Intrusions of sub-Antarctic water across the Subtropical Convergence south of Africa

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The contents of the Cape Basin of the South Atlantic Ocean, southwest of Cape Town, is a melange of water types from a number of different sources. One of the least studied of these water types comes from intrusions of sub-Antarctic water that are associated with the spawning of Agulhas rings. An analysis of a variety of data on the region shows that these intrusions originate along a latitude of 40°S, but only between longitudes of 8° and 22°E. In extreme cases they can extend equatorward beyond the southern tip of Africa. Intrusions take place at least five times per year. Their distinct surface expressions are shown to be but outcrops of water masses that usually are found at greater depths. These vertical perturbations may extend to depths exceeding 1500 m.

The ocean region southwest of Cape Town has an important role in global thermohaline circulation. Here warm, salty surface water of tropical and subtropical origin leaves the South Indian Ocean to be replaced by water of mostly Atlantic origin at intermediate depths.[1] It has recently been demonstrated[2] that this particular inter-ocean exchange has, for example, a marked influence on the thermohaline overturning of the Atlantic Ocean as a whole. The exchange takes place through a number of processes. The most important of these is the formation of Agulhas rings by loop occlusion at the Agulhas Current retroflection.[3] An exchange process of secondary magnitude is the advection of Agulhas filaments into the region.[4] As a result of all these different water masses passing through this veritable oceanic crossroads,[5] it is difficult to quantify the influence and effect of each.[6] For an understanding of global exchanges it is, however, crucial.

To make matters even more complex, into this region of exchange of subtropical water masses an extra water mass is known[7] to penetrate in the upper ocean layers. This intermittent influx comes from south of the Subtropical Convergence, the generic southern boundary to the subtropical ocean waters. It is known that Subantarctic Surface Water is one of its components.[7] The mechanism through which this water is injected into the South Atlantic has to do with the formation of Agulhas rings. As a ring is intermittently occluded, Subantarctic Surface Water moves equatorward into the gap between the newly formed ring and the Agulhas Current retroflection.[3] Usually this cold surface water does not move much farther equatorward, but on occasions it may extend all the way past the latitude of the southern tip of Africa. A vivid example of such cold water penetration is given in Fig. 1.

This portrayal is from observations by a radiometer on board a NOAA (National Oceanic and Atmospheric Administration) orbiting satellite and has been corrected for atmospheric effects as well as geographic distortion. The major circulatory features for which the region is known are immediately evident. First, the wind-driven coastal upwelling along the west coast of South Africa is apparent by surface temperatures lower than 17°C (blue in Fig. 1). The greater area shown has temperatures between 20 and 22°C. The highest temperatures (>22°C) were measured east of 20°E and represent the surface waters of the retroflection of the Agulhas Current. Other bodies with water warmer than 21°C consisted of circular features centred at 17°E and at 10°E, the latter largely obscured by cloud. It is more than likely that both these features were Agulhas rings. Between these rings, as well as between the easternmost ring and the retroflection, extensive meridional strips of water colder than 18°C are evident. These are prime examples of intrusions of Subantarctic Surface Water as part of the process of Agulhas ring shedding. At their southernmost origins their temperatures are below 15°C. This shows that this water indeed has its origin south of the Subtropical Convergence. The core temperature of this front south of Africa is 14.2°C.[8] In order to establish how representative this portrayal is, a study has been made using an eclectic collection of data.

Data and methods

The most readily available data for this ocean region are from satellites. We have used daily images from METEOSAT I and II that have a spatial resolution of about 8 × 8 km in this geographic region and that derive from measurements of thermal infrared radiation in the 10.5–12.5 μm band. Observations from the NOAA 4 to 9 satellite series were in the 10.5–11.5 μm range, but have a much better resolution at nadir of about 1 × 1 km. A period of nine years, from 1981 onwards, was selected for the analysis of these images. Persistent cloud cover severely restricts the usefulness of these observations, particularly in trying to establish time series. Altimetric satellite information, although not affected by cloud cover, was shown to have too coarse a spatial resolution to resolve cold water intrusions adequately except during those few instances when they could be verified by satellite infrared imagery.

Establishing sea truth for these infrared observations is well-nigh impossible, since so few hydrographic observations at sea have been made in the region. Nevertheless, the full data set of all temperature and salinity observations for the region were accessed from the Southern African Oceanographic Data Centre and analysed. Only a few quasi-synoptic cruises in the region were useful. These included the ARC (Agulhas Retroflection Cruise[9]) and the SCARC (Subtropical Convergence and Agulhas Retroflection Cruise[10]). The quality of the data from these cruises is given in the respective data reports.[9,10] Regular observations of sea-surface temperatures in the region of specific interest were made from the South African weather ship *Hughes,* during the 1970s. These transects from Cape Town to the ship's station and back would in principle have been ideal for this investigation, but on closer scrutiny proved to be inadequate since the calibration of the thermograph that was used could not be ascertained.

In a number of cases of cold water intrusions, sea-surface height data from satellite altimetry were used to follow signals first observed in thermal infrared images. Detail on the product used (MODAS), satellites employed, data accuracy and coverage can be found at http://www7300.nrlssc.navy.mil/altimetry/regions/re_agl.html.

Location and dimensions

The orientation of the intrusions that can be identified from satellite infrared observations (Fig. 2) shows a number of fairly distinct patterns. The majority lie in a southwest/northeast direction. A smaller number lie at right angles to this orientation. No intrusions have been observed east of 22°E or west of about

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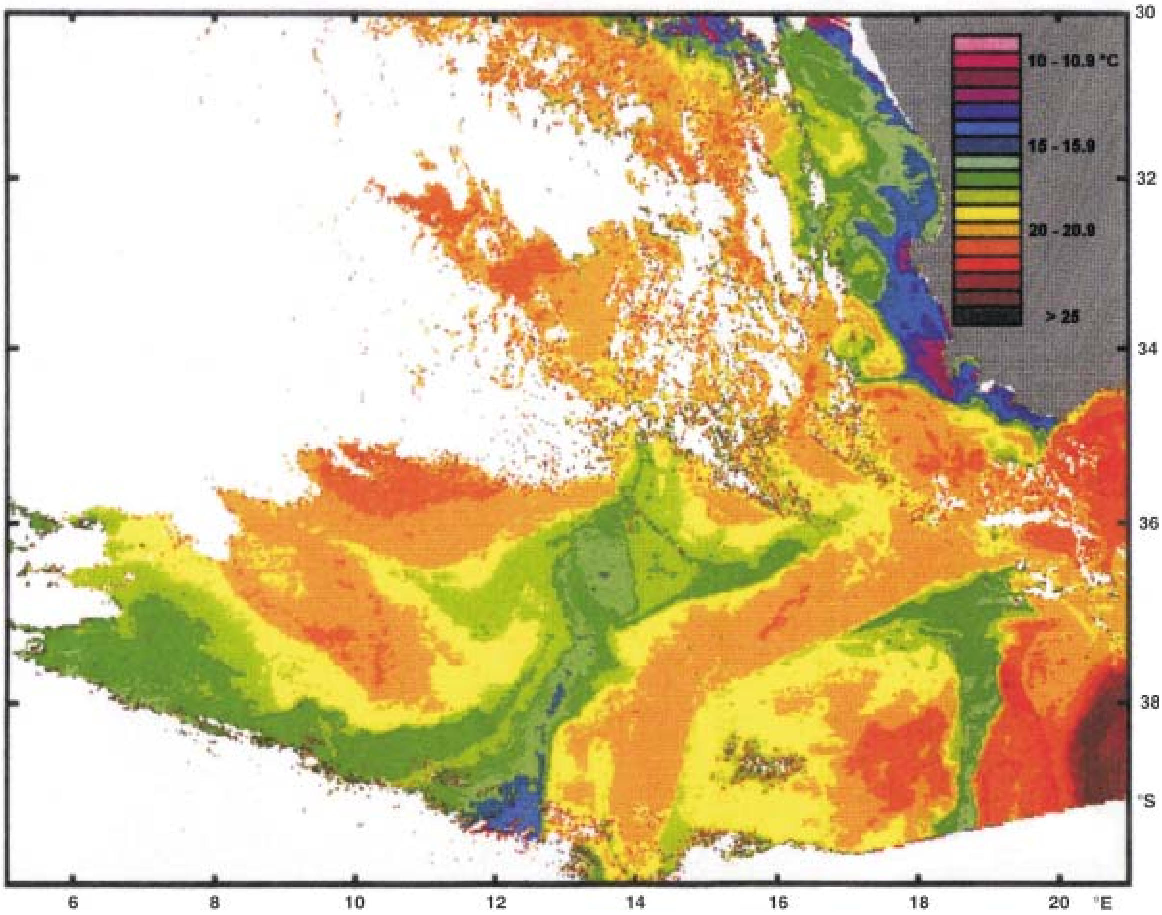

Fig. 1. Sea-surface temperatures southwest of Africa for 28 February 1988. Land masses are grey, clouds are white and the colour scale gives the temperatures of the water in °C. Two prominent green features represent equatorward intrusions of cold Subtropical Surface Water.

8°E. Notwithstanding the problem of severe cloudiness for the region as a whole, the duration of the period of observations gives us confidence that this is a representative sample. None of the intrusions depicted in Fig. 2 extends beyond 35°S, but this may be an artefact of the surface heating of these cold waters in this region, making them indiscernible in infrared imagery far away from their source at the Subtropical Convergence. The equatorward extent of the intrusions may therefore be an underestimate. The source locations may be more reliable (Fig. 3).

The geographic distribution of the locations from where water came to form cold water intrusions follows a curve that correspond well with the known average location of the Subtropical Convergence in this region.[8] There is a considerable meridional range, but this is not unexpected for a region that has been recognized for its extreme variability. The eastern limit to the formation of intrusions agrees with the zonal limit to the formation of Agulhas rings.[3] The equatorward limit (Fig. 3) is in rough agreement with the path taken by Agulhas rings and indicates where most rings would have moved too far from the Subtropical Convergence still to interact with it. This assumes that rings entrain the cold water of intrusions. The portrayals in Figs 2 and

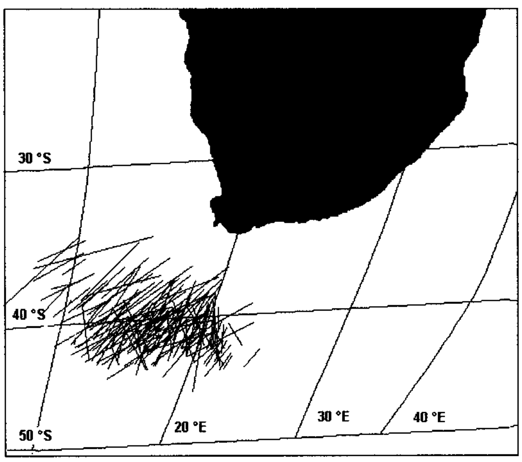

Fig. 2. The orientation and lengthwise dimensions of sub-Antarctic water intrusions into the South-West Atlantic for the period 1981 to 1990.

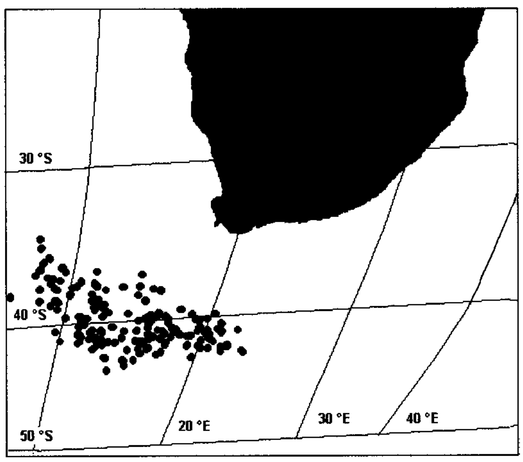

Fig. 3. The geographical location on the Subtropical Convergence from where there were intrusions of sub-Antarctic water into the South-West Atlantic during the period 1981 to 1990.

3 are not exactly the same since they come from somewhat different data sets. For Fig. 2 only those intrusions were selected where the full equatorward extent of an intrusion was visible; for Fig. 3 only those where the origins of these intrusions were clearly evident. In the latter case the farthest equatorward extent of these features may have been obscured by cloud cover. If Figs 2 and 3 give a solid indication of the geographic distribution of these features, it is their areal extent that may have the greatest influence on the region as a whole.

Based on a study of 127 independent intrusions over a period of eight years, a number of quantified conclusions can be reached. First, it is seldom that only a single intrusion is visible at a time. In 49% of the cases where the region was sufficiently cloud-free, two intrusions were evident; in 30% three. Persistent cloud cover obscuring parts of the region probably makes this an underestimate. The average length of the intrusions was 410 km (standard deviation 220 km); the average width 180 ± 100 km. The estimated, average square area of the intrusions was 159×10^3 km^2 ($\pm 118 \times 10^3$ km^2). Intrusions were evident about 38% of the time during the study period, but the occurrence frequency and the dimensions varied considerably from year to year. The occurrence frequency seemed lower during winter months, but this conclusion may not be statistically significant.

The only other study of such intrusions to date has been that of one extreme event by Shannon *et al.*[7] This particular intrusion, in the early months of 1987, covered an area of 734×10^3 km^2, five standard deviations greater than the mean area for the period of nine years covered in our investigation. The next closest event in terms of square area during this period occurred in the summer of 1984/85, but covered a mere 370×10^3 km^2 by comparison. The event of 1987 therefore was truly exceptional.

Persistence and frequency

Estimating the duration of intrusion events with infrared satellite images is fraught with problems. First, cloudiness makes it difficult to track intrusions over lengthy periods. Second, the thermal surface expression may fade fast as the cold water from the sub-Antarctic is heated by the warmer subtropical atmosphere. Altimetric satellite information does not suffer from either of these disadvantages, but the spatial resolution is not optimal to identify cold intrusions unambiguously. By identifying cold intrusion in thermal infrared imagery from the NOAA satellites and then relating these directly to anomalies in sea-surface height, this problem was partially overcome.

Based on seven case studies of this kind, the average duration of sea-surface height anomalies associated with cold intrusions was 28 days. It is impossible to tell if this is the time it took for the intrusions to disperse or whether this is an indication of the durability of a underlying cyclonic motion that carried the cold water equatorward. This unanswered question awaits further study. An equally important question concerns the occurrence frequency of these intrusions.

If every ring-shedding event brings about an intrusion of sub-Antarctic water into the Agulhas retroflection region, the number of intrusions should lie between 4 and 9 per year.[6] Based on nine years of satellite information, we find an average of five per year. One may assume that not all ring-shedding events are of necessity accompanied by a well-developed intrusion. An occurrence of five intrusions per annum therefore seems a reasonable frequency, but may be a slight underestimate due to persistent cloud cover that may have obscured some intrusion events, particularly multiple events.

For easy access, the results described above are tabulated in Table 1.

Table 1. Characteristics of cold intrusions across the Subtropical Convergence.

Zonal distribution	8°E–22°E
Meridional distribution	Subtropical Convergence ~35°S
Average number per year	5
Temporal occurrence frequency	38%
One intrusion present	21% of times when intrusions are present
Two intrusions present simultaneously	49% of times when intrusions are present
Three intrusions present simultaneously	30% of times when intrusions are present
Average length of intrusions	410 (±220) km
Average width of intrusions	80 (±100) km
Average surface area of intrusions	$159 (\pm 118) \times 10^3$ km^2
Average duration of intrusions	28 days

Hydrographic structure

Two oceanographic cruises in the Agulhas retroflection region are known to have crossed intrusions of sub-Antarctic water. Part of the cruise track of one of these, the Agulhas Retroflection Cruise,[9,11] is shown in Fig. 4. The stations along cruise line 1 extended from a newly shed ring, through a sub-Antarctic intrusion, into the Agulhas Current retroflection. Line 2 intercepted an intrusion between two Agulhas rings.[12] According to the statistical results given above, the simultaneous presence of two intrusions is close to the norm. The two intrusions represents the most easterly and the most westerly types (Fig. 2). Vertical sections from these crossings are shown in Fig. 5.

Along section 1 the thermal characteristics of the circulation elements that were crossed can clearly be seen. To the east the symmetrical sloping of isotherms to depths of at least 1300 m shows the shape and location of an Agulhas ring. The two bodies of water with temperatures in excess of 19°C in the upper 50 m represent the annulus of warmest surface water derived from the Agulhas Current. It had by now cooled down sufficiently to have become somewhat indistinct, displaying considerable cooling from the 23°C surface water in the Agulhas retroflection itself, evident at station 65 (Fig. 5). Between these two clearly identifiable elements of the Agulhas retroflection there was a dome of colder water that extended all the way from the greatest depths measured to about 100-m depth. It outcropped at station 68. A potential temperature/salinity diagram of the water characteristics at this station (not shown here) demonstrates that all the central, intermediate and deep-water masses present in Agulhas

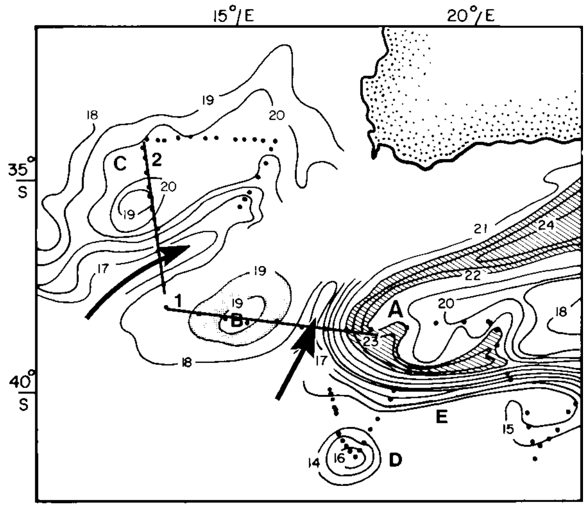

Fig. 4. Surface isotherms of the Agulhas retroflection during October to December 1983 (after Lutjeharms and Gordon[11]). The features identified by letters are: A, the Agulhas Current retroflection; B, a newly spawned Agulhas ring; C, an older Agulhas ring; D, a warm Agulhas eddy; and E, the Agulhas Return Current. Two intrusions of cold sub-Antarctic water are indicated by arrows. Hydrographic sections that crossed these intrusions are shown as heavy lines: line 1, zonal; line 2, near meridional.

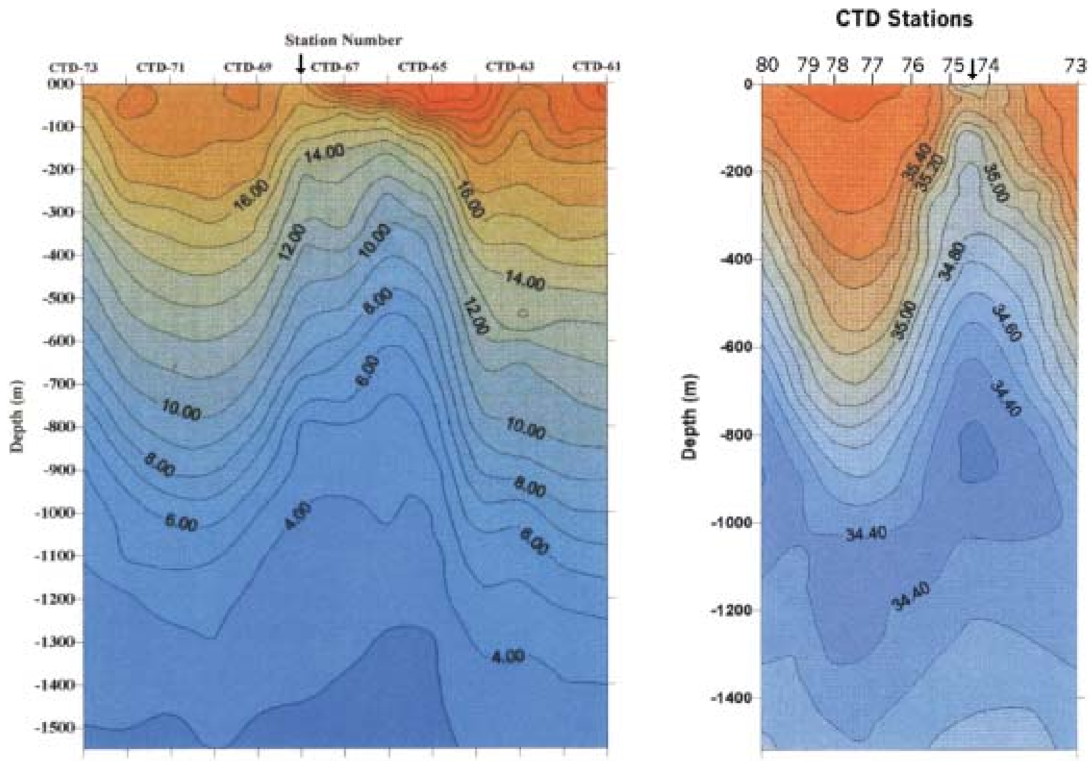

Fig. 5. Vertical temperature section along line 1 (left-hand panel) and a vertical salinity section along line 2 (right-hand panel) of the Agulhas Retroflection Cruise (see Fig. 4). The locations where there is evidence of an intrusion of sub-Antarctic water at the sea surface are indicated by arrows.

waters were present at this intrusion as well, except that Subtropical Surface Water and the Tropical Surface Water were absent. The water in the upper layer was Subantarctic Surface Water with a temperature of <17°C and a salinity of 35.4. The structure underlying the other intrusion (Fig. 5, right panel) was somewhat different.

Here the two anti-cyclonic rings were closer together than the features in the left-hand panel. The outcropping took place more or less centrally between the two rings. The surface water in this intrusion was even colder (<16°C) and fresher (35.10; Fig. 5). There does not seem to have been any underlying mechanism by which this surface water was being carried northeastward (Fig. 4) except an intensification of the vertical shear (as represented by the isotherms) on the intrusion side of the northernmost ring. The water characteristics of the intrusion of sub-Antarctic water, as represented by a potential temperature/salinity diagram, was the same as that of the previously discussed intrusion. From Fig. 5 it is clear that the surface waters represented a disturbance to the average water column that extended to a depth beyond 1500 m. This is not unexpected, considering the large barotropic component of the Agulhas Current.[13]

Conclusions

From this — and from a previous investigation[7] — it is clear that the occasional intrusions of cold, sub-Antarctic water masses into the Agulhas retroflection region contribute a non-negligible part of the water masses to be found in the mixing region south of Africa. From the incident frequency and persistence of this anomalously cold water in the region — shown here — one may assume that on occasion the square area with colder water might potentially have an effect on weather systems[14] and even on the local fisheries.[15] This requires further investigation. Additional, directed investigations are also required to quantify the volumetric contribution of these intrusions to the region and to the inter-ocean exchanges that occur here.

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