A. Project Summary

Collaborative Research: Dynamics and Transport of the Antarctic Circumpolar Current in Drake Passage

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This study will deploy a transport line and local dynamics array of Current Meters and Pressure-recording Inverted Echo Sounders (CPIES) moored for a period of 4 years to quantify the transport and dynamics of the Antarctic Circumpolar Current (ACC) in Drake Passage. Data will be collected annually by acoustic telemetry, leaving the instruments undisturbed until recovered.

Intellectual Merit

The Southern Ocean is especially sensitive to climate change, responding to winds that have increased over the past 30 years and warming significantly more than the global ocean over the past 50 years. The ACC is the pulse of the Southern Ocean, and the Drake Passage chokepoint is not only well suited geographically for measuring its time-varying transport, but observations and computer models suggest that dynamical balances which control its transport are particularly effective through the Drake Passage. This project contributes to the International Polar Year (IPY) through its transport line monitoring of the ACC in Drake Passage. The observations will resolve the seasonal and interannual variability of the total ACC transport, its vertical structure partitioned between barotropic and baroclinic components, and its lateral structure partitioned among the multiple jets comprised by the ACC. Moreover, Drake Passage is a region of high mesoscale variability. The mesoscale eddies are thought to play a mediating role in transferring momentum from the circumpolar winds that drive the ACC, down through the water column to the sea floor, where topographic form stresses regulate its long-term transport. Measurements in the local dynamics array will quantify eddy exchanges with the mean current and density structure, and they will quantify the mean vorticity balance in order to test hypotheses regarding the dynamical balances that govern the ACC.

Broader Impact

Quality-controlled time series of currents, temperature, and density from the CPIES measurements will be disseminated, together with data products (transports, maps, 3D fields) suitable for long-term monitoring of the ACC and validating numerical models. An outcome of this study will be a recommendation for the minimal instrumentation required for long-term monitoring of ACC transport. The subset of instrumentation purchased by Raytheon (10 CPIES) will become part of the U. S. Antarctic Program instrument pool and be available for future investigators. Three graduate students will be sponsored and their thesis research will be mentored by the principal investigators.

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C. PROJECT DESCRIPTION

The goal of this study is to quantify the transport and understand the dynamical balances of the Antarctic Circumpolar Current (ACC) in Drake Passage. For this purpose a transport line and a local dynamics array of CPIES (Current and Pressure recording Inverted Echo Sounders) will be deployed spanning the predominant along-stream wavelength of 250 km for 4 years. Data will be collected annually by acoustic telemetry, leaving the instruments undisturbed until recovered.

Scientific Objectives:

1) Using the transport line, determine the seasonal to interannual varying mean total ACC transport, its vertical structure partitioned between barotropic and baroclinic components, and its lateral structure partitioned among the multiple jets comprised within the ACC.
2) Using the local dynamics array (LDA), map the mesoscale eddy field as a function of (x, y, z, t), its seasonal to interannual variability, cross-front exchanges, and its energetics.
3) Using the LDA, quantify the mesoscale eddy-mean field interactions, and eddy potential vorticity fluxes, which govern the momentum balance along the ACC.
4) Using the LDA, estimate all terms in the mean vorticity balance in order to quantify the vertical transfer of momentum in the ACC, from surface to sea floor.

1 Introduction

The Southern Ocean has been shown to be extremely sensitive to climate change in numerical models (Banks and Wood, 2002), and observations suggest that it is warming at a rate of nearly 1°C/century in the core of the ACC, which is significantly faster than the global ocean as a whole (Gille, 2002). The ACC is forced by circumpolar eastward winds whose dominant mode of variability is the Southern Annular Mode (SAM), characterized by an oscillation in barometric pressure between a node over Antarctica and a latitude band centered at approximately 45°S (Thompson and Wallace, 2000a,b). Circumpolar winds have been increasing over the past three decades, corresponding to a higher SAM index (Thompson and Solomon, 2002); significant interannual variability has also been present and is correlated to ACC transport variations (Meredith et al., 2004). In the ACC, eastward wind stress is balanced by pressure differences across topography, fluxing angular momentum to the solid earth via “form stress” (Munk and Palmén, 1951). These pressure differences across topography can upset the Sverdrup balance through “bottom pressure torques”. Numerical modeling results show that averaged over a latitude band, bottom pressure torques balance wind stress curl in a zonal integral (Hughes and de Cuevas, 2001), but need not balance locally at all longitudes (Hughes, 2005). Drake Passage is an important chokepoint of the ACC because it is where the current is most constricted both in the horizontal and in the vertical (the smallest range of f/H). Because of the reentrant geometry of the ACC, horizontal pressure gradients cannot be maintained above the topography. Eddy transports are of particular importance in the main pycnocline of the ACC because they are the only mechanism for meridional transport of heat above the topography and below the Ekman layer at the latitude of Drake Passage.

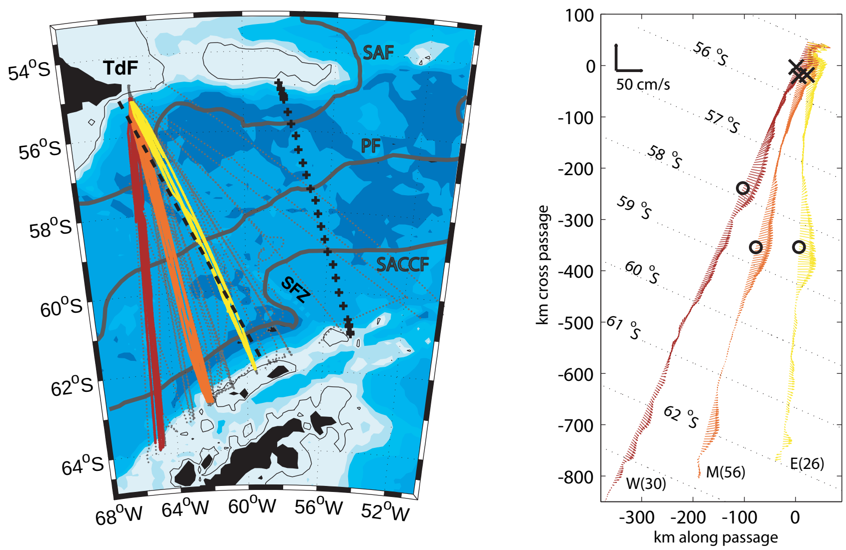


Figure 1: Left: Cruise tracks from 128 Drake Passage transits of the ARSV Laurence M. Gould (LMG) during 1999-2004 (light dotted lines). Oft-repeated tracks shown in red (West), orange (Middle), and yellow (East). The locations of the principal ACC fronts (Orsi et al., 1995) and the SR1b line (+ symbols) are also shown. The heavy dashed line is the y-axis for the along/cross passage coordinate system, with origin at Tierra del Fuego (TdF). Right: Detided mean currents at 150 m depth from LMG ADCP measurements along the repeat tracks; number of repeats for each section is shown in parentheses. The x/o symbols denote the mean locations of the SAF/PF, respectively, from repeat XBT measurements. After Lenn et al. (2006).

1.1 Transport

As part of the International Southern Ocean Studies (ISOS), 1975-1980, a concerted effort was made to determine the transport of the ACC from year-long deployments of moored current meters and a series of hydrographic cruises. From the ISOS measurements, Nowlin et al. (1977) observed that the ACC flow comprised three relatively narrow vertically coherent geostrophic jets associated with sharp fronts now known as the Subantarctic Front (SAF), the Polar Front (PF), and the Southern ACC front (SACCF) (Orsi et al., 1995) in northern, central, and southern Drake Passage, respectively (Fig. 1). ISOS provided the canonical estimate of ACC transport, 134 $\pm$ 11.2 Sv (Whitworth, 1983; Whitworth and Peterson, 1985) and established a widely held tenet that the transport variability was mainly barotropic and could therefore be monitored using across-passage pressure differences (Whitworth and Peterson, 1985; Cunningham et al., 2003).

Since 1988, the Proudman Oceanography Laboratory (POL) has been deploying bottom pressure recorders (BPRs) on either side of Drake Passage for durations of approximately one year. Presently, the POL BPRs are located at either end of a WOCE/CLIVAR repeat hydrographic section (SR1b, Fig. 1) which has been occupied annually since 1993 by scientists from Southampton Oceanography Centre (SOC) and the British Antarctic Survey (BAS) (Cunningham et al., 2003). Although the average ACC transport estimated from SR1b, 137 $\pm$ 7.8 Sv, is not significantly different from the ISOS estimate, the SR1b estimates have shown that the variability in the baroclinic component of transport is at least as large as the barotropic component and that the Polar Front posi-

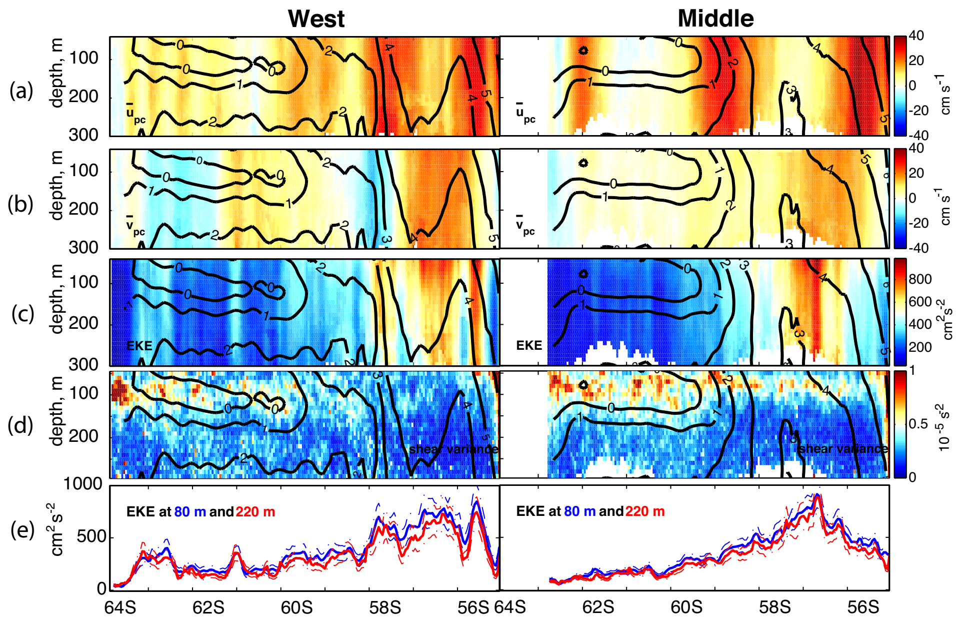


Figure 2: Mean vertical sections for the West and Middle repeat tracks shown in Fig. 1. The panels are: detided mean down-passage (a) and cross-passage (b) velocities; eddy kinetic energy, EKE (c); mean shear variance (d); and EKE values at 80 m (blue) and 220 m (red), dashed curves mark standard errors (e). Average temperature contours from the XBT surveys are superposed (a-d). After Lenn et al. (2006).

tion is bimodal, related to changes in water-mass structure (Cunningham et al., 2003). Upstream of SR1b, repeated sections of upper-ocean currents and temperatures made during 1999-2004 during transits of the U. S. Antarctic supply vessel, Laurence M. Gould (LMG, Fig. 1) also show changes in structure and distribution of transport of the ACC jets as they flow through Drake Passage (Lenn et al., 2006). The West repeat line (30 sections, Fig. 1) shows the PF distributed between a pair of jets centered on the 1°C and 3°C isotherms, respectively (Fig. 2(a)). The SACCF is distributed amongst 3 weaker jets on the West line (Figs. 1, 2). These multiple jets coalesce into a single PF and SACCF as seen in the 3 strong cores (SAF, PF, SACCF) of vertically coherent down-passage flow on the Middle line (56 sections, Fig. 2(a)) . The mean SAF is strongly steered by topography in Drake Passage.

From the BPR observations and numerical model studies, Hughes et al. (1999) made a theoretical case for a southern ACC transport mode at periods from 10 to 220 days wherein the circumpolar transport is dominated by a barotropic mode that follows f/H contours and is highly correlated to the bottom pressure on the southern side of the ACC. However, the observational case for a southern mode is less clear, and local baroclinic processes can swamp the large-scale barotropic variability in local measurements. Additionally, Drake Passage is a region where a second “Sverdrup” mode (crossing f/H contours) may also be important (Hughes et al., 1999).

Given the low frequency variability in the SAM, there is considerable interest in measuring temporal variability in ACC transport over long time intervals. Proxy methods have been developed to estimate baroclinic transport on seasonal to interannual time scales using repeat XBT observations (Sprintall, 2003; Sokolov et al., 2004). However the XBT sampling (6-8/year) is too irregular and too infrequent to avoid significant aliasing. Meredith and Hughes (2005) find that sampling on time scales of less than a week is required to determine an unaliased annual mean; more rapid sampling is required to resolve seasonal variations. Error in the proxy methods is dominated by the inability to resolve the SAF over shallow topography (Sokolov et al., 2004). Additionally, the proxies have least error when a deep isotherm can be used, but XBTs generally sample to only 800 m. Finally, the proxies approximate only the baroclinic component of transport.

1.2 Mesoscale Variability

Eddies are thought to be an important component of the shallow meridional overturning circulation (MOC) of the Southern Ocean (Karsten and Marshall, 2002). The shallow MOC is driven by air-sea fluxes of momentum and buoyancy and has recently been re-examined in the context of a diabatic Deacon cell (e.g., Sloyan and Rintoul, 2000; Speer et al., 2000; Karsten and Marshall, 2002). The balance is between buoyancy loss to the atmosphere, northward Ekman transport and southward eddy transports. At the latitude of Drake Passage, eddies are the only mechanism for transporting heat above the topography and below the Ekman layer. Eddies may be a major mechanism for dissipating the energy input of the wind, via a downward energy flux that balances the surface stress through topographic pressure drag (Bryden, 1979; Johnson and Bryden, 1989).

Using ISOS data, Bryden (1979) estimated a poleward eddy heat flux in Drake Passage and extrapolated the estimate circumpolarly to show that the net eddy heat flux across the PF could balance the 0.4 pW heat loss to the atmosphere estimated by Gordon and Taylor (1975). The sign of the large-scale density gradient, with steeply sloping isopycnals outcropping to the south of the ACC, implies that poleward eddy heat flux is associated with conversion of mean available potential energy to eddy kinetic and potential energy. The ACC is usually described as an equivalent-barotropic current, where the streamlines at depth parallel those at the surface (e.g., Hughes, 2005). Thus the mean surface flow field is indicative of the full-depth structure, although the time-dependent field may be different. Mean surface-layer EKE estimated from repeat ADCP transects (Lenn et al., 2006) decreases poleward from about 800 $cm^2\ s^{-2}$ to 200 $cm^2\ s^{-2}$; the highest EKE is concentrated between the SAF and the PF (Fig. 2).

In addition to the eddies/Rossby waves that we expect to dominate the mesoscale variability in the interior region between the SAF and the PF, the continental slope of South America can support eastward propagating topographic and Kelvin waves. These waves transmit information about transients in forcing over very long distances (teleconnections). They have been observed in coherent sea-level fluctutations along the slope; simple correlations cannot, however, establish the wave speed or the cause of the correlations (Hughes and Meredith, 2006).

1.3 Mean Balances: Momentum and Vorticity

The zonal momentum balance averaged on isopycnals is given by Phillips and Rintoul (2000) as

$$\underbrace{\overline{v'q'}}_{a} = \underbrace{-\frac{\partial}{\partial y}\overline{u'v'}}_{b} + \underbrace{f\frac{\partial}{\partial z}\frac{\overline{v'T'}}{\theta_z}}_{c} = \underbrace{\frac{-\overline{\tau_z}}{\rho_o}}_{d} \tag{1}$$

where ρ_o is the water density, $\vec{u} = (u, v)$ is the horizontal velocity, q is the potential vorticity, f is the Coriolis parameter, T is temperature, θ_z is the vertical gradient of potential temperature and τ_z is the vertical divergence of frictional stress. Overbars denote time averages, and primes denote fluctuations. At the surface, τ is the wind stress, and at the bottom, τ is the topographic form stress. The momentum balance is between the vertical divergence of the frictional stress (d) and the difference between the meridional divergence of eddy momentum flux (b) and the vertical divergence of interfacial form stress (IFS = $\rho_0 f\overline{v'T'}/\theta_Z$, c). Observations suggest that the eddy momentum flux on the northern and southern edges of the ACC is much smaller (and of indeterminate sign) than the O(100 cm^2 s^{-2}) required to balance the wind stress (Bryden, 1979; Bryden and Heath, 1985; Morrow et al., 1994; Phillips and Rintoul, 2000). In the zonally-averaged model of Johnson and Bryden (1989), lateral eddy momentum flux divergence (b) is neglected, and IFS (c) exactly balances the wind stress (d). Eddies transmit eastward momentum downward to the level of the topography where it dissipates by bottom form stress. This mechanism requires substantial baroclinicity in the ACC all the way to the bottom, and it points to the vertical divergence of the eddy heat flux as the critical quantity to estimate. No significant eddy momentum fluxes were observed from the ISOS observations (Bryden, 1979); recent estimates made in the surface layer from the repeat ADCP measurements are only significant in the region between the SAF and PF, but the flux divergence is not significant at 95% confidence (Lenn et al., 2006). Significant poleward eddy heat fluxes were estimated from the ISOS moorings (Bryden, 1979), but these were point estimates made at only a few locations and depths and do not resolve flux divergences. With only 37 coincident ADCP/XBT transects, eddy heat flux cannot be determined with statistical confidence, and although the statistics will improve from ongoing observations, they are not full ocean depth. Hence the mean momentum balance in Drake Passage remains an open question.

Diagnosing meanders of the ACC in the context of the mean vorticity balance has been useful in identifying where topographic form drag is important. The mean vorticity equation,

$$\beta\overline{v} + \overline{\vec{u}\cdot\nabla\zeta} = -f\frac{\partial}{\partial z}\overline{\nabla\times(\vec{\tau}/\rho_0 f)} \tag{2}$$

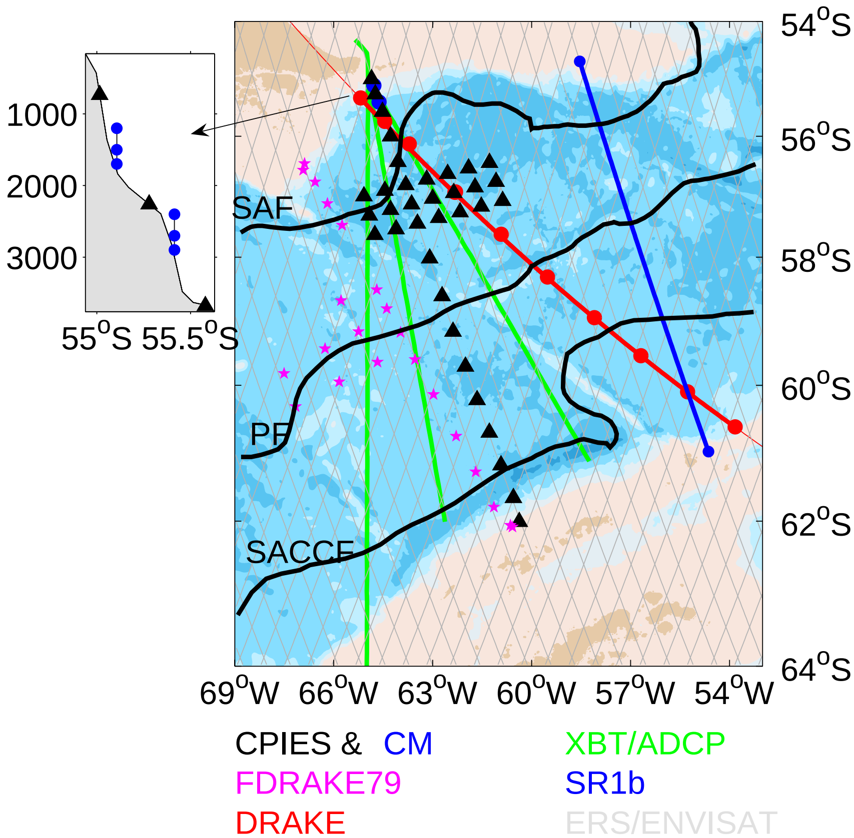
states that meridional meanders (advection of planetary vorticity) and advection of relative vorticity are balanced by the divergence of the curl of the frictional stress, which can also be expressed as the divergence of the eddy potential vorticity flux. Here β is the northward derivative of the Coriolis parameter and $\zeta = v_x - u_y$ is the relative vorticity. The depth integral of (2) relates the total vorticity advection to the difference between surface wind stress curl and bottom torque. Hughes (2005) argues that in the ACC, wind stress curl appears to be a minor influence in meander dynamics. Using a recent surface climatology as a proxy for the depth-integrated ACC, he found two modes of flow: meanders in which advection of relative and planetary vorticity balance, as in a stationary equivalent-barotropic Rossby wave, and a flow with divergence associated with topographic features that he interprets as a scaled measure of bottom torque. Form drag by bottom relief is predicted to be largest in Drake Passage (Hughes, 2005). Although his calculation is based on a surface map, an equivalent-barotropic model interpretation hypothesizes a vertical structure in which $\vec{u} \cdot \nabla\zeta$ more than balances βv at the surface, balances βv at some intermediate depth, and less than balances βv at greater depth, with the residual divergence being transmitted downward to exert a torque on the bottom (Hughes, 2005); however, this remains to be tested by observations.

2 Experiment Design

Our scientific objectives require time series of velocity as a function of depth, from near-surface to sea floor, measured on a lateral spacing that resolves the mesoscale eddy field, and with time interval shorter than weekly to avoid aliasing by rapid barotropic variability. To meet these needs we propose to deploy an array of CPIES, which will measure the ACC across Drake Passage and map the circulation and eddy currents within a local dynamics array centered in the region of highest EKE within Drake Passage (Fig. 2(c,e) and Fig. 3). This array will be deployed for four years, with data collected annually by acoustic telemetry to a ship, leaving each instrument undisturbed on the sea floor.

The pressure-recording inverted echo sounder (PIES) is a seafloor-mounted instrument that measures bottom pressure and emits 12 kHz sound pulses to measure the round trip travel times (TT) of these pulses to the sea surface and back. The CPIES includes a Doppler current sensor tethered 50 m above it to measure the near-bottom current outside the benthic boundary layer. TT measurements from the IES are used to estimate full-water-column profiles of temperature, salinity and density. These profiles are based upon historical hydrography for the region, from which an empirical look-up table (the so-called gravest empirical mode or GEM) is established to use TT as an index for vertical profiles of temperature, salinity, and density. Through geostrophy, laterally separated pairs of these density profiles yield vertical profiles of baroclinic velocity. The deep pressure and current measurements provide the reference velocity to render the velocity profiles absolute. Deep pressures are leveled by adjusting records to the same geopotential surface under the assumption that long time-averages of near bottom currents and bottom pressures are in geostrophic balance. These methods have been successful in many regions including the Kuroshio (e.g., Book et al., 2002), the Sea of Japan (e.g., Mitchell et al., 2004), the North Atlantic Current (e.g., Meinen and Watts, 2000), the North Brazil Current (Meinen and Garzoli, 2006), the Antarctic Circumpolar Current (e.g., Meinen et al., 2002), and the Gulf of Mexico (e.g., Hamilton et al., 2003).

Estimates of temperature and velocity from IES measurements are compared in Fig. 4 with directly-measured temperature and velocity from current meter moorings south of Australia in the ACC. The temperature records agree well and the small rms differences noted on these plots can be accounted for entirely by the uncertainty rms scatter in the GEM look-up table (Watts et al., 2001). The absolute currents can be obtained equally well by referencing the baroclinic velocity profiles with deep current and pressure fields or, as in this example, with vertically-averaged currents using horizontal electric field recorders (Meinen et al., 2002). The current records in Fig. 4 also agree



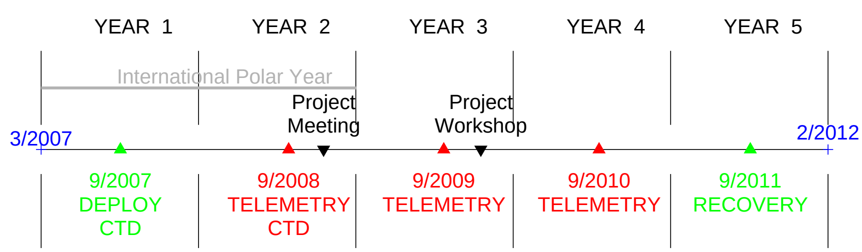


Figure 3: Top panel: Proposed array of CPIES (black diamonds) and current meters (blue circles) which will measure the ACC across Drake Passage and map the circulation and eddy currents within a local dynamics array. The cross-passage array is coincident with an ENVISAT track (grey lines) and lies east of the FDRAKE79 current meter moorings (magenta stars) and beneath the LMG repeat ADCP/XBT transects (green lines). Nearby observational programs include the DRAKE Mooring Line, PI C. Provost (red), SR1b repeat hydrographic section (blue line) and bottom pressure recorders (blue circles at terminations of SR1b). The inset to left of the map illustrates the configuration of two deep current meters moorings (blue circles) above the northern continental slope. Each mooring has current meters 100, 300 and 600 meters off the bottom. ACC frontal locations (bold black lines) (Orsi et al., 1995) are closely tied to bathymetry from Smith and Sandwell (1997) (contoured every 1000 m depth; tans hues represent shallow depths transition to blue hues in the deeper parts of the passage). Bottom panel: time line of experiment.

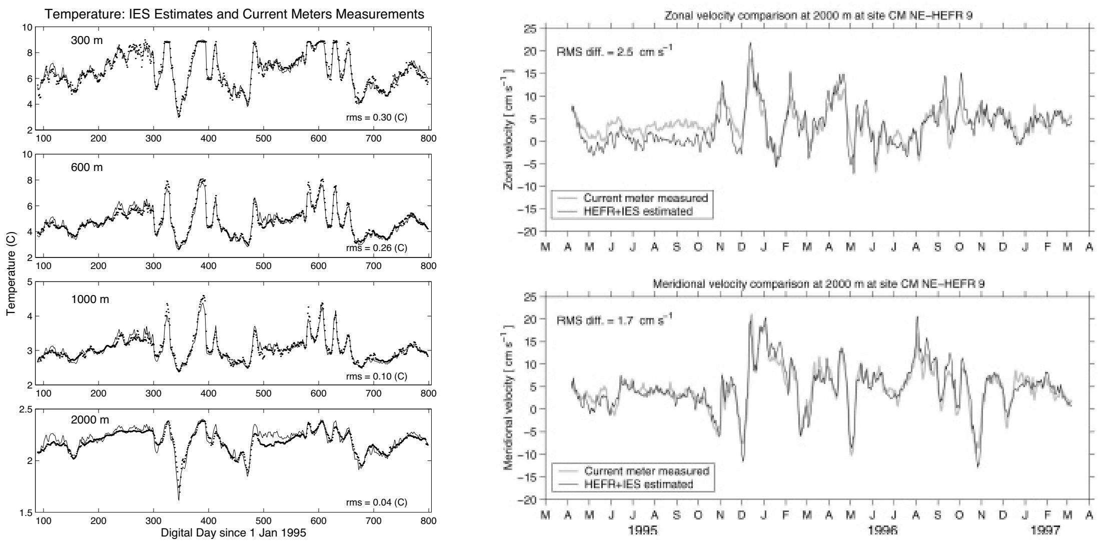


Figure 4: Left panels: Temperatures obtained by two methods in the Subantarctic Front south of Australia: estimates from TT measurements of a single IES using the GEM method (solid) at the same site as temperatures measured by four current meters (dotted) at the different depth levels shown. RMS differences noted, 0.04 to 0.30 °C. Note changes in the ordinate scales between panels. From Watts et al. (2001). Right panels: Directly-measured velocities (grey) and combined horizontal electric field recorder and IES velocities (black) with RMS differences noted, 1.7 to 2.5 cm s^{-1}. From Meinen et al. (2002).

well. The small differences in observed currents can be accounted for entirely in this mesoscale eddy field by sampling differences between point measurements and lateral integrals between IES sites – *i.e.,* even assuming that both the point-measured currents and the lateral integral currents have negligible error.

PIES arrays allow a decomposition of the absolute current structure and the absolute sea surface height into baroclinic and barotropic contributions (Teague et al., 1995; Hendry et al., 2002). The baroclinic component of SSH, the geopotential divided by gravity, represents the steric height contribution to sea surface height. Here we define the barotropic component as the bottom pressure divided by gravity and density; it represents the mass contribution to sea surface height. The baroclinic and barotropic components differ greatly in their temporal and spatial variability. The independent quantification of the baroclinic and barotropic contributions to the velocity structure and the transport is particularly valuable for a number of reasons. First, the role of bottom torques and form drag hinges upon knowledge of the current velocity structure. Second, barotropic eddy currents are observed to cross the meandering baroclinic zone and accurate knowledge of the mesoscale eddy heat fluxes and cross-frontal exchanges depends upon measuring the time-varying current velocity and density structure. Third, we seek to understand the separate time-varying barotropic and baroclinic contributions to the transports of the three separate fronts and relate them to lateral shifting over the bathymetry. Moreover, an improved understanding of these components can guide future transport monitoring.

In Drake Passage, the conversion of TT to geopotential height in order to determine baroclinic

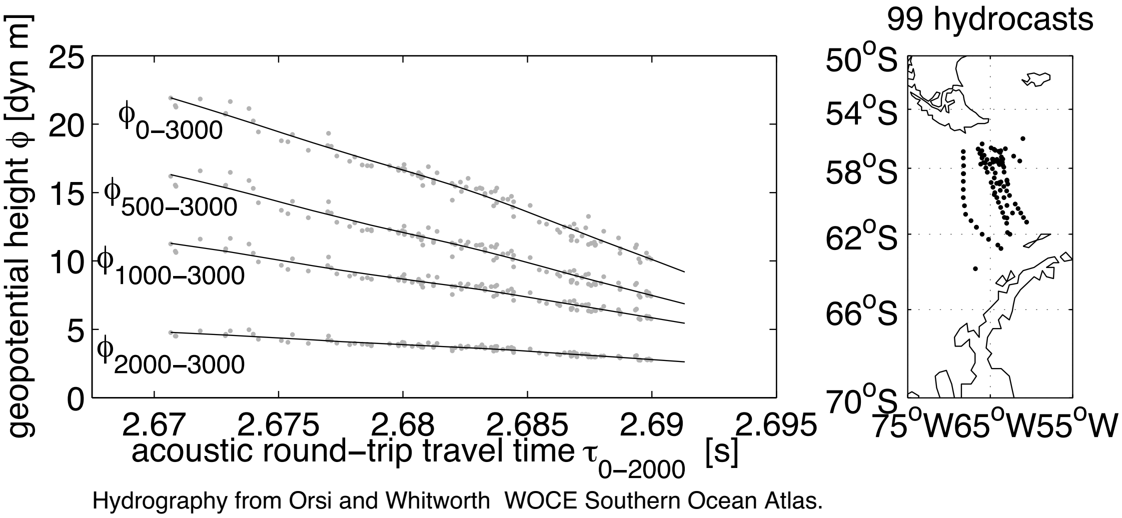


Figure 5: Left panel: Geopotential height referenced to 3000 dbar for four levels plotted against round-trip travel time between the surface and 2000 dbar. Right panel: Location of hydrocasts plotted in the left panel. Hydrography from Orsi and Whitworth WOCE Southern Ocean Atlas.

velocity profiles should work especially well. Fig. 5 shows that a strong relationship exists between TT and geopotential height throughout the water column. This confirms results from the Sun and Watts (2001) circumpolar study, in which the uncertainty estimates in a Drake Passage GEM are as good as in the region south of Australia, where T and (u,v) records were so good.

Acoustic telemetry of the moored CPIES data to a nearby ship is now a standard option and has been successful in Gulf of Mexico, Kuroshio Extension, and in the Deep Western Boundary Current off Abaco. The instrument internally processes data using typical post-processing techniques and saves a mean value. For this experiment a 48-hour mean will be saved. Note that the internal processing with a Godin filter ensures that tides are not aliased. Once the instruments are recovered, time series are detided and typically filtered with a 72-hour 4th order Butterworth filter and subsampled daily.

2.1 Transport Line

Seventeen CPIES span Drake Passage from 500 m isobath to 500 m isobath, with two additional deep current meter moorings on the northern continental slope; together they constitute the transport line (Fig. 3). CPIES are laterally coherent with average spacing near 55 km (spacing ranges from 45 to 65 km) with closer spacing near topography and north of 57.5°S and within the SAF. The two deep moorings each carry three current meters at 100, 300, and 600 m off the bottom, to directly observe the current structure in the bottom-triangles between CPIES on the continental slope. South of 58°S instruments are placed at ERS/ENVISAT cross-over points. Station spacing is comparable to the the FDRAKE79 current meter moorings (Whitworth, 1983; Whitworth and Peterson, 1985); magenta stars in Fig. 3, with the added advantage of employing laterally-integrating measurements, as follows.

The CPIES instrumentation and transport-line design is particularly well suited to measure geostrophic transport. We avoid potential spatial aliasing that results from point current measurements, because the geostrophic calculation between CPIES naturally integrates the average velocity. The conversion of TT to geopotential allows us to determine geostrophic shears, which are then referenced by the geostrophic near-bottom currents determined from the bottom pressures. Bottom pressures are leveled by using the record-mean bottom currents and assuming that the mean currents are in geostrophic balance. The velocity structure in Drake Passage is well represented by two vertical modes (Inoue, 1985; Klink and Hofmann, 1986); the CPIES-GEM methodology resolves these modes. Finally, the instrument records from the CPIES are not susceptible to mooring motion from current drag, which variably draws tall moorings deeper.

Above the continental slope the eddy and mean currents may exhibit an additional bottom intensified structure, that we estimate on the north end could carry approximately 3.5 Sv mean transport and O(10 Sv) eddy (topographic wave) transport, different from the mid-passage baroclinic shear. Corresponding mean and eddy values on the south slope we estimate to be about 1/3 as large. Knowledge of the vertical scales of bottom trapping would enable estimation of these added or subtracted components. The motivation behind this combined array design is to measure the vertical structure directly for two years on the north slope where it has the greatest effect, and parameterize the vertical trapping scale as a proxy to measurements in the subsequent period. On the southern slope, where the corrections are already estimated to be small, the vertical trapping scale proxy approach will suffice for all four years.

2.2 Local Dynamics Array

The local dynamics array (LDA) consists of 21 CPIES centered on the region of high eddy kinetic energy near 63.5°W, 57.5°S (Fig. 2(c,e) and Fig. 3). The grid spacing of 40 km will allow quantitative mapping of the upper and deep circulation in a 240 by 80 km region. The grid spacing has been determined by examination of mapping accuracy from optimal interpolation (Bretherton et al., 1976). Using a Gaussian covariance with e-folding scale of 55 km as determined from the LMG repeat ADCP velocity transects, the LDA will estimate velocity signal to nearly 10 % and vorticity signal within 20% (Fig.6). The horizontal extent of the array encompasses a wavelength of a stationary equivalent barotropic Rossby wave within Drake Passage (see Fig. 4 in Hughes, 2005). The LDA and the transport line share three instruments; the total number of CPIES in the experimental design is thirty five.

Our experiences in other strong current systems illustrate the utility of a mesoscale resolving array of PIES and deep current meters (Fig. 6). In order to understand mesoscale cross-frontal fluxes we must understand the large events well because they account for the bulk of the exchange (e.g., Cronin and Watts, 1996; Howden, 2000). In fact, the analysis of current fluctuations in Drake Passage showed that the statistics were dominated by a few strong events (Sciremammano, 1980).

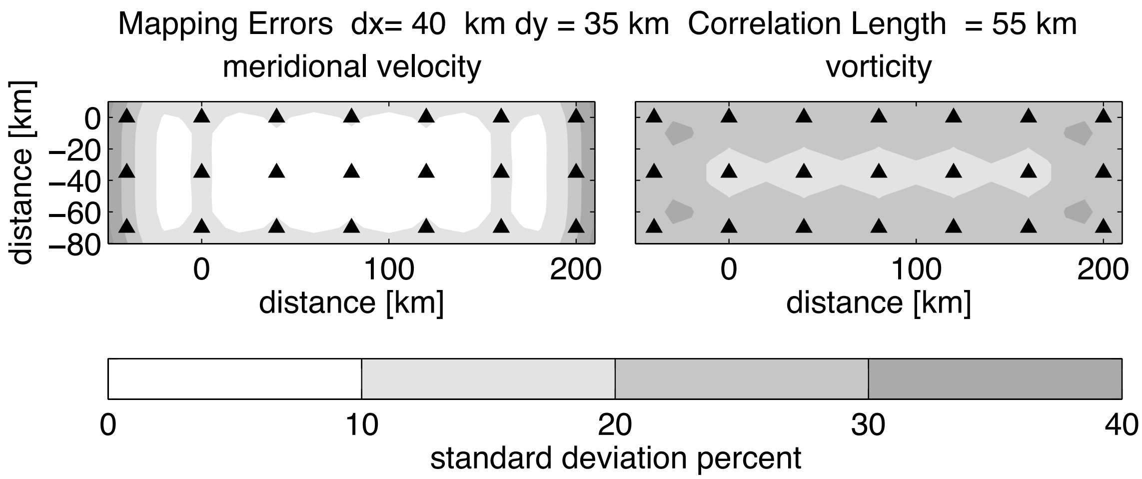


Figure 6: Estimated mapping errors in meridional velocity (left) and vorticity (right) for an LDA with spacing of 40 km predicted by optimal interpolation using a Gaussian covariance. The e-folding scale of 55 km is determined by LMG repeat ADCP velocity measurements.

2.3 Program Plan

The timeline for the project is shown in the lower panel of Fig. 3. We request a March 2007 start date for the project. The deployment cruise for CPIES and current meter moorings is targeted for September 2007, 9 months into IPY. We will telemeter the CPIES data at yearly intervals after the deployment until recovery in September 2011. Full water column CTD casts at each CPIES will be conducted on the deployment and first telemetry cruise in order to calibrate the TT records. In 2009 we will recover the two current meter moorings. URI will be responsible for the CPIES and mooring construction and initial data reduction. Personnel from both SIO and URI will participate on all five cruises, for which we are requesting [24 21 18 17 15] days on the ARSV L. M. Gould in the respective project years.

3 Specific Objectives

The three PIs will work collaboratively on all the science objectives, because of shared interests. Each PI will take lead responsibility for a specific group of topics, as follows: Donohue will take the lead on transport issues (1.1), Watts will take the lead on eddy fluxes and eddy-mean interactions (1.2), and Chereskin will take the lead on eddy fluxes and the mean momentum and vorticity balances (1.3). The measurements from the Transport Line and the LDA will enable us to address specific objectives:

Transport Line Analysis Objectives:

1. Determine the unaliased seasonal and annual-mean total ACC transport through Drake Passage and compare to historical estimates.

2. Determine the lateral partitioning of transport among the multiple jets comprised by the ACC

(the SAF, PF, and SACCF), in the mean and as a function of time.

3. Determine the vertical partitioning of transport between barotropic and baroclinic components in the ACC jets, separately and summed across the current.

4. Relate the long-term and interannual variability of the above combined and partitioned transports to circumpolar and global forcing fields.

5. Determine the contribution of bottom-trapped modes to transport along the northern continental slope in Drake Passage.

6. Test the model-based hypothesis that the barotropic ACC transport can be monitored by bottom pressure at the southern side of Drake Passage.

7. Reference the ERS/Envisat altimeter line along which this array is moored. Also reference the combined altimeter and GRACE regional gridded products for estimating transport in Drake Passage, in an attempt to take advantage of more frequent sampling on multiple lines that cross Drake Passage which thereby may reduce alias error from a single line. The geoid, so referenced, may be applied to improve earlier and future estimates from satellite products.

8. Evaluate the temporal aliasing in transport estimates from other measurements such as altimetry, repeat hydrography, and repeat XBT/ADCP transects.

9. Recommend a minimal array design for future monitoring efforts – of transport in total or partitioned as above.

Local Dynamics Array Analysis Objectives:

1. Map the vertical, cross and alongstream structure of current and temperature fields with mesoscale resolution daily for four years, in a region spanning from sea surface to sea floor, 80 km cross-stream in the EKE maximum, and 250 km along-stream through a full alongstream wave length. Separately determine the baroclinic and barotropic components, and test the postulate that these contributions are aligned in the mean. The mesoscale eddy baroclinic and barotropic components are known to cross variably with time, however.

2. Estimate the along-stream momentum balance on isopycnals through the water column within the LDA. Specifically, quantify the cross-frontal flux of potential vorticity on isopycnals (a in equation 1), the lateral divergence of eddy momentum flux (b in equation 1) and the vertical divergence of cross-front eddy heat flux (c in equation 1 which is proportional to the interfacial form stress under quasigeostrophy).

3. Compare the terms in the momentum balance to the wind input of momentum at the sea surface (d in equation 1). Test the postulate that the mean wind input of momentum is carried downward undiminished through the water column.

4. Quantify the mean vorticity advection (in equation 2, including its vertical structure through the water column to infer local bottom form stress. Test the postulate that the bottom form stress can be inferred from the surface velocity field, under the assumption that the mean current is equivalent-barotropic.

5. Describe and quantify the mesoscale variability. Relate long-term variations of EKE and EPE to circumpolar wind forcing and regional eddy variability detected by satellites, floats, drifters, and other methods.

6. Quantify the eddy-mean exchange of momentum and energy.

7. Diagnose case-studies of major eddy events in the LDA, their kinematics and cross-frontal

fluxes. Test whether a few major events or many small events account for most of the eddy fluxes.

4 Program and Data Management

Program management includes coordination between the project PIs as well as with the broader oceanographic community. We plan to maintain a web site to facilitate inter-PI communication including data exchange and to provide information to peers and to the public. A PI meeting is planned for Year 2 after the first telemetry cruise for data-collection. In Year 3 after the second telemetry cruise we anticipate an open project workshop, for the purpose to facilitate broader collaborations with interested members of the community. In particular, we plan to release the first two years of bottom pressure, bottom current, and round-trip acoustic travel time records at the end of Year 3. The workshop would provide a forum to discuss additional analysis products to be made available, such as metrics for numerical models. For example, the time series of Drake Passage transport decomposed into baroclinic and barotropic components, and deep EKE along the transport line and EKE maps within the LDA would be potentially useful metrics for general circulation models.

5 Relation to IPY and other projects

U. S. IPY: The project will contribute to goal 2 of the 6 IPY observational goals expressed by the U.S. National Academy of Science and to theme 1 of the 6 IPY themes expressed by the International Council for Science (ICSU): *(Goal 2)* Acquire key data sets to understand factors controlling change in the polar environment. *(Theme 1)* To determine the present environmental status of the polar regions by quantifying their spatial and temporal variability.
ADCP/XBT repeat sampling: The CPIES time series of velocity, density, and geostrophic transport from this project will complement the spatial resolution of the ADCP/XBT repeat survey program in Drake Passage. The daily time series will be used to evaluate temporal aliasing that has been predicted by models to spoil annual mean estimates from measurements at time intervals as short as a week and greater. XBT/XCTDs will provide additional calibration for the CPIES.
International Polar Year and CLIVAR: This project complements but does not duplicate the U.K. pressure gauge and repeat hydrography observations (SR1b) and the French moorings (DRAKE) deployed in January 2006 along a Jason ground track (Fig. 1). The DRAKE current meters, whose recovery is planned in March 2008, would overlap the CPIES for about six months. Our goals are distinct from SR1b and DRAKE in that: (Transport Line) we propose to measure the total transport of the ACC with a combination of sufficiently rapid sampling and lateral-integrating resolution to determine the seasonal to annual variability and for a sufficient duration to determine interannual variability; and (LDA) we propose to resolve the mesoscale structure and understand the dynamical balances in the energetic region between the SAF and the PF. The temporal sampling on SR1b is aliased and insufficient to resolve transport on these time scales, and the DRAKE moorings have insufficient duration to estimate transport for periods beyond the initial 26 month deployment. Neither SR1b nor DRAKE has the 2-D horizonal resolution required to map the mesoscale. However,

the temporal overlap of our measurements will provide remarkable coverage of Drake Passage during IPY. Our proposed transport array complements the Australian/French/U.S. effort south of Tasmania (SURVOSTRAL, Dr. Stephen Rintoul, Dr. Rosemary Morrow and Dr. Dean Roemmich P.I.s) and the IPY effort south of Africa (GOODHOPE, Dr. Sabrina Speich, P. I.). We have good working relationships with these investigators, and we plan to work collaboratively with them in interpreting our datasets.
DIMES: The Diapynal and Isopycnal Mixing Experiment in the Southern Ocean (DIMES) is a proposed study of mixing that will focus on the southeast Pacific, Drake Passage and the Scotia Sea during the time period of our proposed measurements. Our programs would be complementary, with the CPIES time series providing a physical context for DIMES and the float releases proposed by DIMES providing a Lagrangian component to our observations.

6 Significance of proposed work

Intellectual Merit: The Southern Ocean responds sensitively to climate change, driven by winds that have increased over the past 30 years, and it has warmed significantly more than the global ocean over the past 50 years. The Drake Passage chokepoint is well suited geographically for measuring the time-varying transport of the ACC and its constituent parts, as a measure of the pulse of the Southern Ocean. Moreover, observations and computer models suggest that dynamical balances which control its transport are particularly effective through the Drake Passage. This project contributes to the International Polar Year (IPY) through its transport line monitoring of the ACC in Drake Passage. The observations will resolve the seasonal and interannual variability of the total ACC transport, its vertical structure partitioned between barotropic and baroclinic components, and its lateral structure partitioned among the multiple jets within the ACC. We have selected a region of highly energetic mesoscale eddies, which are thought to mediate the transfer of momentum from the circumpolar winds that drive the ACC, down through the water column to the sea floor, where topographic form stresses regulate its long-term transport. Measurements in the LDA are designed to quantify eddy exchanges with the mean current and density structure, and determine the mean vorticity balance in order to test hypotheses regarding the suite of processes that together govern the strength of the time-varying ACC.

Broader Impacts: Quality-controlled time series of currents, temperature, and density from the CPIES measurements will be disseminated, together with data products (transports, maps, 3D fields) suitable for long-term monitoring of the ACC and for validating numerical models. An outcome of this study will be a recommendation for the minimal instrumentation required for long-term monitoring of the ACC transport and its constituent parts. The subset of instrumentation purchased by Raytheon (10 CPIES) will become part of the U. S. Antarctic Program instrument pool and be available for future investigators. The project contributes to graduate education (3 students).

7 Results from Prior NSF support

T. K. Chereskin: Collaborative research: Shipboard acoustic Doppler current profiling on R/V Nathaniel B. Palmer and R/V Laurence M. Gould (OPP9816226, $328,437, 1/1/99-12/31/04)

This award and its continuation support the collection, analysis and dissemination of underway ADCP data from the U. S. Antarctic icebreakers, in collaboration with Dr. Eric Firing at the University of Hawaii. Chereskin's main responsibility is the ADCP data collected from the ARSV Laurence M. Gould. During the initial grant period, 128 velocity sections from Drake Passage were acquired and analyzed (http://adcp.ucsd.edu). These high-resolution, long-term, direct velocity observations have been used to describe and quantify the mean jets, mesoscale variability, and eddy momentum fluxes in Drake Passage (Lenn et al., 2006). The grant supported participation in an ecosystem study of Deception Island (Lenn et al., 2003; Smith et al., 2003). Additionally, the data products resulting from this grant have been used by numerous other investigators, including the Southern Ocean GLOBEC program (PIs Padman and Zhou), some marine biology and geology programs (PIs Scheltema, Smith, and Domack), and Argentinean acousticians (Baques and Blanc). The grant supported one PhD student, Yueng-Djern Lenn.

D.R. Watts and K. Donohue: Collaborative Research: Kuroshio Extension System Study (OCE 0221008, $ 3,667,404, 12/01/02 11/30/07)

The goal of this study is to understand the processes that govern the variability of the Kuroshio Extension and its recirculation gyre. Processes coupling the baroclinic and barotropic circulations are being examined by case studies of the local dynamical balances, particularly during strong meander events. We moored a mesoscale-resolving array of CPIES on the ocean floor beneath the Kuroshio Extension east of Japan. The array encompasses the region of high eddy kinetic energy determined from satellite altimetry. The CPIES are spaced at about 70 km to quantitatively map the upper and deep circulation in a 600 by 600 km region. Telemetry in June 2005 retrieved 14 months of records from 42 instruments. Final array recovery will be in Summer 2006. Five presentations have resulted from initial analysis (Donohue et al., 2006a,b; Watts et al., 2006; Tracey et al., 2006; Greene et al., 2006).

The Kuroshio Extension transitioned from a stable period, June to November 2004, to an energetic meandering period. During the stable period, a broad region of anticyclonic circulation existed beneath the stable strong recirculation gyre. During the energetic period, deep anticyclones and cyclones traversed through the region and intensified beneath the large-amplitude meanders. Deep eddy velocities exceeded 30 cm s^{-1}, much larger than the 7 cm s^{-1}deep mean currents. The deep eddy velocities often exhibit a component normal to the upper baroclinic front and this causes substantial cross-frontal exchange of properties and vertical motion along sloping isopycnals. Strong barotropic eddies transited quickly through the array contributing significantly to the overall sea surface height variability. Daily maps of sea surface height show energetic processes not apparent in merged satellite sea surface height products. Short wavelength (160 km) meanders passed rapidly (25-30 km d^{-1}) along the northern edge of the Kuroshio Extension. Initial results by Qiu et al. (2006) document the properties and seasonal evolution of the North Pacific Subtropical Mode Water during the stable period.

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