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A North Atlantic deep-water eddy in the Agulhas Current system

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Abstract

One hundred and twelve stations of CTDO2 and LADCP were collected in the Agulhas Current system as part of the Agulhas Undercurrent experiment (AUCE) in March 2003. Along an offshore section, at approximately 35.6°S and 27.3°E to the northwest of the tip of the Agulhas Plateau, an unusual feature was revealed between 2200 and 3500 m depth, imbedded in the northward moving NADW layer. An anomalously high salinity of 34.83, 0.03 saltier than the surrounding water, was observed. Maximums in the potential temperature and oxygen were also found, with isotherms dropping by about 250 m over 50 km and a doming of the oxygen layers. From the convex lens structure of the neutral surfaces, we conclude that we sampled an anticyclonic eddy of NADW. Since the LADCP data reveal deep velocities up to 20 cm s^{-1}, yet no anticyclonic circulation, whereas the geostrophic velocity referenced to the bottom shows a weak anticyclonic circulation, we inferred that we sampled the outer edge of the eddy and not its core. From an analysis of the water properties within the eddy and a comparison with known properties in the SE Atlantic Ocean and SW Indian Ocean, we conclude that the eddy was formed in the Agulhas Retroflection region. We speculate that the eddy was the result of an instability in the NADW slope current, which flows from the SE Atlantic around the Agulhas Bank. A deeply penetrating Agulhas Ring spun up the deep waters, pinching off an eddy, which later detached from the slope current and was carried southward. Once offshore, it coupled with the surface Agulhas Return Current, whose meandering path advected the eddy northeastward and ejected it over the Agulhas Plateau.

Keywords: Circulation; Indian Ocean; Boundary currents; Agulhas Current; Deep water; Oceanic eddies

1. Introduction

It has been shown that the exchange of water masses between the Atlantic and Indian Oceans is a key component of the global thermohaline circulation. As the Agulhas Current separates from the Agulhas Bank at the southern tip of Africa, it retroflects and periodically sheds large eddies with diameters as large 500 km, known as Agulhas Rings. The surface and intermediate inter-ocean exchanges are dominated by the migration of Agulhas Rings from the Agulhas Retroflection region into the Cape Basin of the eastern South Atlantic (Boebel et al., 2003). The majority of the Agulhas Current retroflects and flows east back into the Indian Ocean as a

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meandering jet known as the Agulhas Return Current (ARC) (Boebel et al., 2003). Although Agulhas Rings have been observed to reach up to 4000 m depth (McCartney et al., 1991; van Veldhoven, 2005), they are identified as surface features. Once the Agulhas Rings drift into the Atlantic Ocean, they significantly alter its heat and salt budgets (de Ruijter et al., 1999; Weijer et al., 2002).

Most eddies observed in the ocean are surface-intensified, although sub-surface eddies, such as the Mediterranean Water eddies (Meddies), which are formed at depths between 500 and 1500 m (Richardson et al., 2000), are also familiar. However, observations of deep-water eddies are rare. Lately some evidence of deep eddies has been found in the Brazil Basin (Weatherly et al., 2002; Dengler et al., 2004). In particular, Dengler et al. (2004) observed that the Deep Western Boundary Current (DWBC), which flows southward along the continental slope of South America carrying North Atlantic Deep Water (NADW), breaks into eddies at about 8°S, which continue to advect south along the western boundary. They speculate that the eddies are generated during periods of strong meridional overturning circulation (MOC), while during periods of weak MOC, the DWBC continues as a more laminar flow south of 8°S. Model results suggest that baroclinic and barotropic instabilities are the responsible mechanism for the eddy generation.

In this study, we report the observation of an unusual, deep feature within the Agulhas Current system, sampled during the Agulhas Undercurrent Experiment (AUCE). We identify the feature as an anticyclonic eddy containing NADW from the SE Atlantic. Contrary to the Brazil basin, there is no DWBC in the Southwestern Indian Ocean, probably owing to the rapidly shoaling topography towards the north. Instead, there is an Agulhas Undercurrent, whose core is positioned against the continental slope at around 1200 m depth, within the intermediate water layers and inshore of the Agulhas Current (Beal and Bryden, 1997). Therefore, it was unexpected to find a NADW eddy in the absence of an energetic DWBC.

In earlier studies of Reid (1989) and Toole and Warren (1993) it had been proposed that the deep boundary current separated from the continental slope near 20°S to continue eastward in the Agulhas return flow. Arhan et al.(2003) and van Aken et al.(2004) showed evidence of a NADW slope current along the African continental slope. Specifically, van Aken et al.(2004) followed the deep salinity maximum associated with the NADW core in a narrow band along the African continental slope from the SE Atlantic near 30°S, around the tip of the Agulhas Bank to the Mozambique Channel east of Africa and estimated that around 2 Sv of upper NADW flows across the sill in the Mozambique Channel into the Somali Basin. However, most of the flow continues eastward at about 45°S. These previous findings are in agreement with Arhan et al.(2003) who concluded that once in the Indian Ocean basin most of the slope current is entrained in the deep return flow of the Agulhas Current or ARC, leaving only 2–3 Sv to continue north. The eastward path of the ARC is not a straightforward trajectory, but instead consists of a series of meanders (Boebel et al., 2003). This meandering path of the ARC has maintained the same meandering pattern of troughs and crests for the past 15 years, in particular the first meander trough that wraps around the Agulhas Plateau which is considered permanent.

In this paper, we present the characteristics of this rare deep eddy and compare them with previous datasets (Section 2). We subsequently seek information on where and how such an eddy could have been formed along with its most likely advection path (Section 3).

2. Data and analysis

The data collected in February–March 2003, was part of the AUCE, which took place off the east coast of South Africa, between 26° and 37°S with the objective of improving our current knowledge of the Indian Ocean's western boundary current system. The survey region consisted of 112 stations distributed among four high resolution cross-stream sections closed by an offshore section (see Fig. 1) encompassing the Agulhas Current system. Full depth hydrographic data were collected with a conductivity-temperature-depth-oxygen (CTDO2) sensor, and full depth profiles of horizontal currents at each hydrographic station were obtained with a lowered acoustic Doppler current profiler (LADCP).

Following the convention of Beal et al. (in press), we define six density layers according to the primary water masses present in the region. The surfaces that define these density layers are shown as thick lines in Figs. 2 and 3. In this paper, we focus on NADW which is split into upper and lower layers, located between neutral densities of 27.92 and 28.08 kg m^{-3},

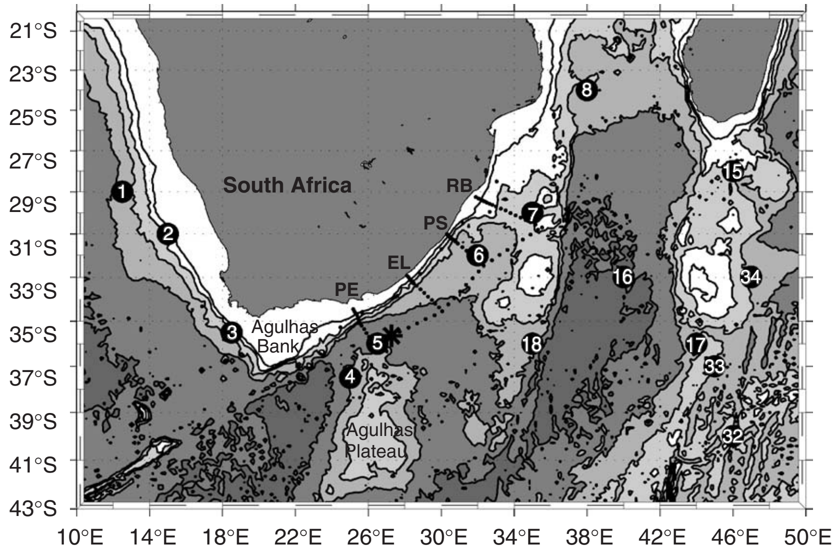

Fig. 1. AUCE stations: PE refers to Port Elizabeth, EL is East London, PS is Port Shepstone and RB is Richards Bay. The asterisk marks the location of the NADW eddy and the circles are clusters described in van Aken et al. (2004). Bathymetry contours are every 1000 m. Important bathymetric features such as the Agulhas Bank and the Agulhas Plateau are indicated.

and greater than 28.08 kg m^{-3}, respectively. The lower layer cannot pass to the north because of local topography (Fig. 1). This modified NADW, which flows in from the SE Atlantic Ocean, is characterized by a deep salinity maximum accompanied by an oxygen maximum and nutrient minimum (van Aken et al., 2004) at depths between 2000 and 3500 m. Beal and Bryden (1999) define the NADW as having a tight potential temperature-salinity relationship with a maximum salinity of 34.83 at 2 °C.

A careful analysis of the deep-water properties from AUCE revealed an unusual feature (Fig. 2) offshore of the Agulhas Current and within the northward moving NADW layer between approximately 2200 and 3200 m depth. An anomalously high salinity of 34.83, 0.03 saltier than the surrounding water, was observed at 35.6°S, 27.3°E (Fig. 1), northeast of a major bathymetric feature known as the Agulhas Plateau. The salinity anomaly was accompanied by large temperature and oxygen anomalies (Fig. 3). The neutral density layers at this location show a convex lens structure with the 2.3 °C isotherm dropping by 250 m over 50 km (Fig. 3a) to give rise to a temperature anomaly greater than 0.2 °C. Moreover, the oxygen maximum of 5 ml l^{-1} domes upward by almost 200 m (Fig. 3b). Fig. 4 shows a θ-S diagram of the deep waters of the Agulhas region using all AUCE stations. The anomalous profile is very distinct as an exceptionally warm and salty feature for the sampling region. Unfortunately, only one station (18) sampled the anomaly, which is sufficiently rare and worthy of further investigation. In the following paragraph we show that this feature represents an anticyclonic eddy containing NADW that is saltier, warmer and younger than the surrounding cooler, less salty and older NADW.

Weatherly et al. (2002) observed two deep cyclonic and two deep anticyclonic submesoscale eddies in the Brazil Basin and proposed that they are a new-found mechanism for transporting NADW eastward, away from the DWBC and into the ocean interior. They concluded that a deep feature is an anticyclonic eddy (or aeddy) if its density field shows a convex lens structure, if its salinity and oxygen properties indicate extrema near the density core, and if the potential temperature-salinity plot of the core shows anomalous properties relative to the surrounding water. Since the properties of our feature are also aligned with all these indicators, we believe we have found a NADW anticyclonic eddy. Henceforth, we abbreviate this NADW eddy as a “Naddie”.

The Naddie signal is also visible in the LADCP data in the form of a velocity core with peak velocities of the order of 20 cm s^{-1} (Fig. 5a). Even though we have a well-defined V shape in the

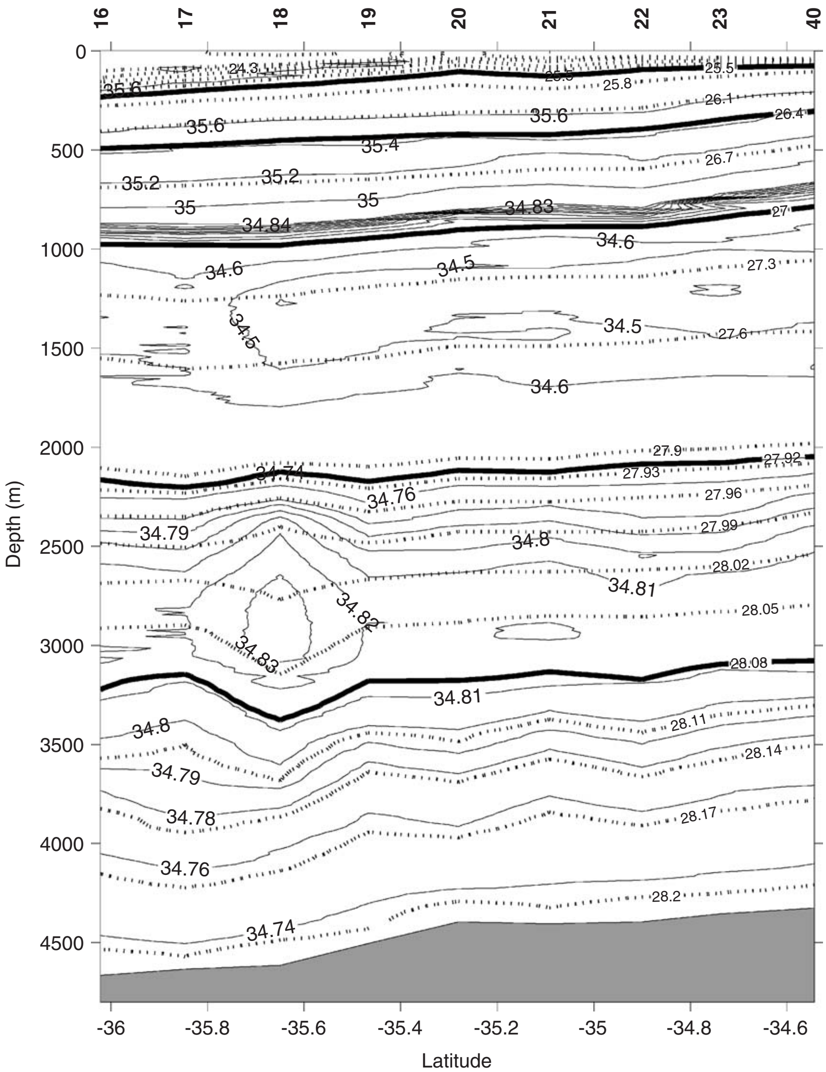

Fig. 2. Salinity section for the offshore transect PE–EL, showing the full column depth versus latitude. Dotted lines represent neutral density surfaces, and thick lines highlight neutral density surfaces that separate the different water masses. Station numbers are shown at the top, and the Naddie is centered at station 18.

density pattern, we deduce that we have sampled the eddy's outer edge and not its center because we do not find two velocity cores of opposing direction in the LADCP data and the geostrophic velocity shows only a weak anticyclonic circulation for a level of no motion (LNM) at the bottom (Fig. 5b). According to the core method, in which a water mass moves away from its source, the eddy is embedded in the northward moving NADW layer. We consider it to be advecting with this layer, since we have no data to validate or contradict this assumption. As to the size of the eddy, we infer that the eddy diameter is less than 100 km because the offshore stations surrounding it are 50 km or less apart (Fig. 1) and exhibit none of the Naddie's properties.

Unlike the NADW eddies observed in the Brazil Basin, this Indian Ocean Naddie is not associated with a DWBC. The topography shallows too quickly towards the north to support a DWBC here. Instead, the Agulhas Undercurrent (Beal and Bryden, 1997) flows northeastward along the continental slope with a core at only 1200 m and a weak, reversing current below. Our Naddie was found 200 km away from the continental slope, at a depth 1000 m greater than the Undercurrent core.

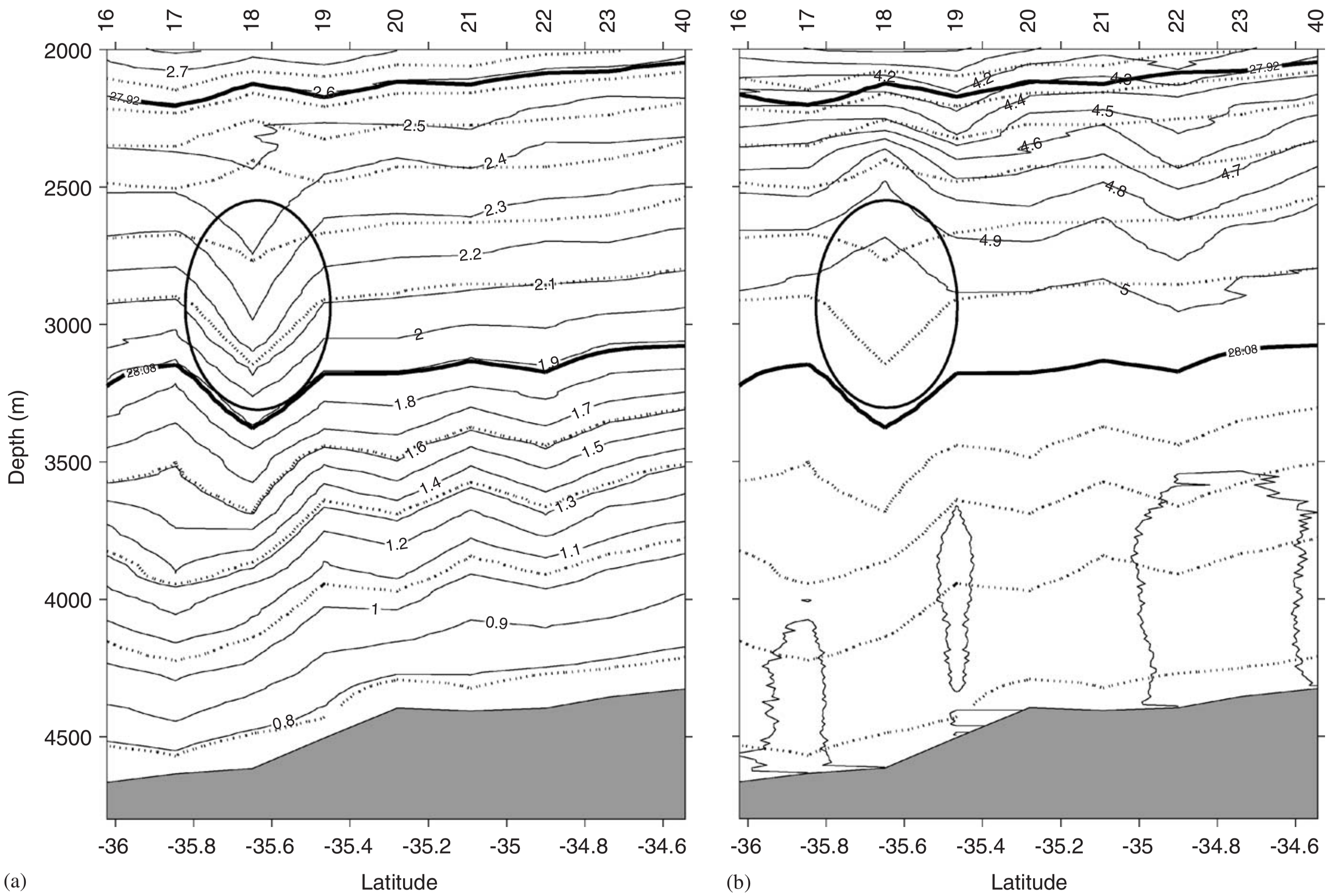

Fig. 3. (a) Potential temperature section for the transect PE–EL, showing the deep layers versus latitude. (b) Same as a for oxygen. Dotted lines represent neutral density surfaces and thick lines represent neutral density surfaces that separate the deep-water masses. The Naddie's location is encircled in both plots.

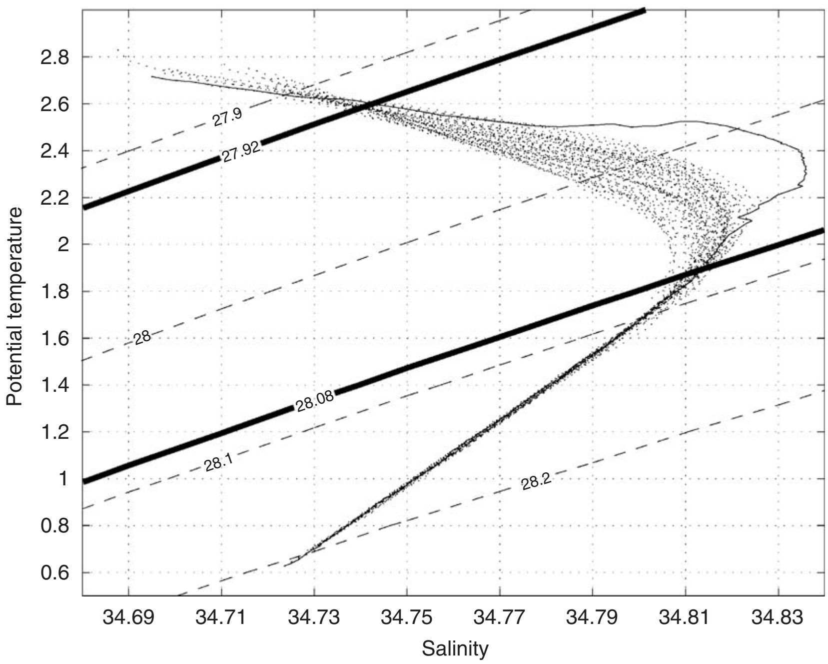

Fig. 4. Potential temperature–salinity diagram for the 112 stations of AUCE. The neutral surfaces dashed contours shown correspond to the offshore section PE–EL, and the thick solid lines represent neutral density surfaces that separate the deep-water masses. The solid line represents station 18 and the dots represent the remaining stations.

Hence, there appears to be no local mechanism for the formation of the Naddie.

In an attempt to shed some light on the formation mechanism of the eddy, we set about finding its origin by comparing its water properties with those found in the eastern Atlantic Ocean and western Indian Ocean. We studied regional water-mass characteristics using the analysis of van Aken et al. (2004), who used WOCE and Dutch–South African Agulhas Current Sources Experiment (AC-SEX) hydrographic observations to create clusters of data (their Fig. 3) representative of several areas in the Southwestern Indian ocean and Southeastern Atlantic. We used all the clusters for comparison with our Naddie as well as the AUCE stations and stations from WOCE I6 (East London to Antarctica along 30°E line, Park et al., 2001) which were not included in van Aken's study. For simplicity we only show the θ/S characteristics of those clusters most similar to our Naddie (Fig. 6). It is clear from Fig. 6 that no waters of similar character are to be found east of the Naddie's position at the tip of the Agulhas Plateau, either within the ARC nor the Agulhas Current system. Waters matching the temperature and salinity characteristics of the eddy are found between van Aken's clusters 3 and 4, which are located west (cluster 3) and east (cluster 4) of the Agulhas Bank, in the oceanic region south of the tip of Africa (Fig. 1) also known as the Agulhas Retroflection region.

We consider it likely, since we only clipped the outer edge of the eddy, that inside its core the anomalies are stronger than those we observed, similar to the Brazil basin deep eddies (Weatherly et al., 2002; their Fig. 5b), where salinities increase by 0.04 from the outer edge to the core. Given this, and the inevitable diffusion of properties during its translation, it is likely that the eddy formation region is even farther to the west of South Africa (west of cluster 3) and deeper into the South East Atlantic.

3. Discussion

Based on the data available, we have inferred that the region of the Naddie formation is the Agulhas Retroflection region known for its strong eddy activity (Stammer and Wunsch, 1999) associated with very high kinetic energy (Schmitz, 1996; Biastoch and Krauss, 1999; Stammer and Wunsch,

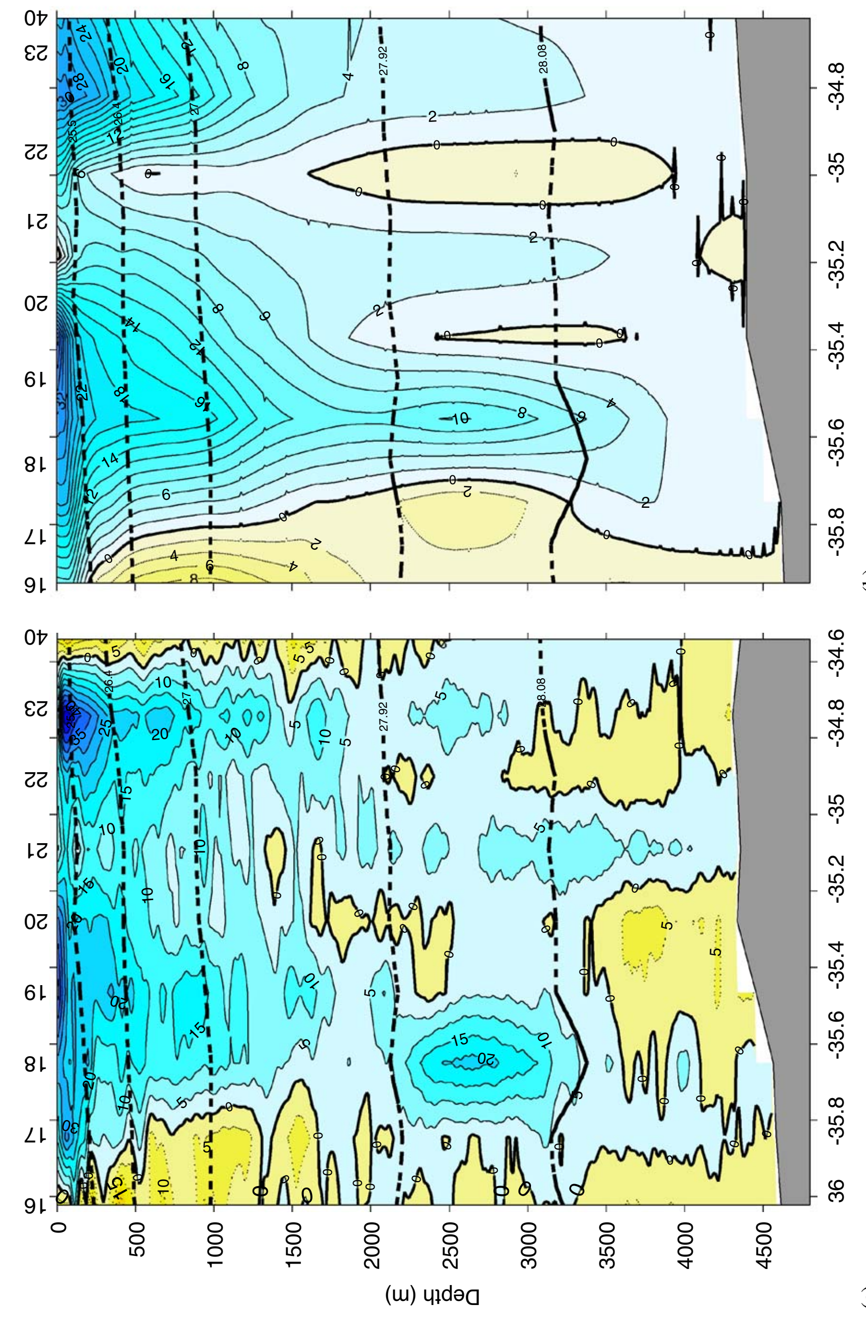

Fig. 5. (a) LADCP velocities for the PE–EL section: (b) Geostrophic velocities referenced to the bottom for the same section. In both plots, solid lines indicate positive velocities directed towards the coast and dotted lines indicate negative velocities away from the coast. Velocities are in cm s^{-1}, the solid thick line is the zero line and dashed lines are the neutral density surfaces separating the different water masses.

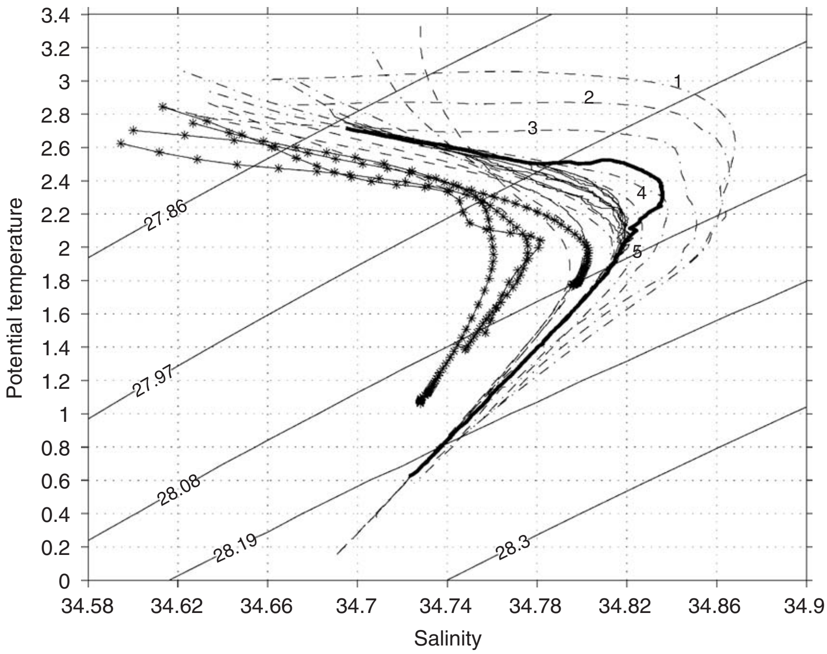

Fig. 6. Potential Temperature-Salinity diagram showing the characteristics of the Naddie compared to regional water masses. The locations of clusters 1–8 (dash dot), 15–18 (dashed) and 32–34 (asterisk) are given in Fig. 1. PE-EL stations from AUCE are shown as solid black lines. The eddy was sampled at station 18 and is highlighted by the thick black line. Van Aken's clusters 1–5 are numbered. Contours indicate neutral surfaces corresponding to the section PE–EL.

1999). Boebel et al. (2003) have shown that this so-called "Cape Cauldron" region (part of the southern Cape Basin) is a zone of turbulent stirring and mixing because of high eddy kinetic energy (EKE) density at both the surface and intermediate depths. They demonstrated that the enhanced field of EKE is for the most part composed of surface-intensified cyclonic and anticyclonic vortices from both the Indian and the Atlantic oceans and with subsurface floats showed that the turbulent exchange reaches intermediate layers. Next, we discuss hypotheses for how such an intense deep eddy may have been formed within this energetic region.

Chassignet and Boudra (1988) studied the energetics and ring formation in the Agulhas Retroflection with a numerical model. They performed several experiments, and the ones that successfully formed rings exhibited considerably larger values of kinetic energy transfer from the mean flow to the eddy field. Of particular note is that the instantaneous flow pattern included both top and bottom layer anticyclonic eddies at the southern tip of Africa. The surface eddy, or retroflection eddy, intensifies because it is fed with Agulhas water, subsequently causing an intensification of the bottom anticyclone as energy is transferred downward. In the model they both initially move westward, but separate as the retroflection eddy becomes a ring. Interestingly, in Chassignet and Boudra's (1988) simulation, the bottom eddy continues to move westward and even leads the surface ring. This westward advection is contrary to what we have deduced for the Naddie. In our case, we have a bottom layer anticyclonic eddy that could well have formed below the retroflection in the manner described by Chassignet and Boudra (1988), since its water-mass properties originate in this region. However, our Naddie must move out of the retroflection region in a east-northeastward direction to end up at the location at which we observed it.

We cannot dismiss the hypothesis that an upper cyclone (rather than an anticyclone such as the retroflection) could also have originated our bottom anticyclone since it is known that both cyclones and anticyclones coexist in the Cape Cauldron region (Boebel et al., 2003). Boebel et al. (2003) classified the cyclones found in Cape Cauldron according to their original formation site. Two types have formation areas similar to that estimated for the

Naddie. The so-called Agulhas cyclones (Lutjeharms et al., 2003) are formed inshore of the Agulhas Current and include cyclones generated at the tip of the Agulhas Bank, where the Agulhas Current detaches from the topography, with diameters ranging from 50 to 200 km (Penven et al., 2001). The Cape Basin cyclones are formed along the western shelf break of southern Africa and are thought to be related to the interaction of Agulhas Rings with the shelf, to the local upwelling along the East African shelf (Shannon and Nelson, 1996), or to an intermediate eastern boundary current (Shannon and Hunter, 1988). They have a typical diameter of only 120 km and swirl velocities of 3.5 cm s^{-1}. Thus, the size and strength of the regional cyclone are much smaller than an Agulhas ring, making the regional cyclone less prone to dynamic instability. Even though the Agulhas cyclones remain a possibility, we favor a formation site west of the tip of the Agulhas Bank underneath the path of an unstable Agulhas ring.

In particular, Arhan et al. (2003) observed a NADW maximum being stirred or torn off the slope current at 34°S as an Agulhas ring passed above. In their Fig. 11c, a parcel of water with salinities higher than 34.84 has separated from the slope water at around 3000 m depth, showing that some NADW has become detrained from the slope current. Extended downward from the surface above the NADW parcel is the signature of an Agulhas Ring, which appears to have coupled with and caused instabilities in the deep flow. Similar features were recently observed during the Agulhas-South Atlantic Thermohaline Transport Experiment (ASTTEX) (Duncombe-Rae, personal communication). They found the slope current with another separated blob of NADW located at 34.123°S, 14.585°E, about 1000 km northwest of the retroflection region. The parcel's maximum salinity is 34.85 (our Naddie is 34.83), and an Agulhas Ring was found during the same survey 2.5° to the west. Both these sets of observations provide strong evidence that Agulhas rings spin up the deep water, destabilize the slope current and create Naddies in their wake.

To test this hypothesis and for a better understanding of the dynamics of the region during AUCE, we examined the surface evolution of the Agulhas retroflection for the shedding of an Agulhas ring during early 2003 using microwave SST and a synthesis of drifter, altimetry and wind observations (Niiler et al, 2003; not shown). Our Naddie was measured on February 23, 2003, and we observed that in early January the retroflection was south of the Cape of Good Hope at 20°E and by January 18 had extended southwestward to 15°E. A ring began pinching off from the retroflection in late January, becoming clearly separated by February 7. However, it is unlikely that this particular ring generated our Naddie, since the latter would have had to translate with speeds of the order of 40 km/day from the retroflection region in order to reach the position in the SW Indian Ocean at which it was observed. Accordingly, we looked for a ring further back in time and found one in late October sitting west of the retroflection (~38°S, 17°E). Ring translation speeds have been reported to vary between 3 and 16 km/day (van Veldhoven, 2005), and using these velocities to calculate the time it would take a deep eddy spawned by the October ring to reach the sampling site in late February, we obtained time periods of about 24 days (using 16 km/day) to 129.5 days (using 3 km/day). Therefore, considering a slow translation speed or an indirect route, we speculate that the October Agulhas ring might have created the Naddie that we observed in the SW Indian Ocean 4 months later.

It is still unclear how the Naddie advected eastward/northeastward rather than westward as the dynamical theory would predict. As stated earlier, Arhan et al. (2003) found that the ARC may be the main eastward route for NADW exiting the SE Atlantic and the Agulhas Retroflection region. A schematic circulation of NADW adapted from Fig. 10 of Arhan et al. (2003) is plotted in Fig. 7 and shows that most of the NADW meanders around the Agulhas Plateau and continues eastward, passing through both the retroflection region (origin of our Naddie) and northeast of the Agulhas Plateau (sampling location). The latest result complies with Boebel et al. (2003), conclusions that the ARC reveals a meandering pattern, in particular a permanent meander wrapping around the Agulhas Plateau. Furthermore, evidence that water parcels are trapped in the ARC came from the same study of Boebel et al. (2003) where eight out of 13 floats launched in the Atlantic at intermediate water levels along the southern boundary of Cape Basin (northwest of the Agulhas Retroflection) were trapped in the ARC. As a result, we speculate that the Naddie, once it was formed, left the slope current and advected south within the NADW layer coupled with the ARC and followed a path similar to the one shown in Fig. 7, until it was ejected into the sampling region.

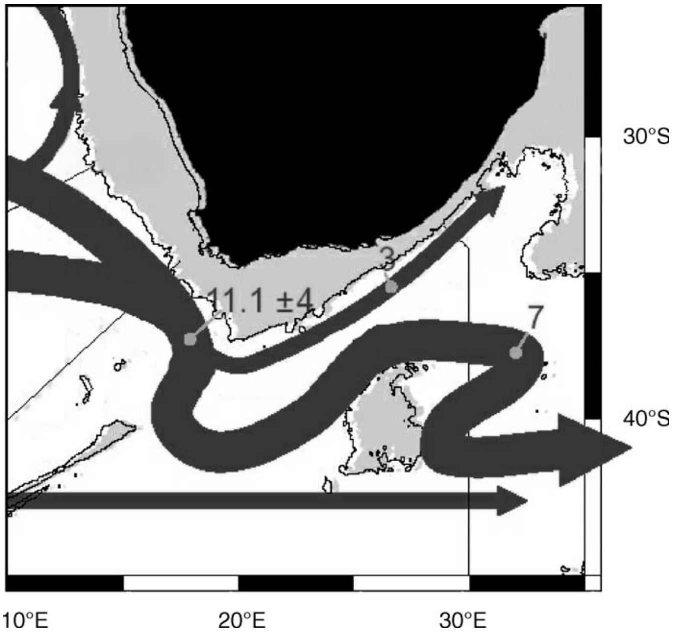

Fig. 7. Schematic circulation of NADW around the southern tip of Africa adapted from Arhan et al. (2003). The 3000-m isobath is shown. The numbers are the transport estimates (in Sv) from their inverse model.

4. Conclusion

During the AUCE survey in February–March of 2003 off the east coast of South Africa, a NADW eddy (Naddie) was found in the northward moving NADW layer between the depths of 2200 and 3200 m at 35.6°S, 27.3°E, just northeast of the Agulhas Plateau. The Naddie has highly anomalous water properties with a high salinity of 34.83, 0.03 saltier than the surrounding water, a positive temperature anomaly of 0.2°C and a doming of the oxygen maximum. The density field revealed a convex lens structure typical of anticyclones, although direct velocities did not show two velocities cores in opposing directions, suggesting that only the edge of the feature was sampled. A weak anticyclonic circulation arose in the geostrophic velocity calculated using an LNM at the bottom. Comparisons of the Naddie's water properties with other measurements from the SE Atlantic Ocean and SW Indian Ocean showed that the Naddie was formed in the Agulhas Retroflection region, known for its intense eddy activity.

Various theories were considered for the formation mechanism of the Naddie and its subsequent advection into the sampling site. The most plausible generation mechanism for our Naddie is the coupling of a deep Agulhas Ring with the NADW slope current in the SE Atlantic, pinching an eddy that was subsequently detached from the slope current and advected southward, where it coupled with the deep imprint flow of the ARC. This coupling advected the Naddie northeastward, and it was likely ejected into the sampling region by the intense permanent cyclonic meander of the ARC around the Agulhas Plateau. Validation or rejection of our hypothesis will require additional measurements and model studies since in-situ observations are relatively sparse in this region. How common/important this mechanism is to the interocean transfer of NADW and the pathways of the global overturning circulation remains an open and interesting question.

Acknowledgments

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