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VARIABILITY OF THE BENGUELA CURRENT OFF THE CAPE PENINSULA, SOUTH AFRICA

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The near-surface flow off the Cape Peninsula, South Africa, was monitored weekly along a 60 km transect between August 1995 and July 1996 as part of the South African Sardine and Anchovy Recruitment Programme. Measurements from small vessels were made by means of tracking drogues by GPS (sometimes differentially corrected) and by an Acoustic Doppler Current Profiler (ADCP) when sampling from large vessels. The currents responded to the presence of Agulhas water, to wind-forcing and to barotropic shelf waves. The results suggest a marked seasonality in the position and amount of equatorward and poleward flow, which needs to be confirmed. Strong north-westward flow close inshore was measured in spring (August–October), turning into the "classic" formation of an equatorward jet, with variable barotropic flow inshore in early summer. In summer, circulation patterns became more complex, with marked southward flow. From February to April, the front was generally far offshore and often not encountered on the transect. Examples of the variability of the flow on a week-by-week basis are provided and are related to the thermal structure and to the wind record from Cape Point. The seasonality of the flow is summarized in terms of estimated mean surface transport per two-month period, and a series of northward and southward components for each cruise throughout the year is provided.

The Benguela upwelling system lying off southern Africa's west coast is one of the world's four main upwelling systems (Parrish *et al.* 1983). Its physical characteristics have been summarized by Nelson and Hutchings (1983), Shannon (1985) and Shannon and Nelson (1996). It encompasses the entire region that can be affected by the upwelling phenomenon, from Cape Agulhas in the south to approximately of 15°S in southern Angola. The intensity of upwelling varies with locality, and a number of upwelling cells can be identified (Nelson and Hutchings 1983, Lutjeharms and Meeuwis 1987). The short-term variability of dynamic features was first highlighted by Airborne Radiation Thermometry (ART) surveys off the Cape Peninsula (Andrews and Cram, 1969, Jury 1985a, b, Jury *et al.* 1985) and spatial complexity over the whole region was revealed by satellite imagery (e.g. Lutjeharms 1981, Agenbag 1992). Whereas the Benguela upwelling system is fairly easily defined, the Benguela Current is a term that has been applied to different aspects of water movement within and on the outer margin of the upwelling system.

Off the Cape Peninsula, the bottom topography deepens rapidly to 200 m water depth, where the slope becomes more gradual before deepening again at the shelf-edge, in the region of the 400–500 m isobath. (Fig. 1). A relatively narrow jet current flowing NNW was measured, using lowered current meters, close to the shelf-edge in regions of considerable southward flow, mainly subsurface (Bang and Andrews 1974, Nelson 1985). Bang and Andrews (1974) named the current the "Good Hope Jet", but the term "jet" is now most commonly used. Tracking of a near-surface drogue and interpretation of the drift of ichthyoplankton (Shelton and Hutchings 1982) supported the concept of a narrow jet of flowing northward, which provided the link between the spawning grounds for pelagic species on the western Agulhas Bank and their nursery grounds farther north on the West Coast. Boyd *et al.* (1992) built upon this concept using data from Acoustic Doppler Current Profiler (ADCP) surveys and anchovy egg distributions, showing the funnelling of eggs on the western Agulhas Bank into the jet current off the Peninsula. The intensification of the NW flow in midwater and near the surface is believed to be attributable to the vertical enhancement of a bottom-mixed layer above the shelf edge by tidal forces raising the overlying isopycnals (Shannon and Nelson 1996). The contributors to the water of the jet current include the surface and thermocline waters of the western Agulhas Bank, whose movement was inferred by Boyd *et al.* (1985) and measured by Largier *et al.* (1992), as well as Agulhas Current leakage in the region of the shelf-edge (Lutjeharms and Cooper 1996). An average near-surface current field was shown by Boyd and Oberholster (1994).

The seasonality of the near-surface flow within the Benguela upwelling system off the Cape Peninsula is

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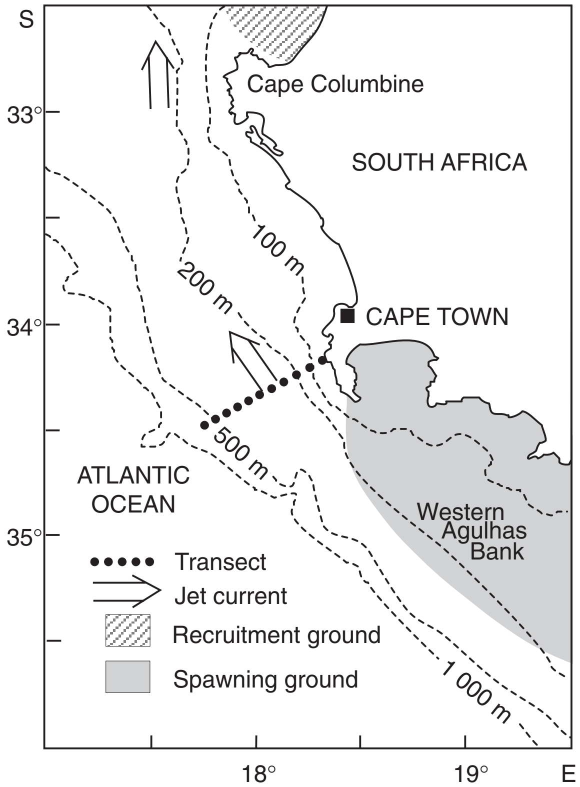

Fig. 1: Location of the SARP monitoring transect in relation to the pelagic spawning and recruitment areas

not clear from previous studies, mainly as a result of its short-term variability. Also, few examples of flow features had adequate spatial resolution on a small scale. Both of these aspects will be addressed in this paper, which reports on the physical results from the first year (1995/96) of the South African Sardine and Anchovy Recruitment Programme (SARP), a project that aims to predict recruitment of pelagic species. Key elements in this programme include appropriate measurements of:

(i) pelagic spawning on the western Agulhas Bank (Richardson *et al.* 1998);
(ii) currents between the western Bank and the West Coast nursery grounds;
(iii) the match between favourable advection and spawning (Huggett *et al.* 1998).

In this paper, the currents off the Cape Peninsula and their relationship to wind and hydrography are described.

MATERIAL AND METHODS

Sampling strategy

The near-surface flow and ichthyoplankton within 60 km of the coast (to the 600-m isobath) have been measured generally on a weekly basis since August 1995 along a transect of 12 evenly-spaced stations south-west of Slangkop Point, Kommetjie, off the Cape Peninsula (Fig. 1). From August 1995 to July 1996, sampling took place in 38 out of 52 weeks. During 28 cruises all stations were sampled and during 6 cruises between 8 and 11 stations were sampled; altogether, about a 65% success rate. Hourly wind data were obtained from Cape Point Lighthouse. Daily N/S wind-runs are given in Figure 2, showing the major upwelling periods and events.

On small vessels, currents were measured mainly by tracking a drifter with a drogue at 2-m depth (Boyd 1982). At each station, the drogue was released and the position and time was noted on the vessel's GPS, or stored on a handheld unit, when available. The latter position was an average of 30 values and the raw data (and mean position) were corrected later using post-processing software and appropriate base station data. When biological/physical sampling (see Huggett *et al.* 1998) was completed, the drogue was retrieved and the time and position noted again.

On the large Sea Fisheries' vessels (F.R.S. *Africana* and F.R.S. *Algoa*), currents were also measured using a hull-mounted 150 kHz RDI Acoustic Doppler Current Profiler (ADCP), as described by Boyd *et al.* (1992). These measurements often replaced drogue tracking on some stations, because of the difficulty in retrieving the drogues from large vessels. However, the ADCP does not measure the currents within 10 m of the surface; the most reliable upper layer data were from the third "bin", centred at 32 or 34 m. In compiling the time-series of currents, drogue data were used, when available. Otherwise, for stations where a drogue was not used, the ADCP data were adjusted by adding the mean difference between drogue and ADCP velocities from other stations. This method was found to be satisfactory (i.e. similar corrections were measured on different stations, except for those close inshore).

Accuracy of the bottom-references ADCP vectors was estimated to be better than 5 cm·s^{-1} (Boyd *et al.* 1992), but addition of the shear between the depth of the ADCP measurements and 2 m would reduce the overall accuracy to approximately 10 cm·s^{-1}. The accuracy of the drogue-sourced vectors varied, depending on the time between deployment and retrieval, and whether differentially corrected or standard GPS

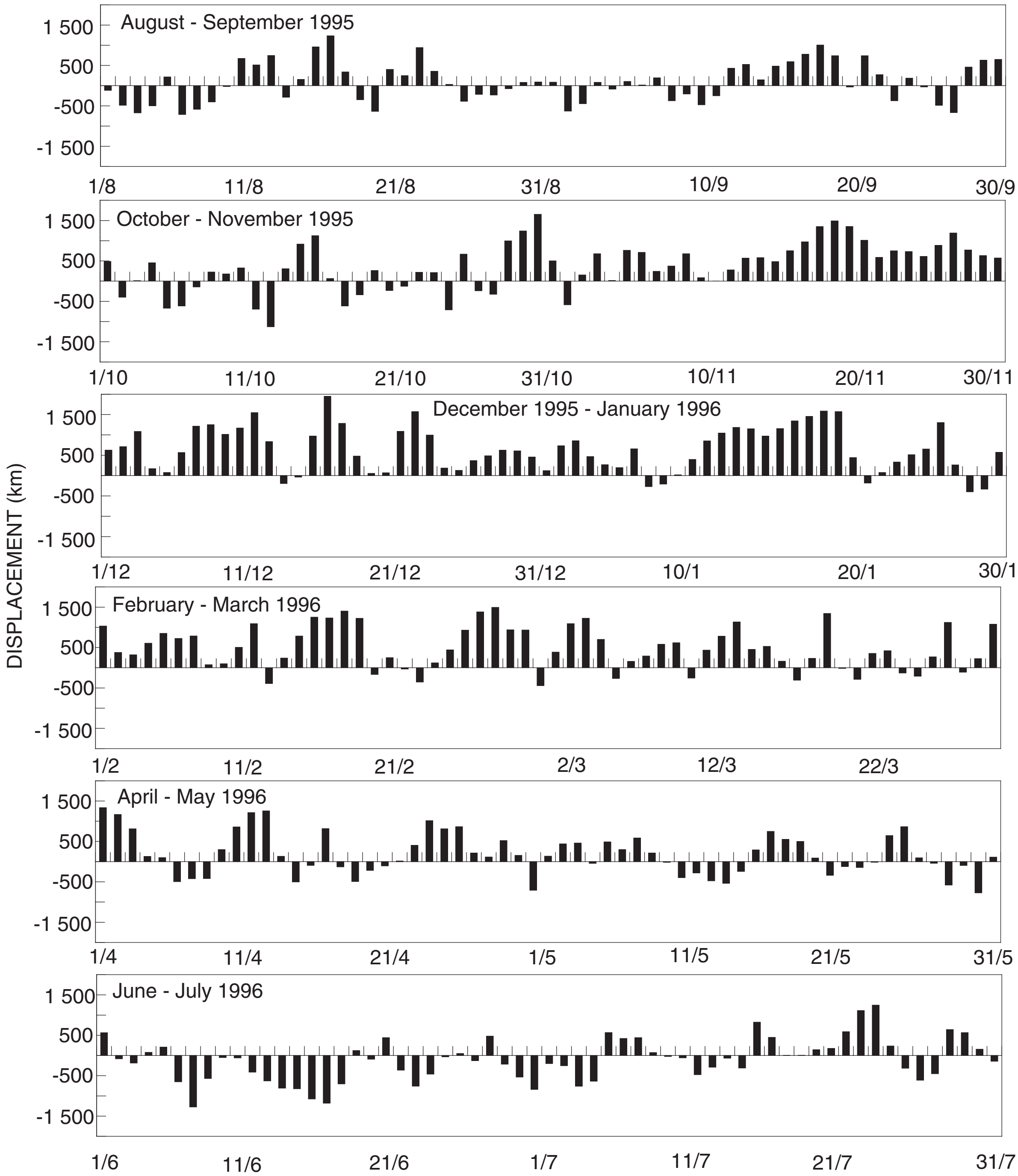

Fig. 2: Daily N/S wind displacement at Cape Point Lighthouse per two-month period from August 1995 to July 1996

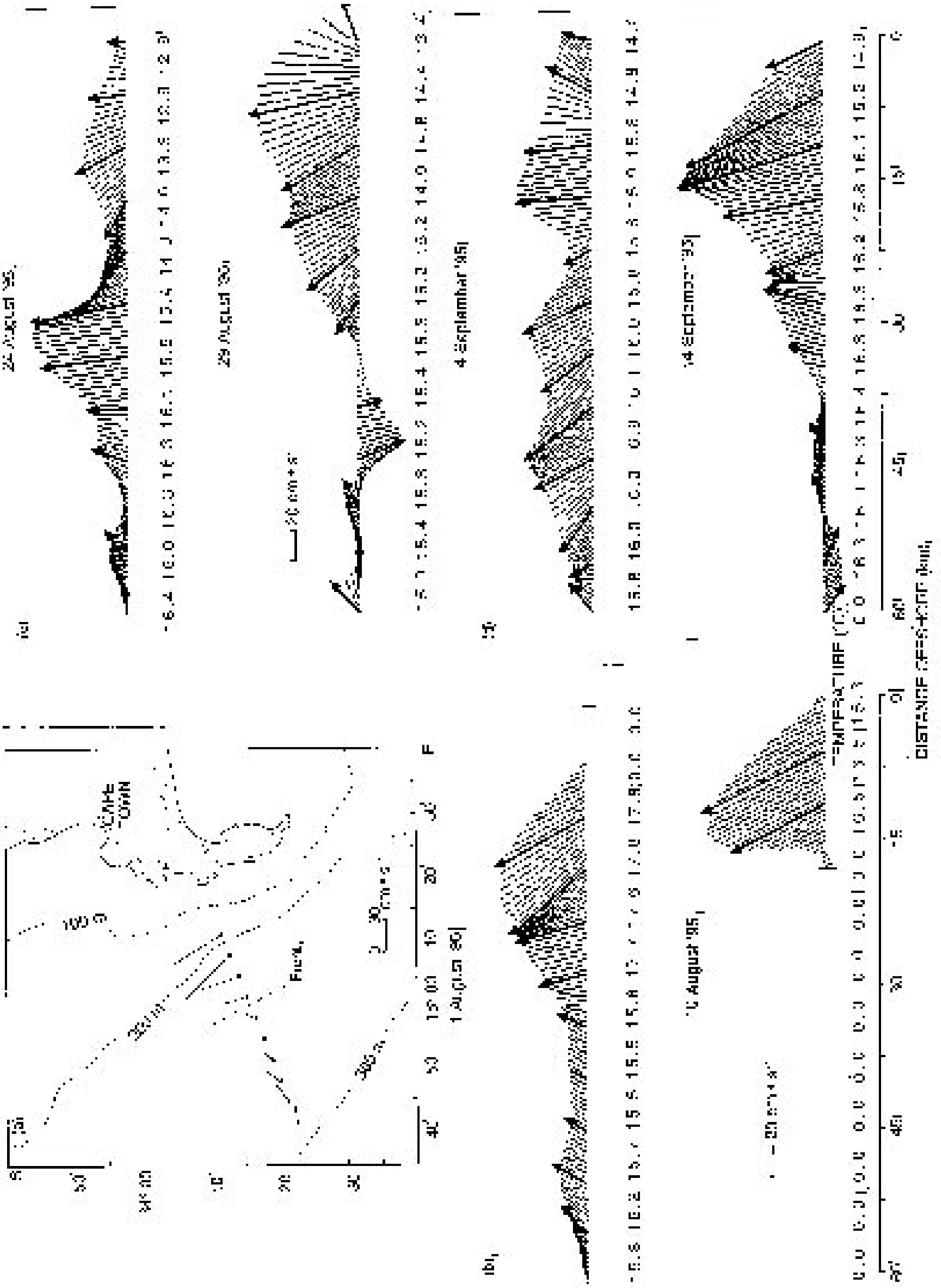

Fig. 3: (a) Current vectors at 2 m measured on 1 August 1995 (with SST) using a mercator projection; (b) current vectors and SST along the transect for 1 and 10 August 1995, and interpolated flow field (data differentially corrected); (c) interpolated flow fields and SST for 24 and 29 August 1995 (data differentially corrected) and (d) interpolated flow fields and SST for 4 and 14 September 1995 (data differentially corrected)

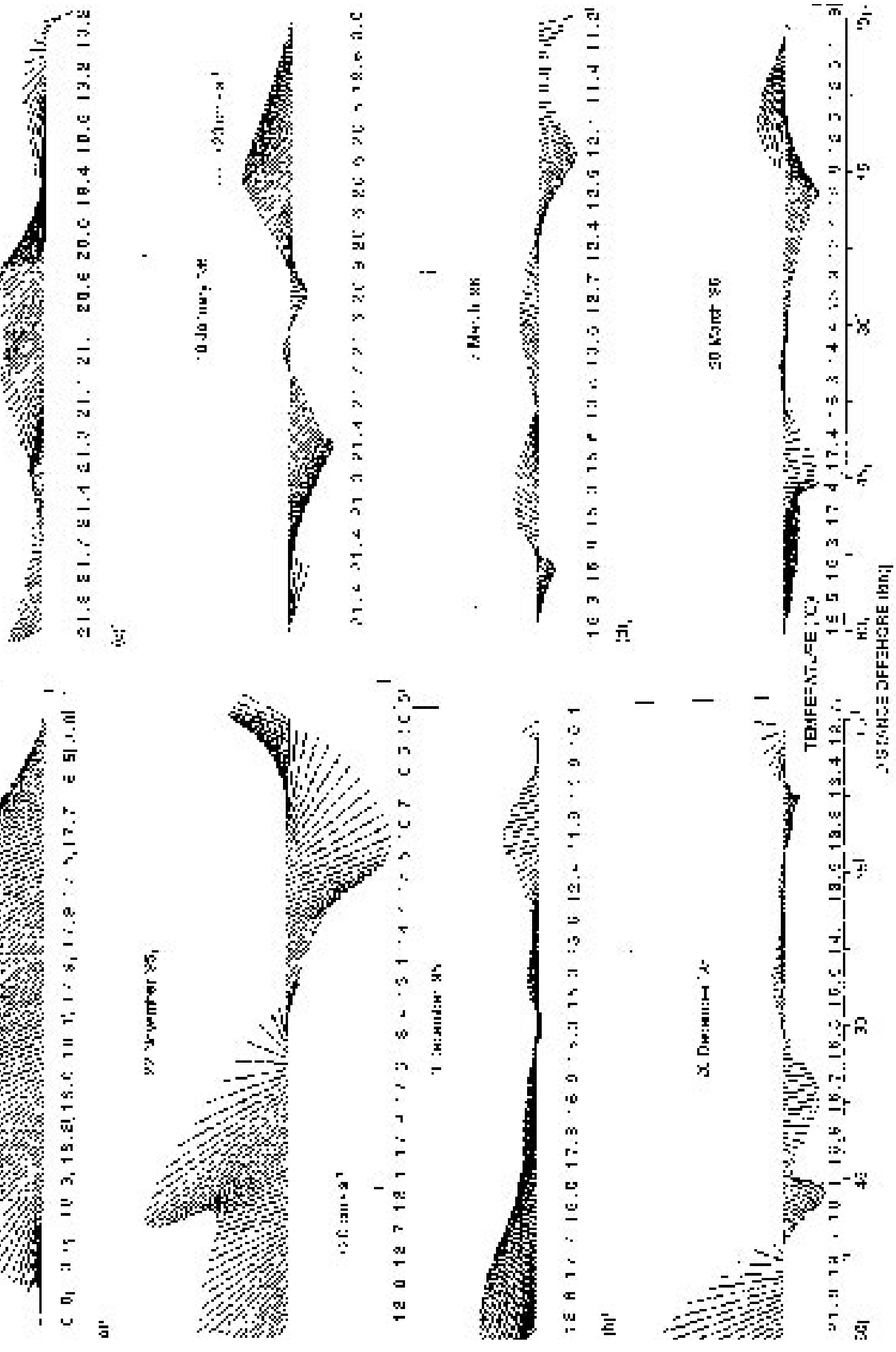

Fig. 4: Interpolated flow fields and SST for (a) 13 and 22 November 1995 (ADCP and drogues; GPS), (b) interpolated flow fields and SST for 3 and 20 December 1995 (ADCP and drogues; differential GPS), (c) interpolated flow fields and SST for 4 and 10 January 1996 (differential GPS) and (d) interpolated flow fields and SST for 7 and 29 March 1996 (ADCP; differential GPS)

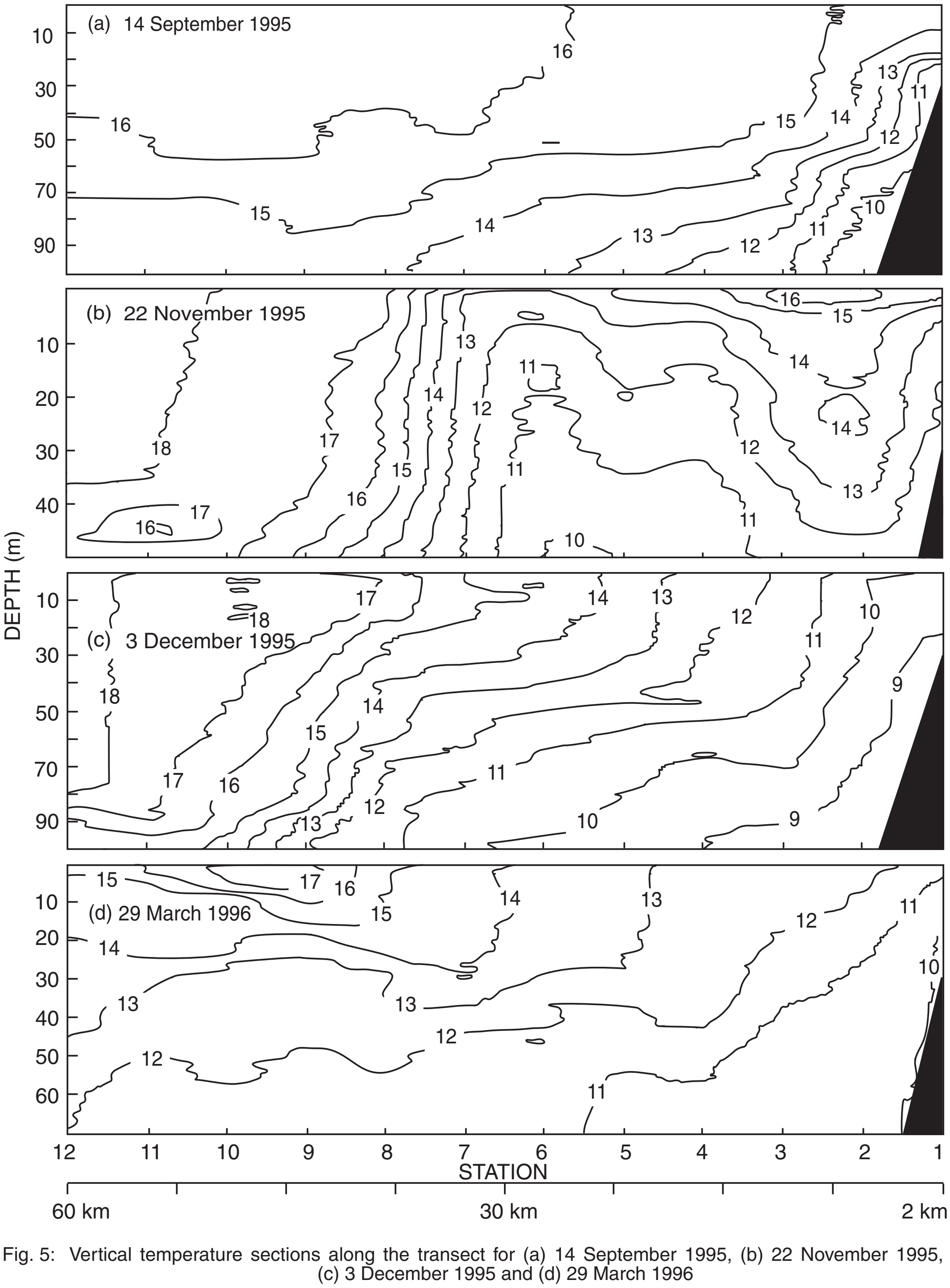

Fig. 5: Vertical temperature sections along the transect for (a) 14 September 1995, (b) 22 November 1995, (c) 3 December 1995 and (d) 29 March 1996

positions were used. In the worst case, a station time of 10 minutes with an opposing 100 m error in either position would result in a vector error of 33 $cm{\cdot}s^{-1}$. However comparison between differential corrected and uncorrected positions indicated a mean difference of 40 m, which would reduce the vector error to 15 $cm{\cdot}s^{-1}$ or less. Many of the cruises had station times of 15–20 minutes, which would reduce uncertainty further to 10 $cm{\cdot}s^{-1}$ (or less, if the position errors were not opposing). Differentially corrected positions are considered accurate to within 10 m, but because of vessel drift during deployment and retrieval, the uncertainty in the resulting current vector is estimated at 5 $cm{\cdot}s^{-1}$.

Windage on the drogues was calculated using the method of Murray (1975), and was minimal, even in strong winds (Bilski 1996). Under such conditions, an extra float and weight were often added underneath the drogue, which aided stability and enhanced visibility. However, there was often considerable shear in the upper water layer as a result of strong windstress. This was not regarded as an error, but it necessitated adjustment to the ADCP data for consistency with the drogue data. Contamination by tides and higher frequency components can be regarded as negligible (Nelson *et al.* 1998).

Data analysis

Current vectors and sea surface temperatures for each station were used to construct profiles of these variables along the sampling transect. Cubic splines were fitted to the current vectors from the 12 stations, resulting in an estimated vector every 500 m. Regions of current shear, convergence and divergence, as well as the position of thermal fronts, could therefore be identified more clearly (Figs 3, 4). For the purpose of comparison, individual vectors are shown by arrows in Figure 3. Vertical temperature sections are shown for four occasions (Fig. 5). The time-series was analysed as a whole, then divided into six 2-month periods corresponding to early spring (August–September), spring/summer (October–November), mid-summer (December–January), late summer (February–March), autumn (April–May) and winter (June–July). In those plots (Fig. 6), currents and surface temperatures were averaged for each station within each time period, then the averaged currents were fitted to a cubic spline. In Figure 7, the temperature means and ranges were calculated from the monthly station averages, not individual cruises. In addition, for each cruise, equatorward and poleward components of transport in the "upper 1 m of the water column" were calculated along the transect (Fig. 8).

RESULTS

Individual flow patterns

Selected individual flow patterns are described mainly in pairs. This allows for changes to be observed over a fairly short period of time in relation to forcing, as well as for individual patterns to be described. Criteria for selection were based primarily on providing an example of each particular type of flow-field. Differentially corrected data were used where possible. Reference will also be made to flow patterns not presented, and presentation of results in sequence should provide a qualitative appreciation of seasonal changes as manifest during the 1995/1996 upwelling season, later given quantitatively.

1–10 AUGUST 1995

Figure 3a shows the measured current vectors and temperatures for 1 August displayed in a geographically correct reference, which can be compared with the processed data for the same date in Figure 3b. An intrusion of Agulhas water, characterized by surface temperatures of 17.8°C on 1 August and 16.5°C on 10 August, was recorded within 30 km of the coast moving in a NNW direction at 40–60 $cm{\cdot}s^{-1}$, with the quickest currents inshore. Offshore of 35 km, the temperatures fell to a uniform 15.5–15.8°C, typical of South Atlantic surface water at that time of the year. The vectors for 1 August show this offshore water being entrained in a NE–N direction by the Agulhas intrusion. Comparison of the current vectors for Station 3 (10 km offshore) between 1 and 10 August shows that the mainly poleward winds (Fig. 2) had not reduced the speed of the flow, and had probably kept the flow close to the coast through Ekman forcing.

24–29 AUGUST 1995

Winds from 10 to 24 August (Fig. 2) were mainly upwelling-favourable (equatorward), and resulted in the development of an upwelling front between Stations 5 and 6 (at approximately 27 km offshore) and a narrow 40–50 $cm{\cdot}s^{-1}$ jet current just offshore of the front (Fig. 3c). Convergence of surface flow was clearly apparent at the front, and there were possible slight remnants of Agulhas Current water at the outer margin of the jet. Offshore of the jet, surface waters were entrained in an E-NE direction, and velocities within the upwelled water inshore were weak and northwards. Weak poleward and onshore winds between

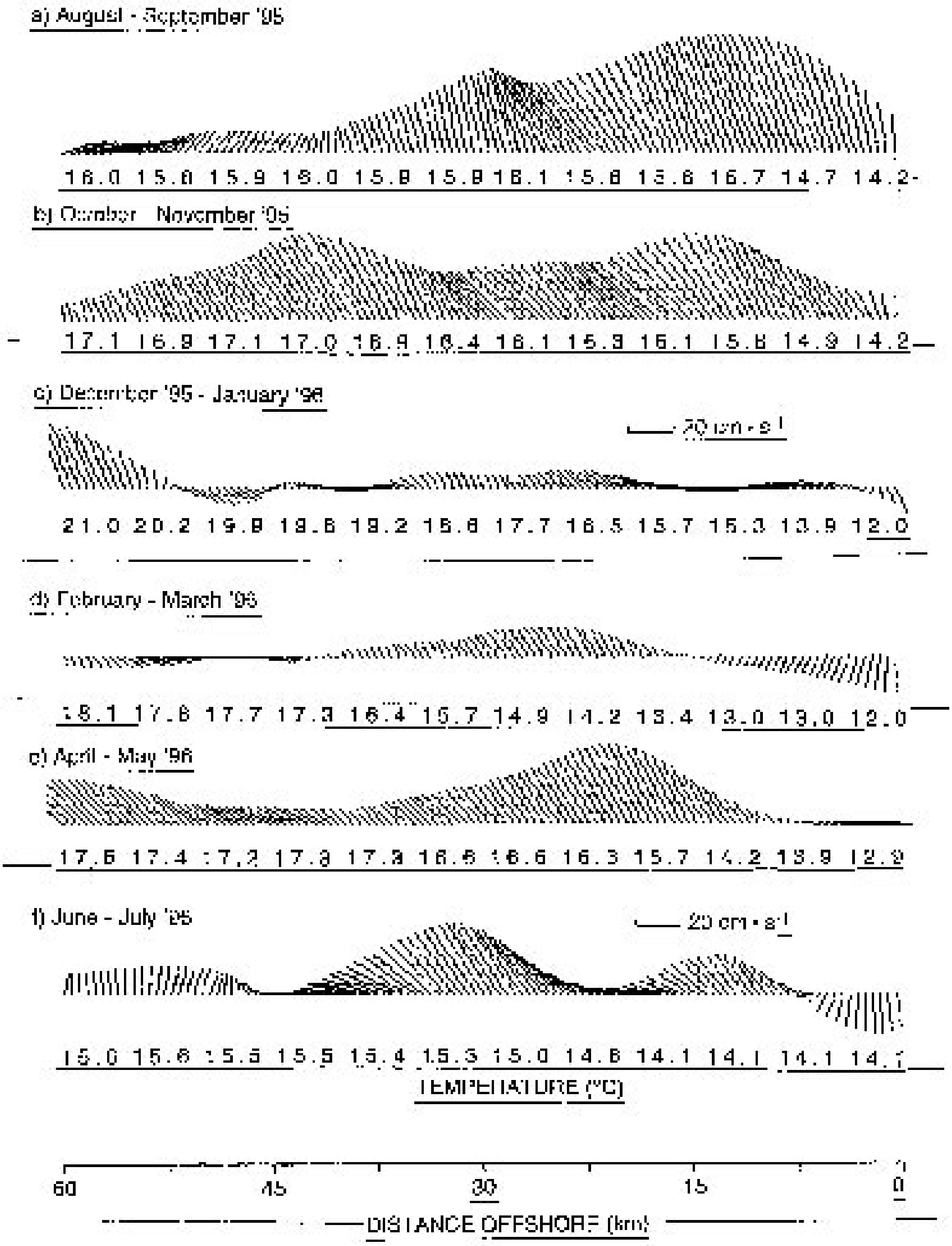

Fig. 6: Vectorically-averaged interpolated flow fields and SST along the transect for two-month periods from August 1995 to July 1996

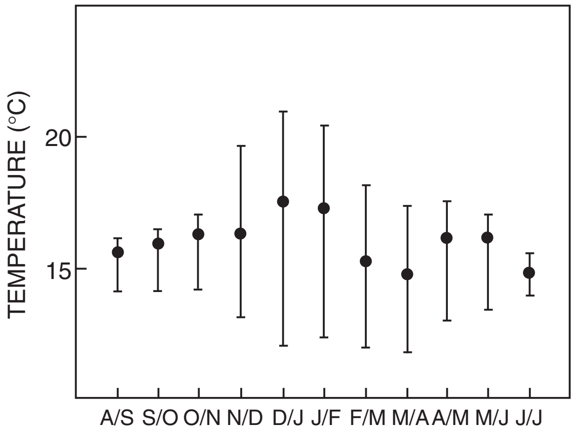

Fig. 7: Mean and temperature range for overlapping two-month periods from August 1995 to July 1996 (see text)

24 and 29 August induced the jet current to move onshore to between 8 and 25 km of the coast, but the fact that the temperature in the current core was 14.4–14.9°C dismisses any possible influence of the Agulhas Current. Offshore flow was weak towards the east and south, probably as a result of the prevailing winds.

4–14 SEPTEMBER 1995

A broad band of N–NW flow was measured along the transect, with suggestions of two velocity maxima 18 and 30–45 km offshore (Fig. 3d). Apart from two days of opposing poleward winds, wind forcing had been weak since the 29 August survey (Fig. 2). The following 10 days experienced variable winds, but the jet current had clearly moved inshore and intensified to 80 $cm \cdot s^{-1}$ between 8 and 18 km offshore. The temperature profile (Fig. 5a) revealed a strong sub-surface front relatively close to the coast and coincident with the strongest currents.

13–22 NOVEMBER 1995

During the second half of September and October, strong equatorward winds alternated with moderate poleward winds (Fig. 2). Early in November, SE winds alternated with periods of calm, but moderate equatorward winds prevailed on 13 November and a broad N–NW velocity structure, with the strongest currents inshore, was recorded using ADCP and drogues. The ADCP data were later corrected to 2-m depth, as described earlier. Surface temperatures were warmer than in September, ranging from 16.5 to 18.3°C. The waters of this flow pattern also contained the greatest numbers of anchovy *Engraulis capensis* eggs recorded during the 1995/96 survey (Huggett *et al.* 1998). Between 13 and 22 November, four days of moderate upwelling winds were followed by five days of constant gales with equatorward and offshore components (Fig. 2). This resulted in the formation of a very steep front between Stations 7 and 8 (Fig. 5b). Warmer water and downwelling inshore were accompanied by strong southward flow, whereas a strong NNW flow was recorded offshore.

This example of southward flow on the inner shelf was only the second measured by SARP since it started in August 1995, and it follows the first major upwelling event. The velocities suggest forcing as a result of a barotropic shelf wave, and the warmer water temperature suggests a major southward advection from north of Cape Town, because there would not have been warm "*in situ*" surface water along the Cape Peninsula following such sustained upwelling winds.

3–20 DECEMBER 1995

The continuation of upwelling-favourable winds (Fig. 2) resulted in the offshore movement of the jet current (Fig. 4b). Sampling during such winds indicated additional offshore shear in the upper layer relative to the ADCP measurements (Huggett *et al.* 1998). Figure 5c shows a "classic" upwelling section, with the 10°C isotherm at the surface inshore. Inshore of the front, currents were weak and probably reflect only the direct influence of the wind. On 20 December, a similar thermal pattern was recorded, but during calm conditions after more upwelling-favourable winds between the cruises (a satellite image for 10 December showed an extensive area of very cool, upwelled water between Cape Agulhas and Cape Columbine, with a filament extending offshore from the Cape Peninsula). On 20 December, the jet current was found only beyond 50 km offshore, with weak, southward or onshore flow closer to the coast.

4–10 JANUARY 1996

Cool water and southward flow were measured only at the inshore station (Fig. 4c), a few days of light winds having resulted in warm water approaching (close to) the coast. Currents offshore of Station 2 were mainly NW, with strong convergence between Stations 3 and 5. However, the extensive belt of 20–22°C water moving in a NW direction on the

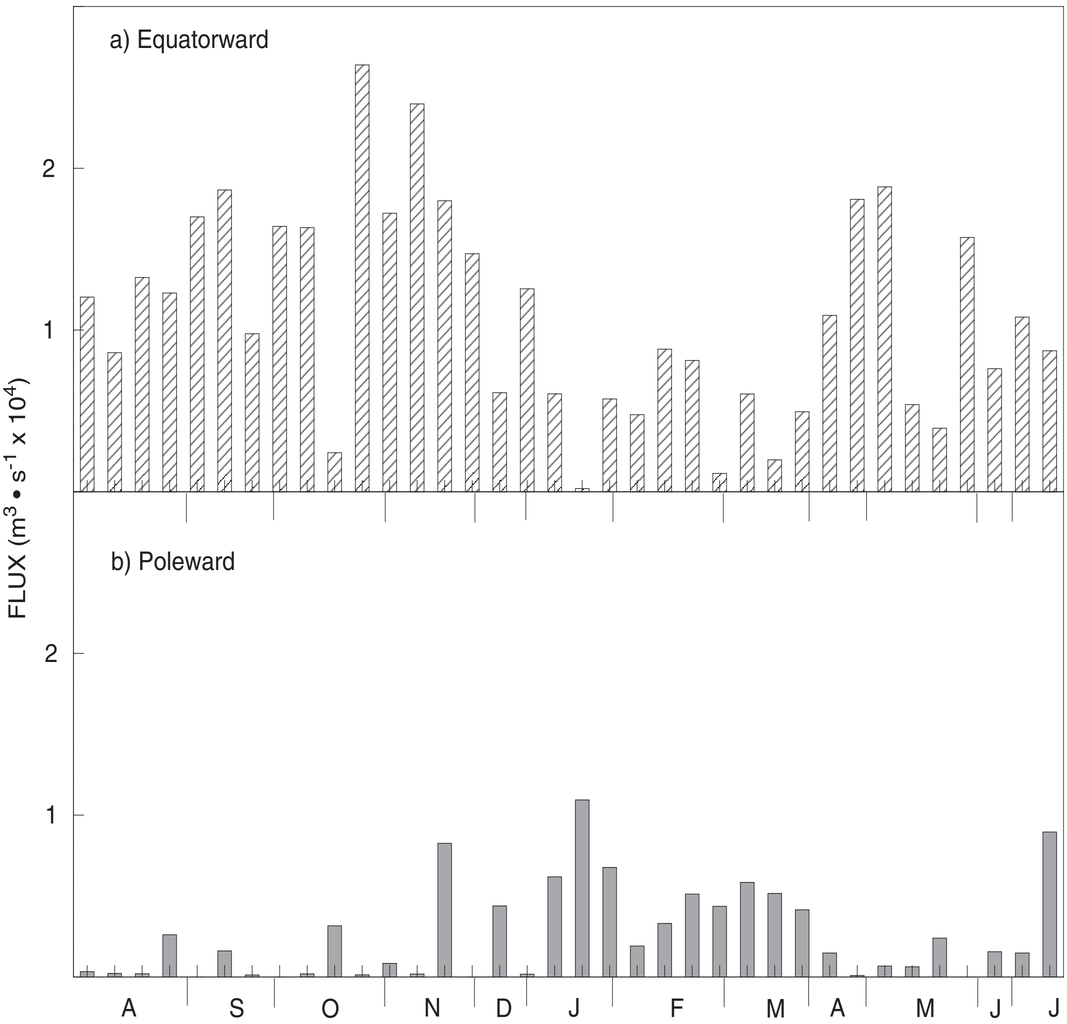

Fig. 8: (a) Equatorward and (b) poleward flux along the transect for the 1 m upper layer in for each cruise

outer half of the transect may have been of Agulhas Current origin. By 10 January, the northward advection of warm water was even closer inshore, but clear SE flow was observed offshore. Similar southward flow of warm water offshore was measured on 22 January, together with strong southward flow inshore, and again on 1 February (although with slightly reduced temperatures of 19–20°C). This feature is apparently the forerunner of the unusual conditions that were found during a filament cruise conducted north-west of the Cape Peninsula in February 1996 (Nelson *et al.* 1998, Duncombe Rae *et al.* in press).

7–29 MARCH 1996

The cruise commencing 7 March was preceded by two days of strong equatorward winds which weakened and changed to a poleward direction. Currents were mainly onshore, but southwards at the four inshore stations. Despite recurring upwelling-favourable winds interspersed with calm periods, there was warming of the outer shelf surface waters between the cruise and those on 17 and 21 March. However, a short, strong upwelling event preceded the cruise of 29 March, causing offshore-directed flow of cool water within 20 km of the coast, which became onshore and southwards as the temperature increased to 17.4°C along the transect. At Station 12, considerably cooler water, with reduced velocity, was encountered, which may originally have been advected from the upwelling regions east of the Cape Peninsula, i.e. the western Agulhas Bank (Lutjeharms and Stockton 1991). The thermal section shows the south-moving warm core dividing the areas of cooler water (Fig. 5d).

Upwelling continued in April, with southerly flow inshore and northerly flow on the outer shelf, whereas in May and early June there was widespread, but weaker, northward flow. Poleward flow was again recorded inshore in July.

"Seasonal" changes in mean transport

Average flow fields and mean temperatures for consecutive 2-month periods are shown in Figure 6. Bimonthly temperature ranges are presented in Figure 7. Equatorward and poleward fluxes, summed for each cruise individually, but presented as a time-series for the whole year, are given in Figure 8. The average flow fields represent a vector summation, showing the mean transport as a function of distance offshore for each period, whereas the development of equatorward and poleward components can be followed separately through the seasons. Because of undersampling, relative to the short-term variability, the averages only give an indication of the seasonality in 1995/96.

The mean flow in August–September 1995 was clearly strongest close to the coast, with weak flow offshore of 45 km having an onshore component (Fig. 6a). The October–November mean flow had a bimodal velocity structure, with peaks at 15 and 45 km (Fig. 6b), and all the vectors were more offshore-directed than in the previous two months. In December–January, NW flow was concentrated on the outer margin of the grid as a result of sustained upwelling for up to 10 days during that period (Fig. 2). The mean flow was weak farther inshore because of the variability in the region (Fig. 6c). Again there were two zones of mean northward velocity, one offshore and the other over the midshelf. In February–March (Fig. 6d), there was only a single northward velocity peak recorded over the midshelf, the offshore branch of northward flow probably having moved beyond the outermost sampling station (and the shelf-edge) owing to repeated upwelling events. The unusual northward and then southward advection of Agulhas Current water on the middle and outer shelf in January (and sustained into February as described earlier) would largely have cancelled each other in the averages in Figures 6c and 6d. Flow within 15 km of the coast was clearly southward on average in February–March (Fig. 6d). The dual northward velocity maxima had returned by April–May (Fig. 6e). Pulsed upwelling continued for most of the latter period (Fig. 2), and mean flow was still relatively strong towards the north-west. In winter (June–July), northward flow was maintained over most of the transect (Fig. 6f), despite the variable winds, except close inshore. The range of temperature along the transect was largest in summer and smallest in winter and early spring (Fig. 7).

There was an increase in equatorward transport from August to November, followed by a decline from November to March (Fig. 8a). The latter phase could have been a result of the substantial equatorward transport associated with the Benguela Current beyond the transect, and the higher levels from April to July a result of the onshore shift in equatorward flow. There was a marked increase in poleward flow after mid-November, following very little in the period August–October, although such flow consisted of both inshore, midshelf and offshore branches on different occasions, as described earlier. The data show that, from December to April, poleward and equatorward surface transport had approximately equal magnitude on the shelf (as far offshore as the 600 m isobath).

DISCUSSION

Previous examples of the use of drogues in small and mesoscale measurements of currents over the shelf include works by Stevenson *et al.* (1974) off Oregon (optical tracking), Boyd (1983) off Namibia (radar tracking) and Lamberth and Nelson (1987) off South Africa (radio tracking). Recently, most detailed work has been done using ADCP, with drogues providing longer time-scale trajectories. Examples are the studies of Strub *et al.* (1991) and Barth and Smith (1998), which investigated the interaction of shelf and adjacent oceanic areas in the California Current system. In the present study, the reliance on small vessels, plus the availability of differential GPS, made drogue tracking the most suitable method for measuring near-surface flow patterns.

The repeated occurrence of relatively strong NNW flow inshore in August and September, accompanied on a few occasions by the presence of Agulhas Current water close inshore, as described by Lutjeharms and Cooper (1996), is a new finding. The development of a jet current off the Cape Peninsula has previously been thought to be a process similar to that in other upwelling regions, in which windstress causes upwelling and the formation of an equatorward jet (e.g. off Oregon – Huyer 1983, Barth and Smith 1998). A recent study by Fowler and Boyd (1998) also showed strong NNW flow close inshore in October 1994, with weaker currents farther offshore in November. However, those conditions were interpreted in relation to event-scale forcing. This "inshore jet" suggests a residual equatorward forcing, which could be driven by the "funnelling" of thermocline waters in a mean north-westerly direction along the western Agulhas Bank, enhanced by a subsurface intrusion of cold, upwelled water onto the shelf in early spring (Boyd *et al.* 1985, Largier *et al.* 1992), in contrast to the warmer water farther offshore. The occurrence of equatorward winds with a strong onshore component, instead of an offshore component, would further encourage longshore flow close to the coast. This was also observed in the peripheral results of a three-dimensional circulation model developed for False Bay (S. Luger, Council for Scientific and Industrial Research, pers. comm.). The direct influence of the wind on the flow 2 m deep would have led to the greater westward component of the mean current vectors when S–SW winds were replaced by SE winds.

In 1995, sustained upwelling as a result of equatorward and offshore winds, which force the NW flow farther offshore and allow barotropic reversals inshore, occurred only after mid-November. However, in some years, upwelling can take place earlier, and the concentrated equatorward flow inshore could be restricted to late winter. The position of peak NW flow along the transect (Fig. 4a, b) could be related to the wind events in the preceding week (up until the end of December) and most previous descriptions of the jet current would apply only to the period from November to December 1995.

Conditions were apparently unusual for most of January and February 1995. There was a substantial surface intrusion of Agulhas Current water in a NNW direction in early January. Thereafter, southward flow developed regularly offshore and over the mid-shelf, and the relationship between currents and wind-forcing appeared weak. Oceanic events in the Cape Basin may have caused this intrusion, as well as its termination and reversal (Nelson *et al.* 1998), and such conditions may not be that unusual. A cruise dedicated to examining flow patterns by ADCP, and making hydrology and plankton measurements (Nelson *et al.* 1998, Duncombe Rae *et al.* in press), observed the situation in early February 1996, when Agulhas water was flowing southwards. Sustained upwelling winds in March and April, and to a lesser extent in May, caused the front to move far offshore, and, for the most part, to remain beyond the shelf-edge. Inadequate sampling farther offshore during late summer 1996 was a major weakness of the present programme (SARP I), leaving a gap in knowledge of both the current structure and the ichthyoplankton assemblage. This problem was addressed in the second year of the programme (SARP II) by extending the sampling grid to 100 km (once per month, when possible), which was replaced subsequently by a standard transect of 14 stations. The first cruise of SARP II (5 August 1996) showed a trimodal velocity structure, with peak flow over the midshelf, at the shelf-edge and offshore, so there is clearly more to learn. Other topics that can be examined in future as more ADCP data became available include the relationship between atmospheric pressure variations and the incidence of southward flow near the coast (i.e. the link between air pressure, shelf waves and surface currents), and variations in the depth structure and volume fluxes of the current.

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LITERATURE CITED

AGENBAG, J. J. 1992 — A procedure for the computation of sea surface advection velocities from satellite thermal band imagery with applications to the South East Atlantic Ocean. Ph.D. thesis, University of Cape Town: 394 pp.

ANDREWS, W. R. H. and D. L. CRAM 1969 — Combined aerial and shipboard upwelling study in the Benguela Current. *Nature, Lond.* **224**(5222): 902–904.

BANG, N. D. and W. R. H. ANDREWS 1974 — Direct current measurements of a shelf-edge frontal jet in the southern Benguela system. *J. mar. Res.* **32**(3): 405–417.

BARTH, J. A. and R. L. SMITH 1998 — Separation of a coastal upwelling jet at Cape Blanco, Oregon, USA. In *Benguela Dynamics. Impacts of Variability on Shelf-Sea Environments and their Living Resources*. Pillar, S. C., Moloney, C. L., Payne, A. I. L. and F. A. Shillington (Eds). *S. Afr. J. mar. Sci.* **19**: 5–14.

BILSKI, S. 1996 — The characterisation of synoptic circulation patterns in Saldanha Bay. M.Sc. thesis, University of Cape

Town: 95 pp.
BOYD, A. J. 1982 — Small-scale measurements of vertical shear and rates of horizontal diffusion in the southern Benguela Current. *Fish. Bull. S. Afr*. **16**: 1–9.
BOYD, A. J. 1983 – Intensive study of the currents, winds and hydrology at a coastal site off central South West Africa, June/July 1978. *Investl Rep. Sea Fish. Res. Inst. S. Afr.* **126**: 47 pp.
BOYD, A. J. and G. P. J. OBERHOLSTER 1994 — Currents off the west and south coast of South Africa. *S. Afr. Shipp. News Fishg Ind. Rev*. **49**(5): 26–28
BOYD, A. J., TAUNTON-CLARK, J. and G. P. J. OBERHOLSTER 1992 — Spatial features of the near-surface and midwater circulation patterns off western and southern South Africa and their role in the life histories of various commercially fished species. In *Benguela Trophic Functioning*. Payne, A. I. L., Brink, K. H., Mann, K. H. and R. Hilborn (Eds). *S. Afr. J. mar. Sci*. **12**: 189–206.
BOYD, A. J., TROMP, B. B. S. and D. A. HORSTMAN 1985 — The hydrology off the South African south-western coast between Cape Point and Danger Point in 1975. *S. Afr. J. mar. Sci*. **3**: 145–168.
DUNCOMBE RAE, C. M., HUTCHINGS, L., SHANNON, L. J., BOYD, A. J., AGENBAG, J.J. and G. NELSON (in press) — Physical and biological observations during the decay phase of an upwelling filament off the Cape west coast. *S. Afri. J. mar. Sci*. **21**.
FOWLER J. L. and A. J. BOYD 1998 — Transport of anchovy and sardine eggs and larvae from the western Agulhas Bank to the west coast of South Africa during the 1993/94 and 1994/95 spawning season. In *Benguela Dynamics: Impacts of Variability on Shelf-Sea Environments and their Living Resources*. Pillar, S. C., Moloney, C. L., Payne, A. I. L. and F. A. Shillington (Eds). *S. Afr. J. mar. Sci.* **19**: 181–195.
HUGGETT, J. A., BOYD A. J., HUTCHINGS L. and A. D. KEMP 1998 — Weekly variability of clupeoid eggs and larvae in the Benguela jet current: implications for recruitment. In *Benguela Dynamics: Impacts of Variability on Shelf-Sea Environments and their Living Resources*. Pillar, S. C., Moloney, C. L., Payne, A. I. L. and F. A. Shillington (Eds). *S. Afr. J. mar. Sci*. **19**: 197–210.
HUYER, A. 1983 — Coastal upwelling in the California Current system. *Prog. Oceanogr*. **12**(3): 259–284.
JURY, M. R. 1985a — Wind shear and upwelling along the SW tip of Africa. In *International Symposium on the Most Important Upwelling Areas off Western Africa (Cape Blanco and Benguela),[Barcelona, 1983]* 1. Bas, C., Margalef, R. and P. Rubiés (Eds). Barcelona; Instituto de Investigaciones Pesqueras: 149–159.
JURY, M. R. 1985b — Case studies of alongshore variations in wind-driven upwelling in the southern Benguela region. In *South African Ocean Colour and Upwelling Experiment*. Shannon, L. V. (Ed.). Cape Town; Sea Fisheries Research Institute: 29–46.
JURY, M. R., KAMSTRA, F. and J. TAUNTON-CLARK 1985 — Synoptic summer wind cycles and upwelling off the southern portion of the Cape Peninsula. *S. Afr. J. mar. Sci*. **3**: 33–42.
LAMBERTH, R. and G. NELSON 1987 — Field and analytical drogue studies applicable to the St Helena Bay area off South Africa's west coast. In *The Benguela and Comparable Ecosystems*. Payne, A. I. L., Gulland, J. A. and K. H. Brink (Eds). *S. Afr. J. mar. Sci*. **5**: 163–169.
LARGIER, J. L., CHAPMAN, P., PETERSON, W. T. and V. P. SWART 1992 — The western Agulhas Bank: circulation, stratification and ecology. In *Benguela Trophic Functioning*. Payne, A. I. L., Brink, K. H., Mann, K. H. and R. Hilborn (Eds). *S. Afr. J. mar. Sci*. **12**: 319–339.
LUTJEHARMS, J. R. E. 1981 — Satellite studies of the South Atlantic upwelling system. In *Oceanography from Space*. Gower, J. F. R. (Ed.). New York; Plenum: 195–199 (*Marine Science* **13**).
LUTJEHARMS, J. R. E. and J. COOPER 1996 — Interbasin leakage through Agulhas Current filaments. *Deep-Sea Res*. **43**(2): 213–238.
LUTJEHARMS, J. R. E. and J. M. MEEUWIS 1987 — The extent and variability of South-East Atlantic upwelling. In *The Benguela and Comparable Ecosystems*. Payne, A. I. L., Gulland, J. A. and K. H. Brink (Eds). *S. Afr. J. mar. Sci*. **5**: 51–62.
LUTJEHARMS, J. R. E. and P. L. STOCKTON 1991 — Aspects of the upwelling regime between Cape Point and Cape Agulhas, South Africa. *S. Afr. J. mar. Sci*. **10**: 91–102.
MURRAY, S. P. 1975 — Trajectories and speeds of wind-driven currents near the coast. *J. phys. Oceanogr*. **5**: 347–360.
NELSON, G. 1985 — Notes on the physical oceanography of the Cape Peninsula upwelling system. In *South African Ocean Colour and Upwelling Experiment*. Shannon, L. V. (Ed.). Cape Town; Sea Fisheries Research Institute: 63–95.
NELSON, G., BOYD, A. J., AGENBAG, J. J. and C. M. DUNCOMBE RAE 1998 — Study of an upwelling filament north-west of Cape Town. In *Benguela Dynamics:Impacts of Variability on Shelf-Sea Environments and their Living Resources*. Pillar, S. C., Moloney, C. L., Payne, A. I. L. and F. A. Shillington (Eds). *S. Afr. J. mar. Sci*. **19**: 75–88.
NELSON, G. and L. HUTCHINGS 1983 — The Benguela upwelling area. *Prog. Oceanogr*. **12**(3): 333–356.
PARRISH, R. H., BAKUN, A., HUSBY, D. M. and C. S. NELSON 1983 — Comparative climatology of selected environmental processes in relation to eastern boundary current pelagic fish reproduction. In *Proceedings of the Expert Consultation to Examine Changes in Abundance and Species Composition of Neritic Fish Resources, San José, Costa Rica, April 1983*. Sharp, G. D. and J. Csirke (Eds). *F.A.O. Fish. Rep*. **291**(3): 731–777.
RICHARDSON, A. J., MITCHELL-INNES, B. A., FOWLER, J. L., BLOOMER, S. F., VERHEYE, H. M., FIELD, J. G., HUTCHINGS, L. and S. J. PAINTING 1998 — The effect of hydrography and food availability on the spawning success of the Cape anchovy *Engraulis capensis* in the southern Benguela. In *Benguela Dynamics: Impacts of Variability on Shelf-Sea Environments and their Living Resources*. Pillar, S. C., Moloney, C. L., Payne, A. I. L. and F. A. Shillington (Eds). *S. Afr. J. mar. Sci*. **19**: 275–290.
SHANNON, L. V. 1985 — The Benguela ecosystem. 1. Evolution of the Benguela, physical features and processes. In *Oceanography and Marine Biology. An Annual Review* ***23***. Barnes, M. (Ed.). Aberdeen; University Press: 105–182.
SHANNON, L. V. and G. NELSON 1996 — The Benguela: large scale features and processes and system variability. In *The South Atlantic: Present and Past Circulation*. Wefer, G., Berger, W. H., Siedler, G. and D. J. Webb (Eds). Berlin; Springer: 163–210.
SHELTON, P. A. and L. HUTCHINGS 1982 — Transport of anchovy, *Engraulis capensis* Gilchrist, eggs and early larvae by a frontal jet current. *J. Cons. perm. int. Explor. Mer* **40**(2): 185–198.
STEVENSON, M. R., GARVINE, R. W. and B. WYATT 1974 — Lagrangian measurements in a coastal upwelling zone off Oregon. *J. phys. Oceanog*. **4**: 321–336.
STRUB, P. T. KOSRO, P. M. and A. HUYER 1991 — The nature of the cold filaments in the California Current system, *J. geophys. Res*. **96**(C8): 14743–14768.