

# PARAMETERIZATION OF EDDY-INDUCED SUBDUCTION IN THE SOUTHERN OCEAN SURFACE-LAYER

JEAN-BAPTISTE SALLÉE AND STEPHEN R. RINTOUL

ABSTRACT. The divergence of the eddy mass flux in the surface layer of the Southern Ocean makes an important contribution to subduction of fluid through the base of the mixed layer. Therefore, accurate parameterization of this process is needed to correctly represent the Southern Ocean ventilation in coarse-resolution models. We test a common approach to the parameterization of eddy fluxes (Gent and McWilliams, 1990) using output from the  $1/6^\circ$  eddy-permitting Southern Ocean State Estimate, which assimilates a variety of ocean observations using an adjoint method. When a constant diffusion coefficient of conventional magnitude ( $O(1000 \text{ m}^2 \text{ s}^{-1})$ ) is used, the parameterized fluxes fail to reproduce the regional pattern and magnitude of eddy-driven subduction diagnosed from the model. However, when an appropriate choice is made for the diffusion coefficient, the parameterization does a good job of reproducing the distribution and strength of the eddy contribution to subduction. Using a spatially-varying coefficient is key to reproduce the regional pattern of the eddy-induced subduction. In addition, the magnitude of the subduction is correctly represented only with a diffusion coefficient that peaks at  $10^4 \text{ m}^2 \text{ s}^{-1}$  in the most energetic areas of the Southern Ocean, a factor of ten larger than commonly used in coarse-resolution climate models. Using a diffusion coefficient that is too small will underestimate the contribution of eddies to the ocean sequestration of heat, salt and carbon.

---

## 1 INTRODUCTION

The Southern Ocean is one of the most energetic regions of the world ocean and it has long been known that mesoscale eddies play an important role in the dynamics of this region (Johnson and Bryden, 1989; Marshall et al., 1993; Marshall and Radko, 2003). The absence of land barriers in the latitude band of Drake Passage prevents any net meridional transport above the shallowest topography except through eddy fluxes and wind-driven Ekman fluxes. Therefore, Southern Ocean eddy fluxes greatly influence the oceanic general circulation by allowing transport across the strong Antarctic Circumpolar Current (ACC) and closure of the global meridional overturning circulation. Accurate representation of the effect of eddies in climate models is essential if such models are to correctly simulate the global ocean circulation and climate. However, observations of eddy fluxes are rare in the Southern Ocean: the few measurements are usually too sparse and time-series usually too short to allow assessment of the circumpolar influence of eddies in the Southern Ocean (e.g. Johnson and Bryden, 1989; Phillips and Rintoul, 2000).

To derive estimates of surface eddy fluxes in the Southern Ocean, a numerical parameterization has recently been applied to hydrographic observations (Karsten and Marshall, 2002; Marshall et al., 2006; Sallée et al., 2010). These studies have consistently described an intense southward eddy flux in the surface layer of the Southern Ocean, reaching a maximum near the Antarctic Circumpolar Current (ACC), that tends to counterbalance the northward Ekman

transport. The adiabatic eddy-induced transport is parameterized in these studies using the Gent and McWilliams (1990; hereafter GM) parameterization. However, the GM parameterization commonly used in coarse-resolution models has not been tested in a quantitative way.

A number of theoretical, modeling and observational studies have focussed on the dynamics of eddy fluxes in the mixed-layer, leading to modifications of the GM parameterization near the ocean surface (e.g. Treguier et al., 1997; Ferrari et al., 2008; 2010). As the mixed-layer is approached, eddy fluxes develop a diabatic component and the adiabatic flux is reduced. Therefore, using the GM adiabatic formalism in the surface layer produced fluxes that are much larger than observed (e.g. Griffies, 2004). Treguier et al. (1997) proposed to smoothly and continuously reduce the GM parameterization in the surface layer. Alternative parameterizations by Greatbatch and Li (2000), Griffies (2004) and Ferrari et al. (2008, 2010) are essentially similar ways of continuously extending the interior eddy flux into the surface layer. In addition to this tapering of the adiabatic flux in the surface layer, recent studies have suggested parameterizations accounting for diabatic eddy flux and submesoscale processes within the mixed layer (e.g. Young, 1994; Fox-Kemper, 2008a,b; 2011; Ferrari et al, 2008; 2010).

Despite the strong efforts to improve the eddy flux parameterization in the surface layer, the parameterization of the net adiabatic flux at the base of the surface layer has never been directly evaluated, primarily because of the lack of large-scale observation of this flux. Given that the net eddy flux through the base of surface-layer has a direct impact on water masses and

---

tracer exchanges between the surface layer and the ocean interior, and therefore has a strong impact on climate, it is important to test the validity of this parameterization. In this study, we attempt to evaluate how well the GM parameterization can represent eddy fluxes through the base of the surface layers in coarse-resolution models, by comparing the explicit fluxes in an eddy-permitting model to the parameterized fluxes. In order to isolate the sole effect of the parameterization, the parameterized flux is computed from the outputs of the eddy-permitting simulation degraded to coarse resolution, rather than by integrating a coarse-resolution model. We focus on the ability of the model parameterization to represent the vertical eddy-induced flux across the base of the surface layer.

## 2 DATA AND METHODS

### 2.1 Eddy-induced flux and its parameterization

The water volume transport across a section of length  $dx$ , in a layer of thickness  $h$  and velocity  $v$  is:  $T = v \cdot h \cdot dx$ . Hence, the time-mean average transport is:

$$(1) \quad \overline{T} = (\overline{v} \cdot \overline{h} + \overline{v'h'}) \cdot dx,$$

where prime denotes an anomaly from the time average. The correlation between velocity anomaly and thickness anomaly ( $\overline{v'h'}$ ) produces an eddy-induced flux. Therefore, in addition to mixing, eddies advect tracer by the eddy-induced velocity, defined here by:

$$(2) \quad \mathbf{u}^* = \frac{\overline{\mathbf{v}'h'}}{\overline{h}}.$$

## 2.1 Eddy-induced flux and its parameterization

---

This eddy flux is usually parameterized assuming the flux to be down the large-scale mean gradient of tracers. However, previous attempts to evaluate this parameterization often found large discrepancies (Griesel et al., 2009; Eden et al., 2007). One reason for these large discrepancies is that the flux of any tracer  $C$  ( $\overline{u'C'}$ ) is composed of a rotational and a divergent component. The only term that enters the actual tracer balance and that is represented in the parameterization is the divergent component (Lau and Wallace, 1979; Marshall and Shutts, 1981; Eden et al., 2007; Griesel et al., 2009; Fox-Kemper et al., 2003). The rotational component does not contribute to the net local tracer budget as the tracer fluxes into and out of a region are balanced (Jayne and Marotzke, 2002).

To avoid this difficulty, we will focus in this study on evaluating the divergence of the eddy flux:  $\nabla \cdot (\overline{u'C'})$ , which naturally removes the rotational contribution (Bryan et al., 1999). The divergence is really what models should get right, as this determines the exchange rate between the surface layer and the ocean interior, and sets the ocean's ability to sequester heat, carbon, and other climate properties.

Subduction is the rate at which ventilated fluid is permanently transferred from the ocean-surface layer to the interior across the base of the winter mixed-layer (Marshall et al., 1993; Sallée et al., 2010). Let  $\sigma_{wML}$  be the isopycnal at the base of the winter mixed layer. The mass transfer by eddies ( $S_{eddy}$ ) between the surface layer and the permanent thermocline is:

$$(3) \quad S_{eddy} = \nabla \cdot \overline{\mathbf{v}'H'_{\sigma_{wML}}},$$

---

where  $H_{\sigma_{wML}}(t)$  is the the depth of the isopycnal  $\sigma_{wML}$ . Following GM and Treguier et al.(1997), the eddy-induced velocity is:

$$(4) \quad \mathbf{u}^* = \frac{\overline{\mathbf{v}'\mathbf{h}'}}{\overline{\mathbf{h}}} = \begin{cases} \frac{\partial}{\partial z}[\kappa \cdot \frac{\nabla \bar{b}}{b_z}] = \frac{\partial}{\partial z}[\kappa \cdot \bar{\mathbf{s}}], & \text{below the mixed layer} \\ [\kappa \cdot \bar{\mathbf{s}}]_{z=-H} \cdot \frac{\partial \mu(z)}{\partial z}, & \text{in the mixed layer,} \end{cases}$$

where  $\kappa$  is the GM eddy diffusion coefficient,  $b$  is the buoyancy in the ocean and  $\mathbf{s}$  is the slope of the isopycnals (i.e.  $\bar{\mathbf{s}} = \nabla \bar{b}/\bar{b}_z$ ), and  $z$  is positive upward.  $\mu(z)$  is a tapering function that smoothly decays from 1 at the base of the mixed layer to 0 at the surface, which is used to extend the horizontal eddy-induced mass transport occurring below the mixed layer through the entire mixed layer (e.g. Treguier et al., 1997; Ferarri et al., 2008; 2010).

No large-scale continuous velocity observations of the Southern Ocean at the base of the surface layer exist yet. Therefore, here we used output from an eddy-permitting model to diagnose the eddy-flux divergence and test how well it can be represented by the parameterization in Eqn. 4. To have a realistic and physically consistent eddy field, we use a reanalysis of Southern Ocean observations: the Southern Ocean State Estimate (Mazloff, 2008). Once integrated above the base of the winter mixed layer, the vertical eddy-induced flux becomes:

$$(5) \quad \nabla \cdot \overline{\mathbf{v}'H'_{\sigma_{wML}}} = \nabla \cdot [\kappa \cdot \bar{\mathbf{s}}]_{\sigma_{wML}}.$$

The definition of time-mean and anomaly is not straightforward as there is no clear gap in frequency between low and high frequency motions. Previous Southern Ocean studies have shown that eddies have energy with periods as long as several months (Nowlin et al., 1985;

## 2.2 The Southern Ocean State Estimate

---

Phillips and Rintoul, 2000; Sallée et al., 2008). To ensure we include the entire eddy energy spectrum in our analysis we define the time-mean as the average of the full length of the model run (2 years), and the anomaly as the difference from this mean. The surface mixed-layer depth has a strong seasonal cycle that would be included in this definition of anomaly, but by integrating to the depth of the base of the winter mixed-layer we minimize the seasonal effects.

## 2.2 The Southern Ocean State Estimate

We use model output from the Southern Ocean State Estimate (SOSE; Mazloff et al., 2008) constrained by observations over the period 2005-2006. SOSE is an assimilation of ocean observations with a high-resolution ocean model. The one-sixth of a degree MITgcm ocean model has been optimized to physical observations in a weighted least squares sense. The adjoint method is used to assimilate observations in this model (Mazloff, 2008). This method ensures a dynamical solution consistent with observations. *In situ* profile observations (Argo, CTD, elephant seal CTD observations, XBTs) are assimilated as well as remote sensing observations of sea surface height and temperature.

The GM parameterization is used in SOSE to represent advection by eddies at scales smaller than the grid. However, the value of the diffusion coefficient is  $10 \text{ m}^2 \text{ s}^{-1}$ , much smaller than conventional values (e.g. Griffies et al., 2009), reflecting the fact that SOSE resolves much of the eddy scales.

---

The Southern Ocean has been relatively well observed in the past decade, and the state estimate is consistent with this wealth of data (Mazloff, 2008). [Figure 1](#) compares the 2005-2006 mean Eddy Kinetic Energy (EKE) resulting from the assimilation with the EKE from the Aviso merged and gridded altimetry product during the same period. The observed EKE is approximately twice the intensity of the modeled EKE (median value of 2.3; [Figure 1c](#)). SOSE reproduces enhanced variability in the western boundary current, and along the path of the ACC, with peaks where the ACC interacts with bathymetry.

### 3 EDDY-INDUCED FLUXES ACROSS THE BASE OF THE SURFACE LAYER

The SOSE model produces significant eddy-induced fluid transfer across the base of the winter mixed-layer. Rates of fluid exchange of the order of  $\pm 200 \text{ m year}^{-1}$  are found in the vicinity of the ACC ([Figure 2a](#)). Fluid is transferred from the ocean interior into the surface layer on the equatorward side of the ACC, and from the surface layer into the ocean interior on its poleward side, the net circumpolar effect of eddy-induced advection, south of  $35^\circ\text{S}$ , being an upwelling of 21 Sv and a subduction of 17 Sv ([Figure 4](#)). Both the pattern and magnitude compare relatively well with estimates based on observations from Sallée et al., (2010), which were derived using the parameterization of Eqn. 4 applied to the observed climatological structure of the Southern Ocean, and a surface drifter-based estimate of eddy diffusion intensity (Sallée et al., 2008).

### 3 Eddy-induced fluxes across the base of the surface layer

---

The fluxes found in the model are, however, more concentrated into regional patches than the observation-based estimate of Sallée et al. (2010; see their figure 8d). Regional intensification of fluxes is found in the western Indian Ocean basin, in the Agulhas Retroflection (30–60° E), south of Australia (120–150° E), in the central Pacific (120–150° W), and at Drake Passage (55–65° W). These high fluxes are found along the path of the ACC, in high EKE regions. The pattern of eddy-induced subduction differs, however, from the EKE pattern as no intense fluxes are found in the western boundary regions. Maxima in eddy-induced subduction have a dipole structure centered on the ACC, with subduction on its poleward side and upwelling on its equatorward side. The dipole structure centered on the ACC is consistent with a cross-stream poleward eddy-induced transport across the ACC that creates a divergence north of the current and a convergence south of the current.

In contrast, the wind-induced Ekman fluxes have a much more zonally symmetric structure over the Southern Ocean. The circumpolar integral of the Ekman flux results in 25 Sv of subduction north of the ACC (to 35° S) and 34 Sv of upwelling south of the ACC. The net effect of eddy-induced subduction is smaller, but significant, of the order of 50-85% of wind-induced fluxes. The eddy-induced fluxes generally reduce the injection in the ocean interior of mode and intermediate water north of the ACC, but strongly enhance it in localized areas (Figure 2c). Eddy-induced subduction locally counterbalances the wind-induced upwelling south of the ACC and strongly affects the regional patterns of upwelling/subduction in the Southern Ocean (Figure 2c). Accounting for these eddy-induced fluxes is therefore important to correctly resolve

---

the sequestration of heat, freshwater, nutrient, carbon, etc. in the ocean interior. But how well can we represent these fluxes in coarse-resolution climate models, which must parameterize the effect of eddies?

Coarse-resolution models typically use a GM diffusion coefficient in the range of a few hundreds to a few thousands of meters squared per second (e.g. Griffies et al., 2009). Some models use a constant coefficient and some others use a temporally and spatially varying coefficient depending on the local stratification (e.g. Visbeck et al., 1997; Eden and Greatbatch, 2008). In this study, we test the eddy-induced subduction produced by the GM parameterization (rhs of Eqn. 5), using a constant diffusion coefficient of  $1000 \text{ m}^2 \text{ s}^{-1}$ , and a spatially varying diffusion coefficient ranging from  $100\text{--}3000 \text{ m}^2 \text{ s}^{-1}$  depending on the eddy length scale (associated with eddy kinetic energy) and stratification (Visbeck et al., 1997; Eden and Greatbatch, 2008; see [Figure 5a](#)). Both of these coefficients are conventional values commonly used in coarse resolution climate models (Griffies et al., 2009).

Any choice of diffusion coefficient needs to be carefully adapted to the resolution of the slope of isopycnal ( $\bar{\sigma}$ ). Indeed, at the base of the winter mixed-layer, a finer resolution model would have, on average, larger isopycnal slopes than a coarse-resolution configuration, due to eddy activity, implying that one would need to use a higher diffusion coefficient in lower resolution configurations to achieve the same intensity of eddy-induced flux. In this study, we consider two coarse-resolution cases of  $1^\circ$  and  $2.5^\circ$ , which are typical of coarse-resolution climate models and

climatological dataset products. For the sake of completeness, we also consider a  $1/6^\circ$  resolution case, although no parameterization of mesoscale eddy induced fluxes would be needed in a model at such high resolution.

The eddy-induced subduction estimated from the GM parameterization of Eqn. 5, using a  $2.5^\circ$  coarse-resolution slope of isopycnals  $\bar{\sigma}$  (from SOSE output, smoothed with a Gaussian filter) are shown in Figure 3a,b. The parameterized fluxes are smaller by one order of magnitude than the fluxes explicitly derived from SOSE (note the change in scale in Figure 3a,b,c relative to Figure 2 and Figure 3d,e). Consistent with the explicit SOSE fluxes, we find larger fluxes near the ACC, consistent with an increased slope of isopycnals there, but the constant coefficient produces large areas of subduction or upwelling and no subduction/upwelling dipole. The net subduction/upwelling produced by the constant  $1000 \text{ m}^2 \text{ s}^{-1}$  coefficient is approximately one fifth of what we explicitly deduced from the high resolution SOSE fields (Figure 4). In addition, the regional distribution produced by the constant diffusion is very different from that found explicitly, which would result in subduction or upwelling in the wrong density class. The correlation with the explicit eddy-induced subduction pattern is 0.36 for points where explicit fluxes exceed  $20 \text{ m yr}^{-1}$  (see Table 1). The regional distribution is improved by using a spatially varying coefficient (pattern correlation of 0.57). However, the magnitude of the flux is still smaller than that explicitly deduced from SOSE fields (approximately one fourth). The magnitude of the fluxes are not significantly improved when considering a  $1^\circ$  resolution slope of isopycnals  $\bar{\sigma}$ . Using an isopycnal slope with a resolution of  $1/6^\circ$  slightly increases the fluxes, but

---

still not enough to be comparable with the explicitly resolved fluxes (Figure 4). Although no parameterization would be needed at such high resolution, the  $1/6^\circ$  resolution case demonstrates that even for large isopycnal slopes (no smoothing of the eddy-permitting outputs in this case), a diffusion coefficient ranging  $100\text{-}3000\text{ m}^2\text{ s}^{-1}$  at the ocean surface is too small to account for the eddy-induced flux through the base of the ocean surface layer.

In contrast to our calculation using a time-mean slope of isopycnal,  $\bar{s}$ , a coarse-resolution model would compute fluxes through the base of the surface layer using the instantaneous isopycnal slope. If using a time-constant diffusion coefficient, the net 2-year averaged flux would not be affected. However, in the case of a time and space variable coefficient depending on the stratification (e.g. Visbeck et al., 1997), the resulting 2-year averaged flux would be different than the flux computed from the time-mean slope of isopycnals. A coarse-resolution model has typically a time step of a few hours, resolving diurnal and seasonal cycles of the slope of isopycnal. The subduction flux is, however, only affected by the integrated transport above the base of the winter mixed-layer, which depends on the slope of the isopycnal at the base of the winter mixed-layer, where the diurnal and seasonal cycle are very small. To investigate the impact of time-variability on the net 2-year averaged subduction, we compute the subduction flux using the 5-day averaged slope of isopycnal produced by SOSE and the corresponding time- and space-variable diffusion coefficient (see the time-averaged coefficient on Figure 5a). Although the resulting pattern of the long-term mean flux is similar, the subduction using the time-varying slope of isopycnal and diffusion coefficient is larger by almost 50% in the  $2.5^\circ$  resolution case.

In higher-resolution cases, using a time-varying coefficient and isopycnal slope also improves the net integrated subduction but to a lesser degree than in the low-resolution case (an increase of about 30% for the  $1^\circ$  resolution case, and 21% for the  $1/6^\circ$  resolution case). The net flux is however still only about half the magnitude of the eddy flux calculated explicitly from the model output. Our results suggest that the coefficient need to be two or three times larger than those conventionally used to represent the eddy contribution to subduction (i.e a coefficient peaking regionally at  $0.6\text{--}0.9 \cdot 10^4 \text{ m}^2 \text{ s}^{-1}$ ).

We now test whether the GM-parameterized subduction can be improved when using a time-constant coefficient derived from ocean surface observations (Sallée et al., 2008). We use a diffusion coefficient derived from the observed dispersion of surface drifters that peaks at  $2 \times 10^4 \text{ m}^2 \text{ s}^{-1}$  in energetic areas and is around a few thousand  $\text{m}^2 \text{ s}^{-1}$  in quieter areas (Figure 5b). Using a  $1^\circ$  or a  $2.5^\circ$  resolution for the slope of isopycnal gives parameterized fluxes in very good agreement with the explicitly resolved fluxes (Figures 3d and 4). However, the  $1^\circ$  case tend to slightly overestimate the fluxes (by approximately 15%), suggesting that the coefficient used is more adapted for resolution of order of  $2.5^\circ$ . We note that the observation-based diffusion coefficient is not entirely consistent with the model: the coefficient used is a climatological estimate for the period 1995–2005, while the model run represents the years 2006–2007. Moreover, the eddy kinetic energy in the model is half of the observed EKE in the ocean. But with this observation-based coefficient, the  $1^\circ$  or  $2.5^\circ$  parameterization does a relatively good job at representing the net fluxes and the regional pattern. The correlation between the

---

explicit and parameterized eddy flux pattern is 0.59 for points where fluxes exceed  $20 \text{ m yr}^{-1}$  (Table 1). The parameterization seems however to overestimate fluxes in the western Atlantic, and to underestimate fluxes in Drake Passage (Figure 3d).

We do not have access to a time-varying diffusion coefficient derived from observation, but our earlier results have shown that using a time variable coefficient increases the net integrated subduction. The increased flux associated with time-variability suggests that in the case of a time-varying coefficient we might want to use a slightly lower diffusion coefficient than the observation-based coefficient used here. Considering an increase of about 50% when introducing the time-variability (Figure 4), we anticipate that a time-varying coefficient should peak regionally at  $10^4 \text{ m}^2 \text{ s}^{-1}$ .

#### 4 DISCUSSION

The skill with which the GM-parameterization can represent eddy-induced subduction across the base of the winter mixed-layer (Eqn. 5) is highly dependent on the choice of eddy-diffusion coefficient. Conventional values of the diffusion coefficient produce local subduction fluxes one order of magnitude smaller than found in the eddy-permitting SOSE model. Although use of a spatially varying coefficient (Visbeck et al., 1997; Eden and Greatbatch, 2008) clearly improves the regional distribution of the subduction fluxes, and hence the ability of the model to subduct in the correct density class, the coefficient has to peak at  $10^4 \text{ m}^2 \text{ s}^{-1}$ , much larger than conventional values, to produce the right magnitude of subduction. We note that in some

coarse-resolution models, eddy-fluxes are tapered based on a maximum isopycnal slope, so even larger diffusivities may be necessary in such models.

This study shows, however, that the GM-parameterization of eddy fluxes in the surface layer of a coarse-resolution ocean model is able to reproduce subduction fluxes well, when using an observation-based coefficient. Using a diffusion coefficient derived from observations has shown improvements in the representation of the eddy-induced subduction. However, the observation-based coefficient used here is not entirely consistent with the output of the model, as it was derived from *in situ* surface drifters that experienced higher eddy energy than represented in the model (Figure 1).

One could seek another choice of diffusion coefficient that gave a better match. However, a better representation of mixing in this particular model is not the focus of this study. Instead, we consider how large the diffusion coefficient would need to be to correctly represent the eddy-fluxes in a coarse resolution version of this model. To simplify the calculation, we neglect the horizontal gradient of  $\kappa$  in Eqn 5, which leads to:

$$(6) \quad \kappa = \frac{\overline{\nabla \mathbf{v}' H' \sigma_{wML}}}{\overline{\nabla \bar{\sigma}_{wML}}}.$$

The slope of the isopycnal field ( $\bar{\sigma}_{wML}$ ) is smoothed with a  $2.5^\circ$  Gaussian filter so the estimated diffusion coefficient is appropriate for a coarse-resolution model. The resulting diffusion coefficient is of similar order to the Sallée et al. (2008) coefficient although approximately 2-4 times smaller in the western boundary current (Figure 5c). Computing the parameterized eddy fluxes

---

using this deduced coefficient gives very similar results to the explicit calculation (despite the assumption of small  $\nabla\kappa$ ; not shown). This calculation shows that it is possible to choose a diffusion coefficient  $\kappa$  for which eddy fluxes can be correctly parameterized using GM, demonstrating that the usual approach to parameterization of the near surface layer in coarse-resolution models can potentially represent the eddy-induced fluxes through the base of the mixed layer, if an appropriate diffusivity is used.

This study suggests that GM diffusion coefficients should be of order of  $10^4 \text{ m}^2 \text{ s}^{-1}$  in energetic areas of the Southern Ocean surface layers. Such diffusion values are consistent with several recent studies that have advocated increasing the near surface diffusion coefficient to better match observations (Ferreira et al., 2005; Eden, 2006; Danabasoglu and Marshall, 2007; Vivier et al., 2010). However, our study emphasizes the importance of the horizontal distribution of the diffusion. The diffusion needs to be increased near the surface with a zonally averaged value around several thousand  $\text{m}^2 \text{ s}^{-1}$  (Eden, 2006; Danabasoglu and Marshall, 2007), but with a regional structure of  $\kappa$  peaking at  $10^4 \text{ m}^2 \text{ s}^{-1}$  in the most energetic areas of the ocean. In contrast, IPCC-class climate models typically use GM diffusion coefficients less than  $1000 \text{ m}^2 \text{ s}^{-1}$  (Griffies et al., 2009). Lee et al. (2010) have compared the subduction processes in the Southern Indian basin in a high-resolution, eddy-permitting coupled model, and a coarse-resolution configuration of the same model, using a GM diffusion coefficient of  $500\text{-}2000 \text{ m}^2 \text{ s}^{-1}$ . Their results show that the parameterized eddy fluxes are a factor of 3-4 times too small, for this choice of diffusion coefficient.

## 4 References

---

Our results suggest the need to increase the near-surface diffusion coefficient. Using a diffusion coefficient that is too small will underestimate the eddy contribution to subduction, with likely consequences for the climate sensitivity of the model. A potential way of improving subduction in climate models would be to apply a spatially varying coefficient, consistent with Visbeck et al. (1997) or Eden and Greatbatch (2008), but strongly increased near the surface of the ocean to reach values of order of  $10^4 \text{ m}^2 \text{ s}^{-1}$  in the western basins.

### Acknowledgments

The authors thank Matt Mazloff for providing the SOSE data and assistance in using the data. Computational resources for SOSE were provided by NSF through TeraGrid resources under grant number MCA06N007. JBS was supported by a CSIRO Office of the chief Executive (OCE) Postdoctoral Fellowship. We thank Bernadette Sloyan, Stephen Griffies and an anonymous reviewer for their helpful comments on the manuscript. SR was supported by the Australian Government's Cooperative Research Centres Programme through the Antarctic Climate and Ecosystems Cooperative Research Centre (ACE-CRC) and by the Australian Climate Change Science Program. JBS, SR were also supported by the CSIRO Wealth from Oceans National Research Flagship.

### REFERENCES

K Bryan, JK Dukowicz, and RD Smith, *On the mixing coefficient in the parameterization of bolus velocity*, Journ. of Phys. Ocean. **29** (1999), 2442–2456.

- 
- G Danabasoglu and J Marshall, *Effects of vertical variations of thickness diffusivity in an ocean general circulation model*, Ocean Model. **18** (2007), 122–141.
- C Eden, *Thickness diffusivity in the Southern Ocean*, Geophysical Research Letters **33** (2006), L11606.
- C Eden and R Greatbatch, *Towards a mesoscale eddy closure*, Ocean Model. **20** (2008), 223–239.
- C Eden, R.J Greatbatch, and J Willebrand, *A diagnosis of thickness fluxes in an eddy-resolving model*, Journ. of Phys. Ocean. **37** (2007), 727–742.
- R Ferrari, S Griffies, G Nurser, and G.K Vallis, *A boundary-value problem for the parameterized mesoscale eddy transport*, Ocean Model. **32** (2010), 143–156.
- R Ferrari, JC McWilliams, VM Canuto, and M Dubovikov, *Parameterization of eddy fluxes near oceanic boundaries*, J. Climate **21** (2008), 2770–2789.
- D Ferreira, J Marshall, and P Heimbach, *Estimating eddy stresses by fitting dynamics to observations using a residual-mean ocean circulation model and its adjoint*, Journ. of Phys. Ocean. **35** (2005), 1891–1910.
- B Fox-Kemper, G Danabasoglu, R Ferrari, S.M Griffies, R.W Hallberg, M.M Holland, M.E Maltrud, S Peacock, and B.L Samuels, *Parameterization of Mixed Layer Eddies. III: Implementation and Impact in Global Ocean Climate Simulations*, Ocean Model. **in press** (2011).
- B Fox-Kemper and R Ferrari, *Parameterization of mixed layer eddies. Part II: Prognosis and impact*, Journ. of Phys. Ocean. **38** (2008), 1166–1179.

## 4 References

---

- B Fox-Kemper, R Ferrari, and R Hallberg, *Parameterization of mixed layer eddies. Part I: Theory and diagnosis*, Journ. of Phys. Ocean. **38** (2008), 1145–1165.
- B Fox-Kemper, R Ferrari, and J Pedlosky, *On the Indeterminacy of Rotational and Divergent Eddy Fluxes*, Journ. of Phys. Ocean. **33** (2003), 478–483.
- PR Gent and JC McWilliams, *Isopycnal mixing in ocean circulation models*, Journ. of Phys. Ocean. **20** (1990), 150–155.
- RJ Greatbatch and G Li, *Alongslope mean flow and an associated upslope bolus flux of tracer in a parameterization of mesoscale turbulence*, Deep-Sea Res. (1 Oceanogr. Res. Pap.) **47** (2000), no. 4, 709–735.
- A Griesel, S Gille, J Sprintall, J McClean, and M.E Maltrud, *Assessing eddy heat flux and its parameterization: A wavenumber perspective from a 1/10 degrees ocean simulation*, Ocean Model. **29** (2009), 248–260.
- S Griffies, *Fundamentals of Ocean Climate Models*, Princeton University Press, 2004.
- S Griffies, A Biastoch, C Böning, F Bryan, G Danabasoglu, E Chassignet, M.H England, R Gerdes, H Haak, R.W Hallberg, W Hazeleger, J Jungclaus, W.G Large, G Madec, A Pirani, B.L Samuels, M Scheinert, A Sen-Gupta, C.A Severijns, H.L Simmons, A-M Treguier, M Winton, S Yeager, and Jianjun Yin, *Coordinated ocean-ice reference experiments (COREs)*, Ocean Model. **26** (2009), 1–46.
- SR Jayne and J Marotzke, *The Oceanic Eddy Heat Transport*, Journ. of Phys. Ocean. **32** (2002), 3328–3345.

---

G C Johnson and H L Bryden, *On the size of the Antarctic Circumpolar Current*, Deep-Sea Res. (1 Oceanogr. Res. Pap.) **36** (1989), 39–53.

WD Nowlin Jr, SJ Worley, and T Whitworth III, *Methods for making point estimates of eddy heat flux as applied to the Antarctic Circumpolar Current*, J. Geophys. Res. **90** (1985), no. C2, 3305–3324.

RH Karsten and J Marshall, *Constructing the residual circulation of the Antarctic Circumpolar Current from observations*, Journ. of Phys. Ocean. **32** (2002), 3315–3327.

NC Lau and JM Wallace, *On the distribution of horizontal transports by transient eddies in the Northern Hemisphere wintertime circulation*, J. Atmos. Sci. **36** (1979), no. 10, 1844–1861.

MM Lee, JG Nurser, I Stevens, and JB Sallée, *Subduction over the Southern Indian Ocean in a high-resolution atmosphere-ocean coupled model*, J. Climate **submitted** (2010).

J Marshall and T Radko, *Residual-mean solutions for the Antarctic Circumpolar Current and its associated overturning circulation*, Journ. of Phys. Ocean. **33** (2003), 2341–2354.

J Marshall, E Shuckburgh, H Jones, and C Hill, *Estimates and implications of surface eddy diffusivity in the Southern Ocean derived from tracer transport*, Journ. of Phys. Ocean. **36** (2006), 1806–1821.

J Marshall and G Shutts, *A note on rotational and divergent eddy fluxes*, Journ. of Phys. Ocean. **11** (1981), no. 12, 1677–1680.

JC Marshall, AJG Nurser, and RG Williams, *Inferring the subduction rate and period over the North Atlantic*, Journ. of Phys. Ocean. **23** (1993), 1315–1329.

## 4 References

---

- M Mazloff, *The Southern Ocean meridional overturning circulation as diagnosed from an eddy permitting state estimate*, Ph.D thesis, MIT (2008).
- HE Phillips and SR Rintoul, *Eddy variability and energetics from direct current measurements in the Antarctic Circumpolar Current south of Australia*, Journ. of Phys. Ocean. **30** (2000), 3050–3076.
- JB Sallée, K Speer, R Morrow, and R Lumpkin, *An estimate of Lagrangian eddy statistics and diffusion in the mixed layer of the Southern Ocean*, Journ. of Marine Res. **66** (2008), no. 4, 441–463.
- JB Sallée, K Speer, SR Rintoul, and S Wijffels, *Southern Ocean thermocline ventilation*, Journ. of Phys. Ocean. **40** (2010), no. 3, 509–529.
- AM Treguier, IM Held, and VD Larichev, *Parameterization of quasigeostrophic eddies in primitive equation ocean models*, Journ. of Phys. Ocean. **27** (1997), 567–580.
- M Visbeck, J Marshall, and T Haine, *Specification of eddy transfer coefficients in coarse-resolution ocean circulation models*, Journ. of Phys. Ocean. **27** (1997), 381–402.
- F Vivier, D Iudicone, F Busdraghi, and YH Park, *Dynamics of sea-surface temperature anomalies in the Southern Ocean diagnosed from a 2D mixed-layer model*, Climate dynamics **34** (2010), no. 2, 153–184.
- W Young, *The subinertial mixed layer approximation*, Journ. of Phys. Ocean. **24** (1994), 1812–1826.

---

Constant coefficient	Spatially varying coefficient (Visbeck et al., 1997)	Observation-based coefficient (Sallée et al., 2008)
0.36	0.57	0.59

TABLE 1. Table indicating the spatial correlations between the eddy-induced subduction fluxes explicitly deduced from the eddy-permitting SOSE model, and the 2.5° coarse-resolution parameterized fluxes using either a constant diffusion coefficient ( $\kappa = 1000 \text{ m}^2 \text{ s}^{-1}$ ), or a spatially varying coefficient depending on eddy length scale and stratification (Visbeck et al., 1997; Eden and Greatbatch, 2008; see [Figure 5a](#)), or a diffusion coefficient deduced from surface drifter observations (Sallée et al., 2008; see [Figure 5b](#)). Correlations are calculated for all grid-points where the explicit flux exceed 20 m/year. All correlations are statistically significant, above the 99% confidence level.

## 5 FIGURES

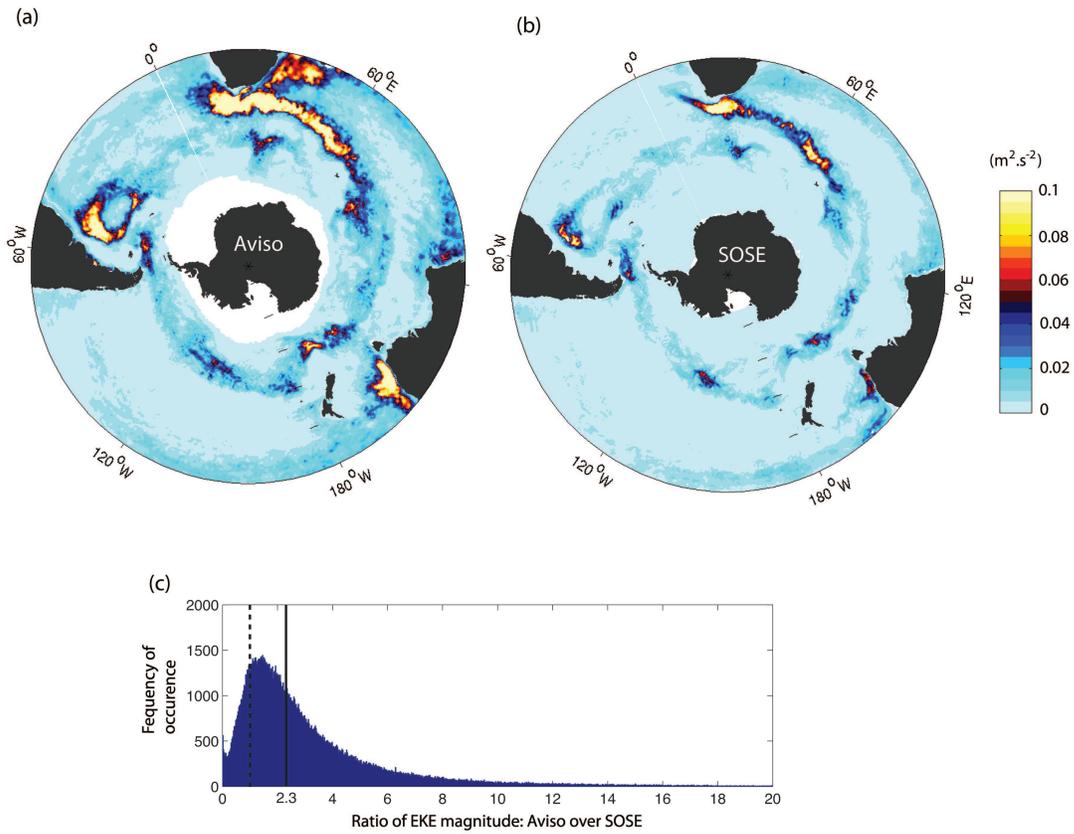


FIGURE 1. Eddy kinetic energy (EKE) from (a) satellite observations and (b) in the Southern Ocean State Estimate. (c) Histogram of the ratio between the observed EKE and the modeled EKE. The vertical lines correspond to (dashed) unity and (plain) the median value of the ratio (2.3)

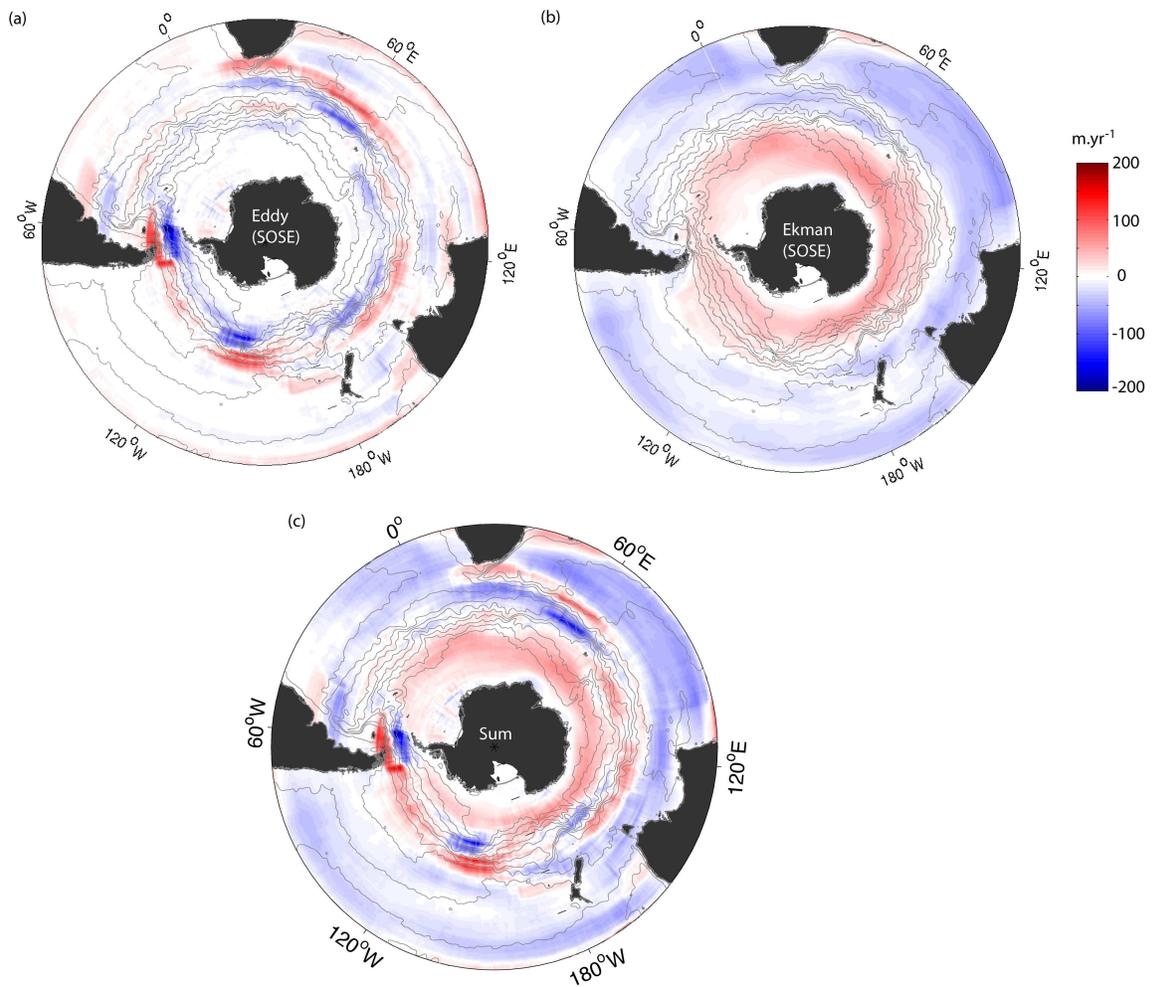


FIGURE 2. (a) Explicit eddy-induced flux and (b) wind-induced Ekman flux in the Southern Ocean State Estimate through the base of the winter mixed layer. (c) Sum of Ekman and eddy-induced flux. Gray lines are the 2-year mean pressure isolines at ocean surface in the model. Upwelling is associated with positive values and subduction with negative values.

## 5 figures

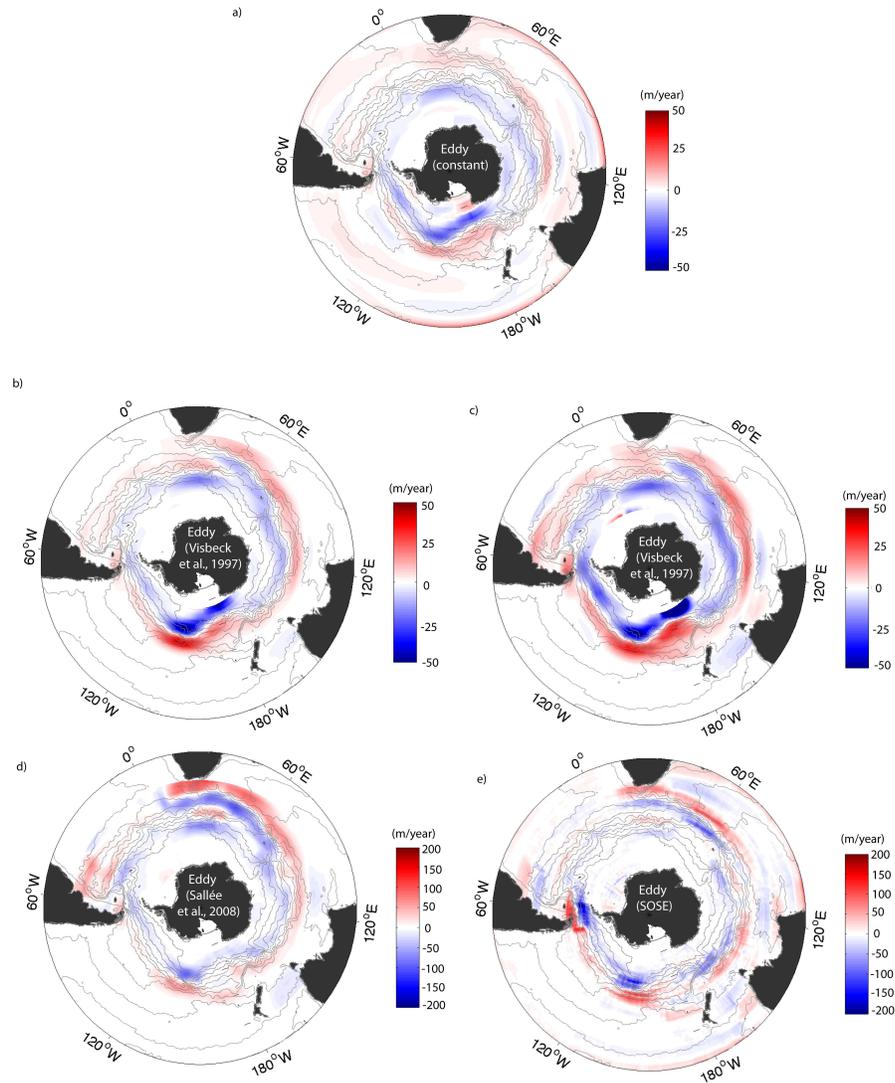


FIGURE 3. Parameterized eddy-induced subduction using using and  $2.5^\circ$  resolution time-mean slope of isopycnal from SOSE output (smoothed with a Gaussian filter) and: (a) a constant diffusion coefficient ( $\kappa = 1000 \text{ m}^2 \text{ s}^{-1}$ ); (b) a spatially varying coefficient depending on eddy length scale and stratification (Visbeck et al., 1997; Eden and Greatbatch, 2008; see Figure 5a); (c) a time and spatially varying coefficient in combination with time-varying isopycnal slopes; and (d) a diffusion coefficient deduced from surface drifter observations (Sallée et al., 2008; see Figure 5b). (e) Subduction fluxes explicitly deduced from the eddy-permitting SOSE model (same as Figure 2a). Gray lines are the 2-year mean pressure isolines at ocean surface in the model. Note the change in color bar for between (a,b,c) relative to (d,e).

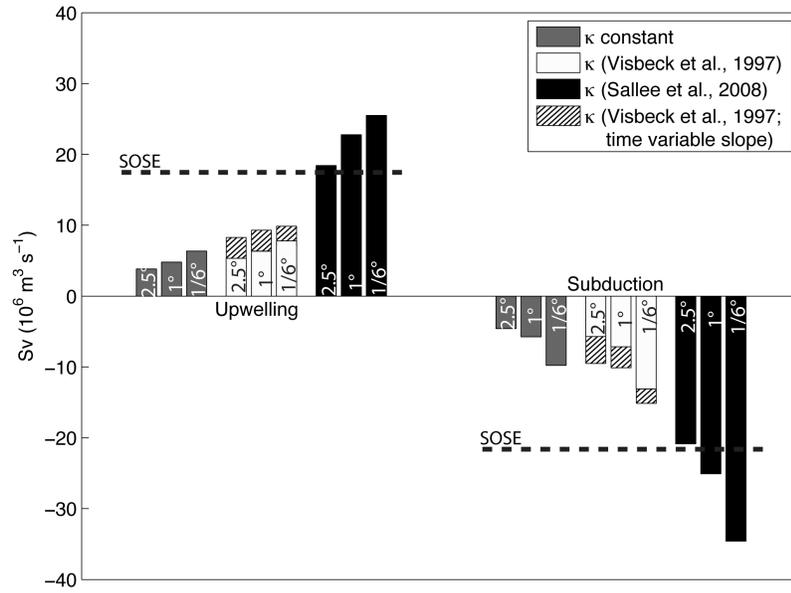


FIGURE 4. Net integrated eddy-induced subduction and upwelling in each of the configurations mentioned in Figure 3, and for three degrees of slope of isopycnal smoothing: (dashed line) SOSE; (dark gray) constant  $\kappa = 1000 \text{ m}^2 \text{ s}^{-1}$ ; (white) spatially varying  $\kappa$ ; (black) observation-based  $\kappa$ ; and (black stripes bars) time and spatially varying  $\kappa$  in combination with time-varying isopycnal slopes.

5 figures

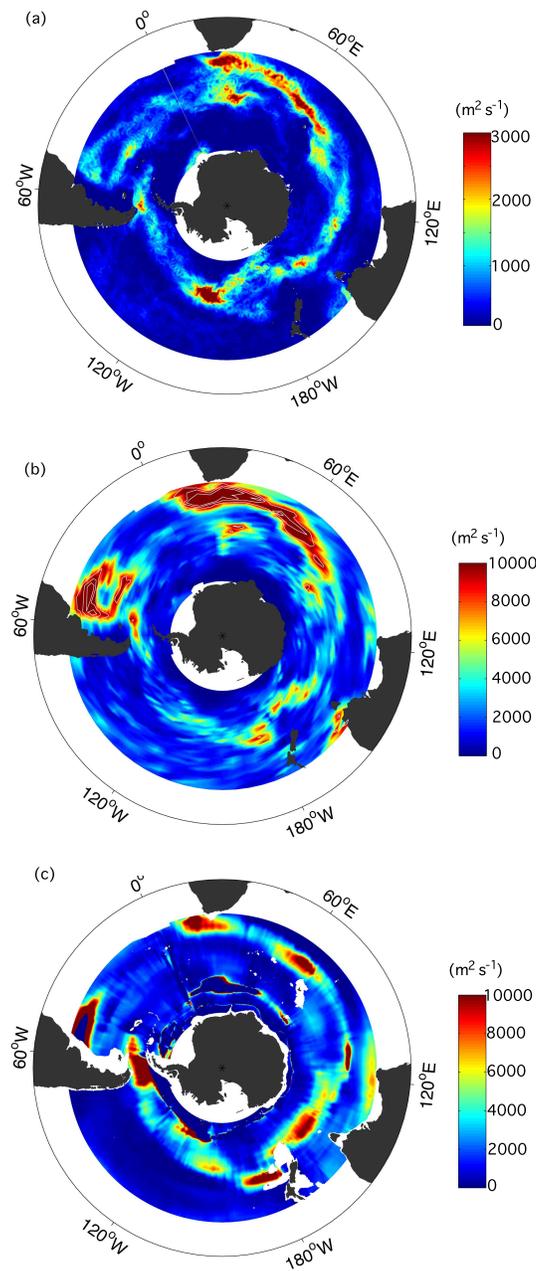


FIGURE 5. Spatially varying coefficient depending on eddy length scale and stratification (Visbeck et al., 1997; Eden and Greatbatch, 2008); (b) diffusion coefficient deduced from surface drifter observations (Sallée et al., 2008) – contours  $1 \cdot 10^4$ ,  $1.5 \cdot 10^4$ , and  $2 \cdot 10^4 \text{ m}^2 \text{ s}^{-1}$  are superimposed (white) ; and (c) deduced diffusion coefficient to best represent the eddy-fluxes in a coarse resolution version of SOSE (Eqn 6).

---

*E-mail address:* Jean-Baptiste.Sallee@csiro.au

(add1) CSIRO MARINE AND ATMOSPHERIC RESEARCH, HOBART, TASMANIA 7001 AUSTRALIA