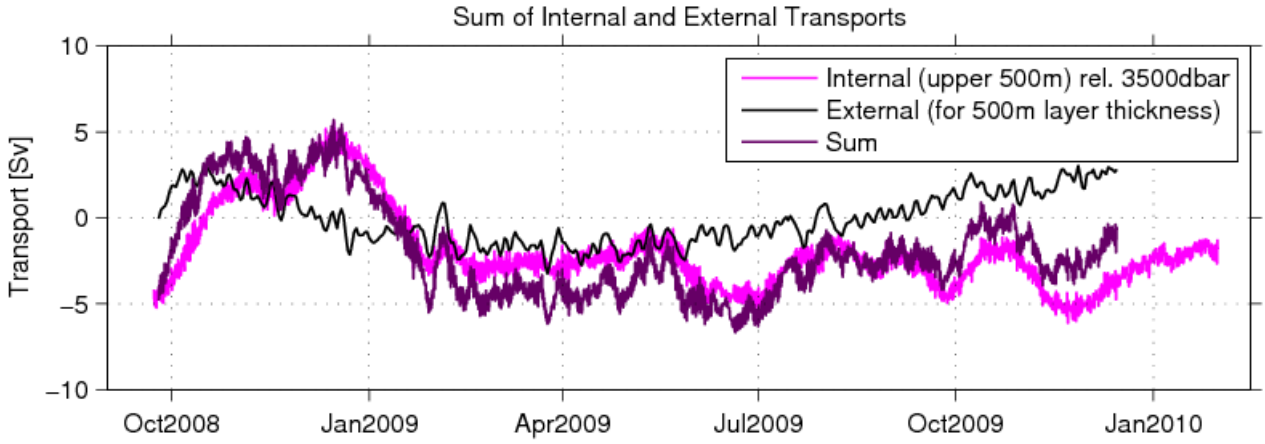


Figure B-7: *Magenta line is the same as in figure B-6. The black line shows the additional transport in the 0-500m layer resulting from geostrophic flows at the 3500m reference level, deduced from the bottom pressure data. Adding these two components gives the* <u>*total*</u> *transport fluctuation in dark violet color.*

Finally, as a further demonstration of the data information content telemetered with the gliders since mid December'09, figure B-8 shows a depth-time plot of the average geostrophic current between the CORC moorings. This currently assumes again that only CORC1 contributes to the variability, since no glider data from CORC2 are currently available. It shows the richness of data retrieved with the gliders until beginning of February 2010.

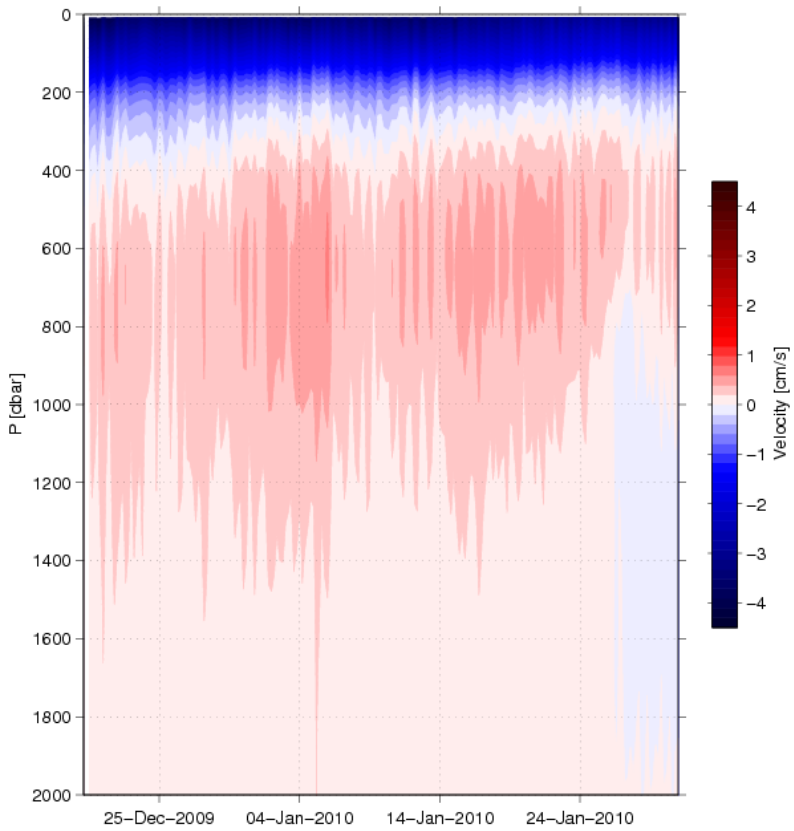


Figure B-8: *Horizontally averaged flow between CORC1 and CORC2 as a function of depth, from mid December until beginning of February, derived entirely from mooring data retrieved the modem gliders from CORC1. Note the non-linear color scale to highlight the weaker flows below 300m depth.*

At the time of writing, the glider which retrieved the above data, is on the way home. Two new modem gliders are under construction which will be deployed in the next months to retrieve CORC1 and CORC2, and the PIES data, for several months continuously.

3.3. Task C: XBT data in support of the California Current observing system *(D.Roemmich)*

Part 1: Analysis of High Resolution XBT transects in the California Current system

The High Resolution XBT Network (HRX) collects eddy-resolving temperature transects along commercial shipping routes. Most lines are sampled on a quarterly basis, with temperature profiles from 0-800 m at horizontal separations ranging from 50 km in mid-ocean to 10 km near ocean boundaries. Two HRX transects cross the California Current system (Fig C-1). These are lines PX37 (San Francisco-to-Honolulu) and PX37S (Long Beach-to-Honolulu). The latter is in close proximity to CalCOFI Line 90. Line PX37 has been sampled continuously since 1992.

Analysis of HRX data from PX37 and PX37S (Fig C-1), including temperature, salinity, and geostrophic velocity and transport, together with Argo data over the northeast Pacific, will allow the more intensive CORC measurement program along CalCOFI Line 90 to be placed in the context of the larger eastern subtropical North Pacific domain.

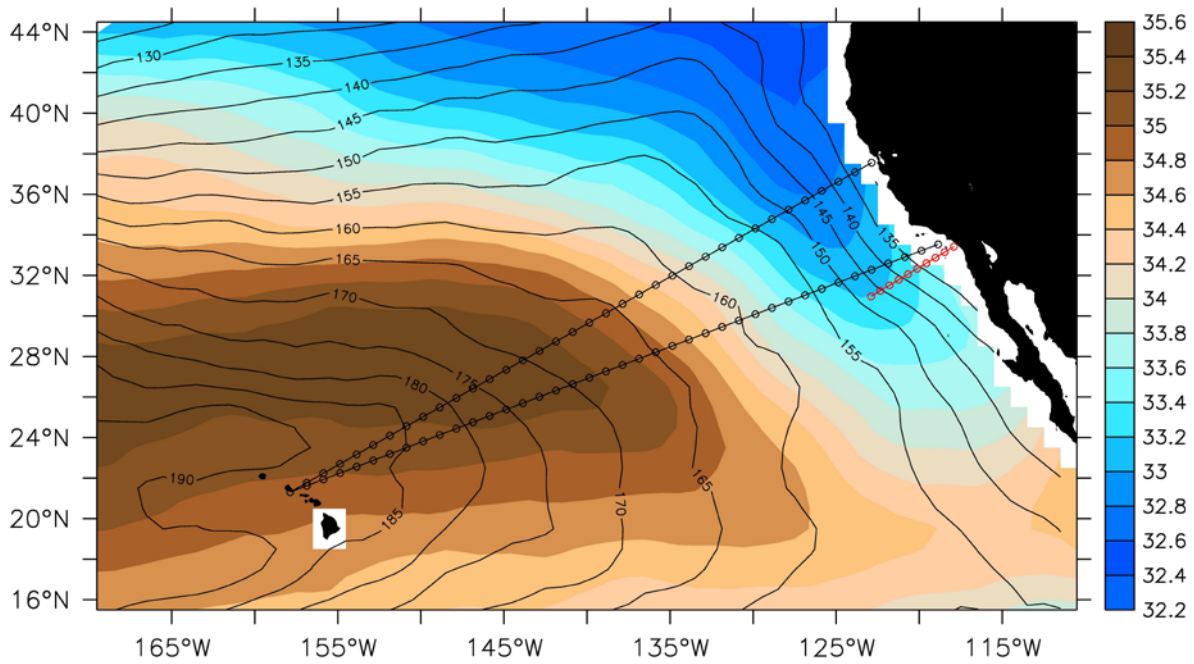


Figure C-1: *HRX Lines PX37 (Honolulu-San Francisco) and PX37S (Honolulu-Long Beach) are shown in relation to CalCOFI Line 90 (red), and to the mean sea surface salinity and mean dynamic height of the sea surface from Argo (0/2000 dbar).*

Goals are to:

1. Define the offshore extent of the California Current and determine how much of its transport is beyond the usual offshore end of CalCOFI Line 90 (Fig C-1).
2. Compare transport and variability variability of the California Current off Southern California (Line PX37S) with that off Central California (Line PX37). Is transport variability correlated alongshore?
3. Optimally merge HRX lines with Argo data in the ocean interior. How should these two datasets be combined in order to observe both the boundary current at high spatial resolution and the large-scale interior?

The results to date are shown in figure C-2 and C-3.

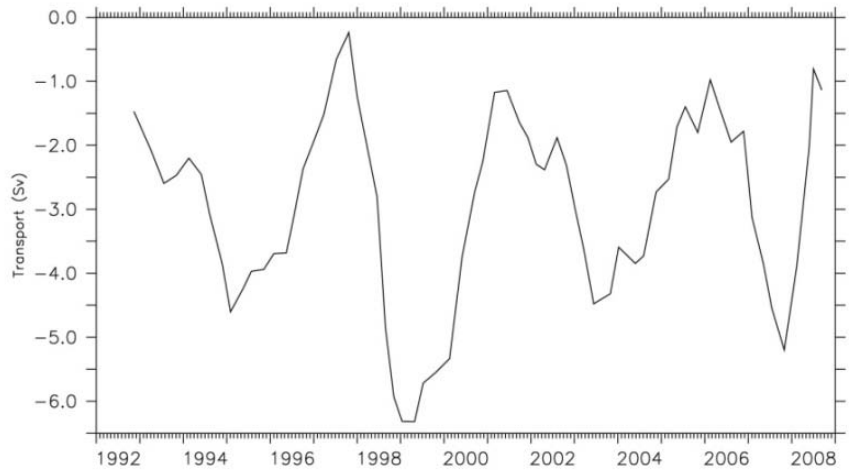


Figure C-2: *Transport of the California Current along line PX37 from HRX data from the coast to 129°W.*

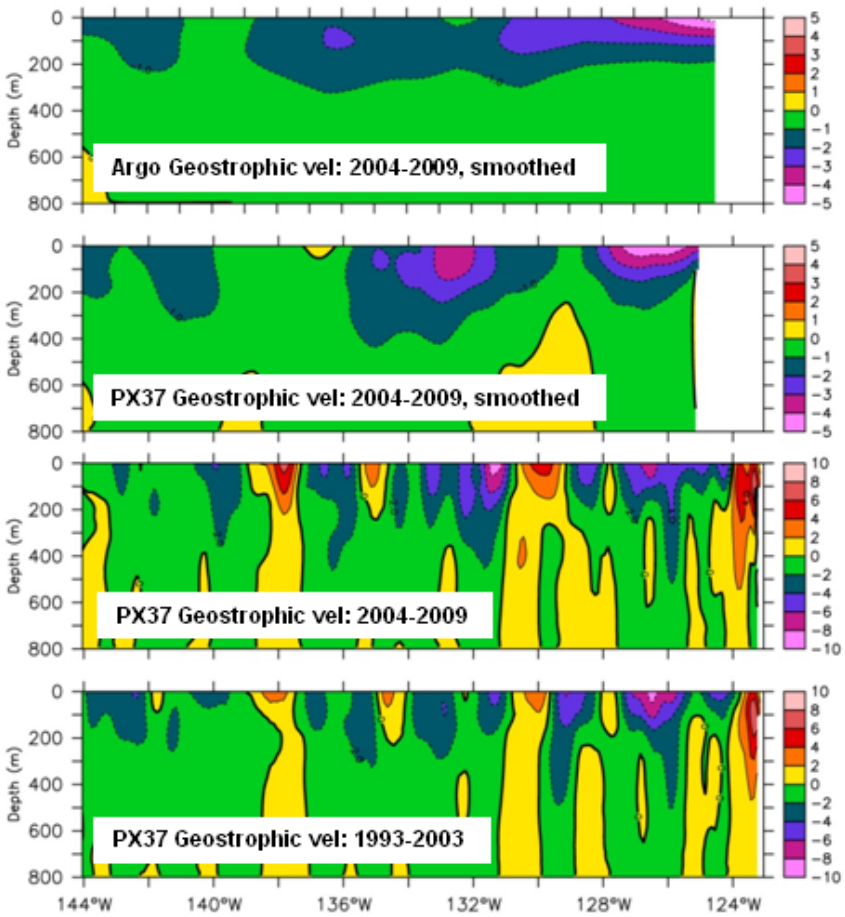


Figure C-3: *ARGO (top) and XBT PX37 (other 3 panels) geostrophic velocities relative to 800m. The bottom two panels show different multi-year averages, high-lighting that the spatial structures are quasi-permanent.*

The main statements so far are that HR-XBT transects

- span the full width of the California Current system, resolving poleward and equatorward flows.
- reveal persistent small-scale filaments in multi-year averages (right).
- close the mass, heat, and freshwater budgets for enclosed ocean regions.
- complement broad-scale views from Argo (above).
- are part of the global HR-XBT Network.
-

3.4. **Task D: Drifter observations and bottom release technology** *(Peter Niiler)*

a) Analysis of historical observations in the Southern California Current System:

The hydrographic data from 1949-2008, the SVP and CODE drifter data from 1985-2008, the satellite altimeter from 1992-2008 and ADCP data from CALCOFI ships are the data base for the continued analysis. The combined drifter, hydrographic and ADCP observations all of the CALCOFI lines, as was completed along Line #90 in 2008 has been completed and comprehensive surface circulation map the CALCOFI region is now under way. These analyses produce time-mean horizontal maps of surface circulation in the southern portion of the CCS and vertical sections along CALCOFI Lines.

In addition to the SVP drifter data, we have obtained 563 CODE drifter data observations (Figure D-1). Analysis shows that the time variable currents have a correlation to the time variable AVISO derived surface geostrophic velocity that is comparable in magnitude to that which is typical of the SVP drifters in the California Current System (Figure D-2). These data, for the first time, will be able to relate SVP velocity observations at 15m depth to the CODE observations at 50cm depth, a problem of considerable interest to the Lagrangian drifter community.

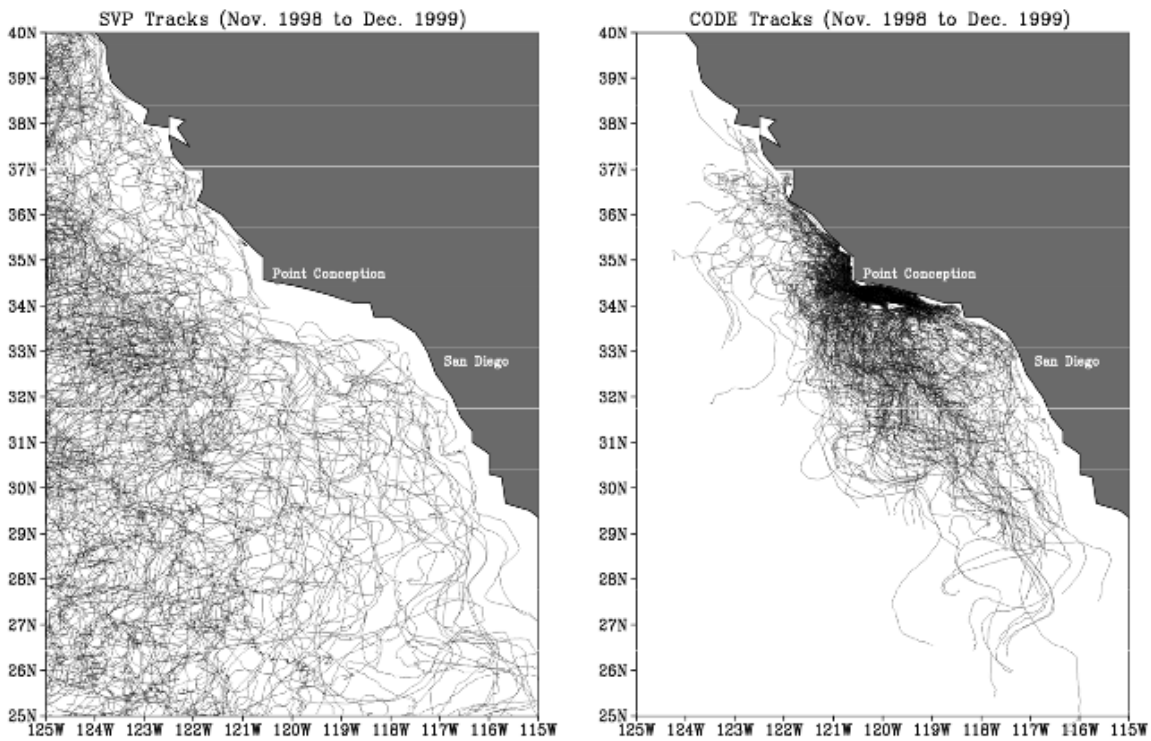


Figure D-1: *CALCOFI region SVP drifter tracks (left panel) and CODE drifter tracks (right panel).*

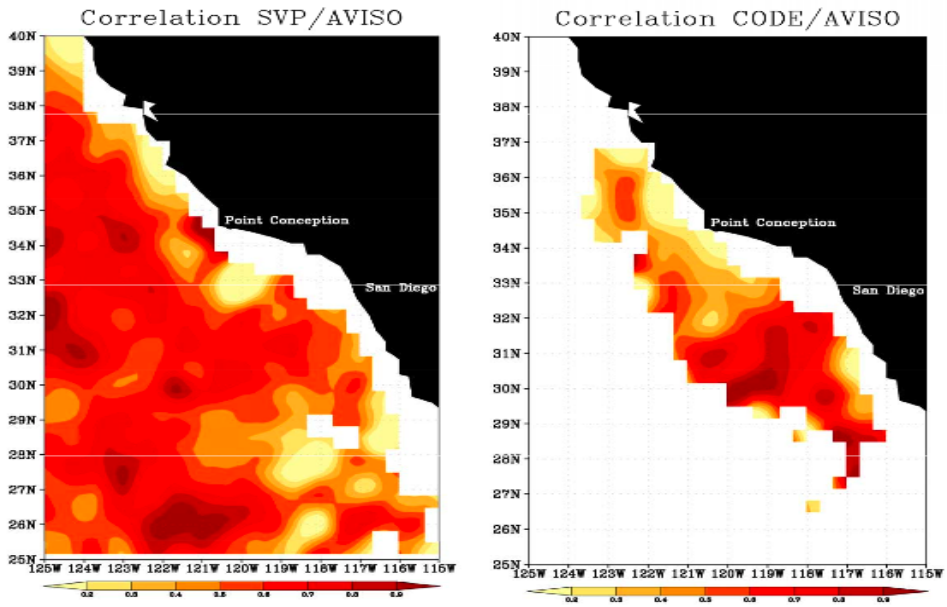


Figure D-2: *The sum of the vector component correlations between SVP drifter (left panel) and CODE drifter (right panel) with the AVISO derived geostrophic time variable currents. Both data sets show significant relationship to the satellite altimeter derived surface geostrophic currents.*

b) Construction and testing of bottom release system for drifters

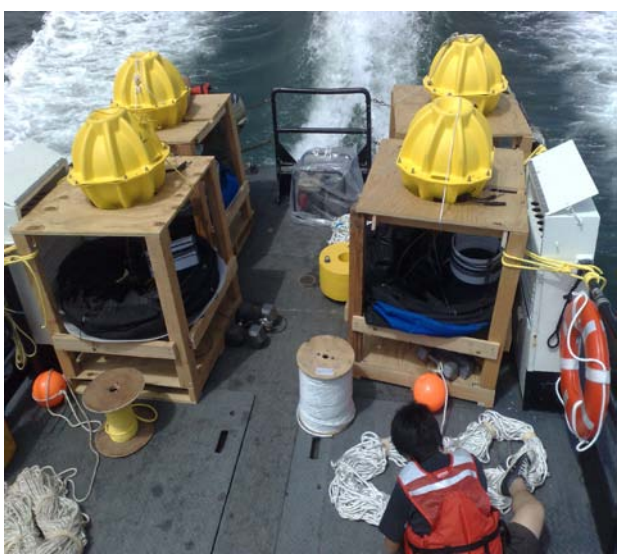


Figure D-3: *Bottom-moored drifters ready for deployment*

The photograph in figure D-3 shows four bottom-moored drifters that are on the fantail of the ship that deployed these in 100m-water depth off Point Loma, San Diego in July 2009. The wooden frames shown on this photo will be replaced with soluble cardboard boxes in operational deployments. This first test at sea was set to release 24 hours after deployment. One drifter worked perfectly, one drifter became entangled in the recovery cord (the white cord with the small orange float), one drifter did not burn the wire completely because the burn section was too long and one drifter became flooded. All four of these drifters are being refurbished for the second test in January 2010 at 100m-depth. The objective is to obtain a perfect release score for 4 drifters and then to progress to deploy 8 drifters along CALCOFI Line #90 in March 2010

c) Deployment of drifters in the CALCOFI observing region:

The first deployment of 14 SVP drifters from the July'09 CALCOFI cruise as resulted in the three month long tracks displayed on Figure D-4. The second release of 14 drifters SVP drifters is going on during 10-12 November '09. Dr. Carter Ohlmann at the University of California at Santa Barbara supervises this activity.

Note that pairs of drifters are released on all seven stations. We anticipate that upon completion of the first year (four CALCOFI surveys), within the next 12-month period, the analysis of the two particle statistics on the drifter pairs can begin. The calculations will include such as the mean square relative velocity, will bear on the QG vs SQG turbulence problems presently being debated in the literature by quantifying eddy energy over spatial scales ranging from 10's of meters to 100's of kilometers

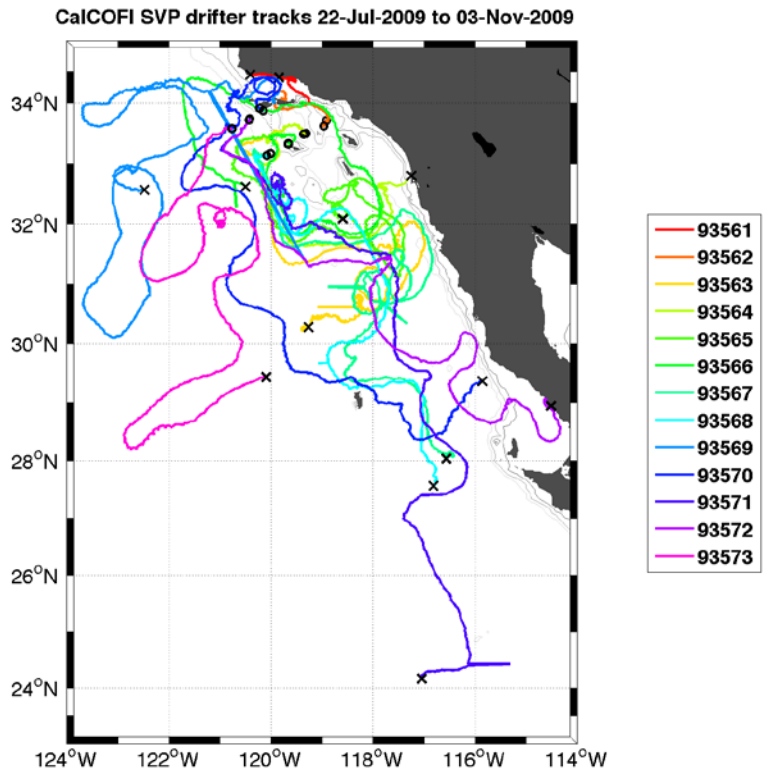


Figure D-4: *Tracks of drifters released during the July '09 CALCOFI survey in the CCS.*

3.5. **Task E: Modelling and assimilation of CORC data in the California Current** *(B. Cornuelle)*

The final paper on the state estimation in the tropical Pacific from the previous CORC project was accepted by JGR-Oceans. JGR. The tropical pacific domain includes the western boundary regions of interest to the current project, and so some work continues on analysis of the results.

The MITgcm/ECCO system has been significantly changed twice since we began the CCS assimilation, and we have upgraded twice and are now using the newest version of the model and the ECCO assimilation package. This version is run by Matthew Mazloff and the set-up is nearly identical to his successful 1/6 degree Southern Ocean State Estimate (SOSE). We have added new features to the code by enforcing smoothness of the controls, using a modal decomposition on the boundaries to deal with the strong sensitivity of barotropic normal velocities, and have altered the output routines to optimize use of local computers.

The current resolution of the CCS model is 1/16 degree and 72 levels, a large improvement in resolution over the previous versions, and extends from 27.2N to 40N and from 230 E to the coast. The first-guess (reference) run used initial and boundary conditions from a global 1 degree state estimate called: OCean Comprehensible Atlas (OCCA) from MIT-ECCO (with thanks to Gael Forget, Patrick Heimbach, and Carl Wunsch) that extends through 2007.

The forcing for the reference run comes from the NCEP reanalysis, not the optimized forcing from the OCCA estimate. If we had used the optimized forcing, the reference run would have been a downscaling of the OCCA estimate for our region, but the forcing optimized for a 1 degree model would not necessarily improve the state of a 1/16 degree model. The observations have been compared with the reference model run (before the fit to observations), and the differences are a few times the expected error bars. This is a reasonable starting point, from which significant improvement in the fit to observations is expected.

We continue to evaluate wind products for the California region, including the NCEP reanalysis, NCEP operational NAM, Navy COAMPS, and UCLA/JPL WRF. None of these products is perfect, and differences in time coverage make it difficult to compare long model runs with different forcing products.

The system is producing iteratively improved state estimates for 2007 while the procedures and software are being refined, but will soon be extended to 2009 to incorporate the observations from the CORC moorings being recovered soon. The state estimate at present uses in-situ observations from CalCOFI, Argo, and Spray gliders, and satellite SSH and SST.

To extend the state estimate into 2008 and 2009 as planned we may need to use different boundary conditions if an updated MIT ECCO solution is not available. To address this we expect to use HYCOM or just to repeat the older boundary conditions, since they will be altered by the state estimation. We have experimented with boundary conditions from assimilated HYCOM in other regions, and have had some success with model runs, so it seems to be a viable option.

One of the challenges of the CCS state estimation is the eddy-resolving model, which permits the growth of small-scale structures taking energy from the larger scales through barotropic and

baroclinic instability. This can result in strong sensitivities to control parameters combined with strong nonlinearities which invalidate the tangent linear approximation used in the adjoint procedure. Increasing the horizontal mixing coefficients can reduce the rate of growth, but too much mixing can distort the larger scales of the solution. The intent is to find the minimum viscosity (diffusivity is not altered) necessary to stabilize the adjoint at every stage and gradually reduce the mixing as the solution improves and the range of linearity needed decreases.Beyond the assimilation, many forward runs have been made with varied viscosities to examine sensitivity to mixing parameterizations. Through the course of 35 iterations, the horizontal viscosity has been decreased a number of times, but the optimal settings have yet to be determined.

The result of the assimilation provides a dynamically-consistent synthesis of the disparate observations. Dynamical consistency means that the state estimate produces an adjusted set of controls: initial conditions, boundary conditions, and forcing that can be used with any model (or model resolution) to perform an integration that should also be consistent (within expected uncertainty) with the observations.

Working with Robert Todd and Dan Rudnick, we have concentrated on the comparison of the optimized model states to the glider observations along several lines. The comparisons are best at large space and time scales, but there are some promising agreements as well as significant differences.

Figure E-1 shows the model domain and the three repeated glider lines. The analysis has been carried out on the two southern lines (CalCOFI lines 80 and 90). Figure E-2 A and B show the 2007 mean flow for the two sections for the observations and model, respectively. The model velocities shown in all figures have been taken from a forward run using the controls set by 35 iterations, and with horizontal viscosity set to 10 m2/s. The main features visible in both panels are the southward-flowing California Current offshore and near the surface inshore, over the northward-flowing undercurrent, which is strongest near the shore and shows several distinct cores in the line 90 section. The model velocities are much smoother than the data, but show similar character. The velocities measured by the glider were not used in the state estimation, although the T and S profiles measured by the gliders were.

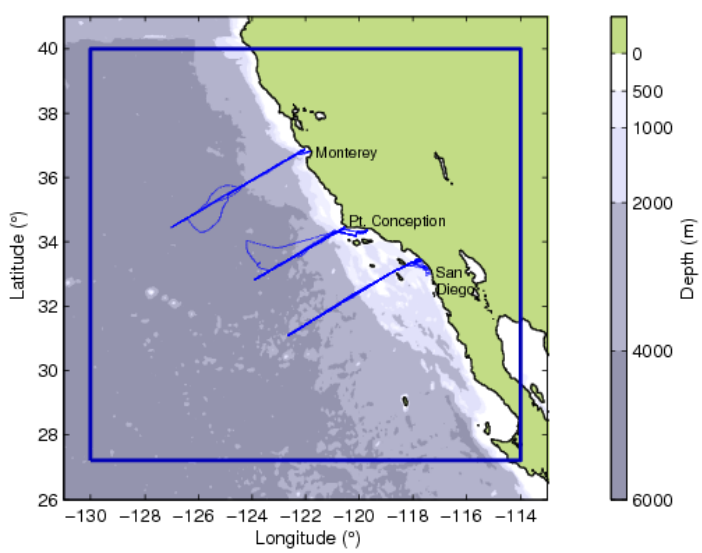


Figure E-1: *Model domain and the positions of observations along the three repeated glider lines (from north to south: CalCOFI lines 66, 80, and 90).*

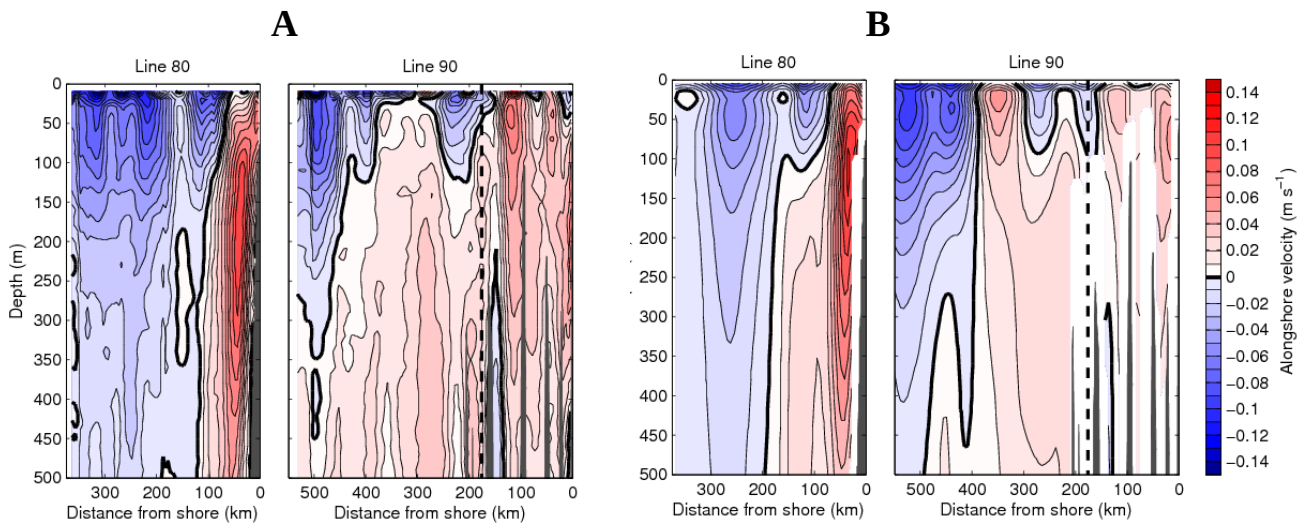


Figure E-2: *Sections of time-mean flow for 2007 for glider observations (A) and model (B) along CalCOFI lines 80 and 90 vs distance offshore and depth.*

Figure E-3 shows depth-averaged alongshore velocity for the two lines as a function of distance from shore and time. The averaging is the bottom, or 500m, whichever is shallower. The glider tracks are superposed on the figure in gray to show the sampling. A roughly seasonal cycle is visible on both lines, with westward propagation of current pulses visible. These are associated with the seasonal upwelling, and are stronger for line 90 than for line 80. Because the model run only covers 2007 at the moment, the same observations are repeated in Figure E-4 A for comparison with the model depth-averaged velocity in Figure E-4 B. The model velocities are again smoother, but do show the upwelling signal with similar phasing to observations, and the offshore propagation. It is interesting to see that the depth-averaged velocities are northward near the coast and in the Southern California Bight for most of the time.

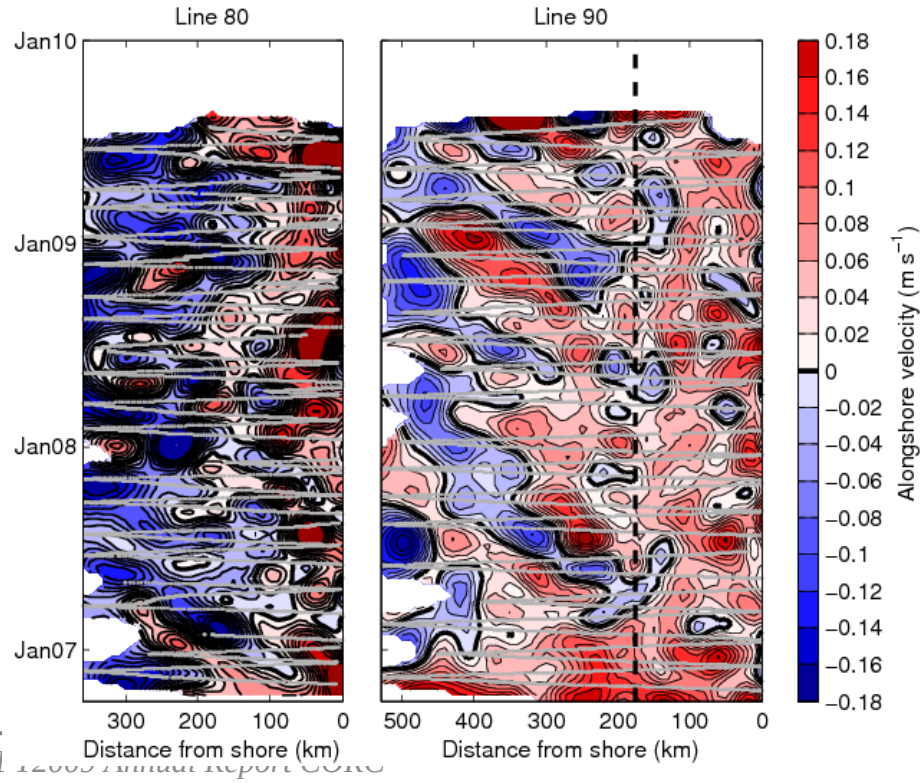


Figure E-3: *Depth-averaged observed alongshore velocity for the two lines as a function of distance from shore and time. The averaging is the bottom, or 500m, whichever is shallower. The glider tracks are superposed on the figure in gray to show the sampling.*

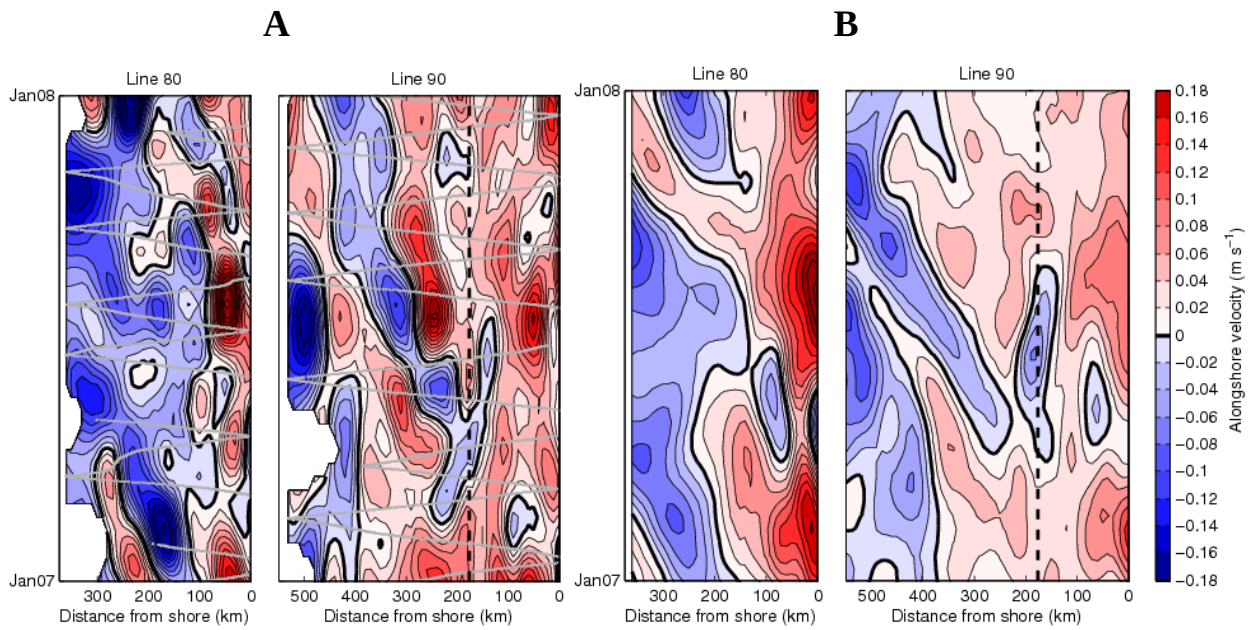


Figure E-4: *Panel A is the same as figure 3, but restricted to 2007. Panel B is the model depth-averaged velocity.*

The model analysis will be used to explore the physics and forcing governing the current and undercurrent behavior, through examination of dynamical balances, water-mass tracking, and adjoint sensitivity runs to examine the forces determining the alongshore flow and the offshore-onshore overturning circulation associated with the upwelling. The state estimates are also useful for observing system simulation experiments (OSSE) to evaluate the observation strategies used in CORC and the validity of dynamical assumptions, such as geostrophy for transport estimates.

Tests of robustness will include re-running the forced forward run at higher resolution and applying the adjusted forcing to another model (e.g. ROMS in the case of MITgcm assimilation).

As a prelude and complement to the dynamical-model-based assimilation, statistical analysis of the CalCOFI time series has been carried out in order to elucidate links between the observations and climate indices such as SOI, NPO, PDO, and CCS upwelling indices. The statistics are made for all CalCOFI variables, including Chl-a and nutrients. The historical variability of T and S are used to inform the error bars used for fitting the profile data. Work is underway to complete the climatology, including objective interpolation to make smooth maps of larger-scale components such as mean and annual cycle amplitudes and phases.

4. Education and Outreach

The CORC project has high visibility on the Ocean Timeseries Group website at SIO (http://mooring.ucsd.edu). The CORC approach and results are featured prominently in each year's introductory oceanography class at SIO (over 50 graduate students from all disciplines) and in each year's specialized class on observational techniques in oceanography, and always attracts a lot of interest/attention from the students. Young graduate students (sometimes even new incoming ones) have participated in CORC cruises, as both an inspirational and educational experience, and thus obtain intense insights into both the drivers and the approaches and techniques for sustained global ocean observations. Students working on CORC related topics are also invited and encouraged to attend meetings, conferences, the NOAA Annual System Reviews, and participate actively where possible. In addition, one post-doctoral scholar at SIO is making critical contributions to the CORC effort, and at the same time is being prepared to continue the mission of global ocean climate observations amoung the next generation of ocean researchers.

5. Publications and Reports

5.1. Publications by Principal Investigators

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