The Sources and Mixing Characteristics of the Agulhas Current

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ABSTRACT

Recent observations taken at four principal latitudes in the Agulhas Current show that the watermass properties on either side of its dynamical core are significantly different. Inshore of its velocity core are found waters of predominantly Arabian Sea, Red Sea, and equatorial Indian Ocean origin, while offshore waters are generally from the Atlantic Ocean, the Southern Ocean, and the southeast Indian Ocean. For the most part, the inshore waters approach the Agulhas Current through the Mozambique Channel, while those offshore are circulated within the southern Indian Ocean subtropical gyre before joining the current. These disparate water masses remain distinct during their 1000-km journeys along the South African continental slope, despite the convergence, extreme velocity shears, and high eddy kinetic energies found within the Agulhas Current. Both potential vorticity conservation and kinematic arguments are discussed as potential inhibitors of along-isopycnal mixing. It is concluded that a high cross-stream gradient of potential vorticity is the dominant mechanism for watermass separation near the surface, while the kinematic steering of water particles by the current is dominant at intermediate depths, where cross-stream potential vorticity is homogeneous. Hence, three lateral mixing regimes for the Agulhas Current are suggested. The surface and thermocline waters are always inhibited from mixing, by the presence of both a strong, cross-frontal potential vorticity gradient and kinematic steering. At intermediate depths mixing is inhibited by steering alone, and thus in this regime periodic mixing is expected during meander events (such as Natal pulses), when the steering level will rise and allow cross-frontal exchange. Below the steering level in the deep waters, there is a regime of free lateral mixing. The deep waters of the Agulhas Current are homogeneous in the cross-stream sense, being from the same North Atlantic source, and their salinity steadily (and rather rapidly) decreases to the north. Here, it is suggested that mixing must be dominated by vertical processes and a large vertical mixing coefficient of order 10 cm$^2$ s$^{-1}$ is estimated.

1. Introduction

The frontal structure of a western boundary current (WBC), as defined by steeply sloping isopycnals, will act to block exchange across it (in the absence of diapycnic mixing). Yet convergence, high-velocity shears, and meandering of the front will act to encourage mixing. In this paper we are interested in the balance of watermass separation on the one hand and mixing on the other for the Agulhas Current, the WBC of the southern Indian Ocean subtropical gyre.

In their canonical paper, Bower et al. (1985) ask whether the Gulf Stream acts as a barrier or blender of water masses from the southern (Sargasso Sea) and northern (Slope Water) sides of the current. From watermass characteristics they find that the Gulf Stream acts as a barrier to mixing from the surface to intermediate depths, while below about 1800 m ($\sigma_t = 27.1$) waters are well mixed. Two physical mechanisms are found to be responsible for setting this mixing depth. Close to the surface cross-frontal mixing is inhibited by a strong cross-stream potential vorticity (PV) gradient. This gradient reduces and eventually disappears with depth, owing to a reduction in layer-thickness changes (isopycnic slope) and, to a lesser extent, horizontal shear (Lozier and Bercovici 1992). The second mechanism is linked to the meandering of the current once it
has left Cape Hatteras, which sets up a “steering level” for fluid particles. Using a simple kinematic model Owens (1984) found that, for small meanders, those particles with downstream speeds exceeding the phase speed of a meander would be trapped, or steered, in the current. As a result, at the depth in the current where downstream speed drops below the meander propagation speed, the so-called steering level, particles would no longer be trapped in the current and cross-frontal mixing would become uninhibited.

Bower (1991) extended the kinematic model of Owens (1984) to study large meanders and found that entrainment, detrainment, and cross-stream exchange all increase with increasing meander phase speed and amplitude. In agreement with float observations (Bower and Rossby 1989) the kinematic model showed that detrainment occurred at the trailing edge of a meander crest, while entrainment was a maximum at the leading edge. This is due to the secondary recirculations set up at the edges of the stream in the meander crests and troughs. In the main, however, particles are inhibited from cross-frontal exchange by the PV gradient, so that most particles are detrained and reentrained at the same edge of the stream without ever crossing the front. Exceptions to this are particles, caught up in Gulf Stream rings, formed by the occlusion of an extreme meander, or in ageostrophic flows (Bower and Lozier 1994).

Because the Agulhas Current experiences strong topographic control, first by the continental slope of Africa, then by the Agulhas Bank, it does not exhibit the continuous meandering of the detached, eastward-flowing Gulf Stream (the Agulhas Return Current is more analogous). As a result, we do not expect to find such a distinct steering level within the Agulhas. However, solitary meanders, often referred to as Natal pulses owing to their apparent origin over an area of wide shelf known as the Natal Bight (Lutjeharms and Roberts 1988), do propagate downstream in the Agulhas Current about 6 times per year. Using current-meter time series measurements, Bryden et al. (2005) show that solitary meanders are the dominant mode of variability in the current. Interestingly, if Bower’s (1991) kinematic model is applied to a typical Natal pulse, with downstream propagation of 10–20 km day\(^{-1}\) (11–23 cm s\(^{-1}\)) and amplitude of 100–200 km (Lutjeharms et al. 2003), we find that there is a predicted detrainment of 50%–90% of the water from the WBC jet. This implies that most of the Agulhas Current will recirculate within the meander trough eddy before eventually continuing downstream, which is supported by recent float trajectories shown in Lutjeharms et al. (2003, their Fig. 7). As a result, it is likely that a Natal pulse event enables cross-frontal mixing within the Agulhas Current in addition to causing straightforward path variability.

In this paper the question of barrier versus blender is examined for the first time in the Agulhas Current. Four synoptic sections crossing the Agulhas Current, taken at approximately 200-km intervals along its path, are used to assess the downstream evolution of its watermass and vorticity structure and thus study its mixing characteristics. The availability of direct velocity data allows a couple of advancements over the study of Bower et al. (1985). First, it eliminates uncertainties in the velocity structure of the current owing to reference-level uncertainties, enabling us to conduct a full-depth study. Second, it provides us with velocity data coincident with water property data for the direct calculation of all components of PV. However, we are limited in our ability to investigate how or when mixing takes place in detail, that is, the importance of the role that solitary meanders or other eddying motions may play, since we do not have floats or other time series data to complement our synoptic study.

In the following two sections we give a brief description of the data and present our method for calculating potential vorticity. A comprehensive guide to the origin of the water masses found in the Agulhas Current is presented in section 4. In section 5 we examine the cross-stream and downstream distributions of water masses and PV and discuss the implications for mixing. Section 6 presents a simple model for estimating the mixing of the deep waters in the Agulhas Current. Our findings are summarized in section 7.

### 2. Data

All measurements were conducted aboard the R/V Melville off the eastern coast of South Africa in February and March 2003 as part of the Agulhas Undercurrent Experiment. Four cross-stream hydrographic sections were occupied in the Agulhas Current at nominally 30°, 32°, 34°, and 36°S (Fig. 1), as well as three offshore sections. Each cross-stream station section was oriented perpendicular to the topography of the continental slope and consisted of between 14 and 16 combined Conductivity-Temperature-Depth-Oxygen (CTD02) and Lowered Acoustic Doppler Current Profiler (LADCP) stations. Station spacing of 5 km (and less) was used over the slope, in order to resolve high horizontal velocity shears and minimize bottom data gaps, and increased to no more than 25 km offshore. From north to south the sections were named Richards Bay, Port Shepstone, East London, and Port Elizabeth, according to the nearest city or town along the Natal bay.
coast of South Africa. The topographic feature that these sections span is called the Natal Valley, which is enclosed to the north by a widening continental shelf and slope, and to the east by the Mozambique Plateau (Fig. 1).

Each of the cross-stream hydrographic sections was preceded by an underway section of Shipboard Acoustic Doppler Current Profiler (SADCP) measurements in order to identify the exact position of the Agulhas jet before finalizing station positions. This was done principally because of the high probability that the jet would meander offshore at some point during our cruise. Given the 4-week duration of the experiment, there was an approximately 50% chance that an extreme meander event (Natal pulse) might occur that could divert the Agulhas Current 100 km or more offshore. No such event was encountered during the experiment. However, an anomalous cyclone was observed at the offshore edge of the current on the 34°S section off East London (Fig. 2). The cyclone appears to push the current unusually far onto the continental shelf, resulting in enhanced horizontal shears (a narrower jet) and reduced peak velocities. Figure 2 shows the SADCP velocities for the whole of the cruise, averaged between 0- and 75-m depth. This figure gives an overall picture of the flow of the Agulhas Current during our experiment. The current is not yet fully developed at 30°S and has a strong offshore component driven by local topography. At 32°S, the canonical World Ocean Circulation Experiment (WOCE) section 15, the current is narrowest owing to the steepness of the continental slope. By 36°S the Agulhas Current has separated from the slope to flow in waters more than 3000 m deep with surface speeds up to 250 cm s\(^{-1}\).

LADCP data were processed to absolute ocean currents using a least squares inversion (Thurnherr 2003), which constrained the shear solution calculated using established techniques (Firing 1998; Fischer and Visbeck 1993) with near-surface SADCP velocities and bottom-track velocities. Bottom-track velocities were calculated using a combination of water-track and beam amplitude data (Visbeck 2002). Thurnherr's
(2003) inversion software allowed for the adjustment of the original Firing profile only within the standard deviations of each binned shear measurement. In this way bad water-track data are not disguised by the least squares fitting.

3. Calculating potential vorticity

The PV structure of the Agulhas Current is useful and informative on two counts: it will enable us to distinguish the origin of some of the water masses within the WBC (for instance, mode waters typically have a low PV), and it can help us in examining possible cross-frontal mixing constraints within the WBC.

The PV was calculated taking into account the relative vorticity resulting from the horizontal and vertical velocity shears of the current, in addition to changes in layer thickness, by combining the available CTD and LADCP data. Because isopycnals within the Agulhas Current are inclined significantly from the horizontal, the vorticity normal to density surfaces has significant contributions from both the vertical and horizontal shears of the current. Therefore, Ertel’s theorem (Pedlosky 1986) was applied to find “vortex tubes” along the axis of the current in a manner similar to that of Beal and Bryden (1999). Thus, all parameters are rotated into an along-stream reference frame and the potential vorticity, $Q$, is given by the equation

$$Q = -\frac{1}{\rho} \left[ f \frac{\partial \rho}{\partial z} + \left( \frac{\partial v}{\partial x} \frac{\partial \rho}{\partial z} - \frac{\partial \rho}{\partial z} \frac{\partial v}{\partial x} \right) \right],$$

where $f$ is the Coriolis parameter, $\rho$ is the in situ density, $v$ is the downstream velocity, and the current and density gradients are given in the cross-stream $x$ and vertical $z$ (positive downward) directions. The three components on the right-hand side are planetary vorticity $Q_p$, relative vorticity from horizontal shear $Q_{hs}$, and relative vorticity from vertical shear $Q_{sv}$. By expressing the vertical density gradient in terms of the buoyancy frequency $N$, and the horizontal density gradient in terms of vertical shear using the thermal wind equation, the vorticity equation becomes

$$Q = Q_p + Q_{hs} + Q_{sv} = \frac{fN^2}{g} \left[ 1 + \frac{1}{f} \frac{\partial v}{\partial x} - \frac{1}{N^2} \left( \frac{\partial v}{\partial z} \right)^2 \right].$$

The assumptions and approximations made for Ertel’s solution to hold are that nonlinearity, friction, and
lateral diffusion must be small. Hence, it is inappropriate to apply this vorticity equation to spatially or temporally small-scale motions, for which the assumptions become invalid. Beal (2005) found that small-scale velocity perturbations are common within the Agulhas Current, particularly close to its dynamical front (or velocity core). These perturbations were found to have a characteristic vertical length scale of 200 m and an amplitude of order 10 cm s⁻¹. For the calculation of potential vorticity in this study, these perturbations were removed using a second-order Butterworth filter with a 100-m cutoff. A second-order filter was chosen because it is the first baroclinic mode that dominates the velocity structure. In this way a background velocity \( \bar{v} \) was calculated for each profile. Subsequently, Eq. (2) was calculated point by point using density and the filtered velocity measurements, by forward differencing. All the terms were then smoothed using a 3 × 3 point box filter.

When calculated with \( \nabla \times \bar{v} \) rather than \( \nabla \times \nu \), the overall PV field is not significantly changed, since its primary characteristics result from variations in layer thickness across the WBC (i.e., \( N^2 \)). However, noticeable differences in detail occur close to the dynamical front, where large, opposing vertical shears resulting from the aforementioned small-scale velocity perturbations were causing regions of elevated relative vorticity. Using \( \nabla \times \bar{v} \), these vertical shears are smoothed and the resulting PV field appears less noisy.

4. Agulhas Current sources

The waters of the Agulhas Current originate from disparate sources. Most are from various reaches of the Indian Ocean, including Red Sea Water (RSW) and Subtropical Surface Water (STSW), and others are re-circulated from the south, such as Sub-Antarctic Mode Water (SAMW) and Antarctic Intermediate Water (AAIW). We think it useful to include here a brief but thorough description of all the water masses that influence the Agulhas Current in order to facilitate later discussions on mixing, and because we have found no other reference that, on its own, provides a full description.

Within the Agulhas Current, isopycnals slope steeply upward toward the north and west and it is therefore misleading to refer to its water masses as having a characteristic depth. The sloping is most dramatic south of 35°S where thermocline waters with a depth of 400 m in the interior can outcrop at the inshore edge of the current. At intermediate depth the isopycnal gradient is further enhanced and waters rise a vertical distance of about 700 m across the current. Hence, for clarity the distribution of water masses in the water column will be defined in terms of neutral density layers (Jackett and McDougall 1997) rather than depth. In Table 1 we define six density layers, corresponding to the primary water masses present, but not representative of all water masses, as will become clear later. Most subsequent figures and discussion will be in density space, or these six density levels will be illustrated in depth space. For instance, the interfaces of these layers are highlighted in Fig. 3 and again later (see Fig. 6). Note that North Atlantic Deep Water (NADW) has been split into upper and lower layers in order to distinguish the proportion of deep water that cannot continue northward into the Indian Ocean, because of the local topography of the Natal Valley (see Fig. 1).

Table 1. Neutral density layers defining water masses of the Agulhas Current.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Water mass</th>
<th>Neutral density, ( \gamma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSW</td>
<td>Tropical surface water</td>
<td>&lt;25.5</td>
</tr>
<tr>
<td>STSW</td>
<td>Subtropical surface water</td>
<td>25.5–26.4</td>
</tr>
<tr>
<td>SICW</td>
<td>South Indian central water</td>
<td>26.4–27.0</td>
</tr>
<tr>
<td>AAIW and RSW</td>
<td>Antarctic Intermediate Water and Red Sea water</td>
<td>27.0–27.92</td>
</tr>
<tr>
<td>NADW</td>
<td>Upper North Atlantic Deep Water</td>
<td>27.92–28.08</td>
</tr>
<tr>
<td>NADW</td>
<td>Lower North Atlantic Deep Water</td>
<td>&gt;28.08</td>
</tr>
</tbody>
</table>

Figure 3 shows the Agulhas Current off Port Elizabeth at nominally 36°S, the most southerly section occupied. The neutral density layers defined in Table 1 are shown in the section in green. Here, the current is strongest and deepest of all the sections and has detached from the continental slope of Africa. As compared with the sections farther north, the horizontal density gradient is greatest and the onshore, or cyclonic side (i.e., the side where the horizontal shear is cyclonic), of the WBC jet is widest here. It is this section that provides the clearest illustration of the frontal structure of the Agulhas Current and the watermass distribution within it. Hence, we will use this section to highlight the watermass sources, using their salinity, oxygen, and potential vorticity signatures (Fig. 4) and follow up with details of their along-stream evolution, using the remaining cross sections, in a later part of the paper.

The surface of the Agulhas Current consists of rela-
tively fresh tropical surface waters (TSWs) with salinity $S$ less than 35.55 (Fig. 4a), formed near the equator by excess warming and precipitation (Toole and Warren 1993). TSW enters the Agulhas via the Mozambique Channel (Duncan 1970; de Ruijter et al. 2002). Below TSW, centered at $S_{25.8}$, is the salinity maximum ($S_{35.55}$) of subtropical surface water (STSW). STSW is formed to the east of $90^\circ E$ (Wyrtki 1971) and between $25^\circ S$ and $35^\circ S$ within the subtropical gyre by high evaporation and is subducted and advected northward by the gyre circulation. Subsequently, it is advected westward along the southern edge of the South Equatorial Current (New et al. 2005, manuscript submitted to Deep-Sea Res. II), then southward via the East Madagascar Current and on into the Agulhas Current (Gründlingh et al. 1991).

Inshore of the STSW core, at a slightly lighter density of about $\gamma = 25.5$, is located an oxygen minimum with values less than 3.8 mL L$^{-1}$ (Fig. 4b). This originates in the northern Indian Ocean (Wyrtki 1971), where both the Arabian Sea and, to a lesser extent, the Bay of Bengal exhibit an oxygen minimum resulting from high consumption related to seasonally high productivity. The vast quantity of organic matter from the upwelling-induced blooms of the southwest monsoon oxidizes as it sinks, causing an oxygen minimum that extends as deep as 1200 m (Olson et al. 1993). We shall call this water Arabian Sea Low Oxygen Water (ASLOW). This low-oxygen layer is not associated with the seasonal production of saline Arabian Sea Surface Waters, which are distinctly lighter and hence shallower.

Between $\gamma = 26.4$ and the base of the thermocline at approximately $9^\circ C (\gamma = 27.0)$ are water masses collectively known as South Indian Central Water. In particular there is Southeast Indian Sub-Antarctic Mode Water (SEISAMW; Hanawa and Talley 2001) with a high-oxygen ($>4.9$ mL L$^{-1}$), low- (negative) PV ($>-1 \times 10^{-10}$ m$^2$ s$^{-1}$; Fig. 4c) core at $\gamma = 26.8$ (Wyrtki 1971). SEISAMW flows into the subtropical Indian Ocean from convection sites along the subtropical convergence zone (STCZ) at various longitudes east of about $80^\circ E$. Mode waters in the Agulhas Current appear to be a mixture of both SEISAMW and a lighter Sub-Antarctic Mode Water (SAMW), which is formed between $46^\circ$ and $62^\circ E$ along the STCZ (Fine 1993), because the oxygen maximum sits between the $10^\circ$ and $14^\circ C$ isotherms, which are indicative of each mode water, respectively.

Below the thermocline, at intermediate depths, there is fresh Antarctic Intermediate Water (AAIW) and relatively saline Red seawater (RSW; Fig. 4a) within a thick layer between densities of $\gamma = 27.0$ and 27.92. AAIW forms a salinity minimum less than 34.7 and RSW modifies this minimum with the interleaving of relatively saline layers. This influence of RSW at the AAIW level is demonstrated more clearly later (see Fig. 6) and will be discussed further in the next section. RSW sinks as a result of excess evaporation within the Red Sea basin, from where it overflows the sill at the Strait of Bab El Mandeb to spread into the Arabian Sea via the Gulf of Aden. Although the volume of RSW is small [$\approx 0.5$ Sv, where $Sv = 10^6$ m$^3$ s$^{-1}$; Murray and Johns (1997)], its source salinity is extremely high (40 psu) and as a result its signature can be traced across the equator and into the southern Indian Ocean, where it enters the Agulhas Current most directly via the Mozambique Channel (Beal et al. 2000). In contrast, AAIW originates in the southeastern Pacific to the west of $55^\circ S$, $80^\circ W$ (McCartney 1977; Saenko et al. 2003). AAIW is thought to be the world’s densest SAMW, subducting into the thermocline from the bottom of a wintertime mixed layer more than 300 m thick, to the

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**Fig. 3.** Direct along-stream velocities across the Port Elizabeth section (nominally 36°S) from combined SADCP and LADCP measurements. Note that red and yellow colors depict the southwestward flow of the Agulhas Current. Overlaid contours in green show neutral surfaces (see Table 1). Boldface numbers along the top axis are station numbers.
Fig. 4. Sections of (a) salinity, (b) oxygen, and (c) potential vorticity plotted in neutral density space, across the Agulhas Current at 36°S. Station numbers are shown along the top of each section. Line contours are chosen to highlight different water masses and are not evenly spaced. Values of potential vorticity $\leq -1 \times 10^{-7} \, \text{m}^{-1} \, \text{s}^{-1}$ are shaded dark blue.
north of the sub-Antarctic front (SAF) (Hanawa and Talley 2001). It reaches the Indian Ocean by way of the Drake Passage, and is thought to continue eastward along the SAF until it is injected northward into the South Indian Ocean gyre at about 60°E (Fine 1993), where the “freshest” AAIW is detected from its chlorofluorocarbon (CFC) age. Also at intermediate depths and just below AAIW, the bottom of the ASLOW layer is evident as an oxygen minimum (<4.3 mL L\(^{-1}\), Fig. 7). At this depth the oxygen minimum results from moderate consumption by the decomposition of falling organic matter in waters of initially low oxygen concentration (Olson et al. 1993). The inflow of AAIW into the basin bisects this thick ASLOW layer, which can be traced in the atlas of Wyrtki (1971) as it accompanies high-salinity RSW on its journey from the Arabian Sea across the equator and along the western boundary toward the Agulhas Current. The signal is very much stronger and somewhat shallower than the oxygen minimum associated with Circumpolar Deep Water, which is not present in the Natal Valley, probably because its pathway is blocked by the Southwest Indian Ridge.

The bottom waters of the Agulhas Current consist solely of North Atlantic Deep Water (NADW), which flows northward within the Agulhas Undercurrent (Beal and Bryden 1997) and may also flow into the region offshore of the highly barotropic Agulhas jet (Fig. 3). It is possible that some, if not all, NADW flows into the region as a slope current around the South African cape from the eastern South Atlantic Ocean (Wyrtki 1971; Arhan et al. 2003; C. Duncombe-Rae 2005, personal communication). Owing to the topographic confines of the Natal Valley, much of the lower NADW likely recirculates back toward the south, perhaps within the deep Agulhas Current or on the eastern side of the valley. The upper layer (above 3000 m) can escape the valley to the east through breaks in the Mozambique Plateau. However, little is known about the bottom circulation in this region. A summary of this section, showing watermass source regions in the Indian Ocean and their pathways into the Agulhas Current is shown in the cartoon in Fig. 5.

5. Cross-stream watermass separation and mixing

Studying all four cross sections of the Agulhas Current from 30° to 36°S, it seems that the watermass distribution within the current is separated into two distinct regions. To the west of the current core, inshore of its velocity maximum and within the region of cyclonic shear flow, are found water masses of primarily northerly origin. In contrast, to the east of the current core, offshore of the velocity maximum and within the region of anticyclonic shear, are found waters of predominantly southerly and easterly origin. To demonstrate this clearly, Figs. 6 and 7 show watermass diagrams for each section, which have been color coded for positive and negative relative vorticities. Waters with negative relative vorticity (blue) are inshore of the current core, while those with positive relative vorticity (red) are offshore. Only those stations that fall within the WBC jet
Fig. 6. Theta–S diagrams depicting the water masses in the Agulhas Current. (top 4) Each of the four sections across the Agulhas Current, color-coded red for water particles with positive relative vorticity (offshore of current core) and blue for those with negative relative vorticity (onshore of current core). (bottom) The mean θ–S curves from each section. Contours depict the neutral surfaces (γ) listed in Table 1.
Fig. 7. As in Fig. 6 but for $\theta$ (°C) vs $O_2$ (mL L$^{-1}$). Again, waters inshore of the current core are shown in blue, while those offshore are shown in red.
have been included, so for example, those in the near-shore northward flow of the 36°S section are not included.

First we note that the \(\theta-S\) and \(\theta-O_2\) curves for all the sections are qualitatively the same: the water masses discussed above (and listed in Table 1), using the Port Elizabeth section at 36°S as an illustration, are observed in all the sections of the Agulhas Current throughout its journey along the African coast. Looking more closely at the \(\theta-S\) diagrams for each of the four Agulhas Current sections (Fig. 6, top four panels) we see that STSW, identifiable by its salinity maximum at about 17°C, is predominantly present offshore of the current core (red), while the less saline TSW is more often found inshore (blue). There is a similar separation at intermediate depths, where AAIW with its salinity minimum is found offshore, while RSW (degraded minimum) is generally found inshore. In the top four \(\theta-O_2\) diagrams of Fig. 7, SAMW, depicted by an oxygen maximum at about 12°C, has a much greater presence offshore. For the shallow oxygen minimum that originates in the Arabian Sea and lies between 15° and 20°C, it is not so clear, partly because of outcropping on the southerly sections, but at least on the northernmost section of Richards Bay the onshore waters exhibit a stronger oxygen minimum than those offshore, on the average. To reiterate then, STSW, AAIW, and SAMW flow into the Agulhas Current from their various sources via the anticyclonic gyre circulation of the South Indian Ocean. They are all found generally offshore of the current core and are evidently inhibited from crossing to its cyclonic side. TSW, ASLOW, and RSW all originate to the north, crossing the equator close to the western boundary and flowing into the Agulhas Current via the Mozambique Channel. They are constrained, for the most part, to the inshore, cyclonic side of the current.

As discussed previously in the introduction, Bower et al. (1985) found a similar partition of waters in the Gulf Stream, where distinctly different water masses were found to the north and south of its meandering dynamical front. They concluded that waters are prevented from crossing the WBC core by strong gradients of PV in the upper water column, while below a density surface at about \(\sigma = 27.1\), PV was homogeneous across the Gulf Stream, indicating a freely mixed regime. To examine the transition from heterogeneous to homogeneous cross-stream PV in the Agulhas Current more closely, we have calculated the PV gradient along density surfaces at each Agulhas section. The choice of how to estimate the PV gradient has a substantial effect on the results. For instance, to take a difference across the whole width of the current as compared with just across the PV front itself can make an order of magnitude difference to the gradient, and a linear fit gives a smaller gradient than a straightforward difference. From attempting a number of different solutions we deduce that the most consistent result is found by taking the difference between the minimum (or maximum negative) PV along a neutral surface and the first following maximum (or negative minimum) in the offshore direction. Thus, the calculation is consistent, in terms of stream anatomy, from one section to another. It also represents an upper bound on the PV gradient, since we choose to differentiate between extrema. The results for each section are presented in Fig. 8.

Of immediate note is that the PV gradient at East London (34°S) is substantially greater than at any other latitude. This is owing to the presence of the cyclone just offshore of the current core, seen earlier in Fig. 2. Its PV minimum is superposed onto that of the Agulhas Current, creating an elevated PV gradient. Excepting the anomalous 34°S section, there is a downstream trend of increasing PV gradient within the current. This follows the speeding up of the jet and the sharpening of the density front. On all sections the maximum PV gradient occurs around \(\gamma = 24.5\), and there is an obvious transition from large to very small PV gradients within the thermocline, at neutral densities between 26.0 and 27.0. There is no downstream trend in the density of this PV gradient transition, but because density surfaces upwell toward the south, the transition does rise in depth in the downstream direction. What is interesting is that the transition from heterogeneous to homogeneous cross-stream PV is well above the inter-
mediate layer, where RSW and AAIW are seen to be separated in the watermass diagram (Fig. 6). Much of the reason that the PV gradient reduces so quickly within the thermoline, despite the fact that density surfaces remain significantly inclined throughout the intermediate waters, is that the gradient of layer thickness across the current changes sign at a density of about 27.2. In other words, while the density layers above \( \gamma = 27.2 \) thicken offshore, the ones below actually become thinner (see Fig. 3), creating a much reduced cross-stream PV gradient for these layers.

This result is at odds with the aforementioned theory that a region of homogeneous PV should be coincident with a regime of uninhibited cross-frontal mixing. On the contrary, RSW and AAIW remain quite separate at densities well below the PV gradient dropoff. Recalling from the introduction Owens’s (1984) kinematic argument to explain increased cross-frontal mixing with depth in the Gulf Stream (his “steering level”), this result implies that within the Agulhas Current the strength and linearity of the flow at intermediate depth inhibits cross-frontal exchange there, despite the zero-PV gradient. Owens (1984) found that, in a meandering current, particles would be trapped in the stream until such a depth (or density level) at which their downstream speed equals the meander propagation speed, the so-called steering level. The steering level is where maximum cross-frontal mixing is predicted to occur (Lozier and Bercovici 1992) and (for growing meanders driven by baroclinic instability) it is generally deeper than the minimum in the PV gradient. Sustained watermass separation at density levels well within the region of homogenized PV implies that the steering level within the Agulhas Current is generally considerably deeper than the PV gradient dropoff. Hence, it is the steering level that provides the overarching constraint to inhibit cross-frontal mixing within the current and not the conservation of potential vorticity. Lutjeharms et al. (2003) estimate the speed of a typical Agulhas meander (a so-called Natal pulse) as being between 11 and 23 cm s\(^{-1}\), which would suggest a steering level in the core of the Agulhas Current somewhere between 1200 and 2500 m, based on observed (LADCP) velocities. Owing to the intermittent nature of these solitary meanders (Bryden et al. 2005), we expect the depth of the steering level to vary over time, and, hence, the depth of maximum cross-frontal mixing is also expected to vary over time. In this way, solitary meanders (and other mesoscale instabilities) may cause “mixing events,” when the steering level is temporarily raised to allow free cross-frontal particle exchange at intermediate depths.

The bottom panels in Figs. 6 and 7 shows the along-isopycnal-mean \( \theta-S \) and \( \theta-O_2 \) curves for each Agulhas section, in order to illustrate the downstream evolution of watermass properties. Focusing on the salinity maxima and minima in Fig. 6, as the parts of the curves with the clearest differences, we see that the changes in watermass properties do not conform to the idea of constant downstream mixing. For instance, in the STSW layer we might expect an influx of a denser offshore AAIW, yet we see that the highest salinities are at 32°S and the lowest are on the northernmost section. Take the intermediate layer of RSW-modified AAIW. Again, we might expect a reduction in salt in this layer as one progresses from north to south, away from the source of saline RSW. However, we see that the East London section at 34°S is freshest. Hence, the changes in watermass properties from one section to the next downstream are not consistent with a simple mixing model in which water properties gradually change in a downstream direction.

In fact, in Figs. 6 and 7, we have seen that the cross-stream property gradients of the Agulhas Current appear larger and more consistent than the downstream property gradients, leading to the conclusion that water masses are better mixed in a downstream sense than a cross-stream one. How can this be? Such a scenario would result from active recirculating flows along either side of the Agulhas Current, but limited cross-frontal exchange. This would be similar to the regime that Bower and Rossby (1989) found in the Gulf Stream upon studying float tracks. Thus, we suggest that eddy mixing is also dominant along the edges of the Agulhas Current. We can go a step further in our interpretation by examining the watermass properties at 34°S more closely. The offshore cyclone (Fig. 2) that was present at the time of sampling at East London appears to be the cause of an influx of fresher offshore waters at intermediate depths there (Fig. 6). This implies that cross-stream mixing events are driven by mesoscale features, such as meanders and shear-edge eddies. Hence, we reaffirm the conclusions drawn above, that the edges of the Agulhas Current are regimes of strong eddy mixing (detrainment and reentrainment), yet kinematic steering (and PV gradient) inhibits cross-frontal mixing within the Agulhas Current.

6. Downstream mixing of NADW

At the depth of the NADW there is no longer a measurable distinction of watermass properties from one side of the Agulhas Current to the other (Fig. 6), which is primarily an illustration of the single, southerly source of these waters. Figure 9 illustrates this assertion
in more detail. It shows values of direct velocity and salinity along the density surface $\gamma = 28.045$, which represents the core of the NADW layer, that is, the location of the deep salinity maximum. Mean values for the whole layer are not used because changing bottom depths render the results misleading. Note that we are limited to presenting direct velocities that are instantaneous and therefore unlikely to reflect the mean flow at these depths, where variability is expected to be considerably greater than the mean. What we see is that there is no discernable relationship between the direction of flow and the strength of the NADW salinity maximum (perhaps not surprising, owing to instantaneous measurements) and more significantly, with the exception of the northern Richards Bay section at 30°S, there is no consistent change in the salinity of the NADW across the Agulhas Current. The 30°S section crosses the narrowing Natal Valley all the way to the 2000-m contour of the Mozambique Ridge (Fig. 1) and here we may have captured a recirculation of the deep water along the eastern edge of the basin. In any case, the difference in cross-stream salinities is not more than 0.006 on any section, while in the downstream direction (Fig. 9, bottom panel, red to blue) there is a steady loss of salt to the layer amounting to more than 0.015 psu.

Since NADW is more or less homogeneous in the cross-stream direction, lateral mixing cannot result in the observed loss of salt, indicating that the dominant mixing mechanism here is very different from that in the waters above. We deduce that property changes in the deep water must be the result of vertical mixing. This appears to be the case despite the likelihood of recirculating flows due to the confines of the Natal Valley on at least the two northerly sections, although it is possible that there could be a strong lateral gradient of salinity farther offshore in waters where we have no measurements. Hence, we estimate the vertical diffusion coefficient $\kappa$, for the NADW layer by using a simple “leaky tube” model, where any reduction of salinity along the layer in the direction of advection is assumed to result from an upward diffusion of salt out of the layer. No salt is lost through the lower interface of the layer because it is at the seabed. Thus, we use the advection–diffusion balance:

$$\frac{\partial S}{\partial y} = \kappa \frac{\partial^2 S}{\partial z^2},$$

where $S$ is salinity, $y$ is the velocity in the downstream direction, $\kappa$ is the vertical diffusion of salt, and depth $z$ is positive upward. The section-mean salinities at $\gamma = 28.045$, the density of the NADW salinity maximum, were used to evaluate the downstream salinity gradient, again since averaging over the NADW salinity maximum introduces false trends due to the differing bathymetry (bottom depths) along each Agulhas section. The vertical salinity gradient was calculated between the salinity maximum and the top of the NADW layer at $\gamma = 27.92$, a mean and standard deviation being established for each section. For $\kappa$, while it is preferable to use time series mean velocities to estimate average advection rates, we are limited here to instantaneous direct velocities. Therefore, the mean velocity of the NADW salinity maximum was found along each section using LADCP data and all the sections averaged together to obtain a mean northward advection of $0.93 \pm 2.74$ cm s$^{-1}$. Of note is that on all the sections except the northernmost (Richards Bay), for the upper NADW layer, maximum northward velocities were found at the first three stations next to the slope, reflecting the presence of an undercurrent (not shown). At Richards Bay the foot of the slope is reduced to a maximum depth of 1700 m, which is too shallow for NADW to flow. Instead, maximum northward velocities were found at 240 km offshore, where the bottom depth has increased to 2700 m. Our mean northward advection can be compared with the annual-mean velocity of 0.5 cm s$^{-1}$ at 2000-m depth given by the current meter mooring array at 32°S (Bryden et al. 2005). In this context our velocity seems somewhat large, but the mooring array did not resolve the undercurrent particularly well (only one instrument positioned somewhat deeper than the core) and therefore the annual-mean velocity may be biased a little low. Equally as well however, our direct velocities may not be representative of the mean.
We found values of $\kappa$ from 7 to 16 cm$^2$s$^{-1}$, with a trend of increasing mixing efficiency toward Richards Bay, possibly due to the shallower topography. However, since estimated errors are of order 200%, the trend is statistically insignificant. These diffusivities are two orders of magnitude greater than measured deep, abyssal values, but similar to the maximum diffusivities of 5 cm$^2$s$^{-1}$ measured by Polzin et al. (1997) over the rough topography of the mid-Atlantic ridge in the Brazil Basin. The fact that our values are somewhat larger even than Polzin's maximum could be owing to the environment of large eddy kinetic energies within the deep waters of the Agulhas Current, which are of order 100 cm$^2$s$^{-2}$ at 2000 m (Bryden et al. 2005), and to the elevated near-inertial wave activity within the current (Beal 2005), in addition to the rough and shoaling topography of the South African continental slope.

7. Discussion and summary

In this paper we have detailed the disparate sources of the water masses that converge into the Agulhas Current and shown that they remain, for the most part, distinct and separate within the current, though they may share density surfaces, throughout a 1000-km journey. This despite a highly energetic, strongly sheared flow. For example, waters from the northern and equatorial regions of the Indian Ocean flow into the Agulhas Current via the Mozambique Channel and are found on its inshore side, while waters from the south and east that circulate via the Indian Ocean subtropical gyre into the Agulhas Current are found predominantly on its offshore side. Only the deep waters below 2000 m exhibit homogeneity in the cross-stream direction, owing to their single source.

Two mechanisms for inhibiting cross-stream isopycnic mixing are considered: large cross-stream gradients of potential vorticity (PV), and the kinematic trapping, or steering, of water particles by the WBC jet. We conclude that the watermass separation within the Agulhas Current is predominantly controlled by the dynamical trapping of water particles down to the so-called steering level. This conclusion results from the observation that water masses remain separated far below the bottom of the thermocline, which is where cross-stream PV becomes homogeneous. This is true throughout the length of the Agulhas Current as it flows along the continental slope of South Africa. For instance, the intermediate water masses of AAIW and RSW share a density surface yet remain separated, even though the PV gradient at their density level is indistinguishable from zero. Thus, the mixing of these intermediate water masses, and indeed any waters below the region of high-PV gradient, is inhibited by particle trapping alone. It is the steering level that dictates the depth at which waters can freely mix across the current.

This mismatch between steering-level density (at $\gamma = 27.9$, or about 2000-m depth, based on watermass distribution) and the level of transition to homogeneous PV ($\gamma = 26.7$, or <1000 m) within the Agulhas Current is in contrast to the Gulf Stream, where the steering level is found just below the PV gradient minimum. This probably results from the topographic trapping of the Agulhas Current in this region, as compared with the freely meandering Gulf Stream. Interestingly, the gap implies that in the Agulhas Current meander events such as Natal pulses, during which the steering level is temporarily raised, are able to greatly enhance cross-frontal mixing of water masses below the thermocline, since at these depths there are no PV constraints once water particles are no longer steered within the current. There is evidence of such enhanced intermediate-level mixing on the Agulhas section at 34°S, where a cyclonic eddy is weakening and bending the WBC. Here, the separation of intermediate water masses is no longer distinct, and AAIW is seen inshore of the Agulhas Current front. In contrast, surface and thermocline waters still appear separated despite larger eddy velocities here, presumably because of the high cross-stream PV gradient (Fig. 6).

The deep waters of the Agulhas Current are homogeneous in the cross-stream direction: the result of a single source of NADW. Owing to a steady downstream loss of salt based on an examination of the four sections of the current at different latitudes, the vertical diffusion coefficient across the top of the NADW layer was estimated as $\approx 10$ cm$^2$s$^{-1}$. This is large, but not inconceivable given the combination of large eddy kinetic energies, enhanced internal wave activity (Beal 2006), and rough, shallow topography in the Agulhas Current. As discussed above, higher up in the water column cross-stream mixing events dominate water property changes and vertical diffusion is not a significant mixing mechanism.

As a result of these observations, we suggest three mixing regimes for the Agulhas Current. The first represents those water masses (surface and thermocline waters) that are constrained by both high-PV gradients and strong steering to remain separated on either side of the Agulhas Current core. The second is the regime (intermediate waters) in which the PV constraint no longer exists and mixing is constrained only by kinematic steering. As a result, this regime is one of highly variable mixing, since it is vulnerable to changes in the steering level resulting from meander events. The third regime is one that is always below the steering...
level, where deep waters mix freely. Given the speed of a typical Agulhas meander, the steering level in the core of the Agulhas Current lies somewhere between 1200 and 2500 m, based on observed velocities. Therefore, we approximate the deep regime of free cross-stream mixing as being in waters below 2500 m. Also, we suggest that extreme meanders (or Natal pulses), which make up the dominant mode of variability in the Agulhas Current (Bryden et al. 2005), will be the primary mechanism for periodic cross-frontal mixing events. Using Bower’s (1991) mixing model based on the steering-level theory, more than 50% of the water within the Agulhas Current will be detrained during a Natal pulse, leaving waters within the second regime (intermediate layer) to mix freely as the meander propagates through.

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