The thermal structure of the upper ocean layers between Africa and Antarctica during the period December 1978 to March 1979

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Simultaneous station lines have been carried out by two vessels between South Africa and Antarctica to study details of the thermal fronts in the upper ocean layers. This cruise was undertaken within a time interval of three months and thus facilitated the investigation of temporal changes in the fronts. Five well-defined fronts were located and are described. The frontal morphologies of the Subtropical Convergence, the Sub-Antarctic Front and the Antarctic Polar Front show development of a step-like structure with the progress of summer. The possibility that the Sub-Antarctic Front south of Africa extends to at least a 1 000 m depth is indicated.

Waarnemingsvaarte langs twee stasielyne is gelyktydig tussen Suid-Afrika en Antarktika uitgevoer met behulp van twee skepe wat in die gebied aanwesig was. Op dié manier is die veranderings bepaal wat met die verloop van drie maande in die termiese fronte in die oseaanbolaag voorgekom het. Die aanwesigheid van vyf duidelike fronte is vasgestel en beskryf. Die frontmorfologie van die Subtropiese Konvergensie, die Subantarktiese Front en die Antarktiese Poolfront vertoon die ontwikkeling van 'n trapagtige struktuur namate die somer vorder. Daar is aanduidings dat die Subantarktiese Front suid van Afrika tot 'n diepte van 1 000 m strek.

Introduction

An extensive research programme to investigate detail of the thermal structure of the upper ocean layers between Africa and Antarctica was started in 1978 and is continuing. A cruise report on the first 16 cruises forming part of this programme has been published (Lutjeharms *et al.* 1986). The results of some of these cruises have been published by Lutjeharms *et al.* (1981), Allanson *et al.* (1981), Lutjeharms & Emery (1983) and Lutjeharms & Valentine (1984). This article presents the results of measurements made in December 1978 and March 1979.

The results presented here are unusual for two reasons. First, two expendable bathythermograph sections from Cape Town to Sanae were undertaken three months apart (Fig. 1), thus laying the basis for establishing possible short-term temporal changes in the thermal fronts of this region. Second, two sections from Antarctica to Cape Town were run simultaneously in March 1979 by the M.V. *Polarsirkel* (Fig. 1) and the M.V. *S.A. Agulhas*. These nearly parallel sections facilitate a study of the longitudinal variability of thermal fronts south of South Africa.

The fortuitous opportunity to study the fronts with two vessels simultaneously arose because the Norwegian Antarctic Research Expedition 1978/79 was scheduled for this period in this area. Other results from this expedition have been published by Foldvik *et al.* (1981).

Five separate thermal fronts have been recognised south of Africa. The stochastic surface characteristics of the Agulhas Front (AF), the Subtropical Convergence (STC), the Sub-Antarctic Front (SAF) and the Antarctic Polar Front (APF) have been established by Lutjeharms & Valentine (1984) while the saline and nutrient surface characteristics of the Subtropical Convergence, the Antarctic Polar Front and the Sub-Antarctic Front have also been investigated (Allanson *et al.* 1981, Lutjeharms & Emery 1983). The geographic

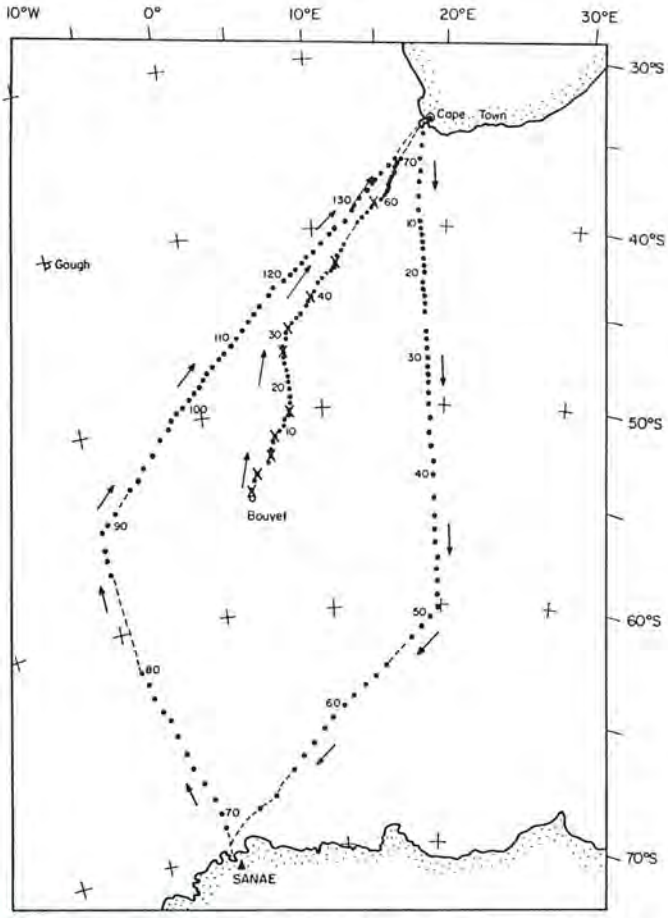

Fig. 1. The geographic location of the cruise tracks and XBT stations during two legs of the relief cruise of the *S.A. Agulhas* to Sanae during the period December 1978 to March 1979 as well as the XBT and CTD stations of the M.V. *Polarsirkel* between Bouvet Island and Cape Town. Broken lines denote breaks in the observation routine while arrows show the sailing direction. Dots indicate XBT stations; crosses CTD stations.

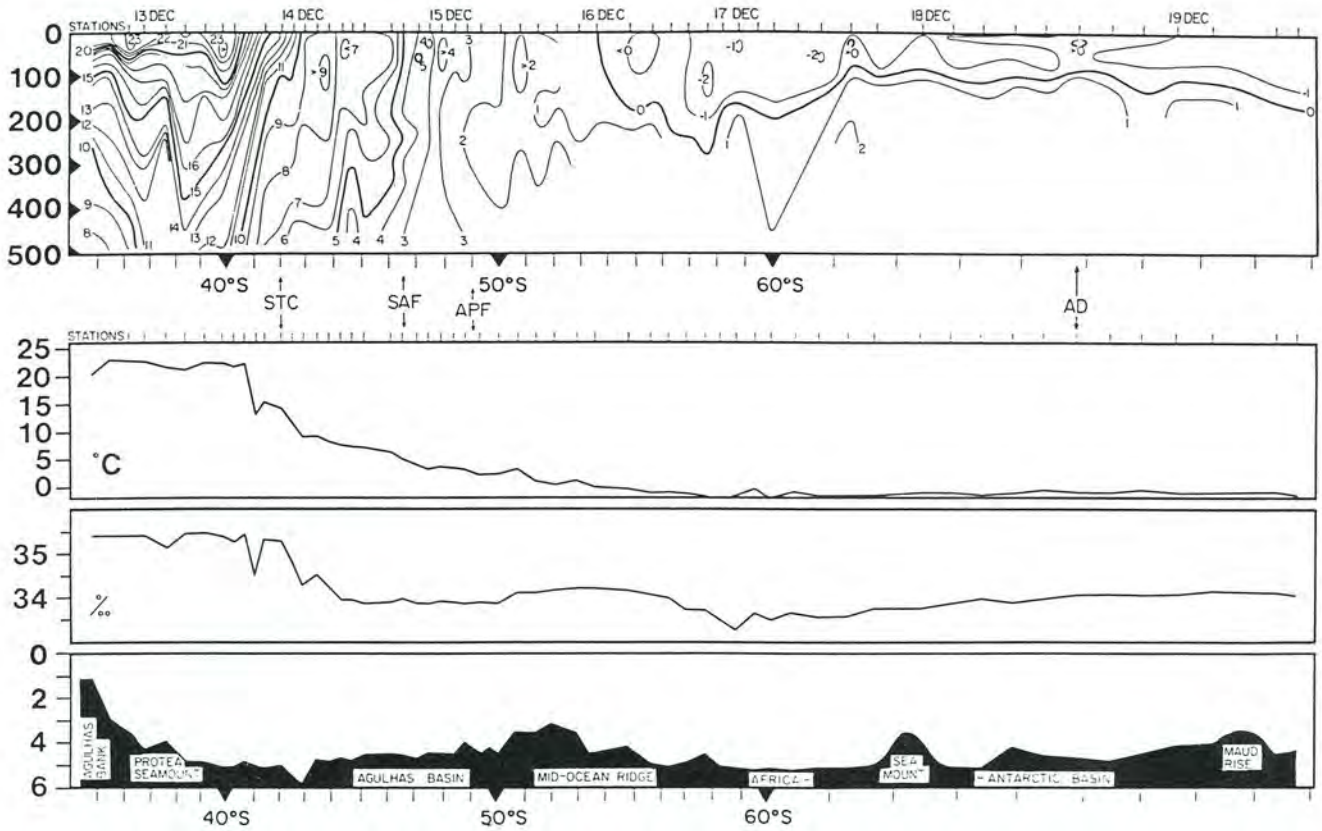

Fig. 2. Results obtained during the first leg of the *S.A. Agulhas* cruise. The upper panel displays the thermal structure of the upper 500 m as obtained from XBT measurements, the second panel the sea surface temperature and the third the sea surface salinities both from Crawford bucket samples, while the bottom panel shows the ocean bottom topography along the cruise track. Significant thermal fronts are indicated.

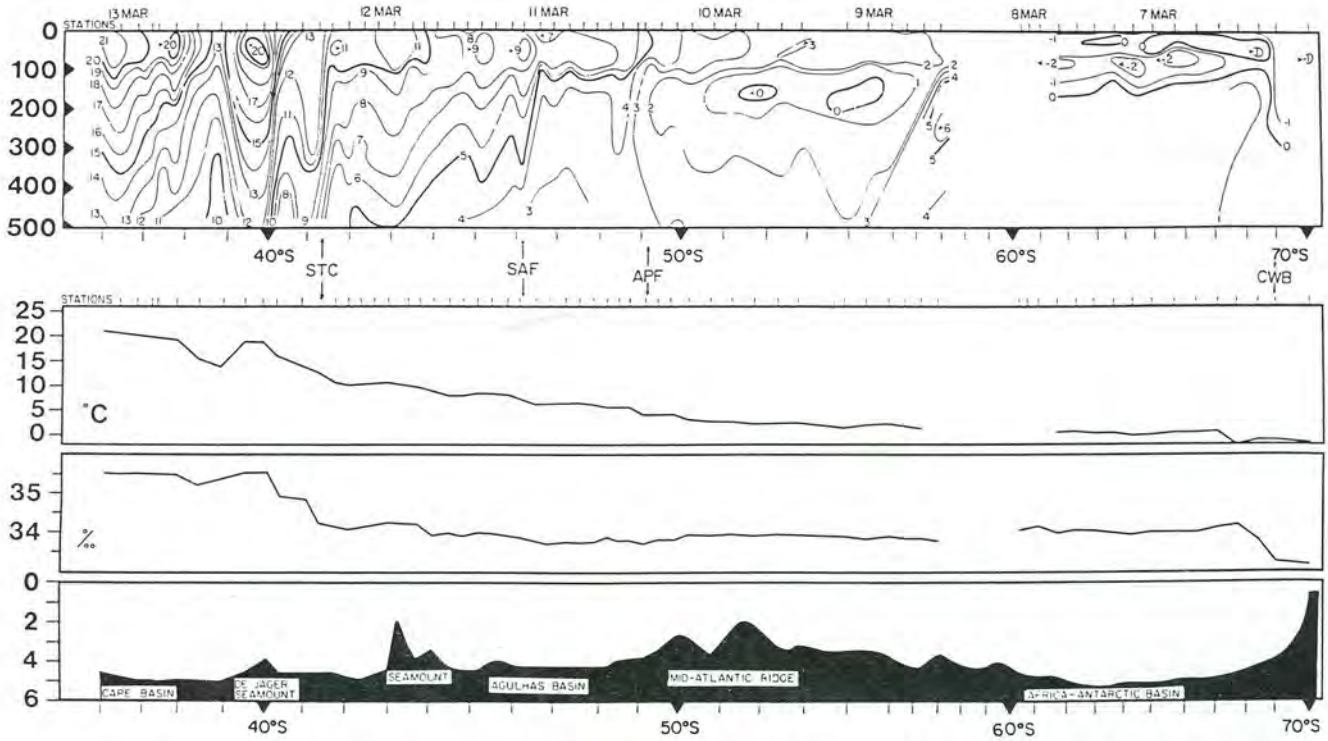

Fig. 3. Results obtained during the second leg of the *S.A. Agulhas* cruise. The upper panel displays the thermal structure of the upper 500 m as obtained from XBT measurements, the second panel the sea surface temperature and the third the sea surface salinities both from Crawford bucket samples, while the bottom panel shows the ocean bottom topography along the cruise track. Significant thermal fronts are indicated.

locations of both the surface and the subsurface expressions of these fronts and of the presumed Antarctic Divergence (AD) have similarly been investigated (Lutjeharms 1985). It may now be possible to enhance this information by using the data collected during the cruises of 1978 and 1979 to investigate temporal as well as latitudinal variability in some of these fronts.

Data and Methods

T-4 expendable bathythermographs (XBTs) were used throughout. The average station spacing was less than 60 km, but near the general locations of the STC and APF station spacing was decreased to less than 50 km to resolve greater thermal detail. Recorder malfunctions were responsible for small gaps in the data in both the northbound leg of the *S.A. Agulhas* cruise (Fig. 1) and during the *Polarsirkel* cruise (Fig. 1). XBT traces were calibrated using sea surface temperature readings taken with a Crawford bucket (Crawford 1965, 1972) on the *S.A. Agulhas* cruise. Bucket and XBT temperatures were most often within 0,5 °C of each other. The XBTs used on the *Polarsirkel* were not calibrated, but since the probes on both vessels came from the same manufacturer's batch it is reasonable to assume that they were equally accurate and that hardly any intercalibration errors would have occurred. Individual XBT traces were checked for errors using the methods of Kroner & Blumenthal (1977) and any showing spikes or radio interference discarded. More than 90 % of all probe deployments on both vessels were deemed to have been successful.

On the cruise of the *S.A. Agulhas* samples of sea surface water were taken at each station and salinities of these samples were determined subsequently by the conductivity method on a Plessey Environmental System Model 6230 N Laboratory Salinometer.

During the cruise of the *Polarsirkel* ten stations were also undertaken with an uncalibrated Neil Brown conductivity-temperature-depth (CTD) probe. The locations of these stations are indicated in Figure 1. For this section the surface temperatures (Fig. 4) are those obtained from XBT and CTD readings, while the surface salinities were obtained from CTD readings.

Results

The results of the XBT measurements for the two legs of the *S.A. Agulhas* cruise, as well as sea surface temperature, sea surface salinity and concurrently measured ocean depth are portrayed in Figures 2 and 3. Isotherms and isohalines to 1 000 m depth, measured during the *Polarsirkel* cruise, are shown in Figures 4 and 5, respectively.

The southward leg of the *S.A. Agulhas* cruise lay due south of Cape Town to a point 60°S, 20°E. From there the ship sailed to the South African Antarctic base Sanae at 70°19′S, 2°21′W (Fig. 1). During this leg the Subtropical Convergence was at 42°S latitude (Fig. 2). Extending over two degrees of latitude, the temperature decreased by 12 °C from 22 °C to 10 °C. The Sub-Antarctic Front was clearly evident at 46°30′S as was indicated by the bunched vertical isotherms between 3 °C and 7 °C. The Antarctic Polar Front was situated at 49°S, identified by means of the definition of Lutjeharms & Emery (1983), namely, the most northerly extent of the 2 °C water at about 200 m depth. At 65°S the cold surface layer of water, with temperatures less than

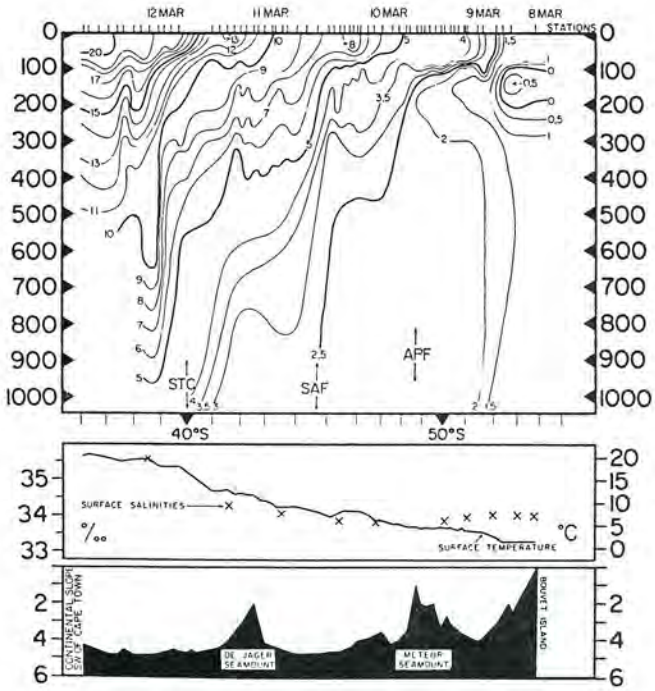

Fig. 4. Results obtained during the cruise of the M.V. *Polarsirkel* between Bouvet Island and Cape Town. The top panel displays the thermal structure of the upper 1 000 m from XBT and CTD measurements. The locations of CTD stations are indicated by crosses in the second panel which portrays the sea surface salinity measurements by CTD and the surface temperature measurements by XBT and CTD. The lowest panel shows the topography of the ocean bottom along the cruise track.

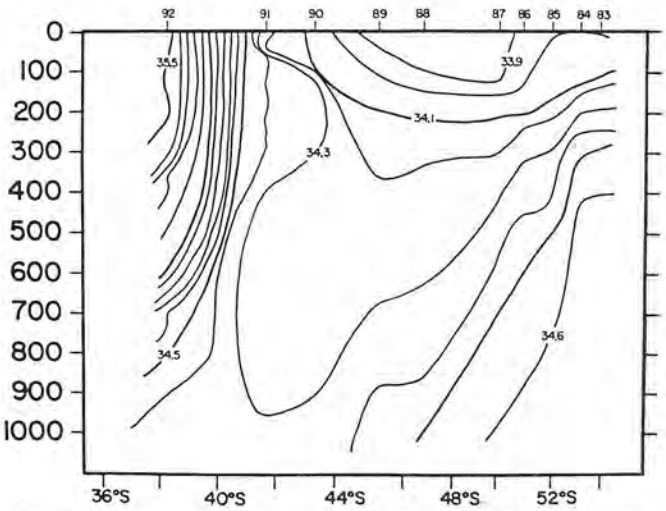

Fig. 5. Isohaline distribution in the upper 1 000 m between Bouvet Island and Cape Town during March 1979. Measurements were made by CTD from on board the M.V. *Polarsirkel*.

−1 °C, was broken. This may be interpreted as the position of the Antarctic Divergence (Deacon 1933, 1982) or the southern influx to the Weddell Gyre (Gordon & Molinelli 1982).

The northward leg of the *S.A. Agulhas* cruise lay 30° of longitude to the west of the southward leg. The ship steamed from Sanae to a position about 10°W and 55°S (Fig. 1) and from there followed a great circle route to Cape Town. Stations were started close enough to Sanae to enable the Con-

tinental Water Boundary (CWB) to be resolved. It is clearly manifest in the isotherm distribution, the sea surface salinity as well as the sea surface temperature trace (Fig. 3). The subsurface expression of the APF was located at 49°30′S and a distinct surface expression immediately north of here. The SAF was found at 46°S exhibiting its characteristic step-like structure, the first vertical part forming the SAF, the horizontal part lying between the SAF and the APF and the last vertical part forming the surface expression of the APF (Fig. 3). This characteristic shape has been observed before (Lutjeharms & Emery 1983). The STC was crossed at 41°30′S. Although the isotherm distribution is not altogether clear in this regard, the sea surface salinity (Fig. 3) defines the STC location unambiguously. The Subtropical Convergence may consist of two cores, the second situated at 40°S. The presence of Agulhas Current rings or filaments is indicated by surface water with temperatures greater than 20 °C north of the STC.

The section carried out by the *Polarsirkel* as part of its Antarctic 1979 cruise programme lay between Bouvet Island and Cape Town (Fig. 2). A significant surface expression of the APF, according to the definition by Ostapoff (1962), was observed south of 52°S and is clearly evident in the sea surface temperature trace of Figure 4. The subsurface expression of the APF was situated only at 48°30′S, about 380 km north of the surface expression. The SAF was clearly evident at 44°30′S except for the upper 70 m where its surface expression lay about 220 km to the south (Fig. 4). This same southward shift of the frontal surface expression was also observed at the STC, the surface expression lying at 40°S, while the subsurface expression, evident from 200 m to 1 000 m depth, was situated at 39°S. The spacing of salinity measurements (Fig. 5) could not resolve this location any closer.

Discussion

Subtropical Convergence

The geographic location of the STC during the three crossings was unremarkable; the surface expression lay between 40°S and 42°S latitude, which was well within the established limits for this front (Lutjeharms & Valentine 1984). The two eastern sections (Figs. 2 and 4) showed singular fronts, particularly deeper in the water column, while the most easterly crossing (Fig. 3) showed a more complicated frontal structure. This has been noted before by Lutjeharms & Emery (1983). While the surface and the subsurface expressions of the STC lay at more or less the same latitude during December 1978 (Fig. 2) this was not so during March 1979. At this time both sections exhibit a step-like structure for the STC with a surface outcropping to the south of the subsurface front, particularly marked in the isotherms of Figure 4. This agrees with the conclusions reached by Lutjeharms & Valentine (1984), namely, that the subsurface expression of the STC lies predominantly to the north of the surface expression.

Sea surface temperature inversions noted on the southern border of the STC on previous occasions (Lutjeharms & Emery 1983) were found on both *S.A. Agulhas* cruises; these are most clearly evident in Figure 2. The surface salinity, a more conservative property than surface temperature, indicates that this inversion may be caused by a body of subtropical water which had been significantly cooled, but which had retained its subtropical salinity.

Mixing of water masses with different thermal and haline characteristics may be inferred from steps and other small-scale perturbations on the temperature traces of XBTs. In Figure 6 temperature traces in the vicinity of the STC have been reproduced for the three sections which crossed this front. During all three crossings mixing and interleaving occurred most intensely to the south of the STC during the *Polarsirkel* crossing, but to the north of the front during the northward crossing of the *S.A. Agulhas*.

Sub-Antarctic Front

The latitude at which the SAF lay had not changed during the three months that had elapsed between the two legs of the *S.A. Agulhas* cruise; its shape had. While in Figure 2, the southward leg, it is a very steep front through at least the upper 400 m of the water column, by March (Fig. 3) the front did not reach water shallower than 100 m but had an outcrop considerably further south. The *Polarsirkel* section, carried out simultaneously, located the SAF about 120 km further north, but with the same shape. Its surface expression is evident in at least two of the concurrent sea surface salinity traces.

The definition of the Sub-Antarctic Front used by Lutjeharms & Emery (1983) follows the one first proposed by Sievers & Emery (1978) and locates the front where there is a subsurface temperature gradient lying between the 3 °C and 5 °C isotherms and in particular where the most vertically oriented isotherms occur within this gradient. In Figure 4 this bunching of isotherms is clearly evident in the surface layer at about 45°S latitude. Below 500 m horizontal thermal contrast in the water masses declines and the SAF loses its definition. There is, however, a continuation of isotherms with increased vertical orientation from 7 °C at 150 m to 2,5 °C at 1 000 m. This may be indicative of a thermal front throughout the upper 1 000 m. The definition used above may thus be useful only for the expression of the SAF in the upper 500 m. By comparing Figures 4 and 5 it may be seen that the SAF lies in the core of the tongue of low-salinity water which subducts between the APF and the STC.

The lateral extent of the STC and the SAF at any particular time may best be studied from satellite remote sensing. Due to persistent cloudiness over the South East Atlantic Ocean during this period, no useful thermal infrared images are available for the cruise leg of the *Polarsirkel* or for the return leg of the *S.A. Agulhas*. A composite portrayal of images for the period 10 to 17 December coinciding with the outward leg of the *S.A. Agulhas* is given in Figure 7. It shows the vessel intersecting the edge of an incipient Agulhas Ring as described by Lutjeharms (1981). This agrees with the thermal section for this period (Fig. 2) which shows the characteristic double channel configuration of a ring with water warmer than 23 °C at both 36°30′S and 39°30′S. A mass of slightly warmer, but decidedly more saline, water south of the Subtropical Convergence (see Fig. 2) is also noticeable in Figure 7 as a detached body of water, probably an almost completely decayed warm eddy.

Compared with the established location of the SAF (Lutjeharms & Valentine 1984) the SAF lay well within the established geographic limits during these cruises. The temperature at the middle of the sea surface gradient, which defines the front, lay within previously determined limits, but shifted from the lower to higher temperatures over the three month period of investigation. The step-like structure of the SAF on this occasion was also observed in January and February 1978 (Lutjeharms & Emery 1983), whereas it was ob-

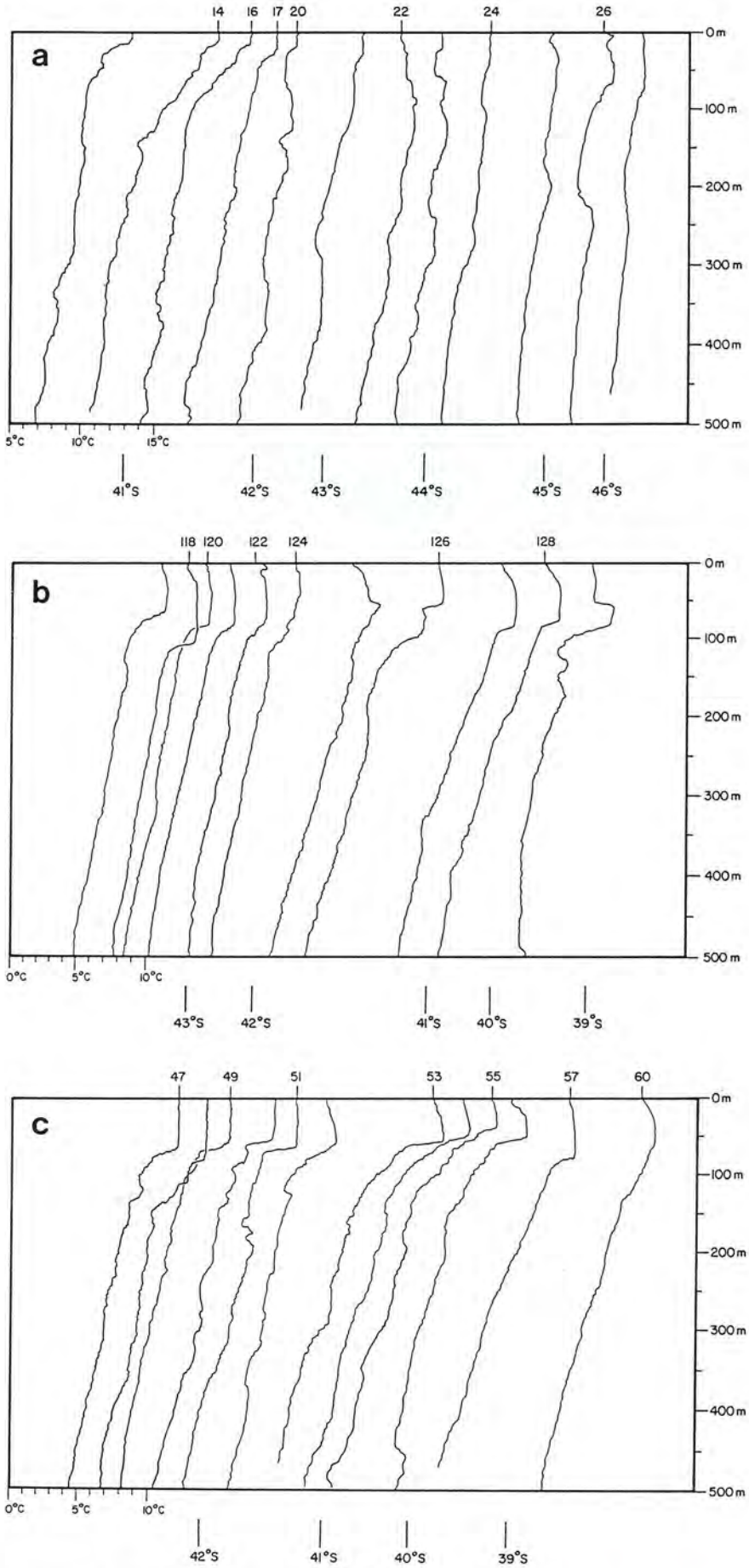

Fig. 6. Selected temperature traces for XBTs undertaken across the Subtropical Convergence during (a) the southward leg of the *S.A. Agulhas* cruise, (b) the northward leg of the *S.A. Agulhas* cruise, and (c) the *Polarsirkel* cruise. To separate them, individual traces have been offset by 4 °C; latitudes are to be read with the sea surface end of the temperature trace.

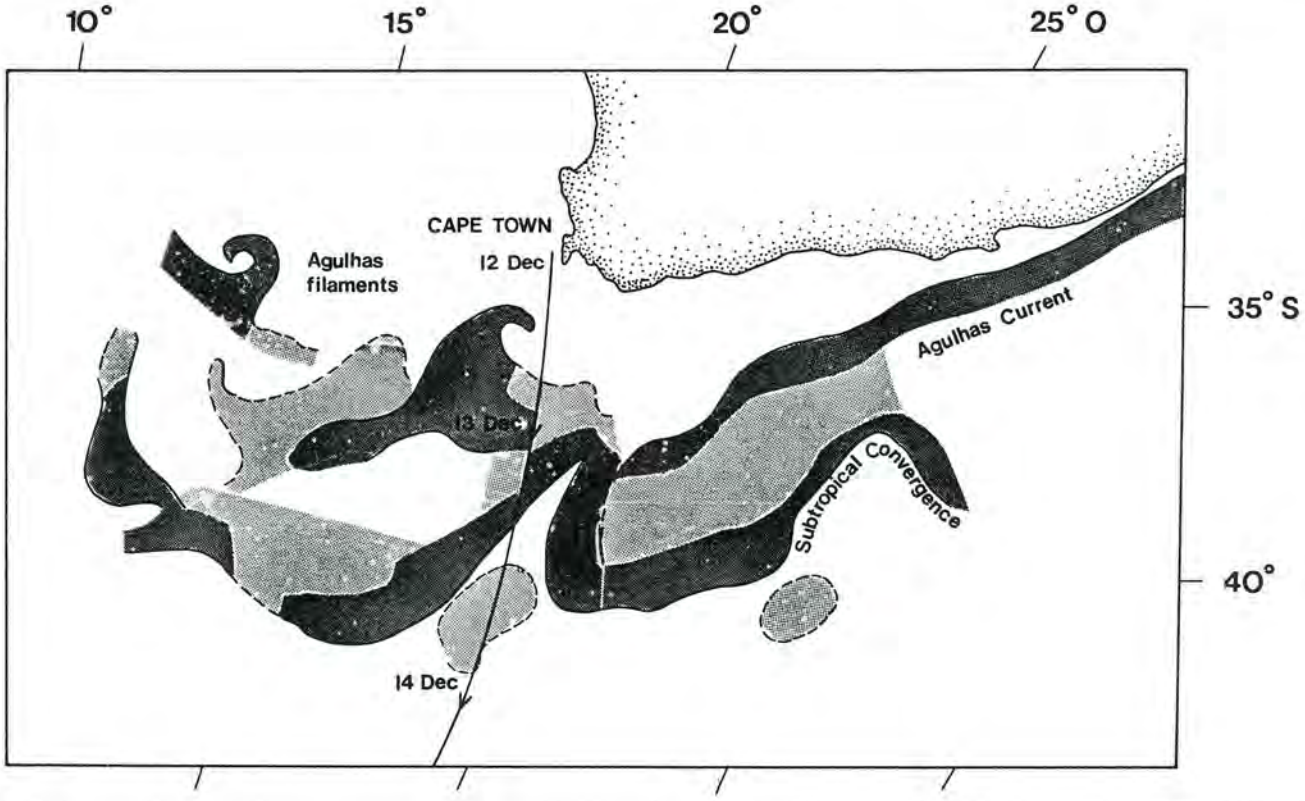

Fig. 7. A composite sea surface temperature image assembled from thermal infrared images produced by the satellites METEOSAT and NOAA for the period 10 to 17 December 1978. The cruise track of the *S.A. Agulhas* is shown with the start of each day indicated.

served to develop between December 1980 and January 1981 (Allanson *et al.* 1981) in a way similar to that in December 1978 to March 1979. The development of this structure may thus be a seasonal effect.

The observed step-like structure also seems to have an effect on the nature of mixing in the water column. In comparing the temperature traces of Figure 8a it should be kept in mind that the SAF lies between 46°S and 47°S. Little evidence for mixing is to be found on these temperature traces. By March (Figs. 8b and c) a well developed warm mixed layer had been established in the upper 70 m, giving the SAF, again at about 46°30′S in Figure 8b and at 45°S in Figure 8c, its step-like structure. At the deeper end of this mixed layer small steps of a few metres on most traces in the vicinity of the SAF indicate mixing.

Antarctic Polar Front

On al three cruises it was observed that the latitude of the subsurface expression of the Antarctic Polar Front remained within 50 km of 49°S, that is, over a period of three months. Its surface expression was slightly south of the subsurface expression in December 1978 (Fig. 2), but by March 1979 (Figs. 3 and 4) the surface expression was found much further south, as is particularly evident in Figure 4. While the cold winter Antarctic Surface Water was still at the sea surface in December 1978 (Fig. 4), by March 1979 it had been capped by a layer of warm water and the subsurface minimum was well-formed. The latter part of this development has also been observed by Lutjeharms & Emery (1983) and Allanson *et al.* (1981).

Antarctic Divergence and Continental Water Boundary

Whenever stations have been undertaken as far south as 69°30′S as part of the programme of which these results form a part the CWB has been observed (Allanson *et al.* 1981, Lutjeharms & Emery 1983) in the proximity of Sanae. Its very low temperatures, salinities and very high chlorophyll *a* values define its geographic location unambiguously. This also occurred during the return journey of the *S.A. Agulhas* (Fig. 3) of the present results.

Similarly, the Antarctic Divergence (Deacon 1933, 1982) has been observed on a number of sections forming part of this programme (Allanson *et al.* 1981, Lutjeharms & Emery 1983). The location of this front has been defined as the latitude at which the subsurface temperature minimum is broken by a column of warmer water (see Fig. 2). With few exceptions this front has been found to lie within 50 km of 65°S. According to Gordon & Molinelli (1982) this front may be an area of influx of warmer water from further north as part of the Weddell Gyre circulation. Allanson *et al.* (1981) have shown that this front coincides with an area of lower nitrate and higher silicate. The location of the AD on the first leg of the *S.A. Agulhas* cruise agrees with the locations found during other cruises; on the return leg no clear indication of an AD was, however, observed. This information does not therefore lend itself to an interpretation of the AD as either a true divergence, or as part of a recirculation.

Conclusions

The subsurface geographic locations of the Subtropical Convergence, the Sub-Antarctic Front, the Antarctic Polar Fronts, the Antarctic Divergence and the Continental Water Boundary south of Africa were unremarkable during the period December 1978 to March 1979. Shifts in latitude with time or with longitude of crossing were well within established limits and showed no clear temporal or longitudinal behaviour.

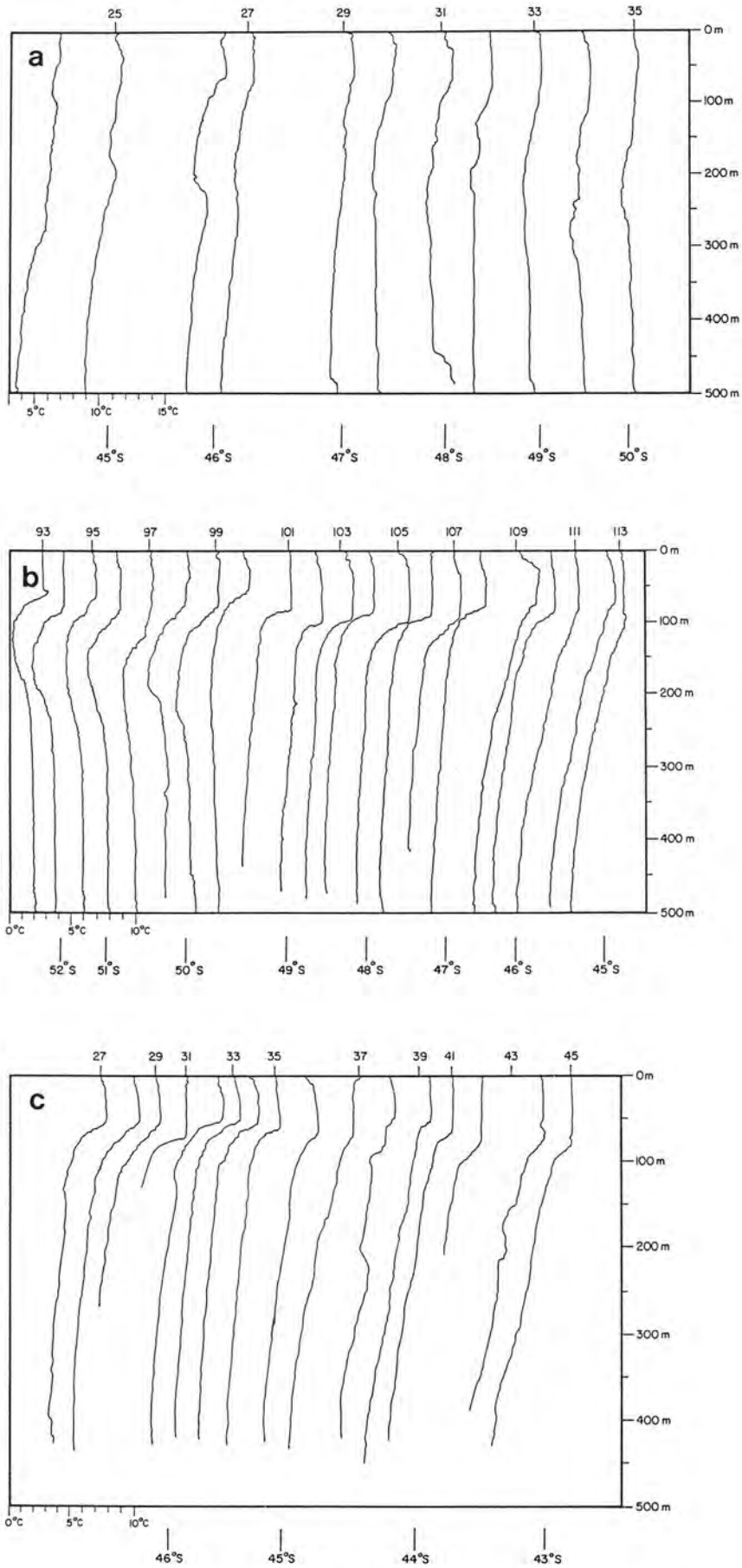

Fig. 8. Selected temperature traces for XBTs undertaken across the Sub-Antarctic Front and, in some cases, the Antarctic Polar Front during (a) the southward leg of the *S.A. Agulhas* cruise, (b) the northward leg of the *S.A. Agulhas* cruise, and (c) the *Polarsirkel* cruise. To separate individual traces they have been offset by 4 °C in (a), 2 °C in (b) and (c). Latitudes are to be read with the sea surface end of the temperature trace.

It was established for the first time that the Sub-Antarctic Front may extend to a depth of at least 1 000 m south of Africa, but that its present definition is not valid at depths greater than 500 m.

The structures of the Subtropical Convergence, the Sub-Antarctic Front and the Antarctic Polar Front developed from a vertical front, with surface and subsurface expressions at about the same latitude, to step-like fronts, with the surface expressions as an outcrop to the south of the subsurface expression. This changing frontal morphology may be a seasonal effect.

Acknowledgements

Measurements on the *S.A. Agulhas* cruise were carried out by Dr P.R. Condy and colleagues from the University of Pretoria while measurements on the *Polarsirkel* were made by the second author. Data analysis was carried out by Dr G.A.W. Fromme and Mr H.R. Valentine of the NRIO/CSIR, while salinities were determined by Dr M. Orren and assistants. To these colleagues, as well as to the captains and crew of the two vessels, the typist and draughtladies we express our thanks.

References

ALLANSON, B.R., HART, R.C. & LUTJEHARMS, J.R.E. 1981. Observations on the nutrients, chlorophyll and primary production of the Southern Ocean south of Africa. *S. Afr. J. Antarct. Res.* 10/11: 3-14.

CRAWFORD, A.B. 1965. Sea surface temperature bucket. Personal publication, Cape Town, 5 pp.

CRAWFORD, A.B. 1972. Sea surface temperature measurements by direct sampling. Maritime Weather Office, Cape Town, 8 pp.

DEACON, G.E.R. 1933. A general account of the hydrology of the South Atlantic Ocean. *Discovery Rep.* 7: 171-238.

DEACON, G.E.R. 1982. Physical and biological zonation in the Southern Ocean. *Deep-Sea Res.* 29: 1-15.

FOLDVIK, A., GAMMELSROD, T. & TORRESON, T. 1981. Measurements of ocean current and bottom pressure near Bouvetoya, January-March 1979. *Nor. Polarinst. Skr.* 175: 105-112.

GORDON, A.L. & MOLINELLI, E.J. 1982. Southern Ocean Atlas. Columbia University Press, New York, 11 pp + 233 plates.

KRONER, S.M. & BLUMENTHAL, B.P. 1977. Guide to common shipboard expendable bathythermograph (SXBT) recording malfunctions. *Naval Oceanographic Office Technical Note,* NAVOCEANO TN 3700-75-77: 48.

LUTJEHARMS, J.R.E. 1981. Features of the southern Agulhas Current circulation from satellite remote sensing. *S. Afr. J. Sci.* 77: 231-236.

LUTJEHARMS, J.R.E. 1985. Location of frontal systems between Africa and Antarctica: Some preliminary results. *Deep-Sea Res.* 32: 1499-1509.

LUTJEHARMS, J.R.E. & EMERY, W.J. 1983. The detailed thermal structure of the upper ocean layers between Cape Town and Antarctica during the period Jan-Feb 1978. *S. Afr. J. Antarct. Res.* 13: 3-14.

LUTJEHARMS, J.R.E., FROMME, G.A.W. & VALENTINE, H.R. 1981. Oceanic frontal systems between Africa and Antarctica. *EOS, Trans. Am. geophys. Un.* 62: 924.

LUTJEHARMS, J.R.E., FROMME, G.A.W. & VALENTINE, H.R. 1986. Die termiese oseaanstruktuur suid van Afrika. Verslag oor sestien navorsingsvaarte. *WNNR Navorsingsverslag* 390 (in prep.).

LUTJEHARMS, J.R.E. & VALENTINE, H.R. 1984. Southern Ocean thermal fronts south of Africa. *Deep-Sea Res.* 31: 1461-1476.

OSTAPOFF, F. 1962. The salinity distribution at 200 m and the Antarctic frontal zones. *Dt. hydrogr. Z.* 15: 133-141.

SIEVERS, H.A. & EMERY, W.J. 1978. Variability of the Antarctic Polar Frontal Zone in the Drake Passage – Summer 1976-1977. *J. geophys. Res.* 83: 3010-3022.