Is Interleaving in the Agulhas Current Driven by Near-Inertial Velocity Perturbations?

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ABSTRACT

Recent observations taken at a number of latitudes in the Agulhas Current reveal that the water mass structure on either side of its dynamical core is distinctly different. Moreover, interleaving of these distinct water masses is observed at over 80% of the stations occupied in the current, particularly within the subsurface density layer between tropical surface water and subtropical surface water masses, and within the intermediate layer between the Antarctic Intermediate Water and Red Sea water masses. Direct velocity measurements allow for a comparison between the characteristic vertical length scales of the Agulhas intrusions and those of velocity perturbations found throughout the current. It is found that the interleaving scales match those of the velocity perturbations, which are manifest as high-wavenumber vertical shear layers and are identified as near-inertial oscillations. Furthermore, the properties of the intrusions indicate that double diffusion is not an important process in their development: they are generally not associated with a density anomaly, their slope and thickness fall outside the predicted maxima for instability, and a strong horizontal shear field acts to separate water parcels more quickly than intrusions would be able to grow by double-diffusive processes. Instead, the position, thickness, and slope of Agulhas intrusions relative to the background salinity and density field suggest that they are forced by rotating inertial velocities, with subsequent growth possibly driven by small-scale baroclinic instabilities. However, not all the evidence points conclusively toward advectively driven intrusions. For instance, there is a discrepancy between the observed salinity anomaly amplitude and the predicted inertial displacement given the background salinity gradient, which deserves further examination. Hence, there is a future need for more pointed observations and perhaps the development of an analytical or numerical model to understand the exact nature of Agulhas intrusions.

1. Introduction

Interleaving is commonly observed throughout the world's oceans where water masses with different temperature and salinity properties but similar densities meet laterally. Such features are generally referred to as intrusions. Intrusions have been observed at the edge of Meddies (Hebert et al. 1990; Ruddick 1992), in the Arctic Ocean (Perkin and Lewis 1984; Rudels et al. 1998), in the equatorial Pacific Ocean (Toole 1981; Richards and Banks 2002), at the Antarctic polar front (Joyce et al. 1978; Georgi 1978), and in the Gulf Stream (Joyce 1976; Williams 1981). Their vertical scales range from 2 m within the thermocline to 250 m in deep water, and coherent features have been tracked laterally for up to 200 km in the equatorial Pacific and for over 1000 km in the Arctic Ocean.

Wherever they are found the observation of intrusions is generally taken as evidence for strong lateral fluxes of heat and salt (Hebert 1999; Ruddick and Richards 2003). However, because these lateral fluxes are estimated to be only several millimeters per second (Ruddick and Hebert 1988) they are almost impossible to determine directly. Hence, it has been important to determine the dynamics driving intrusions in order to estimate the resulting cross-frontal fluxes (Hebert 1999). Theoretical studies attribute double-diffusive processes as the driving mechanism for the growth of intrusions (Toole and Georgi 1981; McDougall 1985; Walsh and Ruddick 1995). Through the differential diffusion of heat and salt, diffusive convection and salt fingering cause divergent vertical density fluxes, which drive the cross-frontal velocity of the intrusions.

Only a few researchers suggest that intrusions are not necessarily synonymous with enhanced mixing. Pingree...
(1971) showed that interleaving layers in the northeast Atlantic had temperature $T$ and salinity $S$ perturbations that were density compensated, implying that the intrusions were a result of sheared lateral velocities and not double diffusion. Characteristics of intrusions in a warm-core Gulf Stream ring were also found to be inconsistent with double-diffusive processes (Ruddick and Bennett 1985), and close to the equator Edwards and Richards (1999) showed that inertial instabilities may play a role in the development of intrusions.

The Agulhas Current is the western boundary current (WBC) of the southern Indian Ocean subtropical gyre. Within the Agulhas Current, as in the Gulf Stream (Bower et al. 1985), there is a sloping frontal surface at its dynamical core across which water mass properties change abruptly. The strong current flow is parallel to this front, yet we find that intrusions across it are common. These intrusions are manifest primarily as salinity anomalies. In this paper we look more closely at these intrusions in tandem with directly measured velocity anomalies in order to shed some light on their driving mechanism.

2. Data

Four cross-stream sections were occupied in the Agulhas Current between $29^\circ$ and $36^\circ$S in February and March 2003 as part of the Agulhas Undercurrent Experiment (AUCE; see Fig. 1). Measurements were conducted aboard Research Vessel (R/V) Melville off the eastern coast of South Africa. Each section was oriented perpendicular to the topography of the continental slope and consisted of between 14 and 16 combined conductivity–temperature–depth–oxygen (CTDO) and lowered acoustic Doppler current profiler (LADCP) stations. Station spacing of 5 km or less was common over the slope, increasing to no more than 25 km offshore. On-station drift was allowed in order to maintain a low wire angle in the strongly sheared current. A fin was mounted on the CTDO–LADCP package to eliminate the enhanced spin associated with a high-velocity environment, thus improving LADCP measurements. Between 10 and 24 bottle samples were collected on each station to calibrate the CTDO sensors. LADCP ensembles were processed into a full-depth velocity profile using the established shear technique (Firing and Gordon 1990; Firing 1998), and were then fitted to shipboard ADCP and postprocessed, bottom-tracking data using an inversion by Thurnherr (2003). The inversion is performed in order to reduce errors primarily in the first baroclinic mode, which are characteristically large using the LADCP technique (Beal and Bryden 1999).
3. Interleaving in the Agulhas Current

The dynamical front of the Agulhas Current, as distinguished by a switch in sign of relative vorticity (i.e., horizontal velocity shear), separates inshore water masses that are advected from the north, from those offshore that have circulated within the Indian Ocean subtropical gyre (Beal et al. 2006). Across this front there are intrusions of one water mass into another. Interleaving is most evident within two neutral density layers: the subsurface layer (25.0 $\leq \gamma \leq 26.4$), between the relatively fresh tropical surface water onshore and saline subtropical surface water offshore, and the intermediate-depth layer (27.0 $\leq \gamma \leq 27.8$), between the relatively saline Red Sea water (RSW) onshore and fresher Antarctic Intermediate Water (AAIW) offshore. Figure 2 shows the water mass characteristics of the southernmost (nominally 36°S) Agulhas section and highlights two profiles that exhibit strong interleaving. Interleaving was observed at over 80% of the stations occupied within the Agulhas Current during AUCE.

For this analysis we concentrate on the characteristics of interleaving between RSW and AAIW at intermediate depth, because the subsurface layer outcrops within the WBC south of 33°S, making an analysis more complex. The presence of interleaving is best illustrated by looking at the spice anomaly, that is, the difference between the in situ and the background salinity at constant density (Richards and Banks 2002). This highlights the presence of warm–salty and cool–fresh anomalies while eliminating anomalies resulting from isopycnic heave. Following the analysis of Richards and Banks (2002), a fourth-order Butterworth filter with an 80-m cutoff was used to calculate the background salinity $\bar{S}$ for each profile. Then, the spice anomaly is calculated as

$$S' = S(\gamma) - \bar{S}(\gamma),$$

where $\gamma$ is neutral density (Jackett and McDougall 1997). To investigate the relationship, if any, between spice anomaly and lateral velocity shear, the direct velocity profiles from LADCP were treated similarly to salinity profiles, so that the velocity anomaly was cal-

![Fig. 2. A T-S diagram of the Agulhas Current at 36°S, highlighting interleaving between tropical surface water and subtropical surface water at $\gamma = 25.5$ (gray line) and between Red Sea water and Antarctic Intermediate Water at about $\gamma = 27.3$ (black line). Waters on the onshore side of the front, with negative relative vorticity, are shown as light gray dots, while those offshore with positive relative vorticity are darker gray.](image-url)
culated equivalently to the spice anomaly. Because the interleaving has cross-frontal orientation, it is the cross-stream velocities in which we are initially interested. In this case, a lower, second-order Butterworth filter was used to find the background velocity, because the first baroclinic mode dominates the velocity structure. Essentially, we have isolated the high-wavenumber, cross-frontal, isopycnic velocity anomaly $U'$. For each section, every profile of $S'$ and $U'$ is shown within the density layer of RSW–AAIW influence, from $\gamma = 27.0$ to $\gamma = 27.8$, in Fig. 3. To separate out the profiles and show them clearly they have each been shifted by 0.1-psu intervals. Although the density surfaces appear flat in Fig. 3, in fact the upper surface of the RSW layer rises by as much as 800 m across the current along the 36°S section, from a depth of 1000 m offshore to just 200 m over the continental shelf, giving a maximum gradient over the slope of 12 m km$^{-1}$. At the northernmost section (30°S) this gradient is still large, but reduces to 5 m km$^{-1}$. There is no evidence of selective positioning of the intrusions within the anatomy of the Agulhas Current; for instance, there is no consistent pattern of more intrusions inshore, offshore, or within the isopycnal front. This indicates that the intrusions are not sensitive to the temperature–salinity stratification and is the first piece of evidence to suggest that they may not be the result of double-diffusive processes. The most significant intrusions are associated with salinity anomalies of the order of 0.1 psu. In some of these cases $U'$ is well correlated with $S'$.

Fig. 3. Profiles of spice (black) and velocity anomaly (gray) within the RSW–AAIW density layer ($27.0 < \gamma < 27.8$) for the four sections across the Agulhas Current at nominally (from top to bottom) 30°, 32°, 34°, and 36°S.
(r > 0.8), for instance, profile 3 at 34°S and profile 9 at 36°S. However, for the most part there is no significant correlation. The patterns of spice and velocity anomaly show some resemblance, but the direct correlation of the instantaneous fields is low. The mean correlation between S and U′ within the RSW–AAIW layer for all of the profiles is 0.23. Such a low correlation was not entirely unexpected, given the limitations of our coarse measurements and the time lapse between up- and downcast velocities.

Next we compare the vertical scales of the spice and velocity anomalies, using a one-dimensional Fourier transform applied to each of the profiles shown in Fig. 3. Most stations exhibited one or two significant spectral peaks, a few exhibited up to four. Wavenumber was noted for all spectral peaks with greater than 0.01 psu² m in the case of spice, and 0.014 m² s⁻² m in the case of velocity anomaly (i.e., intrusions of the order of 0.1 psu and 12 cm s⁻¹). The result is vertical length scales of 205 ± 51 m for S′ and 201 ± 56 m for U′. In other words, the intrusions have the same vertical length scale as those of the velocity anomalies. If smaller intrusions are included in the analysis (peaks over 0.0064 psu² m and 0.009 m² s⁻² m, which is equivalent to 80% of the profiles) the length scales are 180 ± 69 m and 193 ± 66 m, respectively, indicating that smaller spice anomalies equate to smaller vertical length scales. The match in vertical length scale between the spice and velocity anomaly could be circumstantial, but we interpret these results to suggest that the cross-frontal intrusions within the Agulhas Current are driven by these high-wavenumber velocity anomalies.

4. Driving mechanisms

One result that may call into doubt our hypothesis that Agulhas intrusions are driven by cross-frontal velocity anomalies is if the anatomy of the intrusions indicates that double-diffusion plays a dominant role in their development. Most previous studies cite double diffusion as the mechanism for the growth and/or sustenance of intrusions (Ruddick and Richards 2003). The Agulhas intrusions may have been initialized by vertically sheared, cross-frontal velocities, but their subsequent growth could be a result of enhanced double-diffusive mixing.

a. Density anomaly

According to instability theory, subsequent to a frontal perturbation, the growth of intrusions is promoted by the dominance of either salt fingering or diffusive convection, which lead to buoyancy forces that can reinforce the intrusive flow (May and Kelley 2002). It is possibly the background stratification that sets the dominant form of double diffusion. Ruddick and Walsh (1994) show that if salt fingering is dominant, then warm, salty anomalies (positive spice) will rise, resulting in a negative density anomaly. Conversely, if diffusive convection dominates then a warm, salty intrusion will sink, resulting in a positive density anomaly.

We calculate density anomaly γ′ in the same manner as U′ (i.e., second-order filtered) and show it, together with S′, for three profiles on the 34°S section in the right panel of Fig. 4. These closely spaced stations represent our only measurements where intrusions can be clearly traced from one profile to another, as illustrated in the left panel of Fig. 4. There is a total of just 6-km horizontal distance between these three stations. The right panel of Fig. 4 shows that, for the most part, there are no density anomalies significantly above the background noise associated with these intrusions. This is true in general throughout our dataset, with only a small number of γ′ profiles showing a stepped density structure coincident with large spice. This implies that the temperature–salinity characteristics of the intrusions are compensating in density, and thus their formation is inconsistent with local vertical mixing. However, the expected density anomalies are small enough to be potentially masked by sensor response, inertial waves, or other noise. Moreover, following along the upper or lower intrusions in Fig. 4, it appears that they slope relative to isopycnals and geopotential horizons. This could be taken as an indication of double-diffusive processes modifying the buoyancy and density of the layer (May and Kelley 2002), leaving us with an inconsistent conclusion.

If we break down the life of the intrusions into formation, growth, steady state, and decay, we can clarify the effect that double-diffusive processes would have on the anatomy of the intrusion at these different stages. The formation will always consist of an initial perturbation in which double diffusion can have no part, but may set up the appropriate vertical gradients of S and T (i.e., warm and salty over cool and fresh) for subsequent double-diffusive growth. If double diffusion is the cause of subsequent growth, the intrusion will be seen to rise or fall in geopotential space, in other words, the intrusion will become more or less buoyant. This is because, during the growth stage, the intrusive layer is causing a change in the background vertical density gradient of the ambient fluid into which it is intruding by expelling salt or heat into it, as well as obtaining a density anomaly itself. Once the intrusion is grown there may be a steady-state phase, in which any lateral flux of water along the intrusion is matched by the ver-
tical flux divergence from it resulting from double-diffusive processes. In this case, the intrusion will slope up or down in density space, resulting from the differential rejection of heat and salt from the layer. Finally, decay could result from a cutoff of the supply of water to the intrusion, in which case double-diffusion would lead to further sinking or rising of the intrusion relative to density surfaces as it was mixed away.

Therefore, the slope of the Agulhas intrusions relative to geopotential surfaces and density surfaces could indicate that double-diffusive processes are important in the growth, steady-state, and decay phases of the intrusion’s life. However, in baroclinic fronts, that is, fronts with vertical and/or horizontal velocity shear, as in the Agulhas Current, twisting can also alter the slope of the layers. For instance, the upper-intrusion slope lies between horizontal and isopycnic surfaces—the so-called baroclinic instability wedge (May and Kelley 1997, hereinafter MK97)—suggesting that vertical shear is an important driving mechanism. So, are double-diffusive processes contributing to the intrusion growth, and if so, how important are they? This we can test rigorously by applying the MK97 instability criterion for the growth of intrusions in the presence of baroclinic shear. We can also investigate the importance of the role of double-diffusive processes in a hypothetical steady-state Agulhas intrusion, by looking at the advective/double-diffusive balance of salt along its length. We present these calculations in the following section.

b. Double-diffusive interleaving in the presence of background shear

MK97 developed an instability criterion for double-diffusive processes at a baroclinic front in the presence of barotropic, horizontal, and vertical shear. The criterion essentially depends on the background salinity and density gradients. MK97’s results show that isopycnals that slope down toward the fresh side of a front will act to suppress interleaving. They predict vertical length scales for double-diffusive-driven intrusions in the presence of high-velocity shear of between 2 and 20 m [their “Ekman scale,” \(2\pi (A/|f|)^{1/2}\), where \(A\) is vertical eddy viscosity and \(f\) the Coriolis parameter], and their predicted growth rate has an e-folding period of about 3 days for an isopycnal slope corresponding to that measured at 36°S in the Agulhas Current, and 7 days for an isopycnal slope such as that found at 30°S (MK97, Fig. 7). Last, MK97 note that if the background shear is large relative to the growth rate then interleaving

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Fig. 4. Three stations from the 34°S section: (left) Spice (black) and cross-stream velocity anomaly (gray) profiles in neutral density space. Each profile is shifted along the x axis so they do not plot on top of one another. The separation of the profiles is proportional to their distance apart, which is 2.5 km between the first and second stations and 3.5 km between the second and third. On the right is spice (black) and density (gray) anomaly profiles in depth space. Again, each profile is shifted along the x axis for clarity.
layers will be tilted outside their unstable range before significant growth can occur, unless the alongfront wavenumber is zero. In other words, such intrusions would only survive if they occur as coherent sheets that have no alongfront slope.

Comparing these results with our observations in the Agulhas Current, all the evidence points away from double-diffusive-driven intrusions. Recall that the abundance and strength of Agulhas intrusions do not show dependence on the background density gradient. Also, the isopycnals at intermediate depth have a slope oriented to suppress interleaving according to theory, yet maximum intrusion activity is observed there. Moreover, the vertical scale of the intrusions within the Agulhas Current is an order of magnitude greater than the scale predicted to result from double-diffusive processes. This is the case even for extreme values of vertical eddy viscosity, such as that measured by Polzin et al. (1997) for turbulent mixing over the rough topography of the mid-Atlantic Ridge where \( A = 10^{-5} \text{m}^{-2} \text{s}^{-1} \), giving a vertical scale for maximum growth of 22 m at 34°S. Finally, the theoretical growth rates are unfeasibly slow when one considers the horizontal velocity shear in the Agulhas Current, which at depths corresponding to the RSW–AAIW intrusions is \( 1 \times 10^{-5} \text{s}^{-1} \) (up to 10 times greater in the surface layers). Such shear would lead to a 100% increase in the separation of two water parcels in about 3 days. Any temporal and spatial variability of the current would act to further increase distortion of the intrusions. Hence, double-diffusive processes are unlikely to be the cause of intrusion growth in the Agulhas Current.

We can look more carefully at the nature of the Agulhas intrusions by using CTD data from the three closely spaced stations along the 34°S section across the Agulhas Current (shown in Fig. 4) to estimate salinity and density gradients and use these, together with the horizontal and vertical wavenumbers of the intrusions, to evaluate MK97’s instability criterion. Defining \( k \) and \( m \) as the horizontal (cross frontal) and vertical wavenumbers of the intrusions, respectively, and introducing the nondimensional quantity \( e_s = -\gamma (\beta \Delta S / (\rho_s / \rho_0)) \) (Toole and Georgi 1981), MK97 show that the condition for double-diffusive processes is satisfied if the maximum interleaving slope is in the range of

\[
\frac{k}{m} \leq \frac{e_s \sqrt{\frac{\Delta S}{S}} - \sqrt{\frac{\Delta \rho}{\rho}}} {e_s + 1}.
\]

In other words, the maximum layer slope is a weighted average of the isohaline and isopycnal slopes. For \( \beta \), the haline contraction coefficient, we use \( 7.6 \times 10^{-4} \), the value used by Bianchi et al. (2002) in the Brazil Current. The nondimensional flux ratio appropriate for salt fingering \( \gamma \) typically lies between 0.5 and 0.9 (MK97). We use \( \gamma = 0.75 \). The local property gradients necessary to evaluate this expression were calculated over the 6-km separation of the stations shown in Fig. 4 and between 650- and 1100-m depth (the RSW–AAIW layer). They are shown in Table 1.

We estimate that the observed interleaving slope (0.02) is about 3 times greater than the maximum slope that allows double diffusion given by Eq. (2) (0.0072). Thus, it seems unlikely that double diffusion is operating during the growth phase of these particular intrusions. This is mainly owing to their large thickness combined with the low value of the vertical salinity gradient across the RSW–AAIW layer. Looking again at Fig. 2 we see that the Agulhas interleaving is most prominent about the maximum and minimum of the \( \theta/S \) curve, where the vertical gradient of salinity is smallest. These are also the regions in the water column where water mass properties are most different from one side of the dynamic front to the other, as illustrated by the light (onshore waters) and dark (offshore waters) gray shading. This positioning favors the idea of advective-, rather than double-diffusive-driven intrusions.

We note that given the coarseness of our measurements in the horizontal, which is subject to CTD station spacing, the horizontal scale of the Agulhas intrusions is not well resolved. If it were closer to 30 km this would reduce the interleaving slope to values in line with Eq. (2). However, a length scale of less than 20 km seems most likely, because we collected 32 stations within the Agulhas Current with spacings of 20 km or less, yet observed only one case of coherent intrusions. Moreover, while \( k/m \) could conceivably be on target, \( m \) the vertical wavenumber, remains extraordinarily small and outside the range of all MK97’s double-diffusive criteria. In fact, in a case such as the Agulhas, MK97 suggest that a form of small-scale baroclinic instability may be responsible for the growth of intrusions. If isopycnal and isohaline slopes are opposing and the density gradient dominates, as is the case here, then MK97 predict a form of instability dependent on the

### Table 1. Horizontal and vertical property gradients found at intermediate depth in the Agulhas Current at 34°S, plus the scales of interleaving.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S_L )</td>
<td>Lateral salinity gradient</td>
<td>(-2.38 \times 10^{-6} \text{psu m}^{-1})</td>
</tr>
<tr>
<td>( S_V )</td>
<td>Vertical salinity gradient</td>
<td>(2.34 \times 10^{-4} \text{psu m}^{-1})</td>
</tr>
<tr>
<td>( \rho_L )</td>
<td>Lateral density gradient</td>
<td>(-8.37 \times 10^{-6} \text{kg m}^{-3})</td>
</tr>
<tr>
<td>( \rho_V )</td>
<td>Vertical density gradient</td>
<td>(-1.05 \times 10^{-3} \text{kg m}^{-3})</td>
</tr>
<tr>
<td>( k )</td>
<td>Horizontal intrusion wavenumber</td>
<td>(\sim 1/10 \text{km})</td>
</tr>
<tr>
<td>( m )</td>
<td>Vertical intrusion wavenumber</td>
<td>(1/200 \text{m})</td>
</tr>
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inability of double-diffusive fluxes to mix away unstable density anomalies. This theory sounds appealing, although as shown earlier we are unable to find conclusive evidence for density anomalies associated with our intrusions.

The above results do not indicate that double-diffusive mixing is not active on the upper and lower interfaces of an Agulhas intrusion once it is grown, only that double-diffusion is not the driving mechanism for their growth. We can estimate the relative importance of salt-fingering fluxes and velocity perturbation fluxes along the intrusion once it has grown by considering the evolution of salinity within the intrusion, assuming it reaches a steady state. For this we can use a simple balance of advective and double-diffusive fluxes,

$$\frac{\partial S}{\partial t} = -u \frac{\partial S}{\partial l} - \frac{1}{H} F_S = 0, \quad (3)$$

where $u$ is the along-intrusion velocity, $\partial S/\partial l$ is the along-intrusion gradient of salinity, and $H$ is the intrusion thickness (given by our calculated vertical length scale). For the upper intrusion of Fig. 4, $\partial S = 0.027 \text{ psu}$, $\partial l = 6000 \text{ m}$, and $u = 5 \text{ cm s}^{-1}$, giving an advective salinity flux of $2.25 \times 10^{-7} \text{ psu s}^{-1}$. If divergent salt-fingering fluxes were to match this advective flux it would imply that $F_S = O(1 \times 10^{-5} \text{ psu s}^{-1})$, which is two orders of magnitude greater than the fingering fluxes found in a Mediterranean salt lens (Hebert et al. 1990) and in the Brazil–Malvinas Confluence (Bianchi et al. 2002). Such elevated fingering fluxes are very unlikely and therefore we conclude that double-diffusive processes are not implicated in either the growth or developed phases of Agulhas intrusions. This leads us back to our earlier supposition that high-wavenumber velocity perturbations drive interleaving in the Agulhas Current, perhaps enhanced by small-scale baroclinic instabilities. The next question that interests us is what is the nature of these velocity perturbations?

c. Near-inertial oscillations

We suspect that the Agulhas intrusions are primarily driven by near-inertial motions. No time series measurements were taken during our field experiment and therefore we cannot show conclusively that the high-wavenumber perturbations seen throughout the Agulhas Current in the LADCP velocity profiles are due to near-inertial oscillations. However, we can turn to similar LADCP velocity profiles taken during World Ocean Circulation Experiment Hydrographic Program line 11 (T. Chereskin 2005, personal communication) in 1995 for evidence that this is the case. Figure 5 shows two velocity anomaly profiles (in black and gray) measured at time $t$ and $t + 7.5 \text{ h}$ at $8.5^\circ\text{N}$ within the Somali Cur-
rent in the western Arabian Sea. Eastward and northward velocity anomalies, $U'$ and $V'$, respectively, have been calculated as previously, using a second-order Butterworth filter with 80-m cutoff to take out the background velocity field. The inertial period at this latitude is 31.25 h; therefore, the two profiles shown were occupied $\frac{1}{4}$ of an inertial period apart. Over a $\frac{1}{4}$ cycle a positive inertial $U'$ will rotate anticyclonically to become a negative inertial $V'$ (Fig. 5, left panel) and a positive inertial $V'$ will become a positive inertial $U'$ (Fig. 5, right panel). Therefore, we expect the velocity anomaly profiles in the left panel to exhibit anticorrelation, while those on the right should be correlated. These patterns are convincing, although the correlation coefficient of $r = -0.07$ for the left panel is rather low. For the right panel the correlation is 0.69. The low correlation could result from the time elapsed between the upcast and downcast, which would muddy the mirroring. Neglecting the top 800 m in the first comparison results in a higher correlation of $r = -0.44$.

Thus, we can conclude that similar perturbations measured in the Somali Current are consistent with near-inertial motions. It is our experience that such high-wavenumber shears are actually ubiquitous in LADCP velocity profiles taken all around the globe. However, the profiles from the Somali Current are one of only a small number of LADCP stations that were repeated in quick succession, thus enabling an analysis of changes in the velocity profile over time. It is interesting to note that such small-scale perturbations are not seen on profiles of geostrophic velocity (e.g., Beal and Bryden 1999), which is another indication that they represent ageostrophic motions.

Near-inertial or near-inertial velocity perturbations have been reported recently in western boundary currents elsewhere. Winkiel et al. (2002) find high-wavenumber shear features in the Florida Current and Rainville and Pinkel (2004) have observed similar features in the Kuroshio. Through a yo-yo time series experiment Rainville and Pinkel (2004) identified the perturbations as near-inertial internal waves, which propagate upward or downward with respect to neutral surfaces, dependent on their direction of rotation. They find levels of vertical shear variance within the Kuroshio to be enhanced up to 6 times that of open-ocean values. They conclude that modification of the Coriolis frequency $f$ by the strong geostrophic shear of the current acts to trap and amplify near-inertial motions there, in a similar manner to the trapping below warm-core rings first explained in the canonical paper of Kunze (1985). In his paper, Kunze (1985) showed that the presence of horizontally sheared flow the Coriolis frequency would be modified as

$$f_{\text{eff}} = f + 2 \frac{1}{2} \left( \frac{\partial V}{\partial x} - \frac{\partial U}{\partial y} \right).$$

Noting that in the Agulhas Current $\partial V/\partial x \gg \partial U/\partial y$, then $f_{\text{eff}}$ can be approximated as $f + \frac{1}{2} (\partial V/\partial x)$, and we estimate it to be as much as $1.94f$ in the surface waters inshore of the current’s dynamical front (velocity maximum). Hence, the locally enhanced Coriolis frequency will act to promote trapping and amplification of internal waves there. On the offshore side of the front, where $\partial V/\partial x$ changes sign, $f_{\text{eff}}$ drops to $0.8f$.

Despite a lack of time series data, there is some evidence that we can draw from the Agulhas data to support the idea that the high-wavenumber velocity perturbations measured by LADCP do represent near-inertial motions, similar to those found by Rainville and Pinkel (2004). For instance, if $V''$, the along-stream velocity anomaly, looks similar in magnitude to $U'$ then the isotropic distribution of energy about the vertical axis would be consistent with periodic motions. In general, we find that wherever $U'$ is large $V'$ is also, and wherever $U'$ is small, likewise for $V''$. This pattern is consistent with oscillations and is illustrated in Figs. 6a and 6b, where the near-surface cross-stream ($\partial U'/\partial z$) and along-stream ($\partial V'/\partial z$) vertical shears are shown for the 34°S section. Figure 6 also reveals a layered pattern of strong positive and negative shears within the Agulhas Current, with weaker patterns of shear offshore, similar to the findings of Rainville and Pinkel (2004) in the Kuroshio. In this case the layering appears to follow contours of along-stream velocity (shown as overlaid black contours on Fig. 6), but this is not consistently the case on the other three Agulhas sections (not shown) and is not the case on the Kuroshio section. Unfortunately, we cannot examine the shear pattern within the RSW-AAIW density layer in this way, because only the underway ADCP data, which is limited to the upper 300 m of the water column, provides the necessary horizontal resolution. However, comparing the cross- and along-stream velocity perturbations more closely on individual profiles at the depth of the RSW-AAIW interleaving does reveal something interesting. Figure 6c shows that $V''$ leads $U'$ in depth on each profile and, looking from left to right, most features appear to propagate downward over time. This is exciting because it shows that the perturbations are rotating clockwise and propagating downward, consistent with near-inertial, internal waves.

To summarize, the high-wavenumber velocity anomalies (or shears) measured in the Agulhas Current are very likely the result of near-inertial motions. Such motions are trapped and amplified within western boundary currents by the modification of the inertial
Fig. 6. (top) (middle) Sections of near-surface vertical shear in the Agulhas Current at 34°S, taken from underway ADCP data. The top panel is the cross-stream shear ($\partial U / \partial z$), the second panel is the downstream shear ($\partial U' / \partial z$). Contours of along-stream velocity at 20 cm s$^{-1}$ intervals are overlaid on each section in black. Shear is given in units of $\times 10^{-2}$ s$^{-1}$ on the color bar. Shallowing of data to the left is due to the presence of the shelf. (bottom) Profiles of $U'$ (black) and $V'$ (gray) from LADCP along the same 34°S section, but at the depth of the RSW–AAIW layer.
period resulting from the presence of large geostrophic shears (Kunze 1985). This has the implication that the Agulhas intrusions, as driven by near-inertial motions, have far shorter time scales than would be associated with double-diffusive-driven intrusions. In the Agulhas Current the inertial period is 20–24 h \( (\varepsilon_{\text{eff}} \approx 16–48 \text{ h}) \), whereas the time scale for double-diffusive-driven intrusions is between 3 and 7 days, according to the prediction of MK97. Shorter time scales for intrusion growth seems in keeping with the high horizontal shear environment of the Agulhas Current, where slow-growing intrusions would be associated with the strong cross-stream shear and energetic temporal variability of the flow.

5. Discussion

If the Agulhas intrusions are driven by oscillatory motions, we can expect that maximum salinity anomaly \( |S'| \) would coincide with the maximum along-stream velocity perturbation \( |V'| \), rather than with the cross-stream perturbation, as was investigated above. This is because the maximum salinity anomaly would occur when the intrusion length is a maximum, which in turn occurs at the point in the oscillation when \( U' \) is zero. However, upon analysis, \( V'S' \) are no better correlated than \( U'S' \). For the most part this results from the limitations of our measurement technique, but perhaps also from the limitations of our hypothesis? There is another inconsistency between the predicted size of the inertial oscillation amplitude \( s \) and the salinity anomalies in the Agulhas Current. The displacement of a water parcel by an inertial oscillation is predicted by \( s/f \), which is little more than 1 km in the Agulhas \( (s = 5–10 \text{ cm s}^{-1}, \text{ Fig. 3}) \), increasing by at most 20% when one takes into account \( \varepsilon_{\text{eff}} \). Given the observed background salinity gradient, this small displacement would result in spiciness anomalies 10 times smaller than those observed. The lack of agreement in salinity anomalies and the lack of coherence between instantaneous salinity and velocity measurements are strong evidence against a purely inertial explanation. It could be the small-scale baroclinic instability predicted by MK97 that provides a mechanism for the subsequent growth of the intrusions, or possibly the nonlinear interactions of the inertial oscillations with the strong background shear field. The latter would create unclosed circulation of individual water parcels, resulting in greater lateral displacements, as well as stirring, patchiness, and locally enhanced salinity gradients.

As a result of these discrepancies another indicator pertaining to intrusion characteristics is examined: the variance of the vertical scale of splice with buoyancy frequency \( N \) (Fig. 7). Based on analytical theory Toole and Georgi (1981) predict that the dependence of the vertical scale of double-diffusive-driven intrusions goes as \( N^{-1/2} \), while Ruddick and Turner (1979) predict \( 1/N^2 \) based on laboratory experiments. In contrast, the vertical length scale of inertial oscillations varies as \( 1/N \), so that the thickness of the interleaving layers would increase as the buoyancy frequency decreases. Vertical length scales of the splice and velocity anomaly were again calculated using a one-dimensional Fourier transform, but this time the analysis was conducted separately for five different density layers, each of \( \gamma = 0.5 \text{ thickness, and spectral peaks up to 10 times smaller than those previously counted were used in order to obtain statistical robustness; } N \) was averaged over these same layers. Figure 7 shows that the vertical length scales of both the velocity and salinity anomalies vary most closely with \( 1/N \), giving normalized root-mean-square errors 0.25 lower than a fit to \( 1/N^2 \). Although not definitive, this is further evidence that inertial processes seem to be controlling intrusion thickness in the Agulhas Current.

Oceanic intrusions are generally thought to be indicators of large lateral fluxes and so it is useful to discuss here the cross-stream fluxes that could result from the observed interleaving within the Agulhas Current, given the environment in which they appear and the apparent oscillatory nature of their forcing. In the Agulhas Current, a water parcel within the RSW–AAIW density layer is advected downstream, on average, at about 30 cm s\(^{-1}\), corresponding to a distance of 25 km day\(^{-1}\). According to our data, the horizontal velocity shear at that depth is of the order of \( 1 \times 10^{-5} \text{ cm s}^{-1} \), such that water parcels with a cross-stream separation of 10 km will be separated by a downstream distance of 9 km after one day. In other words, water parcels are quickly swept downstream and separated into different environments owing to the horizontal shear field. Two-hundred-meter-thick intrusions grow “through” this shear field in the cross-stream direction at a rate of, say, 5 cm s\(^{-1}\) (see Fig. 3) (the inertial perturbation velocity) for half an inertial period or so, which is about half a day in the Agulhas Current (30°S).

Once the driving inertial velocity perturbation swings around to the opposite direction there are two possible scenarios.

First, it is conceivable that the intrusion, or salinity anomaly, will simply shrink back toward the front. In other words, because of the periodic nature of the driving velocities, the Agulhas intrusions may simply represent an oscillating perturbation, or bulging, of the temperature–salinity front, rather than unidirectionally growing features. In this case, we are led to the coun-
terintuitive conclusion that Agulhas intrusions do not result in cross-frontal fluxes of heat and salt. This implies that the general assertion of Ruddick and Richards (2003)—that the presence of intrusions leads to enhanced lateral fluxes—may be incorrect. However, in a second possible scenario it is conceivable that the Agulhas intrusions, having formed as a result of near-inertial velocity perturbations, may continue to grow as a result of small-scale baroclinic instability (MK97) resulting from locally enhanced property gradients. Their growth must be rapid and their downstream dimension large or they would simply be torn apart. Eventually intrusions will be sheared off and swept downstream by large horizontal velocity shear to subsequently decay and mix, whether by double-diffusive processes or otherwise. In this way there could be a cross-frontal property flux resulting from the oscillating perturbations.

At this point it is worth discussing in more detail what the significance of intrusions crossing density surfaces could be. We saw in Fig. 4 that a warm, salty intrusion at 750-m depth appears to rise in density space and another, somewhat lower in the water column at 1000 m, appears to fall. The explanation for this could be that double diffusion is responsible for the decay of Agulhas intrusions. Although it has been shown that double diffusion is not important during the growth and steady state (if there is one) of the intrusions, it seems likely that if an intrusion is sheared off, double diffusion will act to mix it into the surrounding waters. For an intrusion at the top of the AAIW–RSW layer to become lighter and another at the bottom to become denser is consistent with double-diffusive processes. Both intrusions are warm, salty, but the first is in a background salinity field where the water above the intrusion is saltier than the water below, that is, the intrusion sits just above the AAIW salinity minimum. In this case, salt fingering along the bottom interface of the warm, salty intrusion will dominate (larger $S$ gradient) over the diffusive convection along the top interface, resulting in a net rejection of salt and a lightening of the layer. The second, lower intrusion sits just below the AAIW salinity minimum, so that the water above it is fresher than the water below. Now diffusive convection along the top interface will dominate, resulting in a net loss of heat making the intrusion denser.

Yet double diffusion need not be implicated even in the decay of Agulhas intrusions. Alternatively, the inertial oscillations themselves could drive intrusions across isopycnals. Rainville and Pinkel (2004) show that near-inertial internal waves in the Kuroshio propagate upward or downward with respect to neutral surfaces.
(dependent on their direction of rotation) at a rate of about 100 m (12 h)\(^{-1}\) period (their Fig. 6). Now, the three stations of Fig. 4 were each occupied 3 h apart. Instead of the distance between stations implying that a spatially coherent intrusion is sinking or rising, it could be the temporal lapse between stations that implies a salinity anomaly is occurring at gradually lesser or greater depths. In other words, the upper intrusion gains depth at about 180 m (12 h)\(^{-1}\) and the lower one at 60 m (12 h)\(^{-1}\), both of which are similar rates to those found in the Kuroshio. Thus, the Agulhas intrusions could simply be a marker of downward-propagating near-inertial oscillations. In this case, it is the energy that is propagating downward, not the water parcels, so that the appearance of a continuous intrusion in Fig. 4 could be a product of time and not distance. In this case spice simply traces the inertial oscillations wherever they appear in the water column and there is unlikely to be a net flux of salt across neutral surfaces.

6. Conclusions

At this point it is illustrative to present a point-wise summary of our findings. The evidence against the theory that double-diffusive (DD) processes drive Agulhas intrusions is summarized first. There was no evidence found in support of DD processes.

- The presence of intrusions is not influenced by the background temperature/salinity field.
- Intrusion thickness is an order of magnitude larger than that predicted by double-diffusive theory and is thicker than all previously observed intrusions, except those in the deep sea.
- There is no density anomaly associated with the intrusions.
- The opposing isopycnal slope and salinity gradient within the RSW–AAIW layer should act to suppress interleaving.
- The rate of vertical and horizontal shears in the Agulhas Current are large relative to the predicted growth rate of DD intrusions and would thus cause them to twist and tear apart before significant growth can occur.
- The slope of intrusions falls between density and geopotential surfaces, indicating baroclinic instability rather than DD instability.
- The slope of the intrusions is 3 times that predicted for DD processes.
- Salinity anomalies are largest where the vertical salinity gradient is a minimum.

The evidence for and against advective processes is as follows:

- The spice anomalies have the same vertical scale as both components of velocity anomaly.
- The vertical scale of intrusions varies approximately with 1/N, which is consistent with near-inertial wave theory.
- Yet, instantaneous spice and velocity anomalies are not well correlated.
- Salinity anomalies are 3–10 times that predicted by purely inertial theory.

Interleaving within the Agulhas Current has been shown to have a characteristic vertical length scale of 200 m, which is a scale consistent with high-wavenumber velocity perturbations observed within the current. The thickness of these intrusions and their slope fall outside the criteria for double-diffusive instability, and they do not appear to be associated with a favorable background temperature/salinity field, indicating that double-diffusive processes do not drive them. Instead, the evidence suggests that they are primarily driven by the velocity perturbations, identified as near-inertial oscillations, and that consequently their growth is fast, but not unidirectional. As a result, it is possible that these intrusions may not result in the kind of cross-frontal property fluxes that many investigators would anticipate. However, we do not have a satisfactory explanation from this study for the discrepancy between the small predicted inertial amplitude and large observed salinity anomalies, except to propose that small-scale baroclinic instability, as well as the extreme horizontal shear field, may play a role in the growth of the intrusions. Further examination of this issue, with a more pointed observation program involving time series measurements, and perhaps the development of an analytical model, is needed to unambiguously resolve the nature of Agulhas intrusions. If lateral fluxes do result they will arise from the complex interaction of small-scale vertical shear and baroclinic instabilities with the large-scale horizontal shear on the temperature–salinity field.

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