Eddies at the Subtropical Convergence South of Africa

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ABSTRACT

A descriptive analysis of the occurrence and kinematics of mesoscale eddies at the subtropical convergence south of Africa is presented. Data used in this study include thermal infrared imagery from satellites since 1978 and a number of expendable bathythermograph sections in the geographic area, supported by drift tracks of free-drifting buoys since 1975. The distribution of intense cold eddies to the north and warm eddies to the south of the subtropical convergence shows distinct geographic patterns. The morphology of these eddies is such as to allow them to be categorized into four distinct classes, each with a specific origin and kinematic behavior. This implies consistent underlying dynamics which is shown to include the influence of bottom topography as well as meridional current shear.

1. Introduction

The subtropical convergence (STC) south of Africa has one of the strongest known horizontal thermal gradients at the sea surface (Lutjeharms 1985). A representative thermal section of the upper 500 m across the STC, as well as a representative surface thermograph trace, are given in Fig. 1. The horizontal thermal gradient at the sea surface, representative of the STC on this occasion, exceeds 5°C over a distance of less than 35 km and thus represents a frontal gradient of 0.15°C km⁻¹. A similar strong surface gradient is also evident in the salinity distribution (Lutjeharms and Foldvik 1986) and in closely spaced sea surface readings of soluble nutrients such as nitrates, phosphates and others (Allanson et al. 1981). South of Africa the STC is therefore a very distinct, well-defined feature at the sea surface for a number of measurable oceanic parameters.

As can be seen in Fig. 1a, however, the STC is by no means a surface feature only. Jacobs and Georgi (1977) and Lutjeharms and Foldvik (1986) show consistent evidence for it down to a depth of at least 1 km. Using the results of 24 expendable bathythermograph (XBT) sections south of Africa, Lutjeharms (1985a) has constructed a locational envelope for the subsurface expression of the STC south of Africa. In most respects it is very similar to that shown as a broken line in Fig. 2 based on surface readings.

The location and nature of the near surface expression of the STC in this area is, therefore, fairly well established. What has also emerged is that this general ocean area exhibits extremely intense dynamic variability. Garrett (1981) has analyzed the eddy kinetic energy of the area using the tracks of drifters and has shown a band of high mesoscale variability centered at 40°S south of Africa. Similar distributions, presumably related to the STC, have been shown to occur by Lutjeharms and Baker (1980) based on an analysis of hydrographic data, by Cheney et al. (1983) using satellite altimetric data and also from standard deviations of the sea surface temperatures of the area (Lutjeharms and Van Ballegooeyen 1984). In general, it has been assumed that this high level of mesoscale variability is due to shifts and meanders in this very strong front and possibly due to extensive eddy shedding.

The former, namely the meanders in the STC, have been observed from the tracks of drifters (Gründlingh 1978; Lutjeharms and Van Ballegooeyen 1988), disabled vessels (Pearce 1983), and from thermal infrared satellite imagery (Lutjeharms 1981a, 1981b). Rapid changes in the location of these meanders have been pointed out, as well as frequent eddy shedding. The evidence for the latter, namely the eddies cast off from the front is noticeable in many historical sea surface temperature traces (Niemann 1965), but were not interpreted as such at the time. Duncan (1968), Bang (1970a), and Sarukhanian (1982) have given descriptions of eddies at the STC, but mostly in the retroflection and fragmentation area of the Agulhas Current.

Further evidence for eddies in the vicinity of the STC comes from numerous XBT sections through the area (e.g., Lutjeharms and Emery 1983) and from recent hydrographic work (Buninov et al. 1984). In Fig. 1a, for example, a distinct eddy with surface temperatures exceeding 12°C lies directly south of the STC. A less intense eddy with surface temperatures greater than 10°C is south of 43°S. All indications therefore

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**FIG. 1.** A representative XBT section across the subtropical convergence south of Africa (a) with a simultaneous sea surface temperature and salinity trace taken during January 1978 (after Lutjeharms and Emery 1983). The characteristic sea surface temperature trace (b) from a ship's thermograph was obtained in March 1980 (after Lutjeharms and Valentine 1984). The locations of the subtropical convergence (STC), Sub-Antarctic front (SAF) and eddies are shown.

**FIG. 2.** Geographic distribution of mesoscale eddies observed at the subtropical convergence south of Africa. Open circles denote warm eddies in the vicinity of the Agulhas retroreflection, solid circles: warm eddies at the Agulhas Plateau, solid triangles: cold eddies related to warm features at the Agulhas Plateau, open triangles: cold eddies over the Transkei Basin. The broken lines give the envelope of the surface expression of the subtropical convergence according to Lutjeharms and Valentine (1984, Fig. 2), while background lines depict the bottom topography in km according to Simpson (1974).
suggest that this front, with its extremely strong horizontal gradients, may be an important source of eddies which may play an important role in meridional heat transport (Scientific Committee on Oceanic Research 1985).

This investigation addresses questions concerning the geographic distribution of such eddies, their dimensions and kinematics of formation. Information of this kind is not only crucial to an understanding of the meridional heat transport processes of the area, but also of the biological processes active in the frontal region (Lutjeharms et al. 1985) as well as of the general physical dynamics which play key roles here.

2. Datasets employed

Three basic datasets were used for this investigation; thermal infrared satellite imagery, XBT sections enhanced by continuous thermograph traces and drift tracks of free-drifting weather buoys.

Thermal infrared satellite images are from two main sources, namely the geostationary METEOSAT series and the orbiting NOAA/GOES-N series. The former includes both METEOSAT I and II, their infrared radiometers (10.5 to 12.5 μm) having a spatial resolution of less than 5 x 5 km in the area under consideration. Images for the area were routinely received once per day, contrast enhanced according to the radiance observed in the area, but not atmospherically corrected or calibrated. In the case of the orbiting satellites NOAA-4 and 5 their very high resolution radiometer (VHRR, 10.5–12.5 μm) had a resolution of 1 km at nadir, while the advanced very high resolution radiometer (AVHRR, 10.5–11.5 μm) of the NOAA-6, NOAA-7 and TIROS-N satellites had a nadir resolution of 1.4 km. All these were also suitably contrast enhanced, but not calibrated. Experience has shown that surface thermal expressions of features at the S TC south of Africa agree very well with their deeper expressions in all cases where these were measured at sea (e.g., Lutjeharms and Emery 1983). Thermal gradients are such (see Fig. 1) that finer resolution or calibration was not deemed essential for the purposes of this study.

Since 1978 about 40 closely-spaced XBT sections have been undertaken from Cape Town to Antarctica and the Sub-Antarctic islands in the South Atlantic or South Indian Oceans (Lutjeharms 1985a), in many instances supported by continuous thermography readings (Fig. 1). XBT temperature traces were calibrated by values of water temperatures taken at the sea surface by Crawford bucket (Crawford 1972). Individual traces were checked for errors according to the criteria of Kroner and Blumenthal (1977). A number of intercomparisons have been carried out elsewhere between XBT and CTD (conductivity–temperature–depth) profiles, which show that XBT temperatures may exceed those from the CTD by up to 0.3°C and have a mean depth error of about 7 m at 800 m (Heinmiller et al. 1983). Such discrepancies were considered unimportant for this study because of the extreme temperature differences prevailing in the area.

Drift tracks of a number of free-drifting weather buoys, reporting via satellite, which lay in the general geographic area were studied. Only well-established daily positions were used, giving a positional accuracy of less than 1 km. Most of the buoys were drogued with 2 m² window-shade drogues, but it was not possible to ascertain whether these drogues had remained attached. Studies by Kirwan et al. (1978) suggest that drogues may in any case have a very limited influence on the drift direction of such buoys.

The XBT sections were carried out for the most part in austral summer, thus presenting a possibly seasonally biased presentation. However, obstructive cloud coverage for the thermal infrared imagery shows no clear seasonal bias, while free-drifting buoys were present in the area during all seasons.

3. Distribution and dimensions of eddies

The locations of eddies identified in the collection of METEOSAT images are given in Fig. 2. Only features of which the full extent was visible on at least one occasion were used for this analysis. A host of identical features that could be reconstructed by combining images from succeeding days, were not considered for this analysis. The numbers of features mentioned below therefore constitute a very conservative sample and are really representative of a far larger number during the period covered by this investigation.

Four distinct and nonoverlapping geographical groupings are evident, one near the Agulhas Current retroflection between 15° and 20°E (Lutjeharms and Van Ballegooijen 1987), one over the Agulhas Plateau and directly east of it, one directly north of the Agulhas Plateau and one over the Transkei Basin northeast of the Plateau. The eddies identified for each of these areas have distinctively different characteristics. Those south of the Agulhas retroflection are warm, have diameters of about 220 km (Table 1) with noticeably longer east–west (E–W) than north–south (N–S) axes. Sarukhanyan (1982) described two very similar warm, anticyclonic eddies lying at 43°S, one at 15° and one at 23°E. Eddies at the Agulhas Plateau are warm and two distinctly different types could be identified, namely large warm pools with N–S axes of 200 km and E–W axes nearly triple this on average, and smaller, retort-shaped features with dimensions never exceeding 300 km (Table 1). A number of smaller cold eddies, seemingly related to the warm pools, were observed. In this category the N–S axes were in general longer than the E–W axes. The last category, of which by far the greatest number were observed, consists of cold eddies over the Transkei Basin. Their E–W diameters are on average about 160 km, their N–S diameters smaller. This is considerably smaller than those reported by Lutjeharms (1981a) for
TABLE 1. Dimension of four classes of eddies observed at the subtropical convergence south of Africa.

<table>
<thead>
<tr>
<th>Eddy class</th>
<th>N/S</th>
<th>Stand. dev.</th>
<th>E/W</th>
<th>Stand. dev.</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warm eddies</td>
<td>178</td>
<td>27</td>
<td>251</td>
<td>79</td>
<td>5</td>
</tr>
<tr>
<td>Warm pool 1</td>
<td>206</td>
<td>26</td>
<td>587</td>
<td>74</td>
<td>6</td>
</tr>
<tr>
<td>Warm pool 2</td>
<td>174</td>
<td>52</td>
<td>275</td>
<td>71</td>
<td>12</td>
</tr>
<tr>
<td>Small cold eddies</td>
<td>84</td>
<td>36</td>
<td>38</td>
<td>13</td>
<td>5</td>
</tr>
<tr>
<td>Cold eddies</td>
<td>102</td>
<td>51</td>
<td>155</td>
<td>77</td>
<td>56</td>
</tr>
</tbody>
</table>

this area, but the latter estimate was based on a small sample of only five individual cases.

There is a strong suggestion that the geographical grouping of these four classes of eddies are related to the dynamics of the circulation systems in the area. Because the Agulhas Current system as a whole may be topographically controlled (Lutjeharms and Van Ballegoooyen 1984) this may show that the formation of these eddies is related to underlying bottom topography in the Agulhas Current system. It will be instructive to investigate the morphology, kinematics and behavior of each of these classes of eddies separately.

4. Warm eddies at the Agulhas retroflection

A number of warm eddies were observed at the Agulhas retroflection by satellite remote sensing (class 1, Table 1); eddies that did not necessarily fall into the class of Agulhas rings as their characteristics are notably different. Agulhas rings are formed by the regular pinching-off of the Agulhas retroflection loop (Lutjeharms and Gordon 1987) and drift in a generally northwest direction into the South Atlantic Ocean (Olson and Evans 1985). Agulhas Current eddies are sheared-edge features of the retroflection part of the current and have been observed to move in a variety of directions (Lutjeharms and Van Ballegoooyen 1988). In general they are smaller and without a colder core. A number of warm eddies were also observed in this area by XBT section or by surface temperature readings south of the STC in areas which, owing to persistent cloudiness, were usually not accessible by satellite remote sensing. Drift tracks of free-drifting weather buoys also show noticeable anticyclonic mesoscale activity in the Agulhas retroflection region (Fig. 8).

A number of representative examples of retroflection eddies are given in Fig. 3. In the METEOSAT image (Fig. 3a) an eddy southeast of the Agulhas retroflection at about 40°S, 20°E exhibits a surface infrared radiance and, therefore, presumably a surface temperature not dissimilar to the Agulhas Current further north. Its immediate environment is decidedly colder. Further examples from the TIROS-N and NOAA-7 satellites have very similar dimensions. In all cases shown here (Fig. 3b), in which more than one eddy is visible, there is a noticeable decrease in surface temperature from the northernmost to the southernmost features. This would suggest that eddies may be formed at regular intervals and drift off either southeastwards or southwestwards (Fig. 3b, c) cooling rapidly as they drift off and being replaced at their origin, the Agulhas retroflection, by new eddies. Sarukhanyan (1982) describes precisely such a configuration.

None of the warm eddies observed at the Agulhas retroflection exhibit any noticeable internal thermal structure at the sea surface, such as one would expect from rings. The one exception is the feature in Fig. 3c where a filament of warm Agulhas water is presumably being wrapped around an eddy which has lost its surface thermal expression. It has been shown from theoretical considerations that rings of warm water will cover a cold core with a warm surface layer in time (D. B. Olson, personal communications). This has been observed to happen to Agulhas rings drifting northward (Lutjeharms et al. 1988). It is therefore entirely possible that at least some of the older eddies depicted in Fig. 3 may be true Agulhas rings which have subsequent to their occlusion been covered by warm surface water. The northernmost feature in Fig. 3c might be an early stage in such a development.

Two warm eddies in the retroflection region which were traversed by XBT section are depicted in Fig. 4. The thermograph trace of Fig. 4a shows the warm tropical surface water of the Agulhas Current system, between 20° and 22°C, as far south as 39°30'S where an abrupt temperature gradient signifies the location of the Agulhas front. Between 40° and 42°S an anomalous warm feature, with cross-section of 370 km and with borders consisting of thermal fronts of 3° to 5°C, locates a warm eddy. The southern front of this feature may be defined as the subtropical convergence in this case. From the accompanying thermal section it is clear that this eddy consists of warm Agulhas water to depths as great as were measured. Except in the upper 150 m, the water in the eddy is warmer than the adjacent water mass belonging to the Agulhas Return Current. A smaller eddy, probably much reduced in size and temperature, lies adjacent to the Sub-Antarctic front. The second retroflection eddy shown in Fig. 4b is not as thermally distinct at the sea surface and lies well to the south of the subtropical convergence. The XBT section shows that this eddy is colder than the Agulhas Return Current water north of it, has a diameter of about 250 km, and that its southern border...
Fig. 3. Some characteristic examples of warm eddies formed in the subtropical convergence zone at the Agulhas retroflection. Panel a: METEOSAT thermal infrared image for 1 July 1979, panel b: TIROS-N image for 20 July 1979 and panel c: NOAA-7 image for 6 October 1983. The general drift of the eddies is southeasterly. Arrows indicate the inferred flow directions. Dotted lines show where features were indistinct due to cloudiness.
FIG. 4. Three examples of records of warm eddies at the Agulhas retroflexion as observed at sea. The eddies in panel a were observed during January 1981 from the S.A. Agulhas, the one in panel b in late March 1980. The locations of frontal features on the thermograph traces as well as on the XBT sections are indicated (AgF: Agulhas front). The location of the eddies along the cruise line are given in corresponding maps of the geographic area.
also forms the Sub-Antarctic front. It lies about 300 km further south than the eddy portrayed in Fig. 4a, supporting the conclusion derived from the satellite imagery that eddies spawned at the retroreflection may drift southward for some distance without losing their distinctive characteristics.

The sample of warm eddies occurring at the Agulhas retroreflection shows that in general they have dimensions which are slightly elliptical, that they are not always Agulhas rings, and that they may disperse in a generally southerly direction with smaller, colder ones being found further south. As none have been found further east than 21°E from satellite data, it may be assumed that they moved eastward rather slowly and lose their distinctive surface characteristics quite rapidly, or get reabsorbed by the STC.

5. Warm and small cold eddies at the Agulhas Plateau

A visual inspection of the about 20 satellite images on which mesoscale features are fully visible at the Agulhas Plateau clearly shows that warm eddies formed in this region have two very distinct shapes. The first is a large pool of warm water adjacent to the STC in the south but only partially enclosed to the north by enfolding extrusions of cold Sub-Antarctic surface water. A few prime examples of this configuration are given in Fig. 5. In nearly all cases the cold extrusion from the east moves in to the south of the westerly extrusion thus enfolding the warm pool. The noticeable elliptical shape is found in all cases (see Table 1). Small cold eddies are often spawned from the westerly extrusion. In Fig. 5 this smaller feature is shown for 3 July 1979 (Fig. 5a) and 22 June 1978 (Fig. 5b), while the possibility of an imminent spawning event of a small cold eddy may be surmised from a narrowing in the extrusion for 5 November 1979 (Fig. 5c). These cold eddies are always much smaller (38–84 km, Table 1) with a longer north–south axis.

The second distinct eddy configuration observed over the Agulhas Plateau is a retort-shaped feature with a long warm outlet which, in some instances, may lengthen to resemble an “umbilical cord” attaching the warm eddy to its water of origin. A few representative examples from satellite remote sensing are given in Fig. 6. On average the dimensions of these retort-shaped eddies are smaller than the warm pools mentioned above (see Table 1) but, with the small sample of fully visible eddies available, no definite conclusions can be reached in this regard. Instances have been observed in which this “umbilical cord” may stretch for a couple of hundred kilometers, being only about 20 km wide over most of its length.

According to the distribution of these features from satellite remote sensing they are all found on the Agulhas Plateau or directly east of there (Fig. 2). The drift tracks of a weather buoy (according to Gründlingh 1978) and of a disabled vessel (according to Pearce 1983) shown in Fig. 8 demonstrate the reality of these features to the east of the Agulhas Plateau, their dimensions and, in particular, the circulation inferred from the satellite infrared images. The loci of the centers of the eddies has a definite centroid at 40°S on the plateau (Fig. 2).

At least one, distinct, warm eddy was traversed by an XBT section directly to the east of the Agulhas Plateau (Fig. 7). This warm eddy, with a diameter of 150 km, was found about 200 km south of the STC. Thermal fronts in excess of 5°C formed its borders, while its subsurface expression was evident to the full depth measured. Evidence for additional, but colder and therefore presumably older, eddies lay to the south in the same section as far as the Sub-Antarctic front.

Some hydrographic evidence on the nature of the cold protrusions which may envelop or be drawn into warm eddies on the STC at the Agulhas Plateau was obtained in February 1978 (Lutjeharms and Emery 1983). An XBT section and thermograph trace across a cold extrusion which was clearly delineated in simultaneous satellite imagery showed that on this occasion the STC consisted of a well-defined temperature drop from about 23°C in the Agulhas Return Current to about 14°C at 39°S latitude. A warm eddy with surface temperatures in excess of 17°C was located between 41° and 42°S. A cold sliver of water of less than 11°C was found directly north of the eddy and was evident to a depth of 400 m. On another occasion (Lutjeharms and Valentine 1988) a similar cold filamentous extrusion of 10 km width was crossed representing a temperature drop of between 2° to 3°C. It may therefore be concluded that these cold protrusions are not shallow and ephemeral features restricted to the surface layer, but that they are persistent and ubiquitous features at the Agulhas Plateau, which play an important role in sequestering bodies of warm subtropical surface water.

The notion that the two classes of eddies with their characteristic shapes are related, is borne out by the few available satellite image sequences in which the development of these eddies can be followed (Lutjeharms and Valentine 1988).

In general, meridional disturbances on the STC grow in time. These warm indentations are subsequently enveloped by tongues, or extrusions, of cold water extending both from the east and the west. Warm eddies thus enclosed and drifting southward consistently show long warm connecting filaments to their water of origin; these filaments being remarkably persistent. A reasonable assumption would thus be that retort-shaped eddies in this area are the second, and “warm pools” the first, stage of the warm eddy shedding process at the Agulhas Plateau.

From the above it is clear that although eddies may be formed in this manner mainly on the Agulhas Plateau, this also occasionally occurs in the lee of the plateau, as evidenced by the drifters (Fig. 8), XBT sections (Fig. 7), and some satellite imagery. The overtopping
characteristics of the extrusion of cold water from the west, which is partially responsible for sequestering these pools of warm water, could be the result of a strong south–north current shear. To test this hypothesis, the west–east velocity components of a number of drifters that had passed through the area in a zonal direction were established. Two bands, shown in Fig. 8, were selected and the zonal velocities derived for buoys crossing these bands. In the band upstream of the plateau the zonal velocity peaks at about 40°S lat-
itude, while in the downstream band the maximum is at 39°S. These zones fit roughly the average location of the STC given by Lutjeharms and Valentine (1984). The strongest meridional current shear seems to lie at about 40°S in the upstream band, somewhat further south in the downstream band. The statistical sample on which this is based is small, but indicative and presumably of the correct order. Such a meridional current shear could therefore be invoked as a possible mechanism to explain why the cold extrusions overtake warm meanders lying further south, from the west.

Cold extrusions from the east are consistently ob-
Fig. 7. An example of measurements across warm eddies at the Agulhas Plateau and vicinity. The eddies were observed during March 1981 from the S.A. Agulhas. The locations of frontal features on the thermograph traces as well as on the XBT sections are indicated. The geographic location of the main eddy along the cruise line is given in a corresponding map of the geographic area.

Fig. 8. Information on eddy and zonal motion in the area of the subtropical convergence south of Africa derived from free-floating weather buoys. Solid and dotted lines denote drift tracks of buoys, the broken line: that of a disabled steamer (after Pearce 1983). The numbers in the open arrows give the mean zonal drift velocity of drifters that have passed through this region. The easternmost sector is from 30° to 33°E, the western one from 20° to 22°E.
served to move in a westerly direction, or contrary to the general flow direction described by the drifters. As indicated in Figs. 5 and 6 the eastern cold extrusion invariably lies closer to the core of the eddy being enveloped and, one may assume, feels its influence more directly. A cold filament may thus be advected along the eddy edge.

Very few of the smaller cold eddies spawned by the westerly cold extrusion in the process of enveloping a warm pool were observed (Table 1, Fig. 5). They have been observed in a very small geographic area (Fig. 2) directly adjacent to the area of warm eddy formation. It may be assumed that they drift off in a general easterly direction but that they rapidly lose their surface expression as it has not been feasible to follow any for more than a week from series of satellite imagery.

6. Cold eddies over the Transkei Basin

This last distinct category of eddies observed at the STC south of Africa is found further north on average than any of the preceding classes (Fig. 2). Because this area is cloud free up to 25% of the time, a considerably larger number of eddies of this category were seen than of those discussed above (Table 1). A number of examples are shown in Fig. 9. In many instances, such

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**Fig. 9.** Four examples of satellite images of characteristic cold eddies over the Transkei Basin. Panel a: an image from the NOAA-7 satellite for 24 June 1983; panels b to d: interpretive line drawings for images from METEOSAT 1 for 16 May 1979, 27 April 1978 and 17 June 1979, respectively. Arrows indicate inferred directions of flow; dotted lines indicate areas which were obscured by cloud. The line drawings followed the very distinct and unambiguous thermal surface fronts in the infrared imagery.
as for 27 April 1978 (Fig. 9b), the eddies have a tear shape; in all instances they are adjacent to a cold Rossby wave over or east of the Agulhas Plateau (Harris 1970; Lutjeharms and Van Ballegooien 1984). Their dimensions are given in Table 1. In some satellite images a number of eddies of this nature could be discerned in various stages of warming and decay.

The distribution of eddies of this type (Fig. 2) is such as to invoke the concept of a central spawning ground off the northern Agulhas Plateau with eddies streaming off eastward into the Transkei Basin. None are observed west of the Agulhas Plateau. If they do not propagate downstream rapidly, it may be assumed that they lose their perceptible surface temperature difference before they reach 33°E, as no cold eddies were noted beyond this longitude. The spawning of a cold eddy of this type takes place when a protruded cold wave on the STC lengthens, and a cold, tear-shaped mass of water buds off into the Transkei Basin. This process has been described by Lutjeharms (1981b) and needs no further discussion here.

Only one set of hydrographic measurements of a cold eddy of this kind has been made (Bang 1970b). The surface temperatures and navigational set vectors for the vessel from which the measurements were obtained are portrayed in Fig. 10a while a temperature section through the feature is given in Fig. 10b. The eddy had not been severed completely from its Sub-Antarctic origin at this time. Its borders consisted of very strong thermal gradients. Celestial navigational fixes showed an estimated current set of up to 6.6 knots at its borders. The section across the eddy shows a noticeable decrease in the thickness of the layers of water warmer than 10°C in the eddy itself compared to its environment. This indicates a fair degree of warming which had already taken place in the upper 200 m. Had the layering in the eddy stayed the same as in the surrounding water, its surface temperature would have been less than 12°C, demonstrating its Sub-Antarctic origin. The 35.0% isohaline drawn in Fig. 10 affirms the close correlation between changes in temperature and salinity in the frontal regions of this area. The effect of the eddy was evident to a depth of at least 1.6 km.

7. Conclusions

The subtropical convergence area south of Africa is one of extreme dynamic variability. A range of intense eddies both to the north and the south of this front are distinguishable at the sea surface in historical records of sea surface temperature and in thermal infrared satellite measurements, as well as at depth with the aid.

![Fig. 10. Hydrographic measurements of a cold eddy of the subtropical convergence over the Transkei Basin (after Bang 1970b). Panel a shows the cruise track of the R.V. Thomas B. Davie, station positions and the sea surface temperature distribution in March 1969. Open arrows give the ship's set and drift from twice daily navigational fixes, in knots. In panel b a temperature section is given which corresponds to the unbroken cruise line between points marked A and B on panel a. The 35.0 per mille isohaline has been superimposed and is shown as a broken line.](image-url)
Fig. 11. A conceptual portrayal of the formation processes of the five generic classes of mesoscale eddies that have been observed at the subtropical convergence south of Africa. Arrows denote flow directions while the shaded parts denote areas of Sub-Antarctic surface water south of the subtropical convergence. Classes B and D may be considered different stages of the same eddy type.

of expendable bathythermograph and hydrographic data.

Four distinct geographic groupings, probably related to bottom topographic features, are identified. The eddies found in each area have very distinctive and characteristic shapes that distinguish them from eddies found in the other areas. Five generic classes of eddies are categorized within a conceptual framework of their development in Fig. 11 based on observations and the best synthesis of the available data. All sequences shown have been observed a number of times each.

(A) Warm, slightly elliptical eddies with diameters of about 200 km are formed at the Agulhas Current Retroflection and its general vicinity. In certain circumstances these may be Agulhas rings, formed by the pinching off of an Agulhas retroflection loop, but not necessarily so. Eddies of this nature drift off in a range of general southerly directions losing heat to the atmosphere. They are found as far south as the Sub-Antarctic front in various stages of decay.

(B) At the Agulhas Plateau three types of eddies, which are related, have been observed. The first consists of an oblong pool of warm water with dimensions of about 200 by 600 km which shows a predilection for being formed on, or in the lee of, the Agulhas Plateau. These eddies grow from perturbations in the subtropical convergence which are enclosed by overlapping protrusions of cold Sub-Antarctic surface water (Fig. 11B) which have been shown to extend to at least 500 m depth on occasion. It is hypothesized that the western protrusion overtakes the eddy as a result of the existing
meridional velocity shear at the subtropical convergence, while the eastern protrusion is advected around the edge of the eddy itself. (C) The western cold protrusion may be elongated to such an extent that a small, cold eddy with an average diameter of about 60 km buds off. It is assumed that these small features have a relatively short observable life-time. (D) As the large warm pools become progressively more enclosed by cold Sub-Antarctic surface water they take on a retort shape with a lengthening connection to their water of origin. Features of this kind were, in general, significantly smaller than their assumed predecessors. (E) Planetary waves formed as the Agulhas Return Current crosses the Agulhas Plateau and also in the lee of this bottom topography feature, on occasion lengthen and spawn cold eddies, usually with an initial tear shape. These cold eddies are very prevalent over the Transkei Basin, show little eastward drift and may have a very intense border configuration.

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