From the Agulhas to the South Atlantic: Measuring Inter-ocean Fluxes

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ABSTRACT

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The Agulhas Retroflection transfers heat, salt and vorticity from the Indian Ocean to the South Atlantic. The transfer is accomplished by discrete meso-scale features and by the advection of a water column of mixed Atlantic and Indian Ocean origins. The objectives of this thesis are to measure the strength of the Agulhas-South Atlantic (ASA) exchange and to develop a generalized method for the measurement of mass and thermohaline fluxes.

First, ASA mass and energy fluxes are estimated by using sea surface height (SSH) anomalies from satellite altimetry to monitor Agulhas eddies, a significant component of ASA transport. $\sim$20 eddies are tracked from SSH during 1986 - 1989. Six eddies/year are observed entering the South Atlantic; when combined with information from hydrography this suggests minimum annual ASA mass and energy fluxes of $O(5\times10^6)$ m^3s^{-1} and $O(10^{17})$ J. Next, the accuracy of altimetric tide models, critical to measurements of ASA fluxes using altimetry, is evaluated in the Agulhas region by a comparison with *in situ* bottom pressure (BP). The CSR 3.0 model accounts for 98.5% - 99.4% of the variance in bottom pressure at four locations, with maximum discrepancies between model and *in situ* tides reaching 6.5 cm.

In Enhanced Thermohaline Transport Analysis (ETTA), developed herein, vertically averaged thermohaline transport coefficients are parameterized as functions of SSH and acoustic travel time (τ). These quantities, which can be directly measured, are then used as proxies to determine mass and thermohaline fluxes from time-series of altimetric SSH and τ from inverted echo sounder moorings. Using ETTA, the 1992 - 1993 baroclinic-barotropic ASA fluxes through a moored array at 30°S (2°E - 17°E) are estimated at $O(14.5 \times 10^6)$ m^3s^{-1}, $O(15 \times 10^{20})$ J and $O(83 \times 10^{12})$ kg salt per annum. Meso-scale eddies accomplish at least 18% of the transport. Lastly, ETTA is combined with the Gravest Empirical Mode (GEM) technique to create continuous parameterizations of temperature and salinity fields with pressure, τ and SSH. Thus τ and SSH become proxies for vertically resolved thermohaline profiles. With data from the Caribbean region, GEM-ETTA is shown to have the potential to resolve inter-ocean mass and thermohaline fluxes with time and depth.

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Chapter 1

Introduction

While much has been written about the inter-ocean transport of water masses, (see Schmitz [1995] for a review) mass and thermohaline fluxes and their connection to global climate are still the subject of controversy. Inter-ocean transport controls the equalization of properties between ocean basins. The slower or more constricted the transport the more the water masses on either side may potentially differ. At a number of locations, inter-ocean transport variability and the contrast in water mass properties can be large, with a potentially significant effect on the global climate. The Agulhas Retroflection region is a location of strong and variable inter-ocean transport, where warm, salt-enriched waters from the South Indian ocean enter the South Atlantic (e.g., [Gordon, 1986]). As demonstrated by Gordon [1985] the Agulhas Retroflection region as part of the warm water route is the only possible source for waters warm and saline enough to maintain the observed balance in the Atlantic thermocline, a balance which preconditions it for the formation of North Atlantic Deep water (NADW).

Conceptually, much of the circulation in the subtropical South Atlantic ocean (Fig. 2-4) forms a typical ocean gyre: the Brazil Current is the western boundary current [Stramma and Peterson, 1989], the South Atlantic Current serves as the poleward limb of the gyre [Stramma and Peterson, 1990], while the Benguela [Garzoli and Gordon, 1996, Stramma and Peterson, 1989] and the South Equatorial Currents [Stramma, 1991] close the loop as the returning eastern boundary current. This straightforward schematic breaks down, however, when one considers the influence of the Agulhas Current on this system, for the Agulhas is the western boundary current of the South Indian subtropical gyre. As noted by [Gordon, 1985] this makes the South Atlantic subtropical gyre unique in that it receives heat at its poleward extremity. Leakage from the Agulhas current, in the form of incomplete retroflection [Gordon, 1985], eddies (also referred to as rings in the literature) and filaments [Lutjeharms and Gordon, 1987, Lutjeharms and Stockton, 1987, Luteharms and van Ballegooyen, 1988, Shannon et al., 1990, Duncombe Rae, 1991, Valentine et al., 1993, Byrne et al., 1995] serve as a source of heat and salt to the South Atlantic subtropical gyre [Gordon, 1986, Gordon et al., 1992, van Ballegooyen et al., 1994, Duncombe Rae et al., 1996], changing its thermohaline balance from what might otherwise be a colder, fresher Atlantic [Gordon, 1985, 1986, Gordon et al., 1987, 1992]. The Agulhas Retroflection region is also acknowledged to be the most energetically variable of all inter-ocean connections [Zlotnicki et al., 1989]. The Retroflection is found to meander over more than fifteen degrees of longitude [Luteharms and van Ballegooyen, 1988] with two common positions, 13°E and 19°E [Harris el al., 1978] and with current speeds of up to 119 cm s^{-1} [Gründlingh, 1978].

From time to time, the Retroflection is occluded, pinching off an eddy (e.g, Olson and Evans [1986], Lutjeharms and Gordon [1987], Luteharms and van Ballegooyen [1988]). Each eddy traps at it center a remnant of modified Indian Ocean water [Gordon, 1985, Olson et al., 1992]. Feron et al. [1992] determined from a harmonic and principal component analysis of Geosat altimeter data that eddies form in this manner at quasi-periodic intervals of approximately 56 days (a frequency of 6.5 per year). Luteharms and van Ballegooyen [1988] estimated eddy-shedding events to occur on average 39 days apart. Byrne et al. [1995] and Witter and Gordon [1999] have shown that Agulhas eddies are capable of drifting far into the interior of the South Atlantic subtropical gyre. Individual eddy paths are highly idiosyncratic [van Ballegooyen et al., 1994, Byrne et al., 1995, Witter and Gordon, 1999] and not all Agulhas eddies move northwestward; some drift southward toward the subtropical convergence zone [Lutjeharms and Valentine, 1988] meaning that the number of eddies formed is not necessarily a good estimate of the number contributing to inter-ocean transport from the Indian to the South Atlantic.

The observed characteristics of Agulhas eddies vary widely. Duncombe Rae's, [1991] survey of hydrographic data indicated eddy sizes from 180 km - 300 km in diameter, while van Ballegooyen et al. [1994] recorded diameters from 190 km - 320 km in a single year. Lutjeharm's and Gordon's, [1987] *in situ* survey of one very recently formed Agulhas eddy indicated it to be about 375 km in diameter. Eddy drift (translation) speeds can be anywhere from nearly stationary Byrne et al. [1995] to 9.5 cm s^{-1} [Olson and Evans, 1986, Shannon et al., 1990, van Ballegooyen et al., 1994, Byrne et al., 1995]. Agulhas eddies are subject to intense evaporation and cooling at the surface, increasing their salt content relative to their surroundings [Gordon et al., 1987, Olson et al., 1992].

These losses, estimated at up to 485 W m^{-2} and 1.2 cm day^{-1} by van Ballegooyen et al. [1994] and 610 W m^{-2} and 15 kg s^{-1} by Olson et al. [1992], both enrich the salt content and mask the sea surface temperature signal of an Agulhas eddy before it is very far from the source (e.g., Luteharms and van Ballegooyen [1988], McDonagh and Heywood [1999]). Individual eddies have been estimated to provide as much as 13.10x10^{12} kg salt and 2.6x10^{20} J to the South Atlantic [van Ballegooyen et al., 1994]. With estimates of 4-9 of them being formed and/or entering the South Atlantic each year [Luteharms and van Ballegooyen, 1988, Feron et al., 1992, Byrne et al., 1995, Witter and Gordon, 1999], Agulhas eddies have the potential to significantly influence the thermohaline balance of the central and intermediate waters of the subtropical South Atlantic. The inter-ocean thermohaline exchange is not the only one of significance carried out by Agulhas eddies. Olson and Evans [1986] estimate that one Agulhas eddy brought into the South Atlantic the equivalent of 7% of the total annual wind energy input. Their large available potential energy (APE) may also affect the energy balance of the gyre.

Less well documented but also significant are the other Agulhas transports – leakage inshore of the Retroflection, estimated at 20x10^6 m^3 s^{-1} [Gordon, 1985] and other intrusions (e.g., filaments) of warm water spun off the Retroflection (see Lutjeharms and Gordon [1987], Lutjeharms and Stockton [1987], Shannon et al. [1990]). Recent work by Lutjeharms and Cooper [1996] indicates that Agulhas filaments are a frequent occurrence and may contribute O(5% - 10%) of the interbasin salt flux estimated to be achieved by Agulhas eddies.

More recently, the transport of another anomalous water mass through the Agulhas region has been observed. This transport comes in the form of anticyclonic rings. Smaller than typical Agulhas eddies, these rings were at first posited to be of Brazil Current origin [Smythe-Wright et al., 1996, Duncombe Rae et al., 1996] and more recently have been thought to be Subantarctic Mode Water (SAMW) formed in the Indian Ocean near 60°E which has become entrained into the Agulhas Current [McDonagh and Heywood, 1999]. These rings contain an intense winter or southern mode water of between 12 °C and 13 °C, ~35.35 psu found in extensive (> 400 m) layers, here referred to as "13 °C stad" water.

It is evident from the many studies referred to above that no ship-based program will adequately sample the region and no satellite will resolve the thermohaline transports. Yet the energy and intensity of the Agulhas-South Atlantic (ASA) exchange make obtaining a measure of the Agulhas input into the South Atlantic a critical task; this transport lies at the center of some of the most significant and difficult questions pertaining to variability and control in the global thermohaline circulation. For while eddies are transient phenomena, their cumulative effect on the ocean is not. The large area over which Agulhas exports might occur, the absence of a sea surface temperature signal, the variability in heat and salt content of intruding Agulhas waters, and the irregularity of the phenomena in time and space make such a task problematic.

In the following chapters, two methods of monitoring inter-ocean transport are examined, both of which use combinations of altimetry and hydrography. In Chapter 2 historic hydrography and GEOSAT altimetry are used to obtain a measure of the ASA mass and energy fluxes that are carried by Agulhas eddies. This is done by tracking Agulhas eddies using maps of anomaly sea surface height (SSH) from the GEOSAT altimeter and modeling their volumetric decay over time.

Chapter 3 contains a comparison of *in situ* measurements of ocean tides in the Agulhas region with the CSR 3.0 global tide model used to correct TOPEX/POSEIDON (T/P) sea surface height (SSH$_{T/P}$). As barotropic tides in this area have a peak-to-trough amplitude of ∼2 m while meso-scale features like Agulhas eddies might reach 80 cm, the ability to correct accurately for the tides is essential.

In Chapter 4, a new method of monitoring inter-ocean transport called Enhanced Thermohaline Transport Analysis (ETTA) is developed which uses hydrographic information in conjunction with anomaly acoustic travel time ($\delta\tau$) and SSH. First water column type (a combination of associated water masses) is parameterized as a function of $\delta\tau$ and the baroclinic component of SSH from hydrography. Water column type is also used to determine vertically averaged mass, heat and salt transport coefficients. Mass and thermohaline transports are then estimated from time-series of altimetric SSH and τ (from inverted echo sounder moorings). Regional hydrography and IES data from the Benguela Sources and Transports (BEST) project and T/P altimetry are used to test the ETTA method. An examination of the water mass properties in the BEST hydrography reveals that much of the water which is clearly of subtropical South Atlantic origin has been modified by a significant amount of mixing with water from the Agulhas current, with approximately 38%±4% of the Atlantic subtropical water having been replaced. The transport of three water column types (Agulhas, 13 °C stad, and modified Atlantic) through the BEST mooring array is estimated using ETTA.

In Chapter 5, the initial implementation of ETTA is improved by combining it with the “Gravest Empirical Mode” (GEM) technique developed by Watts el al. [1998] and Meinen and Watts [1999]. In GEM-ETTA, pressure, $\delta\tau$ and SSH from historic hydrography are used to parameterize temperature and salinity fields, creating three-dimensional look-up tables where $\delta\tau$ and SSH become proxies for vertically resolved thermohaline profiles. Thus time-series of $\delta\tau$ from (IES moorings) and SSH (from altimetry) can provide estimates of mass and thermohaline fluxes resolved with time, depth and distance. With hydrographic data from the Caribbean region and simulated time-series of $\delta\tau$ and SSH$_{T/P}$, it is shown that GEM-ETTA has the potential to resolve time-varying inter-ocean mass and thermohaline transports with accuracy and detail.

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Chapter 2

Agulhas Eddies: A Synoptic View Using Geosat ERM Data

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Abstract

Warm core rings formed in the Agulhas Retroflection transfer water from the Indian Ocean to the South Atlantic. In an attempt to measure the strength of this exchange, a combination of satellite altimeter and hydrographic data are used to examine Agulhas eddy paths and decay rates in the South Atlantic. Because the surface dynamic height of a warm-core eddy is higher than surrounding waters, the rings are visible in satellite altimeter measurements. Over 20 Agulhas eddies have been tracked from maps of anomaly sea surface height (SSH) derived from the Geosat Exact Repeat Mission (ERM) dataset. The correlation (r^2) of dynamic height referenced to 2000 dbar and anomaly SSH for one coincidentally sampled area is 97% within an Agulhas eddy, dropping to a fraction of that outside of it, indicating that the SSH anomaly signal is a reliable measure for strong features like Agulhas eddies.

The sizes and distribution of the Agulhas eddies in the ERM record compare favorably with those in recent hydrographic records from the area. Individual eddy tracks from the ERM show the influence of topography, with slowed translation over areas of steep relief. The eddies tracked take a generally WNW course across the South Atlantic, propelled by the mean flow and internal dynamics. While propagating westward, Agulhas eddies decay in amplitude with an e-folding distance of O(1700 km - 3000 km) along-track. As they approach the western boundary of the South Atlantic, at 40°W, the eddies have O(10%) of their initial amplitude remaining.

This study finds the residence time of an Agulhas eddy in the South Atlantic to be 3-4 years. On average, we see six eddies per year formed by the Retroflection which enter the South Atlantic. The 20 eddies tracked therefore represent 50% to 60% of the population that would have been extant during the ERM. We find Agulhas eddies to contribute a minimum of $5 \times 10^6 \mathrm{m}^3\mathrm{s}^{-1}$ to the Indian - South Atlantic water mass transfer, with a corresponding energy flux on the order of 10^{17} Joules.

2.1 Introduction: The Importance of Agulhas Eddies

There has been much discussion in the current literature of the possible sources for South Atlantic thermocline waters and their ramifications. Gordon [1986, 1985] suggests the likelihood of an strong contribution from the Indian ocean, a conclusion supported by recent model studies (e.g. Matano and Philander [1993], Semtner and Chervin [1992, 1988]). The source waters have varying properties, but are referred to collectively as South Indian Ocean Central Water (SICW). Their overall effect is to make the South Atlantic relatively warmer and saltier than do other sources [Gordon et al., 1992, Olson et al., 1992] such as water from the South Atlantic current. Global heat and salinity budgets require an Indian-South Atlantic volume transport of 15 Sv. [Gordon, 1985] where 1 Sv. $\equiv 1 \times 10^6 \mathrm{m}^3\mathrm{s}^{-1}$.

The Agulhas Retroflection produces warm rings which drift into the South Atlantic [van Ballegooyen et al., 1994, Gordon and Haxby, 1990, Lutjeharms and van Ballegooyen, 1988]. These large eddies transfer heat, salt and energy from the Indian ocean into the South Atlantic subtropical gyre [Olson, 1991, Olson and Evans, 1986, van Ballegooyen et al., 1994]. The core of Agulhas eddies carries SICW, which has been modified through evaporation and convection until it is anomalously salty with respect to its origin. A distinct component of this water is a layer originally between 17°C and 18°C, the South Indian Subtropical Mode Water (SIMW). Olson et al. [1992] find the SIMW modified by -0.8°C and $+0.02$ psu within an Agulhas eddy core; dispersed in the subtropical gyre, this water will create a warmer, saltier South Atlantic thermocline. van Ballegooyen et al. [1994] measure heat and salt anomalies of 0.73×10^{20}J-2.36×10^{20}J and 4.35×10^{12}kg-13.10×10^{12}kg for four Agulhas eddies found within 600km from their source in the Retroflection.

Measurements of the Indian Ocean-South Atlantic flux are difficult because of the similarity between the water mass properties of South Atlantic water and those of water leaving the Retroflection [Gordon, 1985, Valentine et al., 1993]. The flux must be calculated before the water is mixed into the South Atlantic thermocline.

We use Geosat altimeter data to examine the volume and energy content of the flux contained within Agulhas eddies. Hydrographic data are used as supporting evidence (see Appendix A). The eddies are detectable in altimetry because the thick layer of SIMW at the eddy center causes an elevation in sea level. As noted by van Ballegooyen et al. [1994], the nature and magnitude of the eddy flux will depend upon the rate at which Agulhas eddies enter the South Atlantic, the extent of their thermohaline anomaly, their subsequent motion and rate of decay, and the processes by which their properties are transferred to surrounding waters. We look at the magnitude of the flux, the number of eddies, their motion in the South Atlantic, and their rate of decay by addressing the following questions:

1. How many Agulhas eddies enter the South Atlantic each year?
2. What path do they take and how long do they survive?
3. How do the energy level and altimeter signal of the eddies change over time?
4. How much mass and energy do they contribute to the Indian Ocean/South Atlantic flux?

2.2 Geosat ERM (Exact Repeat Mission) data

The Geosat ERM lasted from November 1986 to 9 August 1989, $\sim$ 1037 days (2.8 yr). The cycle time for the satellite was 17.05 days, during which it covered 488 ground tracks, 244 descending and 244 ascending. Sixty-one cycles were completed during the mission, but the last two are virtually useless for our purposes, due to extensive data dropout and excessive noise. The initial measurements are every 0.1s, or 0.67 km along-track. Geosat Geophysical Data Records ("GDR", [Cheney et al., 1987]) provide 1s sea surface height (SSH) estimates, 6.7km apart along the satellite track. Each datum is the mean of ten 0.1s measurements by the altimeter. The rms difference between these 10 measurements and a linear least squares fit to them is provided as an error estimate Cheney et al. [1987]. We reject measurements with an associated error $>$ 10cm.

Our data processing scheme follows that of Gordon and Haxby [1990] with the addition of a bandpass filter. In brief, each of the 61 ERM cycles is treated as independent. The data are interpolated to regular points along the groundtrack using an along-track cubic spline. Data gaps are left unfilled. The average slope at every point for which there are 20 or more estimates is calculated. The slopes are integrated to heights, adjusted to minimize the difference between the individual measurements and the time-average profile. This produces a mean SSH field for the dataset. This profile is subtracted from the data of each cycle, resulting in a complete record of residual or anomaly SSH, η, for the world ocean every 17 days.

Orbit error, the difference between an average of each 3 consecutive orbits and the mean over the entire ERM, is modeled and removed from the central orbit of the 3, using a long-wavelength sinusoidal model with a wavelength of 20,000km. We smooth these data with a 5-point running average, leaving us with 512 measurements along each of 488 tracks. Finally, the data along each track are processed using a bandpass filter in the spatial domain with an unattenuated wavelength between 5000 km and 200 km and cutoffs at 100 km and 20,000 km. These filter wavelengths were found by experiment to be the most satisfactory ones for the purposes of identifying Agulhas eddies, which have a characteristic length scale (1/2 wavelength) of O(200 km - 300 km) [Duncombe Rae, 1991, van Ballegooyen et al., 1994].

Binned into $1° \times 1°$ boxes, and averaged over time, the South Atlantic variability in η in the processed data is 3.7cm (Fig. 2-1) for the quiet, mid-gyre area 35°W - 10°E, 35°S - 20°S, which is just above the expected post-processing instrument noise level of 2.2cm (based on Sailor and LeShack [1987]). This variability is comparable to the 3.8cm level reported by Zlotnicki et al. [1989] for the equatorial north Atlantic obtained with a 2500 km second order polynomial orbit correction. However, the bandpass filter, found necessary for efficient eddy tracking, significantly reduces the variability of the Agulhas Retroflection region in our dataset. The maximum variability there is 24.5cm for a 2° square, in contrast with Zlotnicki et al.'s [1989] value of 44cm. The possible effects this reduction will have on our energy calculations will be dealt with in later sections.

The appearance of an Agulhas eddy in the processed data is shown in Figure 2-2. For tracking purposes the processed data from one ERM are interpolated onto a grid and contoured; a least squares planar fit is further removed (Fig. 2-3). From such an interpolation, the position and amplitude of an eddy can be estimated, even if the satellite did not cross the eddy center. Eddy size cannot be determined to within acceptable limits using this method.

For some ocean features, the removal of the 2.8-year mean SSH field can remove a significant portion of its signature on the ocean surface if the feature is not sufficiently variable over the mission time scale [Horton et al., 1992, Kelly, 1991, Kelly and Gille, 1990]. Since Agulhas eddies are transient features that typically translate several km/day, the removal of mean SSH from the data record is not likely to erase the eddy signal. It may however be attenuated, especially if the eddies take a common path in the South Atlantic. We will discuss the effects of this attenuation in Section 2.4.

Horton et al. [1992] show that strong eddies can be reliably identified by satellite altimetry, even in a region of dynamic activity where the SSH variance is high, and van Ballegooyen et al. [1994] have proven the case for the Agulhas Retroflection in particular. In areas of the South Atlantic that are dynamically quiet, Agulhas eddies are even more prominent. As a result, Agulhas eddies can be tracked relatively consistently across the South Atlantic subtropical gyre as long as the data loss remains small.

Instrument and geophysical noise can occur at the wavelengths and amplitudes expected of an eddy. The short-wavelength variability of the atmospheric water vapor signal is inadequately modeled by the corrections applied to the data (FNOC model). An anomalously high water vapor signal produces a low in η which can be of the same horizontal and vertical scales as an Agulhas eddy Monaldo [1990]. It is conceivable that a low water vapor signal might in turn appear identical to the signal of an Agulhas eddy in the data record. The long lifespan of an Agulhas eddy, however, should greatly reduce the likelihood of a misidentification occurring, as water vapor events ought to be much more ephemeral. In practice, the extremely long temporal persistence of Agulhas eddies combined with spatial transience make them ideal candidates for tracking with SSH anomaly data.

2.3 Eddy Paths

More than 20 Agulhas eddies have been tracked from maps like Figure 2-3. The approximate center of the eddy is determined from the map; a succession of such locations determines our estimate of the eddy's path. The eddy-tracking reveals both the rate of Agulhas eddies entering the South Atlantic as their eventual dispersion across the subtropical gyre, moving towards the higher steric heights of the central gyre (see 2-4 4). Some Agulhas eddies have been followed in the ERM record to further than 5000 km from the Retroflection. At the observed translation speeds, (averaging 4.3 cm s^{-1}, $\sigma = 1.8$), and assuming a relatively straight path, this distance indicates the eddy has reached an age of 3-4 years.

Agulhas eddies in the central South Atlantic move westward (Fig. 2-5). The majority of the eddies tracked were first identified around 1°E, outside of the high variability zone of the Retroflection. Tracking proceeded both backwards (east) and forwards (west) in time to obtain the longest record possible of their evolution. A few eddies were followed from a point midway across the South Atlantic ($\sim$ 15°W). For most of the tracks in Figures 2-4 and 2-5, the termination point lies near the end of the satellite lifetime, where data dropout made further tracking difficult.

We have counted 16-18 eddies shed into the South Atlantic during the ERM period; the last two identifications are less certain because of problems with the satellite near the end of its lifetime and the fact that these eddies could not be tracked over a long enough time period to make the identification definitive. The frequency of Agulhas eddies entering the South Atlantic, then, by our estimate averages 6 per year. Feron et al. [1992] using a statistical method with the ERM data to identify eddy shedding variability patterns, found 18 ±2 Agulhas eddies shed during the ERM period. The possible discrepancy, 16-18 vs. 18±2, may be the result of some Agulhas eddies returning eastward and not entering into the region of our study.

Several of the Agulhas eddies that appear in this study have been tracked and sampled in the near-Retroflection area by van Ballegooyen et al. [1994]. The tracking methods of this study is similar to ours and the correspondence is good between features identified in the areas where the studies overlap. This provides a measure of reliability for the tracking method, although we did not have the difficulty in tracking the eddies outside of the immediate area of the Retroflection which they report.

Eddy motion is a combination of self-generated velocity and advection by the surrounding mean flow. Quite visible in Figure 2-4 is the confinement of the eddy tracks to the 28°S-40°S latitudinal band, between the extension of the Benguela current to the north and the South Atlantic Subtropical Front to the south. It is possible this distribution results from limitations in the resolution of the data rather than the influence of large-scale dynamics. However, it is clear from their tracks that the eddies do not simply follow the mean flow, contoured at 500 dbar from Reid [1989] (Fig. 2-4).

Not all Agulhas eddies necessarily take this northwestward route into the South Atlantic; Lutjeharms and Valentine [1988] describe a probable Agulhas eddy south of the Retroflection at 41.5°S and 15°E (perhaps being swept eastward by the Agulhas Return Current). In terms of inter-ocean transport, however, only Agulhas eddies that travel westward from the Retroflection are of interest. Our observations indicate that once westward of 10°E, the eddies' entry into the South Atlantic is assured.

A few of the features that pass our criteria for eddies have been found in the mid-South Atlantic(15°W-30°W, $\sim$ 35°S), outside of where Agulhas eddies have been identified in other studies and somewhat apart from the other eddies tracked in this study (Fig. 2-5). These features are long-lived ($>$ 1 year), of an amplitude 3-4cm above the local noise level, even with the smoothed data, and are observed to translate in a westerly direction at speeds (4-6 cm s^{-1}) like those of other Agulhas eddies (this study, van Ballegooyen et al. [1994], Duncombe Rae [1991], Olson and Evans [1986]).

These features are located in an area where the hydrographic data record is very sparse [Lutjeharms et al., 1992]; so that the fact no Agulhas eddy has been previously observed in the region is not a sufficient criterion to reject the tentative identification. While there is a possibility that these features may be recirculated Brazil Eddies, at this point we include them into our Agulhas Eddy census until further investigation is completed with the more precise TOPEX/Poseidon altimeter data.

Arguably, individual tracks (Fig. 2-5) deviate from the general WNW course in the vicinity of the topographic features like the Rio Grande rise (at 30°S, 35°W) and the Walvis Ridge (stretching from 20°S, 10°E to 40°S, 15°W). Smith and O'Brien [1983] have shown that for an anticyclonic, baroclinic eddy in an ocean otherwise at rest, an eastward component of translation velocity is expected to develop on encountering a meridional ridge. The net velocity is a combination of this self-induced translation and advection by large-scale currents. Eddies tracked with Geosat exhibit a noticeable decrease in their total velocity when crossing the Walvis ridge, even at the 17-day sampling resolution (Fig. 2-6). Drifter data [Olson and Evans, 1986] provide corroborative evidence of topographic steering and slowed translation over steep topography. Eddies moving over steep/shallow ($D < 4000$ m) bathymetry averaged 2.9 km/day ($N = 179$, $\sigma = 1.4$), while those crossing smooth/deep ($D > 4000$ m) terrain averaged 4.1 km/day ($N = 652$, $\sigma = 1.2$). It is possible that the eddies' immediate response to topography is much more complex than a simple deceleration, but the categorization is appropriately detailed for the temporal and spatial resolution of our data.

Agulhas eddies appear more likely to cross the Walvis ridge at gaps in the topographic profile. A plot of the distribution of eddy tracks projected against the ridge topography illuminates this behavior (Fig. 2-7). The eddy center locations have been binned by 0.5° latitude. The distribution of eddies crossing the ridge shows a negative correlation ($r = -0.57$) with topographic height. However, it cannot be concluded from these data if the uneven distribution is a result of the eddies' own interaction with topography, or because of the steering effect of a deep current passing through the ridge gap.

Due to the geography of the Retroflection, Agulhas eddies once formed are free to propagate across the entire South Atlantic basin. This circumstance allows them a lifetime and path length substantially longer than most other warm core rings, e.g. Gulf Stream rings, which have been documented to last a year or two Richardson