*Journal of Marine Research, 46,* 267–279, 1988

# On the surface drift of the Southern Ocean

by J. R. E. Lutjeharms,[1] L. V. Shannon[2] and L. J. Beekman[1]

ABSTRACT

Drift rates of the sea surface have been calculated for the South Atlantic and South Indian Ocean sectors of the Southern Ocean using drift cards and FGGE buoys. Drift patterns and drift rates, based on results from 40,000 plastic drift cards placed from 1978 to 1981, indicate significant equatorward surface exchange between the Southern Ocean and subtropical ocean gyres. Card drift rates increase with latitude up to the 40-45S zone. Average zonal drift rates lie between 10.3 cm/s and 16.4 cm/s. Zonally averaged drift rates of FGGE buoys are also at a maximum between 40 and 45S but are 15% higher; lowest rates are 12.2 cm/s. Significant differences in the drift rates between sectors of the same zone reflect the influence of bottom topography.

## 1. Introduction

We report here the results of a decade-long project to study mean drift rates of the surface layer of the Southern Ocean using drift cards and free-drifting buoys.

The drift of sea surface layers is of importance since it is here that most marine planktonic larvae and eggs are found for a significant period of their lifetime. For this reason surface drifters of various kinds have found special application in fisheries research (e.g. Shelton and Kriel, 1980) and zoogeography (Ekman, 1967). A better understanding of the drift patterns of the very top meter of the surface layer of the ocean has furthermore been shown to be of crucial importance to the biogeography of a significant portion of the marine flora (Andriashev, 1965), including benthic and shore organisms.

The surface drift of the Southern Ocean is particularly important since the larvae and adults of krill, a key element in the Southern Ocean food chain, spend most of their life in the upper ocean layer (Makarov, 1983a,b). Amos (1984) has for instance shown that adult krill spend approximately 2.8 years in the surface layers and that their geographic distribution is largely dependent on large-scale circulation patterns. These are for the greater part only partially known.

Gordon *et al.* (1978) have, for instance, constructed a large-scale climatic distribution of geostrophic surface currents relative to 1,000 m based on a historic hydro-

1. National Research Institute for Oceanology, C.S.I.R., P.O. Box 320, Stellenbosch 7600, South Africa.

2. Sea Fisheries Research Institute, Private Bag X2, Roggebaai 8012, South Africa.

graphic dataset. No attempt was made to present absolute geostrophic currents while caution was advised since some aliasing due to transient features such as eddies might have been included. The typical or characteristic geostrophic velocity of the Antarctic Circumpolar Current has subsequently been estimated at 20 cm/s, which underestimates the absolute mean surface current by about a third (Gordon, 1980). Including the mean barotropic current component raises the estimated mean surface current to between 25 and 30 cm/s of which the net wind-induced Ekman drift may amount to only 1 to 3 cm/s.

Previous studies on the drift rates of the Southern Ocean using drift cards (Stander *et al.*, 1969; Shannon *et al.*, 1973; Marshallsay and Radok, 1972) have, on other hand, estimated the drift rate between South Africa and Australia at between 10 and 25 cm/s. Early experiments with free-drifting weather buoys (Harris and Stavropoulos, 1978) southwest of Africa found that the speeds of these drifters were in fact considerably higher than the calculated geostrophic speeds for the area.

During the FGGE (First Global GARP Experiment, 1978–79) an assortment of up to 300 free-drifting buoys moved through the Southern Ocean. Based on the first results Kort (1981) estimated a mean surface drift of the Antarctic Circumpolar Current of between 25–30 cm/s. Full analyses of the surface circulation based on the FGGE data set have been presented recently by Patterson (1985) and Piola *et al.* (1987) which do not differ markedly from the first results. Hofmann (1985) has, however, shown that drifters accumulated in the regions where frontal systems were found historically.

The true drift behavior of the very upper surface layers of the Southern Ocean is therefore still not understood well. Through the use of large numbers of drifters, statistically reliable estimates can be made that may be ecologically useful.

## 2. Data and methods

Solid, low-density, polythene drift cards (Duncan, 1965) have been used in this experiment. Placed in batches of 20 like-numbered cards they float on the surface skin of the sea, usually covered by a thin layer of water, until making a landfall, picked up by the public and returned to the address embossed on each side. Cards are bleached by the sun when dry and their color may thus be a measure of the period since beaching. Shannon *et al.* (1973) have presented a color plate which illustrates this. In this project all returned cards were used to establish flow trajectories; only totally unbleached cards were used to estimate drift rates.

A number of obvious disadvantages concerning the use of these drift cards restrict their value as true Lagrangian tracers. Although the location and time of deployment are accurately known, the time and place of first beaching is not. Retrievals are dependent on the population density and literacy at the point of beaching. Furthermore only the beginning and end point of the route is known but nothing about the route itself. It has been shown, for example, that drift pumice from eruptions in the South

Shetland Islands reached southern Australia within a year and a half but persisted in these waters for up to four years after its first arrival (Sutherland and Olsen, 1968), which could have lead to erroneous drift rate estimates.

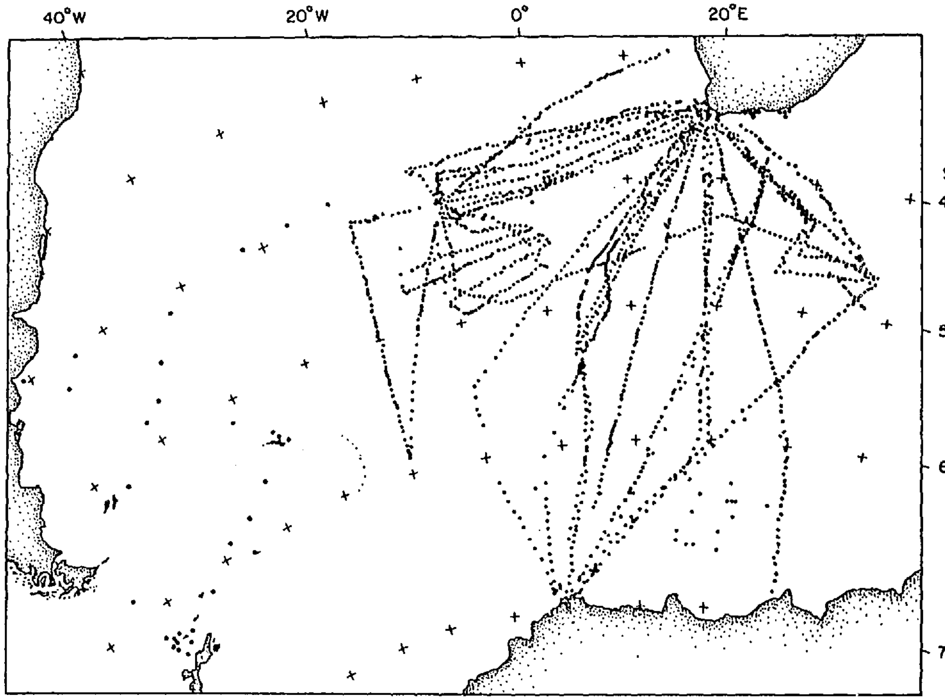
Advantages of drift cards, on the other hand, are that in principle they give a true measure of the average drift rate of the immediate sea surface layer including both the baroclinic and barotropic components. They integrate movements on all spatial and time scales encountered, which include the wave-induced (e.g. Wu, 1983) as well as wind-induced currents (e.g. Kirwan *et al.*, 1979), thus representing exactly the movements of immobile biota in this layer which no other instrument or drifter presently available is able to do. Whereas drift cards float in the upper few centimeters of the water column, drifting weather buoys, such as those used in FGGE, trace the movement of the upper tens of meters of water depending on the attachment of a drogue and its depth setting; drift cards and buoys therefore do not measure exactly the same drift.

As part of this study 40,000 drift cards were deployed from ships of opportunity sailing between Cape Town and Antarctica, most being research or supply vessels. The ocean area covered is shown in Figure 1a and stretches from the east coast of South America to about 40E and from 30 to 70S. Batches of cards were deployed whenever the opportunity arose, which was at irregular intervals (see Fig. 1b). Of the 40,000 cards released between 1978 and 1981, 404 were retrieved by the end of 1982 of which 132 were considered in sufficiently pristine condition to use for the calculation of drift rates. The most probable drift routes for each card were established from the British Admiralty Routeing Charts (British Admiralty, 1969, 1970). Since these are all based on accumulated records of ships' drift, which is also statistically the soundest data set for this area, this information was considered to be the most appropriate for this purpose.

The additional set of data used was the FGGE buoy drift tracks. The details of the assortment of drogued and undrogued buoys, the telemetering of the data as well as the logistics of the FGGE experiment as a whole is dealt with in detail elsewhere (Patterson, 1985; Hofmann, 1985) and will not be repeated here.

## 3. Results and discussion

*a. Drift patterns.* Of the cards deployed 1.01% were retrieved. This compares with a reported return rate of 0.7% for cards placed by Shannon *et al.* (1973). Of the total number retrieved the majority of finds were concentrated in three areas (Fig. 2), namely Southern Africa (28%) Western Australia (33%) and the New Zealand region (11%). Cards returned from South African coasts were mostly those which had been placed shortly after ships' departure from Cape Town. In a number of these instances cards were from further afield and from south of the Sub-Tropical Convergence (Fig. 3). It has been recognized that mesoscale eddies may cross this convergence in



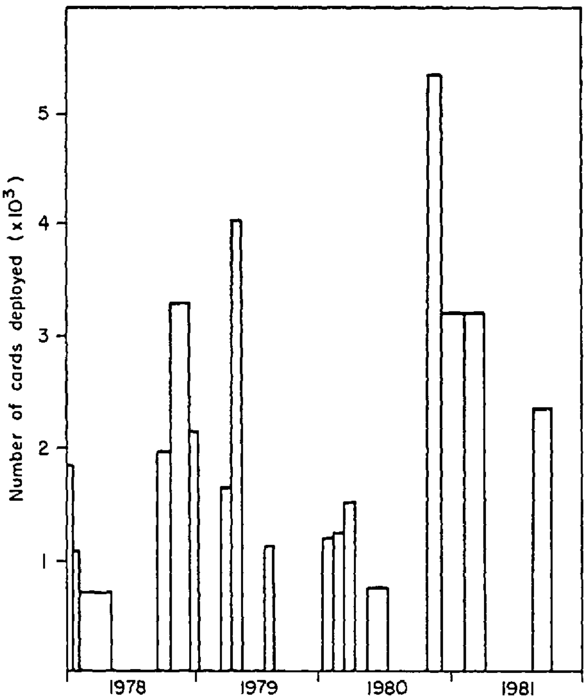




Figure 1. (a) Geographic distribution of stations in the Atlantic and Indian Ocean sectors of the Southern Ocean where drift cards were launched between 1978 and 1981. Note the small number of stations in the southwest Atlantic Ocean. (b) The number of drift cards deployed during each cruise in the years 1978 to 1981.

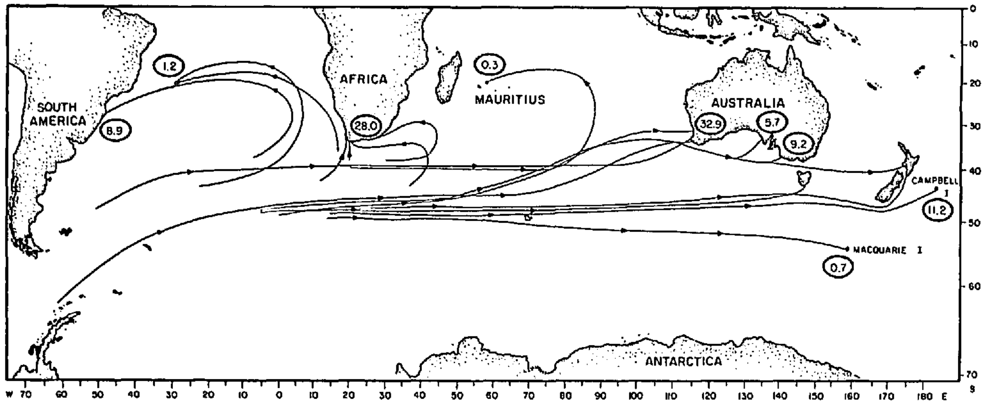



Figure 2. The drift cards recovered for each area as a percentage of the total drift card recovery. Some of the major trajectories are shown. These describe the sea surface drift of up to 65% of the circumference of the globe in the Southern Ocean.

both directions (Lutjeharms, 1987; Lutjeharms and Valentine, 1987) thus establishing at least one frontal-crossing mechanism.

The deployment positions of all batches from which cards were later retrieved on the South American coastline is also shown in the upper panel of Figure 3. The distribution is similar to that for Southern Africa except that all are in the Atlantic Ocean sector, with the exception of a few placed in the Agulhas Current area off the south coast of Africa. These latter ones would have been advected westwards into the South Atlantic by that current.

The geographic distribution of the deployment positions of batches of which cards were subsequently retrieved in western Australia shows a distribution which is not longitudinally bound but which attenuates strongly south of the Sub-Antarctic Front (Fig. 3). The average location of this front in this area is 46° 30′ and its range about ± 1° (Lutjeharms and Valentine, 1984; Lutjeharms, 1985). With one exception, a card placed at about 63S, no cards placed well south of the Antarctic Polar Front were retrieved in western Australia. Two cards placed south of 60S were retrieved in eastern Australia. The latitudinal core of the deployment positions for cards which were retrieved in eastern Australia lies significantly south of the core for those retrieved from western Australia.

This progressive southward shift is also noticeable for the positions from which cards reached the New Zealand area. Most of these were in fact deployed in the area between the Sub-Antarctic and the Antarctic Polar Front. Fewer were placed in the zone between the Sub-Tropical Convergence and the Sub-Antarctic Front. Only one was deployed north of the Sub-Tropical Convergence. Based on these few available data the inference may be made that the farther south cards are placed, the farther east they will have a landfall. Very few cards placed south of the Polar Front were retrieved.

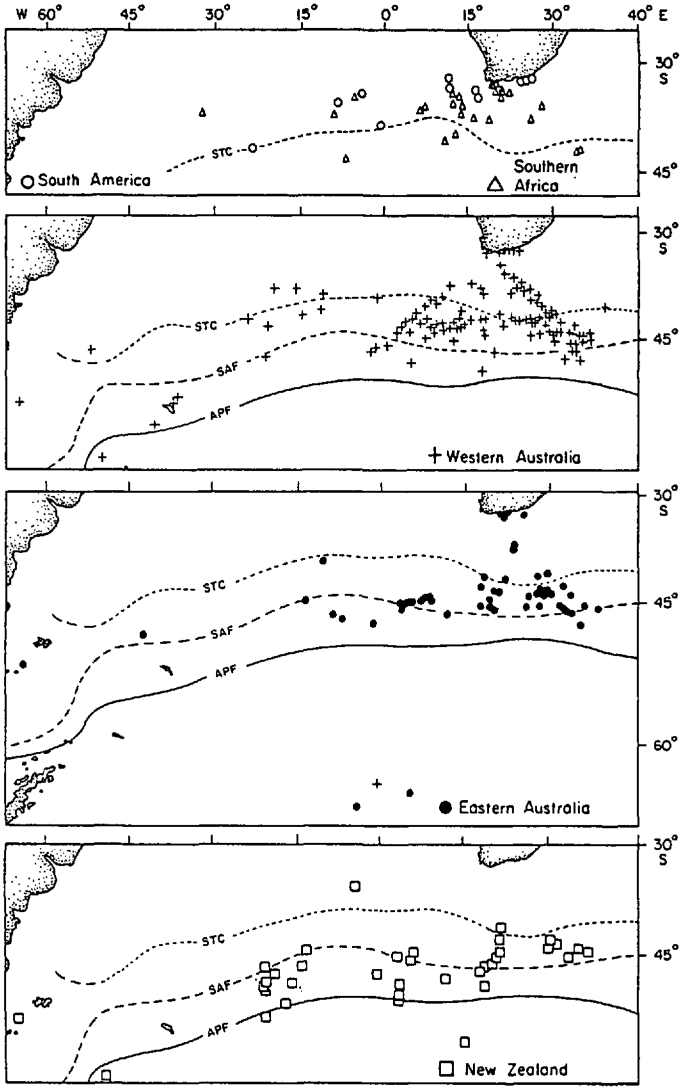



Figure 3. The geographic distribution of locations where card batches were deployed of which cards subsequently beached at particular landfalls. These batch distributions may be compared to the overall station distribution presented in Figure 1. Note that the launching position at high latitude of one card retrieved in western Australia is shown in the panel devoted to eastern Australia. The average positions of the surface expressions of the Southern Ocean fronts east of 30W are after Lutjeharms and Valentine (1984); the frontal locations west of 30W are according to Hofmann (1985).

Out of all the probable drift routes signified in Figure 3 only a small number of representatives are shown in Figure 2. Three recognizable drift patterns are apparent. The first is the system of anticyclonic gyres of the South Indian and South Atlantic Oceans for cards which were released north of the Sub-Tropical Convergence or which crossed this front and which reached places such as Mauritius, Trinidade or the east coast of South America. The surface circulation rates of these ocean basin gyres have been studied in greater detail by Shannon *et al.* (1973) and Stander *et al.* (1969) and will not be dealt with any further here.

The second characteristic flow pattern is the near-zonal drift of a large number of cards. Ten cards in fact were found at precisely the same latitude at which they were deployed. These were released over the full latitude from 30 to 55S and had, on average, drifted 9,300 km. One had drifted 11,200 km. Harris and Stavropoulos (1978) have remarked on the near-zonal drift of weather buoys in the Southern Ocean south of Africa. Similar patterns are evident from the results presented by Shannon *et al.* (1973). Notwithstanding certain meanders in the dynamic topography of the area (Gordon *et al.*, 1978), particularly near mid-ocean ridges and the Kerguelen Plateau, the average isolines from the center of the South Atlantic sector to south of Australia are also near-zonal.

The third characteristic flow pattern is made evident by the significant number of cards which reach western Australia and which must therefore have crossed the Sub-Tropical Convergence as well as the southward flowing Leeuwin Current off western Australia, (Cresswell and Golding, 1980; Legeckis and Cresswell, 1981). Some of these would have had to have crossed the Sub-Antarctic front as well. Such drift behavior has previously been reported by Shannon *et al.* (1973) for one card which also crossed the Antarctic Polar Front. Equatorward drifts have been noted not only for those found in western Australia but also in numerous instances where drift cards were retrieved from New Zealand and other parts of Australia. Although a large number of cards thus indicate near-zonal surface drift, a large number experience a significant equatorward component of advection as well.

*b. Recovery rates.* These characteristic drift patterns may be responsible for the recovery rates presented in Figure 4. Overall the percentage recovery declines with latitude, as could be expected, with very few cards deployed south of 65S ever being recovered. Interference at these latitudes with the surface drift by seasonal ice, the influence of coastal countercurrents (Tchernia and Jeanin, 1980) as well as coastal gyres could all be instrumental in trapping many cards for long periods. Only those experiencing considerable northward drift would reach zones from which they could potentially be retrieved.

An unusual feature negating the trend of southward decreasing recovery rates, is the increased likelihood of cards deployed between 45–50S being recovered (Fig. 4). The representative drift patterns of Figure 2 show that all those placed here would have to

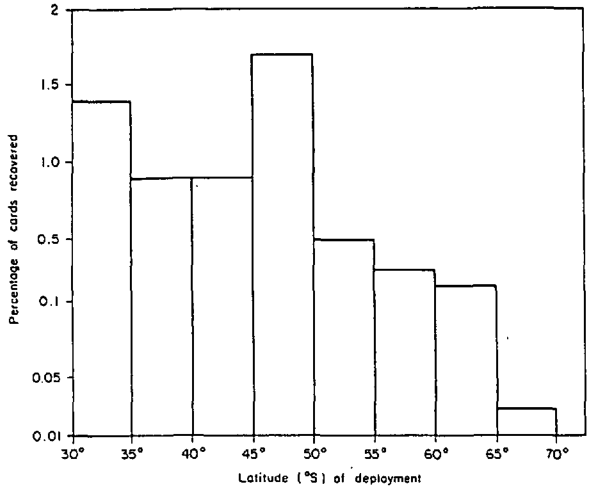



Figure 4. The percentage recovery rate of drift cards deployed in the Southern Ocean as a function of the latitudinal zone in which they were placed.

experience some northward drift to reach Australia and New Zealand. If the average climatic northward surface drift is constant and longitudinally independent, this result might imply that the latitudinal range 45–50S south of Africa is the preferred "window" to reach Australia and New Zealand. Cards placed north of this range would, according to this supposition, advect into the South Indian Ocean gyre while those placed farther south would for the greater part drift into the vastness of the Pacific Ocean before having drifted sufficiently far north to reach the latitudes of the continental coastlines.

*c. Drift rates.* Drift rates were calculated for all unbleached cards and means and standard deviations are presented in Figure 5. Drift rates increase with latitude although there is considerable overlap in the standard deviations. This trend is statistically significant only to 50S. Average drift rates were generally between 10 and 17 cm/s. This may be compared to previous estimated drift rates of 16 cm/s (Stander *et al.*, 1969), 19 cm/s (Marshallsay and Radok, 1972), 25 to 30 cm/s (Gordon, 1980; Kort, 1981) and, for eddies embedded in the main drift, 12 cm/s (Bryden and Heath, 1985). Bearing in mind the viscissitudes of motion along the routes followed by these cards as well as that of their retrieval, the ranges of average drift rates (Fig. 5) seem acceptable and consistent with those established for other surface drifters. The average drift rate of 19.3 cm/s for cards placed at 50S reported by Marshallsay and Radok (1972) may, for instance, be compared to 18.9 cm/s for cards placed between 50 and 55S in this investigation. A reanalysis of the results of the experiment reported by Shannon *et al.* (1973) has been carried out for the same latitudinal zones and is presented in Table 1 for comparison. They exhibit a maximum drift rate in the zone

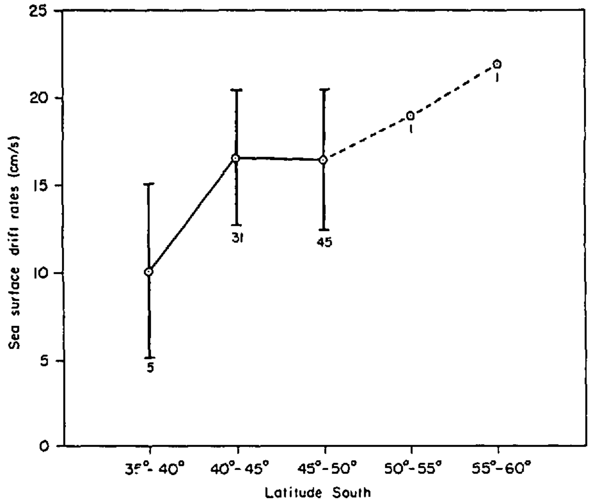



Figure 5. The average drift rates of the sea surface of the Southern Ocean, as determined by drift cards, as a function of the latitudinal zone in which drift cards were placed. Range bars are for one standard deviation while the number of cards involved in each zone are given below the range bars.

45–50S as do the present ones if the statistically less reliable results from the two southernmost zones are not included.

*d. FGGE buoy drift rates.* A comparison was made between the card drift rates and the average drift rates established during the FGGE years by drifting buoys, bearing in mind that buoys measure the drift of a slightly deeper layer. The zonal components of the average drift rates for 5° latitude by 5° longitude blocks as presented by Patterson (1985) were zonally averaged from 60W to 170E and are given in Table 1. Average drift rates for sectors, integrated along a latitudinal zone, are not truly Lagrangian since few or no individual drifters might have moved this total distance at this average speed. Nevertheless, it is interesting to note that for these drifter speeds the maximum

Table 1. Mean surface drift rates of the Southern Ocean according to different sources, in cm/s.

| Latitude | Shannon *et al.* (1973) | Drifting buoys (1979) | Drift cards (1978–82) |
|---|---|---|---|
| 30°–35° | 15.5 (±3.9) | — | — |
| 35°–40° | 15.0 (±3.1) | 12.2 (±7.3) | 10.3 (±5.0) |
| 40°–45° | 14.8 (±3.3) | 18.6 (±8.3) | 16.5 (±3.9) |
| 45°–50° | 16.8 (±3.0) | 18.4 (±5.6) | 16.4 (±4.0) |
| 50°–55° | 14.6 (±6.6) | 17.8 (±4.9) | 18.9 |
| 55°–60° | 27.0 | 15.4 (±6.6) | 21.9 |
| 60°–65° | — | 10.6 (±5.6) | — |

is also found between 40 and 45S with the speed in the zone 45–50S being similar. On average the drift rates expressed by the buoys are 15% higher than those found for the cards. Maxima in surface speeds in the 45–50S zone have also been found by others. Harris and Stavropoulos (1978) have, for instance, shown that south of Africa the peak drifter speed, the peak mean zonal geostrophic surface wind as well as the highest geostrophic surface speed relative to 3,500 db all lie between about 45–50S.

The climatic mean dynamic topography relative to 1,000 m presented by Gordon *et al.* (1978) shows that the Antarctic Circumpolar Current between South America and New Zealand undergoes some topographically determined intensifications. The maxima in the zonally averaged drift rates as identified in the drift card records may be due to such local intensifications of the current. This cannot be tested using the drift card data since there are so few areas where cards were retrieved and longitudinal spacing of landfalls is therefore totally inadequate. The FGGE data set does however allow such an analysis.

In Table 2 the 5° × 5° averages have been grouped in 30° sectors over the area being studied. Areas in which the drift rate exceeds both half and the full standard deviation for the sector have been indicated. Sectors of high drift rates thus identified correspond closely to areas where the mean Antarctic Circumpolar Current (ACC) is intensified by bottom topography features (Gordon *et al.*, 1978). South of Africa, at about 50S and 20E, such an intensification occurs as the axis of the current crosses the Atlantic-Indian Mid-Ocean Ridge. A particularly strong intensification is found where the South Indian Current, the termination of the Agulhas Current, crosses the Madagascar Ridge at 45S, 45E. The intensification north of the Kerguelen Plateau (70E, 60–43S) is not strongly reflected in the buoy drift rates, the intensification to the south of the plateau is. Flowing along the mid-ocean ridge south of Australia at about 50S, 90–120E intensified flow is also reflected in higher drift rates (Table 2). South of New Zealand, between 160 and 170E, the ACC exhibits some of its most severe intensification as it skirts the Campbell Plateau and crosses the MacQuarie Ridge. This is clearly and strongly reflected in the drift rates of the FGGE buoys. It is therefore clear that the maxima in mean drift rates of drift cards as presented in Table 1 for the zone 40 to 45S could be due primarily to the higher velocities of the ACC in parts of the Indian Ocean where bottom topography features are crossed, particularly the Madagscar ridge at 45E.

Hofmann (1985) has analyzed the drift behavior of the FGGE data set and shown that drifters exhibit a distinct tendency to accumulate in certain zones which correspond with the historic locations of the various frontal systems of the Southern Ocean. Gregory *et al.* (1984) have furthermore shown that flotsam such as tar balls and plastic litter also tends to accumulate in frontal areas. Some degree of frontal trapping therefore most probably occurs in the case of drift cards. In each sector the drift velocities in the zones corresponding to fronts were significantly higher than those of areas between fronts (Hofmann, 1985). By following the various fronts from west to

Table 2. Mean zonal drift rate at the sea surface according to FGGE buoys for individual zones and sectors of the Southern Ocean.

| | Sector | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Zone °S | 60–30W | 30–0W | 0–30E | 30–60E | 60–90E | 90–120E | 120–150E | 150–170E |
| 35–40 | 13.3 | 10.2 | 10.0 | [19.0] | 12.5 | 11.0 | 12.5 | 6.8 |
| 40–45 | 18.3 | 16.0 | [23.3] | [27.5] | [22.0] | 18.7 | 11.8 | 8.0 |
| 45–50 | 17.5 | 17.8 | [22.8] | 19.0 | 19.3 | [20.8] | 17.0 | 10.0 |
| 50–55 | 12.3 | 13.5 | [20.0] | [21.8] | [20.3] | 19.2 | 19.0 | [20.0] |
| 55–60 | 15.8 | 11.3 | 8.3 | 14.8 | [22.0] | 12.8 | 16.5 | [25.0] |
| 60–65 | 8.6 | [12.6] | 9.0 | [11.7] | 10.0 | 9.4 | [11.7] | [12.5] |
| Mean | 14.3 | 13.6 | 15.6 | 19.0 | 17.7 | 15.3 | 14.8 | 13.7 |

Single frames denote sectors which exceed the average drift rate for that zone by half a standard deviation; double frames denote sectors exceeding by a full standard deviation.

east in Hofmann's (1985) portrayal, strong increases and decreases in the drift rates are found which agree roughly with those presented in Table 2 suggesting that the same geographic speed patterns probably also apply in the case of drift cards. A large number of cards nonetheless do cross the fronts with a northward drift component as is evident from the large number of cards placed south of the Sub-Tropical and Sub-Antarctic fronts south of Africa which are subsequently picked up in Australia and New Zealand.

## 4. Conclusions

From the results presented above and the accompanying discussion it may be concluded that:

1. Plastic drift cards are eminently suitable for studying drift patterns of the immediate sea surface over long distances although they may underestimate drift rates somewhat due to the method of retrieval by the public.

2. Mean sea surface drift rates in the Southern Ocean lie between 10 and 17 cm/s over distances of about 10,000 km. These are lower than those found from averages for FGGE drifting buoy velocities.

3. Maximum drift rates are found for drift cards placed in the 40 to 50S zone. This corresponds to the zone in which the highest buoy speeds are also found. Actually higher speeds might be found only in certain specific sectors of this zone where the Antarctic Circumpolar Current crosses bottom topography features.

4. Two recognizable drift patterns are found. A proportion of drift cards move

zonally while the drift routes of the rest show a significant northward component, thus crossing a number of frontal regions. Although some accumulation in frontal regions is shown by FGGE drifters and may also occur in the case of drift cards, a substantial exchange of surface water between the Southern Ocean and its northern neighbors is nonetheless indicated.

This experiment is expected to continue. The area being covered has been expanded geographically into the Pacific Ocean with the help of Australian colleagues and ships of opportunity to achieve a circumglobal coverage.

*Acknowledgments.* The onerous task of replying to hundreds of international letters reporting drift card finds was ably carried out by Miss C. M. Illert to whom we are indebted. We thank all those, too numerous to mention by name, who helped by distributing cards in the Southern Ocean from research and supply vessels under conditions both fair and foul. Numbering of thousands of cards was carried out by Mr. M. Timmey and the first author. We thank Mrs. E. E. Winckler for help in the analysis.

## REFERENCES

Amos, A. F. 1984. Distribution of krill (*Euphausia superba*) and the hydrography of the Southern Ocean: large scale processes. J. Crustacean Biol., *4,* 306–329.

Andriashev, A. P. 1965. A general review of the Antarctic fish fauna, *in* Biogeography and Ecology in Antarctica, J. van Mieghen and P. van Oye eds., Monographiae Biologicae, *15,* 491–550.

British Admiralty. 1969. Routeing Chart–South Atlantic Ocean, January–December, 5125 (1–12), Hydrographer of the Navy.

—— 1970. Routeing Chart–Indian Ocean, January–December, 5126(1–12), Hydrographer of the Navy.

Bryden, H. L. and R. A. Heath. 1985. Energetic eddies at the northern edge of the Antarctic Circumpolar Current in the southwest Pacific. Prog. Oceanogr., *14,* 65–84.

Cresswell, G. R. and T. J. Golding. 1980. Observations of a south-flowing current in the southeastern Indian Ocean. Deep-Sea Res., *27A,* 449–466.

Duncan, C. P. 1965. Disadvantages of Olson drift card and description of a newly designed card. J. Mar. Res., *23,* 233–236.

Ekman, S. 1967. Zoogeography of the Sea. Sidgwick and Jackson, London, 417 pp.

Frick, C. and L. E. Kent. 1984. Drift pumice in the Indian and South Atlantic Oceans. Trans. Geol. Soc. S. Afr., *87,* 19–34.

Gordon, A. L. 1980. Comments on Southern Ocean near-surface circulation and its variability. Annl. Glaciol., *1,* 57–61.

Gordon, A. L., E. Molinelli and T. Baker. 1978. Large-scale relative dynamic topography of the Southern Ocean. J. Geophys. Res., *83,* 3023–3032.

Gregory, M. R., R. M. Kirk and M. C. G. Mabin. 1984. Pelagic tar, oil, plastics and other litter in surface waters of the New Zealand sector of the Southern Ocean, and on Ross dependency shores. New Zealand Antarctic Record, *6,* 12–28.

Harris, T. F. W. and C. C. Stavropoulos. 1978. Satellite-tracked drifters between Africa and Antarctica. Bull. Am. Met. Soc., *59,* 51–59.

Hofmann, E. E. 1985. The large-scale horizontal structure of the Antarctic Circumpolar Current from FGGE drifters. J. Geophys. Res., *90,* 7087–7097.

Kirwan, A. D., G. McNally, S. Pazan and R. Wert. 1979. Analysis of surface current response to wind. J. Phys. Oceanogr., *9,* 401–412.

Kort, V. G. 1981. Mesoscale variability of currents and temperature in the Southern Ocean from drifting buoy data. Oceanology, *21,* 291–298.

Legeckis, R. and G. R. Cresswell, 1981. Satellite observations of sea-surface temperature fronts off the coast of western and southern Australia. Deep-Sea Res., *28A,* 297–306.

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

—— 1987. Meridional heat transport by a warm eddy at the Sub-Tropical Convergence. Nature, in press.

Lutjeharms, J. R. E. and H. R. Valentine. 1984. Southern Ocean thermal fronts south of Africa. Deep-Sea Res., *31,* 1461–1475.

—— 1987. The formation of eddies at the Sub-Tropical Convergence south of Africa. J. Phys. Oceanogr., (in press).

Makarov, R. R. 1983a. Some problems in the investigation of larval euphausiids in the Antarctic. Berichte zur Polarforshung, *4,* 58–69.

—— 1983b. Geographical aspects in the investigation of the life history of "Euphausia superba" Dana. Berichte zur Polarforshung, *4,* 47–57.

Marshallsay, P. G. and R. Radok. 1972. Drift cards in the Southern and adjacent oceans. Flinders Institute for Atmospheric and Marine Sciences, Research Paper 52, 15 pp + fig. + addenda.

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.

Piola, A. R., H. A. Figueroa and A. A. Bianchi. 1987. Some aspects of the surface circulation south of 20°S revealed by First Global GARP Experiment drifters. J. Geophys. Res., *92,* 5101–5114.

Shannon, L. V., G. H. Stander and J. A. Campbell. 1973. Oceanic circulation deduced from plastic drift cards. Sea Fish. Branch Investl Rep. 108, 31 pp.

Shelton, P. A. and F. Kriel. 1980. Surface drift and the distribution of pelagic-fish eggs and larvae off the south-east coast of South Africa, November and December 1976. Fish. Bull. S. Afr., *13,* 107–109.

Stander, G. H., L. V. Shannon and J. A. Campbell. 1969. Average velocities of some ocean currents as deduced from the recovery of plastic drift cards. J. Mar. Res., *27,* 293–300.

Sutherland, F. L. and A. M. Olson. 1968. The persistence of drift pumice, from the 1962 South Sandwich Islands eruption, in southern Australian waters. Pap. Proc. R. Soc. Tasmania, *102,* 1–5.

Tchernia, P. and P. F. Jeanin. 1980. Observations on the Antarctic East Wind drift using tabular icebergs tracked by satellite NIMBUS F (1975–1977). Deep-Sea Res., *27A,* 467–474.

Wu, J. 1983. Sea-surface drift currents induced by wind and waves. J. Phys. Oceanogr., *13,* 1441–1451.

Received: *7 July, 1986;* revised: *4 December, 1986.*