North Atlantic Deep Water Pathways and Eddy Generation Beneath the Agulhas Current System

Joni Lum
University of Miami, annularis7@hotmail.com

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the requirements for the degree of
Master of Science

NORTH ATLANTIC DEEP WATER PATHWAYS AND EDDY GENERATION
BENEATH THE AGULHAS CURRENT SYSTEM

Joni Lum

Approved:

Lisa Beal, Ph.D.
Professor of Meteorology and
Physical Oceanography

Igor Kamenkovich, Ph.D.
Professor of Meteorology and
Physical Oceanography

Maria J. Olascoaga, Ph.D.
Professor of Applied Marine Physics

M. Brian Blake, Ph.D.
Dean of the Graduate School
The Atlantic Meridional Overturning Circulation (AMOC) has long been an area of study due to its link to climate change. North Atlantic Deep Water (NADW) forms the deep water limb of the AMOC, ventilating the deep sea by transporting cold saline properties out of the Atlantic basin. We use high resolution model output to show that NADW is strongly influenced by the Agulhas Current System as it flows into the Indian Ocean around South Africa. Eulerian analysis reveals that the high salinity signature of NADW erodes rapidly as it exits the Atlantic basin, underneath the Agulhas Current System and is deflected to the south by the potential vorticity field. A Lagrangian analysis reveals a high degree of eddying and an indirect pathway into the Indian Ocean that favors the area beneath the Agulhas ring corridor, retroflection, and a southern route around the Agulhas Plateau. Of the 17 Sv of NADW in the slope current off South Africa in the South Atlantic, an estimated 10.5 Sv advect into the Indian Ocean after heavy recirculations in these regions. Deep cyclogenesis results from instabilities in the surface flow and is favored in three distinct areas: In the lee of the Agulhas Bank, where cyclones are generated as a result of an anomalously strong northwestward extension of the Current; beneath the retroflection where a dipole forms when the retroflection broadens; and to the east of the Agulhas Plateau where cyclones spin up as the Return Current meander.
deepens. Cyclogenesis is most frequent beneath the retroflection, but eddies dissipate within weeks throughout all regions and hence do not play a significant role in transporting NADW around South Africa.
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Chapter 1 Introduction

The Atlantic Meridional Overturning Circulation (AMOC) refers to the large scale ocean circulation in the Atlantic basin that is driven by buoyancy fluxes as part of the global thermohaline circulation. Because of its contribution to poleward heat flux and its link to climate change (Biastoch et. al., 2008), AMOC variability is an area of continual interest. The deep water limb of AMOC is comprised of North Atlantic Deep Water (NADW) which forms in the Greenland and Labrador Seas, where saline waters from the south cool and eventually sink. NADW is characterized by a salinity and temperature maximum beneath the thermocline of 34.83 and 2°C respectively and is typically found at depths ranging from 1000 m -3000 m (Dengler et. al., 2004). This unique salinity and temperature signature can be used to trace NADW as it flows southward within the deep western boundary current (DWBC). Along the Brazilian continental shelf, the DWBC bifurcates resulting in two pathways: One that carries NADW southward under the Brazil-Malvinas Current and another that flows zonally across the mid-Atlantic Ridge into the Cape Basin (Hogg and Thurnherr, 2004). In the Cape Basin, NADW flows southward along the western edge of the African continent within a broad slope current, continuing around the tip of South Africa to exit the Atlantic basin beneath the Agulhas Current System (Arhan et. al. 2003).

The Agulhas Current System has one of the largest kinetic energy signals in the world. The southward flowing western boundary current retroflects at the tip of the African continent, regularly shedding large rings and eddies as it turns back into the Indian Ocean as the Agulhas Return Current (Figure 1). These mesoscale and
submesoscale features result in a highly turbulent, nonlinear regime that influences the flow at depth. This phenomenon has been seen in both model and observation studies. Van Sebille et. al. (2012) used high resolution OFES model output and Lagrangian analysis to diagnose the pathways of NADW as it crosses the South Atlantic and found that it is shaped by an input of vorticity by Agulhas rings in the Cape Basin. Likewise, Arhan et. al. (2003) used hydrographic data and found a link between anticyclonic Agulhas rings and the NADW slope current off the west coast of South Africa. Arhan et. al (2003) showed that Agulhas rings can squeeze the NADW layer and suggested this could lead to the separation of NADW from the slope and deep water eddy formation.

Observations have revealed evidence of a NADW eddy in the Agulhas region. Casal et.al (2006) found an anomalously high oxygen, salinity, and temperature signal at 2200 m depth just off the northwest tip of the Agulhas Plateau. This deep feature was an energetic anticyclone with swirl velocities of $20 \text{ cm s}^{-1}$. By water mass analysis the authors concluded that this eddy originated in the southeast Atlantic, speculating that it was formed when a deeply penetrating Agulhas ring induced instabilities in the NADW slope current. The formation of NADW eddies is not unique to the Agulhas retroflection region. Dengler et. al. (2004) used a combination of direct velocity and water mass observations, along with high resolution model output to find that NADW is transported southward along the Brazilian continent by a chain of drifting deep water eddies south of $8^\circ \text{S}$. Yet it remains unclear how frequently NADW eddies form in the Agulhas region, what their pathways are, and if they play a role in the interocean exchange of NADW.
Figure 1: (Top) Bathymetry of Agulhas region. Mean sea surface height contours depicting the Agulhas Current System are overlaid in black. AB = Agulhas Bank, AR = Agulhas Ridge, AP = Agulhas Plateau MR = Mozambique Ridge, SWI = Southwest Indian Ridge. (Bottom) Eddy kinetic energy (m²s⁻²) of the Agulhas Current System, defined as the sum of variances of the zonal and meridional velocities. Data is averaged over 28-years.
The mean pathways of NADW in the Agulhas region have been inferred by Arhan et. al. (2003) who implemented an inverse model using one-time hydrographic data from the World Ocean Circulation Experiment (WOCE). They found that NADW from the slope current within the Cape Basin supplies most of the $11\pm 4$ Sv that enters the region south of Africa, where the flow bifurcates. A northern branch carries 3 Sv into the Indian Ocean via the Agulhas Undercurrent, while the southern branch carries 7 Sv eastward beneath the Agulhas Return Current (ARC), meandering to the north of the Agulhas Plateau (see Fig. 1 for bathymetry of the region) and into the Indian Ocean. While the inverse model provides an estimate of the bulk transport through the region, it is limited by a lack of temporal and spatial resolution and unable to address in detail the pathways of NADW propagation and deep eddy generation around South Africa.

Our study investigates mechanisms for NADW eddy generation beneath the Agulhas Current system using high resolution model output. We ask the question: Is NADW exported from the Atlantic Ocean by eddies? The mixing and translation of the water mass is also examined to reveal the main pathways of NADW around South Africa.
Chapter 2  Model/ Methods

2.1 Model

The model used in this study is ORCA05, which is based on the Nucleus for European Modeling of the Ocean (NEMO, v.3.1.1; Madec, 2008) and developed under the DRAKKAR framework (The DRAKKAR Group 2007). It is a coarse \( \frac{1}{2} \) - degree resolution, primitive equation, global ocean model, which utilizes the z-coordinate in 46 vertical levels, and an Arakawa C-type grid to distribute variables. The ocean is interfaced with sea-ice, passive tracer, and biogeochemical models and is driven by the CORE2vb dataset which is on based on a 43-year air-sea flux climatology, providing 6-hourly fluxes of heat, freshwater, wind stress and radiation (Large and Yeager, 2004).

NEMO allows for a wide range of applications including an option for two-way nesting. Within the global coarse resolution model is a high resolution 1/10 degree nest, INALT01 (Durgadoo, 2013), which simultaneously receives and updates the boundary conditions from the global model. Its domain is the South Atlantic basin and greater Agulhas region (70°W – 70°E, 8°N – 50°S). Large water mass properties are preserved using NEMO's two-way nesting and conservative mapping schemes (Biastoch, 2008). Data are outputted in 5-day averages over 28 years. The large high resolution geographical nest contributes to a more realistic simulation, leading to a reasonable AMOC of 18 Sv and a good representation of the mean circulation and mesoscale variability of the Agulhas Region (Durgadoo et al., 2013).
2.2 Lagrangian Particles:

ARIANE (Blanke, 1997) is an offline Lagrangian diagnostic dedicated to Lagrangian analysis using numerical model output. It calculates the 3-dimensional streamfunction to advect particles along streamlines and assigns a finite amount of mass flux to each particle in order to quantify the flow. Quantitative results are achieved by assigning a maximum transport for any given particle and seeding the number of particles that satisfy the equation:

\[ \frac{T_i}{N_i^2} \leq T_0, \]

where \( T_i \) is the incoming transport associated with each grid cell, \( N_i \) is the total number of seeded particles, and \( T_0 \) is the prescribed maximum transport per particle set by the user, taken as 0.1 Sv for our experiment. Hence, particles are distributed along the seeding section according to the velocity at each location and depth. Particles follow the calculated three-dimensional streamlines arriving at a new location every 5 days while conserving their transports. The volume transport carried by the Lagrangian particles is estimated across specified boundaries by summing the number of particles crossing the boundary.

In our study, we release \( O(10^5) \) particles continuously over 28 years within the density and salinity range consistent with simulated NADW over the region (41.29 < \( \sigma_T \) < 41.41, S > 34.8). Particles were released within the South Atlantic north of the Cape Basin, within the NADW slope current (Figure 4) at 32°S, as observed by Arhan et. al. (2003). The particles were advected for 196 years by recycling the 28-yr velocity output.
to ensure complete circulation throughout the region. Boundaries for quantification of volume transport calculations were set along the WOCE A_12 line to the west to capture recirculation within the South Atlantic, along the subtropical front at 44°S, and within the Indian Ocean at 35°E to the east and 31°S to the north (Figure 7). The northern boundary was split into two sections to separate particles that flowed in the narrow Agulhas Undercurrent from those that were advected farther offshore. Preliminary results showed little recirculation of particles that passed 35°E, hence this represents a flow of NADW into the Indian Ocean. To ensure a reasonable seeding location, a backward experiment was run using ARIANE to determine the most likely source of NADW within the Indian Ocean. Particles were released in the Indian ocean at 35°E and advected backward in time.

2.3 Lagrangian Visualization

In order to highlight Lagrangian pathways we create a map which shows the probability that a float will occupy a given grid cell. Probability is calculated by summing up each instance a particle is in a particular cell and normalizing by the total number of particle positions. The result is a probability map showing the most populous grid cells in the region, taking into account every position at every time step, including repetitions. Only particles that eventually reach 35°E are counted, in order to highlight the dominant pathways of NADW into the Indian Ocean.
2.4 Eddy Identification

Eddies are identified by calculating the Eulerian Okubo-Weiss parameter (Okubo, 1970, Weiss, 1991) over the NADW layer. The Okubo-Weiss parameter (OW) is derived purely from an Eulerian framework and compares strain tensors to relative vorticity. The OW parameter is given as:

\[ W = s_n^2 + s_s^2 - \omega^2 \]

where \( s_n = \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} \), \( s_s = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \), and \( \omega = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \).

\( s_n \) and \( s_s \) are the normal and shear components of strain while \( \omega \) is the relative vorticity of the flow. The identification of an eddy using \( W \) is highly sensitive to the threshold value \( W_o \), defined as:

\[ W_o = 0.2a, \]

where \( a \) is the spatial standard deviation of \( W \) with the same vorticity sign as the eddy core, as defined by previous works (Isern-Fontanet, 2004). Eddy cores can be defined by comparing \( W \) to \( W_o \). When \( W > W_o \), strain is greater than vorticity and deformation dominates the flow field. When \( W < -W_o \), vorticity dominates and the OW parameter gives a positive identification of an eddy. When \( |W| < W_o \), background flow dominates, characterized by small positive and negative values of \( W \).
Chapter 3  Model Verification

To investigate the model's ability to represent NADW properties around South Africa realistically, we first compare model salinities with observations. Hydrographic data taken between the Cape of Good Hope and 40°S from the WOCE A_12 hydrographic line and INALT01 show good agreement (Figure 2). The high salinity tongue indicative of the NADW slope current along the west coast of South Africa is well simulated in the model, along with its depth and width (Figure 2b). A T-S diagram taken along the same line shows NADW as an elbow of high salinity (Figure 2a). Model salinities are spread towards too fresh in the NADW layer (green shading), but otherwise represent the observations well.

Next we look at the general pattern in the spreading of NADW throughout the regions comparing the model with data from the World Ocean Atlas. We compare salinity at 3000 m mapped onto a of 1°x1° grid from the 28-year mean INALT01 output and the observation (Figure 3). In the model the salinity signal degrades far more quickly as NADW flows around South Africa. This pronounced erosion of the salinity maximum in the model may be a result of diapycnal mixing with the overlying Antarctic Intermediate Water (AAIW) which is both too fresh and cool in the model (Figure 2a). Despite faster erosion of the signal, NADW spreads in qualitatively the same way in the model, with a southeastward flowing slope current in the South Atlantic feeding a rather broad eastward flow into the Indian Ocean.

A comparison of the strength of the Agulhas Undercurrent (Beal, 2009) between the model and observations shows that the model captures the strength of the AUC below
1800 m (the NADW layer). Mean transports from the model along the Agulhas Undercurrent Experiment mooring line within the NADW layer is 1.9 Sv (28-year mean) which is close to the observed 2.3 +/- 3.0 Sv. However, simulated transports within the slope current are significantly larger than observations suggest. The simulated transport of the slope current is 17.4 Sv, whereas Arhan et. al. (2003) estimated the observed transport to be 11 +/- 4 Sv.

Figure 2: (a) T-S diagram comparing observations from WOCE A_12 (black) and INALT01 (red). Black contours are $\sigma_3$ isopycnals. Highlighted in green is the NADW density range for the Good Hope line. (b) Salinity section taken along WOCE A_12. Black contours are INALT01 data averaged over 28 years overlaid. Highlighted contour is the NADW high salinity signature of 34.8.
Figure 3: Mean salinity at 3000 m from the objectively analyzed distributions from the 2005 World Ocean Atlas (top) and the 28-year averaged INALT01 data (bottom). Data is gridded into 1°x1° boxes and averaged. Black contours are the 3000m isobath.
Chapter 4  Results

4.1  Eulerian Analysis

We begin our analysis of the model by considering the effect of deep eddy kinetic energy (EKE) on water property signals within the NADW layer, where EKE is defined as the sum of the variances of the zonal and meridional velocity components. Figure 4 shows the contour of EKE averaged over the NADW layer superposed on the salinity maximum below the thermocline, obtained by averaging model results over the 28-year record.

Figure 4: Map of maximum salinity below the thermocline. Contours of eddy kinetic energy (EKE) averaged over the NADW layer are in black. Contour intervals are 0.005 to 0.035 m$^2$ s$^{-1}$. Grey shading depicts bathymetry of 3000 m or less. All data is averaged over the 28-year record.

contour of EKE averaged over the NADW layer superposed on the salinity maximum below the thermocline, obtained by averaging model results over the 28-year record. We
first note the strong gradient of the high salinity signal of NADW within the Cape Basin rapidly decreases towards the tip of the Agulhas Bank. At the tip of South Africa, pools of homogeneous salinity and weaker gradients are suggestive of strong recirculation and mixing south of Africa. This pool of homogenized salinity coincides with an area of high mean EKE below the Agulhas retroflection and suggests a role for eddy mixing.

Vertical salinity distributions from three sections around South Africa are shown in Figure 5 to see the changes in the NADW signal as it moves out of the Atlantic basin. The first section is taken within the slope current and shows a wide, thick, tongue of high salinity (34.8) with its core at 2700 m. The second section, taken at the mean position of the retroflection (20°E), shows the squashing and thinning of the high salinity tongue beneath the retroflection. Here, the core of the deep water layer deepens to 3000 m. The third section taken within the Indian Ocean, at 35°E, shows the erosion and southward expansion of the high salinity signal at the Mozambique Ridge from 34.8 to 34.72. Again, it appears that processes beneath the retroflection and around the Agulhas Plateau contribute to the degradation of the high salinity core by enhancing mixing with surrounding waters.

Potential Vorticity (PV) maps (Figure 6a) are valuable for diagnosing circulation, giving an indication of flow paths at depth, assuming particles follow isolines of PV and
Figure 5: Salinity sections taken at the particle release line (Top Right), beneath the retroflection at 20E (Bottom Left), and at 35 E (Bottom Right). Salinity contour of 34.77 is highlighted in each panel, white for the panels that include the NADW salinity core, and black for the panel that lacks the NADW core. Locations of salinity sections are detailed in the top left panel.
favor recirculation in regions of homogeneous PV (Gary et al., 2004). We first calculate PV from 28-year mean data, neglecting the relative vorticity term:

\[ PV = \frac{f_\rho}{\rho} \frac{\partial \rho}{\partial z} \quad (1) \]

where \( f \) is the Coriolis force and \( \rho \) is potential density averaged over the NADW layer (\( 41.29 < \sigma_3 < 41.41 \)). The influence of the surface flow field, depicted by mean sea surface height, on deep PV is clear. A pool of homogeneous PV north, east, and west of the Agulhas Plateau as well as pool of high PV beneath the retroflection and north of the subtropical front (Figure 6a). PV is largely dominated by planetary vorticity and topography in the northeast; however, in the Agulhas Current region, PV reflects the deformation of the NADW layer beneath the retroflection and the Agulhas ring corridor. Meridionally sloping isolines of PV in the Cape Basin are due to the eddy thickness flux of Agulhas rings which drive southeastward flow of NADW at depth (van Sebille et al., 2012).

Inclusion of the relative vorticity term reveals the importance of deep water relative vorticity to the NADW layer. We find that stirring of NADW by barotropic currents associated with the Agulhas retroflection opens up a southward path for waters from the Cape Basin (Figure 6b). The calculation becomes:

\[ PV = \left( \frac{f + \zeta}{\rho} \right) \frac{\partial \rho}{\partial z} \quad (2) \]

where \( \zeta \) is relative vorticity, \( \zeta = \frac{dv}{dx} - \frac{du}{dy} \). The pool of high PV below the Agulhas retroflection to the east shrinks, illustrating the importance of relative vorticity through
Figure 6: (a) Top: Map of Potential Vorticity (PV) of the NADW layer neglecting the relative vorticity term, see eq. (1). Solid black lines are positive mean SSH contours, dashed lines are negative. SSH contours highlight the mean surface flow of the Agulhas Current. (b) Bottom: PV map including the relative vorticity term, see eq. (2). Velocity vectors are overlaid. Data used in both maps were averaged over the NADW layer for 28 years. The 3000 m isobath is represented by a thin black line.
barotropic influence of the surface flow. Relative vorticity input over the region and beneath the retroflection is further illustrated by mean velocity vectors averaged over the NADW layer (Figure 6b). NADW entering the region follows PV isolines, favoring a southward trajectory confined to the slope current at around 35°S. Strong recirculations occur beneath regions of ring shedding and particularly the retroflection, where NADW is spun up by the surface flow. The area beneath the retroflection is also where the highest velocities in the region are found, as supported by Cronin et. al. (2013) who show that currents exceeding 0.2 m/s occur more than 50% of the time below the retroflection.

The addition of relative vorticity into the deep layer balances the thinning of the layer, enabling a direct pathway beneath the retroflection for particles to flow south and then eastward around the southern flank of the Agulhas Plateau. The topography of the Agulhas Plateau block eastward advection and a PV barrier hinders northward advection. This is contrary to Arhan et. al (2004) who proposed a path around the north of the plateau, underneath the ARC. In fact, circulation of NADW around the rim of the Plateau is anticyclonic in the mean, opposing the surface flow of the ARC on its western flank.

4.2 Lagrangian Analysis

With a Lagrangian experiment we can diagnose transport pathways and determine the destination of a particle. Figure 7 shows 200 randomly chosen floats from our 196-year integration that represent the flow field in the region. The trajectories are most dense under the retroflection and Agulhas ring corridor, directly affected by high surface EKE (Figure 1). In these regions they heavily recirculate, with many exiting the region to the
west to remain in the Atlantic. After long residency below the retroflection, the floats that continue into the Indian Ocean must navigate the Agulhas Plateau, most flowing to the south. We see many floats that tend to circulate anticyclonically around the entire Plateau before continuing eastward. Heavy recirculations around the seeding line can be due to the propagation of passing Agulhas rings (van Sebille et al., 2012). This eddy corridor is highly energetic and has been shown to carry a strong barotropic signal so that it can both directly steer and squash the deep water layer, thereby inputting potential vorticity (van Aken (2003) and van Sebille (2012)). The surface flow also strongly influences NADW in the retroflection region. However, this area differs from the region around the seeding line due to the persistence of relatively stationary anticyclonic spin of the retroflection.

Four floats were colored to highlight the complex nonlinear behavior of the flow regime (Figure 7). Three out of the four (all except yellow) colored floats re-cross the seeding line multiple times before eventually entering the Indian Ocean. The floats recirculate extensively throughout the Cape Basin just south of the seeding line (green and blue trajectory) or beneath the retroflection (yellow and blue). The magenta trajectory follows a pathway around the tip of Africa into the Agulhas Undercurrent, before circulating back westward where it gets caught in the anticyclonic spin beneath the retroflection. The yellow trajectory takes a more direct path southeastward and makes some cyclonic loops beneath the retroflection before continuing south of the plateau. All the colored floats eventually cross 35°E, favoring a route south of the Agulhas Plateau, although the green trajectory circulates around it before exiting the domain. The bluefloat
is particularly interesting due to its extraordinarily trajectory throughout the south east Atlantic and under the retroflection.

Figure 7: Spaghetti plot of 200 random trajectories after a 196-year integration. Colored trajectories are to highlight general features of the flow. Solid red line is the particle release line. Dashed blue lines are boundaries where mass transport is calculated. Dashed black contours are 3000 m isobath.

To quantify probable pathways of water particles from our release line into the Indian Ocean, we create a probability map (Figure 8), by calculating the total number of float occupations per grid cell, including repeated cells. To reduce computation time, only 20% of the 38,405 floats are considered. Of these, we select the 4,771 that reach 35°E.
Figure 8: Two dimensional probability plot computed from 4,771 trajectories over a period of 196 years that reached 35E. Black lines depict PV contours averaged over the NADW layer. Color shading is normalized particle density on a log scale. The particle release line is indicated as a solid black line between 10-15 E. Bathymetry less than 3000 m is shaded in grey.

The average float residency time is 30 years, with a minimum of 2.5 years and a maximum of 194 years. The resulting map shows the highest probability around the seeding line and the slope current, as expected (Figure 8). High population is also shown to the west of the seeding line, extending as far west as 10°E. The high float population to the west corroborates the results from Figure 7, where there are indications of heavy
recirculations in this area, highlighted by the blue float. There is strong evidence a well
defined slope slope current along the western edge of the African continent as well as an
indication of a favorite pathway within the Agulhas Undercurrent. Surprisingly, the float
density beneath the retroflection is relatively light, despite heavy trajectory density
(Figure 7) and mean recirculation (Figure 6b) as seen earlier. In this case low float density
must be attributed to higher velocities, and ultimately less residence time per cell. There
are indications of higher float density immediately to the southwest and southeast of the
Agulhas Plateau, which again supports a southward route into the Indian Ocean. There is
lighter density of floats directly south of the Plateau but, again, that can be attributed to
larger velocities in the region (Figure 6b). Overall, the probability map emphasizes
regions of high float density, highlighting favorite pathways in the region. Floats favor the
area south and west of the seeding line, as well as beneath the retroflection. There is also
evidence of a pathway south the Agulhas Plateau and within the Agulhas
Undercurrent (Beal et. al., 2006).

More insight is gained by quantifying the export NADW out of the Atlantic. First,
we estimate the transport into the Indian Ocean using the number of particles that crossed
35°E at any point during its trajectory. Of the 7,681 floats considered, 62% ended in the
Indian Ocean. Assuming each float is represents the same transport, we can estimate the
transport into the Indian Ocean as 62% of the seeded 17 Sv, or 10.5 Sv, which is in good
agreement found by Arhan et. al. (2003) of 11 +/- 4 Sv. Next we calculate the mass
transport across specific boundaries, as shown by the blue lines in Figure 7. Using
ARIANE, we calculate the transports across each boundary, counting only the first crossings of each simulated float (Figure 9).

Figure 9: Schematic of mass transport across the boundaries specified in 7a. Total transport and percent of the total are given. The bold black arrow indicates the amount of transport of NADW that traveled directly into the Indian Ocean, without recirculating across other boundaries. The bold blue arrow indicates the amount of total transport into the Indian Ocean, accounting for recirculations.

A total of 17 Sv were seeded along the red section, reflecting the transport of the NADW slope current along the western boundary of the African continent. Direct pathways of NADW into the Indian Ocean were only 5.3%. Most particles that cross into the Indian Ocean tend to recirculate across the seeding line and to the west before continuing their
trajectory eastward, as highlighted by the blue float in Figure 7. Of the 5.3% of the particles that made it directly into the Indian Ocean, only 0.25 Sv (1.5%) were carried in the Agulhas Undercurrent while a majority entered under the Agulhas Return Current, after passing south of the Agulhas Plateau as shown earlier.

4.3 Eddy Generation

Eddies are identified using the Eulerian Okubo-Weiss (OW) parameter, a favorable method that has been applied to both satellite data and numerical model output with considerable success (Isern-Fontanet et al, 2004; Chelton, 2007). It aims to identify regions in the flow where rotation dominates over strain and defines these areas as eddy centers. To locate regions of eddy genesis and their correlation with surface flow, we use a 20-year movie of OW averaged over the NADW layer (41.29 < \( \sigma_3 \) < 41.41) overlaid with SSH contours. The movie is comprised of monthly-averaged maps plotted every 15 days. Calculation of the OW parameter is detailed in the Materials/Methods section and a color map is chosen to highlight only the eddy cores (W<-0.2a) in red.

The OW parameter has been shown to overestimate the number of eddies resulting in noisy fields (Souza, 2011), but despite this bias we see little eddying activity in the deep water layer. However, we are able to identify three areas of persistent deep eddy generation: cyclone generation at the tip of the Agulhas Bank, dipole generation in the area beneath the retroflection, and anticyclonic generation directly east of the Agulhas Plateau at 39°S (Figure 10). These results support our findings from both the Lagrangian
experiment and Eulerian analysis, where strong velocities and recirculations in these three regions were found. We find that deep cyclogenesis is strongly linked to surface features but do not have a seasonal signal and in most cases, eddies cannot be coherently tracked. They spin up and down in place. The exception is in the lee of the Agulhas Bank where cyclones propagate WSW on only three occasions during the 20-yr study. We note that we also calculated the Lagrangian spin parameter to analyze eddying motions using our particle trajectories (Veneziani, 2005). Spin is based on trajectory curvature, which is related to the ratio of spin to EKE following a fluid particle. However, we found no relationship between EKE and the spin parameter, indicating the regions propensity for non-linear trajectories, but without coherent eddies.

The cyclonic feature in the lee of the Agulhas Bank represents NADW eddies that are the longest lived in the region, surviving up to 105 days before dissipating. We find that 18 eddies spin up at this location during the 20-year study, always beneath a cyclone at the surface. Only three of those eddies last more than 45 days, while a majority dissipate after only one time step. These deep water eddies rarely propagate; however, there are a few instances where these cyclones propagate west southwest, breaking up when they encounter the line of sea mounts to the northwest. The average size of these cyclones is less than 100km in diameter, while the longest lived eddie grew to more than 250 km.
Figure 10: Snap-shot taken from 20-yr movie. Map of Okubo-Weiss parameter (OW) in colors, overlaid with SSH contours in black for monthly-averaged data from July 1980. Blue boxes highlight areas of eddy generation. OW is averaged over the NADW layer. Note the reversed colorbar, blue = positive, red = negative.

The eddies that spin up beneath the retroflection are generally smaller than the cyclones that form in the lee of the Agulhas Bank. Unexpectedly, these eddies are both cyclonic and anticyclonic and tend to spin up in concert as a dipole. Beneath the retroflection, anticyclone formation is very persistent, this the only region to show an eddy in the 28-year mean. Most time steps show at least one small (less than 60km diameter) anticyclone which fluctuates rapidly from one time step to the next. 12 large eddies, greater than 150 km in diameter, spin up beneath the retroflection, while eddies
greater than 200km were generated 5 times in the 20 year study. These large eddies do not last much longer than the smaller eddies, with most dissipating within 30 days. The anticyclonic generation is accompanied by a cyclonic generation just to the east. These cyclones form and grow in concert with the anticyclones just to the west, in an area beneath a meander in the Agulhas Return Current at the surface. This meander is present in all time steps and can oscillate north-south or grow in amplitude to extend northward as far as 38°S. 10 times in the 20 year study this meander influences cyclone generation. These eddies are 100 km in diameter and last 30 days. 2 of these eddies propagated northwest but did not live longer than 45 days.

Less persistent and smaller in size, the anticyclones that spin up directly east of the Agulhas Plateau at 39°S rarely exceed 70km in diameter. They also have a short life, lasting no more than 30 days, with most only lasting one time step. 8 eddies with diameter greater than 100 km spin up in the region, but do not last longer than 30 days.

We look more closely into the connection of deep water eddy generation and surface activity using 28-year point correlation maps (Figure 11) between NADW relative vorticity averaged over the spin up areas and surface relative vorticity across our domain. The maps reveal high correlation ($\rho = 0.7$) between surface vorticity and deep water vorticity of the same sign in all three regions of eddy generation. Composites of sea surface height (SSH), shown as black contours in figure 11, show the shape of the sea surface during events of strong NADW relative vorticity in spin-up regions. Hence, we see how the position and strength of the Agulhas system at the surface influences NADW
Cyclongenesis in the lee of the Agulhas Bank occurs by a flow detachment process, when the Agulhas Current separates from the slope and extends anomalously northwestward (Figure 11a) similar to the process reported by Penven et. al. (2001). This cyclonic spin barotropically influences the NADW layer. Spin up of the deep water is also aided by the motion of the NADW that enters the region from the northwest. This southeastward-flowing NADW reaches the region of cyclonic motion, following lines of constant PV. When it reaches the area at the tip of the Agulhas Bank, it is deflected by the high PV barrier and turns abruptly westward resulting in additional cyclonic movement. In the mean (Figure 7a), the northwestward extension of the current remains close to 40°S, while during strong NADW vorticity events it extends as far northward as 35°S. This hints at a possible relation to ring shedding events.

Instabilities of the Agulhas retroflection create a dipole in the NADW layer just upstream of the Agulhas Plateau which creates deep water rotation that includes both southward and northward trajectories. The continuation of NADW's northward trajectory is blocked by the tongue of high PV to the north which redirects NADW southward along the western edge of the Agulhas Plateau (Figure 7b). The resulting southward trajectory is reinforced by the cyclonic spin at the surface created by a meander in the current above.
Figure 11: Colors are a 28-year correlation of NADW relative vorticity averaged over specific areas of eddy generation with surface relative vorticity. Top left is in the lee of the Agulhas current, top right is beneath the retroflection, bottom is east of the Agulhas Plateau. Overlaid in black contours are SSH composites.

During strong NADW vorticity events beneath the retroflection, we see that the meander west of the Plateau has anomalously large amplitude compared to the mean case. This
meridional broadening of the retroflection is also associated with a large meander to the east that extends much further north than the mean state. It is worth noting that this meander is a product of the model and not seen in 20-year mean altimetry data (not shown). Hence, in the real ocean we might expect the generation of an anticyclone, rather than a dipole, beneath the retroflection.

Eddy formation to the east of the Agulhas Plateau is related to the Agulhas Return Current, which meanders around the Agulhas Plateau (Figure 6a), turning southward on its eastern edge. In the peak of the meander, anticyclonic motion is induced, sometimes throughout the water column spinning up the NADW layer. Strong vorticity events to the east of the Plateau occur when the Agulhas Return Current flows over the northern-most edge of the Plateau. This northward extension over the Plateau creates an abrupt change in direction when the current takes on a strong north-south orientation as it flows along the eastern edge of the Plateau. Overall, deep cyclogenesis is related to instabilities of the strong surface flow and could be termed 'benthic storms' (Cronin et. al., 2012).
Chapter 5 Conclusion

We have shown that the model did well to represent and conserve large water mass properties, simulating the salinity maximum associated with NADW in a manner consistent with observations. However, the model exhibits stronger erosion of the salinity maximum as it moves from the Atlantic to the Indian Ocean, likely due to diapycnal mixing with AAIW or CDW above and below, which are too fresh in the model. The high salinity signature of NADW erodes and deepens as it moved into the Indian Ocean and high levels of EKE in the NADW layer south and west of South Africa suggests rigorous mixing beneath the Agulhas retroflection. Eulerian analysis reveals that particles of NADW are subject to steering by PV. The thinning of the NADW layer is compensated by the persistent anticyclonic spin of the retroflection, opening up a pathway for circulation beneath the retroflection and passage into the Indian Ocean via a southern route around the Agulhas Plateau.

Lagrangian analysis reveals heavy recirculations around the seeding line and beneath the retroflection, where the highly barotropic Agulhas rings propagate and form. The pathways into the Indian Ocean are not direct, with particles often traveling as far as 5°W before entering the Indian Ocean, favoring a pathway south of the Agulhas Plateau and often within the Agulhas Undercurrent. We find that only 5% of the 17 Sv that were seeded within the slope current made it directly into the Indian Ocean; however, the total number of floats that eventually crossed 35°E carried a transport of about 10.5 Sv, close to the transport reported by Arhan et. al. (2003). The rest of the transport recirculates within the South Atlantic, with only 4% crossing into the Southern Ocean.
Three NADW eddy generation sites were identified: Cyclone generation at the tip of the Agulhas Bank, dipole generation beneath the retroflection, and anticyclone generation to the east of the Agulhas Plateau. These deep water eddies are correlated with surface vorticity events of the same sign which suggest it is the shape of the current at the surface that induces deep cyclogensis. The northwestward extension of the Agulhas current generates cyclones at the tip of the Agulhas Bank, while meridional broadening of the retroflection is responsible for the dipole that spins up beneath it. This broadening is also associated with a meander to the east of the retroflection, however the meander is a product of the model and was not seen in mean altimetry data. Eddy generation to the east of the Agulhas Plateau results from a strongly meridional orientation of the current along the plateau's eastern edge.

The deep eddies that form throughout the region are persistent but they rarely advect. The area beneath the retroflection produces the most eddies but as with the other regions, these eddies dissipate quickly. There are a few instances where cyclones from the tip of the Agulhas Bank advect southwestward, but in general, the stationary nature of these deep water eddies do not support the idea that deep eddies are important to the interocean exchange of NADW as proposed by Casal et. al.

In summary, the trajectory of NADW into the Indian Ocean is strongly influenced by the turbulent flow of the Agulhas Current, steered by the input of PV into the deep water layer. The variability of the Agulhas Current also spins up eddies in the NADW layer through instability processes, resulting in three definitive regions of cyclogensis.
References


