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Natal pulses and the formation of Agulhas rings

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Abstract. Large solitary meanders form on the Agulhas Current at irregular intervals as it travels along the east coast of South Africa. These so-called Natal pulses are thought to have a significant effect on the shedding of Agulhas rings downstream at the Agulhas Retroflection and thereby on the exchange of water properties between the Indian and the Atlantic Ocean. Data from the Geosat, ERS 1, and TOPEX/Poseidon satellite altimeters and Advanced Very High Resolution Radiometer (AVHRR) infrared imagery from the Pathfinder project are analyzed and show that this intuitive idea seems to be correct. Close to the coast, individual altimeter tracks are used to identify the cyclonic Natal pulses as depressions in the sea-surface topography. Using different tracks, the pulses can then be followed from close to Durban to the Agulhas Bank. They show that each shedding of an Agulhas ring is preceded by the appearance of a Natal pulse close to Durban. A significant correlation is found with a time lag of 165 days. Interpolated topography maps are used to follow pulses along the Agulhas Bank to the ring-shedding area. They indicate that sometimes pulses trigger ring shedding by themselves or by merging with Rossby wave-like meanders in the Agulhas Return Current. Infrared imagery supports these interpretations.

1. Introduction

The Agulhas Current is a major western boundary current flowing along the east coast of South Africa. Its water originates from the Mozambique Channel *[e.g., Sætre and Jorge da Silva [1984]]* and from east and south of Madagascar and is part of the subtropical gyre in the Indian Ocean *Stramma and Lutjeharms, 1997]*. When the Agulhas reaches the tip of the continent, it makes a large, anticyclonic turn and meanders back eastward into the southern Indian Ocean as the Agulhas Return Current. Near the turning point in the retroflection area (Figure 1) large anticyclonic rings are pinched off that travel into the South Atlantic Ocean *[Olson and Evans, 1986; Lutjeharms and Gordon, 1987; Gordon and Haxby, 1990; Naeije et al., 1992; Feron et al., 1992; Goni et al., 1997]*. These rings are the largest in the world ocean and, together with direct Agulhas leakage, are thought to establish a critical link in the global thermohaline circulation and thus in regional and global climate variability *[Veronis, 1973; de Ruijter, 1982; Gordon, 1986:* Gordon et al., *1992; de Ruijter et al., 1999b]*.

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The shedding of Agulhas rings is strongly related to the retroflection of the current. A number of explanations have been proposed for this retroflection (see *de Ruijter et al. [1999b]* for a review). The anticyclonic turn of the Agulhas follows from conservation of potential vorticity *[Ou and De Ruijter, 1986; de Ruijter and Boudra, 1985; Boudra and Chassignet, 1988; Lutjeharms and Van Ballegooyen, 1984]*.

The relation between ring shedding and retroflection was first investigated by *Ou and De Ruijter [1986]*. They used a reduced gravity model to study the separation and subsequent path of an inertial boundary current from a curved coastline. The volume transport of the current, the coastline curvature, and the angle of separation were found to be critical parameters. A larger volume transport results in earlier separation, increased generation of anticyclonic vorticity, and a sharper eastward turn at a lower latitude. A small volume transport can even cause the current to completely round the continent. For parameter values corresponding to the Agulhas, the theory predicts the jet to double back on itself and thus form a ring. It shows that the Agulhas is strong enough to make the anticyclonic turn and flow back into the Indian Ocean but, at the same time, is weak enough to double back, thus producing large, anticyclonic rings. In an isopycnic numerical model study, *Chassignet and Boudra [1988]* identified the possible importance of stretching on the retroflection dynamics. *Matano [1996]*, using the sigma-

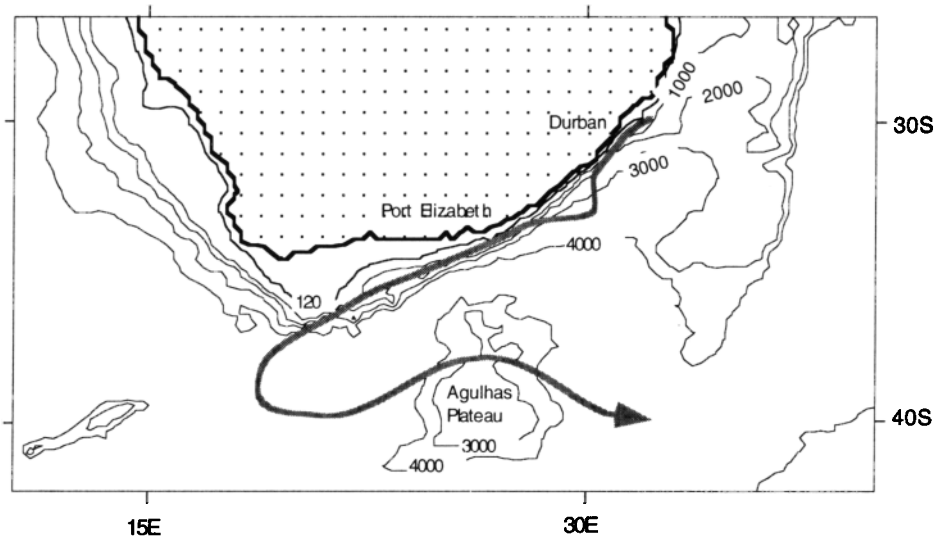


Figure 1. Sketch of the bathymetry and the average Agulhas Current, with a Natal pulse superimposed. In the Natal Bight area, near Durban, the relative weak bottom topographic slope allows the development of Natal pulses.

coordinate primitive equation Princeton Ocean Model (POM), showed that bottom topography may play a role in stabilizing the retroflection.

Recently, *Pichevin et al. [1999]* proposed that ring shedding may also be related to a momentum imbalance in the retroflection area. In their reduced gravity model the eastward transport of eastward momentum is proposed to be compensated by a westward momentum transport due to eddies. However, their analysis assumes parallel geostrophic currents in and out of the retroflection area separated only a few Rossby radii from each other. This does not apply to the meandering Agulhas Return Current, which takes place at much larger scales.

The present paper investigates the possible influence of large meanders in the Agulhas Current, so-called Natal pulses *[Lutjeharms and Van Ballegooyen, 1988b]*, on ring shedding. These solitary meanders have been observed in the trajectory of the Agulhas Current along the east coast of South Africa *[Harris et al., 1978; Gründlingh, 1979; 1992, Lutjeharms and Van Ballegooyen, 1988a, b]*. They generally seem to originate close to Durban in the Natal Bight area (see Figure 1), propagate downstream at a speed of 20 km/d, and can grow laterally to 200 km. The meanders grow while traveling southwestward, and their speed decreases to 4.5 km/d on reaching the Agulhas Bank *[Lutjeharms and Roberts, 1988]*. As hypothesized by *Lutjeharms [1989]*, these meanders may influence the shedding of Agulhas rings.

Recently, *de Ruijter et al. [1999a]* have detected these Natal pulses in individual tracks of Geosat, ERS 1 and TOPEX/Poseidon satellite altimeter data. They showed that the Natal pulses are most probably related to barotropic instability of the Agulhas Current in the Natal Bight area, where the topographic gradient of the continental slope relaxes. The instability seems to be triggered by offshore eddies, which perturb the volume transport of the Agulhas Current.

Feron et al. [1992] and *Feron [1995]* used interpolated maps from Geosat altimeter data to identify the actual shedding of Agulhas rings. Using principle oscillating pattern (POP) analysis, a technique that combines principle component analysis (PCA) with propagation information obtained from lagged covariance matrices *[Hasselman, 1988]*, the instants of ring shedding could be determined from maxima of the time derivative of the correlation of maps of the retroflection area *[Feron et al., 1992]*. *Feron [1995]* confirmed that these instants coincide with ring formation by applying the same analysis to the U. K. Fine Resolution Antarctic Model *[FRAM Group, 1991]*.

In this paper we combine the Natal pulse detection method by *de Ruijter et al. [1999a]* using satellite altimetry (section 3) with the correlation-gradient technique of *Feron [1995]* (section 4) to investigate the correlation between the appearance of Natal pulses and ring-shedding events (section 5). The influence of Natal pulses on the actual ring sheddings is studied in more detail using interpolated maps of sea-surface height of the retroflection area. The results from altimetry are confirmed by thermal infrared imagery.

2. Satellite Observations

Geosat altimeter data for the period November 1986 to September 1989 and ERS 1 and TOPEX/Poseidon data for the period April 1992 to December 1993 have been used for the analysis. The sea-surface height was derived from corrected altimeter heights using crossover minimalization with a Fourier series model up to degree 2 *[e.g., Wisse et al., 1994]*. The resulting sea-surface heights show only the time-varying part of oceanic features because the time-mean currents cannot be separated from the unknown geoid on the spatial scales of interest. (However, see *Feron et al. [1998].*) The ground track patterns of the satellites in the Agulhas area are depicted in Figure 2.

Individual arcs covering the east African coastal area were used to identify Natal pulses. After April 1988 many Geosat tracks close to the coast were too poor for the clear detection of the pulses.

To study the path of the pulses into the retroflection area distance-weighted interpolation was used to produce 0.5° by 0.5° weekly interpolated maps. The interpolation was a Gaussian weighting in space and time with a decorrelation length of 0.5° and a decorrelation time of 1 week. The resulting images are visually the same as those obtained with collocation, the best linear unbiased estimator.

The altimeter observations are complemented with infrared data from the Pathfinder project *[Pathfinder Ocean Project, 1994]*. We used the "best" daily averaged data product interpolated to a 9 km grid (Plate 1). A serious problem with infrared data in this area is the persistent cloud coverage. For instance, in 1987 the Agulhas was not visible for ~80% of the time; the percentages in 1992 and 1993 were even higher. In contrast, the altimeter signal is not very sensitive to cloud cover. However, in the latter case, no information is available between the satellite tracks.

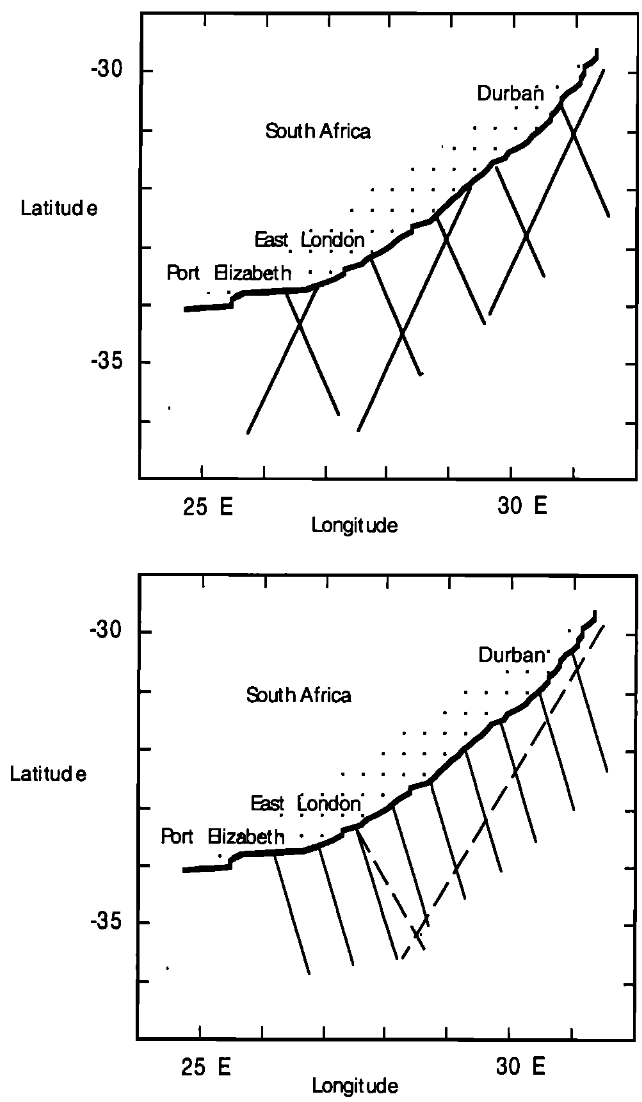


Figure 2. Altimeter ground tracks along the southeast coast of South Africa from (a) Geosat and (b) ERS 1 and TOPEX/Poseidon (dashed line).

3. Identification of Natal Pulses

From thermal infrared and hydrographic data a Natal pulse has been characterized as a solitary cyclonic meander in the Agulhas *[e.g., Lutjeharms and Roberts, 1988; Gründlingh, 1992]*. It has been shown to propagate with a velocity of 13 to 22 km/d downstream, growing in size from 30 to sometimes 200 km. Our infrared data confirm this picture. As mentioned before, persistent cloud cover over large parts of the Agulhas Current makes identification of Natal pulses and their subsequent movement very difficult.

Altimetry provides complementary information because a moving cyclonic feature is visible as a sea level depression along altimeter tracks. The diameter of the Natal pulse as shown in Figure 3 is ~120 km and its sea level anomaly is 75 cm. This pulse is the same as that observed by *Gründlingh [1992]* on a National Oceanic and Admospheric Administration thermal infrared image. Close to Port Elizabeth, its diameter has increased to about 200 km, and its topographic depression has deepened to 90 cm. Its propagation velocity of ~20 km/d is in agreement with earlier estimates from thermal infrared images *[Lutjeharms and Roberts, 1988]*. The swirl velocity of the pulse may give an estimate of the current velocity in the Agulhas. Assuming geostrophy, the swirl velocity is of the order of 0.9 m/s.

In Figure 4 the altimeter data from Geosat, ERS 1 and TOPEX/Poseidon are combined with all usable infrared data to identify the Natal pulses over the period November 1986 to December 1993 (with a gap of 3 years, for which no altimeter data exist).

Propagating Natal pulses are identified when a series of cyclonic anomalies lies along the altimeter tracks, roughly on a straight line with a slope that corresponds with the propagation velocities from earlier estimates *[Lutjeharms and Van Ballegooyen, 1988b]*. In all but one case this identification by altimetry was confirmed by infrared imagery (and vice versa, Figure 4). Occasionally, the complete east coast of South Africa can be seen on an infrared image. When no pulse was present on such an image, this is indicated as a stippled horizontal line in Figure 4.

The results of this procedure are the dashed lines in Figures 4a and 4b. Six Natal pulses can be identified in Figure 4a and five in Figure 4b. They originate close to Durban and travel south along the coast. The large scatter that is sometimes observed in the altimetry data is not completely understood. Part of it may be due to the fact that sometimes more than one meander is

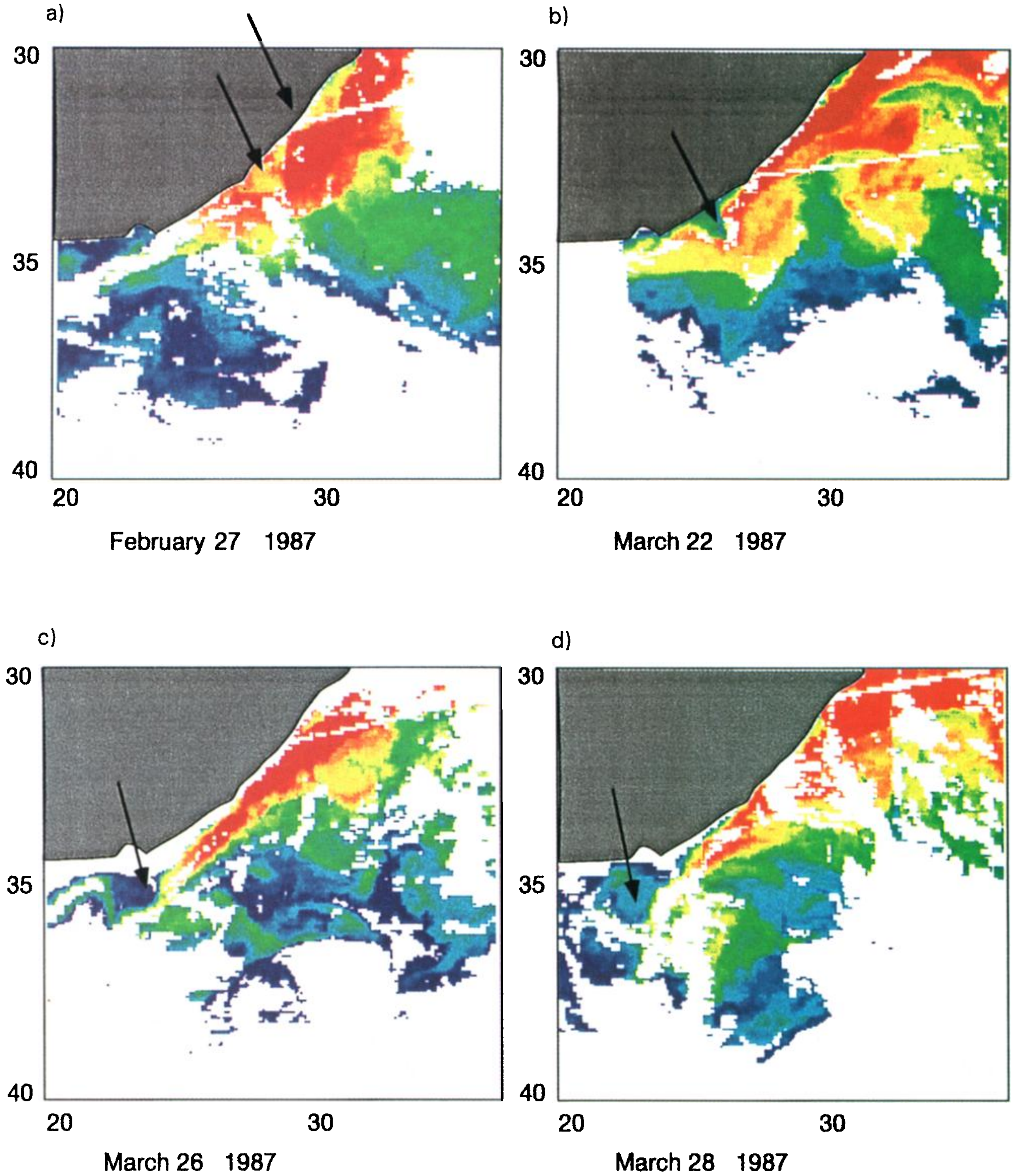


Plate 1. Infrared images of the area southeast of South Africa. The Agulhas Current is visible as a red ribbon, a Natal pulse as an offshore cyclonic meander, indicated by black arrows. (a) February 27, 1987, two pulses are visible. (b) March 22, 1987, a pulse is visible near Port Elizabeth. The growth and downstream propagation of the same pulse is clearly visible on (c) March 26 and (D) March 28, 1997. Eventually, it seems to interact with a westward propagating Rossby wave on the Agulhas Return Current, leading to early retroflection of the Agulhas Current. This picture is confirmed by the altimetry observations (see Figure 6).

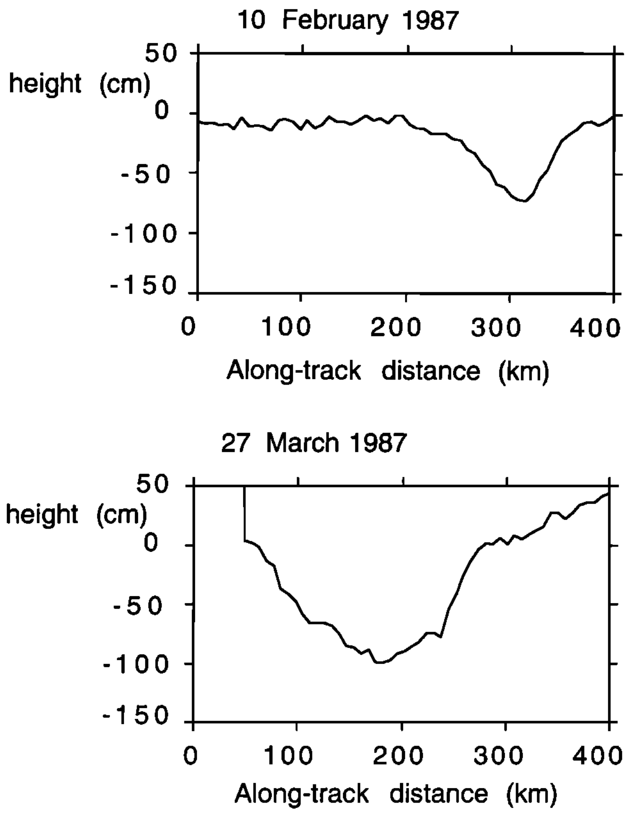


Figure 3. Sea-surface height anomaly (in cm) and distance along individual tracks measured from the land boundary (in km) (a) on a Geosat track close to Durban at Feb. 10, 1987, (b) on a GEOSAT track close to Port Elizabeth at March 27, 1987 (compare with Plate 1a).

present in a pulse as defined above (e.g., see Plate 1). The pulses as located with altimetry agree remarkably well with the pulses determined from the infrared data.

Between 600 and 800 km downstream from Durban a large number of cyclonic features appears which do not seem to be related to cyclonic anomalies farther upstream. This is probably due to the fact that the Agulhas flows along the Agulhas Bank from thereon, so the current reacts to a more relaxed bottom topographic slope, leading to local instabilities and meander formation *[Goschen and Schumann, 1990]*.

Natal pulse movement downstream from Port Elizabeth, more than 800 km from Durban, is not well known. Estimates of only 4.5 km/d have been made, but these are based on two readings only *[Lutjeharms and Roberts, 1988]*. We have been able to follow one pulse farther south in the infrared data and found a propagation speed of ~5 km/d, confirming the earlier estimate.

4. Identification of Ring-Shedding Events

It is extremely difficult to identify ring-shedding events in the infrared data. Clouds are so persistent in the retroflection area (up to ~95% in 1993) that only two ring sheddings could be identified from the infrared data (stippled in Figures 4a and 4b). Direct determination from the altimeter data is impossible owing to the highly variable retroflection characteristics. Therefore we applied the correlation gradient method of *Feron et al. [1992]*. They produced weekly interpolated $1^{\circ}x1^{\circ}$ maps of the time-varying sea-surface height from Geosat data of the retroflection area and determined the correlation matrix of the resulting array of maps. A correlation time was defined by Feron et al. as the time at which the correlation drops below 0.5. A ring is assumed to be shed when subsequent maps change relatively rapidly, i.e., when the gradient in correlation time is at a maximum.

We performed the same kind of analysis on the Geosat and the combined ERS 1 and TOPEX/Poseidon data set. We chose the correlation time as the time interval in which the correlation is above 0.8, because it gives rise to well-defined peaks in the gradients (Figure 5). The results did not appear to be very sensitive to the exact choice of the correlation value. Using the value 0.8, the correlation times appeared to be ~5 weeks.

It is not easy to uniquely determine which peak corresponds to a ring-shedding event and which does not. Assuming that the number of ring sheddings agrees approximately with that estimated by *Feron [1995]* and *Goni et al. [1997]*, we derived a threshold level of 2.5 per week for the correlation gradient.

A difference between the Geosat results obtained by *Feron* [1995, Figure 5.10] and our results is attributed to the better quality of our data. The orbit determination for Geosat has improved significantly over time. A more detailed comparison reveals that *Feron [1995]* seems to have missed an event in the period between June 1987 and December 1987. Our results are supported by correspondingly large changes in the associated interpolated maps (e.g. Figure 7).

Obviously, it remains unclear whether the extremes we determined correspond on a one-to-one basis to ring-shedding events, as *Feron [1995]* pointed out as well. Even his comparison with FRAM is not fully conclusive because the anomaly maps show that the real world is much more erratic than FRAM. We will elaborate on this in the next section.

The two occasions that we could identify the shedding of a ring using satellite thermal infrared imagery are close in time to events identified in the altimetry in the manner described above. The fact that the match is not perfect is probably due to uncertaincy in the exact timing as derived from the altimeter maps owing to the altimeter sampling time (~10 days) and the fact that the exact time of separation on an infrared image is subjective. So, although this is in no way a statistical validation, it gives clear support to our analysis.

Applying the above method, we identified 14 (possible) ring-shedding events over a period of ~1200 days (Figure 5). Ring shedding appears intermittently, and interannual variability in ring shedding is clearly visible. The same holds for the appearance of Natal pulses (Figure 4).

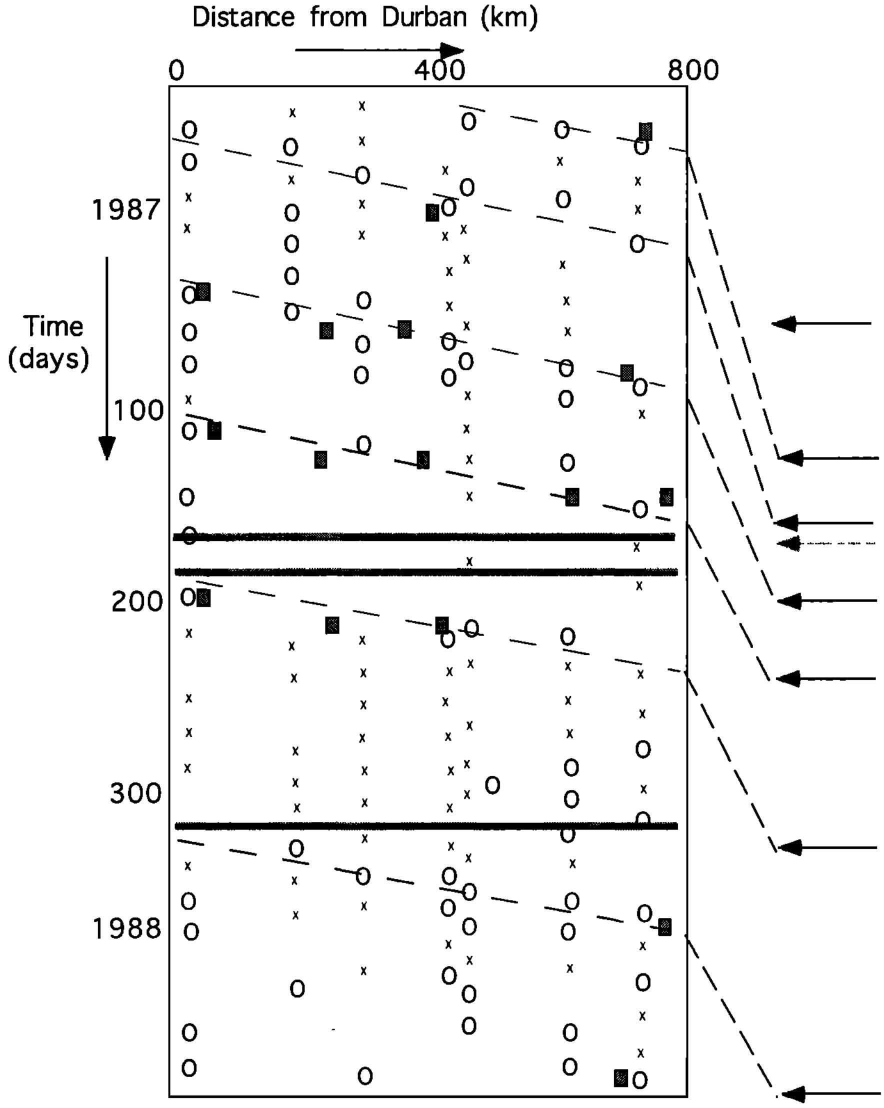


Figure 4. Space-time diagram of altimeter and infrared observations along the southeast coast of South Africa. Distance from Durban along the coast is in kilometers versus time in days. The open symbols denote cyclonic features, crosses denote no significant feature, the absence of a character means poor altimeter data. Stippled squares indicate Natal pulses detected from infrared imagery. Dashed lines show the possible path of a Natal pulse. Stippled horizontal lines denote a cloud free infrared image of the full area in which no pulse was seen. Arrows denote ring-shedding events, and the thick dashed lines represents the connection between arrival of a pulse at 600 km from Durban and a ring-shedding event (see Figure 5). A stippled arrow denotes a ring shedding event as determined from infrared imagery (a) Geosat, time 0 denotes November 1, 1987. (b) ERS 1 (open circles) and TOPEX/Poseidon (open diamonds), time 0 denotes January 1, 1992.

5. Natal Pulses and Ring-Shedding Events

If pulses and ring formation are dynamically connected, the question is which pulse corresponds to which shedding event. The distance from Port Elizabeth to the retroflection region is ~450 km. Assuming a propagation speed over the Agulhas Banks of 4.5 to 5 km/d, as discussed in section 2, it would take a pulse ~100 days to travel this distance. It is unclear what time the highly nonlinear process of actual ring shedding will take, so it is difficult to determine precisely which pulse corresponds to which shedding event, if any.

Nevertheless, to investigate the relation between Natal pulses and ring shedding in more detail, we determined the cross correlation between the two. This is not as simple as it may seem. One could think of using the sea-surface height anomaly time series of the altimeter track closest to the retroflection area, but that track is in an area where numerous smaller-scale meanders appear that are not (directly) related to Natal pulses *[see Goschen and Schumann, 1990 and Figures 4a and 4b].*

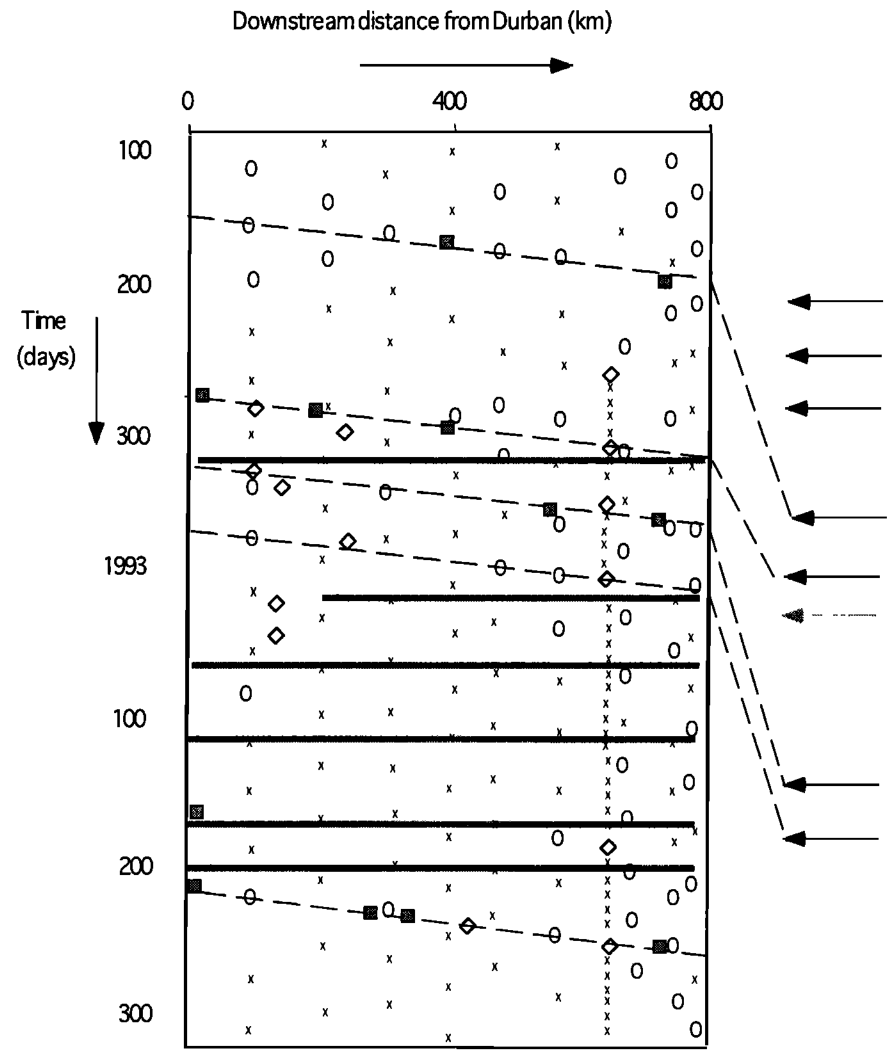


Figure 4. (continued)

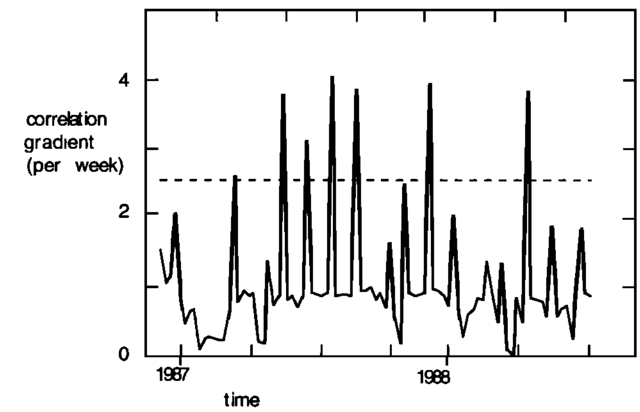
Another possibility is to use the track close to Durban. This track is also not ideal because of missing data, which can strongly influence corelations. We decided to use the starting points of the dashed lines in Figures 4a and 4b, because they comes closest to what we defined as a Natal pulse. A time series was created with positive peaks at the locations where Natal pulses come into existence. To account for timing errors, we centered a Gaussian profile with a standard deviation of 10 days at each peak. This time series was lag correlated with the time series of the shedding events.

Figure 6 shows the lagged correlation for the Geosat and the ERS 1/TOPEX/Poseidon periods. A 95% confidence level on zero correlation is indicated. A significant nonzero correlation can be found at a lag of 170 days for Geosat and 160 days for ERS 1/TOPEX/Poseidon. It is remarkable that the two time periods show the same time lag, supporting our hypothesis that pulses and ring-shedding events are correlated. (Another negative correlation on the edge of significance is found at a lag of 40 days for Geosat. It is unclear what this means at this stage. It might be related to upstream propagating Kelvin wave–like signals that arise due to the shedding of an Agulhas ring, but this is highly speculative.)

Although the correlations are significantly different from zero, a value of 0.35 to 0.5 does not seem too convincing. However, the extreme complexity of the flow field in the retroflection area and the nonlinearity of the shedding process itself are likely to give rise to different time lags at different periods of time. The cross-correlation method gives at least an objective measure of relations between pulses and shedding events.

If we use a time lag of 165 days to reanalyze the connection between pulses and shedding events in Figure 4a, six ring shedding events can be related to Natal pulses, a one-to-one correlation in this time interval. In Figure 4a this possible correlation is indicated by the dashed lines to the arrows. The same is true for all five events in Figure 4b.

The above results indicate a temporal correlation between the arrival of a Natal pulse in the retroflection area



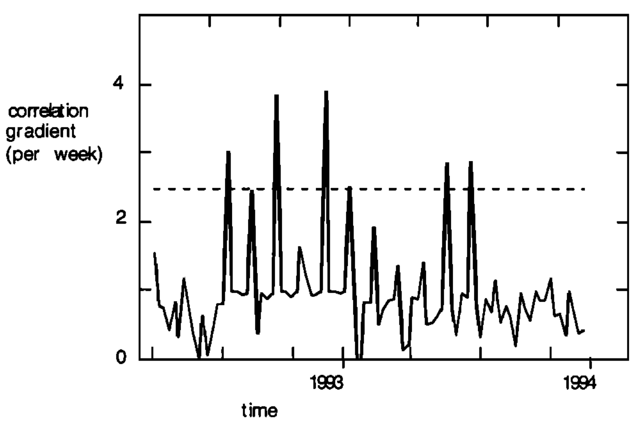


Figure 5. Rate of change of the correlation time given in per week. The correlation time is the time at which the correlation between two interpolated retroflection patterns becomes smaller than 0.8. The dashed line is a threshold level: peaks above this level denote probable ring-shedding events. (a) Geosat starting Novovember 1, 1986, and (b) ERS 1 and TOPEX/Poseidon starting April 1, 1992. Note that ring shedding appears intermittently, sometimes at regular intervals (see Geosat period), and sometimes no rings are shed over an extended period (see ERS 1 and TOPEX/Poseidon period).

and a ring-shedding event. This does not necessarily imply that they are causally related: it is possible that the two processes have the same time scale by coincidence. To investigate this, one has to follow the Natal pulses into the retroflection area. Individual altimeter tracks cannot be used for this because the circulation in this area is extremely complex and variable. Therefore we used gridded altimeter data to identify pulses that had been previously detected in the individual-track analysis. This is only possible when the meander has grown large enough to be identified on the maps. Although some pulses can be followed in the retroflection area in this way, most of the time it is impossible to determine their evolution uniquely because the background time-mean flow is only approximately known *[Feron et al., 1998]*.

An example is depicted in Figure 7, showing gridded altimeter observations together with a suggested interpretation of the total current structure, indicated by a streamline. A Natal pulse has been followed up to position (24°E, 36°S) in the first image from the track analysis (see Figure 4). In the next images it slowly moves downstream into the retroflection area. This large meander in the Agulhas (at 22°E, 38°S) seems to cause the shedding of a large anticyclone (at 18°E, 38°S) that can be followed as an Agulhas ring that leaves the area in subsequent images (not shown here).

Another remarkable feature can be seen in Figure 7. *Lutjeharms and Van Ballegooyen [1988a]* have found from thermal infrared images that Natal pulses sometimes cause an upstream retroflection of the Agulhas, or at least an early leakage of upper Agulhas water to the Agulhas Return Current. In Figure 7 the Natal pulse at (27°E, 35°S) interacts with a large meander in the Agulhas Return Current over the Agulhas Plateau. In the last two images a connection between the two meanders seems to have been established, thus forming an early retroflection of the Agulhas. A comparable situation might be visible in the infrared images given in Plates 1c and 1d.

Sometimes Natal pulses seem to interact with Rossby wave-like meanders in the Agulhas Return Current west of the Agulhas Plateau. These meanders propagate slowly westward. In Figure 8 an interaction of this kind is depicted. In Figure 8 (top) a Natal pulse arrives at (25°E, 35°S) and a Rossby wave-like meander can be observed at (23°E, 40°S). In the subsequent images, two smaller rings seem to be shed from the main current as a result of the amalgamation of the meanders.

6. Summary and Discussion

The impact of growing cyclonic meanders of the Agulhas Current that originate in the Natal Bight, so-called

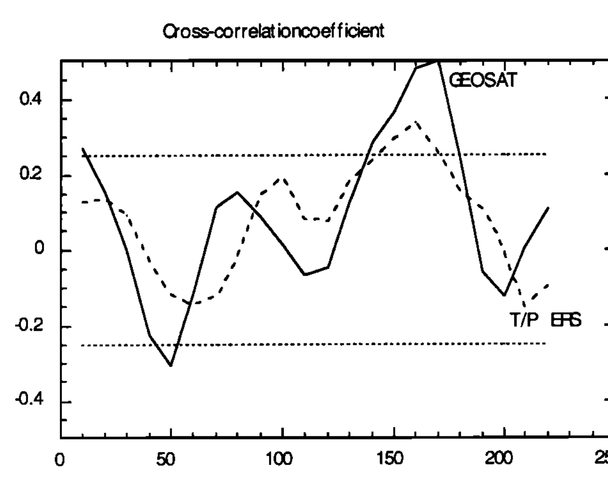


Figure 6. Cross-correlation coefficient between the appearance of Natal pulses close to Durban and the shedding of Agulhas rings. The confidence interval on zero correlation is 0.25. A significant correlation is found at a time lag of 165 days.

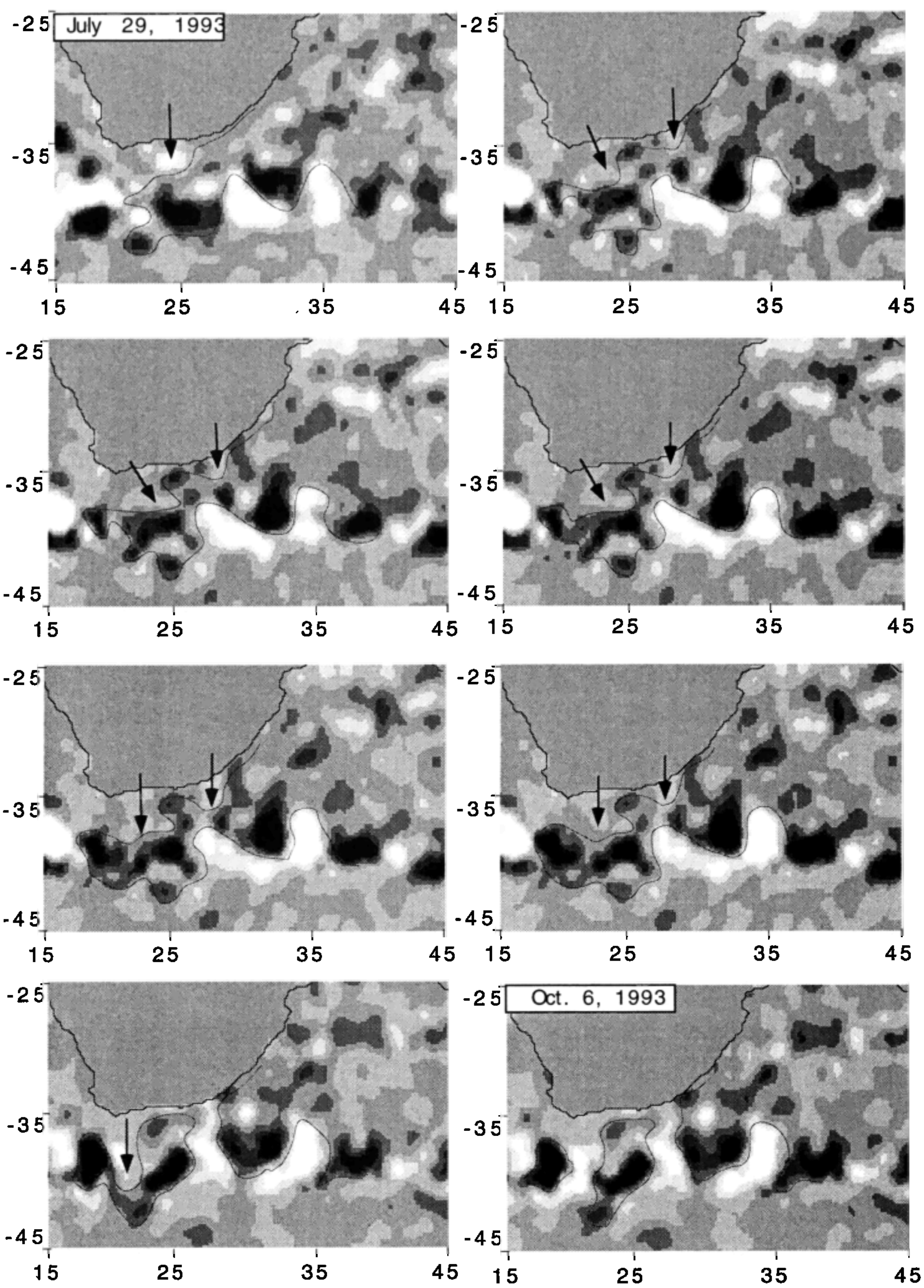


Figure 7. A sequence of sea-surface height maps 10 days apart from July 29, to October 6, 1993. The sequence runs from left to right. White features are cyclonic anomalies (depressions), dark features are anticyclonic anomalies (elevations). The contour interval is 8 cm. The drawn line denotes a possible interpretation of a streamline. Arrows indicate anticyclonic meanders (Natal pulses) at the inshore side of the Agulhas Current. The maps show the pinching off of an Agulhas Ring coinciding with the arrrival of a Natal pulse, which travels from 24°E, 36°S to 22°E, 37°S. They probably also show an early retroflection of the Agulhas at 26°E, 37°S, related to interaction of a Natal pulse and a large anticyclonic meander of the Agulhas Return Current.

Natal pulses, on the shedding of Agulhas rings has been investigated using satellite altimetry and infrared imagery. Geosat, ERS 1 and TOPEX/Poseidon altimeter data complemented with advanced very high resolution radiometer (AVHRR) infrared data have shown that the arrival of Natal pulses at the Agulhas retroflection is correlated with the shedding of large Agulhas rings south of the tip of South Africa. These rings subsequently travel into the South Atlantic Ocean.

Natal pulses could be identified in the time-varying signal of individual altimeter tracks. They appear as sea level depressions with amplitudes of 20 to 90 cm and diameters of 50 to 200 km. Combining different tracks, it has been possible to follow Natal pulses from close to

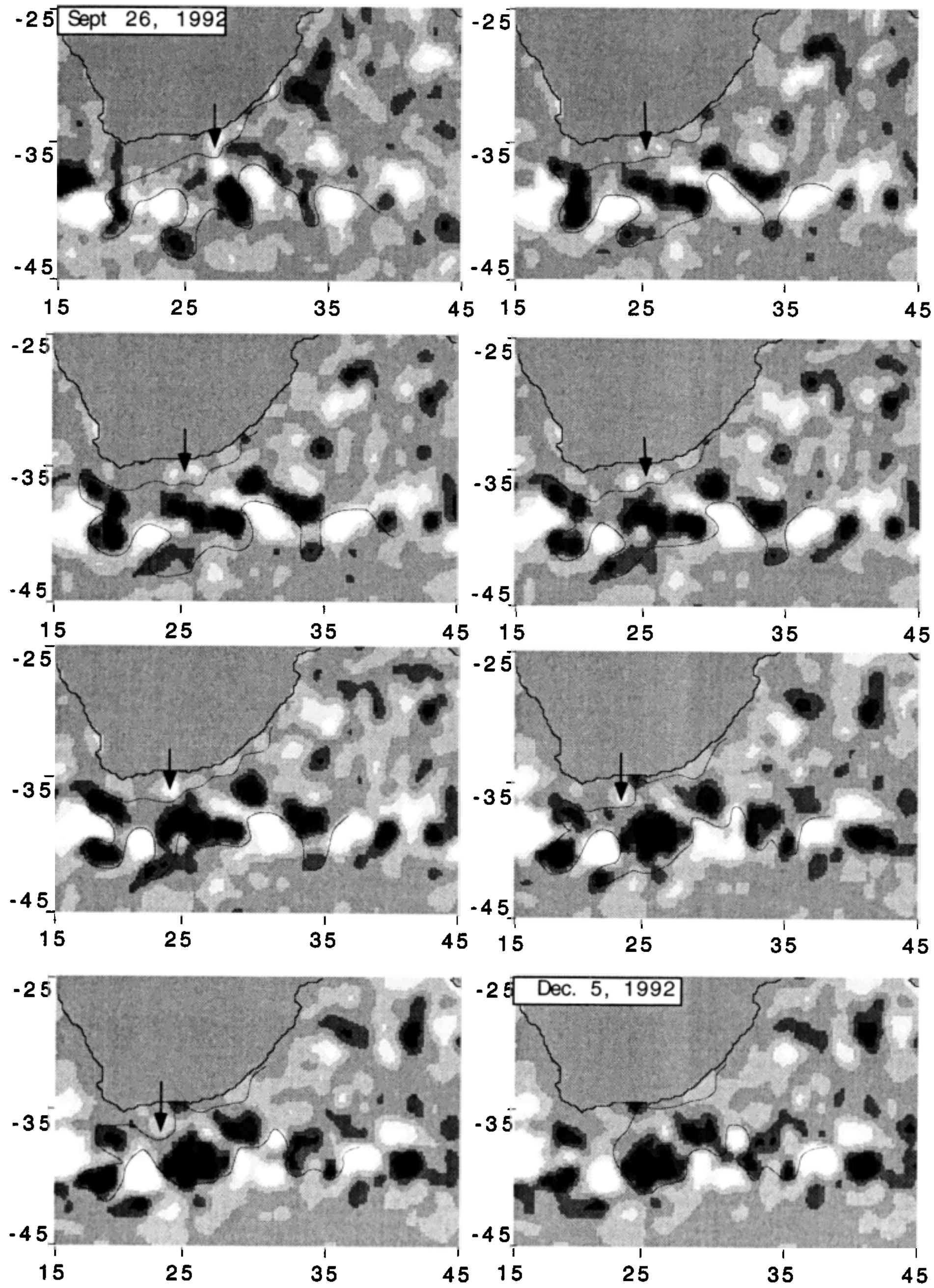


Figure 8. Same as in Figure 6, but from September 26, to December 5, 1992. The maps indicate the pinching off of two Agulhas rings related to the interaction of a Natal pulse from 26°E, 35°S and a Rossby wave-like meander from 23°E, 40°S in the Agulhas Return Current.

Durban to the Agulhas Bank. Almost all of these variations in the altimetric signal have been confirmed to be Natal pulses using available thermal infrared imagery, a totally independent data set.

Each of the appearances of Natal pulses detected in the altimetry data along the South African east coast was followed by the shedding of an Agulhas ring at the Agulhas retroflection with a time lag of ~165 days. The instants of ring shedding have been determined with the correlation technique of *Feron et al. [1992]*. Two ring-shedding events determined in this way could be confirmed using thermal infrared imagery.

Interpolated sea-surface topography maps have been used to show that Natal pulses may trigger ring shedding by themselves (Figure 7) or in strong interaction with Rossby wave-like meanders in the Agulhas Return Current (Figure 8).

The question then arises what the importance is of Natal pulses versus meanders in the Agulhas Return Current for the shedding of Agulhas rings. The latter meanders are larger in amplitude, favoring the cutting short of the Agulhas retroflection loop. However, the Natal pulses in this area are meanders in a nearly freely flowing westward jet. Such jets tend to be more unstable than eastward flowing jets [Gill et al., 1974]: a southward meander of the westward flowing Agulhas will entrain water on its northern and southern sides. On the β plane this entrained water will gain relative vorticity. The currents induced in this way oppose the main current on the northern side and enhance it on the southern side. The result will be a growing southward meander. This interpretation is supported by numerical experiments [e.g., Drijfhout, 1990]. So a relatively small meander like a Natal pulse might have a large impact on closing the Agulhas retroflection loop from the north.

Sometimes Natal pulses seem to cause an early Agulhas retroflection in combination with a northward meander of the Agulhas Return Current (Figure 7). The Agulhas Plateau, a large plateau of ~2 km deep (see Figure 1), might also play a role in this phenomenon. This bottom feature steers the Agulhas Return Current northward, thus decreasing the distance between this current and the Agulhas Current proper. The picture that seems to emerge is that if a Natal pulse has grown large enough on encountering the return current meander over the plateau, then an early retroflection may be expected.

Although some pulses could be followed into the retroflection area, most of the time it is impossible to determine their evolution uniquely without knowledge of the background time-mean flow. In the new approach adopted by *Feron et al. [1998]* the time-mean flow is constructed from altimeter observations without any assumptions concerning the geoid. This method can be used in areas with strong variability and gives realistic results for the Agulhas Return Current and the recirculation into the Agulhas. However, Natal pulses are too close to the continental boundary to apply this method. The solution might lie in assimilating altimeter and thermal infrared data in a numerical model [*van Leeuwen, 1999*].

A remarkable feature of the data sets is the lack of Natal pulse formation over a large part of 1993. If the pulses are important for the shedding of Agulhas rings, this could indicate a lack of rings starting 165 days later. Recently *Goni et al. [1997]* used TOPEX/-Poseidon data to track Agulhas rings from their inception in the retroflection area into the Benguela Current system. They show that no Agulhas ring was formed between April and October 1993, while we predict a lack of Agulhas ring formation from July to the end of 1993. It is not entirely clear to us where the 3 months time difference comes from. Most likely the identification of newly formed rings in Goni et al.'s analysis does not correspond to maximal gradients of decorrelation times. This might be due to their construction of the mean sea-surface topography, which is partly based on the *Levitus [1982]* climatological data. These are known to be in error in the retroflection area itself. So, a large meander in the retroflection area might be mistaken for a separate Agulhas ring. Outside the retroflection area, the method of Goni et al. seems to work well. In spite of this, it is interesting to observe that both methods give a time period of half a year in which no Agulhas ring was shed.

If Natal pulses are of significant importance in ring-shedding events, it is possible that the processes are linked by larger-scale phenomena, such as gyre-scale oscillations. The formation process of the Natal pulses has been investigated by *de Ruijter et al. [1999a]*. They show that pulses are probably due to barotropic instability of the Agulhas Current close to Durban, where the gradient of the continental slope relaxes. An instability may occur when the Agulhas Current increases temporarily in strength. This might be caused by impinging on the Agulhas of cyclonic and anticyclonic features that originate from east and south of Madagascar [*Lutjeharms et al., 1981*] and from the Mozambique Channel. That would suggest a large-scale connection between the dynamics around Madagascar and ring-shedding events south of South Africa. Another possibility is that the recirculation gyre of the Aghulhas system [*e.g. Stramma and Lutjeharms, 1997*] varies on a seasonal or interannual timescale [*Matano et al., 1998*] or that the even tighter recirculation cell that pivots around 30°W, 36°S [*Feron et al., 1998*] has intrinsic variability. Both the appearance of Natal pulses and the varying ring formation at the retroflection might be related to such larger-scale fluctuations. We are currently studying these aspects of the Agulhas Current system.

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References

Boudra, D. B., and E. P. Chassignet, Dynamics of the Agulhas Retroflection and ring formation in a numerical model, I, The vorticity balance, *J. Phys. Oceanogr.*, *18*, 280–303, 1988.

Chassignet, E. P., and D. B. Boudra, Dynamics of the Agulhas Retroflection and ring formation in a numerical model, II, Energetics and ring formation, *J. Phys. Oceanogr.*, *18*, 304–319, 1988.

De Ruijter, W. P. M., Asymptotic analysis of the Agulhas and Brazil Current systems, *J. Phys. Oceanogr.*, *12*, 361–373, 1982.

De Ruijter, W. P. M., and D. B. Boudra, The wind-driven circulation in the South Atlantic-Indian Ocean, I, Numerical experiments in a one-layer model, *Deep Sea Res., Part A*, *32*, 557–574, 1985.

De Ruijter, W. P. M., P. J. Van Leeuwen and J. R. E. Lutjeharms, Generation and evolution of Natal Pulses: solitary meanders in the Agulhas Current, *J. Phys. Oceanogr.*, 29, 3043–3055, 1999a.

De Ruijter, W. P. M., A. Biastoch, S.S. Drijfhout, J.R.E. Lutjeharms. R.P. Matano, T. Pichevin, P.J. van Leeuwen and W. Weijer, Indian-Atlantic inter-ocean exchange: Dynamics, estimation and impact, *J. Geophys. Res.*, 104, 20,885–20,910, 1999.

Drijfhout, S. S., Ring genesis and the related transport of heat, momentum and vorticity, *J. Phys. Oceanogr.*, *20*, 1645–1665, 1990.

Feron, R. C. V., The Southern Ocean western boundary currents: comparison of Fine Resolution Antarctic model results with Geosat altimeter data, *J. Geophys. Res.*, *100*, 4959–4975, 1995.

Feron, R. C. V., W. P. M. De Ruijter, and D. Oskam, Ring shedding in the Agulhas current system, *J. Geophys. Res.*, *97*, 9467–9677, 1992.

Feron, R.C.V., W.P.M. De Ruijter, and P.J. van Leeuwen, A new method to determine the mean sea surface dynamic topography from satellite altimeter observations, *J. Geophys. Res.*, *103*, 1343–1362, 1998.

FRAM Group, An eddy-resolving model of the Southern Ocean, *EOS Trans. AGU*, *72*, 169–175, 1991.

Gill, A.E., J. S. A. Green, and A. J. Simmons, Energy partition in the large-scale ocean circulation and the production of mid-ocean eddies. *Deep Sea Res., Part A*, *21*, 499–528, 1974.

Goni, J. G., S. L. Garzoli, A. J. Roubicek, D. B. Olson, and O. B. Brown, Agulhas Ring dynamics from TOPEX/POSEIDON satellite altimeter data, *J. Mar. Res.*, *55*, 861–883, 1997.

Gordon, A. L., Interocean exchange of thermocline water, *J. Geophys. Res.*, *91*, 5037–5046, 1986.

Gordon, A. L., and W. F. Haxby, Agulhas eddies invade the South Atlantic: evidence from GEOSAT altimeter and shipboard conductivity-temperature-depth survey, *J. Geophys. Res.*, *95*, 3117–3125, 1990.

Gordon, A. L., R. F. Weiss, W. M. Smethie, and M. J. Warner, Thermocline and intermediate water communication between the South Atlantic and Indian Oceans, *J. Geophys. Res.*, *97*, 7223–7240, 1992.

Goschen, W.S., and E. H. Schumann, Agulhas Current variability and inshore structures off the Cape Province, South Africa, *J. Geophys. Res.*, *95*, 667–678, 1990.

Gründlingh, M. L., Observation of a large meander in the Agulhas Current, *S. Afr. J. Sci.*, *65*, 49–57, 1979.

Gründlingh, M. L., Agulhas Current meanders: Review and case study, *S. Afr. J. Sci.*, *74*, 19–28, 1992.

Harris, T. F. W., R. Legeckis, and D. van Foreest, Satellite infra-red images in the Agulhas Current system, *Deep Sea Res., Part A*, *25*, 549–561, 1978.

Hasselman, K., PIPs and POPs A general formalism for the reduction of dynamical systems in terms of principal interaction patterns and principal oscillation patterns, *J. Geophys. Res.*, *93*, 11005–11021, 1988.

Levitus, S., *Climatological Atlas of the World Ocean*, NOAA Prof. Paper No. 13, U.S. Govt. Printing Office, 173 pp, 1982.

Lutjeharms, J. R. E., The role of mesoscale turbulence in the Agulhas Current system., *Mesoscale/Synoptic coherent structures in geophysical turbulence*, edited by J.C.N. Nihoul, and B. M. Jamart, pp. 357–372, Elsevier, New York, 1989.

Lutjeharms, J. R. E., and A. L. Gordon, Shedding of an Agulhas Ring observed at sea, *Nature*, *325*, 138–140, 1987.

Lutjeharms, J. R. E., and H. R. Roberts, The Natal Pulse: an extreme transient on the Agulhas Current, *J. Geophys. Res.*, *93*, 631–645, 1988.

Lutjeharms, J. R. E., and R. C. van Ballegooyen, Topographic control in the Agulhas Current system, *Deep Sea Res., Part A*, *31*, 1321–1337, 1984.

Lutjeharms, J. R. E., and R. C. van Ballegooyen, Anomalous upstream retroflection in the Agulhas Current, *Science*, *240*, 1770–1772, 1988a.

Lutjeharms, J. R. E., and R. C. van Ballegooyen, The retroflection of the Agulhas Current, *J. Phys. Oceanogr.*, *18*, 1570–1583, 1988b.

Lutjeharms, J. R. E., N. D. Bang, and C. P. Duncan, Characteristics of the currents east and south of Madagascar. *Deep Sea Res., Part A*, *28*, 879–899, 1981.

Matano, R. P., A numerical study of the Agulhas Retroflection: the role of bottom topography, *J. Phys. Oceanogr.*, *26*, 2267–2279, 1996.

Matano, R. P., C.G. Simionato, W.P.M. De Ruijter, P.J. Van Leeuwen, P.T. Strub, D.B. Chelton, and M.G. Schlax, Seasonal variability in the Agulhas Retroflection region, *Geophys. Res. Lett.*, *25*, 4361–4364, 1998.

Naeije, M. C., K. F. Wakker, R. Scharroo, and B. A. C. Ambrosius, Observations of mesoscale ocean currents from GEOSAT altimeter data, *J. Photogramm. Remote Sens.*, *47*, 347–368, 1992.

Olson, D. B., and R. H. Evans, Rings of the Agulhas Current, *Deep Sea Res., Part A*, *33*, 27–42, 1986.

Ou, H. W., and W. P. M. De Ruijter, Separation of an inertial boundary current from a curved coastline, *J. Phys. Oceanogr.*, *16*, 280–289, 1986.

Pathfinder Ocean Project, J. Vazquez, E. Smith, M. Hamilton, A Van Tran, and R. Sumagaysay, NOAA/NASA AVHRR Pathfinder Ocean Project, Data management plan, JPL PO.DAAC, Pasadena, 1994.

Pichevin, T., D. Nof, and J. R. E. Lutjeharms, Why are there Agulhas Rings, *J. Phys. Oceanogr.*, *29*, 693–707, 1999.

Sætre, R., and A. Jorge da Silva, The circulation of the Mozambique Channel, *Deep Sea Res., Part A*, *31*, 485–508, 1984.

Stramma, L., and J.R.E. Lutjeharms, The flow field of the subtropical gyre in the South Indian Ocean, *J. Geophys. Res.*, *102*, 5513–5530, 1997.

Van Leeuwen, P. J., The time-mean circulation in the Agulhas region determined with the Ensemble Smoother, *J. Geophys. Res.*, *104*, 1379–1390, 1999.

Veronis, G., Model of the world ocean circulation, I, Wind-driven two layer, J. Mar. Res., 31, 228–288, 1973.

Wisse, E., M. C. Naeije, R. Scharroo, A. [illegible] E. Smith, F. C. Vossepoel, and K. F. Wakker, Processing of ERS-1 and TOPEX/POSEIDON altimeter measurements, Tech. Rep. 95-02, Netherlands Remote Sensing Board, Delft, 1994.

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