Near-Surface Eddy Heat and Momentum Fluxes in the Antarctic Circumpolar Current in Drake Passage

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ABSTRACT
The authors present new estimates of the eddy momentum and heat fluxes from repeated high-resolution upper-ocean velocity and temperature observations in Drake Passage and interpret their role in the regional Antarctic Circumpolar Current (ACC) momentum balance. The observations span 7 yr and are compared to eddy fluxes estimated from a 3-yr set of output archived from an eddy-resolving global Parallel Ocean Program (POP) numerical simulation. In both POP and the observations, the stream-averaged cross-stream eddy momentum fluxes \( (u'v') \) correspond to forcing consistent with both a potential vorticity flux into the axis of the Subantarctic Front (SAF) and a sharpening of all three main ACC fronts through Drake Passage. Further, the POP analysis indicates that the mean momentum advection terms reflect the steering of the mean ACC fronts and are not fully balanced by the eddy momentum forcing, which instead impacts the strength and number of ACC fronts.

The comparison between POP and observed eddy heat fluxes was less favorable partly because of model bias in the water mass stratification. Observed cross-stream eddy heat fluxes \( (\overline{wT}') \) are generally surface intensified and poleward in the ACC fronts, with values up to approximately \(-290 \pm 80 \text{ kW m}^{-2}\) in the Polar and Southern ACC Fronts. Interfacial form stresses \( F_T \), derived from observed eddy heat fluxes in the SAF, show little depth dependence below the Ekman layer. Although \( F_T \) appears to balance the surface wind stress directly, the estimated interfacial form stress divergence is only an order of magnitude greater than the eddy momentum forcing in the SAF. Thus, although the eddy momentum forcing is of secondary importance in the momentum balance, its effect is not entirely negligible.

1. Introduction
The Southern Ocean is one of the most dynamic environments in the global ocean. In sea level anomaly maps, the Antarctic Circumpolar Current (ACC) pathway is marked by exceptionally high mesoscale eddy activity (e.g., Stammer 1998; Hughes 2005). These mesoscale eddies play a significant role in the ACC momentum balance and Southern Ocean overturning circulation. Southern Ocean overturning is commonly cast as the residual circulation in which the Ekman flow driven by the predominantly zonal winds is largely cancelled by poleward eddy fluxes above submarine ridges and by a much smaller geostrophic flow below the ridges (e.g., Karsten and Marshall 2002). This leads to different dynamics dominating the surface (Ekman) and deep (below submarine ridges) layers and the intermediate depths in between. In particular, along-stream pressure gradients at intermediate depths are precluded by the absence of meridional boundaries. The steady and circumpolarly integrated momentum balance is thought to be governed by the vertical stress divergence, the eddy momentum flux divergence, and the Coriolis force (Johnson and Bryden 1989, hereafter JB89; Olbers 1998). Within this balance, mesoscale eddies are simultaneously implicated in the lateral transfer of heat across the ACC and the downward transmission of momentum (i.e., Bryden 1979; de Szoeke and Levine 1981; JB89; Hughes 2005).

Apart from its impact on ACC dynamics, the meridional eddy heat flux is of interest for its role in the global overturning circulation of the oceans. How, where, and...
how much heat is transferred by eddies in the Southern Ocean has repercussions for climate change. Model results (Wolfe and Cessi 2010) suggest that the middepth stratification of the World Ocean is determined primarily in the ACC, from the competition between mean and eddy overturning. Observational studies have recently documented a clear oceanic warming over the last half century (Gille 2002; Vaughan et al. 2003; Stroeve et al. 2007) that confirmed model predictions about the amplification of climate change in polar regions (Holland and Bitz 2003). Hence, information on the vertical distribution of the eddy heat fluxes, particularly in the rarely observed mixed layer and the transition layer below, is needed to improve our understanding of the Southern Ocean overturning circulation and future climate change scenarios.

Estimating eddy fluxes from observations requires densely sampled or long time series data to accurately distinguish transient fluctuations from the mean fields. Efforts to estimate Southern Ocean eddy heat fluxes have been hampered by the difficulty and expense of obtaining observations sufficiently resolved in time and space to attain statistically significant results. Simultaneous observations of both velocity and temperature and consequently statistically significant eddy heat flux estimates are rare and vary by region and depth (negative values correspond to poleward heat fluxes). Prior estimates summarized by Gille (2003b) include values of $-6.7 \text{ kW m}^{-2}$ (2700-m depth; Bryden 1979), $-17 \text{ kW m}^{-2}$ (1000–2500-m depth; Scriemammaamo et al. 1980), $-3.7 \text{ kW m}^{-2}$ (500–2700-m depth; Nowlin et al. 1985), and $-12 \text{ kW m}^{-2}$ (580–3560-m depth; JB89) derived from moorings in Drake Passage and $-11.3 \text{ kW m}^{-2}$ (400–3700-m depth and 2–90 day bandpassed; Phillips and Rintoul 2000) from moorings south of Tasmania. Neutrally buoyant floats provided global eddy heat flux estimates of $-5$ to $-10 \text{ kW m}^{-2}$ at 900 m across the core of the ACC (Gille 2003b). More recently, Walkden et al. (2008) reported moored current meter estimates of $-12 \pm 5.8 \text{ kW m}^{-2}$ at 2750-m depth across the Antarctic Polar Front (PF) at Shag Rocks Passage, downstream of Drake Passage.

Eddy momentum flux divergences, estimated from velocity covariances, are generally thought to be of minor importance in ACC dynamics relative to the terms dependent on the eddy heat flux (JB89; Bryden and Heath 1985; Phillips and Rintoul 2000). The few existing observational estimates of velocity covariance show marked inhomogeneity along the ACC pathway. For instance, altimetric estimates range from 25 to 50 cm$^2$ s$^{-2}$ in energetic regions, whereas zonal averages are typically less than 10 cm$^2$ s$^{-2}$ (e.g., Morrow et al. 1994; Stammer and Theiss 2004). Current meter observations give estimates of 1.6 cm$^2$ s$^{-2}$ (2–90 day bandpassed) over the 420–3320-m depth range south of Tasmania (Phillips and Rintoul 2000) and 52.6 cm$^2$ s$^{-2}$ (all frequencies) at 1000-m depth range in the southwest Pacific (Bryden and Heath 1985). Variability in eddy momentum fluxes may impact the organization of the ACC frontal jets. The time-mean flow of the ACC comprises multiple jets (Orsi et al. 1995; Gille 2003a), with as many as nine observed south of Tasmania (e.g., Sokolov and Rintoul 2007) and typically three in the Drake Passage constriction (Lenn et al. 2008, hereafter L08). Better understanding of Southern Ocean eddy-mean flow interaction requires resolution of the eddy momentum flux terms for each flow regime.

A further complication in assessing Southern Ocean eddy dynamics is obtaining observations of adequate spatial and vertical resolution for evaluating lateral and vertical gradients of the eddy fluxes appearing in the momentum balance. Deep moored current meters provide point estimates of vertical eddy heat flux divergence (Bryden 1979; Bryden and Heath 1985; Phillips and Rintoul 2000). Moored arrays (Phillips and Rintoul 2000) and global studies employing neutrally buoyant floats (Gille 2003b) or altimetry (Morrow et al. 1994; Hughes and Ash 2001; Stammer and Theiss 2004) provide estimates of lateral gradients, although the results thus far have been of varying sign and remain inconclusive. Upper-ocean observations are particularly scarce because of the high probability of damage to moored instrumentation by strong currents, icebergs, waves, and wind. Consequently, numerical models have been used to explore these terms because they can provide fluxes on the required scales (e.g., Stevens and Ivchenko 1997; Drijfhout 2005; Griesel et al. 2009). However, confidence in the modeling results requires validation by observations.

In this regional study, we present new estimates of the eddy momentum and heat fluxes from repeated high-resolution upper-ocean observations in Drake Passage and interpret their role in local ACC dynamics. However, as the narrowest constriction of the ACC, these Drake Passage observations may not be representative of the full ACC because of anisotropy in the mean ACC flow, which varies considerably along its path. Although our observations do not allow for the full evaluation of the regional ACC momentum balance, the eddy terms resolved here represent rare observational estimates of these quantities and provide insight into the eddy impact on local ACC fronts and the transfer of heat. The use of a “natural coordinate” frame defined by dynamic height streamlines allows us to directly compare eddy forcing of the Drake Passage ACC fronts in both the observations and a 1/10° Parallel Ocean Program (POP) global general circulation model simulation, despite marked differences in the mean velocity and temperature fields.
The POP model is used to assess the degree of temporal aliasing in the Drake Passage observational eddy flux estimates and to refine our understanding of the eddy dynamics. A circumpolar analysis of the momentum balance using POP results is not possible using existing archived output. Only in the Drake Passage region are all the needed quantities saved at sufficiently high temporal resolution for a consistent comparison with the observations. It is anticipated that the needed fields for a global analysis will be archived in future simulations.

The study is laid out as follows: Additional background on the theory motivating this study is provided in section 2. The observations and the POP model are described in section 3. Methods used in the estimation of the eddy fluxes, the choice of mean reference velocity and temperature fields, and potential aliasing in the observations are discussed in section 4. The eddy momentum flux estimates are presented and their role in the momentum balance is discussed in section 5, whereas section 6 focuses on the eddy heat fluxes. Note that the model results are compared with the observations throughout the study, and the model biases are discussed where appropriate. Final conclusions are summarized in section 7.

2. ACC momentum balance

Because the ACC path often deviates from a true latitude circle around the Southern Ocean, it is useful to pose its momentum balance in isopycnal coordinates following mean geostrophic streamlines in the horizontal, where s and n are the unit vectors oriented along and cross stream. The along-stream component of the momentum balance is (Marshall et al. 1993)

\[
\frac{\partial u}{\partial t} - u (f + \zeta) + \frac{1}{\rho} \frac{\partial}{\partial s} \left( M + \frac{\partial |u|}{2} \right) = F_s ,
\]

where \( u \) and \( v \) are the along- and cross-stream velocities; \( f \) is the Coriolis parameter; \( \zeta = \partial u/\partial s - \partial u/\partial n \) is the relative vorticity; \( \rho \) is density; and \( M = p + \rho g z \) is the Montgomery streamfunction with pressure \( p \), acceleration due to gravity \( g \), and isopycnal depth \( z \). These LHS terms are balanced by \( F_s = (1/\rho_0) \partial \tau/\partial n \), the divergence of along-stream stresses acting on the fluid.

One advantage of a streamline coordinate frame is that it achieves a clearer separation of the flow into mean (including standing eddies) and transient components. Thus, separating the terms in Eq. (1) into their mean and transient components (e.g., \( u = \bar{u} + u' \) where the overbar denotes time averaging and the prime denotes transient eddy contributions), assuming mass conservation and taking only the steady balance above submarine ridges and below the surface Ekman layer, leads to

\[
\frac{\partial}{\partial s} \bar{u} u + \frac{\partial}{\partial n} \bar{v} v - f \bar{v} = \frac{1}{\rho_0} \frac{\partial}{\partial z} \left( \bar{u}' u' - \frac{\partial}{\partial n} u' v' \right). 
\]

Here, term iii, the cross-stream flux of planetary vorticity due to the ageostrophic flow, and the mean advection terms i and ii remain on the LHS, whereas the eddy momentum forcing terms v and vi are moved to the RHS. The ageostrophic Coriolis term iii can be expressed in terms of a vertical divergence of the cross-stream eddy buoyancy flux (Marshall et al. 1993),

\[
-f \bar{v} = f \frac{\partial}{\partial z} \frac{u' \rho'}{\bar{\rho}},
\]

where

\[
\frac{u' \rho'}{\bar{\rho}} = \frac{1}{\rho_0} F_T
\]

is the interfacial eddy form drag arising from local pressure differences due to depth variations in isopycnal surfaces (Rhines and Holland 1979; JB89; Olbers 2005). In conditions where temperature \( T \) is a good proxy for density, \( F_T \) can be approximated by the widely used JB89 parameterization,

\[
F_T = \rho_0 f \frac{u' \bar{T}}{\bar{g} z},
\]

where \( \bar{\rho} \) is the mean vertical gradient of potential temperature. This \( F_T \) parameterization is widely used (e.g., JB89; Phillips and Rintoul 2000; Gille 2003b), because temperature is one of the more consistently made and reliable measurements available to oceanographers.

When the ACC is discussed on global scales, the momentum balance in Eq. (2) is typically integrated circumpolarly and vertically, which reduces the balance to three terms: iii, iv, and vi. In one such scenario proposed by JB89, if the frictional stress (term iv) and eddy momentum flux forcing (term vi) are negligible below the Ekman layer, then interfacial form stress represented by term iii directly balances the surface wind stress (i.e., \( F_T \sim \tau_0 \)). This explicitly links a poleward eddy heat flux to downward eddy momentum transport (JB89). Although eddies are thought to dominate the balance, there is likely a small contribution from a mean poleward geostrophic flow at depths below the shallowest sills (e.g., Gnanadesikan 1999), which does not appear in the intermediate layer balance [Eq. (2)]. Evaluations of \( F_T \) at intermediate depths (500–3500 m) from observations (JB89; Phillips and Rintoul 2000; Gille 2003b) and numerical models (Stevens and Ivchenko
1997) have been on the order of magnitude required to balance the surface wind stress at each depth and appear to verify the JB89 theory. On regional scales, the imbalance between eddy and mean advection may be important, especially because the time-mean ACC alternates along stream between stable jets and multiple front filaments, indicating inhomogeneity in the eddy forcing. In many locations, the structure of the ACC frontal jets are thought to be subject to both topographic control and the eddy potential vorticity flux that is defined by contours of constant $s$ in stream coordinates. Although the zonal pressure gradient term (A) vanishes in a global integral, it may be large on regional scales, but unfortunately our available observations do not resolve pressure. Consequently, the stream coordinate reference frame of Eq. (2) is best suited to this regional observational analysis and affords two other advantages. First, it allows us to average the observations along streamlines and so improve our eddy statistics. Second, although the ACC fronts differed in geographic location between the observations and model, the stream coordinates allowed us to make direct comparison between them.

As the observations do not allow all terms in Eq. (2) to be resolved, we do not attempt to evaluate the full momentum balance. Instead, this study focuses on the dynamical impact of the cross-correlated eddy momentum flux term (vi) and the eddy heat fluxes appearing in the interfacial form stress divergence (iii), which are resolved by the observations using Eq. (3) with statistical significance. The POP output allows us to extend this analysis by evaluating, in Earth coordinates [Eq. (4)], the balance between the mean advection (I and II) and eddy momentum flux terms (V and VI).

3. The Drake Passage datasets

   a. ADCP and XBT/XCTD observations

Underway upper-ocean velocity and temperature data were collected aboard the Antarctic Research and Supply Vessel (ARSV) Laurence M. Gould (LMG) during transsects between South America and the Antarctic Peninsula. This analysis uses acoustic Doppler current profiler (ADCP) data from 156 Drake Passage crossings made approximately twice monthly in all seasons between September 1999 and October 2006 (Fig. 1), when the LMG was en route to scientific cruises around the Antarctic Peninsula or carrying supplies to Palmer Station. These ADCP observations constitute an irregular 7-yr time series of horizontal currents in the upper 300 m of Drake Passage that has been described in detail by Lenn et al. (2007).

For this study, currents $U_{mm}$ were averaged in 10-m depth bins with the shallowest bin centered at 30-m depth, and the barotropic tide was removed using the TPXO6.2 model (Egbert et al. 1994). Measurement errors in absolute velocities computed from 15-min ensemble averages are negligible compared to the record-length standard deviation of currents in Drake Passage ($\sim 30–60$ cm s$^{-1}$). Calculations are limited to depth bins above 250-m depth as the degrees of freedom decrease at deeper levels because of missing or suspect data. Various coordinate frames are used as appropriate: geographic earth, passage, and streamwise. Passage coordinates $x_{pc}$, $y_{pc}$ are rotated 23.6$^\circ$ anticlockwise from north ($x_{pc} = 0$ axis is shown in Fig. 1) and are mostly used to display quantities in distance cross and along passage. Streamwise or natural coordinates use geostrophic streamlines as defined in section 4. Mean currents and eddy fluxes in this study are calculated from ADCP data taken between September 1999 and October 2006.

Since 1996, the LMG has also conducted repeat expendable bathythermograph (XBT) surveys of Drake Passage approximately six times per year. Sprintall (2003) provides a detailed description of the XBT observations. XBT probes were deployed every 6–10 km across the Subantarctic Front (SAF) and PF and every
10–15 km elsewhere between the 200-m isobaths at either side of Drake Passage (Fig. 1). The XBT probes consistently return water temperatures from the surface down to 800 m and were averaged within 10-m depth bins. The long-term mean temperatures used in this study are calculated from the full XBT time series, from September 1996 to October 2006. Of these, 50 XBT surveys of upper-ocean temperature from September 1999 to October 2006 coincided with roughly 30% of the ADCP sections and are used in the eddy heat flux calculation presented here.

b. POP model output

To complement the observations, this study also used output from a multidecadal \(1/10^\circ\), 40-level global POP simulation (Maltrud and McClean 2005; McClean et al. 2006, 2008). POP is a three-dimensional, \(z\)-level, primitive equation general circulation ocean model with an implicit free surface (Smith et al. 1992; Dukowicz et al. 1993; Dukowicz and Smith 1994; see online at http://climate.lanl.gov). The simulation was configured on a displaced North Pole grid that is Mercator in the Southern Hemisphere. Its horizontal resolution is between 4 and 9 km in the Southern Ocean, such that the first baroclinic Rossby radius is resolved equatorward of 50°S. It includes the \(K\)-profile parameterization (KPP) mixed layer (Large et al. 1994) and has a model time step of 6.3 min. It was forced with daily fields (6-hourly fields averaged to one day) of wind stress, air temperature, air density, and specific humidity derived from a combination of National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis products for the period 1979–2003 (Kalnay et al. 1996). Monthly downward shortwave radiation and cloud fraction came from the International Satellite Cloud Climatology Project (ISCCP) and Rossow and Schiffer (1991), respectively. Monthly-mean precipitation data were taken from the Microwave Sounding Unit (MSU) and Xie–Arkin climatology (Xie and Arkin 1998). The model was spun up for two decades, and daily averages of both state variables and cross terms of the flux components were archived for the Drake Passage region for a 3-yr period, from 1 January 1999 to 31 December 2001. The POP Drake Passage domain ranged from 64°31.23′ to 53°32.18′S and from 67° to 53°W.

4. Methods

In this section, we discuss and compare the choice of the different mean reference fields used in the eddy flux calculations from the \(LMG\) observations and the POP model output. This is followed by a detailed description of how the eddy fluxes are calculated from the observations and POP model output and an evaluation of potential aliasing in the observational results.

a. Mean velocities and streamlines

In Drake Passage, the mean ACC flow is characterized by a steep slope in dynamic height corresponding to a sizeable transport carried primarily within the SAF, PF, and the Southern ACC Front (SACCF) (L08). The slope, transport, and resolution of these fronts provide useful metrics for evaluating the quality of the mean fields used in the eddy flux estimates. In this study, subsurface temperature criteria are used to define the three ACC fronts (summarized in Table 1): the SAF corresponds to the maximum subsurface temperature gradient between the 4° and 5°C isotherms at 400-m depth (Orsi et al. 1995; Sprintall 2003); the PF is defined by the northernmost extent of the 2°C isotherm at a depth of 200 m (Botnikov 1963; Joyce et al. 1978; Sprintall 2003); and the SACCF corresponds to the intersection of the 1.8°C isotherm with the depth of the maximum temperature gradient (Orsi et al. 1995).

In an earlier study, L08 presented a new high-resolution estimate of the mean upper-ocean velocity field and
Table 1. Subsurface temperature definitions for the SAF, PF, and SACCF and the corresponding streamfunction values from the L08 and POP mean fields. The range of streamlines associated with each frontal region is given, and bold numbers indicate individual streamlines associated with the core of each front.

<table>
<thead>
<tr>
<th></th>
<th>SAF</th>
<th>PF</th>
<th>SACCF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (T)</td>
<td>Max gradient between the 4° and 5°C isotherms at 400-m depth</td>
<td>Northernmost extent of the 2°C isotherm 200-m depth</td>
<td>Intersection of the 1.8°C at isotherm with depth of max T gradient</td>
</tr>
<tr>
<td>$\psi_{L08}$ (cm)</td>
<td>$-65 &lt; -60 &lt; -40$</td>
<td>$-125 &lt; -100 &lt; -80$</td>
<td>$-160 \leq -160 &lt; -145$</td>
</tr>
<tr>
<td>$\psi_{pop}$</td>
<td>$-90 &lt; -50 &lt; -20$</td>
<td>$-120 &lt; -110 &lt; -105$</td>
<td></td>
</tr>
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Associated dynamic height streamfunction on a 25 km × 25 km grid in Drake Passage using the LMG ADCP observations and satellite sea level anomalies. L08 subtracted geostrophic velocity anomalies, inferred from sea level anomalies, to reduce aliasing in the velocity observations before objectively mapping with a geostrophic constraint to determine mean near-surface ACC currents ($\mathbf{U}_{L08}$) and dynamic height streamfunction ($\psi_{L08}$; Fig. 2a). The $\psi_{L08}$ streamlines (Fig. 2a) and $\mathbf{U}_{L08}$ currents more sharply resolved the topographically steered pathways and strengths of the SAF, PF, and SACCF than other existing climatologies (L08). For this reason and also because the L08 mean fields were calculated from the existing climatologies (L08). For this reason and also because the mean POP velocities and closely follow the mean flow. The cross-passage slope in the flow. The cross-passage slope in the flow. The cross-passage slope in the flow. The cross-passage slope in the flow. The cross-passage slope in the flow. The cross-passage slope in the flow. The cross-passage slope in the flow. The cross-passage slope in the flow. The cross-passage slope in the flow. The cross-passage slope in the flow. The cross-passage slope in the flow. The cross-passage slope in the flow. The cross-passage slope in the flow. The cross-passage slope in the flow. Notable differences exist between the ACC fronts resolved by the mean modeled and observed dynamic height fields. For instance, in $\psi_{pop}$, there are more densely spaced streamlines of a faster, broader SAF ($-90 cm < SAF_{pop} < -20 cm$; Fig. 2b) than inferred from observations ($-65 cm < SAF_{L08} < -40 cm$; Fig. 2a). In contrast, the PF streamlines are considerably more widely spaced in POP ($-120 cm < PF_{pop} < -105 cm$; Fig. 2b) and trace a more convoluted path compared to $\psi_{L08}$ ($-125 cm < PF_{L08} < -80 cm$; Fig. 2a). In southern Drake Passage, the SACCF_{L08} is clearly defined as a separate front ($-160 cm < \psi_{L08} < -145 cm$; Fig. 2a), whereas the mean SACCF_{pop} is indistinguishable from PF_{pop} (Fig. 2d).

These differences in the fronts are reflected by mean 30–250-m-layer cumulative transports through Drake Passage (Fig. 3), computed from model output along 6°W and from ADCP currents across three frequently repeated LMG transects (locations marked in Figs. 1, 5b). The ADCP transport calculation has been updated from Lenn et al. (2007); for this study, we excluded a 0–30-m slab layer and incorporated an additional 2 yr of data. The cumulative transports show the SAF_{L08} and PF_{L08} carry about 90% of the (30–250 m) ACC transport in roughly equal parts (Fig. 3), whereas the SAF_{pop} carries most of the Drake Passage transport ($\sim 17 Sv$ ($1 Sv = 10^6 m^3 s^{-1}$); Fig. 3), which is roughly $\sim 10 Sv$ more than the PF_{pop} (Fig. 3). However, the total Drake Passage transports from both the $\psi_{pop}$ and $\psi_{L08}$ dynamic height fields agree to within 1 Sv of 27 Sv. This is because both the observed and POP mean dynamic height fields are approximately 140 cm higher at Tierra del Fuego (TdF) than at the Antarctic Peninsula, although their absolute values differ slightly (Figs. 2a,b). Thus, despite discrepancies in the ACC fronts, we note that the agreement between $\psi_{L08}$ and $\psi_{pop}$ with respect to the total Drake Passage upper-ocean transport implies that the large-scale forcing and underlying dynamics of the Southern Ocean is successfully reproduced by the POP model.

One question to be addressed in this study is how eddies influence the mean flow. If the eddy forcing is important in determining the strength and location of the ACC fronts, then it is possible that differences...
FIG. 2. Objectively mapped mean streamlines (white contours) associated with the (a) $\psi_{L08}$ streamfunction (reproduced with permission from L08) and (b) $\psi_{\text{pop}}$ mean POP model sea surface height; bathymetry is shaded in grayscale with streamlines plotted at $d\psi = 5$ cm intervals, alternating between thick and thin lines. (c),(d) Locations of the mean SAF (gray crosses and solid line), PF (gray dots and dashed line) and SACCF (dark gray crosses and thick line) as defined by subsurface temperature criteria are overlaid on $\psi_{L08}$ and $\psi_{\text{pop}}$ streamlines (black lines) plotted at 10-cm intervals. Note that in (c) the instantaneous XBT-inferred front positions are shown, whereas in (d) the mean front positions determined from the mean POP temperature field are shown. Passage coordinates are defined in section 3a and Fig. 1.
between $\Psi_{L08}$ and $\Psi_{\text{pop}}$ may stem from the resolution of mesoscale eddies in POP. For instance, in northern Drake Passage, where ADCP data and altimetry show mesoscale eddy features of up to 100-km scales that are comparable in width to the frontal jets (Lenn et al. 2007), the POP model explicitly resolves realistic mesoscale eddies. In southern Drake Passage, where the first Rossby internal deformation radius is ~9 km, the observed mesoscale eddies tend to be $O(10-20 \text{ km})$. This renders the eddies as subgrid-scale processes in POP, such that the exchange of momentum between the eddies and mean flow is not explicitly resolved.

b. Mean reference temperatures

The mean three-dimensional temperature field ($T_{L08}$) used in this study was computed by first sorting all the XBT temperature profiles from each transect into the same 25 km $\times$ 25 km grid boxes as the ADCP observations and averaging first by transect and then by time (all transects between September 1996 and October 2006). The resulting mean temperature field (Figs. 4a–c) is somewhat less smooth than for the velocities and mean streamfunction, because there are fewer XBT observations than ADCP observations.

The mean XBT temperatures decrease poleward (Figs. 4a–c), reflecting the change in water mass properties across the ACC fronts. The biggest upper-ocean temperature change occurs across the PF, with Subantarctic Surface Water found to the north of the front and Antarctic Surface Water found to the south of the front (Sprintall 2003). In austral winter and spring, the very cold ($T < 0^\circ\text{C}$) and fresh Antarctic Surface Water spreads equatorward from the Antarctic Peninsula in a layer more than 100 m thick (Sprintall 2003). In summer, surface heating caps this cold layer resulting in a mean subsurface temperature minimum of Winter Water located at ~100-m depth (Fig. 4b). Below the Antarctic Surface Water lies the warmer ($T < 2^\circ\text{C}$) and saltier Upper Circumpolar Deep Water (Fig. 4c).

Mean POP temperatures $\bar{T}_{\text{pop}}$ averaged over the 3-yr archived dataset (Figs. 4d–f) are broadly similar in magnitude and spatial distribution to the observations. There is evidence of the cold Antarctic Surface Water to the south of the PF and a subsurface Winter Water temperature minimum (Fig. 4d). However, the Winter Water temperature minimum occurs at a shallower depth (~50 m) than in the observations, and thus the warmer Upper Circumpolar Deep Water is found at 100-m depth in POP (Fig. 4e).

Differences between the mean temperature fields imply that the POP model’s stratification south of the PF was suboptimal in this region. The Winter Water properties and the depth of the winter mixed layer depend on the surface atmospheric fluxes, lateral forcing (e.g., representation of dense overflows from Antarctic shelf seas), and the vertical mixing scheme of the model. It seems likely that deficiencies in the surface and more southerly lateral forcing may be the cause of this model bias. In the future, it is possible that the water mass structure in POP will be improved in fully coupled models that include active atmospheric and ice components. The eddy flux analysis that is the focus of this study is not intended to provide insight into the water mass formation in POP; the imperfect representation of the upper-ocean stratification will, however, influence the POP eddy heat flux estimates.

The JB89 parameterizations require calculations of the mean vertical temperature section by averaging the time-mean gridded temperature profiles along the appropriate mean $\Psi_{L08}$ streamlines (not shown). The mean vertical temperature gradient $\bar{T}_z$ is estimated as the derivative of the time-mean streamwise-averaged vertical section.

c. Calculating observed eddy fluxes

Eddy velocity fluctuations $[\mathbf{U}_{\text{img}}(t) = \mathbf{U}_{\text{img}}(t) - \mathbf{U}_{L08}]$ for each 25 km $\times$ 25 km grid box and depth were calculated from the observations by subtracting the mean velocities $\mathbf{U}_{L08}$ from the instantaneous gridded velocities $\mathbf{U}_{\text{img}}(t)$. Note that we have assumed $\mathbf{U}_{L08}$ applies over the top 250 m, because the time-mean velocity in this region is extremely coherent with depth (Lenn et al. 2007) and exhibits negligible shear [$O(10^{-4} \text{ m s}^{-1})$; Lenn and Chereskin 2009]. Temperature fluctuations $[T'(t) = T(t) - \bar{T}]$, in
each grid box and at each depth during the ADCP observation period from September 1999 to October 2006, were calculated relative to the 10-yr mean temperatures.

In computing the ACC eddy fluxes from observations, statistical significance of the eddy flux estimates is enhanced by increasing the number of degrees of freedom (i.e., independent observations) and thereby reducing the errors. Averaging the eddy momentum and heat fluxes along the mean streamlines (Fig. 2a) allowed us to combine all the available Drake Passage transects to produce mean sections of cross- and along-stream flux estimates. It is then straightforward to compute cross-stream gradients of eddy momentum fluxes to interpret the dynamical impact of this eddy term. Without streamwise averaging, the standard errors of the gridded eddy fluxes are too high to allow for statistically significant differentiation along stream, such that terms \( i \) and \( v \) from Eq. (2) cannot be resolved from the observations. In any case, along-stream differentiation becomes less and less possible as horizontal extent (i.e., \( \delta x \)) of the observations decreases sharply as the LMG cruise tracks converge to the north (Fig. 1).

For the purposes of streamwise averaging (denoted by \( \psi \) superscript), the gridded velocity fluctuations are first projected into mean stream coordinates such that \( u' \) is the along-stream component and \( v' \) is the cross-stream
component. The gridded Reynolds stresses \((u'v', v'v', u'v', u'T', \text{ and } u'T')\) are then averaged along \(\psi\) contours to compute along- and cross-stream velocity variances \((\overline{u'u'}_{\text{pop}}^{(y)} \text{ and } \overline{v'v'}_{\text{pop}}^{(y)})\), eddy kinetic energy \(\text{EKE}_{\psi} = (1/2)\overline{u'u'}_{\text{pop}}^{(y)} + (1/2)\overline{v'v'}_{\text{pop}}^{(y)}\) cross-stream flux of along-stream momentum \((\overline{u'u'}_{\text{pop}}^{(y)})\) and along- and cross-stream eddy heat fluxes \((\overline{u'T'}_{\text{pop}}^{(y)} \text{ and } \overline{v'T'}_{\text{pop}}^{(y)})\).

Standard errors for each eddy flux term were calculated as the standard deviation divided by the square root of the number of degrees of freedom. Bryden (1979) found that velocities observed at deep moored current meters in Drake Passage were decorrelated after 10–12 days on average. Typically, the ADCP transects are separated by more than 9 days but sometimes by as much as up to 4 months so that we assume each transect to provide one degree of freedom. Therefore, eddy momentum fluxes and EKE have 156 degrees of freedom and are presented as momentum fluxes per unit density in units of \(\text{cm}^2 \text{s}^{-2}\), whereas eddy heat fluxes with fewer concurrent ADCP and XBT transects have 50 degrees of freedom and are presented as heat fluxes per unit density per specific heat capacity in units of \(\text{C} \text{m} \text{s}^{-1}\). A typical density for the Drake Passage upper ocean is 1027 \text{ kg m}^{-3} \text{ (Levitus and Boyer 1994)}, and the specific heat capacity of seawater is 4000 \text{ J kg}^{-1} \text{ C}^{-1}.

d. Calculating POP eddy fluxes

Calculating instantaneous eddy fluctuation in velocity and temperature from the model output prior to averaging the Reynolds stresses is computationally very expensive because of the large size of the dataset. Here, the POP Reynolds stress components are calculated from the daily averaged flux cross terms and means accumulated at every time step: for example,

\[
\overline{u'u'}_{\text{pop}} = \overline{u(t)u(t)}_{\text{pop}} - \overline{n_n}_{\text{pop}}, \tag{5}
\]

\[
\overline{u'T'}_{\text{pop}} = \overline{u(t)T(t)}_{\text{pop}} - \overline{n_T}_{\text{pop}}, \tag{6}
\]

\[
\overline{v'T'}_{\text{pop}} = \overline{v(t)T(t)}_{\text{pop}} - \overline{n_T}_{\text{pop}}, \tag{7}
\]

as discussed by Maltrud et al. (1998). The POP eddy momentum and heat fluxes are presented in two ways: projected into stream coordinates and then averaged along mean POP streamlines for comparison with the observations and projected into geographical coordinates and then averaged in two-dimensional maps [Eq. (4)]. To more directly compare the relation of the POP and observed eddy fluxes to the mean flow, the streamwise-averaged POP eddy fluxes will be plotted against a nonlinear \(\psi_{\text{pop}}\) scale that is distorted to better match the mean frontal regions of \(\psi_{\text{LOS}}\) (Table 1).

e. Assessing aliasing in the LMG eddy flux estimates

The representation of eddy variability in the model is first assessed by a comparison of POP and observed EKE (Fig. 5). The POP simulation reproduces the northern enhancement of mesoscale eddy activity observed in Drake Passage (Fig. 5), although the maximum EKE_{pop} (Fig. 5b) is smaller (\(<600 \text{ cm}^2 \text{ s}^{-2}\)) than observed (\(>700 \text{ cm}^2 \text{ s}^{-2}\); Fig. 5a). This ability of POP to reproduce key features in the eddy variability and its lack of data gaps makes it useful for investigating potential aliasing in the observed eddy fluxes due to the irregular LMG sampling scheme. Potential aliasing is evaluated by subsampling the POP dataset in a manner consistent with the frequency and distribution of the LMG surveys and then compared to eddy fluxes calculated from the full POP archive. In the remainder of this section, the “pop” subscript refers to fluxes computed from the full 3-yr POP archive, and the “sub” subscript
refers to fluxes computed from subsampled POP data at the same frequency as the LMG surveys.

The January 1999–December 2001 POP record overlaps with only 28 months of the LMG ADCP observations that began in September 1999. To utilize the full POP record, we transposed individual LMG cruise dates from the 36-month period, beginning January 2000 and ending December 2002, to one year earlier to provide a subsampling template that overlaps with the POP record. Similarly, for the eddy heat flux calculation, we sampled POP data on every day the LMG was in Drake Passage conducting an XBT survey, from January 2000 to December 2002, again transposing individual dates by one year. Note that the observed estimates of eddy fluxes over the 7-yr time period have more than twice the number of degrees of freedom as the subsampled POP eddy fluxes derived from the 3-yr POP archive.

An examination of the terms $\overline{u'v'}_{\text{POP}}$ (Fig. 6a) and $\overline{u'v'}_{\text{sub}}$ (Fig. 6b) involved in the POP eddy momentum flux calculation clearly demonstrates that $\overline{u'v'}_{\text{sub}}$ (Fig. 6c) is a very small difference between two much larger terms. This underlines the difficulty in resolving eddy momentum fluxes with statistical significance from observations. However, we find that the eddy momentum flux calculated from the full 3-yr POP record ($\overline{u'v'}_{\text{POP}}$; Fig. 6c) and the LMG subsampled POP data ($\overline{u'v'}_{\text{sub}}$; Fig. 6d) are remarkably similar, both in spatial distribution and amplitude of the eddy momentum flux. Differences between the two estimates show that $\overline{u'v'}_{\text{sub}}$ has more small-scale structure than $\overline{u'v'}_{\text{POP}}$ (Figs. 6c,d), but these differences are slight within the LMG observation region (as defined by the three repeat cruise tracks; Fig. 6). Hence, we conclude that the $\overline{u'v'}_{\text{img}}$ resolved by the irregularly sampled underway ADCP observations are not substantially aliased.

Eddy heat fluxes computed from the full 3-yr POP record $\overline{u'T'}_{\text{POP}}$ and $\overline{u'T'}_{\text{sub}}$ (Figs. 7a–c, 8a–c) and the LMG-sampled POP data $\overline{u'T'}_{\text{sub}}$ and $\overline{u'T'}_{\text{sub}}$ (Figs. 7d–f, 8d–f) show that the large-scale distribution of the eddy heat fluxes is broadly similar in the two estimates (Figs. 7, 8). However, the subsampled eddy heat fluxes (Figs. 7d–f, 8d–f) are much noisier than the 3-yr record-averaged eddy heat fluxes (Figs. 7a–c, 8a–c), with more small-scale structure and more intense highs and lows. Maps of the meridional eddy heat fluxes (Fig. 7) clearly show that the largest fluxes are associated with the SAF, which is
the strongest front in the model. In the observations, the poleward cross-stream eddy heat fluxes are significant in the SAF, PF, and SACCF (section 6 and Fig. 12a), which are each well defined in the observations (Fig. 2a). These results imply that the observed eddy heat fluxes, where significant, are not subject to appreciable aliasing.

5. Eddy momentum fluxes

a. Results

The streamwise-averaged observed $\text{EKE}_{\text{img}}$ reaches a maximum between the SAF and PF before decreasing in the poleward direction (Fig. 9c), with roughly equal contributions from both $\overline{u'v'}_{\text{img}}$ (Fig. 9a) and $\overline{v'v'}_{\text{img}}$ (Fig. 9b) almost everywhere in Drake Passage. The lack of significant anisotropy in the $\overline{u'v'}_{\text{img}}$ and $\overline{v'v'}_{\text{img}}$ terms, except in the SAF, indicates that the covariance term, $\overline{u'v'}_{\text{img}}$, is unlikely to be very large. $\text{EKE}_{\text{img}}$ is always significantly higher at 30 m than at 250 m (Fig. 9c), in a manner consistent with moored EKE estimates in Drake Passage (Sciremammano et al. 1980) and elsewhere in the Southern Ocean (Bryden and Heath 1985; Phillips and Rintoul 2000). Lenn et al. (2007) showed that the main contribution to EKE in northern Drake Passage came from mesoscale eddies and transient meandering of the SAF and PF, with much smaller contributions from inertial currents and baroclinic tides.

The eddy momentum flux $\overline{u'v'}_{\text{img}}$ represents the cross-stream flux of along-stream momentum, which, unlike $\text{EKE}_{\text{img}}$, has no significant depth dependence in the 30–250-m layer of Drake Passage (not shown). Consequently, for the sake of clarity, we present only the layer-averaged $\overline{u'v'}_{\text{img}}$ (Fig. 10a). The eddy momentum flux $\overline{u'v'}_{\text{img}}$ differs significantly from zero and changes signs across the SAF, is negative in between the SAF and PF, becomes positive in the middle of the PF, and remains mostly positive to the south (Fig. 10a). The decrease in $\overline{u'v'}_{\text{img}}$ with increasing $\psi$ across the PF is consistent with the results of Lenn et al. (2007).

Where significant, our estimates of $\overline{u'v'}_{\text{img}}$ exceed prior Southern Ocean estimates from moored current meters, neutrally buoyant floats, and altimetry (see section 1 for estimates from Bryden 1979; Bryden and Heath 1985; Morrow et al. 1994; Phillips and Rintoul 2000). This may be because of the high spatial resolution of our observations or because they are closer to the surface than earlier estimates. Another possibility is that the spatial inhomogeneity in the observed estimates reflects the circumpolar variability in the ACC dynamics. South of Tasmania and most other locations in the Southern Ocean, the ACC fronts are frequently observed to exist as a braided stream of multiple filaments (Thompson 2008) that coalesce into three single-core ACC frontal jets as they pass through the narrow Drake Passage (e.g., Sprintall 2003; Cunningham et al. 2003; Lenn et al. 2007).

FIG. 6. Momentum and eddy momentum fluxes computed from POP model output at 112-m depth: (a) $\overline{u'v'}_{\text{pop}}$, (b) $\overline{u'v'}_{\text{pop}}$, (c) $\overline{u'v'}_{\text{pop}}$, and (d) $\text{LMG}$ subsampled eddy momentum flux $\overline{u'v'}_{\text{sub}}$. The zero contour is plotted (thick gray lines), and the locations of the three frequently repeated $\text{LMG}$ transects (black dashed–dotted lines) are shown. All quantities are given in cm$^2$ s$^{-2}$. Note the different color scales for (a),(b) and for (c),(d).
FIG. 7. Meridional POP eddy heat fluxes $\nabla T$ are shown at (a),(d) 30-; (b),(e) 100-; and (c),(f) 250-m depths. (a)–(c) The results using all available POP data and (d)–(f) the results produced when the POP model is subsampled on the XBT-transect days. Locations of the three frequently repeated LMG transects are shown (black dashed–dotted lines).
Fig. 8. Zonal POP eddy heat fluxes $\vec{u}T'$ are shown at (a), (d) 30-; (b), (e) 100-; and (c), (f) 250-m depths. (a)–(c) The results using all available POP data and (d)–(f) the results produced when the POP model is subsampled on the XBT-transect days. Locations of the three frequently repeated LMG transects are shown (black dashed-dotted lines).
The streamwise-averaged POP eddy momentum flux \( \overline{u'v'}_{\text{pop}} \) shares some characteristics with the observations (Fig. 10a): \( \overline{u'v'}_{\text{pop}} \) differs from zero in the northern half of the SAF, becomes slightly positive in between the SAF and PF, and falls to near zero to the south. However, unlike the observations, \( \overline{u'v'}_{\text{pop}} \) remains negative with no sign changes across the SAF (Fig. 10a). In addition, the POP estimates have a smaller magnitude compared to the observations.

b. Eddy momentum flux forcing of the ACC

The eddy forcing term (vi) in Eq. (2) depends not on the magnitude but on the lateral gradient of \( \overline{u'v'}_{\text{pop}} \), which is related to the cross-stream gradient by

\[
-\frac{\partial}{\partial n} \overline{u'v'} = -\frac{\partial \psi}{\partial n} \frac{\partial}{\partial \psi} \overline{u'v'}. 
\]

Note that negative values of \( \frac{\partial \overline{u'v'}}{\partial \psi} \) [see Eq. (2)] correspond to along-stream acceleration of the mean flow and vice versa (i.e., acceleration corresponds to negative values to the right of zero in Fig. 10b). Given the difference in the magnitude of the observed and modeled eddy momentum flux (Fig. 10), there is good agreement in the character and distribution of the eddy momentum flux forcing resolved by POP and the observations (Fig. 10b).

In Drake Passage, \(-\frac{\partial \psi}{\partial n}\) is \(~10^{-6}\) in the mean fronts and smaller in between the ACC fronts. Therefore, the observed eddy forcing term (vi) in Eq. (2) is never greater than \(O(10^{-5} \text{ m s}^{-2})\) and is more typically an order of magnitude less. Note that \( \frac{\partial \psi_{\text{pop}}}{\partial n} \) is almost twice as large as \( \frac{\partial \psi}{\partial n} \) in the SAF, where the \( \psi_{\text{pop}} \) streamlines are more closely spaced. Hence, the eddy momentum flux forcing of the SAF in POP will be correspondingly larger, accounting for the SAF being stronger and broader than SAF\(_{\text{L08}}\) (Fig. 2). Likewise, the PF\(_{\text{pop}}\) is much weaker than the PF\(_{\text{L08}}\) (Fig. 2), because the acceleration due to \( \frac{\partial \overline{u'v'}}{\partial \psi} \) is smaller and acts over a narrower range of dynamic heights.

Fig. 9. The observed streamwise-averaged eddy velocity variances (a) \( \overline{u'u'}_{\text{lmg}} \) and (b) \( \overline{v'v'}_{\text{lmg}} \) and (c) EKE\(_{\text{lmg}}\) plotted against \( \psi \) and shown with standard errors (horizontal lines). Shallowest resolved depth (30 m; red lines) and deepest resolved depth (250 m; blue lines) are shown. The locations of the mean SAF, PF, and SACCF are shaded light gray.
compared to the statistically significant acceleration due to $\partial u \overline{v^y} / \partial \phi$ (Fig. 10b). Although we are unable to resolve statistically significant $\partial u \overline{v^y} / \partial \phi$ in the SACC, the observed estimates suggest acceleration and reach values of greater magnitude than any depicted by POP south of the PF. Thus, discrepancies between $\psi_{\text{pop}}$ and $\psi_{\text{L08}}$ pertaining to the number and strengths of the mean fronts are consistent with differences in the magnitude and regional influence of the eddy momentum forcing.

One source of bias in the discrepancies between the observed and modeled eddy fluxes is the limitation in model horizontal resolution discussed in section 3a. Another source of bias in the POP simulation stems from the coarse resolution of the surface forcing. Scatterometer observations have shown that ocean wind stress curl and divergence are characterized by persistent small-scale features unresolved by numerical weather prediction models (e.g., Chelton et al. 2004), such as the NCEP/NCAR products used to force this POP simulation.

The Southern Ocean is richly populated by these small-scale wind features (O’Neill et al. 2003). Chelton et al. (2004) attributed the small-scale features to air–sea heat fluxes that modify the local marine atmospheric boundary layer, with additional drag from sea surface currents further modifying the wind field that feed back on the flow. This is consistent with the small-scale discrepancies between POP and the observations having little impact on the large-scale flow (e.g., similar total Drake Passage transport in Fig. 3).

Despite discrepancies in magnitude and regional influence, broad agreement in $\partial u \overline{v^y} / \partial \phi$ and $\partial u \overline{v^y}_{\text{pop}} / \partial \phi$ paints a consistent picture of how eddy dynamics influences the mean flow. The depth independence of the eddy momentum forcing in both the observations and POP also implies that the eddies accelerate the ACC fronts in a vertically coherent manner, consistent with the observed vertical coherence in the fronts and mesoscale eddies (Cunningham et al. 2003). These results
support the model of the ACC as an equivalent barotropic jet (Killworth and Hughes 2002). A statistically significant $\partial u \overline{v}^\phi_{\text{pop}}/\partial \phi$ sign change across the SAF (Fig. 10b), decreasing poleward from about 10 to $-10 \text{ cm s}^{-2}$, indicates that the SAF is decelerated on its northern edge and accelerated on its southern edge. This is replicated, albeit over a smaller magnitude range ($\pm 5 \text{ cm s}^{-2}$), in $\partial u \overline{v}^\phi_{\text{pop}}/\partial \phi$ (Fig. 10b). This strong curl of the eddy force along the SAF jet axis is consistent with the results of Hughes and Ash (2001), who described the curl in the eddy force along the jet axis as the eddy contribution to a nonlinear torque. Hughes and Ash (2001) equated this torque to an eddy vorticity flux into or out of the jet that partially cancels the bottom pressure torque exerted by a steep slope. This permits ACC jets to be broader than the local steep topography allows.

Statistically significant positive $\partial u \overline{v}^\phi_{\text{pop}}/\partial \phi$ and positive $\partial u \overline{v}^\phi_{\text{pop}}/\partial \phi$ (Fig. 10b) in the SAF and PF interfrontal region indicate that the flow between the SAF and PF experiences net deceleration where the mean currents and streamlines diverge in Drake Passage (Fig. 2). Significant negative $\partial u \overline{v}^\phi_{\text{pop}}/\partial \phi$ shows that the PF is accelerated by transient eddies on its northern flank, where the $\psi_{108}$ streamlines converge in Drake Passage (Fig. 2). Upstream of Drake Passage, the SAF and PF are each filamented into several branches, which merge into single mean fronts as they enter into Drake Passage (Lenn et al. 2007; L08). The eddy momentum forcing resolved by the observations and POP are thus consistent with the divergence of the SAF-related filaments from the PF filaments and the simultaneous merging of the PF filaments.

The POP model provides further insight on the role of the $\partial u \overline{u}'/\partial x$ term, which is unresolved by the observations. The POP eddy momentum flux divergences (V and VI) from Eq. (4), computed in geographical coordinates, show that $\partial u \overline{u}'_{\text{pop}}/\partial x$ (Fig. 11d) partially cancels $\partial u \overline{u}'_{\text{pop}}/\partial y$ (Fig. 11e) such that the total eddy momentum forcing ($-\partial u \overline{u}'_{\text{pop}}/\partial x - \partial u \overline{u}'_{\text{pop}}/\partial y$; Fig. 11f) proves to be nonzero. Near Tierra del Fuego, the total eddy momentum forcing extracts zonal momentum along the northern continental slope while accelerating the SAF$_{\text{pop}}$ core and decelerates the zonal flow between the SAF$_{\text{pop}}$ and PF$_{\text{pop}}$. This is qualitatively similar to the forcing inferred from the streamwise value for $\partial u \overline{v}^\phi_{\text{pop}}/\partial \phi$ (Fig. 10b), implying that in Drake Passage the character of the total eddy dynamics is captured in stream coordinates $\partial u \overline{v}^\phi_{\text{pop}}/\partial \phi$ that is resolved by the observations.

We showed earlier that the POP model mean momentum advection term $\overline{u}_{\text{pop}}$ (Fig. 6b) is an order of magnitude larger than its eddy counterpart $\overline{u}'_{\text{pop}}$ (Fig. 6c). This is also true for the other mean advection and eddy terms, $\overline{u}_{\text{pop}}$ and $\overline{u}'_{\text{pop}}$. However, the mean momentum advection gradients (Figs. 11a,b) are at most half an order of magnitude greater than their eddy counterparts (Figs. 11d,e). In fact, the $\partial u_{\text{pop}}/\partial x$ term (Fig. 11a) partially cancels the $\partial u_{\text{pop}}/\partial y$ term (Fig. 11b), such that their sum (Fig. 11c) is not much larger than and is not well correlated to the total eddy momentum flux forcing in much of Drake Passage (Fig. 11f). Our results show that the mean flow gains the most zonal momentum where the strong SAF$_{\text{pop}}$ currents turn from the north to the east (Fig. 11c). Elsewhere, the mean flow loses zonal momentum as the PF$_{\text{pop}}$ currents turn toward the north and gains zonal momentum when the PF$_{\text{pop}}$ meander passes its northermmost excursion and turns back toward the southeast (Fig. 11c). These results suggest that, in the model Drake Passage, the mean momentum advection terms reflect the steering of the mean ACC fronts and do not balance the eddy momentum forcing, which impacts the strength, width, and number of ACC front filaments.

6. Eddy fluxes

a. Results

As noted in section 4c, the observed eddy heat fluxes have about a third of the degrees of freedom as the eddy momentum fluxes, because we only have 50 cruises with concurrent temperature and velocity observations. This leads to bigger error estimates. To increase the signal-to-noise ratio, the eddy heat fluxes were filtered with a box-car filter of width $d\phi = 10 \text{ cm}$, which reduced the high-frequency noise. Even with smoothing, the calculation is impacted by the fewer degrees of freedom, and only with streamwise averaging are the eddy heat fluxes resolved with some statistical significance. Where significant, positive $u' T'_{\text{pop}}$ corresponds to downstream heat flux, and negative $u' T'_{\text{pop}}$ corresponds to a poleward heat flux.

The along-stream eddy heat flux $u' T'_{\text{pop}}$ is significantly positive on the northern flank and within the mean PF and negative on the northern flank of the SAF and in the SACCf but is not distinguishable from zero elsewhere in Drake Passage (Fig. 12b). Where $u' T'_{\text{pop}}$ is statistically significant, the fluxes tend to be surface intensified, except in the southern half of the PF, where the maximum along-stream heat flux of $7.5^\circ \pm 3.0^\circ \text{ C cm s}^{-1}$ occurs subsurface at 80-m depth. In the PF, $u' T'_{\text{pop}}$ is as high as $14.4^\circ \pm 4.7^\circ \text{ C cm s}^{-1}$ at the surface, decreasing to $6.7^\circ \pm 2.0^\circ \text{ C cm s}^{-1}$ at 250-m depth. Along-stream eddy heat fluxes derived from the POP model ($u' T'_{\text{pop}}$) do not resemble the observations and have a strong downstream flux on the northern edge of the SAF that changes sign with latitude before falling to near-zero values south of the SAF (Fig. 12d).
Fig. 11. Maps of momentum flux divergence, averaged over the top 250 m, calculated in geographical coordinate frame from POP; units are given in m s$^{-2}$. Mean advection terms (a) $\frac{\partial \bar{u}\bar{n}_{\text{pop}}}{\partial x}$ and (b) $\frac{\partial \bar{u}\bar{n}_{\text{pop}}}{\partial y}$ and eddy momentum flux terms (d) $\frac{\partial \bar{u}\bar{v}_{9\text{pop}}}{\partial x}$ and (e) $\frac{\partial \bar{u}\bar{v}_{9\text{pop}}}{\partial y}$. The sum of (c) the mean advection terms ($\frac{\partial \bar{u}\bar{n}_{\text{pop}}}{\partial x} + \frac{\partial \bar{u}\bar{n}_{\text{pop}}}{\partial y}$) and (f) the total eddy momentum forcing ($-\frac{\partial \bar{u}\bar{v}_{9\text{pop}}}{\partial x} - \frac{\partial \bar{u}\bar{v}_{9\text{pop}}}{\partial y}$) are also shown. Note that the color scale for (a) and (b) is shown to the left of (a) and differs from the color scale for (c)–(f) shown to the left of (d). Landmasses (black patches), the three LMG repeat lines (dotted black lines), and mean sea surface height contours bounding the mean SAF and PF/SACCF (thick black lines; see Table 1) are also shown in each panel.
Historical observed estimates of the zonal heat flux have primarily been well below the surface layer and hence are much smaller than those reported in this study. At 900 m, Gille (2003b) reports along-stream heat fluxes along the core of the ACC to be of similar size to the cross-stream heat fluxes $0.12\,^\circ C\, m\, s^{-1}$ and generally directed downstream, although this calculation is very sensitive to the mean field used. Bryden and Heath (1985) found that zonal heat fluxes estimated from current meters southeast of New Zealand decreased with depth, ranging from $-0.69\,^\circ C\, m\, s^{-1}$ at 1000 m to $-0.005\,^\circ C\, m\, s^{-1}$ at 5000 m. These moored estimates were directed westward, upstream along the ACC, except at 2000 m, and were of similar magnitude or smaller than the meridional heat fluxes.

Cross-stream eddy heat fluxes $\psi_{lmg}$ (Fig. 12a) have greater depth dependence than $\psi_{lmg,pop}$ (Fig. 10b) and significantly differ from zero at several locations in Drake Passage. On the northern flank of the SAF and in the SACCF, $\psi_{lmg}$ is poleward and appears surface intensified (Figs. 12a, 13b) with surface values of up to $-7.3\,^\circ C\, m\, s^{-1}$. In between the SAF and PF, there are some significantly positive values of $\psi_{lmg}$ below 60-m depth (Fig. 12a). On the southern flank of the PF ($-140\, cm < \psi_{L08} < -120\, cm$, Fig. 12a), $\psi_{lmg}$ is significantly negative and poleward below 50-m depth. At this location, $\psi_{lmg}$ ranges from $-1.1\,^\circ C\, m\, s^{-1}$ at 250-m depth to $-6.8\,^\circ C\, m\, s^{-1}$ at 100-m depth, and it has a subsurface poleward maximum in close proximity to the subsurface temperature minimum at 100-m depth.

Moored estimates of $\psi_{lmg,pop}$ in Drake Passage decrease with depth from about $-0.4\,^\circ C\, m\, s^{-1}$ at 580-m depth to about $-0.2\,^\circ C\, m\, s^{-1}$ at 3560-m depth (JB89). Moored $\psi_{lmg,pop}$ estimates in the SAF south of Tasmania also decrease with depth from $-2.26\,^\circ C\, m\, s^{-1}$ at 420 m to $-0.19\,^\circ C\, m\, s^{-1}$ at 3320 m (Phillips and Rintoul 2000). Neutrally buoyant float estimates at 900-m depth correspond to $-0.12\,^\circ C\, m\, s^{-1}$ directed poleward across the core of the ACC (Gille 2003b). Here, we report statistically significant upper-ocean $\psi_{lmg,pop}$ in Drake Passage that at some locations is larger than $-5\,^\circ C\, m\, s^{-1}$, exceeding these previously reported estimates (JB89; Phillips and Rintoul 2000). Except on the southern side of the PF, the near-surface eddy heat fluxes decrease with depth such that deeper values of $\psi_{lmg,pop}$ (Fig. 12a) lie within the range of the shallowest moored estimate (Phillips and Rintoul 2000).

Cross-stream eddy heat fluxes $\psi_{lmg,pop}$ from the POP model bear some similarities to the observations in that...
they are poleward in the northern flank of the SAF and in the PF and equatorward in the SAF–PF interfrontal zone (Fig. 12c). Some surface intensification is seen in the middle of the SAF and to the south. The POP results differ from the observations on the southern flank of the SAF, where the model predicts strongly positive (i.e., equatorward) $y^\Psi$ (Fig. 12c). In the southern half of the PF the model eddy fluxes are poleward (Fig. 12c), as are observed (Fig. 12a), although they show surface intensification rather than the subsurface maximum of the observations (Fig. 13a).

An interesting feature of the POP eddy heat fluxes is that both horizontal components are largest and change sign across the axis of the SAF: on the northern flank of the SAF the eddy heat flux is poleward and downstream, whereas on the southern flank of the SAF the eddy heat flux is equatorward and upstream (Figs. 12c,d). This provides the sense of a cyclonic circulation of the heat in the SAF region. Toward the south, the horizontal eddy heat flux components remain anticorrelated, changing sign across the PF near $\psi_{\text{pop}} = -110$ cm (Figs. 12c,d). This pattern may be due to the high rotational component of the POP eddy heat flux noted by Griesel et al. (2009). In comparison, the lateral divergences in the observed cross- and along-stream eddy heat fluxes north of the PF (Figs. 12a,b) appear to correlate in the opposite sense to the POP eddy heat fluxes, suggesting the possibility of an anticyclonic rotational heat flux. However, the correlation in the observed eddy heat flux divergences does not continue across the PF and to the south, implying that the rotational component of the eddy heat flux may be less important in the observations than in POP.

b. Implications for the interfacial form stress

Disparities between the streamwise-averaged observed and POP eddy heat fluxes, together with model bias in the water mass stratification, lead us to confine our discussion of eddy heat flux dynamics to the observations. The meridional eddy heat fluxes appear in the parameterized interfacial form stress $F_T$ in the ACC momentum balance equation [Eqs. (2) and (3)]. In this study, calculations of $F_T$ are limited to where $y^\Psi$ is statistically significant, primarily within the ACC fronts, where it is also poleward (Figs. 12a, 13b). However, because of the limited number of degrees of freedom imposed by the number of concurrent XBT/ADCP observations, the vertical temperature gradient and consequently $F_T$ are not statistically significant and error bars are not assigned. Nonetheless,
as discussed in section 2, the interfacial form stress term is expected to dominate Eq. (2), and thus the following discussion is useful to explore the depth dependence of $F_T$. The study also provides one of the very few Southern Ocean observational estimates of the interfacial form stress in the near-surface ocean.

The JB89 parameterization $F_T$ is a good approximation to $F_T$ over much of the globe where the ocean is stably stratified in temperature, such as in the Drake Passage SAF, where $\overline{T}_z^\psi$ is positive over the 250-m observed depth range (Fig. 13b). However, $F_T$ is inappropriate where temperature is a poor proxy for density, such as in the Drake Passage PF and SACCF, where $\overline{T}_z^\psi$ becomes negative below the Winter Water subsurface temperature minimum at 100-m depth (Fig. 13b). Consequently, $F_T$ is negative at depths where $\overline{T}_z^\psi$ is negative in the PF and SACCF (Fig. 13d), corresponding to an unphysical upward flux of horizontal momentum. At these depths, the interfacial form stress should be evaluated using density (e.g., $F_D$). Unfortunately, there are too few concurrent salinity and temperature observations across Drake Passage for the buoyancy fluxes to be reliably calculated directly from the observations. In addition, given the large errors in the eddy heat flux calculation and the shifting trends in Southern Ocean temperatures over the last few decades (Gille 2003a; Sprintall 2008), climatological temperature–salinity relations are not used here to infer salinity and buoyancy.

Nonetheless, the $F_T$ parameterization is appropriate in the Drake Passage SAF below the surface Ekman layer ($\sim 100$ m deep; Lenn and Chereskin 2009). Our observational estimate of $F_T \sim 0.2$ N m$^{-2}$ in the SAF (Fig. 13d) is of the magnitude required to directly balance the observed mean Southern Ocean wind stress ($\sim 0.2$ N m$^{-2}$; Gille 2005). Mooring estimates (Phillips and Rintoul 2000; JB89), neutrally buoyant floats (Gille 2003b), and numerical models (Stevens and Ivchenko 1997) have also produced estimates of $F_T$ in Drake Passage and elsewhere in the Southern Ocean that were large enough to balance the surface wind stress. However, the divergence of $\delta F_T/\delta z$ in the Drake Passage upper thermocline is $O(10^{-8}$ m s$^{-2}$), only an order of magnitude greater than the observed eddy momentum forcing (section 5b). This implies that, although secondary, the effect of the eddy momentum forcing may not be negligible when compared to the interfacial form stress divergence within the Drake Passage ACC fronts.

7. Conclusions

The main goal of this study was to evaluate the role of eddy momentum and heat fluxes in Drake Passage upper-thermocline dynamics, resolved by observations and $1/10^6$ POP model simulation. POP eddy fluxes, subsampled according to the LMG observational scheme, show that the observed eddy flux estimates are not substantially aliased. However, statistical significance would be improved by increasing the number of degrees of freedom (i.e., increasing the number of concurrent XBT and ADCP observations), particularly in the case of the eddy heat flux calculations. The POP simulation successfully reproduced the upper-ocean transport observed in Drake Passage (section 4a) but inadequately resolved mesoscale eddies at higher southerly latitudes. This was attributed to the model’s horizontal resolution and the coarseness of the NCEP/NCAR surface forcing employed in POP that excludes mesoscale features in the wind stress curl and divergence, which feedback on the local ocean dynamics (Chelton et al. 2004). These model biases resulted in discrepancies with the observed distribution of the eddy momentum flux forcing and the observed location and strength of the ACC fronts.

Despite this model bias, the role of the eddy momentum flux forcing was consistent between the observations and POP. Broad agreement in $\delta \overline{u u}/\delta x + \delta \overline{u v}/\delta y$ and $\delta \overline{v v}/\delta x + \delta \overline{v w}/\delta y$ confirms that the eddies exchange momentum with the mean SAF and PF, acting to strengthen and sharpen the fronts over the observed depth range while decelerating the flow in the interfrontal zones. Additional POP analysis showed that, in Drake Passage, 1) the character of the total eddy momentum flux $\delta \overline{u u}/\delta x + \delta \overline{u v}/\delta y$ computed in geographical coordinates was well captured by the stream-averaged $\delta \overline{u u}/\delta x + \delta \overline{v v}/\delta y$ and 2) the mean momentum advection terms reflect the steering of the mean ACC fronts and are not balanced by the observed distribution of the eddy momentum flux forcing, which impacts the strength, width, and filamentation of the ACC fronts.

The POP eddy heat fluxes are subject to model biases in water mass stratification and are also dominated by the rotational component of the heat flux (Griesel et al. 2009), considerably more than indicated by the observations. Consequently, our discussion of the dynamical implications of the eddy heat fluxes is based on the observations. Where statistically significant, observed cross-stream Drake Passage eddy heat fluxes $\overline{v T}_{\text{long}}$ are poleward in the SAF and PF, and equatorward inbetween the SAF and PF (Fig. 12a). Upper-ocean cross-stream eddy heat fluxes were observed to be as high as $-290$ kW m$^{-2}$ in the southern PF and the SACCF, exceeding those obtained by deeper moored observations. The along-stream eddy heat fluxes $\overline{u T}_{\text{long}}$ are directed downstream in the PF and upstream on the northern flank of the SAF and in the SACCF (Fig. 12b). The eddy heat fluxes tended to be surface intensified, except in the PF, where there was a subsurface maximum (Fig. 12b).
In the SAF, where stably stratified temperatures permitted sensible estimates of the JB89 interfacial form stress, we found that \( F_T \) varied little with depth between 100 (the estimated Ekman depth) and 250 m. We found that \( F_T \) could balance the surface wind stress and transmit the wind-input momentum down below the Ekman layer (section 6b). The vertical divergence estimated over the depth range 100–250 m [term iii from Eq. (2)] was only an order of magnitude greater than the eddy momentum forcing [term vi from Eq. (2)] in the SAF. Thus, although we find the eddy momentum flux forcing to be of secondary importance in Drake Passage, it is nonetheless not negligible compared to the interfacial form stress divergence here.

This study demonstrated how a unique set of concurrent underway velocity and temperature observations in Drake Passage can provide valuable insight into the dynamics of the rarely observed upper-thermocline layer of the ACC. These observations have great potential for advancing our knowledge of upper-ocean dynamics and play a useful role in validating numerical models. However, these observations cannot provide the spatial and temporal resolution required for exhaustive studies on ocean dynamics. The continued development of eddy-resolving ocean models, in terms of both improving submesoscale parameterizations and/or increasing grid resolution, provides further opportunities to better understand Southern Ocean physics.

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