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Indian-Atlantic interocean exchange: Dynamics, estimation and impact

W. P. M. de Ruijter,[1] A. Biastoch,[2] S. S. Drijfhout,[3] J. R. E. Lutjeharms,[4] R. P. Matano,[5] T. Pichevin,[6] P. J. van Leeuwen,[1] and W. Weijer[1]

Abstract. Interocean exchange of heat and salt around South Africa is thought to be a key link in the maintenance of the global overturning circulation of the ocean. It takes place at the Agulhas Retroflection, largely by the intermittent shedding of enormous rings that penetrate into the South Atlantic Ocean. This makes it extremely hard to estimate the inter ocean fluxes. Estimates of direct Agulhas leakage from hydrographic and tracer data range between 2 and 10 Sv (1 Sv = 10^6 m^3s^{-1}). The average ring shedding frequency, determined from satellite information, is approximately six rings per year. Their associated interocean volume transport is between 0.5 and 1.5 Sv per ring. A number of Agulhas rings have been observed to cross the South Atlantic. They decay exponentially to less than half their initial size (measured by their available potential energy) within 1000 km from the shedding region. Consequently, most of their properties mix into the surroundings of the Benguela region, probably feeding directly into the upper (warm) limb of the global thermohaline circulation. The most recent observations suggest that in the present situation Agulhas water and Antarctic Intermediate Water are about equally important sources for the Benguela Current. Variations in the strength of these may lead to anomalous stratification and stability of the Atlantic at decadal and longer timescales. Modeling studies suggest that the Indian-Atlantic interocean exchange is strongly related to the structure of the wind field over the South Indian Ocean. This leads in the mean to a subtropical supergyre wrapping around the subtropical gyres of the South Indian and Atlantic Oceans. However, local dynamical processes in the highly nonlinear regime around South Africa play a crucial role in inhibiting the connection between the two oceans. The regional bottom topography also seems to play an important role in locking the Agulhas Currents' retroflection. State-of-the-art global and regional "eddy-permitting" models show a reasonably realistic representation of the mean Agulhas system; but the mesoscale variability and the local geometrical and topographic features that determine largely the interocean fluxes still need considerable improvement. In this article we present a review of the above mentioned aspects of the interocean exchange around South Africa: the estimation of the fluxes into the South Atlantic from different types of observations, our present level of understanding of the exchanges dynamics and forcing, its representation in state-of-the-art models, and, finally, the impact of the Indian-Atlantic fluxes on regional and global scale both within the Atlantic Ocean and in interaction with the overlying atmosphere.

1. Introduction

The South Atlantic is a wide open basin. Its thermohaline structure is determined largely in other areas of the World Ocean. Water masses are continuously passing through, modified locally by air-sea buoyancy fluxes and mixing, and steered by topographic ridges, wind and thermohaline forcing. To study the stratification of the Atlantic and its overturning circulation, one needs to know precisely the water mass characteristics and fluxes at the open boundaries with the surrounding oceans. The present South Atlantic plays a unique role in the climate system in that it transports heat toward and across the equator. All other oceans have poleward heat transports, as one would expect intuitively.

On its anticyclonic path through the warm and evaporative oceanic region, the subtropical gyre of the South Atlantic, driven by the meridional alternation of trades and west winds, picks up excess heat and gives up fresh water to the atmosphere. Consequently, the Brazil Current exports relatively warm and salty water poleward and much cooler and fresher water flows with the northward branch of the South Atlantic Current and of the Benguela Current in the eastern part of the gyre. So the wind-driven circulation acts according to intuition: it transports heat and salt poleward in the upper layers [e.g., *Rahmstorff,* 1996; *Weijer et al.,* 1999]. The equatorward heat transport of the South Atlantic is therefore established by the global scale thermohaline overturning

[1] Institute for Marine and Atmospheric Research, Utrecht University, Utrecht, The Netherlands.
[2] Institut für Meereskunde Kiel, Kiel, Germany.
[3] KNMI, De Bilt, Netherlands.
[4] Department of Oceanography, University of Cape Town, Cape Town, South Africa.
[5] College of Oceanic & Atmospheric Sciences, Oregon State University, Corvallis.
[6] Service Hydrographique et Oceanographique de la Marine, Brest, France.

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circulation, involving the deep southward flow of North Atlantic Deep Water (NADW) and a compensating northward mixture of warm salty thermocline waters and cooler, fresher intermediate water masses [e.g., *Gordon et al.*, 1992]. These compensating water masses originate partly in the South Atlantic itself, as a result of water mass transformation processes in e.g. the Brazil-Malvinas confluence area and along the subtropical convergence *zone* [*Peterson and Stramma*, 1991; *Piola and Gordon*, 1989]; but a large part of the intermediate and thermocline water masses originates in the Pacific and Indian Oceans, entering the South Atlantic via the Drake Passage and around the tip of South Africa, respectively. Part of the Antarctic Intermediate Water flows eastward around 40°S and leaves the South Atlantic to flow into the southern Indian Ocean [e.g., *Boebel et al.*, 1998; *Warner and Weiss*, 1992]. There it branches and mixes partly into the recirculation regime of the South West Indian Ocean to reenter the South Atlantic via Agulhas Current leakage, embedded in the major Agulhas rings that frequently pinch off from the Agulhas Retroflection loop [e.g., *Boebel et al.*, 1998; *Feron et al.*, 1992; *Gordon et al.*, 1992].

The wind-driven gyres of the South Indian and Atlantic Oceans are connected in the Agulhas retroflection area, south of Africa. The southern boundary of the joint subtropical 'super gyre' of these two oceans is largely determined by the position of the zero wind stress curl [*de Ruijter*, 1982], roughly at the Subtropical Convergence Zone (±45°S). From the above it should be clear that this interocean connection is also a critical link in the global thermohaline circulation. This is supported by paleoceanographic studies [e.g. see *Berger and Wefer*, 1996] that indicate that a specific species of foraminifera became extinct in the South Atlantic during the last glacial period, probably owing to a decrease of the upper ocean's temperatures. Their more recent reappearance might be due to reopening of the Agulhas connection. There seems to have been a common start-up of NADW formation, a reappearance of the species in the southeastern Atlantic and a poleward expansion of the wind-driven gyres some 10,000 years ago. Other paleodata [*Howard and Prell*, 1992] indicate large shifts of the major southern ocean fronts on glacial-interglacial timescales. This suggests that during the last glacial period the position of the Subtropical Convergence zone (i.e., the southern boundary of the subtropical gyres) shifted several degrees northward, effectively shutting off the Indian to Atlantic Ocean connection. If, indeed, this Agulhas leakage is one of the controlling factors of the Atlantic Ocean stratification and thermohaline overturning circulation, then shutting it off during glacial times might have been a strong positive feedback mechanism to reduced NADW formation.

The probable importance of the interocean exchange around South Africa for regional and global climate shifts has triggered many observational, theoretical, and modeling studies in recent years. In this review we attempt to summarize the main outcome of these studies and try to extract from it a coherent conceptual picture of the physics of the interocean exchange, its estimation and its subsequent impact on a regional and global scale. Starting from a regional description of the Agulhas Current retroflection area (section 2), we summarize the estimates of the interocean fluxes from in situ observations, satellite altimetry, thermal infrared data, inverse modeling, and data assimilation. The questions addressed in this paper are straightforward: How much exchange is estimated from the observations and how does it vary (section 3)? What is the impact and fate of Agulhas leakage (section 4), that is what are the paths and decay of retroflection rings and leakage? What contribution do they make to the global thermohaline circulation and climate fluctuations? What role do they play in the basin scale dynamics and water mass structure of the subtropical gyre of the South Atlantic, and what is the regional impact on e.g. the Benguela ecosystem and climate over South Africa? In section 5 the following issues are treated: What drives the interocean exchange? How do the wind-driven and thermohaline far fields connect to the strongly nonlinear local processes? Finally, how well has the Indian-Atlantic Ocean exchange been modeled in view of the insights gained from the observational and dynamical studies?

The different sections of this review will demonstrate that the answers to the above questions are far from straightforward. Many issues are still open and await further dedicated observations and modeling studies.

2. Agulhas Current System

The Agulhas Current constitutes the western boundary current of the wind driven, anticyclonic gyre of the South Indian Ocean (Figure 1). As such it derives its water masses, as well as its mass and heat flux characteristics, from this broader ocean region. Conceivably, any interannual and decadal variabilities in the processes that take place over the expanse of this subtropical gyre could therefore influence the characteristics of the Agulhas Current [*Lutjeharms and De Ruijter*, 1996; *Reason et al.*, 1996a,b]. This is particularly relevant because the subtropical circulation in the South Indian Ocean displays some unusual features for a gyre of its kind. It is inherent to the dynamics of such gyres that they should exhibit some degree of nonsymmetry, with the flow concentrated toward the western side, but in the South Indian Ocean this concentration is extreme. This leads to the formation of a distinct southwest Indian Ocean subgyre that extends to about 60°E [*Stramma and Lutjeharms*, 1997] and from which the Agulhas Current draws part of its constituent water masses. An even tighter recirculation cell appears to be concentrated around 30°E, 37°S stretching only from 25°E to 35°E and from 35°S to 40°S [*Feron et al.*, 1998] (Figure 2).

The Agulhas Current itself can be considered to consist of a northern and a southern part with dissimilar characteristics. The northern part starts approximately at the border between Mozambique and South Africa and stretches along the eastern seaboard of South Africa, down to the latitude of Port Elizabeth. Its trajectory follows the continental shelf break quite closely, and, unlike any other western boundary current, the trajectory is quite stable [*Gründlingh*, 1983]. The strong shelf slope most probably constrains the growth of lateral meanders in the current [*De Ruijter et al.*, 1999]. In general, the current is at least 2000 m deep and carries a mass transport of about 65 Sv (1 Sv = 10^6 $m^3.s^{-1}$) that increases downstream [*Jacobs and Georgi*, 1977; *Gründlingh*, 1980; *Gordon et al.*, 1987; *Beal and Bryden*, 1997].

Farther downstream, the Agulhas Current, by contrast, flows past the broad continental shelf south of Africa, the Agulhas Bank, where the more gently inclined shelf slope allows it to meander in the manner of most western boundary currents. As a result many shear edge features common to such a current, namely eddies and plumes, are formed [*Lutjeharms et al.*, 1989]. These warm plumes move onto the Agulhas Bank to contribute to the very strong vertical stratification in

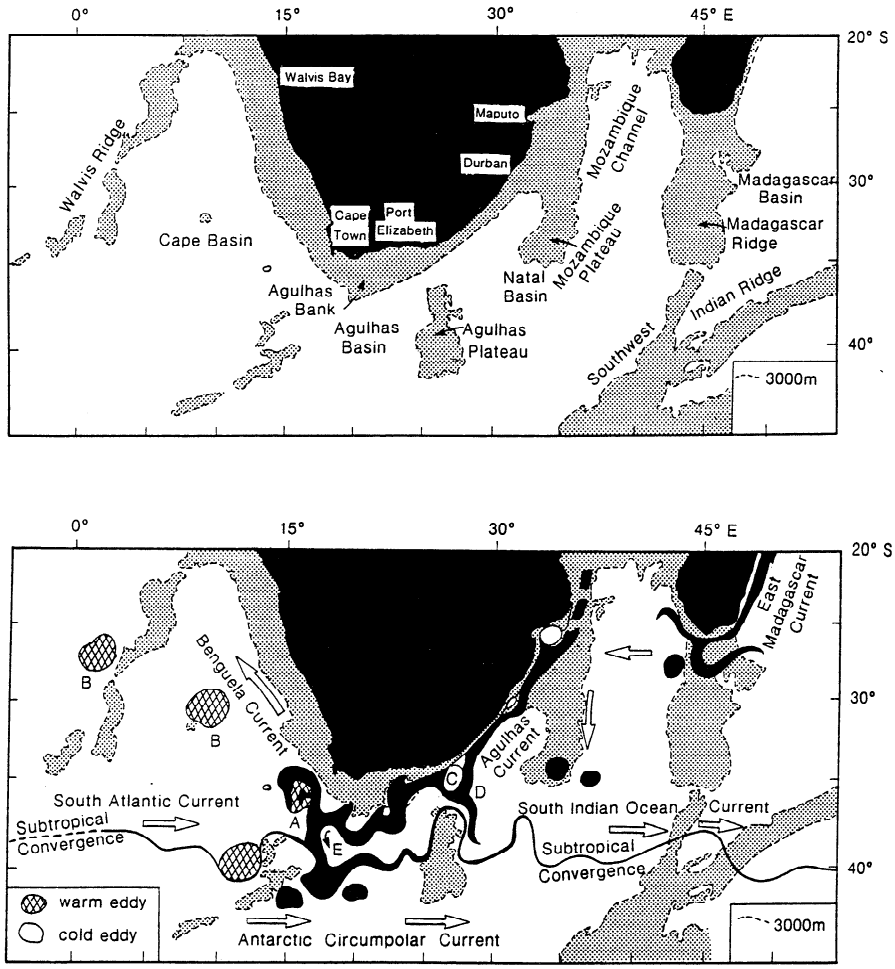

Figure 1. Main mesoscale and larger features of circulation that form part of the greater Agulhas Current system, superimposed on the bottom topography. Abbreviations are defined as follows: A, Agulhas ring, recently shed from the Agulhas retroflection, being encircled by an Agulhas filament; E, Agulhas retroflection; B, Agulhas rings drifting off into the South Atlantic; C, cyclonic eddy forming part of a well-developed Natal Pulse on the Agulhas Current preciding an upstream retroflection at the Agulhas Plateau, the shallow region south of Africa; and D upstream retroflection. The large-scale, general background circulations of the subtropical gyres are shown by open arrows; the shaded areas indicate where the bottom is shallower than 3000 m [after *Lutjeharms*, 1996].

temperature over the shelf, or they drift into the adjacent South Atlantic as Agulhas filaments [*Lutjeharms and Cooper*, 1996] (see Figure 1). When the meandering southern Agulhas Current reaches a latitude of about 37°S it passes the southern tip of the African continental shelf and moves southwestward as a free jet into the South Atlantic. Shortly after, it retroflects in a dramatic way and subsequently carries the bulk of its waters eastward (Figure 1), back into the Indian Ocean. Recently, an Agulhas Undercurrent has been measured directly near Port Edward (31°S) [*Beal and Bryden*, 1997]. Its core is centered

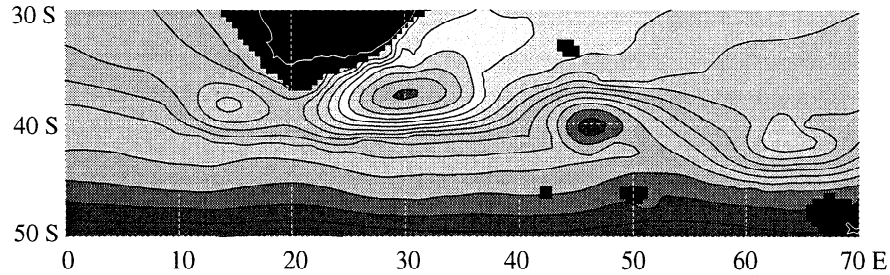

Figure 2. Mean ocean circulation around the southern tip of the African continent, determined from 3 years of Geosat satellite altimeter observations [*Feron et al.*, 1998]. It clearly reveals a tight recirculation cell in the Agulhas Current retroflection region and a mean connection of the upper layer circulation of the South Indian and Atlantic Oceans.

around a depth of 1200 m and hugs the continental slope directly below the core of the Agulhas Current. It transports about 6 Sv north-eastward at maximum speeds of 30 cm s^{-1}. Origin and forcing of this undercurrent are still largely unknown.

2.1. Agulhas Sources

The manner in which the Agulhas Current is supplied from different sources could be a major factor in establishing how variations in its flow come about. Contrary to classical portrayals [e.g., *Möller*, 1929] the sources of the Agulhas are not dominated by the Mozambique Current [*Saetre and Da Silva*, 1984], or by the East Madagascar Current [*Lutjeharms*, 1988] but by the recirculation in the above mentioned South West Indian Ocean subgyre [*Harris*, 1972; *Stramma and Lutjeharms*, 1997]. Of the total volume flux of the upper 1,000 m of the Agulhas Current, (~ 65 Sv) about 20 Sv comes from east of Madagascar, but not necessarily directly from the East Madagascar Current itself [see *Stramma and Lutjeharms*, 1997 a discussion of these fluxes]. In fact, it has been surmised (by *Lutjeharms*, [1988]) that water from this western boundary current may reach the Agulhas Current only intermittently and then predominantly in the form of mesoscale rings and filaments (Figure 1). Estimates of the contribution through the Mozambique Channel range between 5 Sv [*Stramma and Lutjeharms*, 1997] and 21 Sv [*Di Marco et al.*, 1998]. South of Africa, the transport of the Agulhas Current was estimated at 95 Sv by *Gordon et al.* [1987], which is much larger than the transport upstream at about 32°S. From that they concluded the existence of a tight recirculation in which the Agulhas transport grows significantly. This was confirmed from an analysis of satellite altimeter data [*Feron*, 1994; *Feron et al.*, 1998] (Figure 2).

The surface layers of the Agulhas Current contain Indian Tropical Surface Water (potential temperature above 20° C, salinity between 34.7 and 35.3 practical salinity units (psu) as well as South Indian Subtropical surface Water (potential temperatures above 17°C, salinity about 35.6 parts per thousand (ppt) [*Valentine et al.*, 1993]). The former is characterised by water with a slightly lower salinity owing to the excess of precipitation over evaporation in the tropical latitudes of the Indian Ocean. The tropical surface water is found as a recognisable strip on the inshore side of the Agulhas Current proper and is believed to be contributed to the flow via the Mozambique Channel [*Gordon et al.*, 1987]. The South Indian Ocean Subtropical Surface Water is found in the Agulhas Current as a subsurface salinity maximum. These two components of the surface water form only 3 % of the total volume of the current but make up a substantial part of its heat content. The volume of the Central Water is, by contrast, roughly 13% and in the Agulhas Current the Southwest Indian Ocean Central Water has a temperature range of 8°-15° C and salinities between 34.60 and 35.50 ppt. At larger depth the Antarctic Intermediate Water moves with the Agulhas Current [*Shannon and Hunter*, 1988]. It has a temperature range of 2°-10°C and salinities between 33.8 and 34.8 parts per thousand. So far little is known about the way the deeper waters interact or are exchanged at the retroflection [*Gordon et al.*, 1992; *Fine*, 1993]. The pathways of the deeper waters south of Africa are currently the subject of a large international Lagrangian float experiment, the Kap der guten Hoffnung Experimente (KAPEX), which, hopefully, will give some answers to how these waters are exchanged between the two ocean basins [*Boebel et al.*, 1998].

The hydrographic characteristics of waters that constitute the Agulhas Current are of particular importance when estimates are made of the water exchanges that occur south of Africa. In the cauldron of different water masses at the Agulhas retroflection, water of subantarctic origin is drawn northward across the Subtropical Convergence as part of the ring spawning process [*Lutjeharms and van Ballegooyen*, 1988b]. This process can inject large amounts of cold, low-salinity water into the southeastern Atlantic [*Shannon et al.*, 1989, 1990] not only extending the spectrum of characteristic water masses present but also, through mixing, significantly complicating the interpretations of the surface waters.

2.2. Meanders, Eddies, and Rings

The fields of mesoscale variability of the Agulhas system from ships' drift [*Wyrtki et al.*, 1976], from satellite infrared imagery [*Lutjeharms and van Ballegooyen*, 1984] and from satellite *altimetry* [*Cheney et al.*, 1983; *Wakker et al.*, 1990; *Feron et al.*, 1998] show a remarkable resemblance (Figure 3). The highest level of variability is found associated with the termination of the Agulhas Current south of Africa. From there an extensive tongue of increased variability extends eastward, along the Subtropical Convergence and the trajectory of the Agulhas Return Current (Figure 3).

An unusual feature of the flow of the northern Agulhas Current is the intermittent occurrence of a solitary meander in the trajectory of the current, called the Natal Pulse [*Lutjeharms and Roberts*, 1988]. This meander moves downstream at a rather steady rate of 20 km day^{-1} and grows in lateral dimensions on its journey. In cases of meanders with extreme amplitudes, early retroflection of the current even seems to result [*Lutjeharms and van Ballegooyen*, 1988a] (see Figure 1). The depths to which these early retroflections in the northern Agulhas Current extend are not known. Whether they lead to enhanced or reduced leakage of Indian Ocean water into the South Atlantic is not known yet either.

The Agulhas retroflection region exhibits rapidly and markedly changing flow patterns. In general, the sequence of events starts with the Agulhas Current prograding farther and farther westward until the retroflection loop occludes and a separate Agulhas ring is abstricted [*Gordon et al.*, 1987; *Lutjeharms and Van Ballegooyen*, 1988b] (see Figure 4). The frequency of these ring shedding occurrences is irregular [*Feron et al.*, 1992; *Goñi et al.*, 1997] and seems indeterminate, but recent analyses of a variety of satellite data have indicated that most Natal Pulses that reach the Agulhas retroflection precede a ring shedding event [*van Leeuwen et al.*, 1999]. This suggests that these meanders might play a role in the timing of the ring-shedding process.

Theoretical considerations indicate that the shelf-slope configuration alongside the northern Agulhas Current inhibits instabilities in the current trajectory, except at the Natal Bight north of Durban, at about 30°S [*de Ruijter et al.*, 1999] (see Figure 1). Here the weaker gradient in the continental slope allows instabilities intermittently leading to the initiation of a pulse. The required intensification in the Agulhas Current transport may be due to inherent fluctuations in the recirculation gyre or to the entrapment of deep-sea eddies onto the outer border of the current. Such eddies have been observed in the region [e.g., *Gründlingh*, 1988; 1995] (see Figure 1),

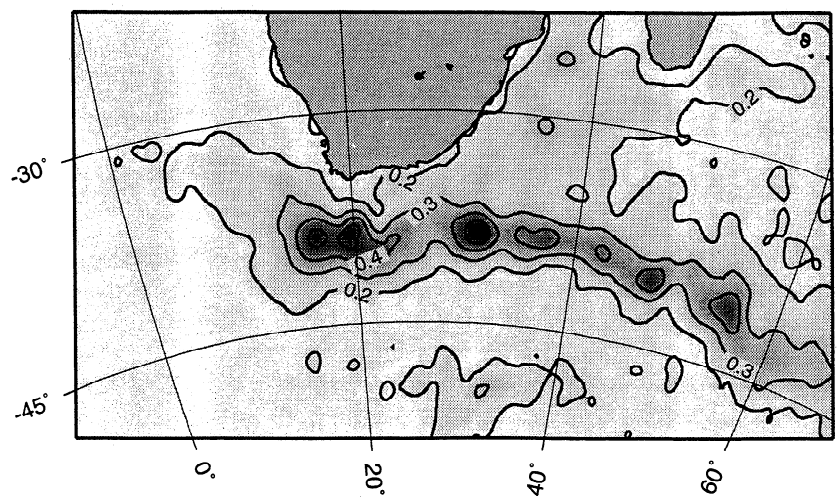

Figure 3. Standard deviation of sea surface height anomalies of the ocean area around South Africa. Numbers shown are rms values from TOPEX/POSEIDON altimeter data over the period November 1992 November 1996 (courtesy of M. Schouten, Institute for Marine and Atmospheric Research Utrecht).

and they have also been observed to interact with the seaward border of the current [*Gründlingh et al.*, 1991]. Some of these eddies have been traced to east of Madagascar [e.g., *Lutjeharms*, 1988a]. Their presence contributes substantially to the high mesoscale variability in the southwest Indian Ocean (Figure 3).

The warm-core Agulhas rings are the most energetic ones shed from a western boundary current in the world ocean [e.g., *Olson and Evans*, 1986; *Goni et al.*, 1997]. They have been observed with diameters as large as 500 km [*Arhan et al.*, this issue] and reach several to more than 4 kilometers deep [*Gordon et al.*, 1987, *Mc. Cartney and Woodgate-Jones*, 1991]. A major part of the interocean exchange at the Agulhas retroflection is contributed by these rings (see also the next sections). They propagate into the South Atlantic with speeds ranging between 5 and 10 km day^{-1} [e.g., *Byrne et al*, 1995; *Wakker et al.*, 1990]. Maximum anticyclonic surface currents are around 50 cm s^{-1} [e.g. *Arhan et al.*, this issue; *Duncombe Rae et al.*, 1992a,b]. These rings have a considerable impact from the local to the global scale (section 4).

The pinching off of large rings at the Agulhas retroflection leads to major exchanges between the subtropical gyres of the South Indian and the South Atlantic Oceans [*Gordon et al.*, 1992; *Olson and Evans*, 1986; *Lutjeharms and Gordon*, 1987]. However, these are not the only vortices formed in this region. The portion of the Agulhas Current that does not get abstricted to form rings moves eastward as the Agulhas Return Current, usually along the Subtropical Convergence [*Lutjeharms and Valentine*, 1984] south of Africa. This produces severe horizontal shear and accompanying flow instabilities. A range of eddy types are thus formed [*Lutjeharms and Valentine*, 1988a], some of which have been observed to cross the front

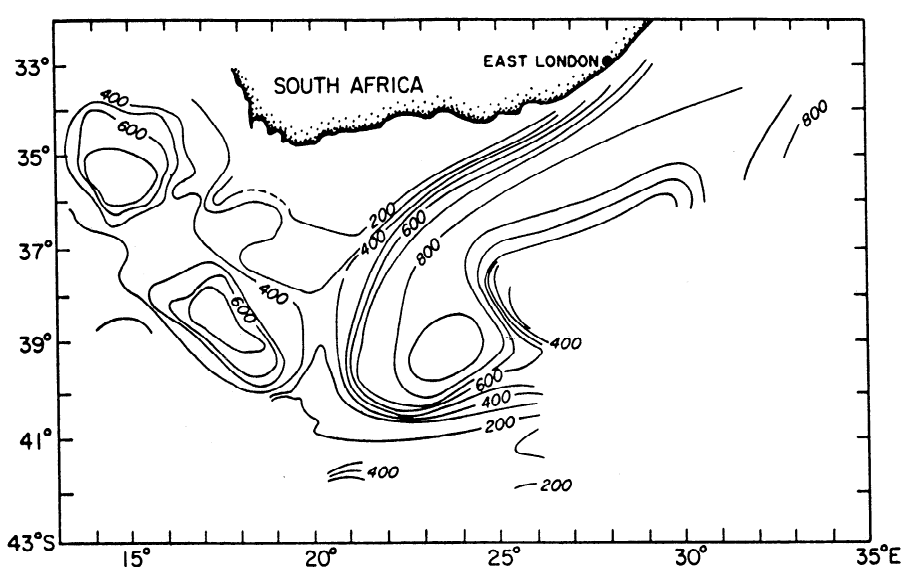

Figure 4. Dynamic height anomaly of the sea surface in the Agulhas retroflection region as observed during the spring of 1983 by the R.V.*Knorr* and *Meiring Naude*. The computed values are given in dynamic meters and are relative to the 1500 dbar surface [after *Gordon et al.*, 1987].

and enhance the cross-frontal exchange of water masses and heat [*Lutjeharms*, 1987]. The associated eddy stresses may also exert a net force and accelerate the mean flow considerably (Figure 2) [*Feron*, 1994; *Feron et al.*, 1998].

2.3. Seasonal Variability

Ffield et al. [1997] have suggested that the Agulhas transport varies with the seasonal wind changes. This seems to contradict *Pearce and Gründlingh* [1982] who reexamined historic estimates of the Agulhas transport and concluded that there were no significant seasonal variations in the mean flow intensity of the upstream Agulhas Current. Seasonal changes in the Agulhas transport have been mostly surmised from satellite observations (although even in 1857 a clear seasonal variation was derived from the analysis of log books of the sailing vessels of the Dutch East Indies Company [*Van Gogh*, 1857 see also *Lutjeharms et al.*, 1992]). Satellite altimeter data and infrared imagery have revealed annual changes in rms variability of the sea surface elevation (Figure 5) and temperature fields. These have been related to zonal displacements of the retroflection region [*Zlotnicki et al.*, 1989; *Quartly and Srokosz*, 1993; *Lutjeharms and van Ballegooyen*, 1988b]. The apparent discrepancy between in-situ measurements and satellite studies may be due to the

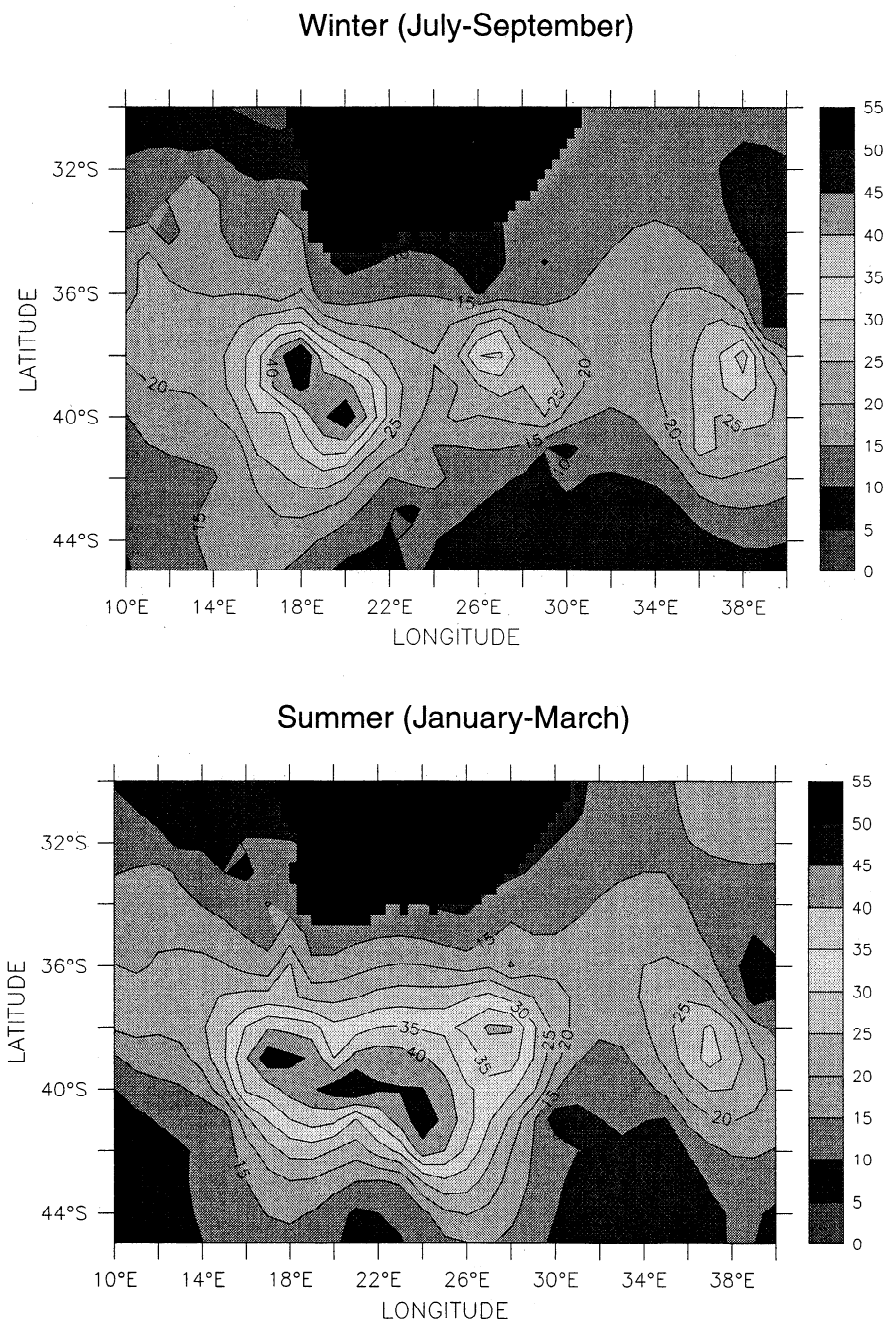

Figure 5. Standard deviation of sea surface height anomalies observed from the TOPEX/POSEIDON altimeter for the period October 1992 through April 1996, for (top) austral winter (July-September) and (bottom) austral summer (January-March).

shielding effect of the ridges to the east of the Agulhas area. It has been argued that the bottom topography of the Madagascar Plateau and Mozambique Plateau probably inhibits the westward propagation of barotropic Rossby waves [*Matano et al.*, 1999]. The latter help to bring about the seasonal adjustment of the South Indian Ocean to wind variations.

2.4. Interannual and Decadal Variability

The most prominent example of interannual variability is that associated with El Niño Southern Oscillation (ENSO) events. Several studies have related these events to sea surface temperature (SST) anomalies in the Agulhas/Benguela region [e.g., *Reason et al.*, 1996b]. During El Niño years the tendency is to have warm anomalies north of approximately 30°S and cold anomalies farther south. The reverse occurs during La Niña years. Observations also indicate the existence of inter-annual events not related to the extremes of ENSO. *Shannon et al.* [1990], for example, observed significant warming south of Africa from August to December 1985, which persisted until the Austral Spring of 1986. Wind anomalies during this period were represented by a large anticyclonic feature centered well south of Madagascar, near 40°S. Probably, the wind anomalies associated with the SST anomalies induced a poleward shift in the zero wind stress curl line that enhanced the flow of Agulhas waters into the southeast Atlantic (see also section 5). Decadal analysis of SST anomalies [*Allan et al.*, 1995; C. Reason, Local air-sea interaction and multidecadal climate variability in the Indian Ocean Region, *Climate Dynamics*, submitted, 1998] suggests that large warming or cooling events in the Agulhas retroflection area are not just isolated episodes but have occurred at frequent intervals during the last century. *Allan et al.*, [1995] found a tendency for the semipermanent South Indian Ocean anticyclone to strengthen and weaken during the austral summer and related these changes to warming and cooling of the sea surface in the Agulhas retroflection region and southern midlatitudes of the Indian Ocean. These changes in SST and atmospheric circulation were later shown to occur for other seasons. Similar variability exists in the South Atlantic anticyclone and SST [*Venegas et al.*, 1996]. On the basis of the results of numerical experiments, *Reason et al.* [1996b] suggested that multidecadal anomalies in SST over the Agulhas retroflection region may be correlated to changes in the Indonesian throughflow. These changes, in turn, appear to be modulated by changes in the Pacific winds. More recent work [Reason, submitted manuscript, 1999] has indicated that local surface heat flux anomalies may also contribute to the multidecadal SST anomalies in the Agulhas reflection region.

3. Estimates of Indian-Atlantic Ocean Exchange

Although it is difficult to estimate the amount of Indian Ocean Water that enters the South Atlantic through Agulhas leakage because of its highly intermittent character, several attempts have been made to quantify this inflow, using a large variety of approaches. A compilation of estimates is given in Table 1.

A common problem to these estimates is that they consider the Agulhas rings to consist of pure Agulhas Current water. Having calculated the volume of the rings and their shedding frequency one then supposedly has a reasonable assessment of the water exchanges. However, this ocean region is known for its very high ocean-to-atmosphere heat [*Bunker*, 1988; *Walker and Mey*, 1988] and moisture fluxes [*Lee-Thorp et al.*, 1997]. These lead to considerable modifications in the water mass characteristics and the heat content of rings while they remain in the Agulhas retroflection region [*Gordon et al.*, 1987; *Olson et al.*, 1992]. The periods they spend here before moving off into the South Atlantic can vary substantially [*Arhan et al.*, this issue; *Goñi et al.*, 1997]. Thermostads to depths of 400 m and salinity boosting in the surface layers of rings found far into the South Atlantic are the products of these processes at the retroflection.

3.1. Geostrophic Calculations of Direct Agulhas Leakage

Several attempts have been made to estimate the amount of interocean exchange by direct geostrophic calculations [e.g., *Harris and van Foreest*; 1978, *Gordon*, 1985; *Bennett*, 1988; *Stramma and Peterson*, 1990] or in combination with other tracer distributions [*Gordon et al.*, 1987, 1992]. These hydrographic observations have yielded a series of snapshots of a highly intermittent process. For instance, geostrophic calculations performed by *Gordon* [1985] have yielded a 14Sv transport between the South African coast and the offshore edge of an Agulhas ring just off-shore of Cape Town. However, *Gordon et al.* [1987] concluded that at least 4Sv of this transport was derived from the South Atlantic Current. *Olson and Evans* [1986] pointed out that a large amount of this transport was due to a jet-like feature between the ring and the coast. It is therefore likely that this transport is quite sensitive to the ring-shedding events.

Gordon et al. [1987] reported a 16Sv mismatch between the volume transport of the Agulhas Current flowing into the Agulhas retroflection area and that of the Agulhas Return Current flowing out. They argued that this imbalance could be accounted for by westward growth of the Retroflection region by approximately 3.0 cm s^{-1}, or by a loss of water of this

Table 1. Geostrophic Estimates of the Direct Flux of Indian Ocean Water Into the South Atlantic

Source	Flux, Sv	Reference	Date
Harris and Van Foreest [1978]	5	1100 dbar	March 1969
Gordon et al. [1987]	10	1500 dbar	Nov.-Dec. 1983
Bennett [1988]	6.3	$T > 8°C$	Nov.-Dec. 1983
	2.8	$T > 8°$	Feb. 3 1985
Stramma and Peterson [1990]	8	1000 m	Nov. 1983
Gordon et al. [1992]	10	$T > 9°C$	Dec. 1989 to Jan. 1990
	15	1500 dbar	Dec. 1989 to Jan. 1990
Garzoli et al. [1996]	4	1000 dbar	Sept. 1992 to Dec. 1995

Table 2. Estimates of Interocean Volume Transports by Ring Translation

Source	Flux/Ring, Sv	Reference	Date
Olson and Evans [1986]	0.5-0.6	T > 10°C	Nov.-Dec. 1983
Duncombe Rae et al. [1989]	1.2	total	April-May 1989
Gordon and Haxby [1990)]	1.0-1.5	T > 10°C	May 1987
	2.0 - 3.0	total	May 1987
McCartney and Woodgate-Jones [1991]	0.4 - 1.1	total	Feb.-March 1983
Van Ballegooyen et al. [1994]	1.1	T > 10°C	Feb.-March 1987
Byrne et al. [1995]	0.8 - 1.7	1000 db	10 cruises in 1980s
Clement and Gordon [1995]	0.45 - 0.90	1500 db	May 1993
Duncombe Rae et al. [1996]	0.65	total	June 1992, May-Oct. 1993
Lutjeharms and Cooper [1996]	0.10	total	Nov. 1983, Dec. 1992
Goñi et al. [1997]	1.0	T > 10°C	Sept.. 1992 to Dec. 1995

Results obtained by *Lutjeharms and Cooper* [1996] concern filaments .

amount to the Atlantic Ocean. These results indicate that, although the ring shedding events are intermittent, interocean exchange might occur at a more constant rate by protrusion of the Agulhas Retroflection, the volume surplus being only now and then released in the form of rings or filaments.

3.2. Interocean Volume Transport by Agulhas Rings

Other estimates of interocean exchange have been based on shedding of Agulhas rings (see Table 2). If the amount of Indian Ocean water that is trapped inside a ring is known, then the volume flux of this water can be deduced from the number of rings shed per year. The large range of volume fluxes per ring (Table 2) is due to different assumptions made in the calculations, to differences between individual rings, and to rings being measured at different distances from the retroflection area and thus in different stages of decay. *Gordon and Haxby* [1990], for example, based their upper estimates of the volume fluxes on the outer diameter of the rim of an Agulhas ring. *Olson and Evans* [1986], however, point out that the maximum velocity should be taken instead. There the density gradients are largest, indicating contrasting water mass characteristics. Also the depth of the rings is chosen quite arbitrarily by different authors. *McCartney and Woodgate-Jones* [1991] show that the depth to which Indian Ocean water is trapped is not necessarily the depth at which the ring signature is still present in the depression of isotherms. They argue that water can only be trapped above the depth at which the maximum rim velocity exceeds the translation speed.

Although the characteristics of Agulhas rings can be evaluated using hydrographic data, accurate counts of the number of rings entering the South Atlantic can only be made using remote sensing techniques, in particular radar altimetry. Different estimates are tabulated in Table 3. An independent estimate of rings crossing the Benguela current, using 16 months of echo sounder data, [*Duncombe Rae et al.*, 1996] has been included for completeness. Infrared thermal images were used by *Lutjeharms and van Ballegooyen* [1988a,b] to study the process of ring shedding in detail. They interpreted abrupt regressions of the retroflection as ring-shedding events, happening between 6 and 12 times per year in a period between 1978 and 1983 (Table 3). The large number of events compared to other estimates may indicate a large ring-shedding activity during that period. However, since a number of rings is recaptured after being shed, this estimate is probably too high. *Lutjeharms and Cooper* [1996] used infrared images to study interocean fluxes brought about by the intrusion of Agulhas filaments into the Atlantic Ocean (Table 2). These features also contain Indian Ocean water but are less coherent than rings. Owing to the small depth of these filaments their volume transport is small and also their thermal signature will be rapidly lost to the atmosphere. However, they might contribute considerably to interocean exchange of salt.

Since atmospheric cooling rapidly attenuates the thermal signature of Agulhas rings, the detectability by infrared methods is low and confined to the Retroflection area. The decay of the sea surface elevation of rings is much slower, and rings can be followed across the entire Atlantic using altimeter data (Table 3). An average of six rings appeared to be shed each year, pinching off at irregular intervals [*Feron et al.*, 1992;

Table 3. Number of Agulhas Ring-Shedding Events as Estimated by Different Authors

Authors	Number per year	Device	Period
Lutjeharms and van Ballegooyen [1988b]	6 - 12 (9)	infrared	1978-1983
Gordon and Haxby [1990]	5	altimeter	Nov. 1986 to Nov. 1987
Feron et al. [1992]	4 - 8 (6)	altimeter	Nov. 1986 to Sept. 1989
van Ballegooyen et al. [1994]	6	altimeter	Dec. 1986 to Dec. 1988
Byrne et al. [1995]	6	altimeter	Nov. 1986 to Aug. 1989
Duncombe Rae et al. [1996]	4 - 6	echo sounder	June 1992 to Oct. 1993
Lutjeharms and Cooper [1996]	6.5	infrared	'1987-1991
Goñi et al. [1997]	4-7 (6)	altimeter	Sept. 1992 to Dec. 1995

Note that the *Lutjeharms and Cooper* [1996] results concern filaments. Numbers in parentheses denote average number of rings shed per year.

Table 4. Agulhas Ring Properties as Found in Literature

Sources	F_Q, 10^{-3} PW	F_S, 10^5 kg s^{-1}	ΔPE, 10^{15} J	KE, 10^{15} J
Olson and Evans [1986]			30.5	6.2
			51.4	8.7
Duncombe Rae et al. [1989]	25	6.3		
Duncombe Rae et al. [1992a]			38.8	2.3
Van Ballegooyen et al. [1994]	7.5	4.2		
Byrne et al., [1995]			18	4.5
Clement and Gordon [1995]			7.0	7.0
Duncombe Rae et al. [1996]	1.74	1.1	11.3	2.01
Lutjeharms and Cooper [1996]	1.1	0.15-0.46		
Goñi et al. [1997]			24	
Garzoli et al. [1996]	1.0-1.6	0.7-1.0	2.8-3.8	

Heat flux F_Q ,salt flux F_S, available potential energy (APE), and kinetic energy (KE) are calculated with respect to the direct surroundings of the rings. (Note that the *Lutjeharms and Cooper* [1996] results concern filaments.) These estimates depend strongly on the properties of the water masses that are assumed to compensate for the Indian Ocean water input by the rings. For instance, estimates based on compensation by North Atlantic Deep Water led to a heat flux increase by an order of magnitude [*Gordon*, 1985].

Goñi et al., 1997]. Sometimes there are long periods without any ring formation. For instance, between April and November 1993, no rings were shed, but three rings were formed rapidly in November and December of the same year [*Goñi et al.*, 1997].

3.3. Heat and Salt Fluxes

Estimates of heat fluxes F_Q and salt fluxes F_S fluxes due to ring translations and their available potential energy (APE) and kinetic energy (KE) are tabulated in Table 4. These estimates are based on the temperature and salinity contrasts between the enclosed water and its surroundings.

There is also a direct leakage from the upper layers of the Indian Ocean into the South Atlantic via the retroflection area (section 3.1). Before one can estimate the associated heat and salt fluxes one needs to know how this upper layer inflow is compensated. If it is part of the coupled wind-driven gyres of the South Indian and South Atlantic Oceans, the so-called "supergyre" [*de Ruijter*, 1982; *Gordon et al.*, 1992; *Schmitz*, 1995] (see also section 5), then it is compensated by South Atlantic upper layer water flowing into the South Indian Ocean. *Gordon et al.* [1987] and *Fine et al.* [1988] found evidence of a large fraction of South Atlantic water in the retroflection region and in the Agulhas Return Current. This suggests that a portion of the Agulhas inflow into the South Atlantic is compensated by an export of South Atlantic water at thermocline and intermediate levels.

In addition the input of Indian Ocean water can be compensated by North Atlantic Deep Water export [*Gordon* 1985, 1986; *Gordon et al.*, 1992]. *Gordon* [1985] estimates a heat input of between 0.023 and 0.47 PW based on a 14 Sv Agulhas leakage, depending on whether it is compensated by export of South Atlantic waters through the South Atlantic Current or by NADW export.

3.4. Inversion Studies

Several attempts have been made to infer the amount of Agulhas inflow by inverting hydrographic data. Most studies have used the inverse method of *Wunsch* [1978] to estimate property balances within an area enclosed by sections of hydrographic data [*Fu*, 1981; *Rintoul*, 1991; *Macdonald* 1993; J. Holfort et al. The oceanic transport of heat and nutrients in the South Atlantic, submitted *J. Geophys. Res.*, 1998.]. Assuming that the flow is in thermal wind balance, reference level velocities are sought so that the resulting flow field approximately conserves properties (mass, heat, salinity) within isopycnal layers. This method assumes that the sections are representative of the mean state of the ocean. *Schlitzer* [1993, 1996] and *Boddem and Schlitzer* [1995] used a large historical hydrographic data set to obtain a more statistically consistent solution. Mass conservation is satisfied in their method, and a geostrophic flow field and tracer distributions are obtained which approximate the measurements best. The data sets used by these studies are often diverse and nonsynoptic. They are not able to account for the intermittent character of the Agulhas leakage process. Furthermore, any intraannual or interannual variability of the system is lost in obtaining a single best estimate of the climatology. In these studies, only net transports within a layer are calculated and water entering and leaving a section at the same density level is ignored. A large inflow of Agulhas leakage does not say anything about the amount of this water that is involved in the global overturning circulation. It might also recirculate in the subtropical supergyre of the Indian-Atlantic Oceans.

Table 5 shows estimated volume and heat transports across 30°S in the South Atlantic. These estimates were divided into four basic layers: Antarctic bottom water (AABW), North Atlantic Deep Water (NADW), Antarctic Intermediate Water (AAIW) and Surface (thermocline) Water (SW). Net northward volume transport within the thermocline layer can be derived from Drake Passage subantarctic water, which is strongly modified by heat gain within the southern South Atlantic, or from Indian Ocean water that enters the basin through Agulhas leakage. Also, transport in the intermediate layer can originate from both sources. None of the inversion studies favors a large contribution from Agulhas inflow.

Fu [1981] ascribed his large northward heat transport across 30°S to heat input through the Antarctic Circumpolar Current (ACC), possibly being unaware of heat input through Agulhas leakage. *Rintoul* [1991], using the same data set at his 30°S boundary, pointed out that *Fu*'s [1981] extreme heat flux value is possibly generated by an overestimation of Ekman transport and underestimation of bottom water transport. His own results need a 5 Sv conversion of subantarctic Drake Passage water into lower thermocline water to satisfy an 8 Sv northward thermocline transport across 30°S. His 0°E section

Table 5. Results of Inversion Studies, Giving Heat Flux Across 30°S, and Transports for Different Water Masses

Authors	SW	AAIW	NADW	AABW	F_Q, PW	Date
Fu [1981]	15	10	-24	-2	0.85	July - Aug. 1925 Meteor
	9	6	-20	1	0.88	April - May 1959 IGY
Rintoul [1991]	8	5	-17	4	0.25	April -May 1959 IGY
Mcdonald [1993]	6.1	7.9	-21.6	7.5	0.3	Feb. 1988 to Feb. 1989
Schlitzer [1993]	2.2	10.0	-15.8	3.1	-0.05	historical
Schlitzer [1996]	2.0	11.9	-18.7	4.2	0.3	historical
Boddem and Schlitzer [1995]	-1.9	9.8	-8.9	1.1	0.04	historical
Holfort et al., (submitted manuscript, 1998)[					0.26	Jan. 1993 WOCE

Transports are in sverdrups. Positive values denote northward transport. Entry "date" refers to 30°S section alone. IGY is International Geophysical Year, WOCE is World Ocean Circulation Experiment. Water masses are SW, Subtropical Water; AAIW, Antarctic Intermediate Water; NADW, North Atlantic Deep Water; AABW, Antarctic Bottom Water.

shows, furthermore, only a 2 Sv net import of upper thermocline water and a 5 Sv export of lower thermocline water, which makes a large contribution of Agulhas inflow to NADW compensation unlikely. However, as the synopticity of his data does not capture the intermittency of the Agulhas leakage process either, it is possible that his study underestimates the contribution from the Indian Ocean. The studies by *Schlitzer* [1993, 1994] and *Boddem* and *Schlitzer* (1995) show a large dominance of intermediate water over thermocline water in the compensation of NADW export. This may be due to smoothing of intense flow structures in the energetic wind-driven gyres, as a result of using a large database.

In addition, several authors [*Rintoul* 1991; *Macdonald* 1993; *Boddem and Schlitzer* 1995] forced a heat flux across 30°S onto their solution to verify whether such a flux could be consistent with the data. Northward heat fluxes of 0.69 and 0.88 PW [*Rintoul*, 1991], 0.8 PW [*Macdonald* 1993] and 0.66 PW [*Boddem and Schlitzer*, 1995] yielded unrealistic circulation patterns. Unrealistic circulation patterns were also obtained with a 13 Sv Agulhas input [*Rintoul*, 1991].

3.5. Model Estimates

Results of several modeling efforts to estimate Agulhas leakage are presented in Table 6 as a layer breakdown in a similar way to table 5. Analysis of the diagnostic phase of the Fine Resolution Antarctic Model (FRAM) shows a number of 2.3 Agulhas rings shed per year, inducing a 0.2 PW heat flux and 20 Sv volume flux [*The FRAM Group*, 1991]. *Thompson et al.* [1997] analyzed the prognostic phase of FRAM and concluded that Agulhas leakage contributes approximately 80% of the 0.65 PW northward heat flux across 34°S in the model Atlantic. The model produces rings that are too large, too warm and too salty relative to observed rings, and the shedding takes place too regularly [*Lutjeharms and Webb*, 1995]. The layer breakdown, as presented in Table 6, displays the same structure as the *Semtner and Chervin* [1992] model.

Matano and Philander [1993] used a model of the southern South Atlantic Ocean, bounded by open boundaries, to study the heat and mass balances of the South Atlantic. They prescribed an 8 Sv Agulhas inflow at their eastern boundary and concluded that the heat divergence in their model, due to the 0.19 PW northward heat flux in their model, was too large with respect to climatology. They suggested that the Agulhas input makes a larger contribution than what they prescribed. *Drijfhout et al.* [1996], studied a low-resolution model of the thermohaline circulation, which did not allow for Agulhas leakage. Nevertheless, they concluded that Agulhas leakage must be important, as their model results indicated that an unrealistic amount of intermediate water was converted.

In general, it might be concluded that the process of Agulhas leakage has not been realistically modeled yet. The same holds for its influence on the global-scale thermohaline circulation. This might be due to the relative inability of ocean models to produce reasonable amounts of Intermediate Water [*McCann et al.*, 1994, *Thompson et al.*, 1997], mainly due to the coarse vertical resolution at this depth range. It seems that the process and amount of Agulhas leakage and its influence on the global-scale overturning circulation cannot be represented in the models in a sufficiently realistic way yet for it to be used as an estimate of the actual amount of Agulhas leakage.

4. Fate and Impact of Agulhas Leakage

4.1. Local Impact

It has been noted for some time that anomalies of sea surface temperature in the adjacent oceans are statistically related to rainfall over the southern African subcontinent [e.g.,

Table 6. Results of Several Modeling Studies, Giving Heat Fluxes Across 30°S Latitude, and Transports for Different Water Masses

Source	SW	AAIW	NADW	AABW	F_Q, PW
FRAM Group [1991]	11	8	-22	3.2	0.56
Semtner and Chervin [1992]	12	4.7	-18	1.3	0.60
Matano and Philander [1993]	6.8	1.6	-10.9	2.5	0.19
Thompson et al. [1997]	12.7	6.8	-20.9	1.4	0.56

Transports are in sverdrups.

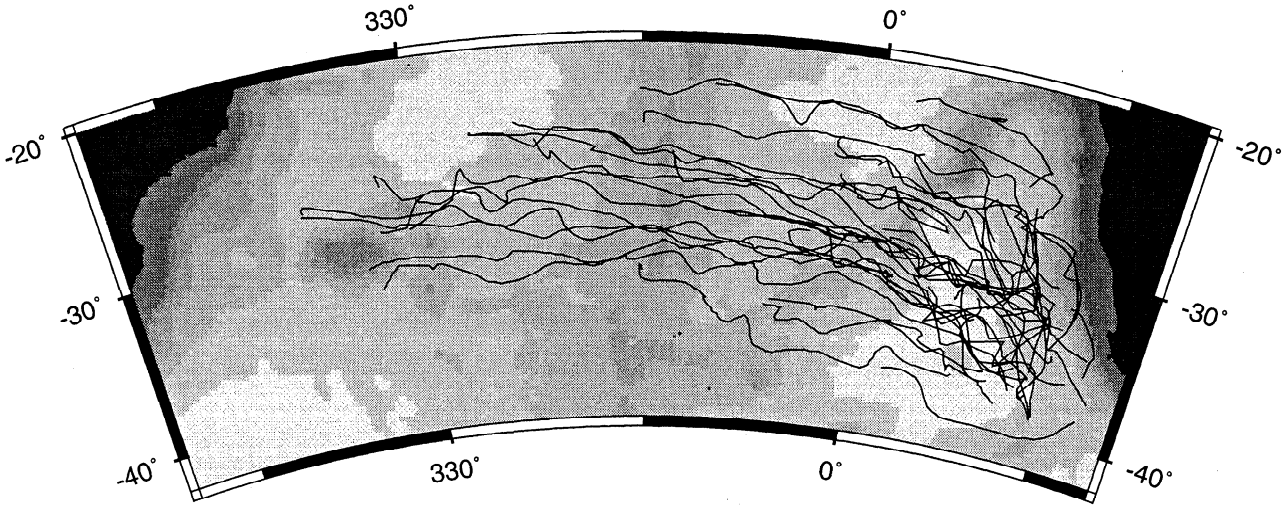

Figure 6. A composite of the tracks of Agulhas rings through the South Atlantic, determined from TOPEX/POSEIDON altimeter data over the period November 1992 - November 1996 (courtesy of M. Schouten, Institute for Marine and Atmospheric research Utrecht). Before the Walvis Ridge most of them seem to be steered in a northwestward direction by the background Benguela Current. In this area they decay to less than half their size [*Byrne et al.*, 1995], shedding the major part of their properties into the surroundings. The dots indicate the position of the rings at a 40 day interval. Only rings that have penetrated the subtropical gyre of the South Atlantic are shown. Approximately 15 rings, not shown here, could be followed only for several months through the Benguela area before getting lost from the altimetry signal. They may provide an important source for the Atlantic thermohaline overturning circulation.

Walker, 1990; *Mason*, 1995; *Jury et al.*, 1993]. As it is also well known that the flux of warm Agulhas Current water into the South Atlantic, either by rings or by filaments, is extremely variable [e.g., *Shannon et al.*, 1990; *Feron et al.*, 1992], it is conceivable that changes in the flow parameters at the retroflection could have noticeable effects on the local rainfall [e.g., *Rouault and Lutjeharms*, 1994]. Agulhas rings that pass close to the coast may also have effects on the inshore circulation which may in turn influence marine biota. Rings passing close to the Cape of Good Hope will enhance the shelf edge jet that is reputed to carry pelagic fish larvae from their spawning grounds on the Agulhas Bank to the wind driven coastal upwelling off the South African west coast. On moving closely to this extensive upwelling system the passing Agulhas rings have also been observed to interact with upwelling filaments [*Duncombe Rae et al.*, 1992a], and it has even been surmised that such events could have an influence on the success of the pelagic fish recruitment [*Duncombe Rae et al.*, 1992b]. Although the paths of the larger Agulhas rings seem to diverge rapidly from the coast [*Wakker et al.*, 1990; *Byrne et al.*, 1995; *Garzoli et al.*, 1996; *Goñi et al.*, 1997] (see Figure 6] it is not known how much influence these interactions have on the upwelling regime.

4.2. Fate and Gyre-Scale Impact of Agulhas Rings

After formation, some Agulhas rings remain in the spawning area for a considerable time, sometimes for more than a year [*Goñi et al.*, 1997]. Between September 1992 and December 1995 two to five warm rings coexisted continuously in the region east of Walvis Ridge [*Goñi et al.*, 1997]. This might have been due to strong interaction of these features with local topography such as the Agulhas Ridge or to interaction between rings. Furthermore, as the background flow close to the retroflection area is small, they move mainly because of their intrinsic drift. Once they are picked up by the Benguela Current, most of the Agulhas rings translate northwestward crossing the South Atlantic/Benguela Current, and move into the inner regions of the South Atlantic subtropical gyre (Figure 6). The rings are observed to cross the Atlantic within a 15° latitude band between 25°S and 40°S. Satellite altimeter data have confirmed that Agulhas rings can be tracked for several years all the way across the South Atlantic to the region of the Brazil Current [*Gordon and Haxby*, 1990; *Byrne et al.*, 1995, Figure 6].

After their separation from the retroflection, Agulhas rings undergo strong direct and evaporative cooling and convective overturning [*Olson et al.*, 1992], interaction with the Benguela Current [*Duncombe Rae et al.*, 1992a,b; *Clement and Gordon*, 1995], and interaction with the Walvis Ridge [*Kamenkovich et al.*, 1996, *Wakker et al.*, 1990]. These processes enhance mixing with the surrounding waters and accelerate the decay of the rings. During the first year of their life this water and property exchange between Agulhas rings and their surroundings is a most likely source for the Benguela Current. A remaining part of the water contained in Agulhas sings is mixed within the subtropical gyre, saltening and stratifying the South Atlantic. Quite a few rings seem to get lost from the altimetric signal within the Benguela region, probably because of a decay to a size that is too small (M. Schouten, personal communication, 1998).

Agulhas rings are a source of salt and kinetic and potential energy for the South Atlantic (see Table 4). Although the water mass characteristics of the trapped Subtropical Indian Ocean water do not deviate substantially from the characteristics of subtropical Atlantic water, strong evaporation in the retroflection region boosts the salinity within the rings. *Olson and Evans* [1986] concluded that Agulhas rings are

among the most energetic in the world ocean with available potential energy of values up to 70PJ [*Goñi et al.*, 1997]. Their energy input to the subtropical gyres amounts to about 7% of that by the wind. Almost all eddy energy in the subtropical gyre is from Agulhas rings [*Olson and Evans*, 1986].

4.3. Fate of Agulhas Leakage Water

Most of the direct Agulhas leakage that enters the Atlantic feeds into the Benguela Current [*Stramma and Peterson*, 1989]. This eastern boundary current flows northward adjacent to the southwestern coast of Africa and is continued by the South Equatorial Current (SEC), which transects the South Atlantic [*Reid*, 1989; *Peterson and Stramma*, 1991]. The Benguela Sources and Transport (BEST) experiment (1992-1993) revealed that the annual mean transport of the Benguela Current, 16 Sv, is much smaller than previous estimates obtained from snapshots during hydrographic surveys [*Garzoli and Gordon*, 1996; *Garzoli et al.*, 1996]. A large variability was observed owing to the passage of Agulhas rings, especially in the western part of the Benguela Current. A detailed decomposition of the source waters of the Benguela Current is not yet available, but it appears that the average input of warm Indian Ocean water is of the order of 5 Sv [*Garzoli and Gordon*, 1996].

Off the Brazil coast the South Equatorial Current bifurcates. It is here that the ultimate fate of the remainder of the Agulhas leakage water is decided: one part is fed into the southward flowing Brazil Current and will recirculate in the South Atlantic as part of the subtropical gyre. It will finally be exported into the South Indian Ocean with the South Atlantic Current or mix into the Antarctic Circumpolar Circulation. The other part of the SEC is fed into the North Brazil Current, which is the source of cross-equatorial flow [*Schott et al.*, 1995; *Stramma et al.*, 1995; *Schmitz and Richardson*, 1991; *Frantantoni et al.*, 1995]. This part will possibly become involved in the global thermohaline circulation.

4.4. Warm Versus Cold Water Route

Gordon [1985, 1986] recognised the possible role of Agulhas leakage for the global thermohaline circulation, proposing a warm water route for the North Atlantic Deep Water return flow. In his concept a critical link is formed by a branch of the Agulhas Current flowing into the South Atlantic, introducing warm and salty thermocline and intermediate water into the South Atlantic subtropical gyre. Shortly after, the role of the warm water route for the NADW return flow was questioned [*Rintoul*, 1991; *Broecker*, 1991]. An alternative cold water route was proposed, consisting of intermediate water flowing from the Pacific into the Atlantic via the Drake Passage. This intermediate water follows the South Atlantic Current [*Stramma and Peterson*, 1990] from which one branch feeds directly into the Benguela Current. In the cold water path, heat is gained and freshwater is lost in a broad outcropping region in the South Atlantic, and water mass transformation by air-sea interaction plays a more prominent role.

Gordon et al., [1992] proposed a scheme in which the controversy between the warm and the cold water paths was partly reconciled. They proposed a South Atlantic-Indian Ocean circulation loop in which the cold water path makes an excursion into the Indian Ocean and passes into the Atlantic via the Agulhas link. In this scheme the mixing and transformation processes at the retroflection play a large role; in particular high evaporation boosts the salinities in the retroflection area.

The results of the BEST experiment do not support or dismiss the conjecture that the cold water path dominates over the warm water path [*Schmitz*, 1995; *Macdonald and Wunsch*, 1996]. *Garzoli and Gordon* [1996] show that the sources of the baroclinic part of the Benguela Current are almost equally divided between the South Atlantic subtropical thermocline and Antarctic Intermediate Water on the one hand, and the Indian subtropical thermocline and tropical Indian Ocean water on the other hand. Although the composition of the water masses still has not been fully analyzed, this result implies that in the present situation Agulhas water and AAIW are about equally important sources for the Benguela Current. This leaves about 5 Sv for Central South Atlantic Water as a third source of the Benguela Current. It is unclear yet where this water mass originates. It could be South Atlantic upwelling or a mixture of the warm (ring) water and South Atlantic Current water.

It could be that the source of AAIW is underestimated by the baroclinic calculations *of Garzoli and Gordon* [1996]. The total transport of the Benguela Current (16 Sv), however, is only slightly larger than the baroclinic transport (13 Sv) [*Garzoli et al.*, 1996]. Moreover, the barotropic component is more important in the western part of the Benguela Current, dominated by Agulhas leakage. An alternative route by which AAIW spreads northward along the South American coast was proposed earlier but has been ruled out by recent observations [*Larquw et al.*, 1997]. It is unclear whether the transport of the Benguela/South Equatorial Current increases downstream. Transport estimates for the North Brazil (Under) Current are highly variable [*Da Silveira et al.*, 1994; *Schott et al.*, 1995; *Stramma et al.*, 1995], ranging from 5 to 32 Sv. It is not clear from these measurements whether the North Brazil (Under) Current is significantly stronger than the Benguela Current and whether it has other sources that contribute to the cross-equatorial flow. At present, it seems unlikely, however, that a significant component of AAIW contributes to the North Brazil Current via another route than the Benguela/South Equatorial Current. This rules out the possibility that AAIW is a much larger source for the North Brazil Current than Agulhas water.

Since the debate between the cold and warm water routes started, a variety of observational [e.g., *Macdonald*, 1993; *van Ballegooyen et al.*, 1994; *Schmitz*, 1995; *Boddem and Schlitzer*, 1995; *Byrne et al.*, 1995; *Saunders and King*, 1995; *Macdonald and Wunsch*, 1996] and modeling studies [e.g., *Matano and Philander*, 1993; *Doos*, 1995; *Cai and Greatbatch*, 1995; *Drijfhout et al.*, 1996; *Thompson et al.*, 1997] have appeared, on the subject of the interocean exchange in the South Atlantic. However, a common conclusion has not been reached. Obviously, both sources of compensation are active, their relative (and absolute) strengths varying in time.

4.5. Global Impact

An interesting question is whether the dominance of the warm over the cold route (or vice versa) influences the process of NADW formation. The fact that deep water forms mainly in the North Atlantic, rather than in the North Pacific, is generally ascribed to the high surface salinities found in the Atlantic Ocean [*Warren*, 1983], which enables subpolar winter cooling of the surface water to increase the density toward deep

water values. *Gordon et al.* [1992] argue that the input of salty subtropical Indian Ocean water by Agulhas leakage might be partly responsible for this salty Atlantic thermocline: as this salty input is compensated for by the export of fresher water masses (whether NADW or South Atlantic "shallow" water masses), it effectively removes freshwater from the Atlantic. They speculate on the possibility that the production of NADW exists owing to the presence of Agulhas leakage, assigning a possible key role to Agulhas leakage for maintaining the present-day climate.

Another explanation for the high Atlantic surface salinities is the distillation of freshwater from the Atlantic Ocean's surface layers, owing to the fact that evaporation exceeds precipitation and continental run off [*Warren*, 1983; *Gordon and Piola*, 1983]. This, in turn, may be due to the anomalous northward heat transport across the entire Atlantic Ocean, including the South Atlantic, as shallow and warm water masses are drawn northward to compensate for the production of NADW [e.g., *Stommel*, 1980]. This completes a powerful feedback between overturning strength and the Atlantic evaporation rates [*Gordon*, 1986, *Rahmstorf et al.*, 1995]. It is probable that the injection of warm subtropical Indian Ocean water into the southeastern corner of the Atlantic is responsible for, or at least contributes significantly to, the Atlantic northward heat flux [*Gordon*, 1986; *Thompson et al.*, 1997]. *Gordon* [1986] concludes that Agulhas leakage might therefore play an important part in the above-mentioned feedback, which suggests a link between Agulhas leakage and the production rate of NADW.

These views concentrate on the influence that surface buoyancy fluxes have on the production of deep water as a result of mesoscale convection in the North Atlantic. However, these fluxes may play a more direct role as a supply of potential energy, which can be made available for driving the large-scale overturning circulation. A study of the zonally averaged Atlantic overturning circulation [*Weijer et al.*, 1999] has confirmed that in this respect the circulation strength is directly related to surface buoyancy fluxes [e.g., *Zaucker et al.*, 1994; *Rahmstorf*, 1996], indicating that Agulhas heat input influences the overturning strength by stimulating net surface cooling and evaporation. However, this effect is opposed by lateral buoyancy input by Agulhas leakage at shallow levels. The more these buoyant lateral fluxes are confined to the surface layers, the less is the combined effect of lateral and surface buoyancy fluxes on the strength of the overturning cell. Another energy source in the model, although relatively weak in strength, turned out to be the vertical buoyancy difference, which is related to downward buoyancy diffusion. Agulhas leakage may play a role in this mechanism, as it basically reduces the stratification of the Atlantic by raising the salinity of the surface layers [*Weijer et al.*, 1999].

The role played by the South Atlantic horizontal gyre circulation on the salt balance of the Atlantic has not been completely clarified yet. *Rahmstorf* [1996] noted that the wind-driven circulation of the South Atlantic induces a net northward freshwater flux, and that the overturning circulation even exports freshwater, because the exported NADW is fresher in the mean transports than in the return transports. This has been confirmed by analysis of recent World Ocean Circulation Experiment (WOCE) data [*Weijer et al.*, 1999; Holfort et al., submitted manuscript, 1998] and contradicts the notion that NADW exports the excess of salt caused by excess evaporation in the Atlantic [*Broecker*, 1991].

4.6. Modeling the Impact

Several modeling studies have attempted to estimate some of the impact of Agulhas leakage on the global thermohaline circulation. In a coarse-resolution model study by *Cai and Greatbatch* [1995] a shutoff of Agulhas leakage resulted in a cooling and freshening of Atlantic intermediate waters, although the impact on NADW formation was negligible. They also showed that the heat transport from the Indian Ocean into the South Atlantic was almost insensitive to Agulhas leakage, whereas in the South Atlantic heat gain from the atmosphere increased as Agulhas leakage decreased. A similar result was found by *Drijfhout et al.* [1996]. In their model Agulhas leakage is totally absent. This is compensated for by an excess diabatic forcing of AAIW through increased ventilation within the South Atlantic midlatitudes. The latter is due to a restoring boundary condition for surface salinity. *Piola and Gordon* [1989] demonstrated that upper AAIW is ventilated in the western part of the Argentine Basin between 55°S and 45°S. Owing to the absence of Agulhas leakage, in the numerical model of Drijfhout et al., the stratification within the thermocline is reduced in the South Atlantic, resulting in unrealistically deep winter mixed layers. As a result, too much AAIW is entrained into the winter mixed layer and becomes too warm and salty before it subducts again.

Thompson et al. [1997] compared a fine resolution Southern Ocean model (FRAM) with a coarse resolution version (CRAM) and found a significant reduction in northward heat transport in the Atlantic and NADW formation in the coarse resolution case. The smaller heat transport was attributed largely to a reduced heat input from the atmosphere in the Agulhas region. The heat transport between the two basins dropped from 0.5 PW to 0.02 PW between FRAM and CRAM. This contradicts the result of *Cai and Greatbatch* [1995]. It should be noted that in both models more heat is gained from the atmosphere in the South Atlantic, in response to reduced Agulhas leakage. The results from FRAM could be biased by a lack of equilibrium in the deeper ocean at the open boundaries. Although Agulhas ring shedding is represented rather realistically, Agulhas Rings are too large and shedding occurs too regularly [*Lutjeharms and Webb*, 1995]. As a result, the exchange of Agulhas water between the Indian and South Atlantic Ocean is probably overestimated in the model.

5. Dynamics and Modeling

As discussed earlier, the mass and heat transfers between the Indian and South Atlantic Oceans are achieved largely by rings and filaments originating at the Agulhas retroflection. The substantial range in observed exchange values (see Table 1) is probably due to real variations in the general circulation and not to differences in the methods or data used [e.g., *Gordon et al.*, 1992]. It seems natural then to ask what drives these exchanges and what causes their observed variability. A study of the structure of the subtropical gyre might help us to find an answer to these questions.

5.1. Subtropical Supergyre

The subtropical gyre system of the Indian and South Atlantic Oceans is so unique because the vorticity input by the surface wind stress curl remains positive as far south as 47°S whereas the African continental shelf already terminates at about 37°S. This suddenly leaves the Agulhas Current in the

open ocean without a western boundary to trap and steer it. Without inertia or some other mechanism to force it southward, the free Agulhas would be dispersed by the westward propagation of planetary waves. It would then make the full turn westward into the Atlantic, cross it as a free jet, merge with the Brazil current to form an impressive western boundary current along South America and flow back into the Indian Ocean closing the supergyre as a west wind drift along the zero wind stress curl curve [*de Ruijter* 1982]. Clearly, this is not what happens in the actual ocean as the observations show (see section 2). Available paleo-oceanographic information [e.g., *Howard and Prell*, 1992] indicates that no such full connection existed in the past either.

So the question raised earlier: "what drives the interocean exchange?" now turns into the question: "why is there so little interocean exchange, given the present (and past) wind forcing?" Although the exchange is surprisingly small in the sense that it is only a minor part, some 10% of the Agulhas Current transport, it still is a major input into the South Atlantic, amounting some 30 to 50% of the transport in the South Atlantic subtropical gyre. Therefore, from the climatological point of view it is also extremely important to determine the causes and effects of the observed variability of the exchange. A quest for answers to these questions leads to an investigation of the causes of the retroflection of the Agulhas Current after its separation from the South African shelf, to the associated dynamics of ring shedding and to their variability.

5.2. Agulhas Retroflection

From a series of theoretical and modeling studies it seems that the main factors that control the meridional excursion and anticyclonic turning of the major part of the Agulhas Current are: (1)Inertia and planetary vorticity advection (β effect); (2) Vortex stretching; (3) Geometry and curvature of the coastline; (4) Bottom topography; (5) The structure of the wind field, particularly over the southern part of the Indian Ocean subtropical gyre (see also section 5.1).

Inertial and β effect. A linear analysis showed that inertia must be incorporated into any model that is to reproduce a significant retroflection [*de Ruijter*, 1982]. Inertia forces the Agulhas Current southward into the open ocean. This overshoot could partly choke the gap between the tip of South Africa and the latitude of zero wind curl. Thus a substantial part of the Agulhas would immediately turn back into the Indian Ocean to match the wind-driven far field to the east (Figure 7). The remainder of the transport would have to turn into the South Atlantic, establishing a subtropical supergyre spanning the South Atlantic and Indian Oceans and wrap around the separate gyres in the two oceans. The qualitative picture of a large-scale loop through the upper layers of the Indian and Atlantic Oceans was later also derived from an analysis of data from the South Atlantic Ventilation Experiment (SAVE) [*Gordon et al.*, 1992]. The hypothesis of the effect of inertia was confirmed in a series of numerical nonlinear modeling studies in which the basin geometry was highly idealized [*de Ruijter and Boudra*, 1985; *Boudra and de Ruijter*, 1986; *Boudra and Chassignet*, 1988]. The separation of the anticyclonic gyres east and west of the African continent increased with increasing inertia (Figure 7). On top of the inertial "choke effect" described above, in the local dynamical balance the decrease in planetary vorticity appeared to be partly compensated by the accumulation of anticyclonic relative vorticity [*de Ruijter and Boudra*, 1985]. This β effect facilitated the retroflection of the Agulhas current.

Vortex stretching. In the eddy-resolving stratified experiments with realistic inertia [*Boudra and de Ruijter*, 1986] the transfer of water from the Indian Ocean to the South Atlantic Ocean was achieved largely by a deep flow that was driven by a downward transfer of momentum in the highly variable retroflection area. The retroflection is also affected by vortex stretching in the upper layer, both locally and on the gyre scale [*Boudra and Chassignet*; 1988]. The large-scale isopycnal field is set up by the structure of the wind field, sloping upward toward the west and toward the subpolar gyre. After separation the south or southwestward flowing Agulhas Current is squeezed into this large-scale stratification. This physical mechanism tends to generate positive relative vorticity, encouraging the flow to return in an anticyclonic loop by enhancing the β effect.

Coastline geometry. In a generalized nonlinear theory *Ou and de Ruijter* [1986] investigated the effects of coastline curvature on the separation of the Agulhas Current from the coast and its subsequent retroflection (Figure 8). The addition of a positive curvature to the coast was shown to reinforce the β effect in two ways. Directly, the cyclonic coastline forces the current to acquire anticyclonic shear to compensate; the speed along the coast increases, which is balanced by a raising of the upper layer interface at the coast. Indirectly, the induced centrifugal force also contributes to the surfacing of the

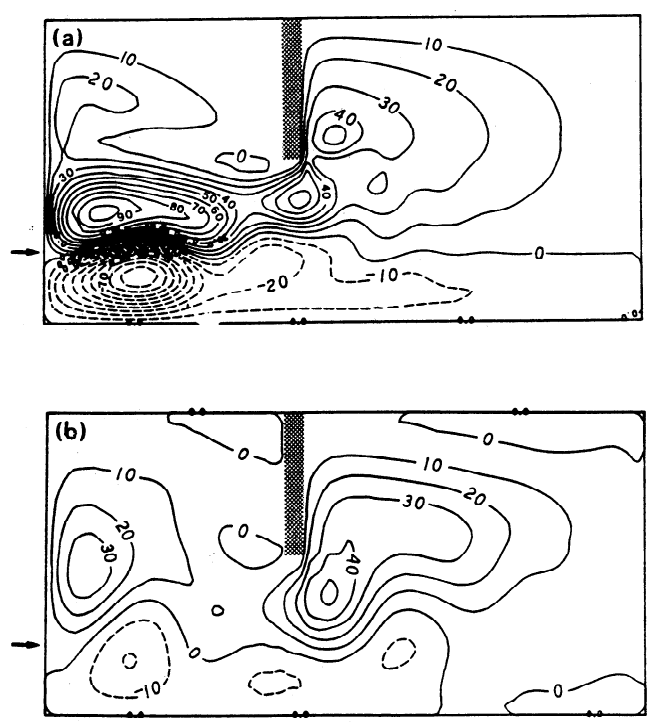

Figure 7. Mean stream function distribution in a barotropic, flat-bottom experiment to show the significant role of inertia in reducing the interocean exchanges. In the experiments shown the same wind forcing was applied while the depth of the basin *H* was 2000 m in the upper panel, and 500 m in the lower panel. The contour interval is in Sverdrups, while the latitude of the zero wind stress curl is indicated by the arrows at left (adapted from *de Ruijter and Boudra* [1985]).

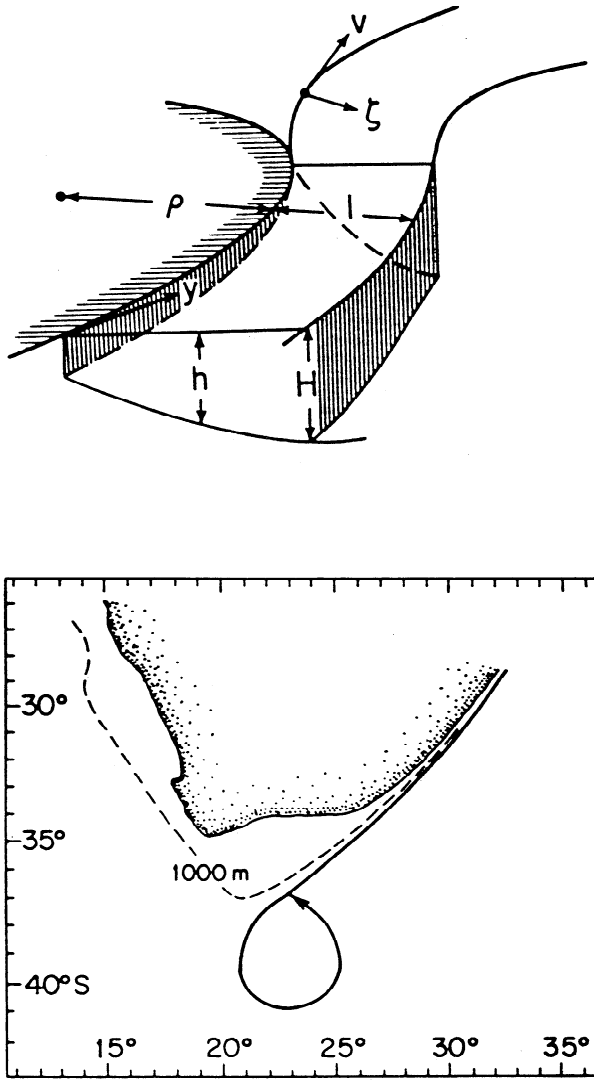

Figure 8. (top) Schematic of the reduced gravity model used by *Ou and de Ruijter* [1986] to investigate the influence of coastline curvature on outcropping and subsequent separation of the Agulhas Current from the coast. The western boundary current is confined to the upper layer, and its offshore limit is marked by a free streamline of depth *H*. (bottom) Model-calculated path for the Agulhas Current based on observed upstream conditions. The dashed lines mark the 1000m isobath (adapted from *Ou and de Ruijter* [1986].

interface. These two factors reinforce each other (they are of opposite sign for an eastern boundary current) and reinforce the β effect, leading to an earlier current separation by non-linear interface outcropping. The non-linear effect of coastline curvature appeared essential. Application of linear theories of baroclinic western boundary current separation [*Fofonoff*, 1962, *Parsons*, 1969; *Veronis*, 1973] could not produce Agulhas separation. An obvious direct conclusion to be drawn from the nonlinear theory is that for a larger transport the boundary current separates earlier and makes a sharper retroflection loop. Application to the Agulhas Current led to a separation at approximately 35°S and a retroflection loop that compared favorably with observations [*Gordon et al.*, 1987]. The calculated retroflection loop appeared to be very sensitive to the volume flux of the current. A reduction of only 10% led to a completely different behaviour: in that case there was no separation at all. Instead the full current flowed around the continent into the Atlantic. The retroflection also appeared to depend strongly on the angle of the jet on separation and thus on the coastline orientation at the separation location [*Ou and de Ruijter*, 1986; *Boudra and Chassignet*, 1988]. A westward component of the separated current facilitates leakage into the Atlantic and reduces the change in planetary vorticity. An associated reduced retroflection results. Friction against the continental boundary also affects the overall exchange dynamics as friction partly controls the separation of the Agulhas from the coast and modifies its potential vorticity while flowing along the shelf and slope. All these sensitivities indicate the importance in numerical models to correctly solve the evolution of the potential vorticity structure of the Agulhas Current along the western boundary. It is that structure that determines the upstream condition for the separated current and thus largely its subsequent retroflection and eventual ring shedding.

Bottom topography. All the above studies involved flat-bottomed or infinitely deep oceans. The possible effect of bottom topography on the Agulhas path was investigated in a series of single-layer modeling studies based on *Warren*'s [1963] semi analytical model for a free barotropic jet that conserves its potential vorticity [*Darbyshire*, 1972; *Lutjeharms and van Ballegooyen*, 1984]. In that model the penetration of the Agulhas Current into the Atlantic Ocean appeared to be very sensitive to the shear and bottom velocity of the current with more westward penetration at lower volume transports. Sensitivity to bottom topography was unrealistically large owing to the barotropic nature of the model flow. More recently, a series of experiments using a bottom-following coordinate in a steady 15-layer numerical model revealed that the vortex stretching exerted by the bottom topography, in particular by the Agulhas Plateau and the Agulhas Ridge, may play a dominant role in the retroflection dynamics [*Matano*, 1996] (see Figure 9). Experiments conducted in a basin with realistic dimensions and coastline geometry but a flat bottom failed to produce a realistic retroflection.

This result differs from isopycnic coordinate three-layer model simulations [*Boudra and de Ruijter*, 1986; *Boudra and Chassignet*, 1988], where significant retroflection was found in flat-bottom experiments both with rectangular and with triangular shaped "African" continents. The latter experiments also employed eddy-resolving horizontal resolution. A dominant term in the vorticity balance at the retroflection was the mean stretching in the upper layer, generating anticyclonic relative vorticity. However, comparison with altimeter data [*Feron et al.*, 1998] suggests that the parameter setting in the experiments of *Boudra and de Ruijter* [1986] and *Boudra and Chassignet* [1988] has probably led to an overrepresentation of the mean upper layer stretching in the average vorticity balance. A dedicated series of experiments to compare these dynamics in both models would be necessary to clarify this issue.

Matano [1996] obtained a significant retroflection by adding realistic bottom topography (Figure 9). The vorticity balance indicated that inertial and β effects do indeed force the western boundary current to leave the continental slope and to loop offshore. Above the topographic ridges the dominant balance is between planetary vorticity advection (β) and the torque exerted by the bottom topography. Although the role of

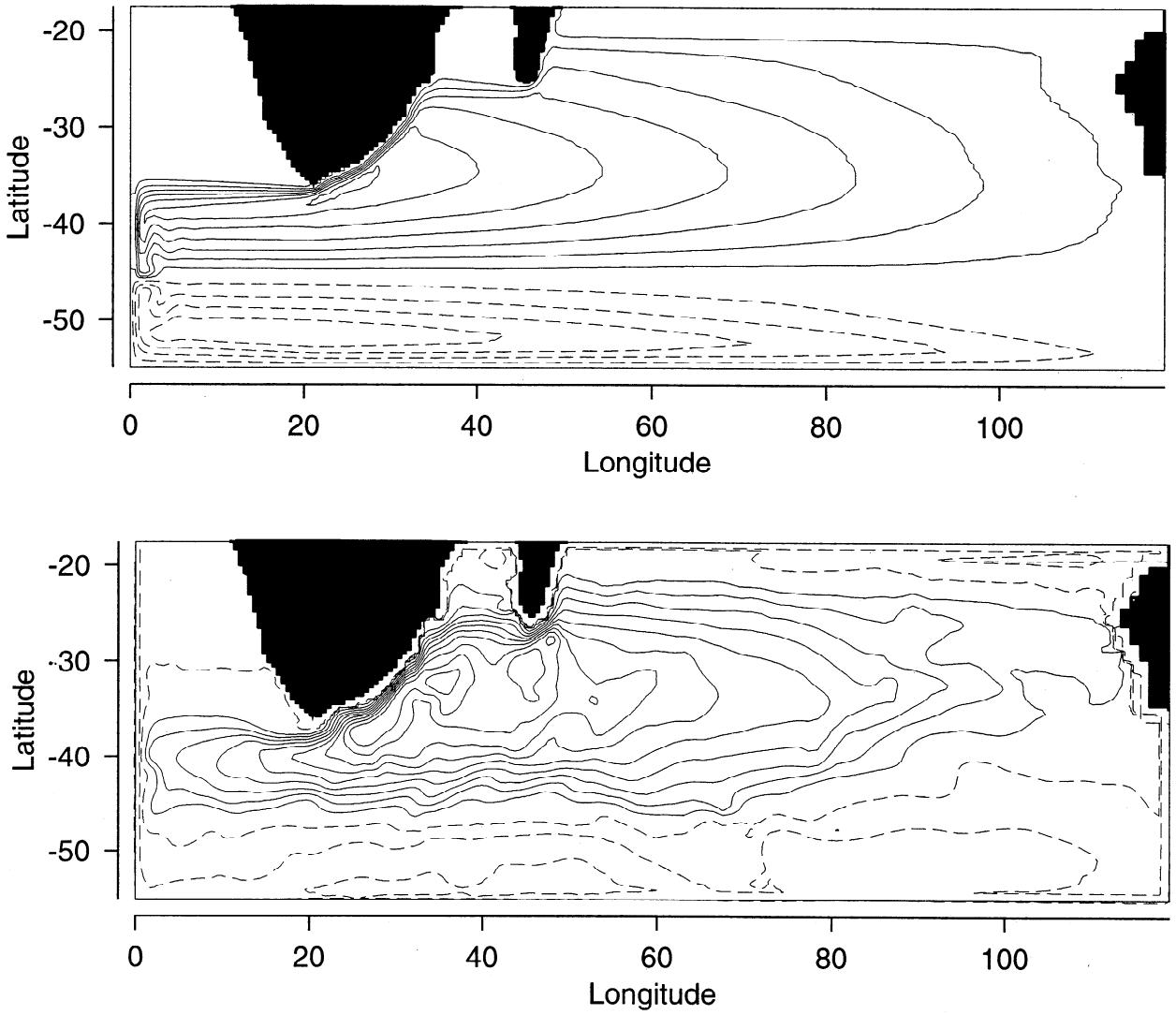

Figure 9. Sea surface elevation in numerical simulations that investigate the role of bottom topography in the retroflection of the Agulhas Current. (top) Steady state of an experiment conducted in a basin of constant depth (H=2000m). (top) Steady state in an experiment which included realistic bottom topography (adapted from *Matano* [1996]).

bottom topography might be overestimated in the level model, with relatively weak upper layer flow, these results indicate that bottom topography may play an important role in locking the Agulhas Current's retroflection. Such topographic locking might also provide a clue as to why the observed retroflection and leakage do not show much larger variations, given the large sensitivities that emerged from the studies without topography.

5.3. Ring Shedding

Variability of the Agulhas is an important aspect of the climate system because it can drive a large portion of the interocean exchange. The large rings that are pinched off at an average frequency of about six per year form a major component of the so-called warm water path (section 3). Having explored the reasons for the Agulhas retroflection in the previous section, we now address the dynamics of ring shedding.

In the nonlinear reduced gravity model of *Ou and de Ruijter* [1986] it is the flow direction of the jet at the separation point from the coast which determines whether it becomes a meandering eastward jet or a current looping back upon itself (Figure 8). Application of the model to the Agulhas Current suggested a "ring generating type" behavior of the separated current (Figure 8). The same physical mechanism may be applied to explain the shedding of comparable loop rings like those in the Gulf of Mexico loop current [e.g., *Hurlburt and Thompson*, 1980] and the North Brazil Current [*Schott et al.*, 1995] In the idealized model, this process of ring formation appeared to be very sensitive to the jet structure at separation from the coast.

Chassignet and Boudra [1988] showed that inertia and baroclinicity had to be relatively weak for rings to form in the isopycnic model. As inertia increased, more fluid retroflected and fewer rings were formed. They suggested that the actual shedding of rings was brought about by a mixed barotropic-baroclinic instability in the strong shear zone where the current loops back upon itself. They also confirmed the importance of the injection angle with respect to the north-south axis. Changing the shape of the African continent from a rectangle to a triangle facilitated ring generation.

The main focus of the previously discussed studies were the local dynamics of Agulhas variability and ring shedding. An important question left unanswered is whether ring shedding and associated leakage are driven by these local dynamical processes or by the far-field conditions imposed by the large-scale forcing. This issue was recently addressed by *Nof and Pichevin* [1996] and *Pichevin et al.* [1999]. In a nonlinear reduced gravity model it was shown that if an inertial, uniform, potential vorticity-conserving flow on the beta plane enters and leaves a bounded domain as a parallel geostrophic flow across the eastern boundary, if it retroflects steadily within the domain (turning eastward), and if this all happens at the characteristic length scale of the internal radius of deformation, then there can be no integrated momentum flux balance over the boundaries of the domain. This so-called "retroflection paradox" may be solved by the periodic shedding of rings. A major question that was left unanswered by the previous studies is whether the generation of Agulhas rings is the only possible way to balance the momentum of a retroflecting current. After all, *Moore and Niiler* [1974] and *Ou and de Ruijter* [1986] both found analytical solutions for steadily retroflecting currents. Dedicated numerical experiments showed that there are indeed two possible regimes for retroflecting currents: one shedding rings and one not [T. Pichevin, What leads retroflecting currents to shed eddies?, *J. Phys.Oceanogr.*, Submitted, 1999.]. The solution depends upon two main parameters, the latitude of retroflection of the current compared to the latitude of the tip of the continent and the angle of the coast. In all cases the retroflected current meanders, and those meanders have a tendency to drift westward under the influence of beta, eventually closing upon themselves to form rings. Whether or not these rings will subsequently be shed is then the crucial point. The geometrical configuration of the coastline from which the current retroflects plays a key role in that respect. In the reduced gravity model [T. Pichevin, What leads retroflecting currents to shed eddies?, *J. Phys.Oceanogr.*, Submitted], when the coastline continues beyond the retroflected current and when it is not sufficiently tilted to permit a fast enough along-wall eddy drift, rings could not escape from the approaching current and could not be shed. Otherwise, rings were produced. With the Agulhas system parameters the solution did indeed appear to be the shedding of rings. In a reduced gravity model the generation of rings seems to be inherent in the structure of a retroflecting current. In the real stratified ocean the momentum imbalance mentioned above could also be resolved by, e.g., the generation of a flow in the lower layers [*Boudra and de Ruijter*, 1986].

The possible role of Natal Pulse type meanders on ring shedding was addressed using a reduced gravity model [*Pichevin et al.*, 1999]. Without any pulse Agulhas rings were shed at regular intervals (that were too large compared to the observations). Inclusion of meanders in the upstream Agulhas did not change the frequency of ring shedding significantly. However, a short pulse in the strength of the upstream Agulhas did cause the shedding of an Agulhas ring some time later. The experiments suggested that only transport pulses can trigger ring formation and only if their own periodicity is close to the natural periodicity of Agulhas loop occlusion. Otherwise the transport pulses seem to contribute to the aperiodic character of ring generation [*Pichevin et al.*, 1999]. It has been argued that the formation of Natal Pulses is caused by barotropic instabilities of the Agulhas Current close to Durban [*De Ruijter et al.*, 1999], where the stabilising slope topography relaxes. This instability seems to be triggered by anticyclonic seaward anomalies that show up in the altimeter signal., Sometimes such anomalies seem to be related to rings that are shed in the retroflection southeast of Madagascar or that enter the area via the Mozambique Channel [e.g., *Gründlingh*, 1995; *Biastoch and Krauss*, 1999; *Van Leeuwen et al.*, 1999]. Their effect on the path of the Agulhas Current seems very small, except if the rings hit the Natal Bight [*Gründlingh*, 1995]

5.4. Eddy-Permitting Models

To simulate the interocean exchange numerical models must describe the Agulhas Current and its retroflection, ring shedding, and drift, i.e., the leakage of warm and salty water into the Atlantic, in a qualitatively and quantitatively correct way. Successful simulations of the formation and drift of Agulhas rings and other vortices depend on parameters such as grid resolution and viscosity [e.g., *Chassignet et al.*, 1989]. The vertical coordinate system, governing equations, boundary conditions and details of geometry all have direct impacts on the number of model rings formed, their lifetime, and propagation speeds [*Chassignet*, 1992].

Comparisons of models with different resolution [e.g., *Thompson et al.*, 1997] have shown that only models with horizontal grid spacing finer than 1° have the potential ability to generate Agulhas rings and to fulfil the above requirements. So only these "eddy-permitting" models are treated in the following. Table 7 summarizes the characteristics of all models cited here.

In the Fine-Resolution Antarctic Model [*FRAM Group*, 1991], the simulation of the Agulhas Current system appeared reasonable only in a qualitative sense [*Lutjeharms and Webb*, 1995]. The general mesoscale surface features in FRAM are comparable to those seen by satellites, but the calculated Agulhas transport is too high and, consequently, the model Agulhas Current retroflects too far upstream (see section 5.3). Agulhas rings are too big, too warm and too salty and Agulhas rings are spawned too seldom and too regularly compared with observations with every ring drifting along the same path in the South Atlantic [*Quartly and Srokosz*, 1993].

In the global simulations of *Semtner and Chervin* [1988, 1992] the grid spacing has been refined to a nominal resolution of 1/4° in the current version called the Parallel Ocean Climate Model (POCM), [*Stammer et al.*, 1996] (Table 7). The model Agulhas has a realistic barotropic transport (66 Sv) and retroflects around 20°E (Figure 10). It spawns Agulhas rings too frequently, which travel into the South Atlantic on a too regular path. The temporal variability, compared with satellite data, is too low, a general shortcoming of numerical models with this resolution [*Beckmann et al.*, 1994; *DYNAMO Group*, 1997]. It simulates only 50% of the amplitude of TOPEX/POSEIDON (T/P) sea surface height variability (Figure 3), irrespective of whether monthly or daily wind forcing is applied [*Stammer et al.*, 1996]. As in FRAM [*Thompson et al.*, 1997], there is a clear interconnection between the Indian Ocean and the South Atlantic in the mean field (compare with section 2). The same holds for the global model Ocean Circulation and Climate Advanced Modeling (OCCAM) project (see *William*, [1995] and Table 7), of which, so far, only a movie is available. It indicates a good representation of the Agulhas system (http://www.soc.soton.ac.uk/JRD/OCCAM/).

In the Parallel Ocean Program (POP) [*Maltrud et al.*, 1998] (Table 7) the first baroclinic Rossby deformation radius, computed from the *Levitus* [1982] data, is resolved for latitudes

Table 7. Resolution and Forcing of the Model Runs

	Regional		Global			
	FRAM	AGAPE	POCM	POP	OCCAM	MICOM
Coverage	< 24° S	Atlantic and South Indian Ocean	75°S-77°N	77°S-65°	fully	69°S-64°N
Resolution	1/2° x 1/4°	1/3°	0.4x0.4 cosϕ	0.28x0.28 cosϕ	1/4°	0.225x0.225° cosϕ
At 35° S km	45 x 28	30 x 37	36 x 36	25 x 25	22 x 28	20 x 20
Levels	32	29	20	20	36	15
Wind forcing	HR	ECMWF	3-day ECMWF	3-day	ECMWF	COADS
Thermal forcing	*Levitus* '[1982]	ECMWF	ECMWF	ECMWF	*Levitus* [1982]	COADS
Haline forcing	*Levitus* [1982]	*Levitus* [1994]	*Levitus* [1982]	*Levitus* 82	*Levitus* [1982]	NOAA

Vertical resolution in MICOM is given in number of isopycnic layers Abbriviations are as follows: FRAM, Fine-Resolution Antarctic Model; AGAPE, Agulhas Area Primitive Equation model; POCM, Parallel Ocean Climate Model; POP, Parallel Ocean Program; OCCAM, Ocean Circulation and Climate Advanced Modeling program; MICOM, Miami Isopycnic Coordinate Model; HR, *Hellerman and Rosenstein* [1983]; ECMWF, European Centre for Medium-Range Weather Forecasting; COADS, Comprehensive Ocean-Atmosphere Data Set; and NOAA, National Oceanic and Admospheric Administration.

lower than 40°. One can therefore expect a better ring and eddy formation in this integration. However, temporal variability still reaches only 60% of the variability of T/P [*Maltrud et al.*, 1998; *Fu and Smith*, 1996]. The model does not produce enough rings and their paths are more irregular and realistic if the model is forced by thrice daily than by monthly wind stress data. A direct comparison of POP, POCM and T/P [*McClean et al.*, 1997] shows that the tracks of the Agulhas rings in POP are much closer to T/P than in POCM, a direct consequence of the increased resolution.

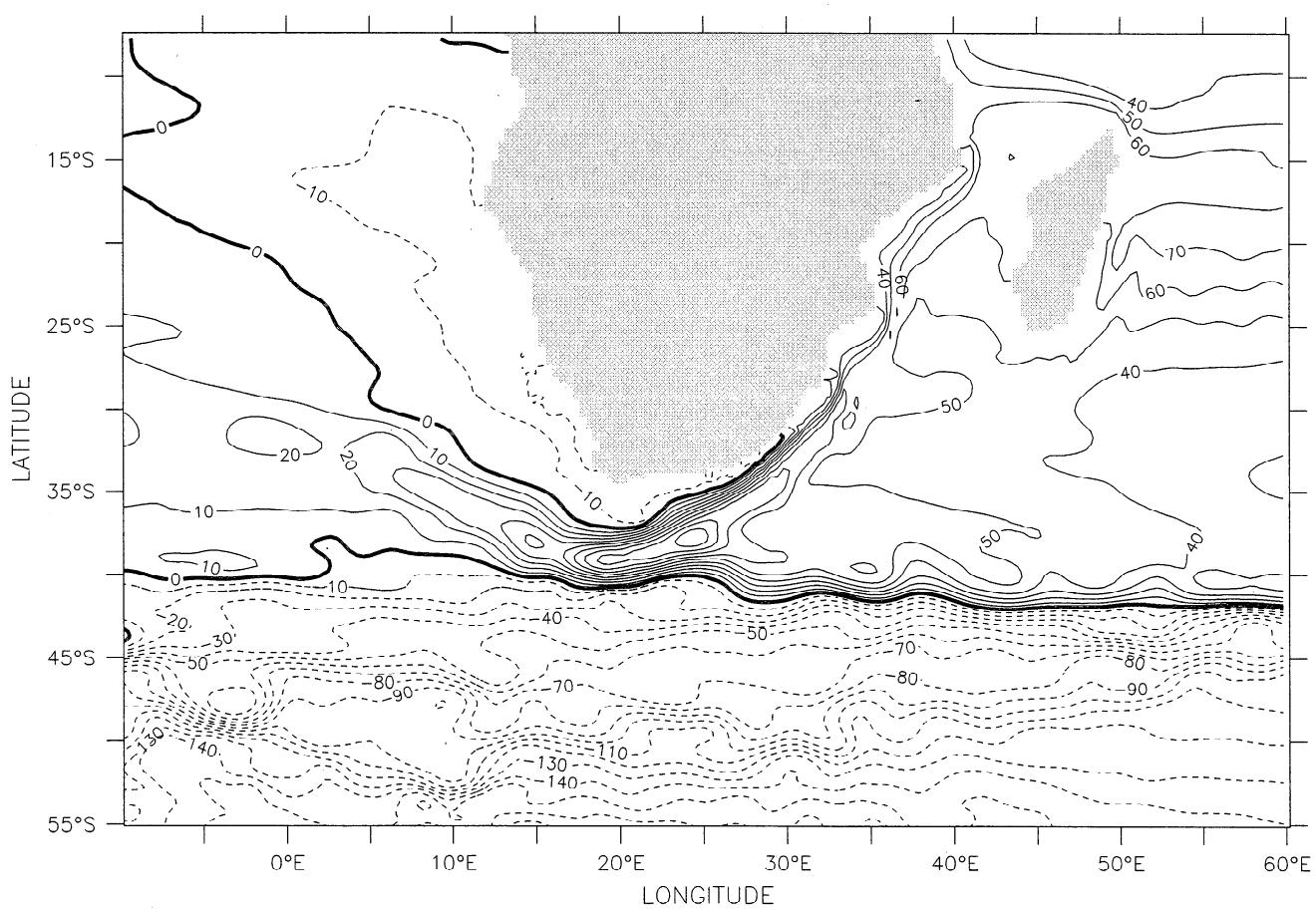

Figure 10. Sea surface height (centimeters) in a 9-year ensemble of an eddy-resolving numerical experiment (Parallel Ocean Climate Model_4B, Table 7). The model resolution was 0.25°. The model was forced with European Center for Medium Range Weather Forecasts (ECMWF) daily wind stresses for the period 1987 through 1994, as well as monthly mean sea surface heat fluxes produced by *Barnier et al.* [1996] from ECMWF analysis.

Other than in the above models, in the Miami Isopycnic Coordinate Model (MICOM) [*Bleck and Chassignet*, 1994] (Table 7), the vertical axis is not discretized in depth levels but in a set of isopycnal surfaces separating layers of constant densities. This partitioning avoids spurious diapycnal mixing and is less sensitive to small-scale topographic variations than level models [*DYNAMO Group*, 1997]. A snapshot of the Agulhas region calculated in a high-resolution (0.225°) global simulation [*Bleck et al.*, 1996, Table 7] suggests a good representation of the mean Agulhas Current and retroflection, but no detailed analysis of the model results is available yet.

In the Agulhas Area Primitive Equation (AGAPE) model, designed for the Agulhas region [Biastoch and Krauss, submitted manuscript, 1998] (Table 7), the connections to the world ocean are made via open boundary conditions [*Stevens*, 1990] with the barotropic transports prescribed from the POCM model. Compared to POCM, the simulated Agulhas Current is focused more along the coast and is somewhat stronger at the surface (Figure 11). Temperature and salinity anomalies of the rings appear to diffuse too fast. The formation and drift of the rings are irregular. Anticyclonic rings traveling from southeast of Madagascar and through the Mozambique Channel toward the Agulhas Current are adsorbed and advected southward by the current [*Biastoch and Krauss*, 1999]. These phenomena, which may have an important impact on the formation of Agulhas rings in the models, exist also in POCM and POP and are probably related to similar features observed hydrographically [*Gründlingh*, 1988] and from satellite altimetry (see also section 2). The mean model Agulhas Current transport and the splitting of the sources of the current into three different branches seem close to the observational results (section 2). The degree of nonlinear recirculation in the gyre is a major difference between observations and model, only half of the observed transport in the model is simulated. (This seems to be related to a too large volume transport (170 Sv) in the Antarctic Circumpolar Current imposed by the POCM model via the open boundary conditions.) Consequently, the mean transport from the Indian Ocean into the South Atlantic is much larger than the observed.

All in all, state-of-the-art models show that a realistic representation of the Agulhas system is possible as far as the mean circulation is concerned. However, the mesoscale variability that quantifies the interocean exchange is still poorly represented. The sensitivity of the solutions to the different parameters of the system indicates that many features have to be improved. In particular, we need models with much higher resolution to correctly simulate essential features such as Natal Pulses or the separation and outcropping of the Agulhas Current.

5.5. Discussion

The dynamics of the interocean exchange as investigated in a series of studies (described earlier) can be roughly subdivided into local studies of retroflection and ring shedding and basin-scale studies (section 5.3). The main issue, not explicitly

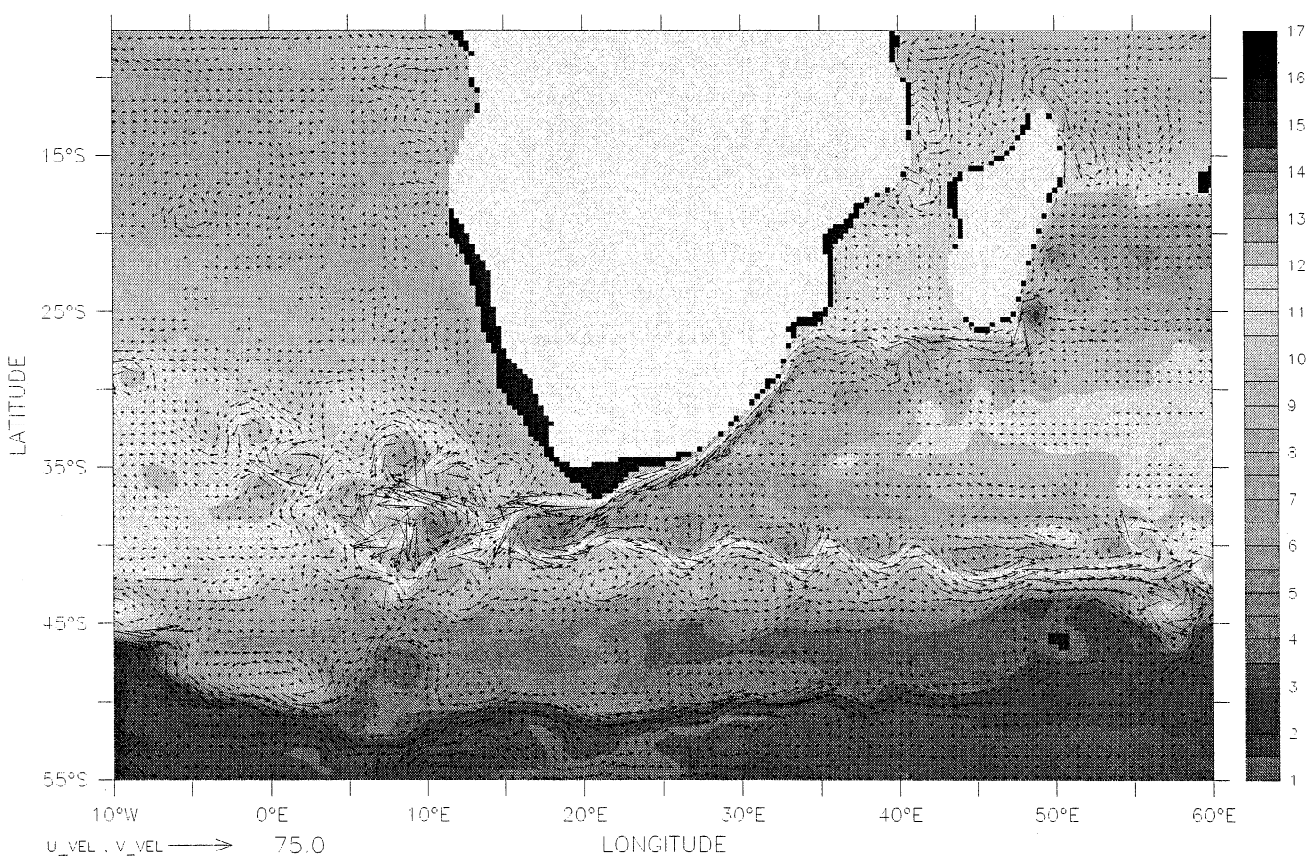

Figure 11. Snapshot of the AGAPE model (see Table 7) showing potential temperature and velocity at 436 m depth for model day 18. (For velocity vectors, every second grid point is shown, values less than 2 cms^{-1} are omitted.)

addressed in these investigations, is how the retroflection, eddy-shedding dynamics, and far field dynamics match: so how important is the structure of the far field, and to what degree are retroflection and eddy shedding local phenomena?

One aspect that emerges from all basin-scale studies is that without forcing over the Atlantic there is a widening zonal band west of South Africa all the way to South America through which the Agulhas leakage flows westward and (if there is no forcing in the South Atlantic to divert it) through which it also returns to close the supergyre. So, conceptually, there is a nonlinear boundary layer region around and west of South Africa where, to first order, potential vorticity is conserved. This region extends westward to South America as a zonal free (inertial) boundary layer (the westward extension due to β). The transport distribution (the 'far field') at the eastern edge of the nonlinear domain then determines how much of the incoming Agulhas transport, all of which enters the boundary layer, retroflects somewhere within the nonlinear zonal band and what part leaks out to the west.

Whether retroflection takes place in the immediate vicinity of the South African tip depends on whether the separated current, while conserving its potential vorticity, can get far enough southward to reach a latitude where the wind already drives an eastward flow in the Indian Ocean. If that is not the case, then the flow has to turn westward and, without additional forcing (e.g., wind), can only close the circuit along South America and return straight zonally to the east within the same boundary layer. This can also happen through rings that form owing to local dynamics. Some widening of the zonal westward flow may be due to, e.g., (eddy) friction. Consequently, part of it can return (retroflect) somewhere between South Africa and America. If a ridge is encountered on the way (or some other mechanism), then this can steer the flow southward and stimulate (earlier) retroflection [*Matano*, 1996]. So any physical mechanism suffices that can bring the flow far enough southward to match the wind-forced eastward current. If far enough southward then the current is forced to turn eastward as determined by the (wind driven) far field. Note that this can happen throughout the zonal band between South Africa and South America.

From the modeling studies it was very clear that it is the meridional excursion of the Agulhas flow after separation from the African continent which determines whether the flow makes a full excursion through the Atlantic or retroflects somewhere on its path. Consequently, if one aims at realistic modeling and estimation of leakage and retroflection then local features need to be included. This means that the local details of baroclinicity, continent geometry, Agulhas separation and inertia, bottom topography, and ring formation all have to be represented with great precision. Moreover, the (mostly) wind-driven circulation in the Indian Ocean that the Agulhas Return Current has to match must have the correct meridional structure. This circulation determines largely the (far field) meridional slope of the isopycnal field into which the separated current is 'squeezed'.

The mean circulation of the Agulhas region appears to be simulated reasonably well in most recent models. However, regarding the mesoscale variability all models have serious problems. None of them reached values as high as those obtained from T/P altimetry [*Stammer et al.*, 1996]. The frequency of ring shedding and the drift paths are sensitive to a series of factors. Finer grid spacing has led to an improvement [*Beckmann et al.*, 1994, *McClean et al.*, 1997], but the levels of eddy kinetic energy still do not reach the values of T/P [*Stammer and Böning*, 1996]. Improved vertical resolution is essential to correctly simulate transports of heat and salt into the South Atlantic and the crucial interaction with topography (see section 5.2). Finer resolution is also necessary for the inclusion of regional features such as Agulhas filaments [*Lutjeharms and Cooper*, 1996], a possible Agulhas Undercurrent [*Beal and Bryden*, 1997], Natal Pulses [Van Leeuwen et al., 1999] and other instabilities of the flow. It is still not clear to what degree these small-scale structures affect the gyre-scale transports.

For a correct simulation of the transport of mass, heat and salt it is necessary to represent realistically the source regions of the Agulhas Current and the Indonesian throughflow [*Ribbe and Tomczak*, 1997] as well as the bathymetry [*Matano*, 1996]. An important point is also the correct forcing at the sea surface by wind, heat and salt fluxes. Daily wind data seem to improve the ring formation and drift [*Maltrud et al.*, 1998], leading to higher mesoscale variability. In POCM, POP, and AGAPE different levels of complexity were used in the thermal flux formulation (Table 7). It is hardly known how these details affect the solution, but it is expected that the choice of the thermal forcing will significantly affect the basin-wide heat transport in the models [*Böning and Bryan*, 1996; *Stammer et al.*, 1996]. Because of the large uncertainties in estimated precipitation, evaporation and river runoff most models restore salinity to climatological values. This must lead to an underestimation of salinity in some regions [*Stammer et al.*, 1996]. Finally, the model type itself may be important. Except for MICOM, all models cited above are level models. No systematic comparisons are available for the Agulhas region. An intercomparison of models of the North Atlantic [*DYNAMO Group*, 1997] shows that level models have serious problems in regions of strong topographic or isopycnal slopes, as is the case in the Agulhas region. In isopycnal coordinate models serious problems could result from their systematic deviation of the thermal wind relation in the deeper layers.

6. Conclusions

The interocean exchange between the Indian and Atlantic Oceans is characterized by high spatial and temporal variability. This means that it is difficult to make reliable estimates of the interoceanic fluxes. The varying fluxes of heat and salt are important climatic components, both locally because of their direct impact on regional climate and the Benguela ecosystem and on a basin and global scale via the wind-driven and thermohaline circulation (section 4).

The shedding of Agulhas rings is highly intermittent. Sometimes very large anticyclonic structures are pinched off [e.g., *Shannon et al.*, 1990; *Arhan et al.*, this issue]. These megastructures may consist of several connected rings. They seem to break up into several rings on encountering the topography of the Agulhas ridge or several of the seamounts in the area. Little is known about the effect of these ring-topography interactions on the mixing of the rings with the surrounding waters. Observed temperature and salinity characteristics on isopycnal surfaces [e.g., *Van Ballegooyen et al.*, 1994] (Figure 12) suggest that double-diffusive interleaving is an important process by which ring properties are transferred to the environment. Air-sea interaction is a dominant water mass transformation process close to the

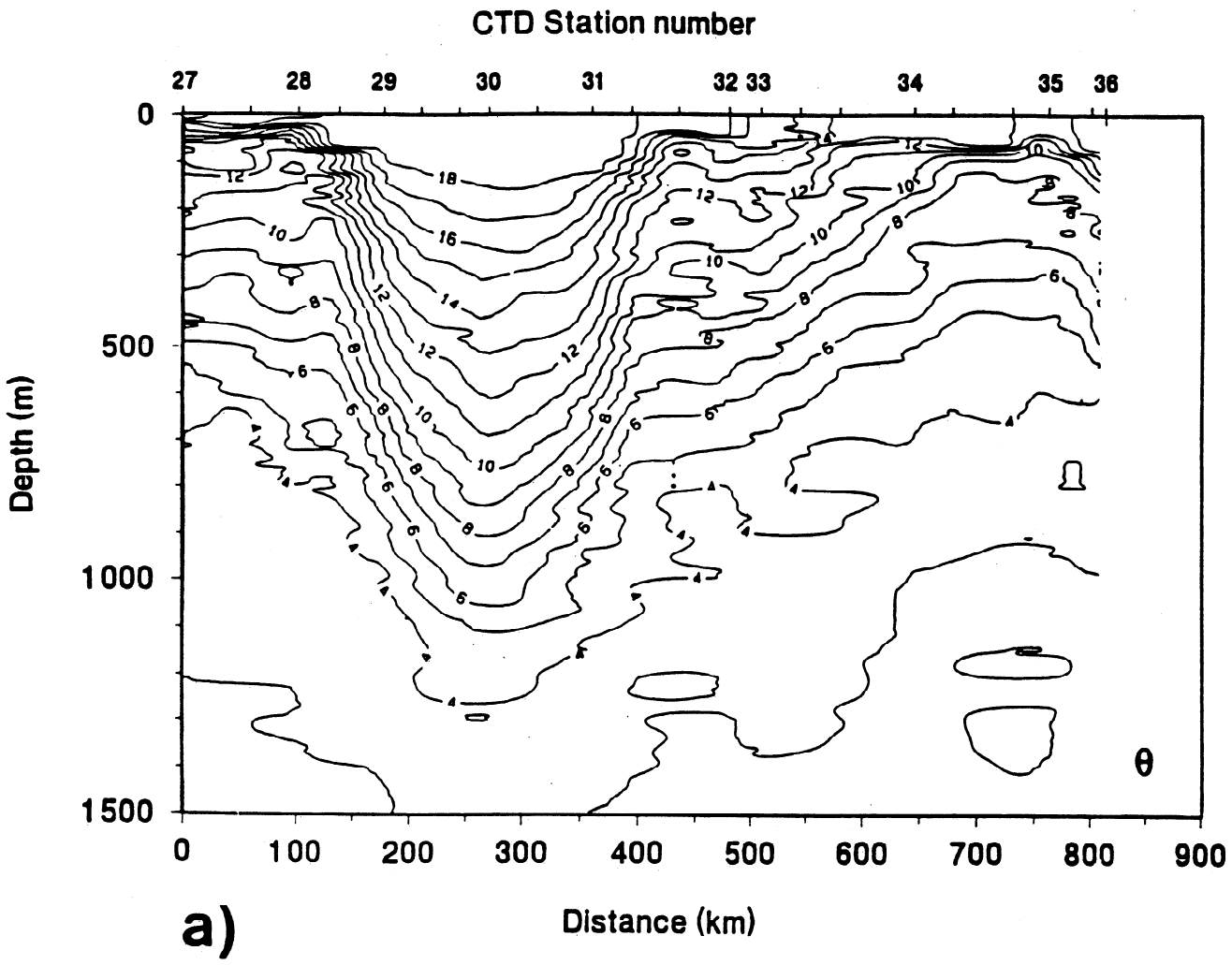

Figure 12. Vertical distribution of properties in an Agulhas eddy observed during a hydrographic cruise in the Agulhas retroflection region in February/March 1987. The section extended from approximately 37°S 17°E to 39°S 13°E (NW to SE). (a) Potential temperature, (b) Salinity, and (c) Potential density [after *Van Ballegooyen et al.*, 1994]. The salinity field indicates strong interleaving as a result of double-diffusive processes.

retroflection [*Olson et al.*, 1992]. In particular, rings that are shed just before the austral winter encounter enormous heat and freshwater fluxes with associated convective modification (section 3) when still in the area throughout the winter. Rings shed in spring or early summer experience much less modification and leave the area with characteristics that differ markedly from those of winter cousins. Double diffusion seems to be active all along their northwestward path into the South Atlantic [*Arhan et al.*, this issue]. The rings are very salty and warm compared to their surroundings, meeting the necessary conditions for salt fingering and double diffusive interleaving. To estimate the role of the different mixing processes in the decay of the rings and quantify the transfer of their properties into the surrounding waters one would have to follow them on their path through the area. The evolution of their surface expression can be followed remotely by satellite altimetry, but the interleaving and mixing below the surface can only be quantified by repeated in situ observations. Detailed descriptions of quite a few rings have been (section 3) and are still being made [e.g., *Boebel et al.*, 1998] as a result of ship-borne observations. However, each individual ring has different properties upon being shed and has gone through a different history of transformation and mixing when investigated. Such one-time hydrographic surveys provide very useful snapshots of individual rings and the combination of several tracers has given important information on their life history; but, to quantify the partitioning of their heat and mass transfer into the Benguela, the South Atlantic wind-driven gyre or the global thermohaline overturning circulation, one has to reexamine the same ring and its surroundings several times.

Together with their input of volume, heat, salt, and energy, the Agulhas rings contribute a considerable amount of anticyclonic vorticity to the South Atlantic subtropical gyre. Their potential vorticity structure upon entering the South Atlantic will strongly influence their paths and fate in that basin. To what degree they contribute to the strength of the South Atlantic anticyclonic subtropical gyre is related to the question of the decay of the rings and their mixing with the gyre. So far, the latter is very poorly known. A portion of the ring vorticity will be mixed into the subtropical gyre, another

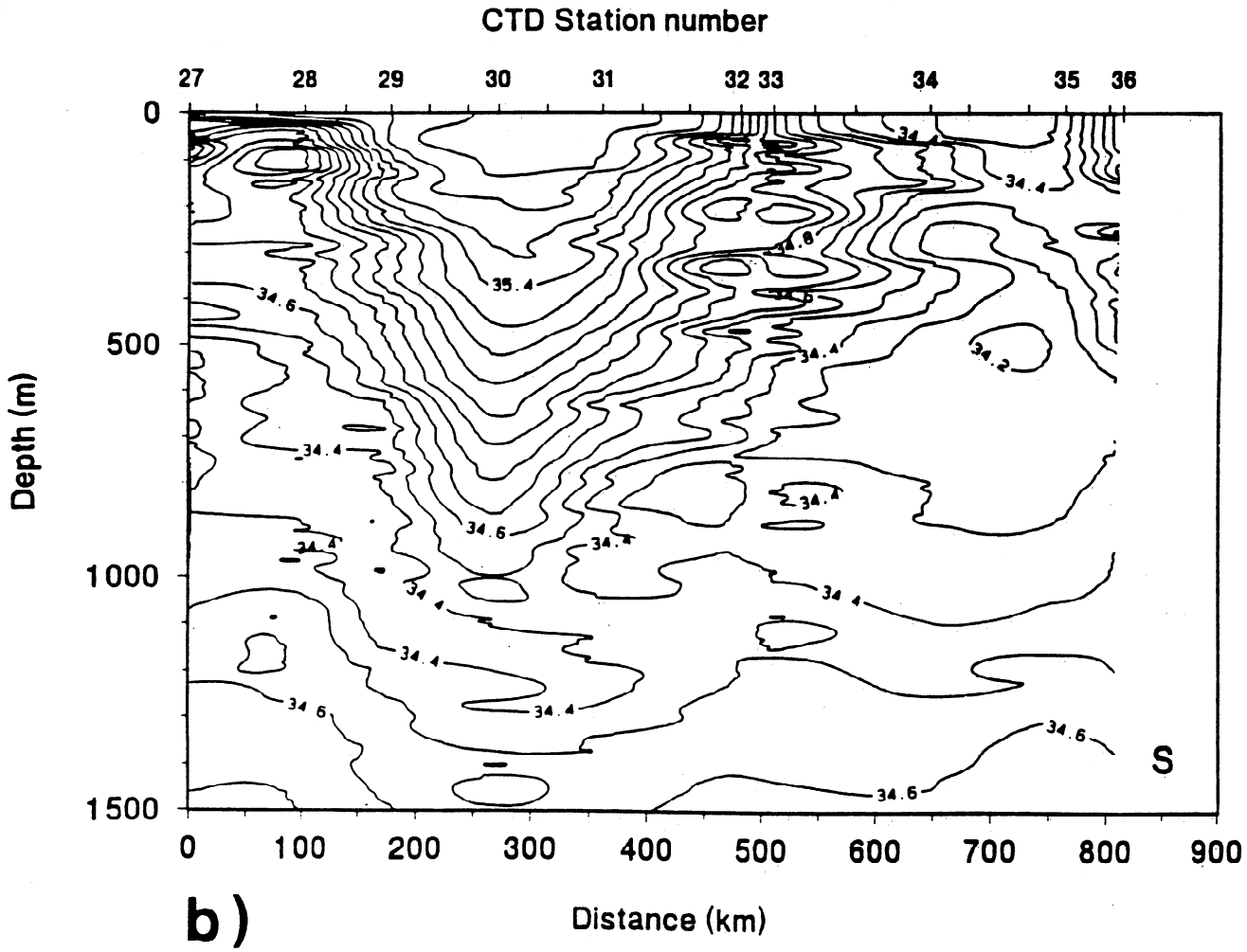

Figure 12. (continued)

part will be dissipated at the western boundary along Brazil and upon crossing the major topographic ridges. Estimates of this partitioning have not yet been made.

Several rings have been observed to travel across the South Atlantic all the way to South America (section 4). There they seem to disappear from the altimeter signal when they are several hundreds of kilometers offshore. What happens to them there is unknown. They will interact with the Brazil Current in some way, probably giving it a sudden transport pulse. This may propagate downstream and have an impact on the cross-gyre exchanges in the Brazil-Malvinas confluence area. Also, these Agulhas rings might leak part of their contents northward [*Nof*, 1988], feeding into and strengthening the North Brazil Current (and, eventually, crossing the equator as part of a thermohaline circulation branch). Clearly, the Agulhas rings affect the stratification of the Atlantic by their heat input and particularly, by their salt input. They also affect the basin-scale circulation of the South Atlantic and, in a subtle and still largely unknown way, the global stratification and thermohaline overturning circulation (sections 4 and 5).

The overall picture that seems to emerge from the modeling and observational studies is that to first order the interocean exchange around South Africa is winddriven, it forces the subtropical supergyre. This exchange is largely interrupted by local retroflection dynamics, including geometric and topographic steering, which allows leakage mainly by rings and filaments. Variations in the supergyre and the exchange are related to variable wind forcing but most probably also to the intrinsic variability of the nonlinear recirculation cell in the southwest corner of the Indian Ocean subtropical gyre. In the next order one encounters the thermohaline component of the flow. Part of the exchange flow takes part in this overturning circulation via small and mesoscale mixing processes that establish the cross-gyre transports of heat and salt but probably also via direct (intermittent) leakage.

The degree to which the interocean exchange is determined by or determines the Atlantic overturning circulation is still a matter of much debate (sections 3, 4 and 5).Global scale ocean-only model studies [e.g., *Shriver and Hurlburt*, 1997] suggest that the rate of North Atlantic Deep Water exchange has a direct impact on the Indonesian Passages throughflow and the Indian to Atlantic Ocean flow. On the other hand, e.g., *Weijer et al.* [1999] have shown that the shape and strength of lateral fluxes prescribed at 30°S have a direct impact on the Atlantic overturning strength. Also, the shutoff of Agulhas leakage that probably appeared during the last glacial period [*Howard and Prell*, 1992] does not give us a clue as to whether this shutoff led to or was led by a cessation of the Atlantic overturning. These questions can only be answered by coupled ocean-atmosphere modeling studies that involve realistic feedbacks between varying interocean exchanges and

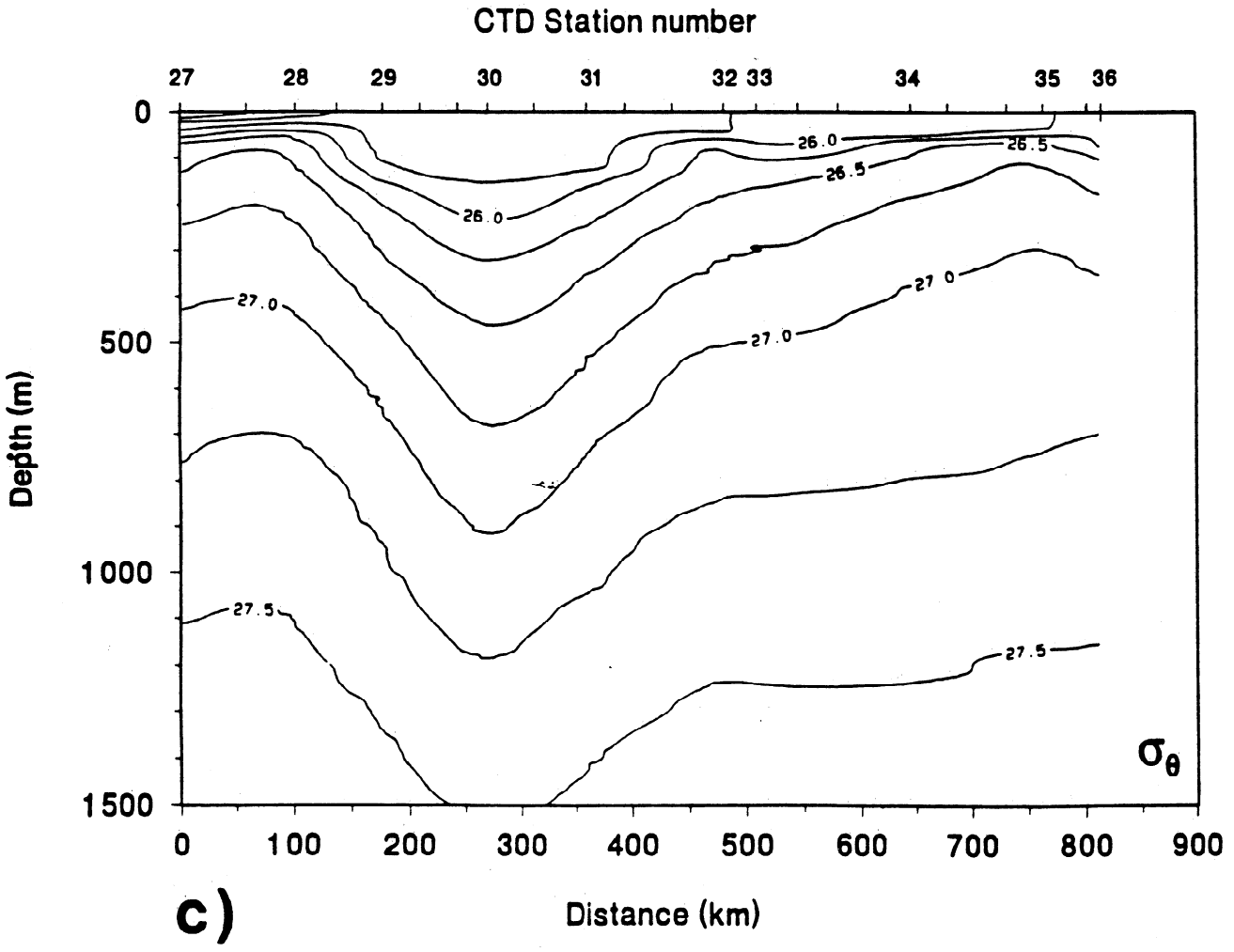

Figure 12. (continued)

changing global-scale buoyancy fluxes across the air-sea interface. More locally a related question to be addressed is whether varying Agulhas leakage is due to intrinsic ocean-only variability, in which also the interaction with the Antarctic Circumpolar Current may be important, or whether there are coupled modes of varying interocean exchange and associated atmospheric pressure field responses.

On the basis of this review of the theoretical, observational, and modeling studies of the Indian-Atlantic Ocean exchange, we can conclude that a very detailed representation of the oceans around South Africa should be an essential ingredient of such studies in the future.

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A.Biastoch, Institut für Meereskunde Kiel, Düsternbrooker Weg 20, 24105 Kiel, Germany. (abiastoch@ifm.uni-kiel.de)

W.P.M. de Ruijter, P.J. van Leeuwen, and W. Weijer, Institute for Marine and Atmospheric Research, Utrecht University, POB 80.005, 3508 TA Utrecht, The Netherlands.(w.p.m.deruijter@phys.uu.nl;leeuwen@phys.uu.nl; weijer@phys.uu.nl)

S.S. Drijfhout, KNMI, POB 201, 3730 AE De Bilt, The Netherlands. (s.s.drijfhout@knmi.nl)

J.R.E. Lutjeharms, Department of Oceanography, University of Cape Town, Private Bag, Rondebosch 7700, Cape Town, South Africa. (johann@physci.uct.ac.za)

R.P. Matano, College of Oceanic & Atmospheric Sciences, Oregon State University, Corvallis,OR 97331-5503. (rmatano@oce.orst.edu)

T.Pichevin, Service Hydrographique et Oceanographique de la Marine (SHOM), 13 rue de Chatellier, BP 426, 29275 Brest Cedex, France. (pichevin@shom.fr)

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