S. Afr. J. mar. Sci. 22: 71–79
2000

SURFACE DRIFT IN THE SOUTH-EAST ATLANTIC OCEAN

P. M. WEDEPOHL, J. R. E. LUTJEHARMS*† and J. M. MEEUWIS**

Surface drift in the South-East Atlantic Ocean is described using historical shipdrift data. The Benguela Current has a width of 200 km in the south and 750 km in the north. The mean speeds of the current vary from <11 cm·s^{-1} to a maximum of 23 cm·s^{-1}. The highest current speeds occur during summer in the southern regions and during winter in the northern regions, and this seasonality corresponds well with seasonal wind speeds. Eddy kinetic energy is enhanced in the Subtropical Convergence zone and is highest in the general vicinity of the Agulhas Current retroflection. The Subtropical Convergence is evident as a line where northward Ekman drift terminates.

The wide Benguela Current constitutes the eastern boundary current of the South Atlantic subtropical gyre. Despite the importance of surface drift to a better understanding of the dynamics of the current, it has to date not been investigated particularly thoroughly (Peterson and Stramma 1991). This lack of information also affects understanding of the manner in which the surface motion of the Benguela Current interacts with the adjacent coastal upwelling and the passive transportation of immotile organisms in the very surface layers of that region.

The Benguela Current consists of water from the eastward flow in the southern South Atlantic as well as of water from the South Indian Ocean (Garzoli *et al.* 1996). It flows in a north to northward direction along the west coast of southern Africa. North of 24°S the major part of the flow bends offshore (e.g. Harris and Shannon 1979, Shannon 1985), but a branch of the current nonetheless continues along the coast up to the Angola-Benguela front at about 16°S (Moroshkin *et al.* 1970, Shannon *et al.* 1987, Meeuwis and Lutjeharms 1990). The surface speeds of this general equatorward movement have been reported to be between 7 and 50 cm·s^{-1} (e.g. Nelson and Hutchings 1987, Peterson and Stramma 1991). Shannon (1985) has summarized all available information and given the mean surface speed as 17 cm·s^{-1}. The width of the general equatorward flow has been estimated at 200–300 km.

The westward South Equatorial Current forms the northern limb of the subtropical gyre. A corresponding westward drift is found between 10 and 20°S (Richardson and McKee 1984, Arnault 1987, Peterson and Stramma 1991), but with lower speeds. By contrast to this northern termination, the southern border to the Benguela Current is a well-defined front, the Subtropical Convergence, which separates it from the Antarctic Circumpolar Current (Peterson and Stramma 1991, Lutjeharms *et al.* 1993). The South Atlantic Current lies along this front (Stramma and Peterson 1990) and contributes to the southern part of the gyre. The speed of the current decreases eastward to about 10 cm·s^{-1} when feeding into the Benguela Current (Peterson and Stramma 1991). The second tributary to the Benguela Current is the Agulhas Current.

The Agulhas Current constitutes the western boundary current of the Indian Ocean. South of Africa it retroflects to form the east-flowing Agulhas Return Current. This retroflection continually shifts its position between 22 and 13°E (Gründlingh 1978, Lutjeharms and Van Ballegooyen 1988) as rings are shed from it. These rings then move into the Benguela Current (e.g. Byrne *et al.* 1995, Goni *et al.* 1997). Although the Agulhas Current itself is therefore not formally a part of the surface circulation of the South-East Atlantic Ocean, its retroflection and rings do periodically penetrate into this ocean (Lutjeharms 1996) and have an effect on the surface motion.

The water masses in the South Atlantic are strongly influenced by the geographically extensive, wind-driven coastal upwelling along the west coast of southern Africa (Shannon 1985, Lutjeharms and Valentine 1987). Similarly, the surface drift offshore is largely controlled by the reigning wind systems. This was recognized by Defant (1936), who first analysed Dutch archival material on seasonal winds and currents for this region. A more modern interpretation has been given by Parrish *et al.* (1983). In the northern part of the Benguela Current the winds are relatively persistent from the South-East. However, over the southern part of the current, the winds are more variable, particularly in winter, owing to the influence of mid-latitude cyclones (Kamstra 1985, Peterson and Stramma 1991).

* Department of Geography and Environmental Management, Rand Afrikaans University, P.O. Box 524, Auckland Park 2006, South Africa
† Department of Oceanography, University of Cape Town, Rondebosch 7700, South Africa. E-mail: johann@physci.uct.ac.za

Manuscript received March 1999; accepted February 2000

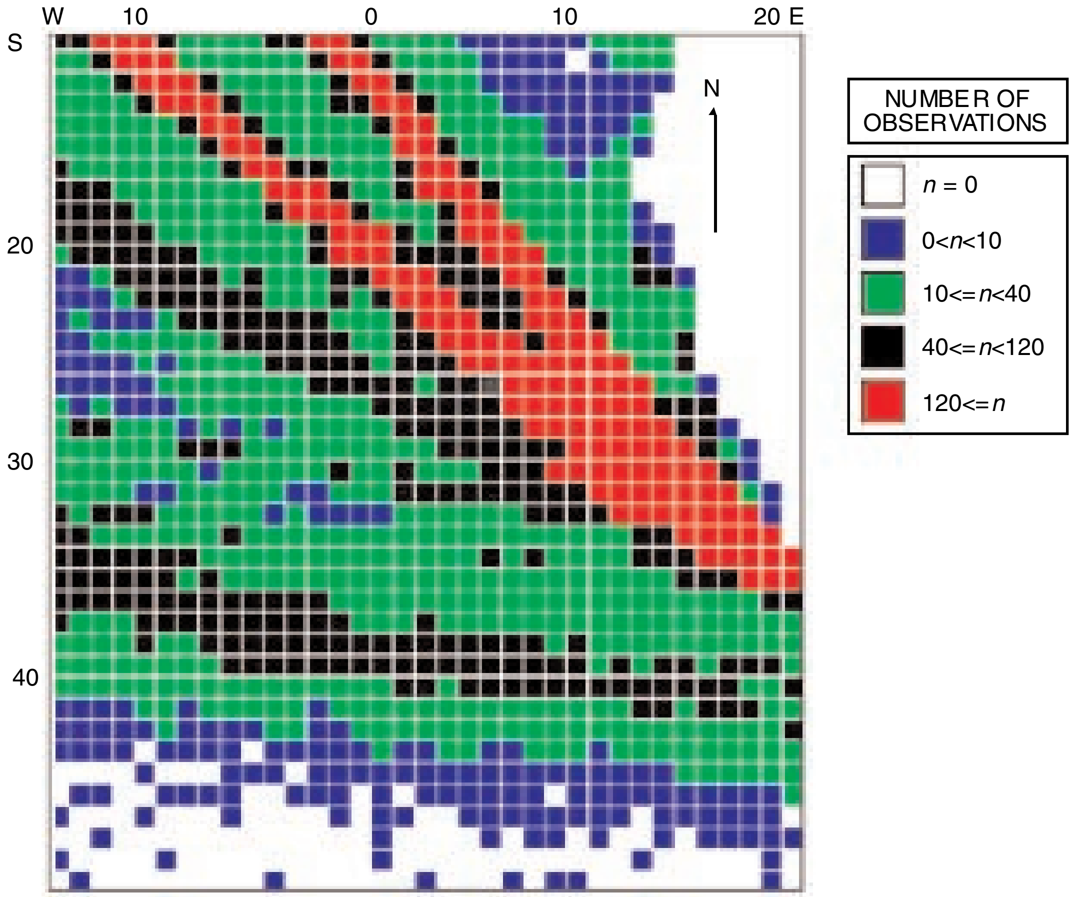

Fig. 1: Spatial distribution of the number of shipdrift observations per one degree by one degree square for the South East Atlantic Ocean

DATA AND METHODS

Investigating drift at the sea surface is beset by a number of fundamental problems. First, there is the question of establishing surface drift accurately. Geostrophic calculations using existing hydrographic data are of limited use because Ekman drift is usually excluded. Further, the database of deep hydrographic stations in the South Atlantic is small and the geographic distribution is strongly biased to the shelf regions. Estimates of the surface flow by passive drifters is more appropriate (e.g. Piola *et al*. 1987, Patterson 1985), but such data are also sparsely distributed. A potentially richer data source for the region 10–50°S, 15°W–20°E, that has to date not been used adequately is historical shipdrift.

A shipdrift observation is the vector difference between the course steered and the actual course made good between two navigational fixes of position. The main contributors to such drift are surface currents and wind stress on the vessel. No corrections for the downwind sideslip of the vessel as a result of winds are made. Windage errors are usually much smaller than the mean surface currents, except in regions of slow currents and persistently high wind speeds (Richardson 1997). The average of many shipdrift observations in regions of variable winds is therefore a fairly reliable surface current indicator (Richardson and McKee 1984). The problem of possible systematic errors because of mean prevailing winds remains. Arnault (1987) has investigated surface currents in the tropical Atlantic where such conditions would prevail. He has showen that, if the geostrophic and the Ekman components of the surface currents are combined, there is good agreement with shipdrift data. A number of authors (e.g. Richardson and McKee 1984, Sætre 1985) have therefore stated that, because of their abundance, shipdrift data remain the only suitable source for resolving long-term seasonal current patterns at the sea surface in regions where few other data are available.

The main source of data for this investigation was the Surface Current Data File compiled by the NODC of the USA (National Oceanographic Data Center 1991). Most of the data in this source are from the period 1920–1940, but a substantial number are from 1941 to the present. No sorting into bins has been done for these data, the original data being retained intact. However, observations of shipdrift made during extremely strong wind conditions have been automatically eliminated from this dataset (*viz.* National Oceanographic Data Center 1991). An important advantage of the dataset is its geographic density, especially along the main shipping routes. The data distribution for the South-East Atlantic Ocean is given in Figure 1. South of Africa and in the region of the southern Benguela Current, along the main shipping routes to North America and Europe, there are more than 120 observations for each trapezoid of one-degree latitude by one-degree longitude. Adjacent to these regions and along the main shipping route to South America, between 40 and 120 observations are available. Two regions are particularly poorly covered: south of 41°S, particularly west of 10°E; and the Angola Current, north of 17°S and east of 5°E (Fig. 1). Notwithstanding this geographic lack of homogeneity, large parts of the South-East Atlantic Ocean are sufficiently covered with observations to deduce information regarding the mean surface currents. Increasing the grid size would have increased the number of data per trapezoid, and thus the statistical reliability, but it would have reduced the spatial resolution to an unacceptable level.

Data on prevailing winds for each month of the year were obtained from an oceanic climatic atlas (United States Navy 1978). The main disadvantage of this meteorological dataset over the ocean is that the statistical mean winds are only available for specific regions where there are sufficient observations. However, these regions fortuitously include those representative of the southern and northern regions of the Benguela Current.

Calculations of the mean drift speed and direction for all data as well as for each season were carried out. Seasons are: austral spring (September–November), summer (December–February), autumn (March–May) and winter (June–August). A one-degree trapezoid (centred at 33.5°S, 16.5°E) with a very high number of observations (Fig. 1) and considered representative of the southern Benguela Current was selected for a seasonal analysis. A chart showing the mean drift for the region was generated using the Seaplot software package (Brown 1992). For ease of calculation, all charts were drawn on an equi-rectangular projection that has minimal distortions for such a relatively small area.

The eddy kinetic energy (EKE) for the South-East Atlantic Ocean was calculated following Wyrtki *et al.* (1976). The EKE per unit mass is the kinetic energy associated with variations around the mean surface current and gives an indication of the variability in the speeds and directions of the surface ocean currents (Wyrtki *et al.* 1976, Patterson 1985). A map of the geographic distribution of the EKE was generated using ILWIS GIS software (Computer Department 1993).

RESULTS AND DISCUSSION

Figure 2 shows the mean surface drift for the South-East Atlantic Ocean. The eastern boundary current nature of the Benguela Current is evident. It lies along the west coast of southern Africa between 21 and 35°S. Based on mean drifts of more than 10 $cm \cdot s^{-1}$, the Benguela Current has a width of 750 km in the north and a width of 200 km in the south. Such values are considerably larger than those put forward by Nelson and Hutchings (1987) and by Shannon (1985), who estimated the Benguela Current at only 200–300 km wide. In general, the Benguela is a weak current, making it difficult unambiguously to determine its seaward edge. This may have led to the discrepancy. The direction of the Benguela Current is north-north-west to north-west (Fig. 2). North of 26°S, the surface drift, at least for the seaward part of the current, turns westwards (Fig. 2) as the Benguela Current flows into the central regions of the Atlantic Ocean. This divergence from the coast occurs about 2° of latitude farther south than previously reported (e.g. Moroshkin *et al.* 1970, Shannon 1985). North of 26°S, there still is an equatorward movement along the coast that may be considered to be a branch of the Benguela Current. The Angola-Benguela Front (Meeuwis and Lutjeharms 1990) is the northern border to this northward branch of the Benguela Current, but the available drift data in this region are insufficient to resolve this convergence (*viz.* Fig 1).

The mean drift speeds for three zonal bands at dif-

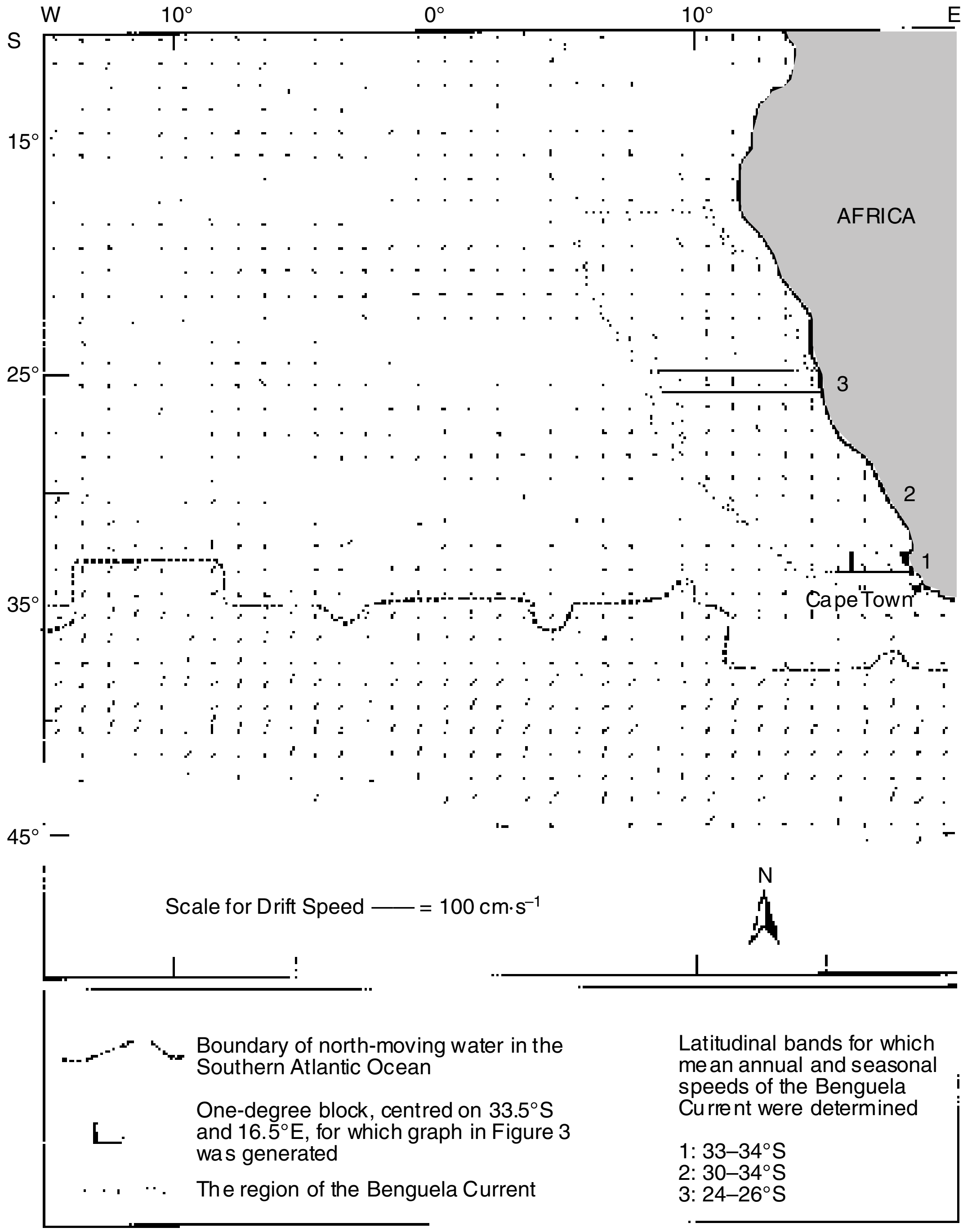

Fig. 2: Mean surface drift in the South-East Atlantic Ocean based on available shipdrift information. Blank spaces represent regions for which there are fewer than five observations per one-degree square. Vectors representing the drift point away from the dots that define the grid point and have a magnitude shown by the scale

Table I: Mean speeds of drift of the Benguela Current in zonal bands

Latitude	Number of observations	Mean speed of drift ($cm \cdot s^{-1}$)
33–34°S	2 522	13
30–31°S	1 949	12
25–26°S	876	9

ferent latitudes across the Benguela Current are shown in Table I. The width of the Benguela Current evident in Figure 2 was used to delimit the zonal extent of the strips. The number of observations exceeds 1 500 for two of the zonal bands and 800 for the third (Fig. 1). The exact number of observations is given in Table I. The drift rate is highest in the south, weaker in the centre and stronger again in the far northern part of the current. These mean drift speeds are in rough agreement with Shannon's (1985) estimate of 17 $cm \cdot s^{-1}$. Occasional high values of drift have been observed, but such outliers show no consistent geographic pattern and are therefore not given here. There is no evidence in these data for an intense, meandering core as has been found for the California Current. High-speed jets between 50 and 120 $cm \cdot s^{-1}$ have been observed along the continental shelf (Nelson and Hutchings 1983, Peterson and Stramma 1991), but these jets are not wider than 30 km and would therefore not be resolved by the relatively coarse, one-degree grid of Figure 2.

The South Atlantic Current is also not resolved in Figure 2. This may be because it is narrow and also because it is weak in the South-East Atlantic (Stramma and Peterson 1990), as is all eastward flow of the subtropical gyre in this region. It is particularly noticeable that south of 35°S all surface drift has a strong northward component (Fig. 2). This is most probably the Ekman drift induced by the westerly winds over the Antarctic Circumpolar Current. The location of the roughly zonal line where this northward drift terminates agrees remarkably well with the geographic location of the Subtropical Convergence (e.g. Lutjeharms *et al.* 1993). East of 10°E, this convergence is forced farther south by the Agulhas retroflection, as is also evident in Figure 2. At 37°S there is a zonally persistent, but unexplained, reduction in drift speed as well as northward drift component.

Table II: Mean seasonal speeds of drift for the Benguela Current in zonal bands

Latitude	Season	Number of observations	Speeds of drift ($cm \cdot s^{-1}$)
33–34°S	Spring	603	12
	Summer	637	18
	Autumn	661	14
	Winter	621	11
30–31°S	Spring	449	12
	Summer	513	16
	Autumn	482	10
	Winter	505	9
25–26°S	Spring	195	9
	Summer	185	7
	Autumn	228	8
	Winter	268	10

Table III: Mean wind speeds and directions in the southern and central Benguela Current (after United States Navy 1978)

Month	Speed ($cm \cdot s^{-1}$)	Direction
January	750	SSE
February	750	SSE
March	750	SSE
April	595	SSE
May	425	SSE
June	390	SSE
July	410	SSE
August	460	SSE
September	600	SSE
October	640	SSE
November	720	SSE
December	715	SSE

Mean seasonal drift speeds for the same zonal bands across the Benguela Current used in Table I are given in Table II. The data numbers are reduced by being split into seasons, but they are still relatively high. It can be seen that, for the southern parts, the maximum speeds are in summer and the minimum speeds during winter. For the central region, the maximum speeds occur during summer and the minima during winter. In the north, speeds are maximum during winter and minimum during summer. Figure 3 shows the mean monthly vector components of the surface drift, their standard deviations as well as the mean monthly speeds for a one-degree trapezoid centred on 33.5°S, 16.5°E. This trapezoid is considered representative of the southern regions of the Benguela Current, because the seasonal trends for neighbouring trapezoids are roughly the same. Trapezoids closer to the coast may not be representative of the current because they lie within coastal upwelling cells. Trapezoids farther west are outside the main shipping lanes and have insufficient observations to justify dividing the data into calendar months. Figure 3 indicates a seasonal variability in the drift speeds. The maximum mean drift speed is 24.5 $cm \cdot s^{-1}$ during January and the minimum drift speed is 5.5 $cm \cdot s^{-1}$ during June. Some caution should be taken in interpreting these results because the standard

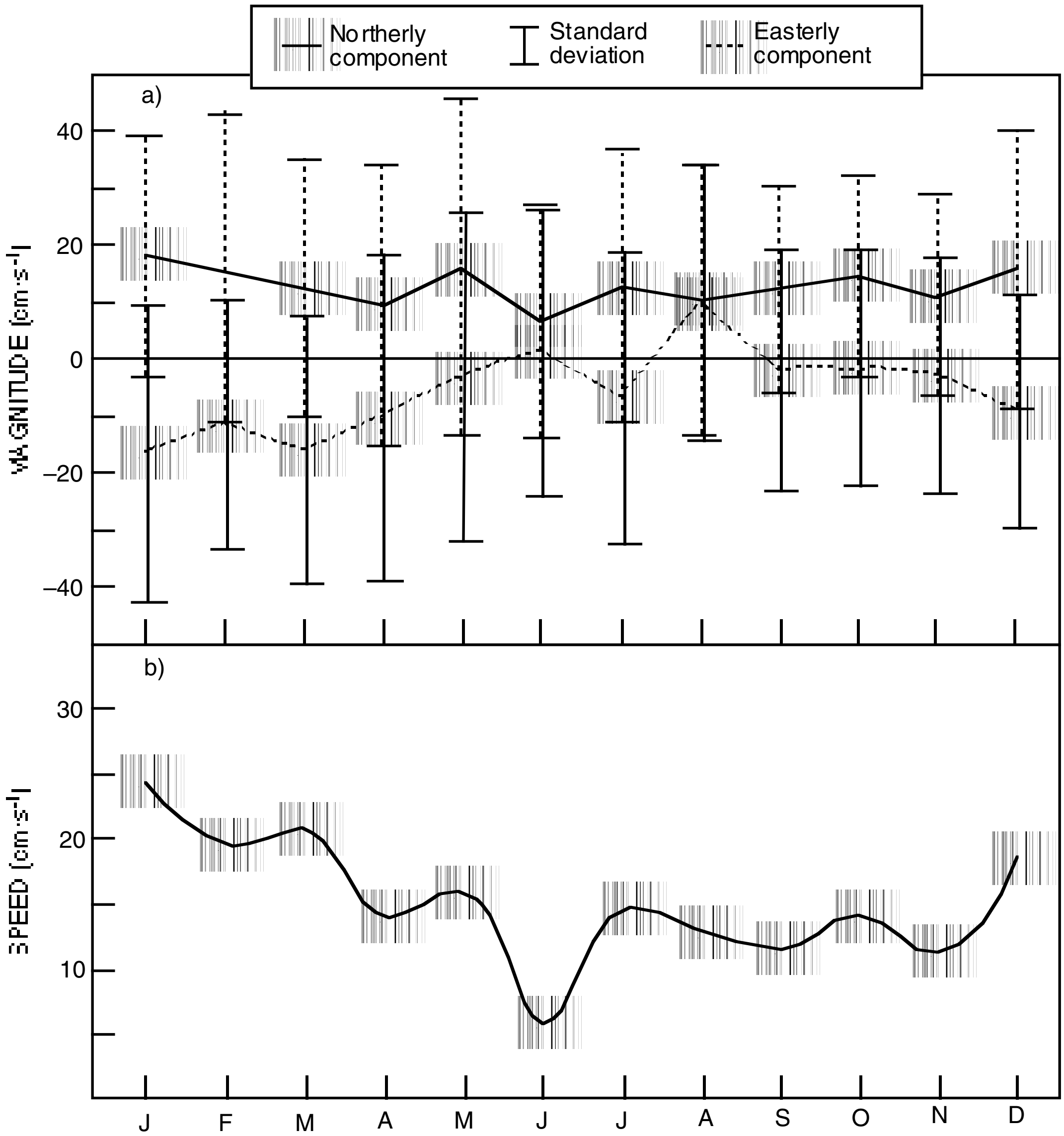

Fig. 3: (a) Mean vector components and (b) mean speeds for the surface drift of the Benguela Current at 33.5°S and 16.5°E for each calendar month using accumulated shipdrift data

deviations are large. There is agreement with the results in Table II as to the season of maximum drift speeds, but Table II indicates that the weakest flow is in spring and not in both spring and summer. The data used for Table II cover a larger zonal band than those for Figure 3 and may therefore be representative of a larger region. It would be instructive to compare this drift seasonality with the seasonal changes in the winds.

Table III shows the monthly mean wind speeds and directions for the region 27–30°S, 12–15°E. The winds in this region are considered representative of the winds over the southern and central parts of the Benguela Current. The estimated maximum drift over the southern and central parts of the Benguela Current

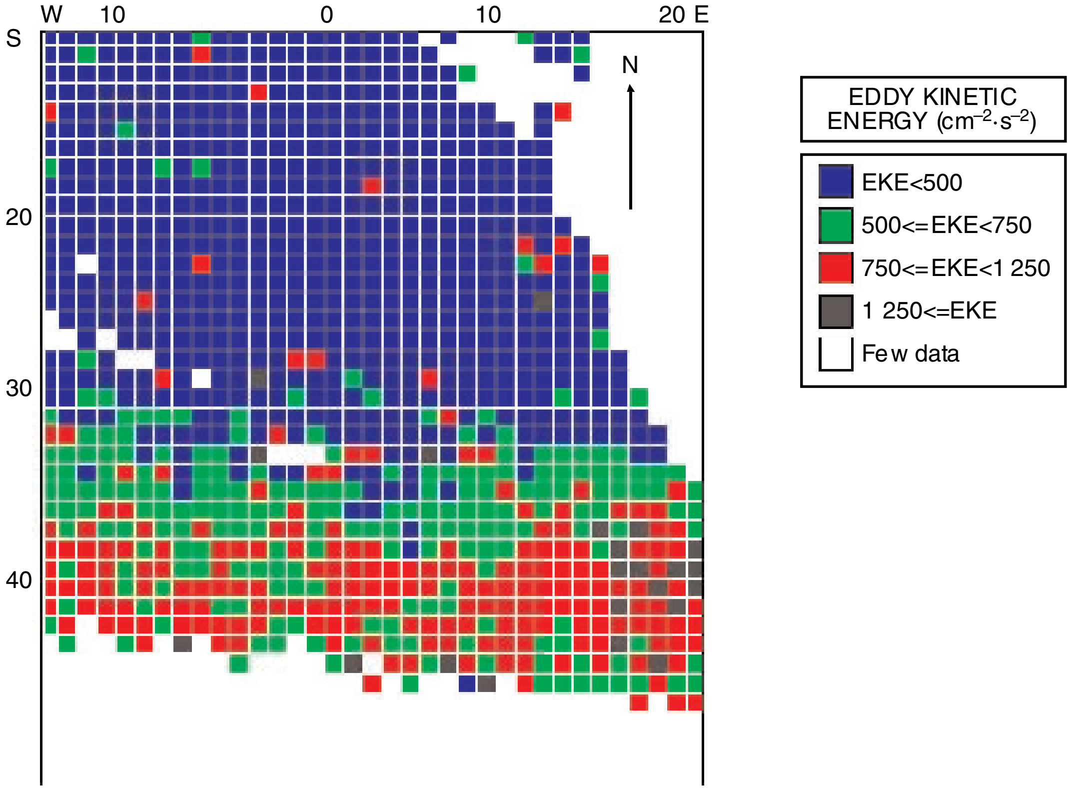

Fig. 4: Mean eddy kinetic energy for each one-degree latitude by one-degree longitude square in the South-East Atlantic Ocean based on historical shipdrift data

(Fig. 3) occurs during the month of maximum winds from the south-south-east, namely January. Likewise, the month of least drift (June, Fig. 3) is in turn the month of lowest wind speed (Table III). Table IV shows the mean monthly wind speeds and directions for the region 20–22°S, 7–9°E, representative of the northern sections of the Benguela Current. The winds from the South-East are strongest in late winter and early spring. These winds may partly explain the high current speeds found there during winter, but they do not explain weaker currents in spring than in summer. The relationship between the winds and speeds in the northern sections of the current is therefore not as strong as it would seem to be farther south.

The seasonal drift results presented above largely agree with those of the only similar study to date (United States Naval Oceanographic Office 1977). In that analysis the season of fastest northward drift for the southern coastal regions of the Benguela Current is also summer. Farther from the coast, the greatest northward speeds are in late summer and early autumn. The dataset used for those results to some extent overlaps that for the present investigation, so the results are not entirely independent. It is nonetheless noteworthy that there is no indication of seasonal variability in the surface drift speeds in any other published results on the Benguela Current, probably because of a dearth of data. Establishing this seasonality with shipdrift data therefore vindicates the use of these data for such an investigation, because it could not have been resolved with any other dataset currently available.

The strong currents at the Agulhas retroflection are not evident in Figure 2. This is probably owing to the highly variable nature of these currents (Lutjeharms and Van Ballegooyen 1988), leaving a small net drift in the long-term averages. Eddy kinetic energy may give an indication of this assumed variability. If the mean flow is small, but the EKE values are large, it would be consistent with a situation of highly variable currents. South of Africa, there is indeed a region of

Table IV: Mean wind speeds and directions in the northern Benguela Current (after United States Navy 1978)

Month	Speed ($cm \cdot s^{-1}$)	Direction
January	640	SE
February	625	SE
March	665	SE
April	655	SE
May	605	SE
June	575	SE
July	650	SE
August	680	SE
September	710	SE
October	680	SE
November	620	SE
December	620	SE

extremely high EKE, greater than 1 250 $cm^2 \cdot s^{-2}$ (Fig. 4). This corresponds to the location of the Agulhas retroflection (Gründlingh 1978, Lutjeharms and Van Ballegooyen 1988). The region of high EKE resembles that of high current variability found in altimetry (e.g. Cheney *et al*. 1983), trajectories of surface drifters (Piola *et al*. 1987, Patterson 1985) and similar analyses of ships' drift (Wyrtki *et al*. 1976). There is also a zonal band of higher EKE west of the Agulhas retroflection, between 35 and 42°S (Fig. 4). This band lies abreast the Subtropical Convergence in this region (Lutjeharms *et al*. 1993, Fig. 2) and is probably attributable to meanders in this front and in the South Atlantic Current, as well as the formation of eddies. South of Africa eddies are formed on both sides of the Subtropical Convergence (Lutjeharms and Valentine 1988), but little information of this kind is available on the South Atlantic sector of this front. Figure 4 suggests that eddy formation may also be prevalent there. A few squares with very high EKE values lie dispersed in a broad north-westward band from the Agulhas retroflection to about 18°S (Fig. 4). This is the path taken by the intense Agulhas rings shed from the Agulhas retroflection (Byrne *et al*. 1995). Caution is advised in concluding that these spots of high EKE are necessarily associated with such rings, because the density of drift data along this band is low (Fig. 1).

CONCLUSIONS

Based on surface drift, the geographical location of the Benguela Current is between 21 and 35°S along the west coast of southern Africa. The surface expression of this current is wide, with a minimum width of 200 km in the south and a maximum of 750 km in the north. The direction of the surface drift of the Benguela Current is north-north-west to north-west. North of 26°S it turns westwards, somewhat farther south than was previously reported, but a northward branch continues along the coast. The mean drift speeds of the Benguela Current vary from <11 to 23 $cm \cdot s^{-1}$, with the current weakest in the extreme northern regions and strongest in the southern.

There appears to be seasonal variability in the surface drift speeds of the Benguela Current. The minimum speeds for the southern regions of the current are found during winter (10 $cm \cdot s^{-1}$) and the maximum during summer (18 $cm \cdot s^{-1}$). In the central regions, the speeds are minimum during winter (9 $cm \cdot s^{-1}$) and maximum during summer (16 $cm \cdot s^{-1}$). In the northern region, speeds are maximum during winter (10 $cm \cdot s^{-1}$) and minimum during summer (7 $cm \cdot s^{-1}$). There are indications that there is a positive relationship between the local mean wind and these seasonal changes in the drift speeds of the Benguela Current. The Subtropical Convergence is seen as a limit to northward Ekman drift in the Southern Ocean.

High values of eddy kinetic energy are found in the region of the Agulhas Current retroflection, extending as far west as 16°E. High values are also evident along the Subtropical Convergence, over the full width of the South-Eastern Atlantic Ocean.

LITERATURE CITED

ARNAULT, S. 1987 — Tropical Atlantic geostrophic currents and ships' drift. *J. geophys. Res*. **92**: 5076–5088.

BROWN, M. L. 1992 — *Seaplot Oceanographic Charting Software for the World's Seas. Version 1.3*. New Orleans, La.; U.S. Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Regional Office: 139 pp.

BYRNE, D. A., GORDON, A. L. and W. F. HAXBY 1995 — Agulhas eddies: a synoptic view using Geosat ERM data. *J. phys. Oceanogr*. **25**: 902–917.

CHENEY, R. E., MARSH, J. G. and B. D. BECKLEY 1983 — Global mesoscale variability from collinear tracks of SEASAT altimeter data. *J. geophys. Res*. **88**(C7): 4343–4354.

COMPUTER DEPARTMENT 1993 — *ILWIS 1.4. User's Manual*. Enschede, Netherlands; International Institute for Aerospace Survey and Earth Sciences: 89 pp.

DEFANT, A. 1936 — Das Kaltwasserauftriebsgebiet vor der Küste Südwestafrikas. *Landerkundliche Forschung*, Festschrift, Norbet Krebs, Stuttgart: 52–66.

GARZOLI, S. L., GORDON, A. L., KAMENKOVICH, V., PILLSBURY, S. and C. DUNCOMBE RAE 1996 — Variability and sources of the south-eastern Atlantic circulation. *J. mar. Res*. **54**: 1039–1071.

GONI, G. J., GARZOLI, S. L., ROUBICEK, A. J., OLSON, D. B. and O. B. BROWN 1997 — Agulhas ring dynamics from TOPEX/POSEIDON altimeter data. *J. mar. Res*. **55**(5): 861–883.

GRÜNDLINGH, M. L. 1978 — Drift of a satellite-tracked buoy in the southern Agulhas Current and Agulhas Return Current. *Deep-Sea Res*. **25**: 1209–1224.

HARRIS, T. F. W. and L. V. SHANNON 1979 — Satellite-tracked drifter in the Benguela Current system. *S. Afr. J. Sci.* **75**(7): 316–317.

KAMSTRA, F. 1985 — Environmental features of the southern Benguela with special reference to the wind stress. In *South African Ocean Colour and Upwelling Experiment*. Shannon, L. V. (Ed.). Cape Town; Sea Fisheries Research Institute: 13–27.

LUTJEHARMS, J. R. E. 1996 — The exchange of water between the South Indian and the South Atlantic. In *The South Atlantic: Present and Past Circulation.* Wefer, G., Berger, W. H., Siedler, G. and D. Webb (Eds), Berlin; Springer: 125–162.

LUTJEHARMS, J. R. E. and H. R. VALENTINE 1987 — Water types and volumetric considerations of the South-East Atlantic upwelling regime. In *The Benguela and Comparable Ecosystems*. Payne, A. I. L., Gulland, J. A. and K. H. Brink (Eds). *S. Afr. J. mar. Sci*. **5**: 63–71.

LUTJEHARMS, J. R. E. and H. R. VALENTINE 1988 — Eddies at the subtropical convergence south of Africa. *J. phys. Oceanogr*. **18**(5): 761–774.

LUTJEHARMS, J. R. E., VALENTINE, H. R. and R. C. VAN BALLEGOOYEN 1993 — The Subtropical Convergence in the South Atlantic Ocean. *S. Afr. J. Sci*. **89**: 552–559.

LUTJEHARMS, J. R. E. and R. C. VAN BALLEGOOYEN 1988 — The Agulhas Current retroflection. *J. geophys. Res*. **18**: 1570–1583.

MEEUWIS, J. M. and J. R. E. LUTJEHARMS 1990 — Surface thermal characteristics of the Angola-Benguela front. *S. Afr. J. mar. Sci*. **9**: 261–279.

MOROSHKIN, K. V., BUBUNOV, V. A. and R. P. BULATOV 1970 — Water circulation in the Eastern South Atlantic Ocean. *Oceanology* **10**: 27–34.

NATIONAL OCEANOGRAPHIC DATA CENTER 1991 — *User Guide*. Washington, D.C.: 75 pp.

NELSON, G. and L. HUTCHINGS 1987 — Passive transportation of pelagic system components in the southern Benguela area. In *The Benguela and Comparable Ecosystems*. Payne, A. I. L., Gulland, J. A. and K. H. Brink (Eds). *S. Afr. J. mar. Sci*. **5**: 223–234.

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.

PATTERSON, S. L. 1985 — Surface circulation and kinetic energy distributions in the southern hemisphere oceans from FGGE drifting buoys. *J. phys. Oceanogr*. **15**: 865–884.

PETERSON, R. G. and L. STRAMMA 1991 — Upper-level circulation in the South Atlantic Ocean. *Prog. Oceanogr*. **26**: 1–73.

PIOLA, A. R., FIGUEROA, H. A. and A. A. BIANCHI 1987 — Some aspects of the surface circulation south of 20°S revealed by First GARP Global Experiment drifters. *J. geophys. Res*. **92**(C5): 5101–5114.

RICHARDSON, P. L. 1997 — Drifting in the wind: leeway error in shipdrift data. *Deep-Sea Res*. **44**(11): 1877–1903.

RICHARDSON, P. L. and T. K. MCKEE 1984 — Average seasonal variation of the Atlantic Equatorial Currents from historical ships' drifts. *J. phys. Oceanogr*. **14**: 1226–1238.

SÆTRE, R. 1985 — Surface currents in the Mozambique Channel. *Deep-Sea Res*. **32**: 1457–1467.

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., AGENBAG, J. J. and M. E. L. BUYS 1987 — Large- and mesoscale features of the Angola-Benguela front. In *The Benguela and Comparable Ecosystems*. Payne, A. I. L., Gulland, J. A. and K. H. Brink (Eds). *S. Afr. J. mar. Sci*. **5**: 11–34.

STRAMMA, L. and R. G. PETERSON 1990 — The South Atlantic Current. *J. phys. Oceanogr*. **20**: 846–859.

UNITED STATES NAVAL OCEANOGRAPHIC OFFICE 1977 — *Surface Currents – Southeast South Atlantic Ocean*. Mississippi, Department of the Navy: 136 pp.

UNITED STATES NAVY 1978 — *Marine Climatic Atlas of the World*. **4**. *South Atlantic Ocean*. Asheville, North Carolina; Naval Weather Service: 89 pp.

WYRTKI, K., MAGAARD, L. and J. HAGER 1976 — Eddy energy in the oceans. *J. geophys. Res*. **81**(15): 2641–2646.