Vertical Structure and Transport of the Antarctic Circumpolar Current in Drake Passage From Direct Velocity Observations

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Abstract.

The structure of the Antarctic Circumpolar Current (ACC) in Drake Passage is examined using four and a half years of shipboard Acoustic Doppler Current Profiler (ADCP) velocity data. The extended 1000-m depth range available from the 38kHz ADCP allows us to investigate the vertical structure of the current. The mean observed current varies slowly with depth, while eddy kinetic energy and shear variance exhibit strong depth dependence. Objectively mapped streamlines are self-similar with depth, consistent with an equivalent-barotropic structure. Vertical-wavenumber spectra of observed currents and current shear reveal intermediate-wavenumber anisotropy and rotation indicative of downward energy propagation above 500 m and upward propagation below 500 m. The mean observed transport of the ACC in the upper 1000 m is estimated at 95±2 Sv or 71% of the canonical total transport of 134 Sv [Whitworth and Peterson, 1985]. Mean current speeds in the ACC jets remain quite strong at 1000 m, 10 to 20 cm s$^{-1}$. Vertical structure functions to describe the current and extrapolate below 1000 m are explored with the aid of full-depth profiles from lowered ADCP and a three-year mean from the Southern Ocean State Estimate (SOSE). A number of functions, including an exponential, are nearly equally good fits to the observations, explaining >75% of the variance. Fits to an exponentially decaying function can be extrapolated to give an estimate of 154±38 Sv for the full-depth transport.
1. Introduction

The Antarctic Circumpolar Current (ACC) is unique among major ocean currents in its lack of complete meridional boundaries as well as its low stratification and large depth extent. Its role in connecting the Pacific, Atlantic and Indian Oceans and in the meridional overturning circulation means that it is a crucial feature for models of global circulation and climate to reproduce accurately. Model predictions of the degree and distribution of eddy stirring depend on the current’s structure and large-scale dynamical balances, but observations that can be used to quantify its transport and structure are sparse. In particular, there are few datasets with the depth range and resolution necessary to define the vertical structure. Satellite measurements provide valuable coverage of the surface ACC, and a better understanding of its vertical structure could allow mapping from these surface observations to metrics such as transport.

Drake Passage, bounded by South America and the Antarctic Peninsula, has been the site of a number of attempts to quantify and describe ACC transport. Whitworth [1983] and Whitworth and Peterson [1985] estimated transport from International Southern Ocean Studies (ISOS) mooring and cruise data to give the canonical ACC transport of 133.8 Sv with a standard deviation of 11.2 Sv. They calculated relative transport using temperature and salinity moorings on either side of the passage between 500 m and 2500 m depth and historical hydrography between 500 m and the surface. Pressure sensors at 500 m on either side of the passage were leveled using direct current measurements from three hydrographic cruises, and after adjustments to remove contributions from the slope regions above 2500 m, they provided a reference velocity at 500 m. The year-long average
total transport above 2500 m was found to be 124.7±9.9 Sv [Whitworth and Peterson, 1985], of which 87 Sv was due to shear above 2500 m and 37.7 Sv to the velocity at 2500 m [Whitworth, 1983]. An estimated 9.1±4 Sv of transport below 2500 m [Whitworth, 1983] brought the total to 133.8±11.2 Sv. Cunningham et al. [2003] revisited the ISOS dataset and the sources of uncertainty to arrive at an upper bound of 27 Sv for the measurement uncertainty on the mean total transport.

Whitworth and Peterson [1985] used the correlation between transport and current derived from the cross-passage pressure difference at 500 m to extend the ISOS transport time series to five years, and found a range of 95 to 158 Sv. Cunningham et al. [2003], however, calculated that only 65% of the total variability in the ISOS transport was barotropic, leaving a significant remaining fraction in the baroclinic component. This is consistent with the results of Sprintall [2003] and Olbers and Lettmann [2007], who found large baroclinic transport variability from upper ocean XBT measurements and numerical model results, respectively.

Other velocity observations point to significant deep structure in both time-varying and mean velocities. Instantaneous measurements have shown large near-bottom currents: from a shipboard Acoustic Doppler Current Profiler (SADCP) and hydrography, Donohue et al. [2001] inferred speeds of 4 to 10 cm s$^{-1}$ in the Subantarctic Front (SAF) in the Pacific, while Cunningham et al. [2003] reported lowered ADCP-measured velocities of as much as 10 to 20 cm s$^{-1}$ in Drake Passage. Mean speeds are also substantial; one-year mean near-bottom velocities from an array of current meters in Drake Passage were in excess of 10 cm s$^{-1}$ in the northern part of the passage [Chereskin et al., 2009]. Using moored
current meter records from the SAF south of Australia, Tracey et al. [2006] found mean speeds of 4 to 6 cm s\(^{-1}\) at 3500 db and deep-reaching baroclinic shear (to at least 2000 m).

Observational constraints on the vertical structure of the ACC are essential. The strength of deep currents has implications for the dominant dynamical balance: the interaction of near-bottom currents with topography leads to vortex stretching, momentum, energy, and vorticity dissipation through bottom friction and torque, and ultimately to turbulence production resulting in mixing. Meanwhile, validation of the vertical shear structure is important for models which use shear to parameterize mixing. Definition of the vertical structure of the ACC could also allow single-level observations, such as mid-depth float data or satellite observations of the surface, to be mapped to the full ACC. Many observations and models of the ACC are consistent with an equivalent-barotropic (EB) vertical structure; that is, that streamlines are parallel at all depths, unless velocity goes to zero. Hughes and Killworth [1995] and Killworth and Hughes [2002] showed how EB structure results from geostrophic flow with a relatively weak planetary vorticity gradient. Sun and Watts [2001] found that first empirical modes calculated by the Gravest Empirical Mode (GEM) method, in which an EB structure for the baroclinic current is inherent, explain 97% of the density variance in the ACC at all longitudes. In both the Fine Resolution Antarctic Model [Killworth, 1992] and the global OCCAM [Killworth and Hughes, 2002], velocity in the ACC has a separable EB structure, such that it is a function of the horizontal coordinates alone multiplied by a function of the vertical coordinate alone. Exponential decay with depth is one explored EB form: Gille [2003] calculated an average vertical e-folding scale of 700 m from float velocity and atlas hydrography, and Karsten and Marshall [2002] found that climatological buoyancy data are
well-described by exponential decay with depth, but that length scales vary from under 500 m to over 1000 m from south to north, which implies a non-separable EB structure for velocity. Observations of quasi-stationary short barotropic Rossby wave-like meanders by Hughes [2005], Tracey et al. [2006], and Chereskin et al. [2010] also support an EB vertical structure.

Understanding the structure of the ACC depends upon understanding the eddy dynamics which both forces and is forced by the mean current [e.g. Bryden and Cunningham, 2003; Karsten et al., 2002]. The horizontal and vertical distributions of eddy momentum fluxes set the locations and structures of the mean jets [Lenn et al., 2011], which are highly time-variable [Sokolov and Rintoul, 2007, 2009b]. The interaction between eddies and jets also influences the rate and distribution of heat and salinity transport across the current. Intensification of eddy kinetic energy (EKE) around complex topographic features is evident in both altimeter data and numerical models [Gille, 1997; Williams et al., 2007]. Lenn et al. [2007], from measured currents down to 250 m, found high EKE in the Polar Frontal Zone (PFZ) in Drake Passage. Multiple studies have found evidence that the observed eddies, which have horizontal scales of up to 100 km, are generated by baroclinic instability [Phillips and Rintoul, 2000; Smith, 2007; Smith and Marshall, 2009], although barotropic instability and eddies also have been seen [Nowlin and Klinck, 1986; Tracey et al., 2006]. The locations of instability growth and eddy stirring depend on the mean current structure; strong potential vorticity (PV) gradients associated with strong fronts can act to inhibit eddy stirring and therefore mixing. Smith [2007] computed PV gradients from a hydrographic atlas and inferred multiple locations of baroclinic instability growth down to 1500 m, while Smith and Marshall [2009] and Abernathey et al.
[2010] found a deep (≥1000 m) maximum in eddy stirring below the core of the ACC, with stirring inhibited in the surface layer within the current. The analysis of Thompson et al. [2010], however, suggests that this effect is not uniform throughout the ACC.

The studies described above, which suggest important roles for both barotropic and baroclinic components of transport, as well as mesoscale variability and deep eddy stirring, point to the need for direct current measurements with high spatial resolution to confirm inferences drawn from climatology and models. In this paper we use a new dataset of direct velocity observations collected by a deep-profiling sonar over a 4.5 year period to examine the vertical structure of the ACC in Drake Passage. In Section 3 we describe the mean current and find that the direct current observations are generally consistent with an equivalent-barotropic vertical structure. In Section 4 we examine the vertical structure of velocity, EKE, and Reynolds stresses with an eye to illuminating the distributions of energy and eddy stirring, and we search for vertical structure functions to describe the mean and time-varying currents. We calculate top 1000-m transport in Section 5, and use the vertical structure from the previous section to extrapolate in depth. In Section 6 we summarize our findings and discuss the implications for ACC dynamics and transport.

We describe the SADCP dataset and other datasets in the following section.

2. Data

The ARSV Laurence M. Gould (LMG) crosses Drake Passage repeatedly in all seasons in the course of supplying Palmer Station on the Antarctic Peninsula and conducting research in the area. Lenn et al. [2007] described processing and analysis of data from a 153.6 kHz SADCP on the LMG. Since late 2004, the LMG has also been outfitted with a 38 kHz RD Instruments ADCP. The 38 kHz ADCP has a transducer depth of 6 m, a
blanking distance of 16 m, and samples in narrowband mode with a 24 m bin and pulse, so 
that the first depth bin is centered at 46 m and every other bin is independent. Returned 
ping data are averaged over 5-minute ensembles, which are screened using amplitude, 
error, and percent good criteria. An Ashtech GPS is used to correct heading from the 
ship’s gyrocompass, with the difference between instrument and ship coordinates corrected 
for by bottom tracking (see Appendix). Data are converted to earth coordinates using 
the corrected heading and the ship’s GPS.

Data from 105 crossings (tracks shown in Figure 1) from November 2004 through 
June 2009 have been processed and edited using the CODAS3 software package 
(http://currents.soest.hawaii.edu/software/codas3). The 38 kHz instrument records data 
from as deep as 1222 m; in this dataset just over 50% of ensembles at 1030 m contain 
good data. Velocities are further averaged to 15-minute bins (covering approximately 
5 km along-track) and the barotropic tide from the TPXO6.2 tidal model [Egbert et al., 
1994] is removed. Baroclinic tidal predictions vary substantially; however, Lenn et al. 
[2007] analyzed ISOS mooring records from mid-passage and found a maximum baro-
clinic semidiurnal and first harmonic peak in kinetic energy of no more than 15 cm² s⁻², 
so we expected the baroclinic tidal currents to be negligible in most of the passage and 
did not attempt to remove them from our data. A correction for heading-error-induced 
velocity bias is described in the Appendix.

Calculation of geostrophic current shear using density profiles and the thermal wind 
balance sheds light on the geostrophic vs. ageostrophic and baroclinic vs. barotropic 
components of the SADCP-measured total velocity. The LMG also hosts the high reso-
lution expendable bathythermograph (XBT)/expendable conductivity-temperature-depth
(XCTD) sampling program [Sprintall, 2003]. These data are made available by the Scripps High Resolution XBT program (http://www-hrx.ucsd.edu). XBTs are dropped on six crossings each year at intervals of 6 to 15 km, and generally obtain temperature measurements to about 850 m depth. On the same crossings, twelve XCTDs deployed at a spacing of 25 to 50 km measure temperature and salinity to around 1000 m. A position-dependent T-S-z relation constructed from historical hydrography gives a salinity profile for each XBT temperature profile; where XCTD temperature-salinity data are available, they are used to correct the derived salinities (J. Sprintall, pers. comm.).

To give spatial and temporal context to the irregularly sampled LMG datasets, optimally interpolated satellite altimeter sea level anomalies (SLA) were obtained from the Archiving, Validation and Interpretation of Satellite Oceanographic data (AVISO) project [Ducet et al., 2000]. The AVISO mapped SLA product is derived from multiple satellite altimeters. We recalculated anomalies with respect to the November 2004 to June 2009 mean.

To extend the top 1000-m SADCP observations in depth, we examined full-depth current profiles from a lowered ADCP (LADCP) from four Drake Passage cruises (cDrake) in November-December of four consecutive years, with 56 casts in 2007, 47 in 2008, 67 in 2009, and 62 in 2010. The LADCP is a 153.6 kHz broadband RD Instruments ADCP, with a 30° beam angle and a 16-m vertical bin, pulse, and blank before transmit. Data were processed following Fischer and Visbeck [1993] using the UH CODAS LADCP software developed by Eric Firing. LADCP measurements of water velocity relative to the instrument are differenced to obtain vertical shear, which is gridded into 20-m depth bins and integrated to obtain the baroclinic velocity profile. Measured velocity is also inte-
grated over the cast and added to the ship drift to get the depth-averaged, or barotropic, velocity. Errors in the baroclinic (barotropic) component of velocity with this instrument, sampling scheme, and processing method are 4 cm s\(^{-1}\) (1 cm s\(^{-1}\)) [Chereskin et al., 2010].

For this study, we averaged up- and down-cast velocity profiles.

We also considered the Southern Ocean State Estimate [SOSE, Mazloff et al., 2010], an eddy-permitting state estimate which iterates via the adjoint method to minimize misfit between the estimate and observations, subject to uncertainties in the inputs. Pressure, temperature, salinity, velocity, and other variables are calculated on a 1/6° grid with 42 depth levels. Here we used daily mean velocity output from a run over 2005 through 2007. Neither the LMG SADCP nor the cDrake LADCP data are included in the constraints on SOSE, although the LMG XBT/XCTD dataset is.

Multibeam bathymetry data collected on the RVIB N.B. Palmer were combined with the dataset of Smith and Sandwell [1997] to give high-resolution bathymetry in the Drake Passage area.

In addition to geographic coordinates, we use a coordinate system \((x_p, y_p)\) rotated 23.7° counter-clockwise from zonal and meridional directions, so that \(x_p\) runs through-passage towards the Atlantic and \(y_p\) across-passage towards Tierra del Fuego. For some analyses, velocities from each crossing were vector-averaged to a horizontal grid with a grid spacing of either 5 or 25 km; the results are referred to as “gridded velocities”. Once gridded, velocity measurements may be averaged over all cruises. Following Lenn et al. [2008], we subtracted geostrophic surface current anomalies calculated from AVISO SLA from gridded SADCP currents at each depth before averaging to produce “improved mean” currents with reduced aliasing. We note that while the altimeter-derived surface current
anomalies are an overestimate at depth, they are an underestimate at the surface [see Lenn et al., 2007, Figure 9]. Depth sections come from the most commonly visited line (54 to 97 crossings through each 25 km by 25 km grid box), marked by the 25 km-wide gray box in Figure 1. For calculation of transport we assumed slab motion in the top 46 m.

3. Mean Structure and Streamfunction

The 46-1030 m depth-mean ACC (Figure 2a) has a strong resemblance to the 26-250 m depth-mean calculated by Lenn et al. [2007] (see their Figure 5), with slightly lower speeds and energies. Although the instantaneous current field is a complex mixture of eddies and jets with an often-multivalued transport streamfunction, the SAF, PF, and Southern ACC Front (SACCF) jets are clearly visible in the Eulerian mean (Figure 3a). Mean speeds over the top 1000 m are 30 cm s$^{-1}$ in the SAF and PF, and 15 cm s$^{-1}$ in the SACCF. Standard deviations are 10 to 30 cm s$^{-1}$ and variance ellipses are oriented along or slightly to the right of the mean current direction in the SAF; in the SACCF and PF they are oriented across the mean current direction. Eddy kinetic energy (EKE = $\frac{1}{2} < u'^2 + v'^2 >$, $\vec{u}' = \vec{u} - < \vec{u} >$) is highest in the PFZ (between the SAF and PF), consistent with the surface-layer analysis of Lenn et al. [2007] and with EKE from altimetric SLA. The “improved mean” (see Section 2, above) has similar speeds but lower standard deviations (8 to 20 cm s$^{-1}$) and less directional variation in the jets. Variance ellipses relative to the “improved mean” are generally anisotropic and oriented across the mean flow over most of the area. We consider the “improved mean” to be a better representation of the long-term mean than can be attained from only 4.5 years of SADCP data, and therefore use it as the mean field in the rest of this paper.
We objectively mapped improved mean current vectors to streamlines. The mapping algorithm uses Gaussian covariance functions that satisfy geostrophic continuity as derived in Gille [2003] and incorporates error estimates on the data to produce a mapping error [Bretherton et al., 1976]. We used an isotropic decorrelation scale of 50 km determined from track data and a data fractional error of 0.2. We found the results to be insensitive to changes of ±10 km in the decorrelation length scale as well as to the size and structure of the data error within a reasonable range. We tested several options for the background mean streamfunction, and found that the mapped streamfunctions and currents are not sensitive to the background mean as long as it is geostrophic, has some gradient across the passage, and is defined beyond the data points. For the results presented here we used the surface dynamic topography of Maximenko and Niiler [2005]. We show and consider only results with a mapping error of ≤0.3, as determined by the objective mapping procedure based on data locations and the decorrelation function. Residual velocities are relatively small (rms 4.5 cm s$^{-1}$ over all depths) and apparently randomly oriented, lending confidence in the assumption of geostrophy.

Maps at selected depth levels are shown in Figure 2. The objectively mapped depth-mean field (Figure 2a) has large meanders both in the PFZ and in the SACCF area. The SAF is aligned to the north-northeast; the PF turns from northeast entering the passage to nearly due east exiting the passage, while the SACCF has a large northward meander. While the SAF deviates north following the bathymetry, the other meanders do not appear to be related to local bathymetry. The PF strengthens slightly (streamlines converge) going alongstream through our sampling area. The widths of the Eulerian-mean SAF, PF, and SACCF are approximately 100, 200, and 75 km, respectively, while
the SAF and PF are separated by about 200 km and the PF and SACCF by over 200 km; we note that the instantaneous jets are narrower. The objective maps are consistent with EB structure in most locations: mapped streamlines are strongly self-similar with depth (Figure 2), with gradients decreasing only gradually and features including the three major fronts and the meander in the PFZ visible at all depths. The streamline shapes in the area of the SACCF are the most variable with depth. The position of the PF jet, as represented by the intersection of the highest-gradient streamline in the PF area and \( x_p = 0 \), has a tilt of 81 km towards South America over 1000 m of depth. The SAF and SACCF positions do not have significant tilts over this depth range.

From the objectively mapped streamfunctions at each depth we constructed a set of local mean stream coordinates, with \( x_\psi, u_\psi \) along the local mean streamline and \( y_\psi, v_\psi \) across it. These coordinates are used in the following sections.

4. Vertical Structure

In this section we examine the vertical structure of the top \( \sim 1000 \) m of the ACC in Drake Passage. We look for a simple function or set of functions to describe the low-mode vertical structure of the current and use spectra to explore higher-wavenumber processes. We also investigate the distribution of eddy fluxes and eddy kinetic energy and their implications for instability and eddy stirring.

All three Eulerian-mean jets (Figure 3a) extend to the limits of our depth range below 1000 m, and the current speed in the center of each jet at 1000 m is approximately half its maximum at 46 m. The mean jets are all somewhat skewed, having higher horizontal shear on their northern sides and higher vertical shear on their southern sides, although the latter gradient is more pronounced for the PF and SACCF. With the exception of
the surface-intensified coastal current observed at the northernmost point, current speed
decreases slowly as a function of depth (Figures 4 and 5a) and orientation varies little
(Figure 5b), especially within the mean jets. Mean-current vertical shear, which is of
order $1 \times 10^{-4}$ s$^{-1}$ except at the northernmost point, is generally positive in the SAF and
PF, and weakly positive to moderately negative outside the jets. Shear in the gridded
currents, even when smoothed, can be a factor of two or more stronger than that in the
mean currents. Shear variance below the surface layer is around $(2 - 4) \times 10^{-6}$ s$^{-2}$, which
implies a 95% confidence interval on mean shear estimates of $\pm (3 - 4) \times 10^{-3}$ s$^{-1}$, larger
than any individual shear value. As suggested by the success of the geostrophic objective
mapping procedure (see Section 3), mean geostrophic shear (not shown) from XBT/XCTD
data and derived salinities (see Section 2) is in general agreement with directly-measured
mean vertical shear in across-track currents, especially in the northern part of the passage.
The mean SAF and PF jets are clearly identifiable in geostrophic shear, with the same
depth-average values as directly measured shear in these jets, and coincident with their
directly measured locations. The SACCF is less well defined in geostrophic shear and in
velocity from the XBT-assimilating SOSE (Figure 3b) than in the SADCP observations
(Figure 3a).

Given the strength and proximity of the PF and SAF, it is not surprising that EKE
(Figures 5c and 6b) is by far strongest in the PFZ at all depths. The maximum EKE is
significantly larger than the maximum kinetic energy of the mean flow (Figure 6a), and
EKE in the PFZ drops off faster with depth than does KE in the jets. It is also unevenly
distributed between along- and across-stream contributions (Figure 6c, d). The ratio of
KE to EKE in the jets is large enough that by the criterion of Ferrari and Nikurashin [2010]
they would act as mixing barriers all the way down to 1000 m; however, the derivation
of Ferrari and Nikurashin [2010] is not expected to apply to the constrained and highly
nonzonal fronts of Drake Passage, so it remains uncertain to what extent the jets in this
area impede mixing.

The across-stream eddy flux of along-stream momentum, \(<u'_{\psi}v'_{\psi}>\), is relatively depth-
independent in sign and even in amplitude (Figure 6e). From this dataset we could only
calculate statistically significant divergences on a rather large scale; we found divergence
of \(<u'_{\psi}v'_{\psi}>\), corresponding to deceleration, on the northern side of the PF jet, and con-
vergence, corresponding to acceleration, on the southern edge of the SAF jet. This pattern
is similar to the divergences calculated by Lenn et al. [2011] with a 7-year timeseries in
the upper 250 m, suggesting that their results for the pattern of acceleration by eddies
may be extendable to a greater depth range.

4.1. Spectra

The energy-containing vertical and horizontal length scales of the ACC are of basic
interest and are essential to theoretical models of the current system. Spectra can also re-
veal information about rotation at internal wave scales and, therefore, about the dominant
direction of energy propagation in different regions [Leaman and Sanford, 1975].

We computed vertical wavenumber spectra over several depth ranges using the 15-
minute averaged profiles (see Section 2). We averaged spectra over cruises and over
location points within five regions (from south to north: SACCF, Antarctic Zone (AZ),
PF, PFZ, and SAF) defined by the positions of the main fronts, and calculated confi-
dence intervals from the resulting degrees of freedom assuming a 50 km decorrelation
scale (see Section 3). Spectra of \(u_{p}, v_{p}\) and \(u_{\psi}, v_{\psi}\) are red in all regions (Figure 7) and
depth ranges (not shown). Low-wavenumber (1000-m wavelength) energy is greater in the northern passage than in the SACCF, but the difference is not significant. Intermediate-wavenumber anisotropy in mean stream coordinates, with cross-stream energy greater than along-stream, is significant at the 95% confidence level in the PF below about 400 m at wavelengths of 150 to 350 m; this anisotropy is also significant in shear spectra (not shown) in this wavelength range. In the PF cross-stream energy at these wavelengths is \sim 50-100% greater than along-stream. Shear spectra in the AZ, PF, and PFZ have significant peaks at about 350 m for $\partial u_\psi / \partial z$ and about 250 m for $\partial v_\psi / \partial z$; in the SAF there is no significant peak, but energy decreases at wavelengths shorter than these, while in the SACCF the shear spectra are nearly white. Energy in spectra computed from profiles gridded to the estimated decorrelation scale of 50 km is significantly lower at all wavenumbers, implying that motions with vertical scales of up to \sim 1000 m have horizontal and/or time scales shorter than 50 km and/or 2.5 hr.

Rotary spectra (not shown) reveal a small but significant preference for counterclockwise (CCW) rotation with increasing depth above 500 m and clockwise (CW) rotation with increasing depth below 500 m, at wavelengths of \sim 200-450 m. The shallow signal is more consistent and is found in the three fronts and the PFZ, while the deeper signal is significant only in the PF and PFZ. The predominance of CCW rotation above 500 m is as expected; in the Southern Hemisphere CCW rotation with increasing depth is associated with internal waves with downward group velocity. The only significant rotary anisotropies that extend over the entire SADCP depth range are found at the longest wavelengths (400-500 m): CW in the PFZ and CCW in the AZ and SACCF regions. In the SACCF region the anisotropy derives from just south of the mean SACCF jet.
We calculated horizontal wavenumber spectra (not shown) from the set of individual transects as in Lenn et al. [2007], extending their calculation to greater depth. Data gaps of up to 50 km were filled by linear interpolation. Energy peaks at 350 km for both velocity components. Lenn et al. [2007] found energy in the across-passage velocity \( v_p \) peaking at a lower wavenumber than that in the along-passage velocity \( u_p \), but the difference was not significant. The spectral energy level decreases with depth, but neither the location of the peak nor the spectral slopes change significantly with depth. As in Lenn et al. [2007], the spectra are anisotropic, with \( u_p \) having significantly more energy at all but the lowest and highest wavenumbers. Very similar results exist for spectra of velocity anomalies relative to the gridded (improved) depth mean, with the exception that the peak energies for both \( u_p \) and \( v_p \) decrease, and the peak wavelength for \( u_p \) is lower, around 230 km; in Lenn et al. [2007] the energy of \( v_p \) stayed the same in the surface layer.

### 4.2. Vertical Structure Functions

Visual inspection of the mean SADCP currents (e.g. Figures 3a, 4, and 8) reveals fairly smooth, gently-sloping profiles; non-time-averaged currents (gridded SADCP or LADCP) are less smooth but still show significant low-wavenumber structure, suggesting large depth-attenuation length scales. Empirical orthogonal function (EOF) analysis of gridded currents supports this impression. We divided gridded currents on the most commonly sampled line into five regions defined by the positions of the mean fronts as in Section 4.1, removed the depth mean from each profile, and calculated the EOFs over all the profiles in each region. The first empirical mode explains 47% of the variance in gridded currents in regions south of the PF; in the PF and SAF 62% and 65%, respectively; and in the PFZ 70%. Each region’s first mode is a good approximation of a straight line, with a
slight decrease in shear around 150 m in all regions, and again below 600 m in and south of the PF and below 900 m in the PFZ and SAF (Figure 8). The second modes, which have two zero-crossings, explain only 9 to 16% of the variance. These results echo those of Inoue [1985], who found that at most of the ISOS moorings the first EOF captures > 92% of the total energy in the year-long current profile timeseries.

The EOFs show that certain characteristics of the mean jets also apply to the time-varying current. The dominance of the first modes, particularly in the jet regions, confirms the result of Section 3 that the current in the SADCP depth range is generally equivalent-barotropic. Differences in the shapes of the mean jets visible in Figure 3a also appear in the EOFs. The SAF is deeper than the PF, while the PF has stronger vertical shear in the upper part of the SADCP range (Figure 8). The SACCF has higher near-surface vertical shear relative to the size of the current. The EOF results also illuminate the sources of EKE in the PFZ: around 40% of individual profiles reconstructed from the first mode plus the depth-mean components are westward in this region, as compared to ≤ 15% in the PF and SAF; westward flow likely indicates mesoscale eddies as opposed to a meandering jet.

Encouraged by the high proportion of variance explained by the first modes, we sought simple functions to describe the vertical structure of the velocity data. We investigated a number of smoothly-varying functions that might match well with the EOF results, including linear, exponential, or hyperbolic tangent (as in Killworth and Hughes [2002]), and the first few flat-bottom dynamical modes from different parts of Drake Passage. We also tested the thermal wind profile resulting from exponential buoyancy profiles with length scale a function of the across-stream coordinate [Karsten and Marshall, 2002]. Vertical profiles of complex velocity $u_p(z) + iv_p(z)$ at each grid point (or cast location)
were least-squares fit to a function of $z$ with parameters allowed to vary from grid point to grid point. Constraints on the fit parameters were included in order to limit our search to “appropriate” fits. We used two criteria for “appropriateness”: 1) the observed profile should not be a residual of much larger terms; and 2) any nonlinear term should be distinguishable from a straight line over the depth range of the fit. We applied the first criterion by limiting the depth-maximum value of each component of the fit to $1 \text{ m s}^{-1}$.

To apply the second criterion, for instance, we limited the length scale of an exponential term to twice the depth range. For linear fits, confidence intervals were derived from estimates of the data covariance matrices; for nonlinear fits parameter covariances were estimated by bootstrapping [Efron and Gong, 1983]. All of the fits had both a mean and a depth-varying component. Most tested shapes were able to explain over 60% of the gridded or mean SADCP variance on average, with rms residuals of the order of or less than the data standard deviations. No one shape stood out as significantly better than the others for describing the vertical structure of the SADCP velocity over the whole sampling area; however, two of the shapes, summarized in Table 1, found some support in the LADCP and SOSE datasets as descriptors of the full-depth structure, and we explored these further.

4.2.1. Linear velocity

We first investigated the simplest possible description for the velocity profiles, the line. Ferrari and Nikurashin [2010] explored the ACC as a surface quasigeostrophic (SQG) system and showed how a linear mean velocity profile and exponential EKE profile result from a constant surface buoyancy gradient. Although the SQG model should only be a good description above about 500 m [Lapeyre and Klein, 2006], the SADCP EKE (Fig-
Table 6b) is well described by an exponential shape with length scales of 300 to 900 m: the best fit profiles explain 97% of the variance and have rms differences of 16 cm s$^{-2}$ (compare to rms profile standard deviations of around 100 cm s$^{-2}$). Linear fits ($\vec{u} = \vec{u}_0 + \vec{a} z$) to SADCP velocity explain 65% of the variance and have rms differences of 1.9 cm s$^{-1}$ on average. Simple linear fits to SOSE or LADCP velocity profiles leave quite a bit of the full-depth structure unexplained; however, piecewise linear fits with slope allowed to change at 1030 m approach the performance of the more complex shapes discussed below.

In the LADCP dataset the mean shear above 1030 m is on average about twice as large as that below 1030 m, while in SOSE it is three times as big.

4.2.2. Exponential velocity

We fitted velocity profiles to the function

$$\vec{u} = \vec{u}_0 + \vec{a} e^{z/L},$$

(1)

where $\vec{u}_0$, $\vec{a}$, and $L$ are the fit parameters and $z$ increases upwards from $z = 0$ at the free surface. SOSE mean velocity profiles are very well-described by (1), with 98% of the variance explained and rms errors of 10% the size of data standard deviations. Length scales $L$ are mostly between 1100 and 1700 m ($\pm$ standard deviations of 10 to 30 m), and increase slightly from south to north (Figure 9b). Fitting of (1) to SADCP mean velocity produces “appropriate” fits at 79% of SADCP grid points, and at these points the fits explain 76% of the variance with a rms error of 2.0 cm s$^{-1}$—about half of the rms of the original profile standard deviations. However, half of the “appropriate” fits have length scales (Figure 9a) at the upper limit (twice the depth range) imposed by the fit constraints, indicating that the best exponential fit is no better than a straight line fit; another 10% have indeterminate length scales (standard deviation of $L \geq L$). Fits to gridded SADCP
velocity give similar results: at the 84% of points where an “appropriate” fit could be made, the rms error is 4.9 cm s$^{-1}$ (as compared to rms profile standard deviations of 9 cm s$^{-1}$), while about half the length scales are at the upper limit. Exponential decay with depth tends to be a better fit to SADCP velocities in the southern part of the passage. Both SADCP and SOSE $L$ are noisy in the alongstream as well as across-stream direction.

The SADCP depth range appears generally insufficient to determine the length scales of best-fit exponential decay in the full-depth ACC, particularly if our goal is not only to describe the upper 1000 m but also to extrapolate below them. We therefore turned to the full-depth SOSE and incorporated the length scales $L_{SOSE}(x_p, y_p)$ (Figure 9b) from nonlinear fits to SOSE mean profiles (gridded in the same way as the SADCP data) into fits to mean SADCP profiles, with $\vec{u}_0$ and $\vec{a}$ determined by the linear least-squares fit. The results (e.g. Figure 8) explain 65% of the SADCP variance on average and have similar rms error, 1.9 cm s$^{-1}$. Fits to (1) using $L_{SOSE}$ thus seem promising for extrapolating observed currents in the upper 1000 m to deeper levels. However, as can be seen in Figures 3 and 4, there are some significant differences between SADCP and SOSE, especially in the jets (Figure 3c, d). SOSE underestimates the strength of the PF and SACCF and overestimates the strength of the SAF (Figure 3b). Most relevantly for the problem of determining the vertical structure, SOSE appears to overestimate shear in both the SAF and PF and underestimate the length scale in and just south of the PF.

4.2.3. Thermal wind from exponential buoyancy

*Karsten and Marshall* [2002] described climatological buoyancy profiles in the ACC decaying exponentially with depth below the mixed layer, with length scales that in-
crease equatorward. We found that buoyancy profiles from the XBT/XCTD dataset are
well-described by a decaying exponential $b_1 e^{-z/L}$, where $z = 0$ at the base of the mixed
layer, plus a constant offset term $b_0$; both terms and all three parameters ($b_0$, $b_1$, and $L$)
vary across the current. Along the most commonly sampled line (see Figures 1 and 2a),
mean buoyancy length scales increase from just over 100 m in the south of the passage
to 600-1000 m in the PF and 500 m in the PFZ (depth coverage in the SAF was insuf-}
hicient to determine a length scale). Given that a large portion of the mean velocity,
least, is geostrophic, we might expect that velocity observations would be describable
by the corresponding geostrophic velocity profile. The functional form resulting from
exponential buoyancy does describe both LADCP and SADCP currents quite well in a
least-squares sense—unsurprisingly enough, given the additional degrees of freedom relative
to (1). However, the best-fit velocity coefficients do not show the expected relationships
to the buoyancy fit coefficients from which they should derive, so we cannot justify using
this more complex form.

4.2.4. Combination of functional forms

No single functional form appears satisfactory for describing the SADCP data at all
locations (or even all locations within a particular region). For mean SADCP velocity,
(1) is best at 30% of points and a linear fit at 70%; for gridded SADCP the proportions
are 55% and 45%. There is no clear spatial pattern to which fit works best, and the rms
error is not improved by combining the two forms. Given this, in Section 5.1 we use (1)
to extrapolate below the SADCP depth range, while keeping in mind its shortcomings.

5. Transport
We estimated mean transport in the top 1042 m from the most commonly sampled section (see Figure 1). The result, 95.1 Sv, is a sizeable fraction of the canonical value for time-mean full-depth total transport [134 Sv, Whitworth and Peterson, 1985]. Mean transport from this dataset increases nearly linearly with depth and is consistent with the 27.8±1 Sv in the top 250 m calculated by Lenn et al. [2007] over a longer time period. Of the mean 0-1042 m transport, the SAF carries 35.6 Sv, the PF 48.4 Sv, and the SACCF 11.1 Sv (Figure 4b). The proportions of transport carried by each front in the top 1000 m are within error bars of the proportions calculated by Cunningham et al. [2003] from baroclinic transport relative to the deepest common level at WOCE SR1b.

We also calculated time-varying transport by year and from individual transects (see Appendix A1 for description of gap-filling). Yearly-mean transport in the top 1042 m ranges from 77.6 Sv (2008) to 104.5 Sv (2006). The standard deviation of transport from 53 crossings is 15.5 Sv (Figure 10b), giving a standard error of the mean of 2.1 Sv. As a fraction of the mean value, this standard deviation is twice as large as that of the five-year net transport record constructed by Whitworth and Peterson [1985] using the correlation between transport and cross-passage pressure difference at 500 m. The calculation of Whitworth and Peterson [1985] requires the assumption that baroclinic variability below 500 m is negligible, an assumption supported by the finding of Sokolov and Rintoul [2009b] that variability in total baroclinic transport is small. In the SADCP timeseries, however, the variability in transport due to the depth-mean component over the top 1000 m is comparable to the variability due to shear, both above and below 500 m (Figures 10c and 11).
The cross-passage distribution of transport (Figure 10a) changes from crossing to crossing. Transport in the northern part of the passage is more variable than in the southern, and variability is maximum in the mean PFZ. This pattern likely reflects the distribution of eddies—the northern jets provide more energy to generate eddies—as well as variability in the PF and SAF positions (meandering or filamenting). While the Rossby radius is smaller in the southern part of the passage, the smaller envelope of transport in this area suggests that unresolved variation is also likely to be small. Mean transport is insensitive to subsampling transects to as much as 100 km resolution, and variability is insensitive to subsampling to >50 km.

5.1. Extrapolation to Full-Depth Transport

We used the vertical structure functions discussed in Section 4.2 to extrapolate from the observations in the top 1030 m to a value for full-depth transport by integrating the fitted functions. Our estimate of the error on mean transport from a fitted function has two components: that associated with our estimate of the mean, and that associated with the misfit between the fit and the actual current. For the first we used the standard deviation of transport from the fit, obtained by propagating the parameter standard deviations. For the second, in order to account for the misfit over the whole depth range of integration, we used the minimum data standard deviation as an estimate of misfit at all depths below our data range.

As might be expected from the change in shear in the LADCP data above and below 1000 m, fits involving linear trend terms result in unrealistically large or unrealistically small full-depth transport estimates (although similarly large error bars put them within error of the canonical value). Meanwhile, (1) using length scales from SADCP gives
98±10 Sv in the top 1042 m and 154±38 Sv over the full depth. With length scales from SOSE, the full-depth extrapolated transport is larger, at 164±23 Sv, but not significantly so (and note that the error bar on this latter estimate does not take into account the failure of SOSE to accurately reproduce the vertical length scales of the real current). Of the 154 Sv of full-depth extrapolated transport, 64 Sv, 63 Sv, and 26 Sv are carried in the SAF, PF, and SACCF, respectively. These proportions are within 10% of the observed partitioning in the top 1042 m, and are thus also similar to those observed by Cunningham et al. [2003].

Both extrapolations from (1) are consistent with the canonical 134±11 Sv of Whitworth and Peterson [1985]. We also used the observed upper-ocean transport to put bounds on the full-depth transport in a simpler manner. Figure 12 shows the area-weighted observed mean velocity profile in the top 1000 m, and the transport resulting from a linear fit to this profile; then it shows two possible methods of linearly extrapolating. The first, extrapolating with the same slope as in the top 1000 m until the current goes to zero, at around 1800 m, and then letting the current be zero below that, gives a value of 117 Sv. We consider this a lower bound, based on numerous observations of eastward flow at depth. For the second estimate we extrapolate linearly at each location from the current at 1000 m to zero at the bottom, giving 220 Sv, which we consider an upper bound.

6. Discussion and Summary

The LMG SADCP observations confirm that the mean ACC in Drake Passage is equivalent-barotropic (streamlines are self-similar with depth), at least over the sampled 1000-m depth range; the same is true of the low-wavenumber part of the time-varying
current. The vertical structure does not appear, however, to be separable equivalent-
barotropic: vertical length scales vary across the passage. Shear is on average lower in
the region of the SAF than in the PF region, but there is significant time variability in
vertical scale as well.

Both mean and time-varying vertical shear are observed to be small all the way down
to 1000 m; this extends the observations of Lenn and Chereskin [2009] in the surface
layer. The direct current measurements reveal that mean currents at 1000 m are quite
strong (20 cm s\(^{-1}\) in northern Drake Passage). The mean 0-1042 m transport of 95±2 Sv
(standard error) is 71% of the canonical total transport of 134±11 Sv [Whitworth and
Peterson, 1985] in ~30% of the depth range. Given the observations of eastward mean
bottom currents discussed in the introduction, we expect transport to be positive at all
depths. If we are to reach a total transport of 134 Sv under this condition, the mean
shear below 1000 m must be only slightly smaller than that above (see Figure 12). The
LADCP data, however, indicate a more pronounced decrease in shear (a factor of two on
average), as do the results of Inoue [1985] on the vertical structure of currents measured
by the ISOS moorings and the exponential or exponential-like vertical structure found by
Karsten and Marshall [2002] and other studies of measured or modeled density profiles.
Alternatively, the 71% ratio might reflect the large time variability observed in this dataset
as well as in studies by Cunningham et al. [2003] and others. We note, however, that the
4.5-year 38 kHz SADCP timeseries is a relatively long one in this region, and that the
longer dataset available for the upper ocean [Lenn et al., 2007, 2008] shows no significant
difference between upper ocean transport over this time period and over the full decade
of that record. It is also possible that the barotropic component of the current is larger
than previously thought and that the total transport of the ACC through Drake Passage
is greater than the canonical value. Both the ISOS estimates of Whitworth [1983] and
Whitworth and Peterson [1985] and additional estimates of Cunningham et al. [2003]
relied on just a few synoptic sections to infer the barotropic component of the transport.
From the present analysis we produce several different estimates of total transport, and
conclude that 154±38 Sv is a reasonable estimate of the mean, with 117 and 220 Sv
representing lower and upper bounds.

The results of our calculation of transport from direct velocity measurements reinforce
the conclusion of Cunningham et al. [2003] that the baroclinic component of transport
variability is significant. The depth-mean and shear components of transport variability
in the top 1000 m are of similar size; since variability in the depth-mean over the top
1000 m can result from barotropic variability or from variability in sub-1000 m shear, the
baroclinic component likely makes an even larger contribution to the full-depth transport
variability.

An equivalent-barotropic structure permits the ACC to act as a waveguide for Rossby
waves and could allow the eddies observed in satellite altimetry to be interpreted as
Rossby waves advected downstream by the mean current [e.g. Hughes, 1996]. Such an
interpretation is necessary for the critical layer theory elaborated by Smith and Marshall
[2009] as an explanation of a deep maximum in eddy stirring—although Abernathey et al.
[2010] showed that linear critical layer theory is not necessary to explain a subsurface
mixing maximum. The conclusions of Hughes [2005] about the ACC vorticity balance
also rely on an equivalent-barotropic vertical structure to extrapolate surface dynamic
topography to the current as a whole. In general, the confirmation of equivalent-barotropic
structure, at least in Drake Passage, is promising for extrapolation of the better-observed
surface to properties and dynamics of the full water column. However, we were not
able to find a simple functional form to reliably describe the vertical structure; other
observations and analysis are still needed to better determine length scales and structure
in Drake Passage and elsewhere.

The resolution of the LMG SADCP dataset allows us to observe three distinct jets
in the mean, while the multiple filaments observed by Sokolov and Rintoul [2007] and
Sokolov and Rintoul [2009a] are observable in individual transects. The consistency of
the large-scale vertical structure in each frontal region, despite variability in jet position
and number, matches the finding of Sokolov and Rintoul [2009a] that given fronts are
consistently associated with certain SSH contours. Meanwhile, the SADCP observations
are compatible with the role of the ACC as a partial mixing barrier [Marshall et al.,
2006]. One indication that mixing across the current may be restricted is that EKE
in Drake Passage is concentrated between the mean PF and SAF regions and is much
smaller than mean KE in the jets themselves, possibly indicating that the PF and SAF
are barriers to mixing [Ferrari and Nikurashin, 2010]. While the Reynolds stress $\langle u'_\psi v'_\psi \rangle$
is nearly depth-independent over the 1000-m range of the SADCP, the ratio of mean KE to
EKE increases over this depth range, suggesting that the maximum in effective diffusivity
described by Smith and Marshall [2009] and Abernathey et al. [2010] at 1000 to 1500 m
below the core of the stream-averaged ACC would, in Drake Passage, have to occur at
the deeper end of this range. However, the KE:EKE criterion of Ferrari and Nikurashin
[2010] may not apply to Drake Passage, where scale separation between jets and eddies
is doubtful and the shifting and meandering of the jets may reduce their effect as mixing
barriers [Thompson, 2010; Thompson et al., 2010]. In addition, the high EKE in the PFZ does indicate significant eddy stirring above 1000 m in the center of the ACC in Drake Passage.

The observed current structure also has implications for numerical modeling. There are clear differences in the details of the vertical structure between the SADCP and LADCP observations and the model output of SOSE, and between observations and other climate models, but accurate representation of the mean current structure is a precondition for accurate parameterizations of mixing. Comparison with observations is important for testing numerical models used in climate studies. Further measurements over a more extensive depth range would enable us to refine the vertical structure and length scales of the current, and provide a better estimate of the full-depth transport and eddy activity of the ACC, while the extension of the LMG SADCP timeseries will provide insight into their time variability. In addition, future runs of SOSE will archive profile data with sampling matching that of the LMG SADCP dataset, allowing both a more accurate comparison and an evaluation of the possibility of assimilation of the SADCP dataset into SOSE or another assimilating model.

Appendix A: Velocity Bias Correction

When we initially examined transport from the 38 kHz ADCP (os38) on individual crossings, a systematic offset between transport from southbound legs and that from northbound legs was revealed: the mean transport over 27 southbound cruises was 24 Sv less than the mean over 26 northbound cruises. Upon investigation, this large transport offset appears to be due to a very small velocity bias (see Donohue et al. [2001]). The source of this bias and our attempt to correct for it are described here.
A1. Transport Calculation

Most LMG Drake Passage crossings are accomplished in around 2 days and are thus suitable for calculation of transport. We calculated transport between the surface and 970 m for crossings that met the following criteria: 1) crossing covers less than 4 days; 2) data extend to at least the 300 m depth contour in the north and the 700 m contour in the south; and 3) after filling as described next, data coverage is at least 90%. The 15-minute data were vector-averaged to a 25-km along-track grid. Profile (partial-depth) gaps up to 50 km (150 km) were filled using an objective interpolation procedure with Gaussian covariance with horizontal and vertical scales of 50 km and 480 m, respectively. The horizontal decorrelation scale was determined from lagged autocorrelations of 15-minute data, and the vertical scale reflects the low shear of the mean profiles. We assumed slab motion above 46 m (the first depth bin). Velocities were transformed into along- and across-track components (where track orientation varies by grid point) to calculate the flux of water across the sampling line and give transport as a function of along-track distance and time.

The resulting transport time series has a bimodal distribution; ignoring two outliers, values from the 26 southbound cruise legs are 24.3 Sv less on average than those from the 25 northbound legs (Figure A1). The southbound series has a standard deviation of 12.3 Sv and the northbound series of 8.0 Sv (outliers again excluded). The disparity in transport appears at all depths and all locations across the passage (Figure A1), and differences in transport do not correspond to differences in track longitude, season, coverage, range, or depth extent. Thus we turned to the velocity.
A2. Velocity Distributions

Probability density functions (PDFs) constructed from the 15-minute velocities show the same bias as transport: the distribution of across-track velocity from northbound legs is shifted higher than that from southbound legs. The two distributions are significantly different at the 99% confidence level by the Kolmogorov Smirnov test ($P_{ks} < 10^{-3}$), with means that differ by 3 cm s$^{-1}$. No bias is evident in along-track velocity; its distributions are not significantly different ($P_{ks} > 0.3$). The across-track bias has the same sign independent of location. A constant bias in across-track but not along-track velocity is consistent with a misalignment angle error, as described below.

To help rule out the possibility of ship navigation errors or of high-frequency motion correlations that affect the average water motion relative to the ship, we also examined velocities from the other ADCP on the LMG, a 150 kHz RDI. Its distributions of across- and along-track velocity both have means that differ by less than 0.5 cm s$^{-1}$. (The along-track velocity distributions are different at the 98% confidence level; a small difference in the along-track component is expected because this instrument requires an amplitude correction). We infer that neither navigation errors nor high-frequency motion correlations are an issue because the misalignment angle of the 150 kHz ADCP has been fully accounted for by the normal processing with bottom-tracking; the 38 kHz velocity bias seems to be peculiar to that instrument.

A3. Angle Correction

The standard SADCP data processing procedure includes a correction for misalignment angle, the angle between the ADCP beam 3 and fore. This angle can be determined by either water-track or bottom-track, as described in Joyce [1989]; bottom track values are
generally more stable and have been used for the LMG data. Where Ashtech GPS or bottom track data are not available the appropriate correction for a given cruise leg is estimated using corrections to adjacent legs. The 7 of 54 os38 legs on which this estimation was required are not associated with anomalous transport values.

The size of the misalignment angle correction to the across-track component of velocity is approximately

$$\Delta u \simeq |u_{ship}| \sin \theta_{mis},$$

(A1)

where $u_{ship}$ is the ship velocity and $\theta_{mis}$ the misalignment angle. Assuming an average ship speed of 5.5 m s$^{-1}$, and keeping in mind that the mean velocity difference of 3 cm s$^{-1}$ corresponds to a bias of 1.5 cm s$^{-1}$ (up for northbound, down for southbound), we have an unaccounted-for misalignment angle of about $0.16^\circ$. The bottom-track misalignment angle corrections used for the os38 have a mean of $0.416^\circ$, a standard deviation of $0.046^\circ$, and a range of $0.200^\circ$. Given this, it is puzzling that a bias of as much as $0.16^\circ$ should remain, and we are not able to explain why it is not accounted for by the normal bottom-track processing. Nevertheless, we can still correct for it; first we calculated the remaining misalignment angle more carefully.

We used the assumption that the time-mean transports from northbound and southbound legs should be the same. Using the 5-minute velocities, we calculated transport $U$ on each suitable leg (see Section A1), and then calculated the constant velocity offset necessary to change $U$ to $U_{mean} = 90$ Sv, the mean of all the transport estimates. From (A1) and the leg-mean ship speed, we then obtain the corresponding $\sin \theta_{mis}$. Excluding the two outliers, the mean of this series corresponds to an angle of $\theta_{mis} = 0.16^\circ$, and the standard deviation to $0.15^\circ$ (standard error of $0.02^\circ$).
We applied the additional angle correction to the 5-minute data by

$$\tilde{u}(t) = u_{\text{meas}}^{-}(t)e^{-i\theta_{\text{mis}}} + u_{\text{ship}}^{-}(t),$$

(A2)

where the measured velocity $u_{\text{meas}}^{-}$ has already been corrected by the bottom-track-derived misalignment angle. As expected, on average the resulting change in cross-track velocity is approximately $+1.5 \, \text{cm s}^{-1}$ for southbound and $-1.5 \, \text{cm s}^{-1}$ for northbound data.

By propagating the standard error of the additional misalignment angle through the calculation, we obtained an error bar on the velocity correction of less than $2 \, \text{mm s}^{-1}$, well within the expected noise.

Southbound and northbound distributions of corrected velocity are not significantly different ($P_{ks} > 0.3$) in either component. Due to the small velocity correction and the fact that approximately equal numbers of southbound and northbound legs pass through a given grid box, the mean velocities are barely affected. EKE is reduced by a small amount in most locations; large-scale patterns remain the same. Transport between 0 and 970 m from the corrected velocity has a mean of 90.5 Sv as opposed to 90.2 Sv from the uncorrected records. The standard deviation for the corrected transport time series is 15.5 Sv (standard error 2.1 Sv). The misalignment angle correction rectifies not only total transport (by definition) but $U(y, z)$ as well (compare Figure 10 to Figure A1).

Appendix B: Shear

In the examination of velocity distributions and transport as a function of time, an apparent northbound-southbound difference in os38 velocity shear near the surface also came to our attention (Figures 10 and A1). PDFs reveal that the bias is even larger in the along-track component of velocity shear, $du_{a}/dz$. This component differs significantly
at all depths and in all water depths, while the across-track component $du_c/dz$ is different only between 46 and 118 m. Above 118 m, the difference between the northbound and southbound mean shears is $3 \times 10^{-4}$ s$^{-1}$ in the across-track direction and $1 \times 10^{-3}$ s$^{-1}$ in the along-track direction. The standard error of the mean is only about $8 \times 10^{-5}$ s$^{-1}$.

The 150 kHz instrument also gives northbound and southbound $du_a/dz$ distributions that are significantly different at all depths, but the differences between the means are much smaller.

The disparity in shear distributions leads to reduced confidence in the near-surface data from the os38 in particular. Recalculation of the mean transport using a slab assumption from 118 m to the surface gives a value 0.55 Sv (from individual crossings) to 0.88 Sv (from the average velocity on the most common track) less than that with a slab starting at 46 m. As the difference in transport is well within our error bars we have continued to use near-surface data for this calculation.
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References


Figure 1. Left: LMG tracks with 38 kHz data (black lines) over Orsi et al. [1995] fronts (gray lines) and bathymetry (described in text). Top right: most commonly sampled line (gray box) and cDrake LADCP profile locations (black dots), with Orsi et al. [1995] fronts in gray. Bottom right: larger view; the box outlines the study area shown at left.

Figure 2. Objectively mapped streamfunction $\psi$ contoured at 5 cm intervals: (a) depth-mean streamfunction overlaid on bathymetry $H$, with the most commonly sampled line in white; (b)-(d) streamfunction and current vectors at several depths, with only currents larger than 15 cm s$^{-1}$ plotted.

Figure 3. Time-mean speed from SADCP (a) and SOSE (b) on the most commonly-repeated section (see Figures 1 and 2a). Difference SADCP speed - SOSE speed, scaled by the SADCP standard deviation, for means from all available data (c) and from SOSE data coincident with SADCP data during 2005-2007 (d). The black lines on each plot are the 20 cm s$^{-1}$ contour of SADCP speed and indicate the locations of the mean observed fronts, from south to north, the SACCF, PF, and SAF.

Figure 4. Time-mean across-track velocity $u_\perp$ on the most commonly sampled line. SADCP (solid) and SOSE (dashed) profiles relative to the depth mean $\bar{u}_\perp$ are shown in the top panel. The bottom panel shows the SADCP depth mean-velocity in cm s$^{-1}$ (colored line; line color connects profiles and across-passage locations) and depth integrated 0-1042 m transport in Sv km$^{-1}$ (black line), as a function of distance along the line.
**Figure 5.** At 118 m (black lines) and 886 m (gray lines): (a) current speed $<u_\psi>$, (b) current angle $<\theta_\psi>$, and (c) $EKE = \frac{1}{2} <u'^2 + v'^2>$ on the most commonly-sampled line (Figures 1 and 2a). Filled areas indicate standard error about the mean at 118 m (dark gray) and 886 m (light gray).

**Figure 6.** Average section along the most commonly-repeated transect (see Figures 1 and 2a): (a) mean KE, (b) EKE, (c) $<u'_\psi u'_\psi>$, (d) $<v'_\psi v'_\psi>$, (e) $<u'_\psi v'_\psi>$. In (c), (d), and (e), only values significantly different from zero are colored. Note the nonlinear colorbar in (a)-(d), selected to show more detail at low values and specific values at color transitions.

**Figure 7.** Vertical wavenumber spectra of $u_\psi$ (solid) and $v_\psi$ (dashed) from 46 to 1030 m, averaged over regions defined relative to the mean fronts, as indicated. 95% confidence intervals for each region are indicated by thin vertical lines.

**Figure 8.** Mean SADCP speed profile in each frontal region (symbols) with the first EOF in each region (black lines) and fits to (1) using mean length scales $L_{SOSE}$ determined from fits to SOSE profiles (gray lines). The EOF first modes were scaled to match the mean speed profiles. From north to south $L_{SOSE} = 1635, 2126, 1355, 1289, \text{ and } 1355$ m.

**Figure 9.** Length scales of best-fit exponentials determined by fitting (1) to (a) SADCP mean velocity profiles and (b) SOSE mean velocity profiles.

**Figure 10.** Transport: (a) cumulative from 0-970 m (southbound gray solid line, northbound black dashed line); (b) total from 0-970 m (southbound circles, northbound squares); (c) per unit depth (southbound gray solid line, northbound black dashed line). The black bars in (a) indicate the frontal zones, delimited by the points where mean transport per unit distance falls to $e^{-1}$ of its maximum value in each front.
**Figure 11.** Transport per unit depth relative to 502 m (southbound gray solid line, northbound black dashed line).

**Figure 12.** Schematic showing mean SADCP transport in the top 1000 m (black line, dark gray shaded area) and two possible linear extrapolations for full-depth transport: extrapolating the transport profile with the same shear until it reaches zero (light gray line); or extrapolating each velocity profile linearly from its value at 1000 m to zero at the bottom at each location (gray shaded area). The full-depth transports corresponding to these two extremes are 117 and 220 Sv, respectively.

**Figure A1.** Uncorrected transport: (a) cumulative from 0-970 m (southbound gray solid line, northbound black dashed line); (b) total from 0-970 m (southbound circles, northbound squares); (c) per unit depth (southbound gray solid line, northbound black dashed line).
Table 1. Performance of two types of fits to vertical profiles of time-mean velocity$^1$

<table>
<thead>
<tr>
<th>fit</th>
<th>equation</th>
<th>% grid points with “appropriate” fit</th>
<th>rms difference (cm s$^{-1}$)</th>
<th>% var. explained</th>
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</thead>
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<td>linear vel.</td>
<td>$\vec{u} = \vec{u}_0 + \vec{c}z$</td>
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<td>1.9</td>
<td>65</td>
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<tr>
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<td>76</td>
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<td>exp. vel. SOSE</td>
<td>$\vec{u} = \vec{u}<em>0 + \vec{a}\vec{e}z/L</em>{SOSE}$</td>
<td>100</td>
<td>1.9</td>
<td>65</td>
</tr>
<tr>
<td>combined best</td>
<td></td>
<td>100</td>
<td>2.0</td>
<td>67</td>
</tr>
</tbody>
</table>

$^1$Fit parameters are $\vec{u}_0, \vec{c}, \vec{a}, L,$ and $L_{SOSE};$ fits are explained in more detail in Section 4.2. For comparison, standard deviations of observed $\vec{u}(z)$ are about 4.3 cm s$^{-1}$. 
Figure 1. Left: LMG tracks with 38 kHz data (black lines) over Orsi et al. [1995] fronts (gray lines) and bathymetry (described in text). Top right: most commonly sampled line (gray box) and cDrake LADCP profile locations (black dots), with Orsi et al. [1995] fronts in gray. Bottom right: larger view; the box outlines the study area shown at left.
Figure 2. Objectively mapped streamfunction $\psi$ contoured at 5 cm intervals: (a) depth-mean streamfunction overlaid on bathymetry $H$, with the most commonly sampled line in white; (b)-(d) streamfunction and current vectors at several depths, with only currents larger than 15 cm s$^{-1}$ plotted.
Figure 3. Time-mean speed from SADCP (a) and SOSE (b) on the most commonly-repeated section (see Figures 1 and 2a). Difference SADCP speed - SOSE speed, scaled by the SADCP standard deviation, for means from all available data (c) and from SOSE data coincident in time with SADCP data during 2005-2007 (d). The black lines on each plot are the 20 cm s$^{-1}$ contour of SADCP speed and indicate the locations of the mean observed fronts, from south to north, the SACCF, PF, and SAF.
Figure 4. Time-mean across-track velocity $u_\perp$ on the most commonly sampled line. SADCP (solid) and SOSE (dashed) profiles relative to the depth mean $\bar{u}_\perp$ are shown in the top panel. The bottom panel shows the SADCP depth mean-velocity in cm s$^{-1}$ (colored line; line color connects profiles and across-passage locations) and depth integrated 0-1042 m transport in Sv km$^{-1}$ (black line), as a function of distance along the line.
Figure 5. At 118 m (black lines) and 886 m (gray lines): (a) current speed $\langle u_\psi \rangle$, (b) current angle $\langle \theta_\psi \rangle$, and (c) $EKE = \frac{1}{2} \langle u'^2 + v'^2 \rangle$ on the most commonly-sampled line (Figures 1 and 2a). Filled areas indicate standard error about the mean at 118 m (dark gray) and 886 m (light gray).
Figure 6. Average section along the most commonly-repeated transect (see Figures 1 and 2a): (a) mean KE, (b) EKE, (c) $\langle u'_\psi u'_\psi \rangle$, (d) $\langle v'_\psi v'_\psi \rangle$, (e) $\langle u'_\psi v'_\psi \rangle$. In (c), (d), and (e), only values significantly different from zero are colored. Note the nonlinear colorbar in (a)-(d), selected to show more detail at low values and specific values at color transitions.
Figure 7. Vertical wavenumber spectra of $u_\psi$ (solid) and $v_\psi$ (dashed) from 46 to 1030 m, averaged over regions defined relative to the mean fronts, as indicated. 95% confidence intervals for each region are indicated by thin vertical lines.
Figure 8. Mean SADCP speed profile in each frontal region (symbols) with the first EOF in each region (black lines) and fits to (1) using mean length scales $L_{SOSE}$ determined from fits to SOSE profiles (gray lines). The EOF first modes were scaled to match the mean speed profiles. From north to south $L_{SOSE} = 1635, 2126, 1355, 1289,$ and $1355$ m.
Figure 9. Length scales of best-fit exponentials determined by fitting (1) to (a) SADCP mean velocity profiles and (b) SOSE mean velocity profiles.
Figure 10. Transport: (a) cumulative from 0-970 m (southbound gray solid line, northbound black dashed line); (b) total from 0-970 m (southbound circles, northbound squares); (c) per unit depth (southbound gray solid line, northbound black dashed line). The black bars in (a) indicate the frontal zones, delimited by the points where mean transport per unit distance falls to $e^{-1}$ of its maximum value in each front.
Figure 11. Transport per unit depth relative to 502 m (southbound gray solid line, northbound black dashed line).
Figure 12. Schematic showing mean SADCP transport in the top 1000 m (black line, dark gray shaded area) and two possible linear extrapolations for full-depth transport: extrapolating the transport profile with the same shear until it reaches zero (light gray line); or extrapolating each velocity profile linearly from its value at 1000 m to zero at the bottom at each location (gray shaded area). The full-depth transports corresponding to these two extremes are 117 and 220 Sv, respectively.
Figure A1. Uncorrected transport: (a) cumulative from 0-970 m (southbound gray solid line, northbound black dashed line); (b) total from 0-970 m (southbound circles, northbound squares); (c) per unit depth (southbound gray solid line, northbound black dashed line).