Improving Estimates of the Antarctic Circumpolar Current Streamlines in Drake Passage

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ABSTRACT

Accurately resolving the mean Antarctic Circumpolar Current (ACC) is essential for determining Southern Ocean eddy fluxes that are important to the global meridional overturning circulation. Previous estimates of the mean ACC have been limited by the paucity of Southern Ocean observations. A new estimate of the mean ACC in Drake Passage is presented that combines sea surface height anomalies measured by satellite altimetry with a recent dataset of repeat high-resolution acoustic Doppler current profiler observations. A mean streamfunction (surface height field), objectively mapped from the mean currents, is used to validate two recent dynamic height climatologies. The new streamfunction has narrower and stronger ACC fronts separated by quiescent zones of much weaker flow, thereby improving on the resolution of ACC fronts observed in the other climatologies. Distinct streamlines can be associated with particular ACC fronts and tracked in time-dependent maps of dynamic height. This analysis shows that varying degrees of topographic control are evident in the preferred paths of the ACC fronts through Drake Passage.

1. Introduction

Southern Ocean eddies are important to the global meridional overturning circulation and climate. Their importance lies in their role of transferring heat poleward and momentum downward in the Antarctic Circumpolar Current (ACC; e.g., de Szoeke and Levine 1981; Johnson and Bryden 1989). A limitation in determining eddy variability is the accuracy of the mean state relative to which eddy fluctuations are defined. Recent observations from autonomous Lagrangian drifters and floats and satellite altimeters have increased the resolution and improved estimates of mean global and Southern Ocean dynamic topography (e.g., Gille 2003a; Rio and Hernandez 2004; Maximenko and Niiler 2005). Numerous studies of ocean variability and dynamics have been based on these recent mean climatologies (e.g., Gille 2003b; Hughes 2005; Tokinaga et al. 2005; Seidler et al. 2006; Dong et al. 2007). Validating the available Southern Ocean climatologies remains a challenge, however, because there is a paucity of direct observations compared to other parts of the World Ocean.

Here we show how directly observed surface layer velocities, sampled with high lateral resolution but non-uniform frequency over a period of 5 yr, may be combined with altimetric sea level anomalies to produce a highly resolved improved estimate of the mean surface layer currents in Drake Passage. A streamfunction is objectively mapped from the improved mean currents and used to validate two independent dynamic topography climatologies in Drake Passage. By adding the altimetric sea level anomalies to the mean dynamic topographies we can map the instantaneous dynamic height. We evaluate the correlation between streamlines of instantaneous dynamic height and the location of the ACC fronts as determined from subsurface temperature observations in Drake Passage. This dynamic height streamline analysis allows us to investigate the meandering of the ACC fronts. An appreciation of the mean flow and its variability in Drake Passage is timely given the International Polar Year 2007–08, which brings heightened interest in studying Southern Ocean physical processes, and while the Drake Passage choke point remains a focus for studies of the ACC.

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2. The Drake Passage datasets

Underway acoustic Doppler current profiler (ADCP) data were collected aboard the R/V Laurence M Gould (LMG), which frequently crosses Drake Passage in all seasons to supply Palmer Station and participate in scientific cruises (Fig. 1). The high-resolution ADCP observations constitute an irregular time series of two-dimensional vector currents with 5-km along-track resolution in the top 300 m of Drake Passage and are described in detail by Lenn et al. (2007). This analysis incorporates ADCP data from 156 Drake Passage crossings undertaken between September 1999 and October 2006 (Fig. 1), adding a further 28 sections to those used by Lenn et al. (2007). The barotropic tide predicted by the TPXO6.2 global tidal model (Egbert et al. 1994) is removed from all the ADCP velocities. Measurement errors in the absolute velocities computed from 300-s ensemble averages are of $O(1 \text{ cm s}^{-1})$ (Chereskin and Harris 1997; Chereskin and Harding 1993) and small relative to the record-length standard deviation of currents, $O(30–60 \text{ cm s}^{-1})$, observed at any given location in Drake Passage. Following Lenn et al. (2007), currents are projected into a down–cross-passage Cartesian coordinate system $(x_{pc}, y_{pc})$ roughly aligned with local continental boundaries and the mean flow and rotated 23.6° anticlockwise from north such that the $x_{pc} = 0$ axis coincides with the dashed line in Fig. 1.

Repeat expendable bathythermograph (XBT) surveys of Drake Passage, 6 times yearly, are also part of the ongoing observations conducted by the LMG and are described in detail by Sprintall (2003). XBT probes are deployed every 10–15 km between the 200-m isobaths at either end of Drake Passage (Fig. 1), with higher resolution (5–10 km) across the Subantarctic Front (SAF) and Polar Front (PF). Water temperatures are consistently returned down to a depth of 800 m. This study uses 50 XBT surveys of upper-ocean temperature coincident with ADCP velocities between September 1999 and October 2006 to infer the instantaneous positions of the SAF, PF, and the Southern ACC Front (SACCF). The maximum subsurface temperature gradient between the 4° and 5°C isotherms at 400-m depth defines the SAF (Orsi et al. 1995, hereafter OWN; Sprintall 2003), the northernmost extent of the 2°C isotherm at a depth of 200 m defines the PF (Botnikov 1963; Joyce et al. 1978; OWN; Sprintall 2003), and the intersection of the 1.8°C isotherm with the depth of the maximum temperature gradient defines the SACCF (OWN).

Maps of weekly sea level anomalies are produced by the Archiving, Validation, and Interpretation of Satellite Oceanographic data (AVISO) Collecte Localisation Satellites (CLS) Space Oceanography Division. There updated (UPD) sea level anomaly product used in this study is produced by merging altimetric observations from the Ocean Topography Experiment (TOPEX)/Poseidon, the European Remote Sensing Satellite (ERS), Geosat Follow-On (GFO), Jason-1, and the Environmental Satellite (Envisat) to objectively map sea level anomalies onto a 1⁄3° Mercator grid (Ducet et al. 2000; Le Traon et al. 1998). To consider anomalies specific to the LMG observation period, we removed the mean UPD sea level anomalies from September 1999 to October 2006.

3. Improving estimates of the mean ACC

The ADCP measures total current ($U_A$), which has both ageostrophic and geostrophic components. The geostrophic flow includes mesoscale eddies and jets associated with the three ACC fronts: the SAF, PF, and SACCF. The ageostrophic flow consists principally of Ekman and inertial currents and baroclinic tides. Lenn et al. (2007) showed that the variance in Drake Passage is dominated by mesoscale eddies and near-inertial currents, with a relatively minor contribution from baroclinic tides. They found the near-inertial variability to be largely contained in the mixed layer and greatly re-
duced below. A mean Ekman spiral determined from the ADCP observations is composed of small currents, of a few centimeters per second at most, which penetrate to a maximum depth of $\sim 100$ m (Lenn 2006). The mean observed Ekman transport is in good agreement with that predicted from the mean Drake Passage wind stress ($\sim 0.1$ N m$^{-2}$; Lenn 2006). Shear in the ADCP currents, averaged by transect for the subset of transects with XBT observations, falls from $\sim 7 \times 10^{-4}$ s$^{-1}$ at a depth of 30 m to $1 \times 10^{-4}$ s$^{-1}$ at depths below 100 m in all seasons (Lenn 2006). Below 100 m the weak ADCP shear is independent of depth and in good agreement with geostrophic shear inferred from the concurrent XBT observations (Lenn 2006), providing further evidence that the ageostrophic currents do not significantly penetrate below the annual mean mixed layer depth located at 120 m. Averaging our observations in time and space below 120 m therefore minimizes contributions from Ekman and randomly phased inertial currents, as well as transient mesoscale eddies. ADCP velocities ($U_A$) from each transect are first gridded into $25$ km$\times 25$ km boxes and averaged to produce one velocity profile per grid box per transect. Averaging the gridded velocity profiles in time (all cruises) and depth (120–300 m) produces ensemble-averaged layer-mean currents ($\overline{U_A}$) similar to Lenn et al. (2007) that are characterized by a structured flow with three jets (Fig. 2a). Standard deviation ellipses ($\sigma_A$, Fig. 2b) calculated from the gridded ADCP velocity profiles ($U_A$) show that velocity variance is elevated in the northern half of Drake Passage.

Lenn et al. (2007) found estimates of eddy kinetic energy from ADCP and altimetry to be highly correlated in Drake Passage, although the altimetric estimate is lower, principally due to unresolved horizontal scales. Over 80% of the correlation coefficients between the ADCP velocities and the surface geostrophic current anomalies inferred from UPD sea level anomalies in Drake Passage are $\geq 0.5$ or higher and significant at 95% confidence (Fig. 3). No spatial biases are apparent in the correlation coefficient maps, except for fewer significant values where the ADCP observations are less dense (Fig. 3). This suggests that mesoscale eddies observed in the ADCP transects are likely to compare reasonably well with surface geostrophic current anomalies estimated from concurrent UPD sea level anomalies; three typical examples are shown in Fig. 4. During each of these three cruises, strong currents seen in the instantaneous depth-averaged ADCP velocities often follow contours of UPD sea level anomalies and coincide with steep UPD sea level anomaly gradients (Fig. 4). However, discrepancies between the locations of the strongest currents and the steepest gradients in the UPD sea level anomalies (Fig. 4) exist because the mean is present in the ADCP currents.

The good spatial coverage and temporal resolution of

![Gridded ensemble-averaged currents, depth averaged below the mixed layer (120–300 m): (a) mean ADCP currents $\overline{U_A}$ (red) and improved mean currents $\overline{U_D}$ (black) and std dev ellipses (b) $\sigma_A$ and (c) $\sigma_D$ are plotted in passage coordinates. Scale vectors are shown in the top-left-hand corners of each subplot. Gridded velocities are shown in each grid box crossed 3 times or more and std dev ellipses are drawn for grid boxes crossed 15 times or more. The mean SAF, PF, and SACCF positions (thick gray lines) from OWN are overlaid in (a).](image)
the subset of cruises with XBT observations in Drake adjustment since the geostrophic shear estimated from tational acceleration. We neglect any geostrophic shear northern Drake Passage, but are obviously smaller than retain the pattern of elevated velocity variance in

FIG. 3. Maps of correlation coefficients ($r$) between the ADCP velocities and the surface geostrophic current anomalies inferred from UPD sea level anomalies in Drake Passage for the (a) zonal and (b) meridional components of velocity. Only correlation coefficients that are significant at 95% confidence are shown. Significant correlation coefficients (for each velocity component) that are equal to or greater than $0.5 (r \approx 0.5)$ account for over 80% of the grid boxes used in the objective mapping. Note that significant correlation coefficients between $-1$ and 0 are plotted in black.

the sea level anomalies complements the ADCP velocities and may be used to account for some of the variability in the observations. We find that the gridded ensemble-averaged currents of Lenn et al. (2007) can be improved by a priori subtracting geostrophic current anomalies, determined from the UPD sea level anomalies, from the coincident ADCP observations. The geostrophic current anomalies are calculated by

$$U_{\eta} = u_{\eta} + i v_{\eta} = g \left( \frac{\partial \eta}{\partial y} + i \frac{\partial \eta}{\partial x} \right), \quad (1)$$

where $U_{\eta}$ is the vector geostrophic current anomaly, $u_{\eta} + iv_{\eta}$ are the complex surface geostrophic current anomalies, $\eta$ is the instantaneous UPD sea level anomaly, $f$ is the Coriolis parameter, and $g$ is the gravitational acceleration. We neglect any geostrophic shear adjustment since the geostrophic shear estimated from the subset of cruises with XBT observations in Drake Passage yields a correction of $\sim 2 \text{ cm s}^{-1}$ in the 120–300-m layer, small compared to the layer-averaged $U_A$ that ranges from 15 to 60 cm s$^{-1}$. The improved mean velocity, $\bar{U}_D = \bar{U}_A - U_{\eta}$, is calculated by gridding and averaging the difference in the ADCP currents and the surface geostrophic current anomalies.

The standard deviation ellipses for $U_D$ ($\sigma_D$, Fig. 2c) retain the pattern of elevated velocity variance in northern Drake Passage, but are obviously smaller than $\sigma_A$ (Fig. 2b). The reduction in the standard deviation ellipses ($\sigma_A > \sigma_D$, Figs. 2b,c) clearly illustrates a reduction in variance of $U_D$ currents relative to $U_A$. As a result, the improved mean currents ($\bar{U}_D$, black arrows in Fig. 2a) trace a much more organized flow through Drake Passage than the original mean currents ($\bar{U}_A$, red arrows in Fig. 2a). The ACC frontal jets, especially the SAF jet (north of the OWN mean SAF) and PF jet ($\sim 450 \text{ km} \leq y_{\text{PF}} \leq -250 \text{ km}$), are now more well defined because the flow between the fronts is markedly more quiescent in $U_D$ than in $U_A$ (Fig. 2a). If the ADCP time series were sufficiently long and uniformly sampled in each grid box, we would expect $\bar{U}_D = \bar{U}_A$. However, differences between the two means suggest a bias in $\bar{U}_A$ due to the irregular sampling per grid box. In southern Drake Passage, where the LMG cruise tracks fan out (Fig. 1) reducing the number of observations per grid box, the $\sigma_D$ ellipses (Fig. 2c) are less markedly smaller than the $\sigma_A$ ellipses (Fig. 2b) as compared to northern Drake Passage.

4. Defining a mean streamfunction

The mean improved Drake Passage Currents are thought to be dominated by the geostrophic flow of the ACC which satisfies the geostrophic continuity relation:

$$\nabla_h \cdot f\bar{U} = 0, \quad (2)$$

where $\nabla_h$ is the horizontal divergence. Following the methods of Gille (2003a) and Davis (2005), velocities and an associated height field (streamfunction $\psi$, where $-f\partial \psi/\partial y$, $i(\partial \psi/\partial x) \equiv f\bar{U}$] consistent with geostrophy may be objectively mapped from the observed mean currents. Covariance in the ADCP observations was a good fit to an isotropic Gaussian covariance function with a decorrelation scale of 75 km. Related covariance functions for velocity and streamfunction that satisfy Eq. (2), derived from a generalized Gaussian covariance function, are given in Gille (2003a).

Since the covariance functions describe variability, it is prudent to perform the objective mapping on fluctuations relative to a mean field. Prior to objective mapping, we subtracted surface geostrophic velocities ($\bar{U}_{\text{MN05}}$) inferred from the mean dynamic topography of Maximenko and Niiler (2005, hereafter MN05) from $U_D$. The MN05 climatology, derived from satellite altimetry, gravity measurements, and near-surface drifters, was chosen because it satisfied Eq. (2) and compared better with the improved mean currents $\bar{U}_D$ than other climatologies considered. Objective maps, utilizing the derived covariance functions and with the noise set to 10% of the variance in the velocity fluctuations ($\bar{U}_D - \bar{U}_{\text{MN05}}$), were then calculated separately for velocity and streamfunction from the velocity fluctuations. Finally, the MN05 mean velocities ($\bar{U}_{\text{MN05}}$) and
mean dynamic height ($\psi_{\text{MN05}}$) were added back to the mapped quantities to produce the total streamfunction $\psi_{D}^{\text{om}}$ and velocities $\mathbf{U}_{D}^{\text{om}}$.

Streamlines of $\psi_{D}^{\text{om}}$ (Fig. 5c) appear to follow the bathymetric contours of the continental slopes bounding Drake Passage and increase from about $-170$ cm to about $-30$ cm northward. The velocity residuals ($\mathbf{U}_{D}^{\text{om}} - \mathbf{U}_{D}$, Fig. 5f) are disorganized, randomly phased, and of generally small amplitude ($\sim 5$ cm s$^{-1}$) everywhere in Drake Passage compared to the strong mean jets ($\approx 25$ cm s$^{-1}$) in both $\mathbf{U}_{D}^{\text{om}}$ and $\mathbf{U}_{D}$ (Fig. 2a). Larger residuals are found at the northern and southern edges of the objective map where there is less data to constrain the mapping (Fig. 5f). In central Drake Passage, very small velocity residuals (Fig. 5f) indicate that the objectively mapped $\psi_{D}^{\text{om}}$ and $\mathbf{U}_{D}^{\text{om}}$ resolve the strong currents of the mean PF particularly well. Overall, the pattern of closely spaced streamlines separated by regions of widely spaced streamlines (Fig. 5c) shows that the strength of the three ACC fronts and the relative quiescence of the flow between the fronts seen in $\mathbf{U}_{D}$ are well represented by $\psi_{D}^{\text{om}}$. This suggests that the $\mathbf{U}_{D}$ currents are very nearly nondivergent and dominated by the geostrophic component of the mean flow.

Objective maps of velocity ($\mathbf{U}_{A}^{\text{om}}$) and streamfunction ($\psi_{A}^{\text{om}}$) using the same covariance functions and noise were also computed from the original mean ADCP currents $\mathbf{U}_{A}$. These objectively mapped fields were similar to $\psi_{D}^{\text{om}}$ and $\mathbf{U}_{D}^{\text{om}}$ and were most useful for quantifying the improvement in our estimate of mean currents. Velocity residuals from the comparison between the observed mean currents and associated objective maps were clearly larger in the case of $\mathbf{U}_{A}$ than $\mathbf{U}_{D}$ (Figs. 6 and 5f). The root-mean-square (rms) of velocity residuals computed across the objective map was $8$ cm s$^{-1}$ for $\mathbf{U}_{A}^{\text{om}} - \mathbf{U}_{A}$ (Fig. 6) and $6.5$ cm s$^{-1}$ for $\mathbf{U}_{D}^{\text{om}} - \mathbf{U}_{D}$ (Fig. 5f). These rms values are both biased by the larger velocity residuals at the northern extremity of the objective maps and are higher than typical velocity residuals in the interior of the objective maps (Figs. 5f and 6). Nonetheless, the smaller rms velocity residual is clear evidence that $\mathbf{U}_{D}$ calculated by combining the ADCP and altimetric observations better satisfies the geostrophic relation [Eq. (2)], and hence improves upon $\mathbf{U}_{A}$ estimated from the ADCP observations alone.

Comparison with mean climatologies

The improved gridded mean currents $\mathbf{U}_{D}$ were compared with two independent estimates of mean dynamic topography: the MN05 mean and the mean dynamic topography relative to 2500 m computed from the Olbers et al. (1992) Southern Ocean Atlas climatology (SOA) that was based on historical hydrographic data. We have subtracted an arbitrary constant 230 cm from the SOA-inferred dynamic topography (hereafter $\psi_{\text{SOA-230}}$) that allows for easier comparison with $\psi_{\text{MN05}}$.
and \( \psi_{om} \) while preserving the dynamically important lateral gradients. The MN05 mean dynamic topography increases by \( \sim 140 \) cm northward across Drake Passage (Fig. 5b), whereas the lower-resolution SOA mean dynamic topography increases by only \( \sim 110 \) cm (Fig. 5a) principally because dynamic height inferred from SOA is referenced to zero at 2500-m depth and does not include the barotropic component of the flow. We also considered RIO05 mean dynamic climatology computed from altimetry, in situ observations, and a geoid model (Rio and Hernandez 2004) and the World Ocean Atlas 2001 (WOA01) mean climatology (Conkright et al. 2002) that was based on historical hydrography. The RIO05 and WOA01-inferred mean dynamic topographies were similar to the MN05 and SOA, respectively, and are not shown in this analysis.
direction of the mean PF currents, neither climatology adequately resolves the strength of the observed mean frontal jets. The slightly northward flow in southern Drake Passage \((y_{pc} \sim -600 \text{ km}, x_{pc} \sim -170 \text{ km})\) seen in the \(\mathbf{U}_{MN05}^0 - \mathbf{U}_D\) difference (Fig. 5e) highlights the northward deviation of the \(\psi_{MN05}\) streamlines through a region with little bathymetric variability where the \(\psi_{MN05}^m\) contours are widely spaced (Fig. 5c).

A comparison of \(\psi_{MN05}^m, \psi_{SOA-230}\) and \(\psi_{SOA-230}\) shows that the lowest resolution (1° latitude \(\times 1°\) longitude) \(\psi_{SOA-230}\) has the largest rms velocity difference relative to \(\mathbf{U}_D\) (10.3 cm s\(^{-1}\), Fig. 5d). The streamfunction \(\psi_{SOA-230}\) slopes too gently across Drake Passage, consistently underestimates the size of the mean currents, and does not adequately resolve the paths and current strengths of the mean ACC fronts (Fig. 5a). This is not surprising as, in addition to concerns about the sparseness of historical hydrography, it is important to have accurate estimates of bottom velocities or the barotropic component of the flow when inferring dynamic height from hydrographic data. The bottom velocities of the ACC are thought to be significant and eastward, but remain poorly known, and therefore estimates of dynamic topography inferred from hydrographic climatologies in the Southern Ocean should be used with caution.

The higher resolution \(\psi_{MN05}\) is a clear improvement over \(\psi_{SOA-230}\) with a smaller rms velocity difference relative to \(\mathbf{U}_D\) (8.8 cm s\(^{-1}\), Fig. 5e). The streamfunction \(\psi_{MN05}\) traces the paths and estimates the strength of currents in the ACC fronts more accurately than \(\psi_{SOA-230}\). Despite producing weaker, wider jets in the ACC fronts than \(\psi_{MN05}\), similar total cross-passage dynamic height gains in \(\psi_{MN05}\) and \(\psi_{MN05}^m\) imply that the ACC transport is similar in both estimates. Both \(\psi_{MN05}\) and \(\psi_D^m\) are mean dynamic height estimates based on observations from two different time periods, October 1992–October 2002 and September 1999–October 2006, respectively. To assess the effect of natural interannual variability on the different means, we computed the mean UPD sea level anomalies for each of the two time periods. Flow patterns in the difference between the two period-mean sea level anomalies (not shown) show no correspondence to the flow patterns seen in the difference between \(\psi_{MN05}\) and \(\psi_{MN05}^m\) (Figs. 5b,c). Therefore, interannual variability cannot be the primary cause for differences between \(\psi_{MN05}\) and \(\psi_D^m\). These differences are more likely to stem from the lower resolution (1° latitude \(\times 1°\) longitude) of \(\psi_{MN05}\) or fundamental differences in the velocity observations used in each estimate. Niiler et al. (2003) pointed out that the effects of Stokes drift or wind slip of the surface drifter drogues are not well known and may bias velocity measurements from surface drifters used in the \(\psi_{MN05}\) climatology.
The significant differences between $\psi_{\text{SMN05}}$ and $\psi_{\text{D}}^{\text{om}}$ (Fig. 5) indicate that the objectively mapped streamfunction $\psi_{\text{D}}^{\text{om}}$ is strongly dependent on the improved mean currents $\mathbf{U}_D$ rather than the choice of the a priori mean field used in the calculation. Compared to $\psi_{\text{SOA-230}}$ and $\psi_{\text{SMN05}}$, the objectively mapped streamfunction $\psi_{\text{D}}^{\text{om}}$, defined where $\mathbf{U}_D$ currents are known with 90% confidence or better, has the smallest rms velocity residual relative to $\mathbf{U}_D$ (6.5 cm s$^{-1}$, Fig. 5f). Note that the rms velocity differences for $\psi_{\text{SOA-230}}$ and $\psi_{\text{SMN05}}$ are representative of typical velocity differences across Drake Passage (Figs. 5d,e), whereas the rms velocity residual for $\psi_{\text{D}}^{\text{om}}$ is biased by the larger-than-average residuals at the map edges (Fig. 5f). The streamfunction $\psi_{\text{D}}^{\text{om}}$ most clearly distinguishes the ACC frontal jets from the quiescent mean flow between the fronts and shows the influence of bottom topography on the SAF and SACCF paths (Fig. 5c). Hence, the most highly resolved ($25 \text{ km} \times 25 \text{ km}$) $\psi_{\text{D}}^{\text{om}}$ can be said to improve upon prior estimates of the mean dynamic topography in Drake Passage and provides an independent mean field that may be used to validate other climatologies.

5. Time-dependent streamlines and ACC front meanders

South of Tasmania, Sokolov and Rintoul (2002) computed maps of instantaneous dynamic height and, hence, time-dependent streamlines by adding AVISO sea level anomalies to the SOA-inferred dynamic height referenced to 2500-m depth ($\psi_{\text{SOA}}$). They then carefully compared these maps to numerous definitions of the ACC fronts determined from hydrographic and ocean velocity data along 140°E. The SAF, PF, and SACCF were observed to be filamented, comprising multiple branches, with each filament corresponding to large lateral dynamic height gradients occurring within distinct narrow ranges of dynamic height. Steep dynamic height gradients are expected to indicate the presence of the geostrophic ACC fronts (Gille 1994), and south of Tasmania, Sokolov and Rintoul (2002) were able to identify each front filament by its dynamic height range. In a recent refinement, Sokolov and Rintoul (2007, hereafter SR07) extended their analysis to a broader region from 100°E to 180° and showed that the frontal jets remain strongly correlated with particular dynamic height streamlines over the whole region.

Identifying ACC fronts in the instantaneous ADCP velocities is nontrivial because the mesoscale eddies have similar amplitudes and length scales to the fronts (Lenn et al. 2007). Lenn et al. (2007) showed that the subsurface temperature definitions of the SAF and PF inferred from XBT measurements generally coincided with velocity jets in the ADCP observations, while the agreement was less good for the SACCF. The SACCF was more reliably identified as a velocity jet than by its subsurface temperature criterion (see Fig. 2 of Lenn et al. 2007). To assess the Sokolov and Rintoul (2002) method for identifying and tracking the ACC fronts by their time-dependent streamlines in Drake Passage, we examined the distribution of time-dependent streamlines computed from $\psi_{\text{SOA-230}}$, $\psi_{\text{SMN05}}$, and $\psi_{\text{D}}^{\text{om}}$ at the XBT-inferred locations of the ACC fronts (Fig. 7a). For the SACCF we also computed the instantaneous streamline distribution based on the location of the southernmost velocity jet on the most frequently sampled middle cruise track (Fig. 7a).

Probability distributions of the instantaneous streamlines associated with the SAF, PF, and SACCF in Drake Passage have distinct peaks for each front that vary with each climatology (Fig. 7a). The peak streamline values for the SAF and PF are nearly identical for all three climatologies (Table 1), but the gentler slope of the $\psi_{\text{SOA-230}}$ climatology causes the peak SACCF streamline to be much closer to the peak PF streamlines than the $\psi_{\text{D}}^{\text{om}}$ and $\psi_{\text{SMN05}}$-based peak SACCF streamlines (Fig. 7a; Table 1). The 95% confidence limits, corresponding to twice the standard deviation, are about ±18 cm for the dynamic height streamlines of the SAF and PF determined from all three climatologies and the XBT temperatures. The 95% confidence limits are typically ±38 cm for the XBT-inferred SACCF streamlines and only ±9 cm for the ADCP-inferred SACCF streamlines. XBT-inferred SACCF streamlines occurring in the dynamic height range from −180 to −90 cm (Fig. 7a) result in the broader confidence limits for this front. This supports the conclusion of Lenn et al. (2007) that the SACCF is more easily identified by velocity than from subsurface temperature in Drake Passage. Notably, however, the peak streamline value itself is independent of whether the SACCF was identified by velocity or temperature (Fig. 7a).

The dynamic heights of the ACC fronts in Drake Passage based on the $\psi_{\text{SOA-230}}$ instantaneous streamlines (Table 1), can be directly compared to those found by SR07 south of Tasmania ($\psi_{\text{SR07}}$) after subtracting 230 cm ($\psi_{\text{SR07-230}}$, Table 1). SR07 found the standard deviations for the SAF, PF, and SACCF streamlines to be typically ~2 cm, which implies 95% confidence limits of approximately 4 cm. The streamlines SR07 associated with the northern and middle branches of the SAF south of Tasmania agree with the SAF dynamic height streamline in Drake Passage at 95% confidence (Table 1). The SR07 streamlines for the SAF south branch and the PF north and middle branches in turn agree with the Drake Passage PF streamline at 95%
The Tasman sector streamline for the southern PF branch and the northern and middle SACCF branches coincides with the SACCF at 95% confidence in Drake Passage (Table 1). These results suggest that the northern and middle SAF front filaments observed south of Tasmania have converged in Drake Passage, as have the southern SAF and the northern and middle PF filaments. Therefore, because the ACC front filaments merge at some locales and diverge at others alongstream, particular dynamic height streamlines need to be locally assigned to individual fronts and cannot be assumed to represent the fronts elsewhere in the Southern Ocean. The convergence of filaments associated with the southern SAF branch and the northern PF branch in Drake Passage is consistent with the observed redistribution of ACC transport between Tasmania and Drake Passage. The SAF carries most of the ACC transport south of Tasmania (e.g., Rintoul and Sokolov 2001; Phillips and Rintoul 2002), whereas the SAF and PF carry roughly equal proportions of the ACC transport in Drake Passage (Cunningham et al. 2003).

The strong correlation between instantaneous dynamic height and the well-defined peak dynamic height value for each front (Fig. 7a) suggest that, as Sokolov and Rintoul (2002; SR07) found, it is possible to track the meandering of the ACC fronts by the spatial distribution of specific dynamic height streamlines in Drake Passage (Figs. 7b–d). First, the streamline associated with each front is located in each instantaneous dynamic height bin (bin width = 5 cm). The PDs of the instantaneous streamlines coincide with the ADCP-inferred SACCF velocity jets are distinguished by the red dashed lines and open symbols (diamonds, squares, and circles). The spatial distribution of the peak streamline associated with the SAF (blue), PF (green), and SACCF (red) during the LMG observation period for the instantaneous dynamic height referenced to the (b) \(\psi_{SOA-230}^{D}\) climatology, (c) \(\psi_{MN05}^{D}\) climatology, and (d) \(\psi_{OM}^{D}\) (shown only where \(\psi_{OM}^{D}\) is defined): the fronts are found within the thick colored lines 80% of the time, within the lightly shaded regions 60% of the time, and within the intensely shaded regions 40% of the time. In (d), the region omitted by \(\psi_{OM}^{D}\) is masked by hatching. Bathymetry is contoured in gray; labeled contours indicate the 0-, 1000-, 2000-, and 3000-m depths. White regions mark depths below 4000 m.

**Table 1.** Peak values of dynamic height streamlines (in cm) associated with the SAF, PF, and SACCF in Drake Passage deduced from maps of instantaneous dynamic height computed by adding sea level anomalies to the objectively mapped mean streamfunction \(\psi_{SOA-230}^{D}\) climatology and the MN05 and SOA-230 mean dynamic topographies \(\psi_{MN05}^{D}\) and \(\psi_{SOA-230}^{D}\) respectively. The 95% confidence limits for the dynamic height streamlines are typically ±18 cm for the XBT-inferred SAF and PF and ±9 cm for the ADCP-inferred SACCF in Drake Passage. The corresponding streamline values (adjusted by 230 cm) that SR07 associate with the various ACC front filaments found south of Tasmania \(\psi_{SR07-230}\) are also shown. Superscripts indicate the northern (N), middle (M), and southern (S) branches of the Tasmanian sector fronts.

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<th>Drake Passage</th>
<th>South of Tasmania</th>
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<td>(\psi_{OM}^{D})</td>
<td>(\psi_{MN05}^{D})</td>
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<td>SAF</td>
<td>-60</td>
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<td>PF</td>
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<td>SACCF</td>
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namic height map for the LMG observation period. Then the probability of finding the streamline as a function of latitude is calculated for each longitude. Integrating the probability functions with respect to latitude at each longitude allows us to define meander envelopes within which the streamlines associated with the ACC fronts may be found with a given probability (e.g., 80%, 60%, and 40%, Figs. 7b–d). The meridional width of the meander envelopes in which the peak streamlines for each ACC front are found 80% of the time are widest when computed from the SOA climatology (Fig. 7b) and narrowest when computed from $\psi_D^{om}$ (Fig. 7d). This is to be expected as the gradient of dynamic height across the fronts is greatest in $\psi_D^{om}$ compared to the other dynamic topographies in Drake Passage (Figs. 5a–c). Nonetheless, the mean location and meridional distribution of the peak streamlines for each ACC front are in relatively good agreement from climatology to climatology (Figs. 7b–d).

A comparison of the SAF meander envelopes, where $\psi_D^{om}$ is defined west of about 64°W, shows that the $\psi_D^{om}$-based streamlines are found much more closely clustered along Patagonian continental slope contours (Fig. 7d) than streamlines calculated from $\psi_{MN05}$ or $\psi_{SOA-230}$ (Figs. 7b,c). Although farther downstream in Drake Passage, east of 62°W, the $\psi_{MN05}$ and $\psi_{SOA-230}$-based streamlines also frequently occur close to the continental slope (Figs. 7b,c). Over flatter topography west of the West Scotia Ridge (see Fig. 1 for location), PF peak streamlines spread out more widely and show a tendency to meander preferentially to the north of their mean location than to the south for all three climatologies (Figs. 7b–d). This result may explain some of the high eddy kinetic energy between the mean SAF and PF observed by Lenn et al. (2007) in the ADCP velocity observations. Downstream, along the West Scotia Ridge, the PF streamlines become more densely clustered (Figs. 7b–d), showing a similar association topography as the SAF. These results are consistent with the observations of Lenn et al. (2007) that show multiple mean filaments of the PF entering Drake Passage and converging downstream into singly branched mean fronts. Meander envelopes for the SACCF, computed from all three climatologies, show the SACCF closely following contours of the continental slope, particularly east of 63°W (Figs. 7b–d).

6. Conclusions

Our results have shown that the LMG high-resolution ADCP observations can be used to make an estimate of the mean surface layer currents $\mathbf{U}_D$ in Drake Passage in which the deficiencies of irregular temporal sampling are ameliorated by using AVISO altimetric sea level anomalies to reduce the variance. Objective mapping, performed using covariance functions that satisfy geostrophic continuity, is used to estimate the mean surface layer streamlines of the ACC from the observed mean currents. Smaller residuals, between the mapped velocities and the mean currents used in the objective mapping, verify the improvement in the mean current estimate $\mathbf{U}_D$ achieved by excluding the altimetry-derived geostrophic variability compared to estimating mean currents $\mathbf{U}_A$ from the ADCP observations alone. The objectively mapped currents ($\mathbf{U}_D^{om}$) and streamfunction ($\psi_D^{om}$) resolve the ACC fronts with greater detail than other climatologies, showing that the mean ACC fronts in Drake Passage are characterized by steeper dynamic topography gradients and larger currents than can be inferred from the SOA and MNO5 climatologies. Although confined to a small region of the Southern Ocean, our improved estimate of mean currents is useful for validating other climatologies.

Sea surface height, estimated by adding the instantaneous sea level anomalies to the mean climatological dynamic topographies, proves to be correlated with the ACC fronts in Drake Passage. Therefore, the Sokolov and Rintoul (2002) technique for identifying the instantaneous ACC fronts is useful for studying meandering and topographic control of the fronts and representing the time-dependent streamlines of the Drake Passage flow. Our results show that the multiple filaments of the SAF, PF, and SACCF observed south of Tasmania (Sokolov and Rintoul 2002; SR07) converge into three singly branched fronts in Drake Passage. This leads us to conclude that although dynamic height streamlines are useful for tracking ACC front filaments locally, in situ observations are still necessary to identify particular streamlines with particular fronts.

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