Integrated Boundary Current Observations in the Global Climate System

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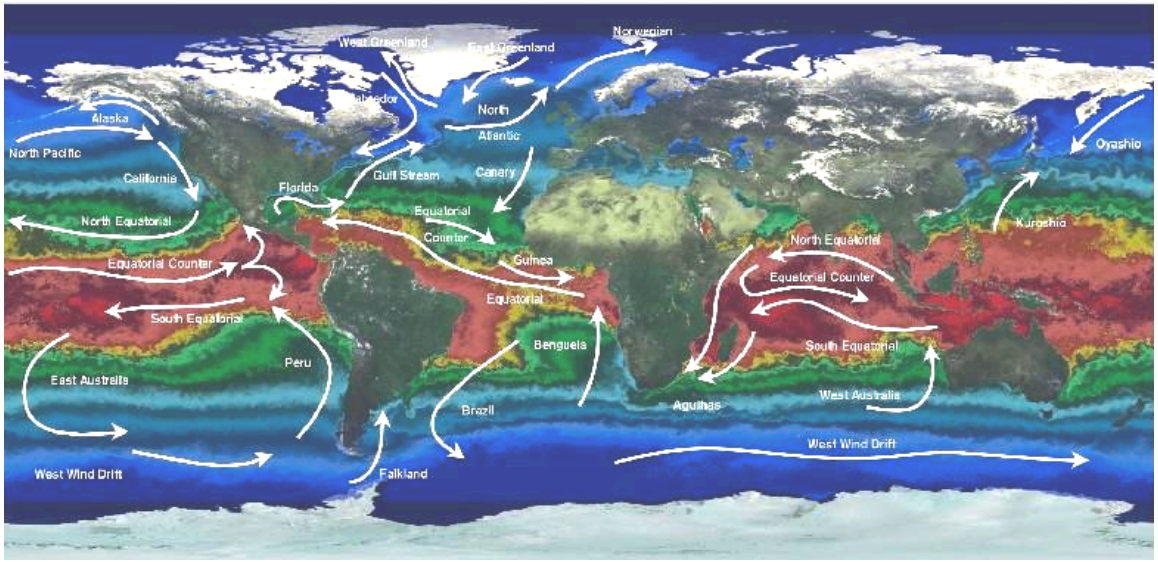
1. Project Summary



The current national and international ocean observing system for climate consists of several components, none of which are designed for capturing intense, concentrated, or deep circulation systems. Therefore, additional approaches and infrastructure are needed for observing western and eastern boundary currents, throughflows/overflows, and deep circulation regimes.

The goal of the current CORC project is to develop, demonstrate, and implement a system that can fully monitor the intensity (mass and heat transports) of most boundary currents in a sustained and routine mode, delivering indicators about the state of those regimes in near-realtime. To this end we will merge several technologies and techniques that have been used by the P.I.'s in the past, and that were partly developed in prior CORC phases. These include:

- *end-point moorings* (with CTD sensors throughout the water column and bottom pressure sensors) at the ends of a section to determine the dynamic height difference, and thus geostrophic transports, as a time series.
- *underwater gliders* to estimate the heat transport through a section, by providing the horizontal (and vertical) distribution of heat content and its correlation with the flow.
- *inverted echosounders plus bottom pressure (PIES)* distributed along the section to be monitored. These will yield 2 vertical integrals (e.g. dynamic height and heat content) at each location, providing the depth (and time) coverage along the section that the gliders can not.
- *data telemetry* for the PIES and (subsurface) moorings using acoustic modems between these and the gliders. In very high (surface intensified) current regions, the gliders may need to remain submerged on one of the round-trip crossings each time. In this case, a navigation capability will be needed in the gliders to pass within close enough proximity of the PIES and moorings.

- *data assimilation* for determining heat and flow distributions, and thus the full mass and heat transports, that are consistent with all the data types collected, with satellite altimetry, with the forcing fields (wind) and with up/downstream and offshore information.

The pilot and testbed application is being carried out in the California Current which has large climate and socio-economic relevance and does not have a routine monitoring system. Operation along CalCOFI line 90 in southern California assures synergy with other programs, and coincides approximately with the high resolution XBT line PX31 which are contributing comparison data and connect sampling to the basin interior. In addition automated surface drifter releases will quantify the eddy variability and the Ekman flow in the boundary current region.

Later in the project, implemention of the system in the climatically highly relevant western boundary current of the low-latitude western Pacific is planned (which feeds the Equatorial Undercurrent through the Solomon Sea). This is already partially under way with regular glider deployments there.

2. PROGRESS REPORT

2.1. Glider Measurements in the South Pacific

Goal: There is a relatively direct oceanic connection between the subtropical South Pacific and the equatorial zone where air-sea interaction is strong. This connection is potentially important to coupled climate variability on interannual and, even more, on decadal time scales. The goal of this task is to exploit underwater gliders to gather preliminary observations and time series of this subtropical-equatorial connection.

Role in CORC: As the result of a sustained improvement effort within CORC over the last 5 years, the underwater glider Spray is relatively mature and economical to operate and achieves a relatively high success rate. Consequently, gliders are potentially a useful in CORC's overall objective to develop and exploit methods for monitoring climatically important characteristics of boundary currents. Consequently, South Pacific gliders are being used to: (a) test their stand-alone capabilities in boundary current monitoring, (b) to begin a time series of transport the climatically significant oceanic transport, and (c) to survey potential sites for eventually using the full CORC system to observe this current.

Progress:
There are two basic mechanisms by which conditions in the subtropical ocean might impact sea-surface temperature along the equator where air-sea coupling is strong and, consequently, might impact global atmospheric climate. 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,[1] air-sea interaction in the subtropics can change the temperature and/or salinity properties of subtropical surface waters. These anomalies then subduct in the shallow overturning cell and flow below the surface back to the equator where they upwell

[1] Gu, D., and S.G.H. Philander, 1997. Interdecadal climate fluctuations that depend on exchanges between the tropics and extratropics. *Science*, **275**, 805-807.

and produce anomalous air-sea fluxes. McPhadden and Zhang[2] have suggested that a more direct and faster mechanism may be variability of the transport of the subtropical cell that, by modulating advective supply of water to the equator, also affects the properties of water upwelled on the equator.

In the South Pacific, as depicted in Figure1, the South Equatorial Current (SEC) carries water into the Coral Sea and directly past New Guinea in the Solomon Sea. Some of the flow into the Coral Sea turns eastward south of New Guinea and then enters the Solomon Sea. Our initial studies, in cooperation with W. Kessler (PMEL) and the IRD laboratory in Noumea, New Caledonia, began with a pair of glider cruises across the SEC between New Caledonia and Guadalcanal, Solomon Islands, roughly along 160°E. Results reported by Gourdeau et al[3] include the zonation of the SEC into jets.

Although logistically more difficult, a more direct measure of the subtropical-equatorial connection is the flow from the SEC through the Solomon Sea toward the equator. The western boundary current (New Guinea Coastal Undercurrent, NGCUC) in the Solomon Sea links the SEC to the equatorial zone with an equatorward flow of water at densities near that of the equatorial undercurrent that upwells on the equator. In 2007 CORC began 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. Figure 2 shows the glider cruises completed in 2007 and 2008.

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[2] McPhadden, M.J., and D. Zhang, 2002. Slowdown of the meridional overturning circulation in the upper Pacific Ocean. *Nature*, **415**, 603-608.

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

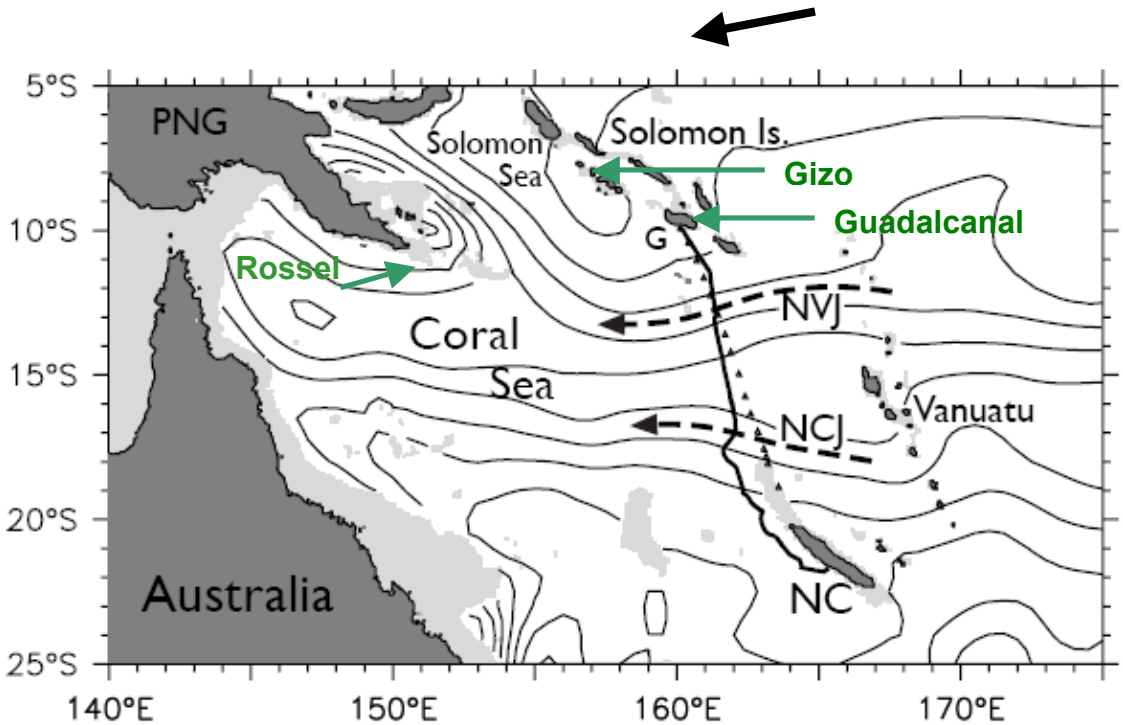


Figure 1. Flow from subtropical South Pacific toward the equator. NCJ and NVJ denote jets in the SEC. Solid line from New Caledonia (NC) and Guadalcanal is track of Spray glider. Green labels are termini of ongoing glider sections in the Solomon Sea.

Figure 2 shows 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-July 2008 cruise during a La Niña. 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 from 2007-08 are plotted in Figure 3. Transport is the double integral with depth and distance along the measured section of the velocity normal to the section toward the equator.

The x integral begins at Rossel Island (the easternmost of the New Guinea archipelago) and ends at the Solomon Islands. Transits in both directions are included. Transport is computed from measured depth-average velocity typically spanning the upper 600 m. Interpretation of Figure 3 requires care because the sections are far from straight (currents are frequently too strong to maintain a track) so the distances to the same point along two sections are quite different.

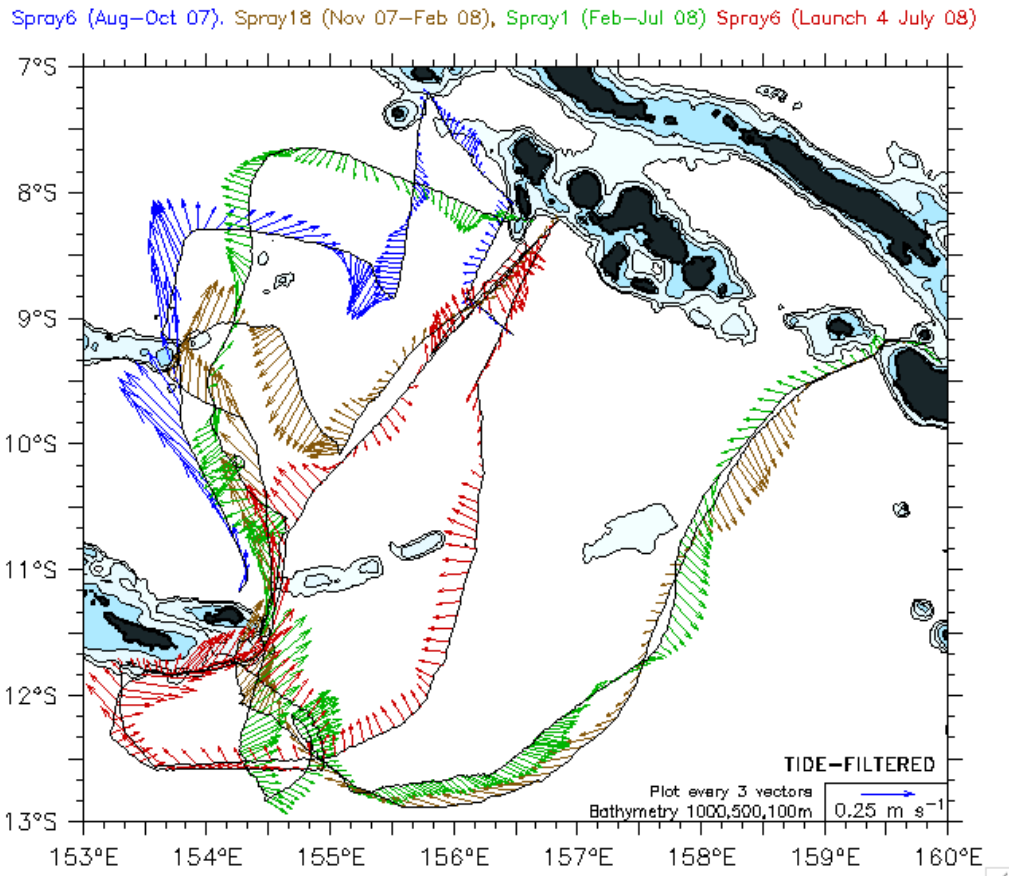


Figure 2. The four Solomon Sea glider cruises completed in 2007 and 2008 (figure by W. Kessler, PMEL). The first cruise (blue) was deployed at Rossel Island and effectively ended at Gizo. Cruises 2 and 3 are from Gualdalcanal to Rossel to Gizo. Cruise 4 (and cruise 5 not shown) were Gizo-Rossel-Gizo. Arrows show the depth-averaged velocity between the surface and 600 m depth. Currents on cruise 3 (green) during La Nina had anomalously low equatorward transport. The top legend gives each cruise's time period.

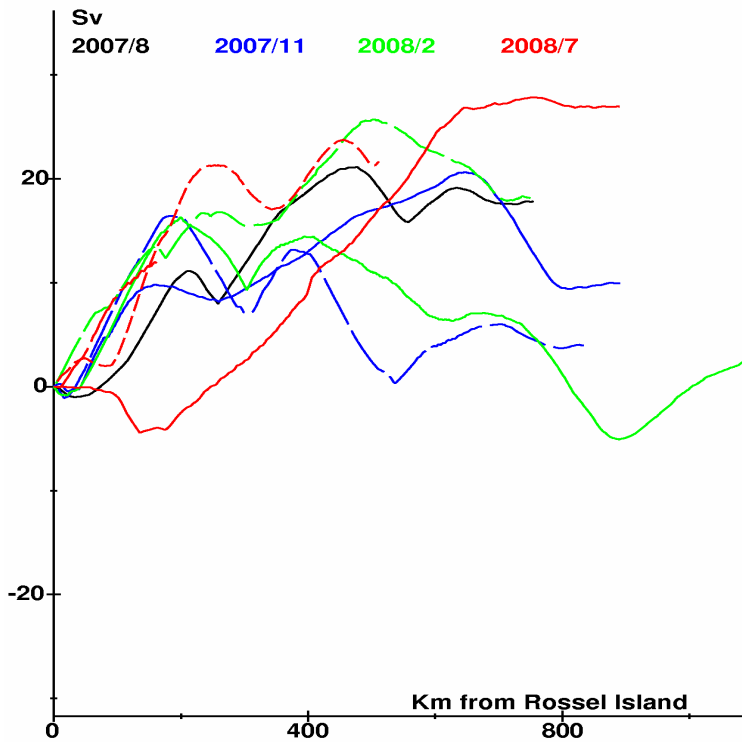


Figure 3. Volume transport Q(X) (in Sverdrups) integrated from the Rossel Island on the western boundary. Transport is based on measured depth-average velocity to ~600 m. The value for the largest distance plotted is the net equatorward transport above 600 m. Colors refer to cruises begun on the year/month given at the figure top. The dashed blue and solid green curves are from June-July 2008 during La Nina conditions. The largest transport variations appear to be in the ocean interior rather than the western boundary current.

The results in Figure 3 show that the transport associated with the strong western boundary current (NGCUC) is reasonably constant between the different sections but interior transport varies markedly. The largest change is between June-July 2008, when the net equatorward transport above 600 m essentially vanished, and August-September 2008, when there was strong northward transport (the figure misrepresents the distance of the flow from the western boundary because the glider was southwest of Rossel Island for the 150 km before reaching the western boundary). Because we have observed only one year and do not know the seasonal cycle of the Solomon Sea, it is dangerous to ascribe causes but the period of minimal transport was a period of La Nina conditions in the western tropical Pacific.

2.2. Glider Measurements in the California Current

Goal: The California Current System (CCS) was chosen as the operational site for developing our suite of techniques for monitoring boundary currents for because it is logistically convenient and because there is known to be significant climate variability of the CCS, which has at least strong statistical connections to the ecosystems and fisheries production. The goals of glider operations in the CCS are threefold: (a) provide a platform for acoustic transponders to report results from subsurface instrumentation, (b) provide continuous time series of offshore sections of velocity, temperature, salinity, chlorophyll fluorescence as a proxy for phytoplankton abundance, and acoustic backscatter as a proxy for zooplankton abundance along the section defining our testbed (CalCOFI Line 90), and (c) in order to explore alongshore coherence of fluctuations of the CCS, maintain a similar continuous time series on CalCOFI Line 67 off of Monterey CA.

Role in CORC: In addition to the intrinsic interest in the related variability of physical and biological conditions within the CCS, gliders are integral to CORC in three ways: (a) they carry acoustic transponders to report results from subsurface instruments (surface mooring are impossible in many strong boundary currents), (b) they provide spatially extensive reference observations to interpret the point observations from moorings along Line 90, and (c) they provide some alongshore sampling to understand which climate variations in the ocean are connected between Southern and Central California, supplementing the spatial information that comes from VOS sections, altimetry, surface drifters, and CalCOFI sampling, all of which will help constrain the CORC data assimilating model of the CCS.

Progress:
Figure 4 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 67 began in April 2007 and became continuous in April 2008.

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.

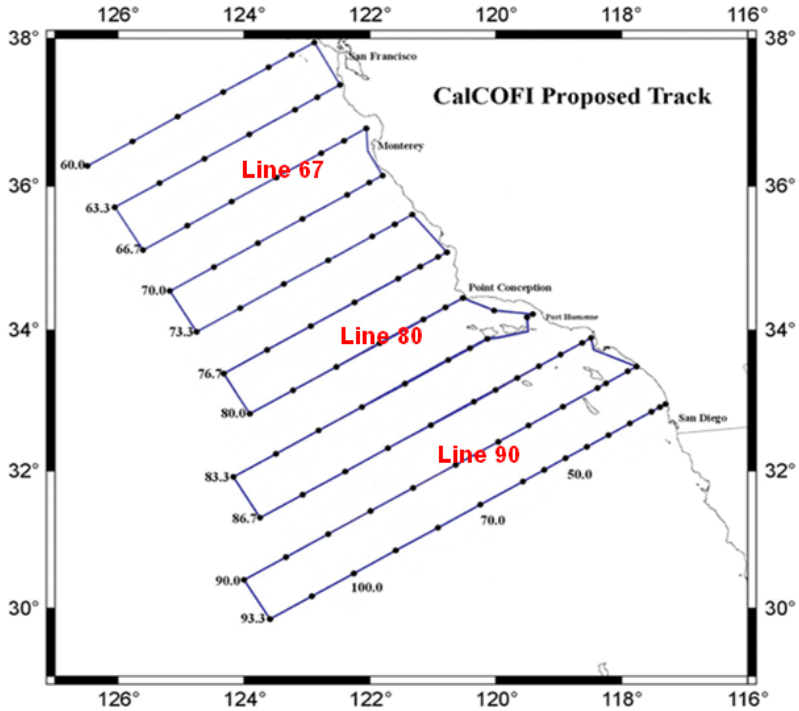


Figure 4. The full CalCOFI survey grid. CORC gliders continuously observe the length of Lines 67 and 90 while Line 80 is continuously observed under separate funding. Spray gliders sample T, S, absolute velocity, acoustic backscatter, and chlorophyll fluorescence.

A preliminary analysis of data on CalCOFI Lines 80, 90 and 93 appeared in *Limnology and Oceanography*[4]. 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 5 and 6.

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 6 is an offshore section of mean velocity computed from 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 5) are manifestations of largely subsurface undercurrents.

[4] 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.

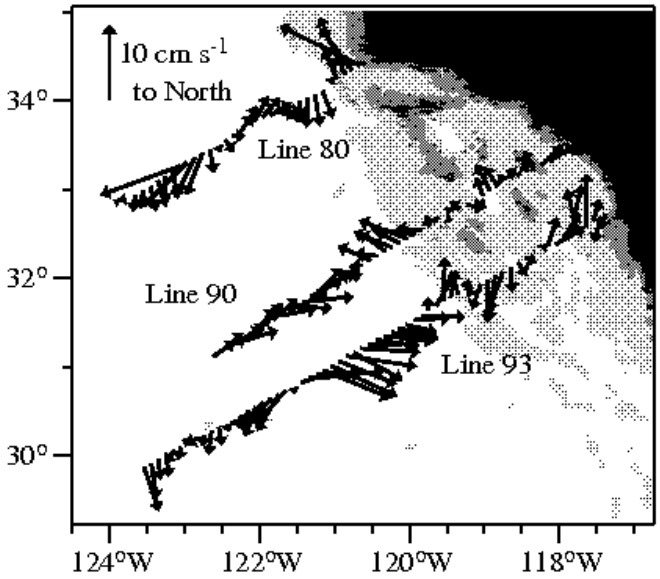


Figure 5. Annual average of the depth-average velocity from the surface to 500 m depth from about 3 years of glider data.

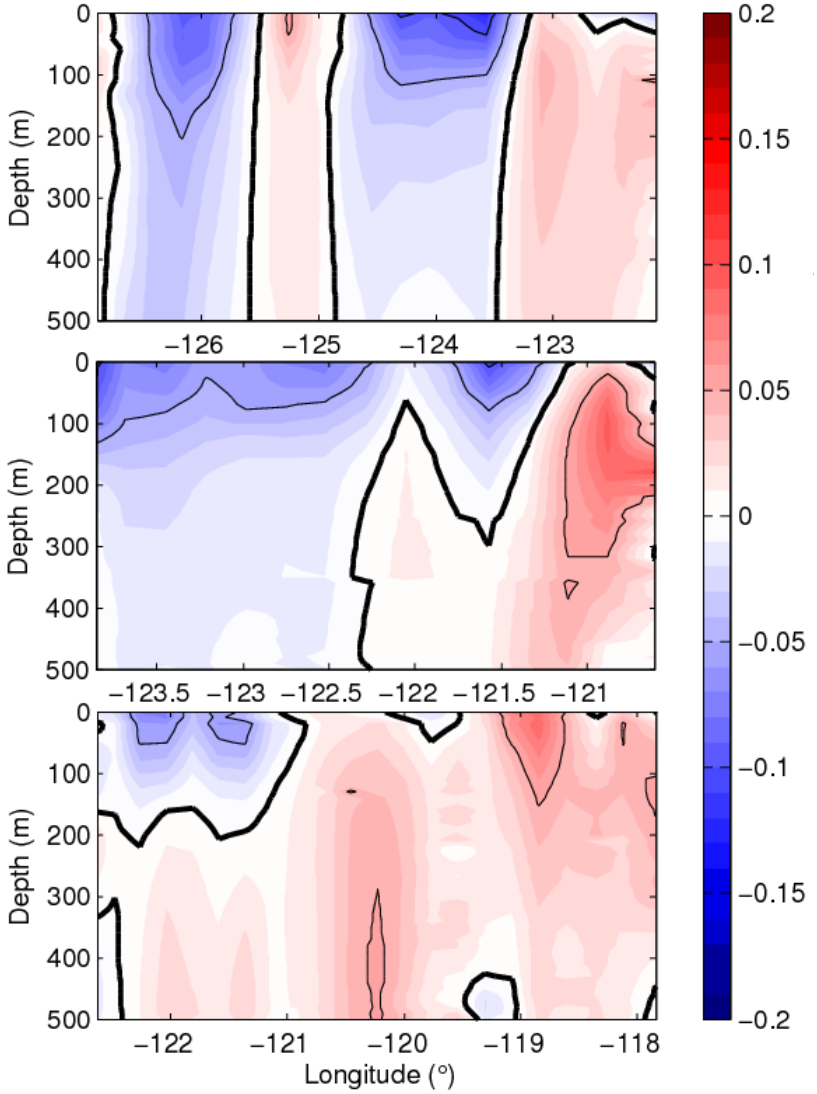


Figure 6. Sections along Lines 66 (top), 80 (middle) and 93 (bottom) of mean poleward flow (cm/s) based on geostrophic shear referenced by measured depth-averaged flow (in m/s). The California Current is the shallow fresh equatorward flow largely above 200 m that is apparently split into two branches. Near the continental slope, the depth-intensified poleward flow at all depths is the California Undercurrent of warm, salty water. Offshore there is a second poleward flow that had previously only been hinted at in hydrographic data. Neither poleward flow is clear in the geostrophic shear.

Figures 7 and 8 show the variability of the depth-averaged flow between glider transects, as well as the distribution of time-depth averaged flow and the cumulative transports, at each of the three locations.

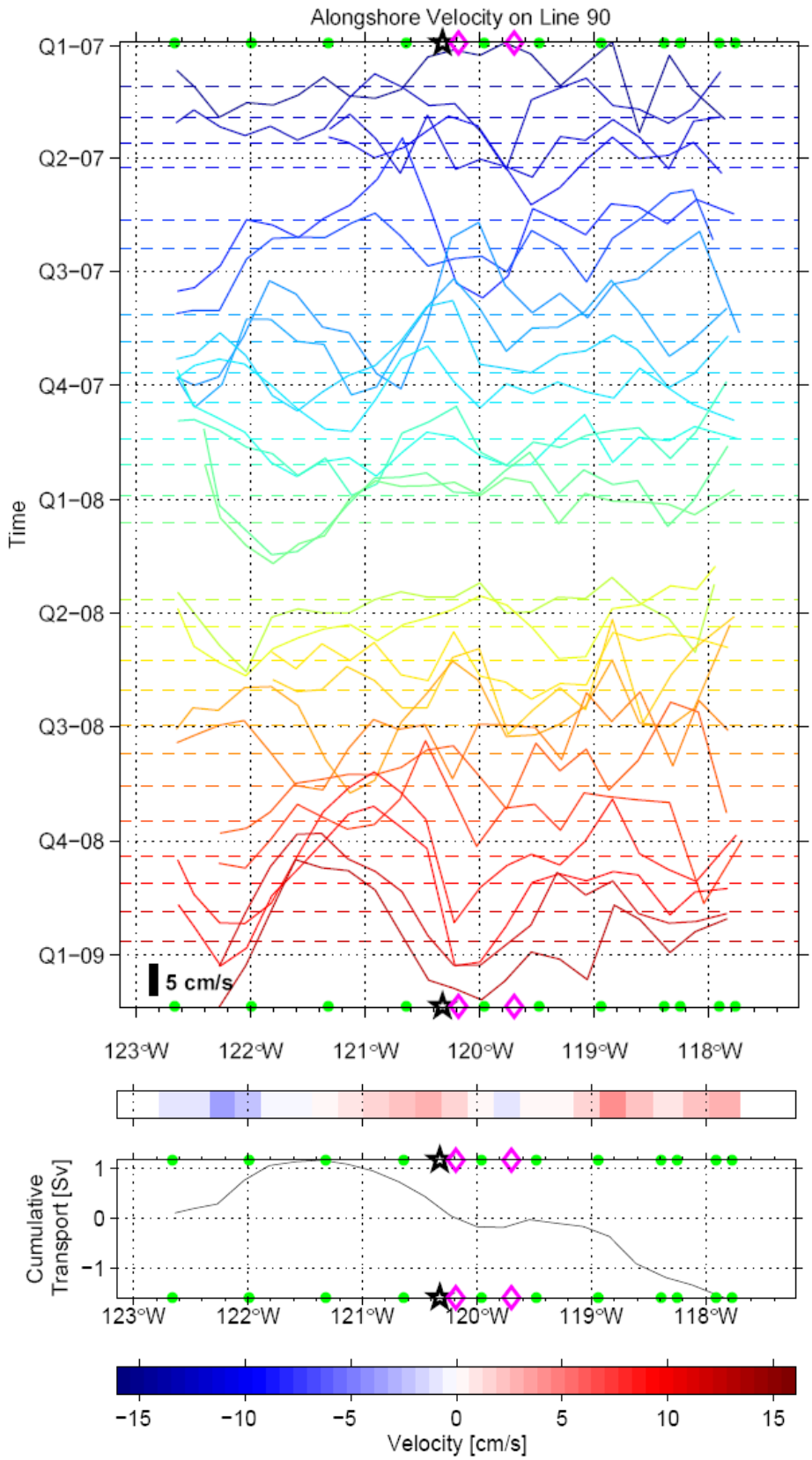


Figure 7. Top panel shows depth averaged flow along each glider transect on line 90. The pink diamonds mark the 1000m and 3000m isobath location, the black star is the inner CORC-1 mooring. The color strip in the middle gives the distribution of the time-mean depth-averaged flow across the section.The bottom panel is the cumulative transport set to zero at the 3000m isobath. All currents are taken over upper 500m.

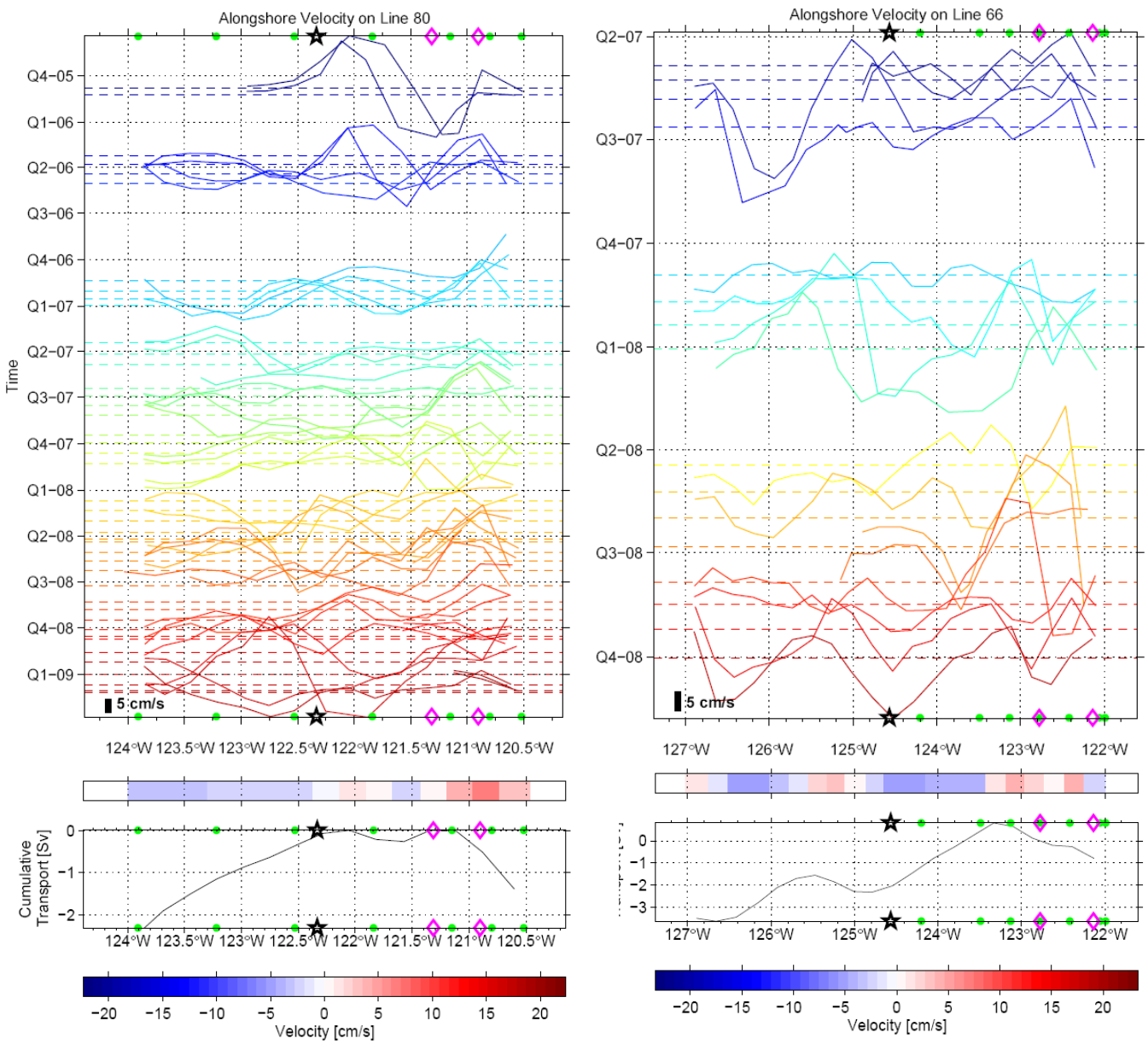


Figure 8. Same as Figure 7 but for CalCOFI line 80 (left) and line 66 (right).

The depth-averaged velocity sections in Figures 7 and 8 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 6. As expected, the main undercurrent cores are located against the continental slopes (3000m-1000m isobaths), but there are indications of more offshore flow cores. The cumulative transport shows 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.

2.3. Technological developments for acoustic data retrieval

Goal: High temporal resolution and deep water column coverage is being pursued with endpoint moorings and bottom-mounted PIES (pressure+inverted echsounders). For the PIES, an attractive data link to the surface is acoustic, and for moorings this is also the case for subsurface moorings (which are more economical and less prone to damage or vandalism). A communication capability between gliders and PIES and subsurface moorings is being developed via underwater acoustic modems.

Role in CORC: The goal of CORC is to deliver data from the integrated boundary current observing system in near-realtime, i.e. every 1-2 weeks, for direct analyses and for feeding data into the assimilation system. Therefore the gliders on the main CORC section are expected to ultimately be equipped with modems to telemeter (relay) the PIES and mooring data to shore during each transect.

Progress:
In year 1 of the project (summer'06-summer'07) the available modem options were researched and the Teledyne Benthos ATM-885 model was chosen, several of them were purchased, with and without pressure case (OEM version), for attachment to the PIES and to the moorings, and also for incorporation into a glider.

A hierarchy of modifications of the PIES instrument was designed and agreed on with the manufacturer (Univ. of Rhode Island, URI), for attaching and later incorporating the acoustic modems to/into the PIES. This requires diverting some of the internal data streams to an extra line/port going to the acoustic modem, which was also implemented with the manufacturer. The present configuration of the modified PIES with an external modem attached, is shown in the foto in Figure 9.

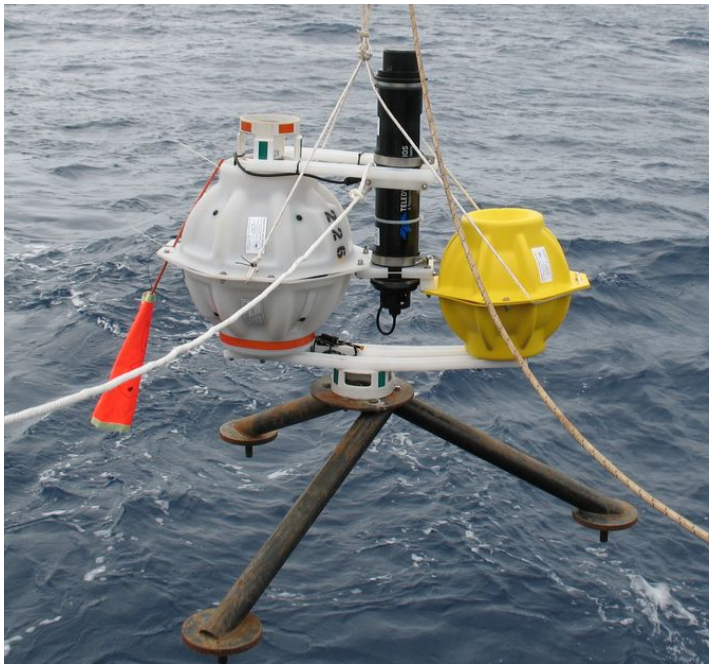


Figure 9. Assembly of the modified PIES (white sphere) with an external modem (black cylinder), mounted onto a stable bottom tripod (together with extra buoyancy, yellow sphere). Foto from them main CORC deployments in September'09.

At the same time, a new controller was designed and built for incorporation into the subsurface moorings. This controller was to collect data from all T/S sensors (microcats) along the entire mooring length via inductive telemetry through the mooring wire, and then pass the data to an external acoustic modem for telemetry to the gliders. The block diagram for this controller set-up is shown in Figure 10.

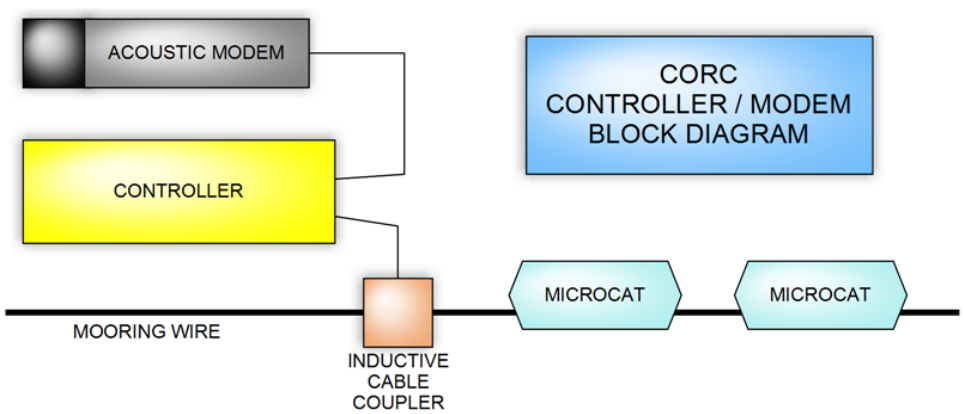


Figure 10. Schematic design of the mooring controller built in year 1.

At the same time, the OEM version of the acoustic modem was incorporated into the glider. The electronics boards were distributed over the available internal space, and the transducer incorporated into the tail section, looking downward, as shown in Figure 11. The glider software was modified to communicate with the modem, and telemeter the modem data back to shore. In addition a long suite of lab/bench/pool tests were carried out to make the different modems (glider, PIES, mooring controller) communicate with each other.

Figure 11. Transducer of acoustic modem incorporated into tail section of the Spray glider.

In year 2 (summer'07-summer'08), in-water field testing was initiated. First a test PIES with a modem assembly was deployed in 900m of water depth 13nm off San Diego, later a test mooring with a controller and two microcats was set next to the PIES. This then allowed a hierarchy of tests to be performed, for communicating with the PIES and mooring from small ships and with the new prototype modem glider. In this period, five opportunities were used to gather experience with the deployed modems.

At the beginning of year 3, in September'08, the first CORC array was deployed across the California Current (see the subsequent section 4), and for this 2 new mooring controllers were built and equipped with modems, and 5 new PIES had the modems added to them. The total of used modems in CORC thus increased to 10, plus several in the lab for development and testing. The glider deployments around the test sites off San Diego were not convincing enough at the beginning of year 3, thus further modifications and test deployments took place. Between fall'08 and the writing of this report, more software upgrades were performed, the test PIES was recovered and redeployed with a latest generation modem, and the modem transducer in the glider was moved to behind the tail fin to be freely exposed to the surrounding water, see Figure 12.

Figure 12. Reconfigured glider tail with modem transducer fully exposed.

After improvements were found with the new transducer position and internal software and the generation 4 modems, a second glider was completed and deployed with this configuration. Trials with this glider around the test PIES were highly successful. The improvement in data success rate at the test PIES off San Diego is shown in the history graph Figure 13.

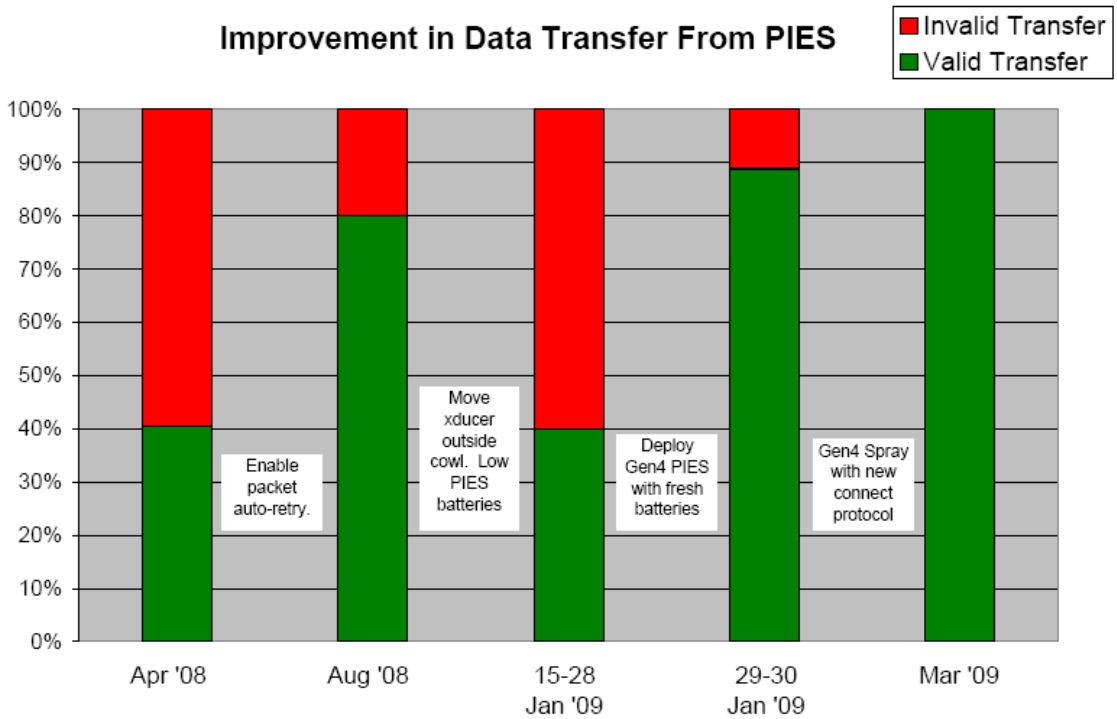


Figure 13. History of success rate at data transfer between Spray modem glider and the test PIES off San Diego in 900m of water depth. It shows the percentage of error-free data transfer once a connection has been established. Some transfers were as far as 5km distant.

At the time of writing both modem gliders are orbiting the moorings and PIES on the main CORC section on line 90 (see below), in water depth of approximately 4000m. For currently not understood reasons, the successful data transfer rate in those conditions is not very high. We are continuing to analyze and assess the diagnostics from those attempts. Some sparse results are presented in the following section.

2.4. Mooring and PIES measurements in boundary currents

Goal: Geostrophic end-point moorings and bottom-mounted PIES (pressure+inverted echsounders) are the only feasible in-situ techniques which can provide rapid enough sampling to avoid aliasing, and which cover the entire water column, in boundary current regimes. Both provide integrals (horizontal and vertical, respectively) and therefore need to be merged with more spatially resolving techniques. The goal is to develop the right technologies and demonstrate their value in boundary current settings.

Role in CORC: In CORC end-point moorings and PIES will be used in conjunction with gliders to fully describe and constrain the circulation and transports in boundary currents. The initial deployment is in the southern California Current, an eastern boundary current. Each setting requires different approaches, and a western boundary environment will be targeted later.

Progress:
In year 2, a test PIES and test mooring was deployed 13nm off San Diego in 900m of water depth, see Figure 14. They were used to gain experience with the modems and test the modem gliders.

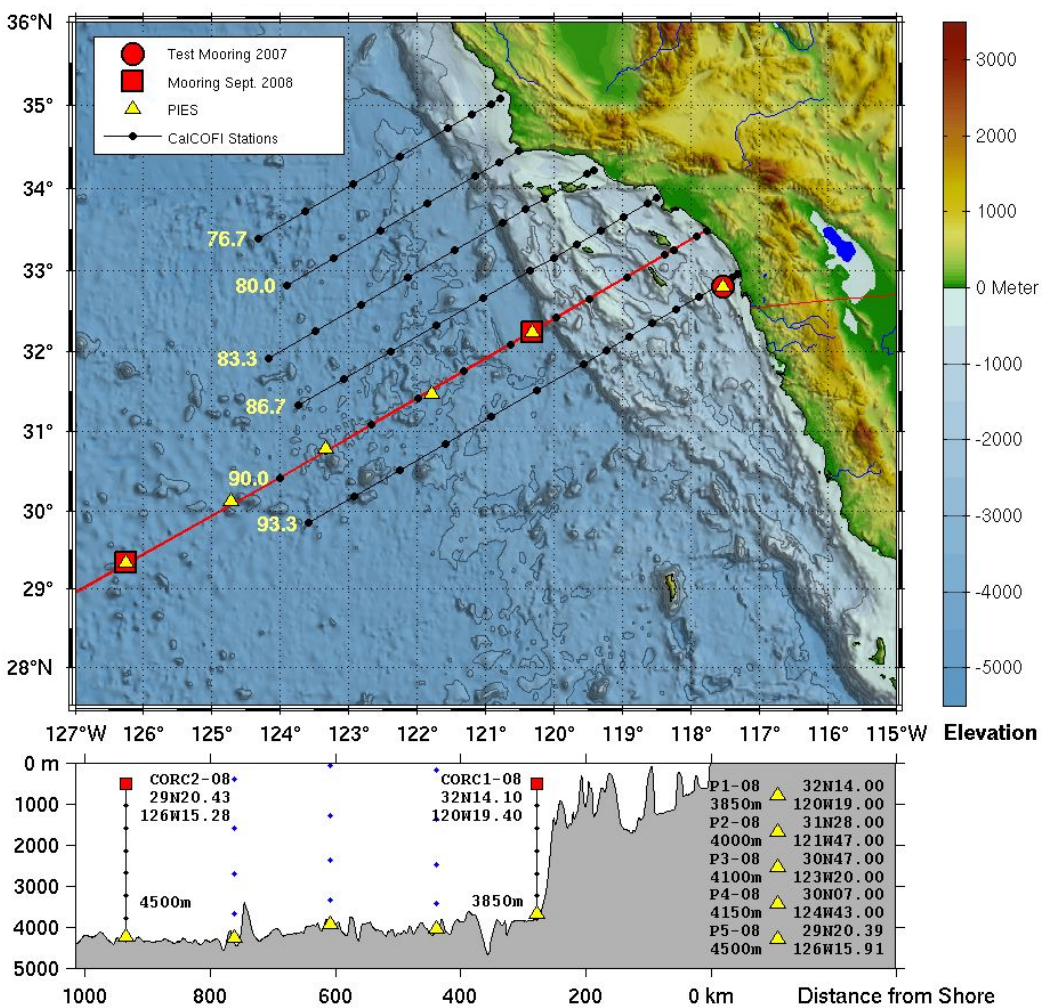


Figure 14. Locations of test mooring/PIES near San Diego on CalCOFI line 93 (red circle, 13nm from coast) and of the initial boundary current mooring/PIES section on line 90 (two red squares for the moorings and five PIES). The bathymetry along the mooring section is shown in the bottom panel.

Much of the spring and summer in year 2 (2008) was used to design and build the two endpoint moorings for deployment on line 90, to improve and build the mooring controllers, to modify, test, and prepare 5 PIES with acoustic modems, to carry out bench and lab tests for the entire communication path, and to prepare for the mooring deployment cruise.

The end-point mooring approach uses moored density measurements throughout the water column (here 15-20 discrete Seabird microcat sensors) to calculate dynamic height, relative to the seafloor or a pressure reference level. It was shown in the MOVE project that with extremely careful calibrations this can be done over the entire watercolumn with such accuracy that at CORC latitudes a mooring pair would determine transports to within 0.2Sv for a 1000m thick layer. Since the California Current is a baroclinic eastern boundary flow system with only moderate flows and largely confined to the upper 500-1000m, we expect the above 0.2Sv to be the approximate accuracy for this flow component (geostrophic transport referenced to a fixed level). The presence of deeper flow can be tested with shear estimates from the density data in the lower water column, and also from the bottom pressure gradients provided by the PIES (giving a measurement of the integrated flow near the bottom).

The original intent was to have mooring-based density measurements only from the seafloor to about 1000m, and to use the vertical integral from the PIES or profiles from the glider data for the upper 1000m. However, initially gliders will only pass by the moorings every few weeks, thus giving insufficient temporal resolution to complete the mooring measurements in the upper layer. Simulations for the skill of the PIES traveltime measurements were then carried out with ARGO data, and revealed that the correlation between acoustic traveltime (from the PIES) and dynamic height (needed for transport estimates) was very low due to high salinity variability in the region. Figure 15a shows scatter in 0-1000m dynamic height of +/-5dyn cm resulting mainly from salinity effects to which the acoustic traveltime measurement is not sensitive. This drove the mooring design to go as close to the sea surface as feasible, i.e. 50m or less. As Figure 15b shows, the scatter then is reduced to 1dyn cm. Over the 50m layer where that uncertainty applies, this results in a transport error of approx. 0.1Sv.

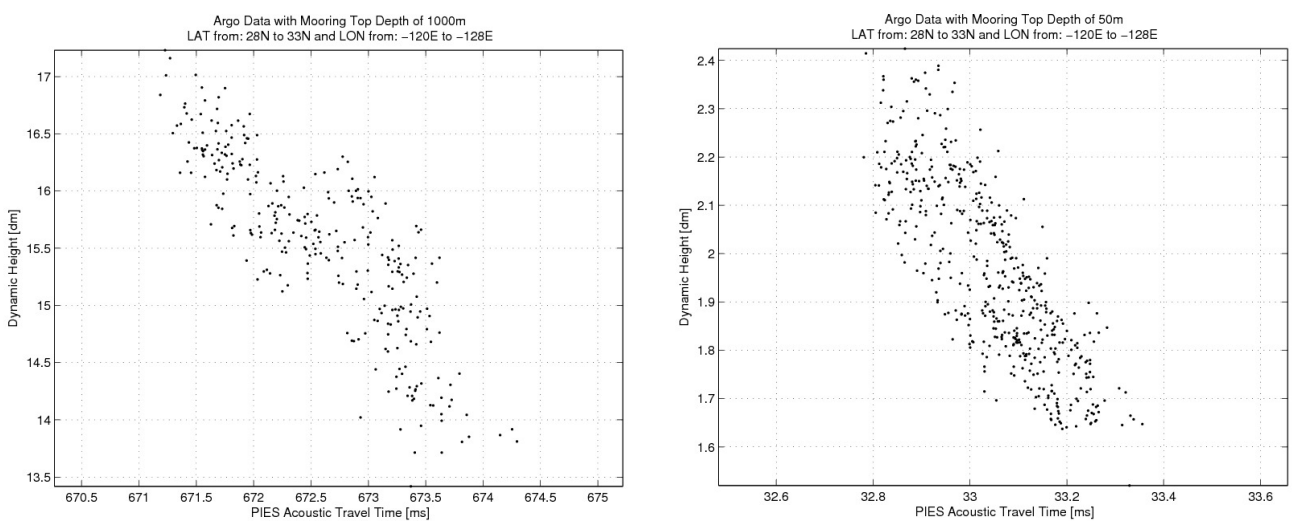


Figure 15. Simulation from ARGO float data of relation between dynamic height and PIES acoustic traveltime measurement, for (a) 0-1000m (left) and (b) 0-50m (right).

The resulting mooring design for the endpoint moorings is shown in Figure 16. They carry 14 and 15 microcats, respectively, reach to within 30m of the sea surface, and have the controller at 800 and 1800m depth to test the impact of controller depth on the glider communication. Both controllers communicate inductively with all microcats and pass the data to an attached acoustic modem.

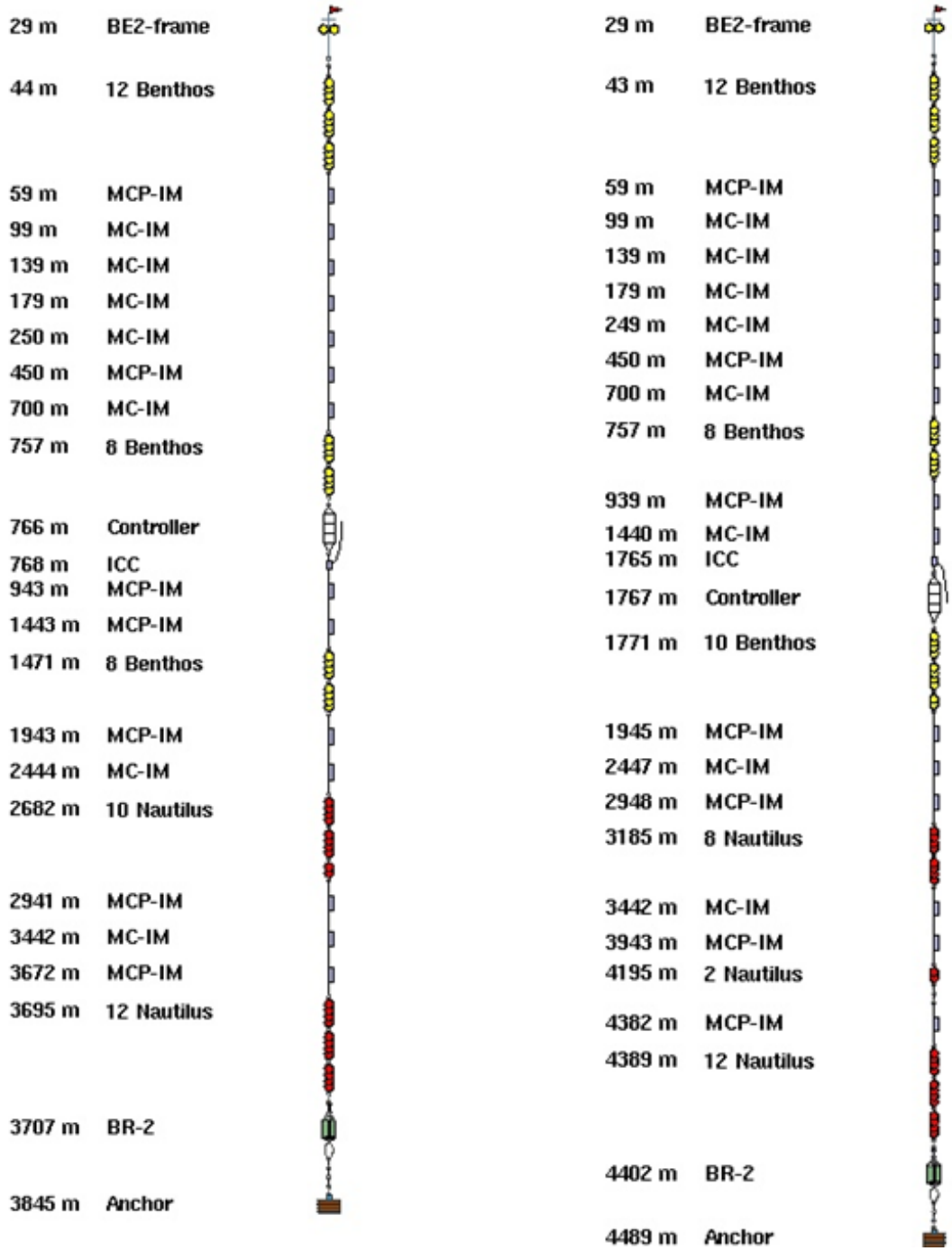


Figure 16. Design of the two endpoint moorings as now deployed on line 90 (see Figure 14). The left column shows the instruments depths, MC and MCP are microcat T/S sensors, Benthos and Nautilus are flotation, ICC is the inductive modem coupler, BR is the acoustic release.

A goal for the end-point mooring placement was to make the transport section longer than the CalCOFI line 90 since it was clear that the CalCOFI sampling misses much of the California Current. One constraint was shiptime, since extending the mooring/PIES section much beyond 1000km distance from shore would have required several more days of transit. The compromise geometry for the first demonstration deployment is shown in Figure 14, with a mooring separation of approximately 700km and a total distance from shore of close to 950km. That figure shows the CORC array as deployed in September 2008 including 5 PIES along the section. It required 6 days of shiptime from/to San Diego to install this. The adopted length makes sure that the core of the California Current is captured, but future implementations may need a longer section. The actual positioning of the moorings during the cruise was made very difficult due to extremely rough and irregular bathymetry, making placement of the anchor in a depth known to about 10m (necessary to reach the 30m below the surface with the top instrument) very challenging.

During deployment of the moorings, the inductive communication with the microcats already in the water (and being towed behind the ship) was continuously tested to verify functioning of the inductive loop and bypasses. After deployment, acoustic communication was established with the controller of one of the moorings, and one data cycle from the entire suite of microcats was successfully downloaded from the ship. The resulting profiles are shown in Figure 17.

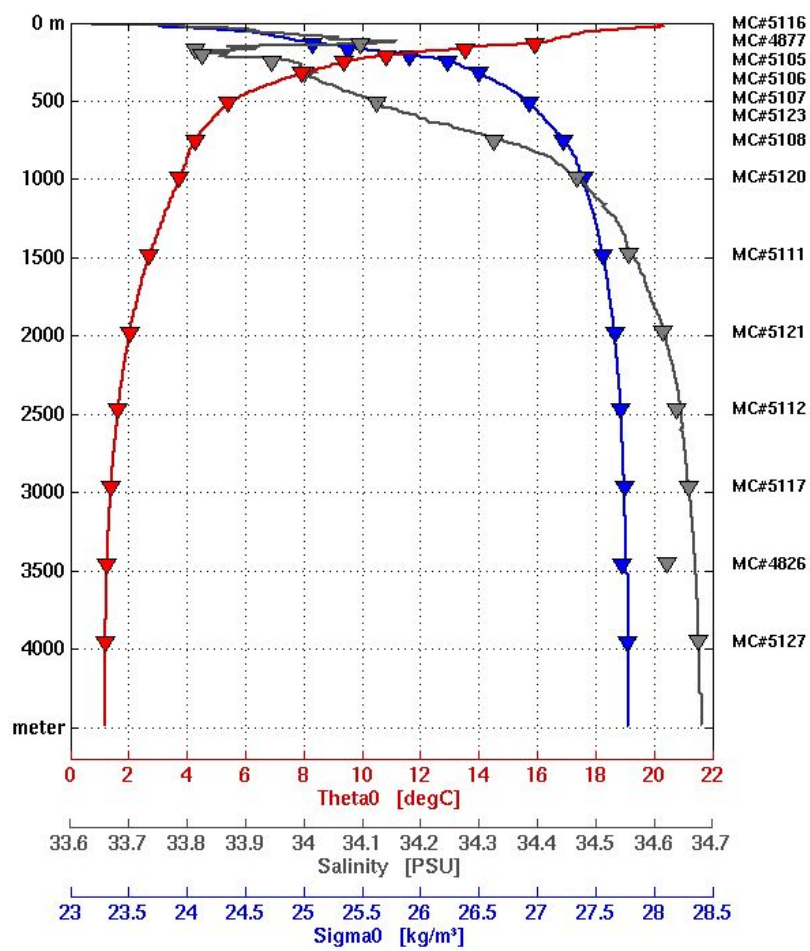


Figure 17. T, S, and density data recovered from the 14 mooring microcats (triangles) 30min after anchor dropof the offshore mooring, plotted together with a continuous profile from a comparison CTD cast nearby. The microcat data were collected by the mooring controller via inductive communication along the mooring wire and then passed to an attached acoustic modem. From there, the data were downloaded acoustically from the research vessel. The top instruments have not yet settled at their near-surface target depth.

At the time of writing, only very limited datasets from the now 6 months long mooring and PIES deployment are acoustically available. Some data from the inner mooring CORC-1 could be downloaded during a recent cruise, and a modem glider retrieved a partial dataset from the innermost PIES (P1). If one assumes that at the far offshore end no or small variability in dynamic height or bottom pressure exists, these data can be converted into velocities or transports, to give a feel for the expected variability (see Figures 18, 19). The figures show that the shear relative to 500 or 950db implies baroclinic transport changes of 2-3Sv (which may be eddies). The bottom pressure time series from the PIES suggests barotropic variability of order 3Sv per 500m layer.

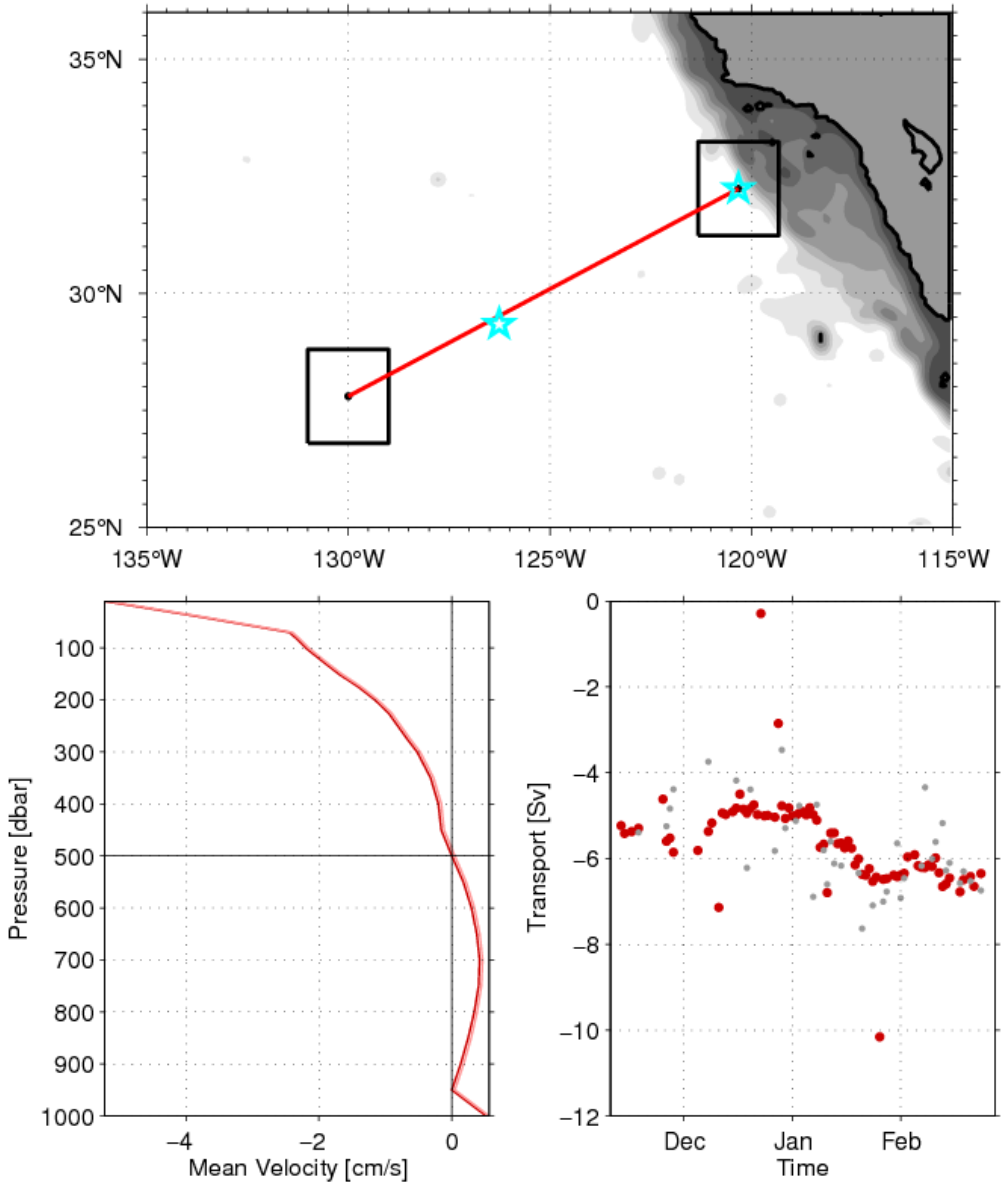


Figure 18. Geostrophic currents computed from a preliminary geometry with the eastern CORC-1 mooring and a constant climatology (SIO Argo Climatology, J. Gilson) at the western end. Transports across the red line are computed. Acoustically downloaded CORC-1 (eastern star) data are used to compute dynamic height there. Data from the outer mooring (western star) is unavailableat present, hence it is replaced by the climatology at a convenient location further offshore. Bottom left: mean velocities across the section,relative to 500db (dark) and relative to surface flow climatology (light). The curves are indistinguishable. Bottom right: transport time series over the top 500m layer, relative to 500db (red) and over the top 950m relative to 950db (grey). All data are raw and uncalibrated, hence the noisy appearance.

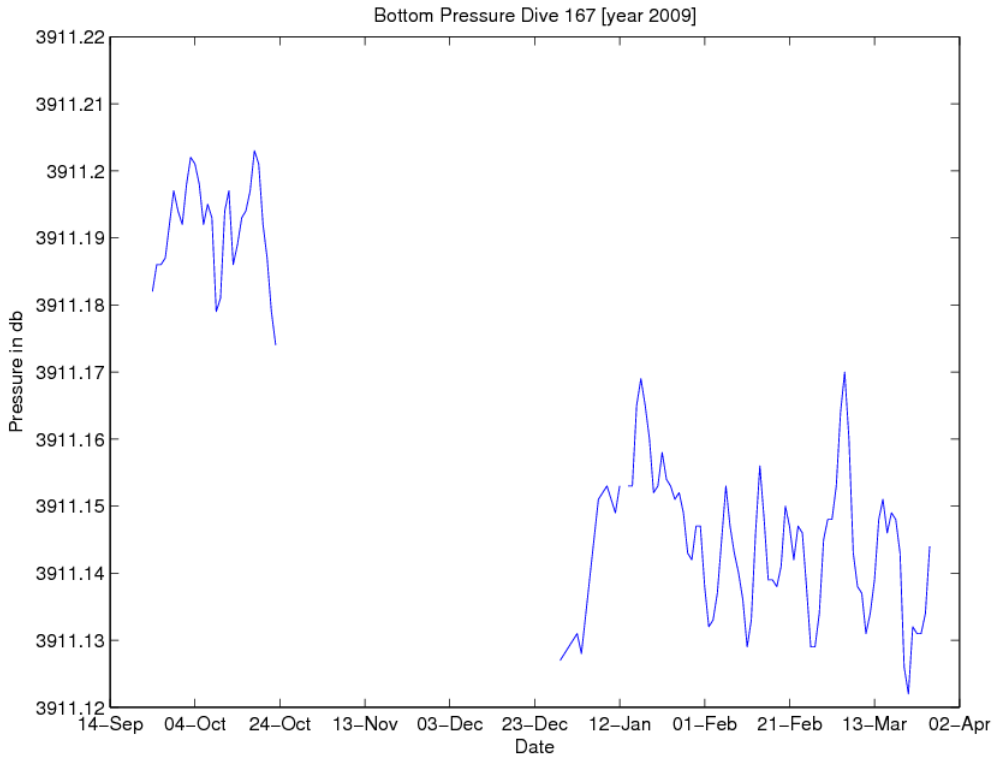


Figure 19. Bottom pressure from easternmost PIES, downloaded by modem glider. Daily averaged and detided data, showing a range of 4cm equivalent sea surface height over short periods, suggesting a fluctuating barotropic flow component (the large difference between the two data segments is likely to be slow drift of the pressure sensor).Each cm translates into 0.7Sv over a 500m thick later when taken as a difference with an unchanging offshore site. Thus this signal would add another 3Sv variability to the 0-500m transport changes shown in Figure 18.

2.5. XBT data in support of the California Current observing system

Goals: High-resolution XBT data have been collected for many years and provide an important data base for boundary current observations. The XBT lines across the California Current will be analyzed to provide complimentary information for CORC. Another goal was to evaluate a 2000m (LMP5-T1) XBT for ocean boundary current and ocean interior sampling.

Role in CORC: Analysis of HRX data from PX37 and PX37S (Figure 20), 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.Specifically the analyses will help 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. Comparison of transport and variability variability of the California Current off Southern California (Line PX37S) with that off Central California (Line PX37) can estimate the degree to which transport variability is correlated alongshore. This will help to assess how representative a single section like the CORC mooring/PIES/glider line is. Optimal merging of HRX lines with Argo data in the ocean interior will guide methods to combine the CORC boundary current observations at high spatial/time resolution with the large-scale interior observations.

Progress:

a) Analysis of PX37 and PX37S lines and interior ARGO data

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 (Figure 20). 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.

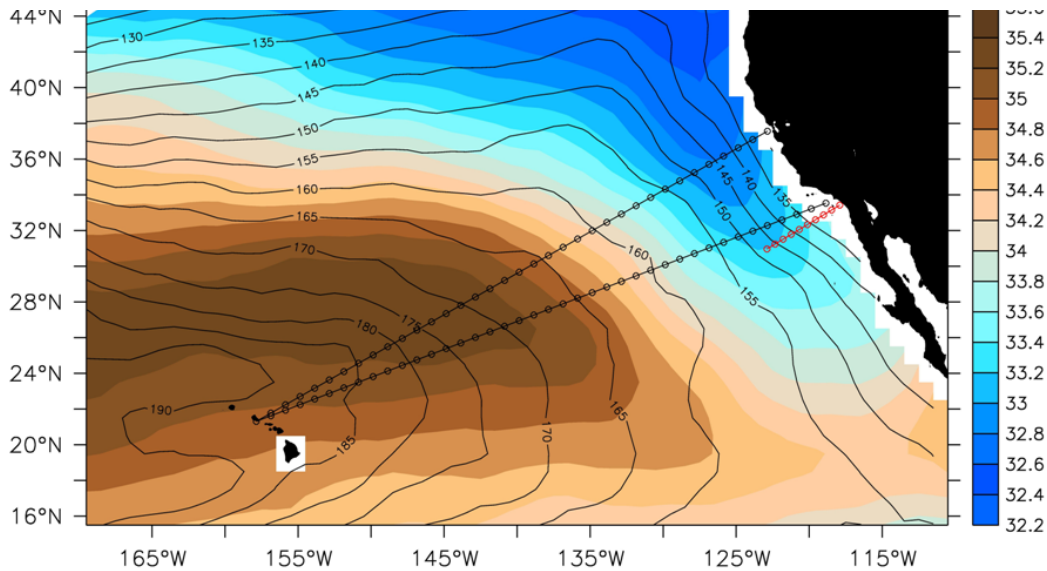


Figure 20. HRX Lines PX37 (Honolulu-San Francisco) and PX37S (Honolulu-Long Beach) are shown in relation to CalCOFI Line 90 (red), and to the mean sea surface salinity and mean dynamic height of the sea surface from Argo (0/2000 dbar).

Analysis is proceeding concurrently on the three datasets (Argo, HRX, CalCOFI). Analysis of Argo data (Figures 20 and 21a) indicates that using either the maximum horizontal gradient in surface layer salinity or the minimum in southward geostrophic velocity suggests the offshore end of the California Current is located at about 129-130°W. A significant fraction of the Current is beyond the end of CalCOFI Line 90.

The cumulative transport shown in the top panel of Figure 21 does not show a strong change in slope at the transition from the boundary current to the interior. This is due to the deep-reaching and wide-spread background flow (green colors) which causes much of the cumulative transport, to which the shallow and slightly enhanced boundary current flow adds little transport, at least in this analysis.

Geostrophic velocity on large spatial scales are similar in multi-cruise averages from HRX data (Figure 21b) and multi-year averages from Argo. But Argo does not sample close enough to shore to observe the poleward countercurrent, nor does it capture small spatial-scale features in the mean field. There also appears to be persistent northward flow around 130°W in the HRX data.

In support of CORC sampling has recently begun (November 2008, Figure 22) along HRX Line PX37S (previous sampling from Fiji to Long Beach, PX31, ended in mid-2007 when the ship changed its routing). Line PX37S includes XCTD profiles because of the importance of the salinity field as a tracer and in geostrophic velocity calculations.

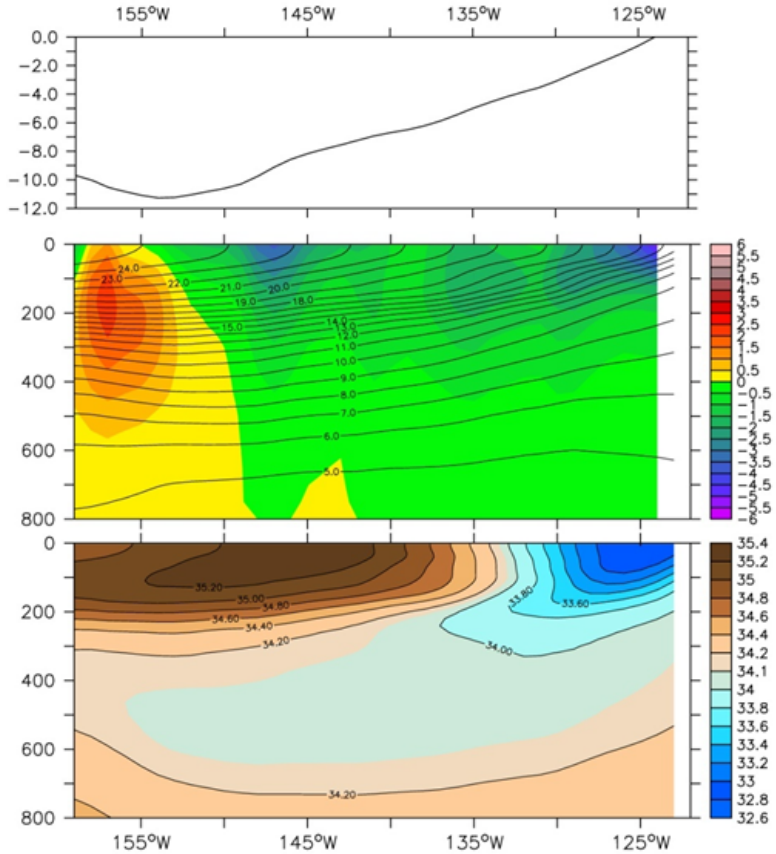


Figure 21a. 2004-2008 mean ARGO data along PX37 yielding cumulative geostrophic 0-800m transport in SV (top), geostrophic flow(cm/s) and temperature (middle), salinity (bottom). Geostrophic flow relative to 800db.

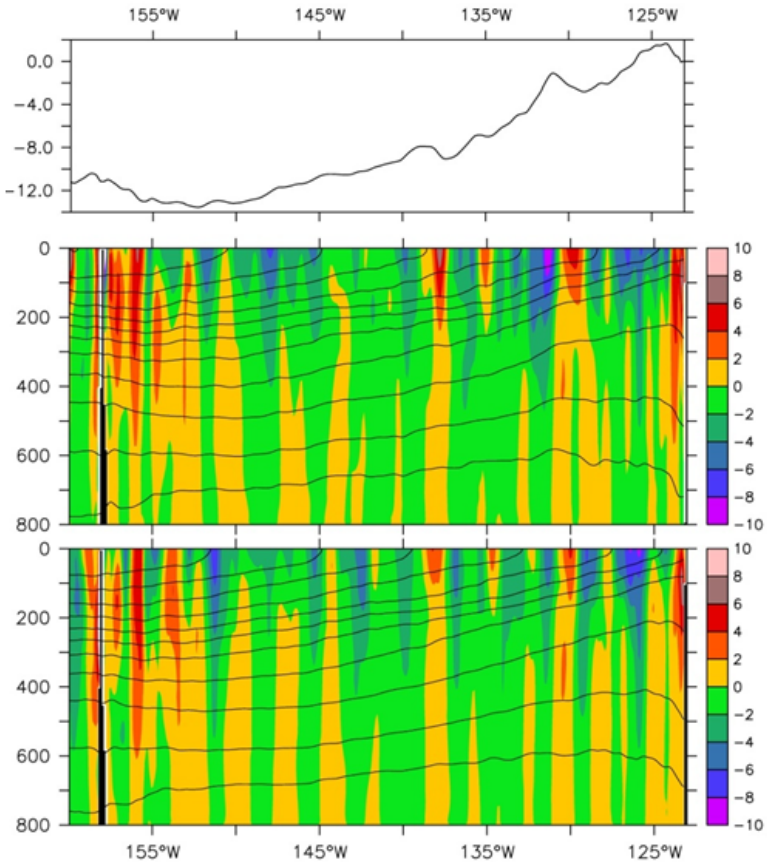


Figure 21b. Similar to 21a but from PX37 XBT data. Top: Transport integral (Sv), 2004-2008 21-cruise mean. Middle: T and velocity (cm/s), 2004-2008, 21 cruise mean.Bottom: T and v, 1993-2003, 46 cruise mean.

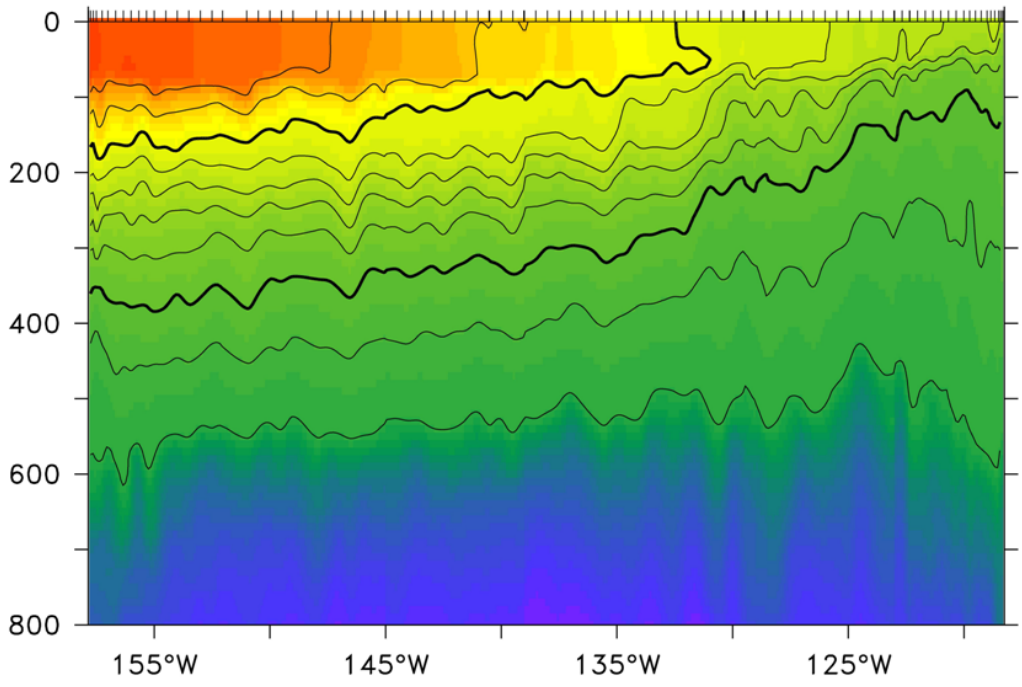


Figure 22. Temperature transect along PX37S, Honolulu to Long Beach, November 2008.

b) Evaluation of 2000 m (LMP5-T1) XBT for ocean boundary current and ocean interior sampling:

Present sampling with expendable bathythermograph (XBT) probes at high ship speeds is limited to 800 m. A new XBT probe (LMP5-T1) is under development by Lockeed Martin Co (formerly as Sippican Corp) to provide research-quality temperature versus depth measurements to 2000 m at ship speeds of 20 knots. The HRX program is assisting this development by testing prototype LMP5-T1 probes.

If the effectiveness of the LMP5-T1 could be demonstrated, combining it with Deep Blue XBT and Argo float data would have widespread usage in the HRX Network for ocean circulation and heat transport estimation.

Development of the LMP5-T1 probe by Lockeed Martin has been suspended, and the company is marketing a deep analog probe rather than the planned research quality probe. We will therefore not be further testing or acquiring LMP5-T1 probes, and will instead use residual funds for XCTD sampling that is badly needed along line PX37.

2.6. Surface drifter observations in boundary currents

Goals: The objectives are to utilize historical and real-time drifter, ADCP, hydrographic and satellite sea level data to construct maps of surface circulation of ocean boundary regions that transport ocean properties and thermal energy across latitudes. A novel contribution is the development of a bottom-release technology for surface drifters,

Role in CORC: The special contribution of the drifter data is to provide spatial patterns of near surface circulation that surround the data lines occupied by moorings, PIES, XBTs and gliders in CORC. Drifters will be deployed from ships of opportunity (in the CALCOFI region and Solomon Sea) and where ships do not visit on a regular basis, drifters will be positioned by a newly developed mooring system on the ocean floor, to be released at preset times. Presently, the period of 1993 to 2008 is being analyzed to form a 15-year time mean, which will be followed by analyses that describe the evolution of the circulations systems that accompany or influence climate change. The near surface data provided by this effort will be provided to the CORC data assimilation effort.

Progress:

a) Analysis of historical observations in the Southern CCS:

The hydrographic data from 1949-2008, the SVP drifter data from 1985-2008, the satellite altimeter from 1992-2008 and ADCP data from CALCOFI ships were combined to compute comprehensive horizontal maps of velocity along CALCOFI Lines 77-93. These analyses produce time-mean horizontal maps of surface circulation in the southern portion of the CCS and vertical sections along CALCOFI Lines (Figure 22).

The data on Line #90 shows significant ageostrophic velocity component normal to Line #90 line in water depths shallower than 100m (Figure 22). The spatial structure of ageostrophic velocity cannot be entirely due to wind driven Ekman currents because the wind along Line #90 does not have a spatial structure commensurate with the location of the spatial structure of the ageostrphic current patterns. Data on Line #90, as well as the other CALCOFI lines where ADCP data is available, is being inspected to determine whether interaction with the wind and the relative vorticity of the time mean circulation might lead to these anomalies.

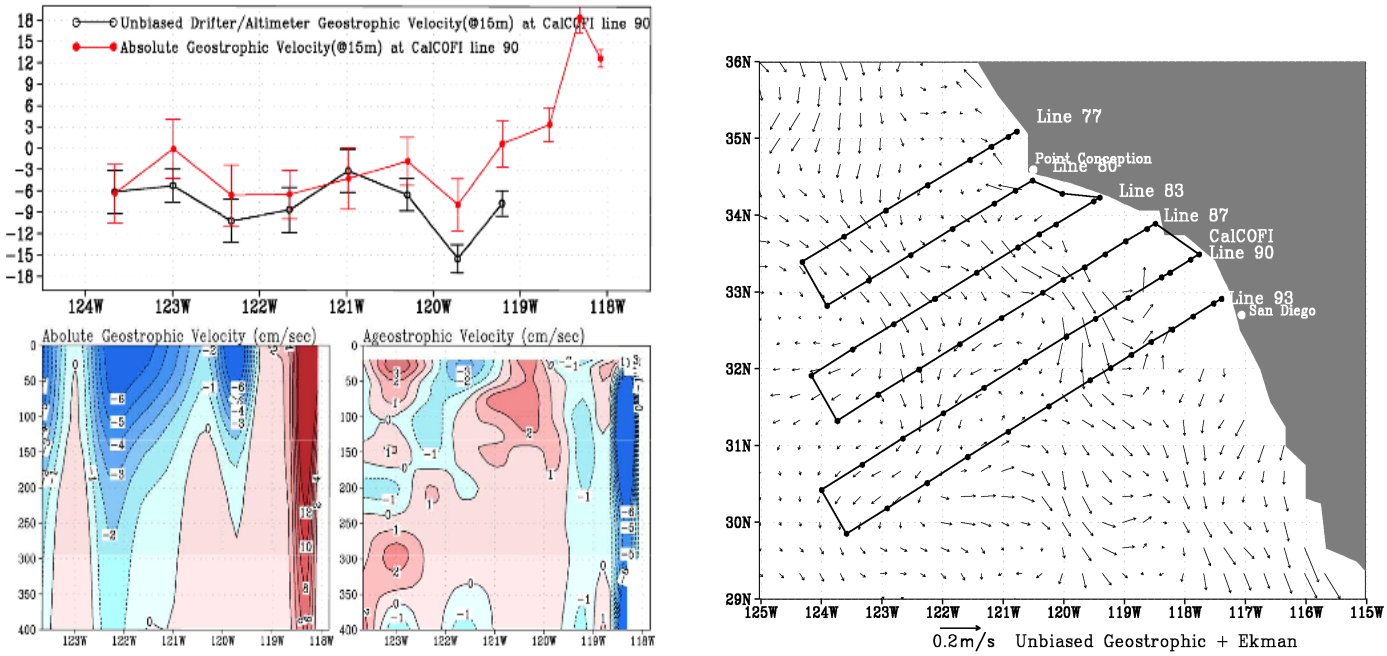


Figure 22. The 15m depth drifter/altimeter velocity component normal to Line #90 (black) and the 250m relative to ADCP geostrophic velocity component from CALCOFI (upper panel). The geostrophic velocity relative to ADCP data at 250m (middle left panel) and the ageostrophic velocity from ADCP measurements (middle right panel lower panel). The 15m velocities derived from drifter and altimeter data (bottom panel). It is apparent that Line #90 is imbedded in a complex flow pattern with at least three cores of southward flow and a northward current along the coast.

Analysis has also been completed for the time variable EOF's of the transport, surface velocity and hydrographic properties (not shown). We anticipate having complete description of Line 90 completed with FY'08 funding.

b) Analysis of the surface circulation of the Solomon Sea

Drifters have been deployed in the western tropical Pacific since 1988. The historical ensemble of tracks (Figure 23 top panel) reveals currents in excess of 50cm/sec in the Solomon Sea and the passage from the northeast into the Solomon Sea between New Ireland and Buka Island. The average 15m-depth velocity (Figure 23 bottom panel) shows that there is an inflow of surface water through this strait that makes up the surface water of the New Guinea Current. No apparent connection of the New Guinea Current appears to the circulation of the Coral Sea. This is in marked contrast what is implied by water mass distributions and direct flow measurements below the surface, where a direct link the Coral Sea conditions is established. More comprehensive definitions of the Solomon Sea circulation patterns and its time evolution is an objective of CORC in which drifter observations will be playing an important role. Our analysis of this region is not complete because we have not combined the drifter data with altimeter and wind observations, but these tasks will be completed in the next several years.

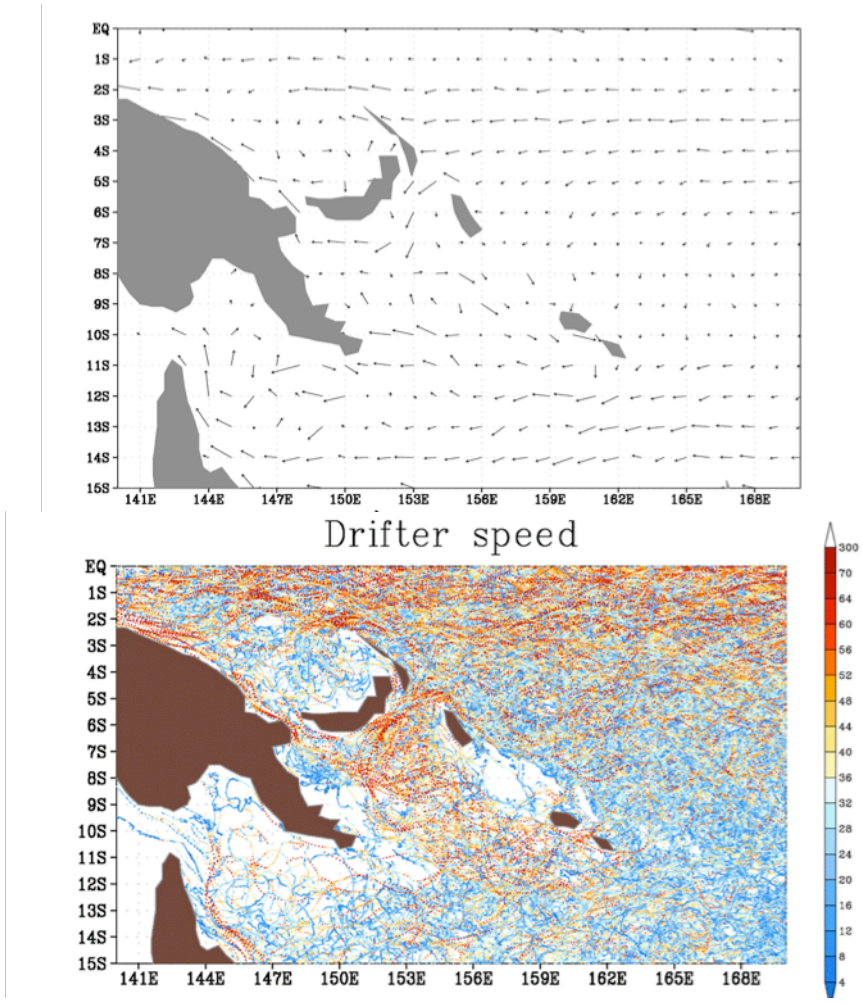
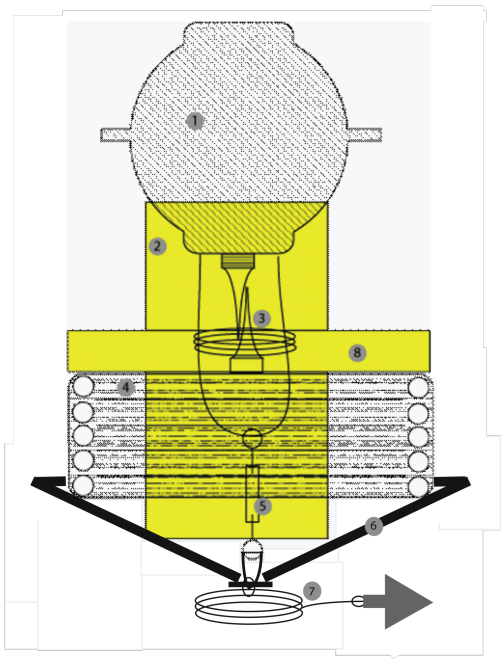


Figure 23. Historical drifter tracks in the vicinity of the Solomon Sea (top panel) and the ensemble mean velocity at 15m-depth on 0.25º resolution (bottom panel). Note the strong inflow of surface water into the Solomon Sea from the northeast and the anticyclonic gyre in within the basin.

c) Construction and testing of bottom release system for drifters

We have built four test drifters that are to be moored to the bottom and will be released at preset times, Figure 24. Test in 10m-depth pool at Scripps were continued in the ocean off Scripps pier. Numerous electrical and electronic problems have been identified and corrections are being implemented. We anticipate the first deployment of 6 units in the deep ocean along line 90 within six months. The long-term objective is to place arrays of such drifters in regions where regularly time spaced ship deployment is not practical.

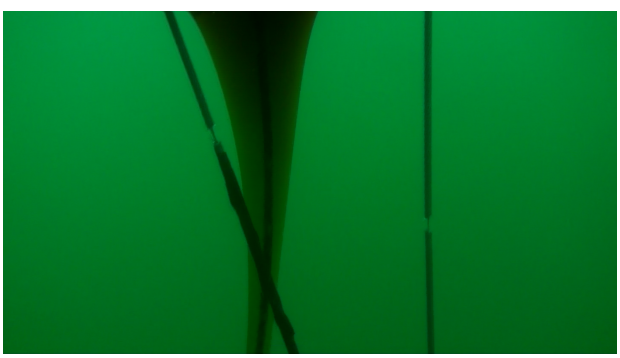
Drawing 1.1 Packaged Long Term Bottom Release Mooring



1) Surface Sphere
2) Sonotube Mount
3) Carrot, burn wire, and excess tether setup
4) Drogue
5) Tensioner and shackle system to calibrate mount
6) Conical cap for mounting package, anti-tumbling during deployment, and anti-skating during mooring phase
7) Thimble, excess tether, and anchor setup

Figure 24. The schematic on the left shows the initial design of the timed-release mechanism and ocean bottom-resting configuration for drifters. Burn wire technology was adopted from geophysics research group at SIO that forms the connection to a low cost resting pod on the ocean bottom. The new drifter configuration float is a 4000m pressure resistant Benthos glass sphere with a thru-hull cable to the burn wire. The burn circuit works well in the laboratory. Underwater tests in the OAR salt-water pool are continuing to be problematic in stabilizing the entire configuration of the float, drogue and the anchor. We anticipate a series of test is the first two weeks in January to solve problems.

The underwater photograph (lower green panel) taken on 3/20'09 shows a burn wire test at 30m of water depth off Scripps Pier. Note that both wires that are holding the mooring in place have burned their stainless steel strength members and the remaining cotton cord around which the wire was wound is ready to break. Upon rupture, the drogue deployed correctly and the ARGOS transmitter started working correctly.



d) Deployments of drifters within CALCOFI

The project is focused on the analysis of historical Lagrangian surface current data collected off the Central and Southern California coasts, and additional data collection with SVP surface drifters. The research will provide new insight into the connection between continental shelf flows and the larger scale California Current located further offshore. Dr. Carter Ohlmann at the University of California at Santa Barbara supervises this activity.

The following two tasks have been performed during the period:
• Historical CODE drifter data for the study region have been obtained and organized.
• SVP drifters (27) have been purchased and a deployment plan is being developed.

Historical drifter data collected as part of the MMS funded Santa Barbara Channel – Santa Maria Basin circulation study (SBC-SMB) and through the Global Drifter Program (GDP) have been obtained and organized. The SBC-SMB dataset is comprised of observations from 536 CODE style drifters drogued at a depth of one meter. The drifters were launched within the SBC-SMB between October 1992 and December 1999, but moved throughout the southern branch of the California Current system. Mean track length is 25.8 days and the longest track length is 89.9 days. The intermittent ARGOS position data have been filtered for erroneous position records, linearly interpolated to a 6-hour time grid, and velocity values computed as a first difference in position.
A set of 27 SVP drifters (drogued at 15 meters) has been purchased from Technocean Inc. (Cape Coral, FL). The drifters are expected to arrive at UCSB within the next few days. Development of codes to obtain the drifter position data from Service Argos in near-real time has begun. Obtaining data from sampling units will help guide the deployment of subsequent units. Historical drifter tracks have been examined to identify flow features that characterize the circulation and will guide deployment of the 27 units. The historical drifter data and model results published by Dong et al. (in press) show a somewhat persistent sub-mesoscale cyclonic gyre centered near 33.5° N, 119.5° W. The feature may be significant for material retention in the Southern California Bight circulation and may be an initial "target" for drifter deployments.

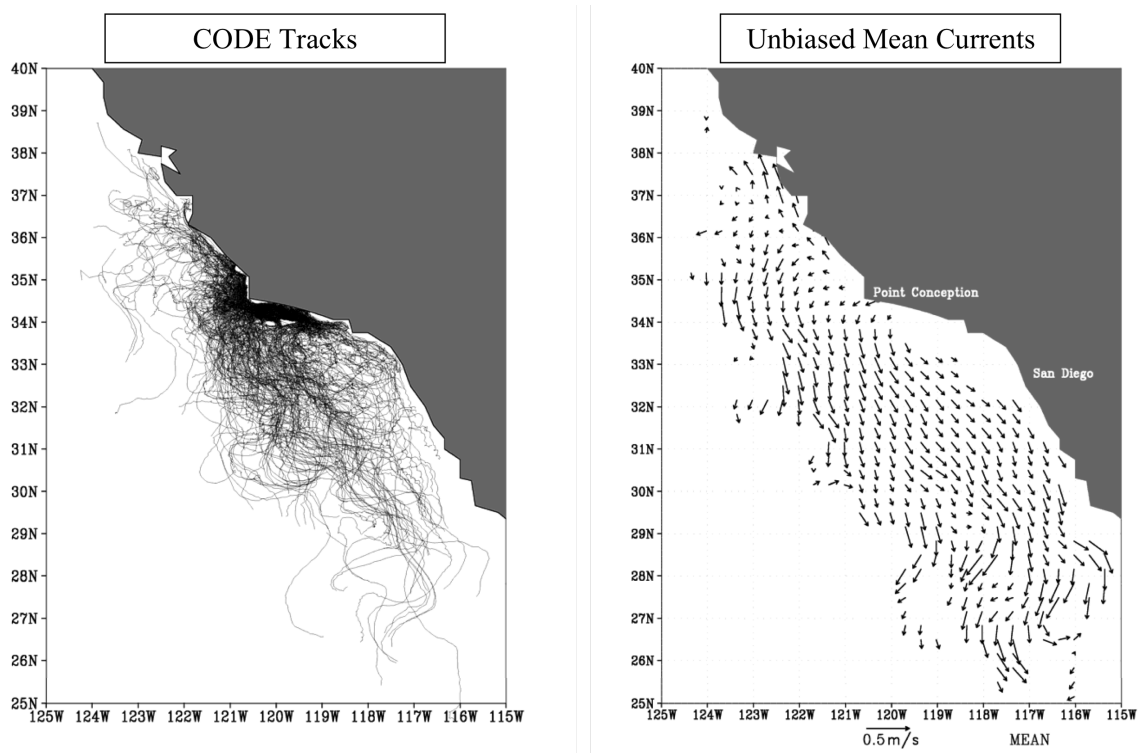


Figure 25. CODE drifter tracks within the CALCOFI region (left panel) and the 'unbiased' 1m-depth average surface current (right pan. Comparison with SVP data at 15m-depth velocity is ongoing.

2.7. Modeling and assimilation of CORC data in the California Current

Goals: Our primary goal is to provide a physical way to merge the datasets together using a regional model of the CCS to come up with a detailed picture of the current system, both upstream and downstream of the primary sampling line. The synthesis will cover the intense years of observations, and provide a testbed for sampling plans. The assimilated results will show space and

timescales of the variability for term-by-term analysis of heat, salinity, momentum, and vorticity balances.

Role in CORC: Our role in CORC is to tie the various observation programs together, to provide a coherent synthesis that all PIs can use to evaluate their observations and do further analysis. We should be responsive to PI interests in providing analysis to work in collaboration to write papers, to optimize the observation network, and to construct routine products and indicators.

Progress:

a) MITgcm/ECCO assimilation

A paper on the modeling and assimilation in the tropical pacific from the previous CORC project was accepted to the Journal of Atmospheric and Ocean Technology, and an article on the completed assimilation for the year 2000 is in revision at JGR. The tropical pacific assimilation showed that eddy-resolving assimilation could work for periods as long as a year in the energetic tropical circulation. In addition, the MITgcm/ECCO system was validated as a tool for analysis. This same tool has been applied to eddy-resolving assimilation in support of the observations in the CCS.

The same system was applied to a 1/10 degree and 50 level grid of the CCS, using satellite SSH and SST observations for a proof-of-concept demonstration, and the iteration converged well, although because of the use of ECCO boundary conditions, the assimilation was done for 2003, before the new sampling in the CCS.
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 isnearly identical to his successful 1/6 degree Southern Ocean State Estimate (SOSE), Figure 26.

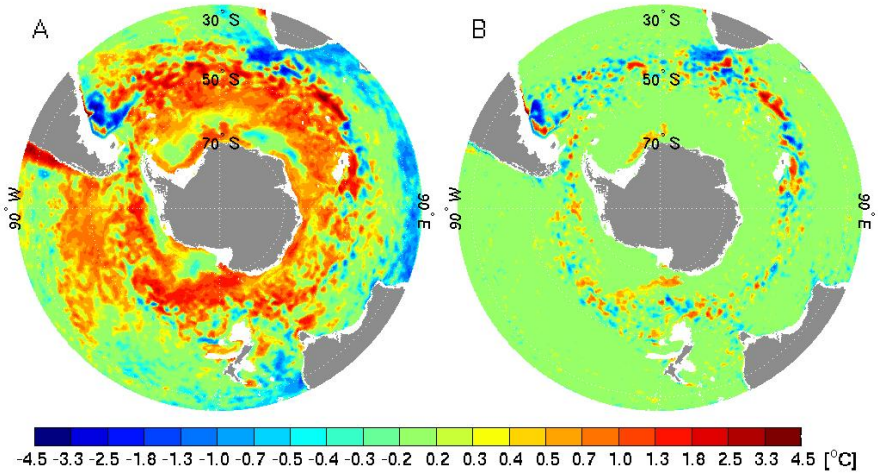


Figure 26. Successful eddy-resolving assimilation over 2 years with MIT/ECCO model at similar resolution as the CORC model in a very dynamic region. Time average of model solution minus observations [°C] for the best guess forward model solution (left) and after 23 iterations of assimilation (right). Observations are combined mean from infrared (AVHRR) and microwave (TMI AMSR-E) radiometers.Exponential color axis.

In addition to the code updates, we have implemented new features, notably an Ensemble Kalman Filtering option to complement the adjoint-based 4DVAR assimilation already in use. We have also extended the system to accommodate non-ECCO models (notably HYCOM) as boundary conditions, since the available assimilated ECCO ocean states lag behind the current time. We have

been evaluating the HYCOM estimate in a few regions, starting with the local San Diego region, and the assimilated model output seems to have useful skill.

One of the data sources in the monitoring array are inverted echo sounding with bottom pressure (PIES), which measures round-trip travel time between the bottom-mounted instrument and the surface. This is processed by some investigators using a "gravest mode" method that assumes a dominant mode of variability. We intend to instead use the bottom pressure and vertical integral of sound speed as a constraint on the assimilating model, but this has meant the enabling of integral observations, which have not yet been used in the ECCO system. We have investigated the problem, and it should be possible to add these data to the assimilation by adjusting the cost function without large changes to the code.

The latest version of the CCS model is 1/16 degree and 72 levels, a large improvement in resolution over the previous versions, and embedded in a new global 1 degree state estimate from MIT-ECCO (with thanks to Gael Forget, Patrick Heimbach, and Carl Wunsch) that extends through 2007. To assimilate data into 2008 and 2009 we will need to use different boundary conditions if MIT ECCO does not produce an updated solution. To address this we expect to use HYCOM or just to repeat the older boundary conditions, since they will be altered by the assimilation in any case. 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 (Figure 27).

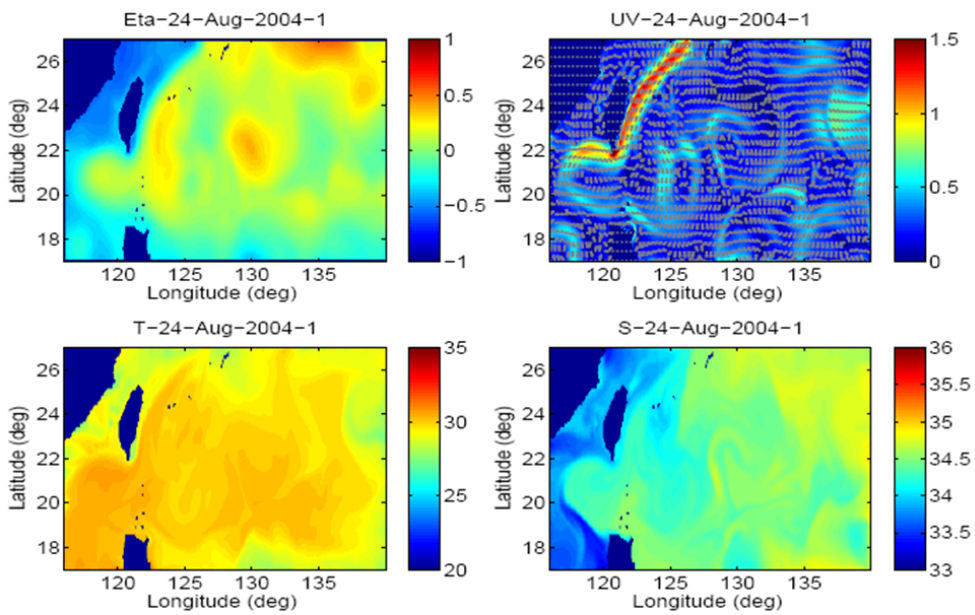


Figure 27. Example of successful regional MIT/ECCO run with original bathymetry, using HYCOM as intial and boundary condition, here for the region off Taiwan (panels show full domain SSH, surface velocity, SST, and SSS).

Much time was spent on debugging and recreation of local modifications to the code, since many features changed. Not all local modifications have been transferred to the new code yet, but while that is underway we are beginning hindcast experiments using the in-situ observations from CalCOFI, Argo, and Spray gliders to evaluate the model skill.

In addition to the MIT-ECCO boundary conditions and initial conditions the reference (starting) model run before assimilation is forced by NCEP reanalysis winds. 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 do long model runs with a single forcing product. In addition, several forward runs have been made to examine sensitivity to mixing parameterizations.

The in situ observations have been compared with the forward model run (Figure 28), and the differences for the downscaled assimilated system are encouragingly small, (see Figure 29) although significant improvement is still possible. The reference run is 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.

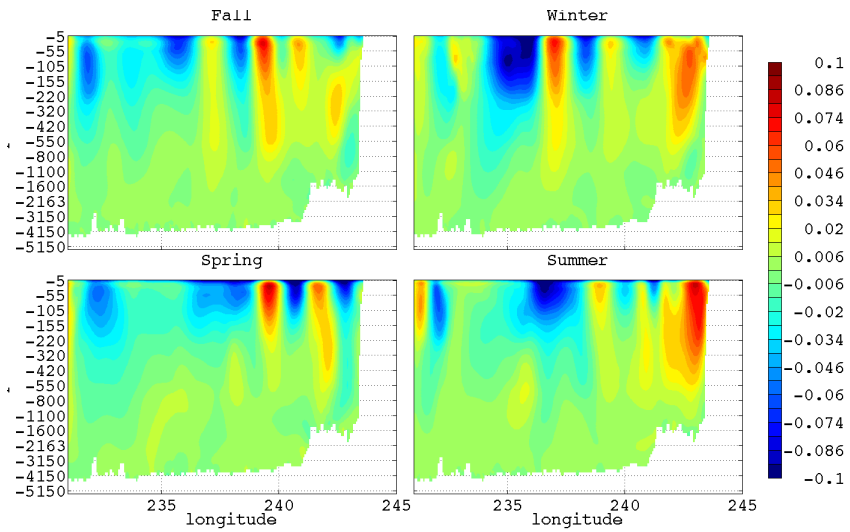


Figure 28. Forward run (no assimilation) of the MIT/ECCO CORC model, with boundary/initial conditions from the global ECCO model, after 1 year. Shown is the meridional velocity across 31S for four seasons. The California Current core (blue) and the northward undercurrents are reminiscent of the glider transects in section 1.

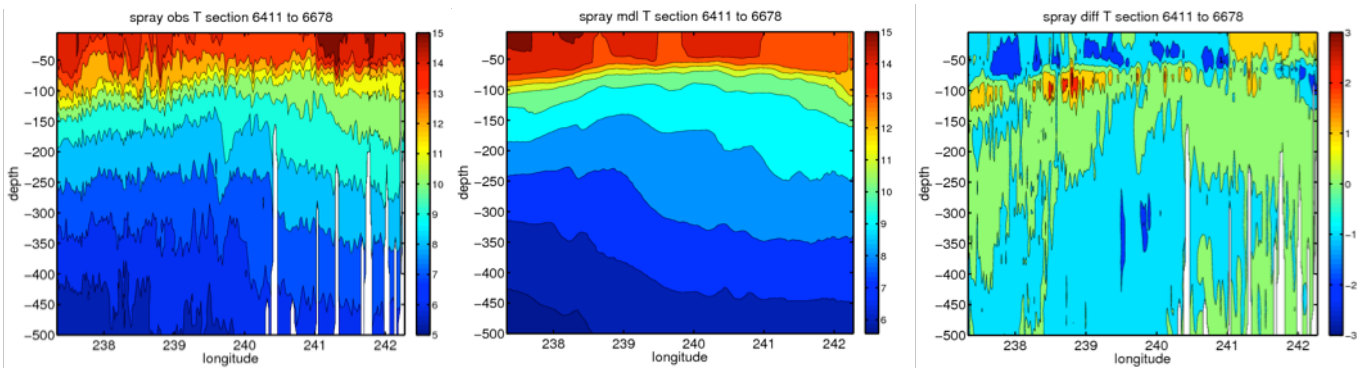


Figure 29. Forward run (no assimilation) of the MIT/ECCO CORC model, with boundary/initial conditions from the global ECCO model, after 1 year. The three panels show temperature for a Spray section on Line 90; 19 Jan 2007 to 17 Feb 2007. The first panel is observed temperature, the second is model temperature, and the third is observation - model misfit. Contour interval is 1 degree C. The agreement is remarkable since the glider data are not assimilated into the global ECCO model which provided the initial/boundary conditions. Thus this is an independent data set.

The result of the assimilation should provide a dynamically-consistent synthesis of the disparate observations, including those made as part of the project and can be compared with the analyses produced by the PI's making the observations. The state estimate will be dynamically consistent in that the assimilation will produce 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 without internal forcings driving the model to the observations.
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).

b) ROMS

As a complement to the MITgcm assimilation, adjoint-based assimilation using ROMS is also being implemented for the CCS. ROMS is an S-coordinate (terrain-following) model, in contrast to MITgcm, which is z-level. This allows ROMS to maintain vertical resolution of near-bottom variability, which can be an advantage in coastal regions. In addition, ROMS includes more turbulence closure options than the MITgcm, some of which are thought to be useful in shallow water and coastal regions. It will be useful to compare and contrast the results from these different options. ROMS can now adjust initial conditions (IC) and forcing, but the adjustment of open boundary conditions (OBC) are not yet possible, in contrast to MITgcm, which can adjust IC, OBC, and forcing. In preliminary experiments, ROMS shows strong growth of the adjoint sensitivity (related to model nonlinearities and chaos) over a 1-month period, compared to several months for the MITgcm. These differences are likely due to viscosity differences, but they remain to be explored.

c) Statistical analysis

As a prelude and supplement 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. 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 (Figure 30).

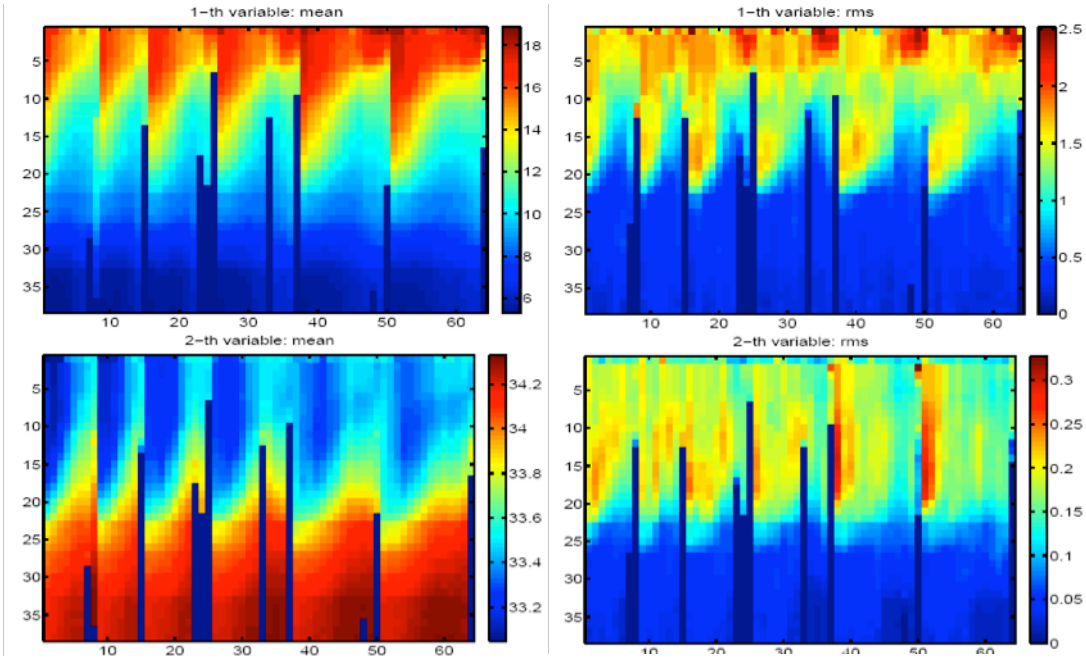


Figure 30. Mean temperature (top left) and salinity (bottom left) for the 25 years of the 64 CalCOFI repeat stations. The cross-shore isotherm tilt is clear in each of the CalCOFI lines. The mean salinity shows the saline undercurent water, tilted up against the coast showing the long term balance between upwelling of the salty deep water and mixing of the surface fresh water of the southward-flowing current. The right panels show total RMS variability for temperature (top) and salinity (bottom) for the CalCOFI stations, including the annual cycle. The variability decreases sharply in the cold and salty deeper water below 200m offshore and about 100m inshore. Salinity variability inshore is less strongly trapped to the surface, but the gradient in variability is sharp, and there is little variability below 200m relative to the surface.

3. NEXT STEPS

In year 4 of the project we will migrate the California Current monitoring system to full operation and start to produce indices and assimilation products. The Solomon Sea efforts will be focused on exploring details about the circulation system for planning a future integrated system there including moorings.

In the Solomon Sea we intend to maintain one glider on the section between Rossel Island and Gizo at all times (requiring a deployment every 3 to 4 months). The first analysis product will be an extended time series of volume, heat, and freshwater transport toward the equator. As the record grows it will be possible to refine the annual cycle and define specific anomalies, perhaps including June 2008. Beginning July 2009 we plan to put a second glider in operation on other transects with the dual purposes of exploring suitable sites for any eventual CORC moorings and partitioning the net transport toward the equator into specific pathways. Collaborator W. Kessler is initiating a modeling program for the area and the comparison of observations and model results will help us refine the limitations of glider monitoring and contribute to CORC's developing picture of the capabilities of different approaches to monitoring boundary currents.

In the California Current, the glider observations will focus on the transport and partitioning of both the equatorward cold-fresh California Current and the poleward warm-salty Undercurrent. Analysis is now underway to summarize our observations of these currents to date as part of the Ph.D. thesis

of Robert Todd. He has identified various cores of the CCS and is exploring their time variability. Seasonal cycles and anomaly patterns are being constructed as well as time series of transport. The CCS measurements are also describing how eddies and fronts organize the biology as marked by chlorophyll and acoustic backscatter measurements and provide a baseline for detecting climate-scale variability in the ecosystem. In cooperation with zooplankton biologist Mark Ohman we are seeking compact descriptions of both large-scale and eddy-scale variability in the biology and physics.

Continuous sampling of a single glider will continue on Line 67. Continuous sampling with one ADP-Spray will be continued on Line 90 and sampling will be extended further offshore to reach the CORC mooring at the end of the Line. Our two modem-Sprays, and three additional units to be completed this year, will be placed in service providing acoustic data relay of the mooring and PIES data and more frequent sampling of T, S and chlorophyll.

The acoustic data recovery and transmission via the modem gliders will be made more robust, and as back-up option alternative modems will be tested.

In fall 2009, the moorings and PIES from line 90 will be recovered and all data will be in hand then. Based on the ongoing analyses from gliders, XBTs, mooring/PIES data, and altimetry, such as those presented above, an improved layout of the end-point mooring section and the PIES will be decided. It seems clear that we will have to extend the present length of the section across the California Current, enhance the existing 5 PIES with additional instruments depending on a study of the dominant scales that need to be resolved with these systems. The ARGO and XBT analyses such as those in Figure 3, seemed to suggest an "edge" of the California Current around 130°W. This choice is also supported by contouring the mean surface dynamic topography from blended drifter/altimeter analyses (e.g. Maximenko&Niiler) and the SSH variability, Figure 31. Around 130°W on extensions of CalCOFI lines 80 or 90, there is a minimum in southward surface flow and also the SSH variability has decayed to a minimum there. Offshore of this limit, the boundary current data will be merged with interior ARGO data, as is being studied at present (see section 2.5).

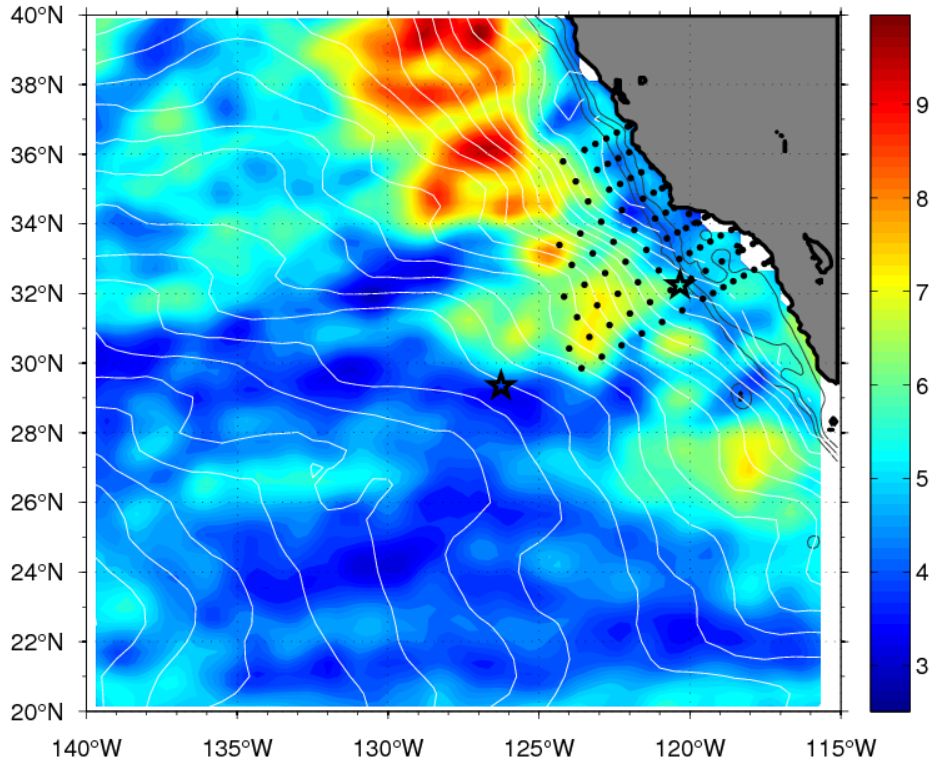


Figure 31. Contour map of rms sea surface height variability in cm (color) from 5 years of altimeter data, and of surface dynamic topography from 6 years of drifter/altimeter data (white contours at 2cm interval). The CalCOFI station grid and the current two CORC moorings are indicated with dots and stars, respectively. At 128-130°W a minimum is found in SSH variability and in the surface flow.

The mooring and PIES (especially bottom pressure) observations will allow to address the more rapid timescales which are not captured or aliased by the glider and XBT data. In addition these timeseries will for the first time quantify the deep flow and its variability (as suggested from Figure 19 and some model results, the flow below 1000m may not be negligible).

The data will be quality checked and used for quantitative analysis of the transports. Data from the moorings, PIES, and gliders will be merged for direct estimates of the transports in near real-time. The telemetered data will also be prepared and provided for assimilation into the model described above in section 2.7. From these data integration activities we will begin to produce indicators and assimilation products in a quasi-operational manner.

For the XBT/ARGO data, work during the coming year will focus on integration of datasets, including Argo, High Resolution XBT, CalCOFI, and CORC glider transects. After defining the offshore extent of the California Current, the transport and variability of the current will be combined with the interior datasets. Fine spatial resolution in the HRX and CORC glider data will enable temperature and velocity fields to be estimated at finer resolution nearshore and more smoothly offshore. A research goal, working with the CORC data assimilation modeling effort, is to study interannual variability in the salinity budget of the salinity minimum in the California Current, including interannual variability due to changes in the salinity of source waters, in the strength of alongshore advection, and in coastal upwelling. The re-initiated sampling of the Honolulu-Los Angeles XBT line will also be maintained, which is supported by the non-CORC XBT grant but directly contributes to the CORC objectives.

For the surface drifter work, analysis of the CALCOFI region, including all the lines that have ADCP will continue. The objective is to provide the CCS model initialization and assimilation velocity fields from both CODE and SVP data sets. The emphasis will be expanded to include real time velocity data sets. In addition, we will build, deploy and test 6 pop-up drifters for the CALSOFI Line 90 deployment in 2009 and starting in 2010 begin to provide pop-up drifters for the Solomon Sea and other CORC relevant areas.

Manpower and computer power are now in place for construction of a multiyear state estimate for the CCS region using glider, mooring, drifter, float, and remotely sensed observations. The assimilation window will be as near to the current time as possible depending on the availability of boundary conditions and forcing fields. The results will be shared with the observation PI's to do analysis and to plan future observational approaches. Studies of the boundary currents in the western pacific will also take place using the output from the tropical pacific model.

The result of the assimilation should provide a dynamically-consistent synthesis of the disparate observations, including those made as part of the project and can be compared with the analyses produced by the PI's making the observations. The state estimate will be dynamically consistent in that the assimilation will produce 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 without internal forcings driving the model to the observations.

4. OUTLOOK

In the California Current, we expect to have a sufficient understanding of the cross-shelf scales and flow distributions, the variability, the transports, and the along-shore coherence, to leave in place an efficient monitoring system for the southern California Current by the end of the current CORC phase. It may turn out that it makes most sense to move the mooring/PIES section from line 90 to line 80. In that location, there would also be optimum synergy with the additional carbon/ecosystem moorings planned there.

The assimilation system will be fully running and producing products and indicators for the state of the California Current, including its mass, heat, freshwater transports, its eddy activity, and possibly forcing of carbon and biological processes.

In the last year of the current CORC phase we plan to turn attention to a more comprehensive implementation of the integrated observing system in a western boundary current, most likely the Solomon Sea. The appropriate blend of observing techniques is likely to be different there, compared to the eastern boundary current off California. Reasons are very swift flows which sometimes make it impossible for gliders to reach a specific location, large barotropic and deep-reaching flow components (which require methods other than gliders or XBTs), and rapidly changing eddying flows which strongly alias glider transects. Also the surface flow, as measured by drifters, may show rather different distributions compared to the subsurface current systems. If gliders cannot reliably reach moorings/PIES for acoustic data downloads, it may be necessary to employ surface moorings. Suitable locations in terms of geometry and current intensities will be explored by gliders, drifters, and in collaboration with field work by French collegues.

An example of a flow section derived from a glider crossing of the Solomon Sea is shown in Figure 32. It shows a boundary current of 20-40cm/s in the upper 100m, and 10-20cm below that. Those conditions would allow deployment of an endpoint surface mooring, to capture the full time variability and depth extent of the flow through the Solomon Sea.

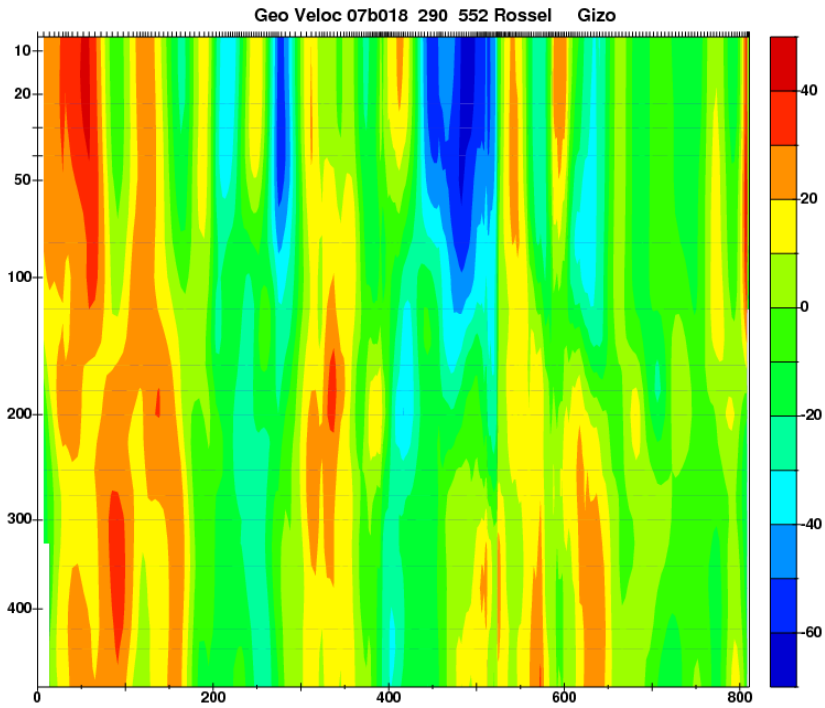


Figure 32. Geostrophic flow referenced to directly measured 0-500m average from a glider section across the Solomon Sea (Rossel to Gizo, see Figure 1). It shows a strong equatorward flow near the boundary, and generally strongly barotropic current distributions.