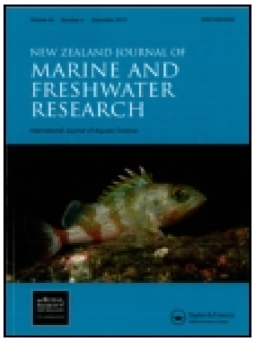

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W. N. Jenks , J. Grindrod & J. A. Peterson

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Drift currents in the southern New Zealand region as derived from Lagrangian measurements and the remote sensing of sea-surface temperature distributions

W. N. JENKS
Department of Geography
Monash University
Clayton
Victoria
Australia 3168
J. GRINDROD
Department of Biogeography and Geomorphology
Australian National University
Box 4, P.O.
Canberra
A.C.T., Australia 2600
J. A. PETERSON
Department of Geography
Monash University
Clayton
Victoria
Australia 3168

Abstract Four drift bottles, cast adrift south of the Subtropical Convergence at 48°S, 156°E in November 1980, landed within 123 days of release at a short stretch of coast north of Banks Peninsula. A high degree of coherence in the responsible drift pattern is indicated. The contemporary surface circulation inferred from satellite-derived sea-surface temperature distributions indicates that the bottles were entrained in a meridionally-converging flow after drifting across the southern Tasman Sea without crossing the Convergence. They were prevented from further eastward drifting because of a marked southward flexing of the Convergence east of the Southland Current during February 1981. Because of local weather and tide effects, the bottles finally beached in Pegasus Bay.

Keywords wind-driven currents; New Zealand; South Island; Southern Ocean; Subtropical Convergence; Lagrangian methods; drifters; temperature; surface water; remote sensing

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INTRODUCTION

On 3 November 1980, 4 unballasted, cork-sealed wine bottles were cast into the southern Tasman Sea at 48°23′S, 155°38′E (Fig. 1). Within 123 days all bottles had been recovered from a short stretch of coast north of Banks Peninsula, New Zealand (Fig. 2). The minimum sum of great circle distances travelled must have been 1550 km. The first bottle was recovered after 111 days, so that the average drift speed of the fastest bottle was no less than 0.16 m s^{-1}. Though few in number, these recoveries are the last in a reported series that dates back almost a century. Since the last review of drift results for this part of the world was published (Brodie 1960), knowledge of the oceanic fronts and circulation around southern New Zealand has increased and advances in remote sensing now allow the results of a drift experiment to be examined in the light of contemporaneous sea-surface temperatures (SSTs). Thus the location and seasonal changes in the disposition of the Subtropical Convergence (STC) zone and of surface drift currents during the drift experiment can be inferred and more satisfying explanations for drift patterns attempted.

DRIFT EXPERIMENTS AND OCEAN CURRENTS

Previous drift experiments have been important in helping to define the direction and strength of surface currents in the New Zealand region (Fig. 3, inset). In conjunction with more detailed oceanographic work they have also assisted in helping to define the disposition and seasonal migration of oceanic fronts (Fig. 5). Present knowledge of these patterns has been summarised by Heath (1973a, fig. 2; 1975a, fig. 1; 1981), and it is within the context of these syntheses that the present results are reported and discussed.

Drift bottles and drift cards

In a series of 8 papers Russell (1894–1902) and Lenehan (1904) reviewed the recovery (1887–1904) of 1107 drift bottles released over wide areas of ocean from ships trading out of Sydney. Later Dell (1952) analysed recoveries at the New Zealand coast

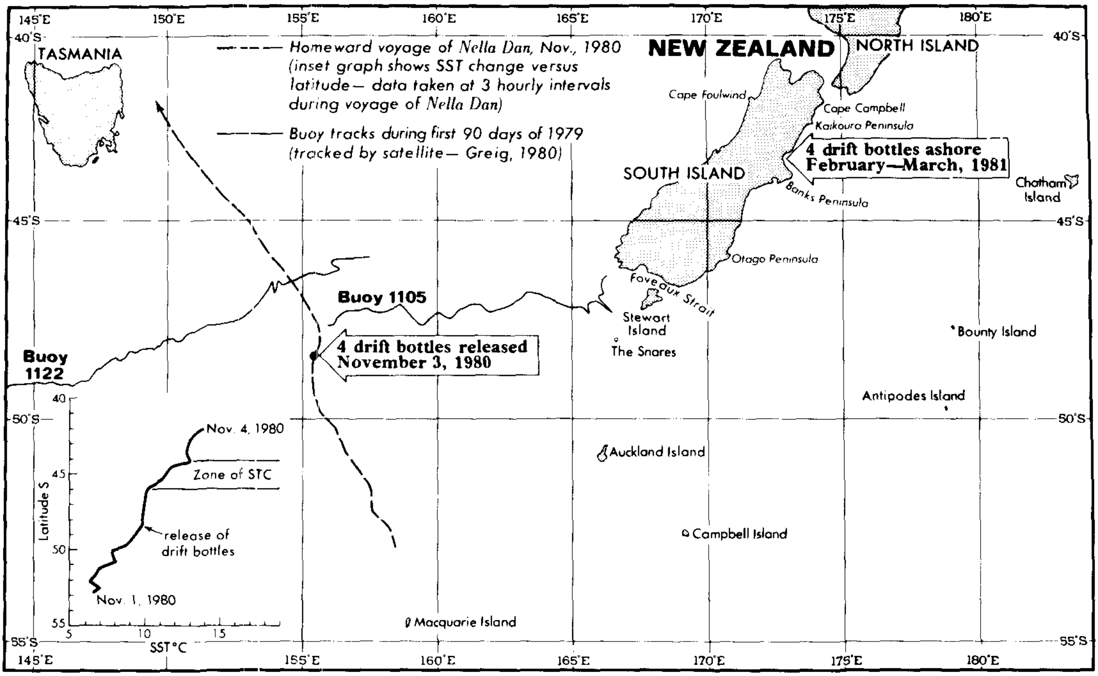

Fig. 1 Location map, showing ship and buoy tracks, and start and finish locations of drift-bottle paths. **Inset**: shipboard observations of sea-surface temperature.

of items released in this series. Dell indicates that bottles released from positions south or southwest of the southern Australian coast were recovered at various New Zealand locations, whereas a substantial proportion of those released off New South Wales were recovered along the western North Island coast. Some, however, evidently tracked south and east out of the Tasman to eventually become stranded at the eastern South Island coast. Dell regarded these patterns of movement as evidence of a splitting of the southern Tasman surface circulation at Fiordland (Fig. 1).

Among the first batch of recoveries (Russell 1894) we note that 1, released on 31 January 1892, at 46°S 163°E, stranded near Lake Ellesmere (Fig. 2) after drifting for 396 days. Assuming, as Russell did, that this bottle arrived from the south, we estimate its minimum mean rate of travel to have been 0.17 m s^{-1}. Of other bottles in this set, several were recovered at the western North Island coast. These had been released either at places well west of Australia, or close to the Convergence, so that subsequent movement toward and across the STC, thence into the Tasman circulation, was facilitated.

The second batch of recoveries (Russell 1896) reinforces this observation. Many bottles released south of the Convergence in the Atlantic and Indian Oceans subsequently stranded along the southern Australian coast. However 1 bottle, released on 9 October 1894, at 45°S 63°E in the southern Indian Ocean, drifted for 645 days before stranding at Chatham Island (Fig. 1). The minimum mean rate of travel in this instance is 0.17 m s^{-1}.

Of interest among the third group reviewed by Russell (1898), are 2 bottles released in the vicinity of Kerguelen Island (49°S 69°E). The first, released on 16 August 1896, drifted for 615 days, at a minimum mean rate of 0.17 m s^{-1}, to strand at the Northland west coast (Fig. 1). The second, released on 7 August 1897, drifted for 372 days, at a minimum mean rate of 0.23 m s^{-1}, before stranding at the North Otago coast (Fig. 1).

Two retrievals among the fourth set (Russell 1899) occurred at the Otago (east) coast. One bottle, released on 20 November 1897, at 46°S 82°E, drifted for 366 days at a minimum mean rate of 0.21 m s^{-1}. The other, released on 18 January 1898, at 43°S 42°E, drifted for 493 days at a minimum mean rate of 0.25 m s^{-1}.

A few brief points may be made in connection with these and later recoveries reported by Russell and Lenehan. Firstly, though many bottles released in the Tasman eventually stranded at the western North Island coast, so too did many released south of the STC, and at longitudes ranging to near the Cape of Good Hope. Secondly, despite the dearth of recoveries from the South Island east coast, there is a certain statistical probability that items drifting

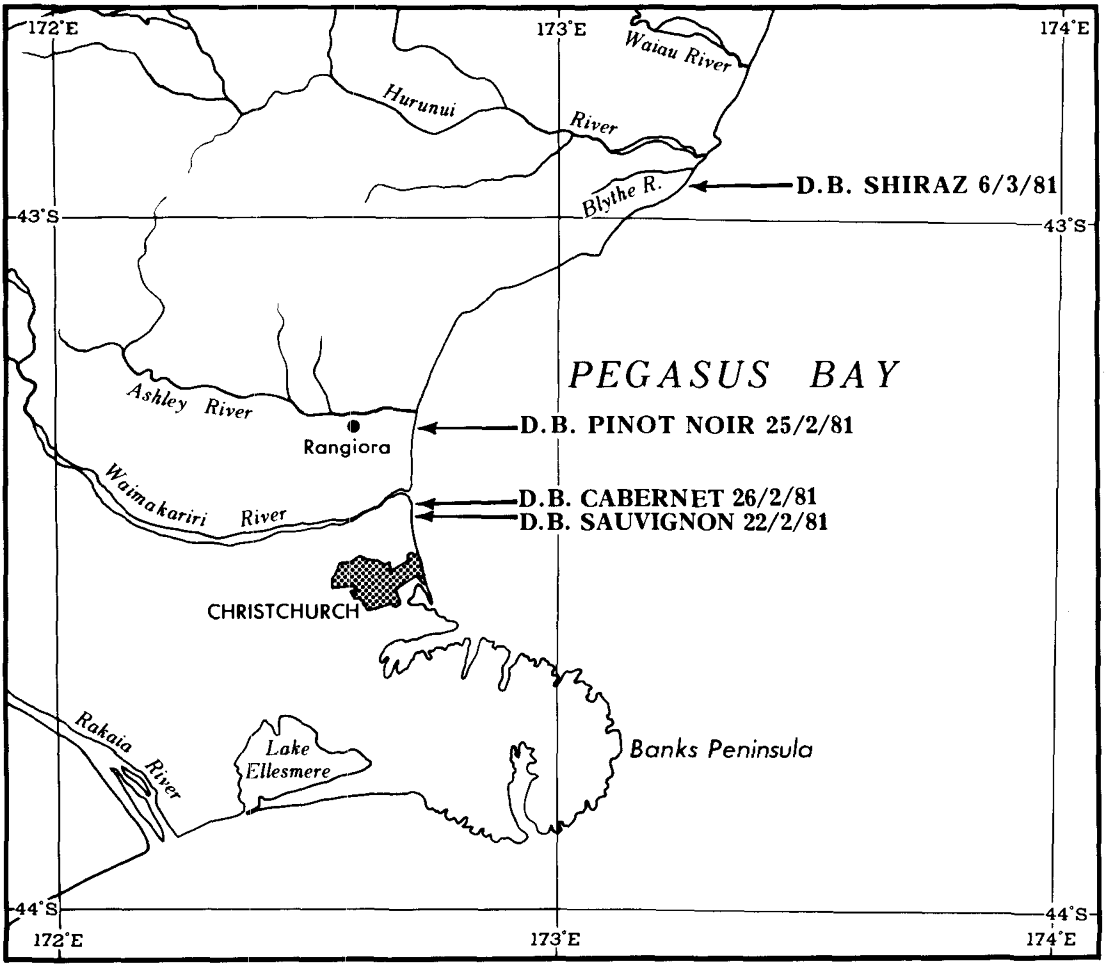

Fig. 2 Locations and dates of drift-bottle recoveries.

in the vicinity of the STC will bypass the internal Tasman circulation. Thirdly, there is a statistical probability also that items drifting with the internal Tasman circulation will exit southeastward from it. Lastly, minimum mean rates of travel increase southward from the STC. In the southern Tasman region, these rates are of the order of 0.17 to 0.18 m s^{-1} in the immediate vicinity of the convergence. As noted previously by Burling (1961) movement in the Ekman layer of this sector of the circumpolar circulation is principally toward the northeast.

More recently, Brodie (1960) has summarised recoveries from a batch of 12 000 drift cards released over the 12 months to July 1954 at numerous points on the seas surrounding New Zealand. Of the 2930 cards released within 257 km of the New Zealand coast, only 5.2 per cent were recovered.

Among the summer 1953–54 releases in the Fiordland region, a marked tendency to track through Foveaux Strait, thence around Banks Peninsula and into Pegasus Bay, was demonstrated. Brodie regarded these results as being indicative of a Southland Current (Fig. 3), which he named and identified as a mixture of southern Tasman Subtropical Surface and Subantarctic Surface Water.

Brodie summarised also the results of earlier drift experiments through the period 1918–52. Those items released in Foveaux Strait and off Otago which were subsequently recovered north of Banks Peninsula clustered preferentially in the southern portion of Pegasus Bay. The distribution of recoveries included Chatham Island as well as many places south of Banks Peninsula. There were no reported recoveries indicative of tracking southward from the North Canterbury coast. Viewed in conjunction with our results, the pattern of recovery suggests that a consistently high rate of retrieval is associated with the lee counter-current now known to exist downstream from the Banks Peninsula promontory (e.g., Fig. 6). This point is further emphasised by the drift-card recoveries of Carter & Herzer (1979, p. 25), who show a number of dominant drift vectors terminating in Pegasus Bay. Similarly, Robertson (1980, p. 27) has shown that cards released southwest of Otago Peninsula tend to travel around it and be recovered on its lee side. Brodie's conclusion that the influence of oceanic circulation upon the drift patterns observed was more important than the influence of local winds, seems to have been supported by subsequent work.

Earlier results from other parts of the Southern Ocean and neighbouring seas have also been supported by later experiments. Ten of the South Atlantic (South African) drift-card releases reported by Shannon et al. (1973) were recovered at the New Zealand coast. Two recoveries were from the North Island, 1 being from the west coast and the other from the extreme southwest. The latter may possibly have travelled along the STC to reach its destination via the South Island east coast, but the former is likely to have entered the internal Tasman circulation directly. Eight recoveries were from the South Island, all being from the south and east coasts (Stewart Island to the vicinity of Banks Peninsula). Released through the period 14 January–10 March 1969 at a mean latitude of 45°13′S, and mean longitude 10°17′E, the minimum mean group velocity is estimated to have been 0.19 m s^{-1}, with minimum mean rates of travel varying from 0.15–0.25 m s^{-1} in individual cases. According to Shannon et al. (1973:15) the results of the South African experiment indicated that the West Wind Drift maintains its latitudinal position over a distance of thousands of kilometres, and that the Drift intensifies southwards from about 0.15 m s^{-1} at 40°S to 0.19 m s^{-1} at 45°S and 0.29 m s^{-1} at 50°S.

More recently, a bottle released in Drake Passage on 16 January 1977, was subsequently recovered near the Rakaia River mouth (Fig. 2) on 17 September 1979 (Wace pers. comm.). The minimum mean rate of travel in this instance is 0.21 m s^{-1}, through a distance of approximately 17 700 km.

Satellite-tracked buoys

Recently earth-satellite-based programmes have offered new scope for mapping ocean surface features, because they offer the chance for simultaneous monitoring of current velocity and SST. The programmes have included investigations of the area of concern here.

Through 1979 the positions of 38 Australian Bureau of Meteorology buoys were monitored by satellite in the Australian region as part of the F.G.G.E. (First GARP Global Experiment) buoy system (Garrett 1980). During that year the mean drift speed of those buoys tracked between latitudes 40°S and 50°S was 0.19 m s^{-1}. The progress of buoys from 1 January to 25 March is summarised by Greig (1980).

Among buoys released in the Tasman Sea, a strong tendency has been observed for drift paths to loop around gyres (Andrews et al. 1980, fig. 1a) associated with the Tasman Front (Denham & Crook 1976), and in some cases, for buoys to even track westward. None of these buoys passed southward out of the internal Tasman circulation (Cresswell 1976, fig. 1).

Of the 11 buoys released in the region separating the Antarctic (Polar Front) and Subtropical Convergences, 2 released west of Tasmania crossed the STC into the Great Australian Bight. A further 2 buoys, released farther south, tracked toward New Zealand. Buoy 1122 commenced drifting at 49°S 142°E, thence headed slightly north of east and increased speed at a linear rate from 0.02 m s^{-1} (1/1/79) to 0.07 m s^{-1} (25/3/79) at 46°S 157°E in the central-southern Tasman. Buoy 1105, released at 48°S 156°E (a position close to our releases), similarly gained speed through the same period from 0.03 m s^{-1}, to 0.10 m s^{-1} at 46°20′S 166°30′E. This buoy tracked slightly north of east to approach Southwest Cape, Stewart Island, on a course which would have enabled it to clear southern Stewart Island. At 166°30′E, the buoy commenced a zig-zag course north toward Puysegur Point to be in the central approach to Foveaux Strait on 25 March 1979.

When viewed in conjunction with our results, those outlined above suggest that surface drift rates immediately south of the STC in the southern Tasman Sea are of the order of some 0.2 m s^{-1} or less. Items commencing an eastward passage from either side of the STC in that area may come ashore on the east coast of the South Island provided they are entrained within the Southland Current (Fig. 3, inset).

DRIFT PATTERNS AND OCEAN FRONTS

Explanation of our drift-bottle results must be related to the behaviour of the STC zone and the Southland Current during the 124 days following 3 November 1980. The drift paths all started south of the convergence, and, because none of them entered the internal Tasman circulation, it is very likely that the Convergence was not crossed by any of our drift-bottles. The position of this oceanic front has an important influence upon the pattern of regional circulation and oceanographers have paid special attention to mapping its position, which for

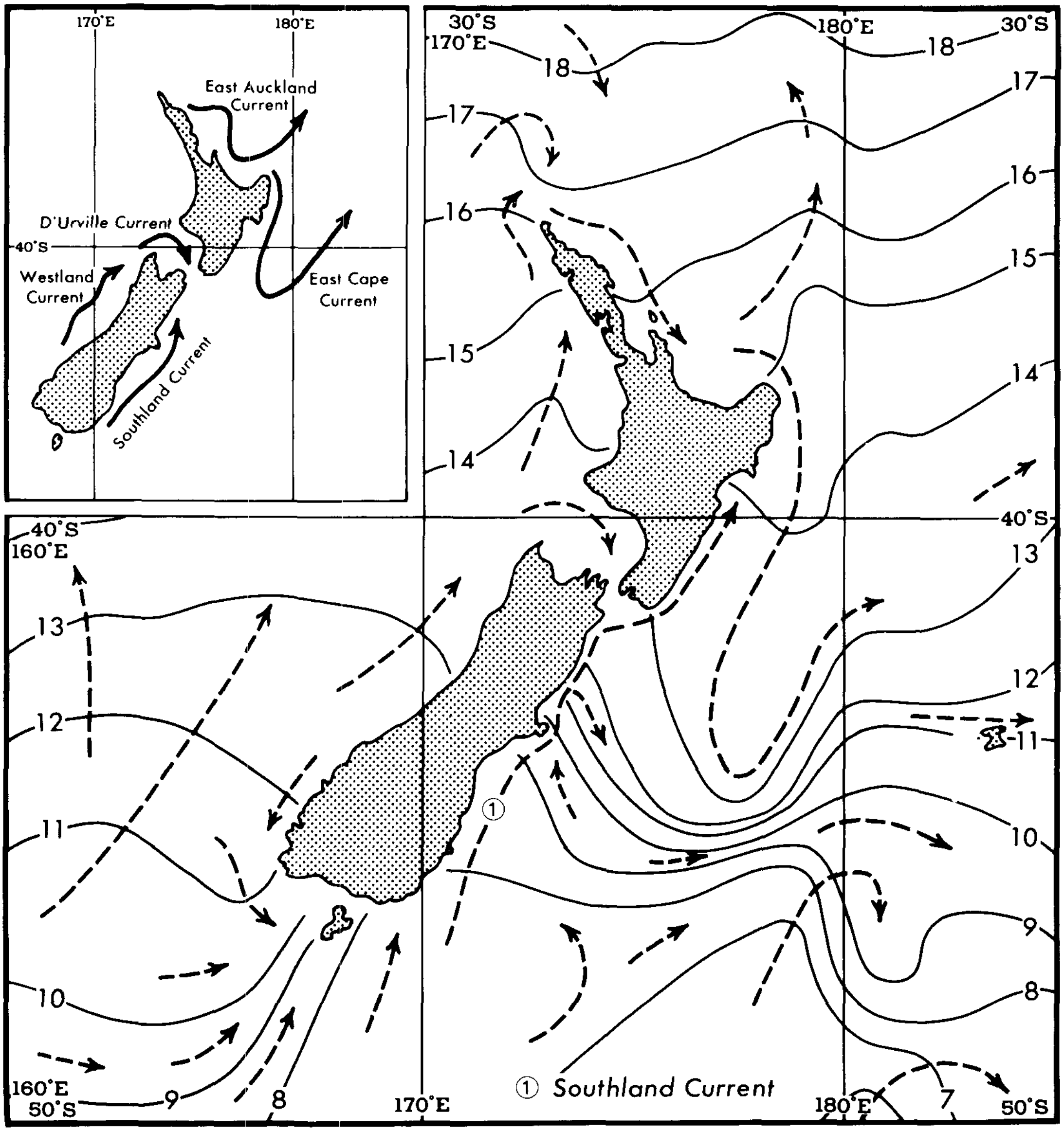

Fig. 3 Surface currents around New Zealand (arrows) for the week ending 5 August 1980. The circulation is inferred from the advection pattern indicated by SST contours and the general circulation as previously deduced; e.g., the principal currents (**inset**) as represented by Heath (1973a, fig. 1). SST data are from NOAA – 6 and refer to the 100-km resolution grid.

20 years at least has been recognised as seasonally variable (Wyrtki 1960). Certainly the extreme seasonal poleward boundaries of Subtropical Surface Water can be deduced in the New Zealand region from SSTs (Deacon 1937; Garner 1959, 1961; Heath 1973a, 1975a, 1981).

The position of the STC at the southern boundary of Subtropical Surface Water is known from numerous time-transgressive shipboard observations of SST and salinity. Typically, it has been associated with the 15°C isotherm for February, the 10°C isotherm for August, and with salinities of 34.7–34.9‰ (e.g., Deacon 1937; Garner 1959, 1961). Some interest, therefore, attaches to the availability of regional SST data from the National Oceanic and Atmospheric Administration, National

Environmental Satellite Service, U.S. Department of Commerce (NOAA/NESS 1980), since this is a source from which the oceanic fronts and surface current directions for the period of our drift paths can be inferred.

REGIONAL SST DATA: A BASIS FOR EXPLANATION

Remote sensing of SST by multi-spectral scanners receptive to radiation in the infrared and near-infrared frequencies has made possible the analysis of time-series data for all of the Earth's major water bodies, and thus complements other data sources. Aerial radiometry has been used in our region by Ridgway (1970) and Heath (1973b). More recently Legeckis (1978) and Legeckis & Cresswell (1981) have used satellite-derived (TIROS-N and NOAA − 6) grey-tone infrared imagery. Legeckis & Cresswell observe the Leeuwin Current, an autumn-winter intrusion of tropical water that flows southward along the western Australian continental slope and pivots at Cape Leeuwin, to flow eastward across the shelf in the Great Australian Bight. Their study is a particularly good example of the way in which regional synoptic images, at various times, can be used to update conventional understandings of surface circulation.

To infer the synoptic pattern of surface circulation in the region traversed by our drift bottles, we use computer-mapped SST charts. The satellite source, NOAA − 6, is operated by NOAA/NESS. The AVHRR (Advanced Very High Resolution Radiometer) carried by NOAA − 6 has 2 channels which scan in the thermal infrared area (3.74 and 11.00 μm), with a nominal resolution at the satellite subpoint of 1 km, and a temperature sensitivity of 0.1°C per digital interval at wavelength 11.00 μm. Orbits are near-polar and sun-synchronous, the view at the subpoint being from 850 km. Information concerning the receipt, central processing, and archiving of this data is provided by NOAA/NESS (1980).

The computer-mapped data is generated by a maximum-likelihood technique applied to 50-km-resolution target arrays of initial 4-km-resolution data. For those target areas that are cloud free, data are corrected for atmospheric attenuation before being further degraded into 100-km (1°) grid SST fields for contouring within the Mercator segment 20–70°S, 135°E–175°W (NOAA/NESS 1980).

Observations in the vicinities of the 100-km grid points are assigned a weight which depends upon reliability, the average temperature gradient, and distance from the grid point. The weighted data and the existing SST field are then used to arrive at the daily updated grid-point values, which generally have an absolute error of ± 1.5°C. These values are contoured weekly and mapped at a scale of 1:45 000 000.

Although the multi-day compositing procedure is capable of filtering out gaps in coverage arising from the presence of cloud, it tends to smooth out SST detail associated with transient warm-core eddies, frontal meanders, and other detailed structure. Moreover, the initial number of observations varies widely in the New Zeland region. During January 1981, when surface air temperatures were high and the anticyclonic track was well south, at least 600 SST observations per 2.5° × 2.5° unit-area were obtained in areas off East Cape, but less than 10 in areas south of Otago Peninsula. It is because of the limited availability of satellite-derived SST data in the area of drift-bottle release, October–November 1980, that we have chosen to refer to the shipboard SST observations (Appendix 1) in locating the STC zone (inset graph, Fig. 1) at that time.

The 100-km grid scale precludes accurate definition of SSTs across narrow, steep-gradient frontal zones. It also precludes rendition in close proximity to coasts. Nevertheless, an examination of SST charts compiled over recent years indicates to us that the currents illustrated by Heath (1973a, 1975a) are reflected generally in SST contours at this scale (e.g., Fig. 3). Establishment of a regional data-receiving station, and/or a lesser degree of data degradation, would greatly enhance the usefulness of signals currently generated aboard NOAA − 6 in our area. While the use of 2-dimensional grey-tone imagery for oceanographic interpretation overcomes the data-degradation problem, it does not permit time-series analysis of SST data for the New Zealand region as a whole. In order to infer the pattern of surface circulation for the period of our experiment, therefore, we base our interpretations upon the 100-km resolution data.

ANALYSIS OF SST DATA

The NOAA/NESS data have been used to plot the position of the Convergence for each month from August 1976 (when the use of surface climatological data in producing the SST field was discontinued) to March 1981. A sinusoidal interpolation of the Deacon-Garner seasonal-extreme SST estimates for the southern limit of Subtropical Surface Water was used to compile monthly sets of 4 (weekly) STC plots, and these were subsequently used to produce the monthly plots. Until February 1979 SSTs were sensed by the VHRR (Very High Resolution Radiometer) carried by the NOAA − 2, 3, 4, and 5 satellites (1972–79). The VHRR possessed a single IR channel (11.5 μm) which, with a temperature sensitivity of 0.5°C, was less sensitive than the AVHRR described above. SSTs were sensed by the

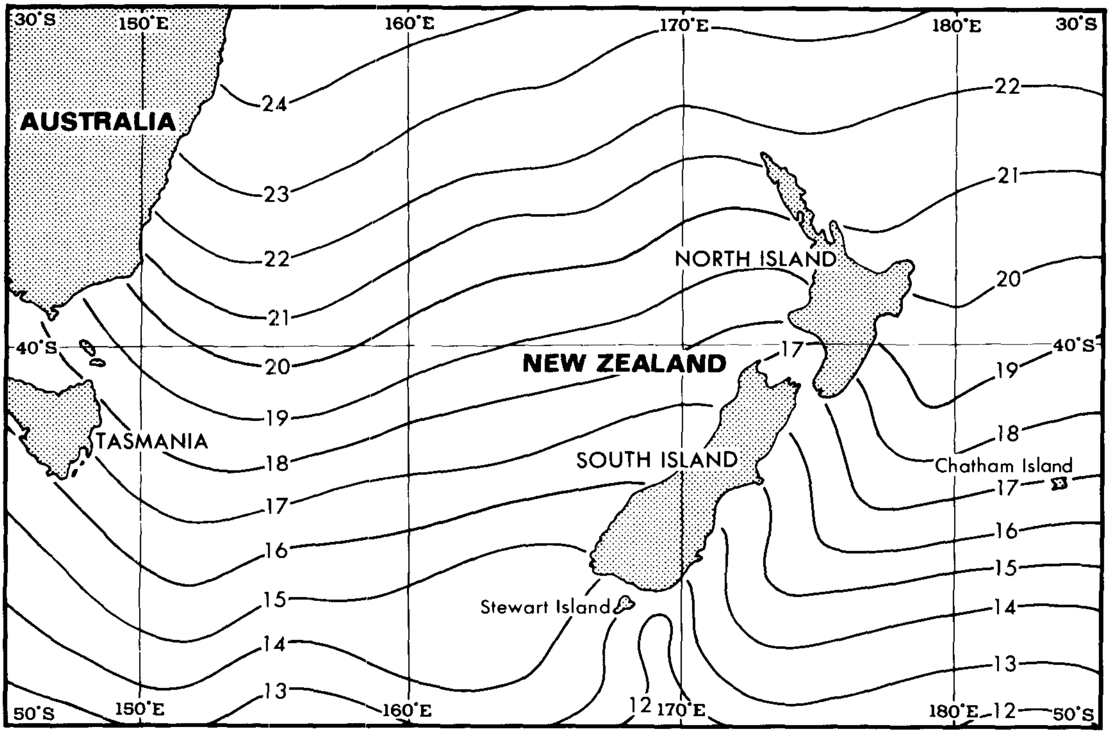

Fig. 4 Mean isothermal pattern (°C) of the sea surface around New Zealand during February, 1981. Data are from NOAA – 6.

AVHRR aboard TIROS-N from January 1979, and subsequently by the first generation AVHRR aboard NOAA – 6 from January 1980.

The southern Tasman Sea

According to the plots thus obtained, the convergence would appear to lie farthest north in the months August to September, and farthest south February to March, as would be expected from previous work. Specifically, we find that west of the South Island the Convergence may occur as far north as the latitude of Cape Foulwind, and as far south as 48°S. Similarly, to the east it may lie between Cape Campbell and the vicinity of Stewart Island. In the latter instance the offset configuration (see, e.g., the STC medial zone plotted in Fig. 5) may be lacking. The median position of the STC zone is close to that illustrated for 1980 in Fig. 5.

The medial zone occupied by the Convergence within the southern Tasman Sea during the 1980 calendar year prescribes a single symmetric wave. This same pattern was found to exist through all 12 months and must therefore have physical significance. For the east Tasman Sea region this pattern does not conform with the interpretations of Deacon (1937), Rochford (1957), Wyrtki (1960, 1962), or Highley (1967), but is supported by the interpretations of Garner (1954, 1967b), Heath (1973a, 1975b, 1981), and Edwards & Emery (1982).

The Southland Current

While the STC zone west of New Zealand may occur as far north as the latitude of Cape Foulwind (see above), the monthly plots for 1980 clustered closely about the medial position shown in Fig. 5. It is therefore likely that Subtropical Surface Water contributed directly to the Southland Current throughout that year. Previously Garner (1961) viewed the current as a branch of the Tasman circulation of Subtropical Surface Water extending eastwards through Foveaux Strait into the surface water of the Otago coast. This view is supported by Brodie's (1960) analysis of drift-card recoveries. Burling (1961) suggested that the current originates southwest of Stewart Island and consists mainly of water from the STC region, together with an admixture of Circumpolar Subantarctic Surface Water. The eastern boundary of the current was defined as the Southland Front. Subsequently Jillett (1969: stations A–D, October 1966–December 1967) showed that off Otago Peninsula the current is persistently located on the outer continental shelf and slope. Jillett viewed the current as a northward-extending tongue of relatively warm, high-salinity water, bounded on the landward side by low-salinity coastal water and on the seaward side by low-salinity Subantarctic Surface Water (Circumpolar Subantarctic Surface Water, sensu Burling 1961; Emery 1977). Jillett suggested minimum temperatures of 9.5°C (winter) and 12.0°C (summer) for Subtropical Surface Water off Otago Peninsula, with corresponding seasonal salinities of 34.5 and 34.6‰. He also noted the variable strength and mixing status of the current.

Later Heath (1972) used Jillett's data to calculate a mean geostrophic surface speed of 0.07–0.08 $m\ s^{-1}$. He noted that beyond Banks Peninsula the subtropical component is considerably diluted, so that the current as a whole is cool, and of low salinity relative to the Subtropical Surface Water of the adjoining East Cape Current (Fig. 3). According to his (1972) study of the geostropic circulation, the strength of the Southland Current varies north of Banks Peninsula in accordance with the varying effect of wind shear and contact with the adjacent East Cape Current.

On the basis of drift-card data compiled by Herzer, Carter & Herzer (1979) have suggested a minimum surface speed of 0.13 $m\ s^{-1}$ for the Southland Current in the vicinity of Pegasus Bay.

Using a parachute drogue off Otago Peninsula, Heath (1973c, station J124) observed a reversal of the general northeasterly set over the continental shelf on 19 April 1971. This was ascribed to winds prevailing at the time. More recently Robertson (1980) has determined an average minimum surface velocity of 0.15 $m\ s^{-1}$ from drift-card/direct-current measurements off the Otago coast. Robertson conducted monthly temperature-salinity observations at 6 shelf locations off Otago Peninsula (stations G-L: April 1971–June 1972), and observed a persistent presence of high-salinity Subtropical Surface Water over the mid to outer shelf. From a series of non-seasonal transects, Robertson (1980, p. 22) also showed that the current, as identified by its subtropical component (>9.5°C and >34.5‰S: 11–14 August 1971) is a narrow feature, some 20–30 km wide off the South Otago coast. The current was shown to be narrowest (no more than 20 km in width) off Otago Peninsula (Roberston 1980:27).

The preceding interpretations are consistent. There is no indication that the direct-entry source of Subtropical Surface Water may be switched off, and it appears that the Southland Current is not subject to vicissitudes similar to those documented for the Cape Leeuwin Current (Legeckis & Cresswell 1981). On the other hand, the SST plots indicating STC positions as far north as North Westland suggest preclusion of the direct-entry source of Subtropical Surface Water, and are accordingly difficult to reconcile. These plots derive in particular from winter and spring data obtained with the earlier VHRR equipment, and if an allowance of 2°C is made for negative bias in SST data, the STC will plot to the south. Moreover, the seasonal minima specified for Subtropical Surface Water off Otago Peninsula by Jillett (1969) indicate that the Deacon-Garner minima may be too high for application in that region. We are not able to test this discrepancy here, but we note that a further allowance of approximately 1°C is sufficient to produce an STC plot that lies south of Fiordland in all cases. Assuming that short-term (weekly chart) bias concels out in the AVHRR SST data used to locate the February 1981 position of the STC in Fig. 5, a downward adjustment of the Deacon-Garner summer minimum by 1°C would achieve a similar result. The probem of reconciliation can therefore by solved by allowing for negative bias in SST data and/or adjusting the Deacon-Garner seasonal minima criteria. Finally, we emphasise that the effect of these same adjustments upon many of the more southerly SST-derived STC positions would result in their relocation toward the Snares Islands (Fig. 5).

Surface and bottom temperature-salinity data are available for 29 January 1981 at 6 stations, located off Otago Peninsula and extending to the shelf break (Jillett pers. comm.). These data indicate that surface salinities exceeded 34.7‰ on the outer shelf, and suggest the likelihood of a strong flow of Subtropical Surface Water in the Southland Current at that place and time. Our bottles would almost certainly have been entrained within the current by 29 January 1981, having previously passed along the convergence to enter the meridionally-converging regional flow implied by the position of the convergence (Fig. 5) for February 1981. According to our interpretation, this flow was bounded to the east by a marked southward flexure of the Convergence—as distinct from the Southland Front—and we suggest that it was this disposition of the STC during February 1981 that created the converging corridor along which our bottles passed, and forced the high degree of coherence in the surface drift between the STC and the Otago-Canterbury coast. Moreover, Coriolis forces are likely to have produced an onshore vector in the flow, thus further ensuring the presence in the Southland Current of our bottles during the later part of their voyage.

East of the Southland Current

Although the SST data do not permit direct identification of the Southland Current and its associated oceanic front, they do permit comment on the eastward circulation for the period August 1976–February 1981. Importantly, they indicate that

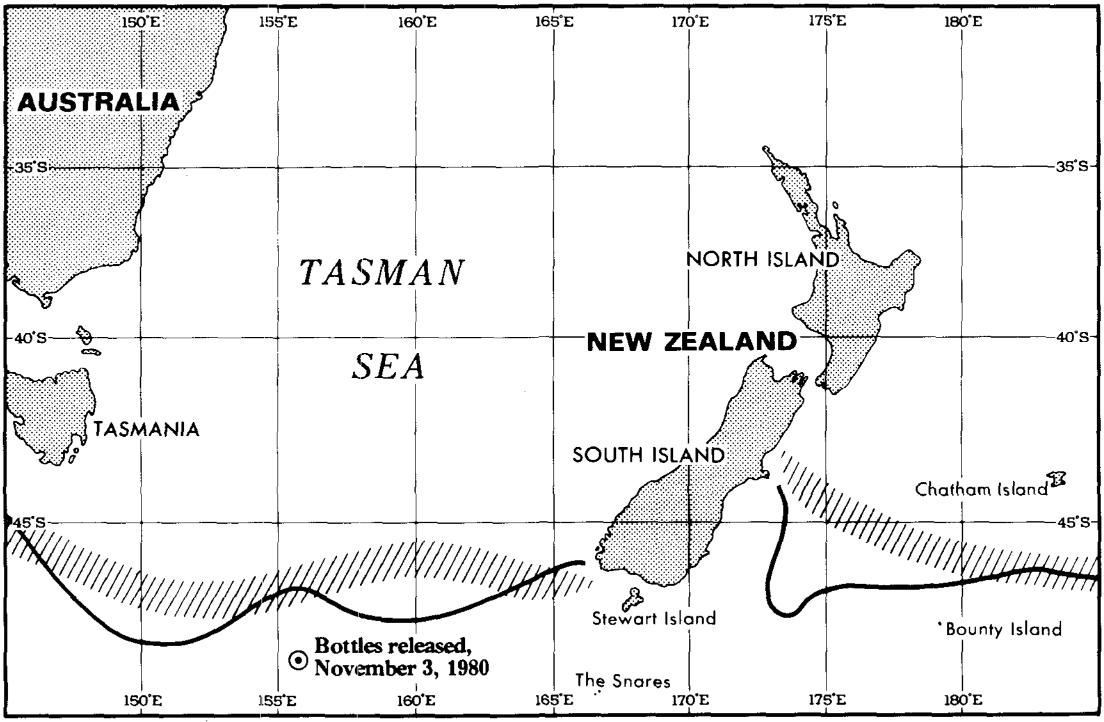

Fig. 5 Mean southern limit for Subtropical Surface Water in the New Zealand region as determined from NOAA – 6 SST data for February 1981 (solid line), together with the medial zone occupied by the Subtropical Convergence during the 1980 calendar year (hatched).

surges of cold water during late winter and spring appear to progress northward from the Campbell Plateau to occupy the entire region bounded approximately by Bounty Island, South Island, and the Chatham Rise. Some instances are given below.

During the period 2–7 September 1976, very cold water extended north into the region and remained through September. Surface temperatures of 5–6°C occurred at the South Otago coast, creating a very strong east-west temperature gradient in the Stewart Island region, while a steep north-south gradient lay off North Canterbury. At this time the Convergence extended from near Kaikoura to Chatham Island, with strong definition. This pattern persisted into October, with SST variation of as much as 5°C per degree latitude at 43°S, 178°E. It is pertinent to add that the steepness of SST gradients across the Convergence in the area immediately east of South Island generally is not exceeded elsewhere in the entire Australasian region.

During June 1977 surface temperatures of 6–7°C extended from the eastern margin of Foveaux Strait as far north as North Otago. A further surge occurred during August and September, with surface temperatures falling below 6°C off the Otago Coast in the week to 13 September.

Another cold surge occurred during August 1980, with surface temperatures again less than 7°C off the Otago coast. At this time the convergence was still located off the western approaches to Foveaux Strait, its 'normal' position.

Even allowing for the possiblility of very cold air over the region, we cannot explain these occurrences other than by invoking the concept of a cold surge. There is, moreover, some independent support, for according to Garner (1959), patterns of surface temperature and salinity between New Zealand and Chatham Island show a tendency for Subantarctic Water to push north. In this context the sighting of numerous large icebergs in this region in 1892–98 (Brodie & Dawson 1971), and another in 1931 (Gaskin 1972) is significant, as is the likely presence of ice-rafted rock fragments on the Chatham Rise (Cullen 1962). Though the latter could well have a Pleistocene origin, the stranding of ice at Chatham Island at 44°S during October 1892 is curious, especially since this is the area in which the Convergence is usually located during that month. Clearly a number of coincidental occurrences are required for bergs to reach this area, and we wonder if a surge of Subantarctic Surface Water might not have been one of them. With the exception of the

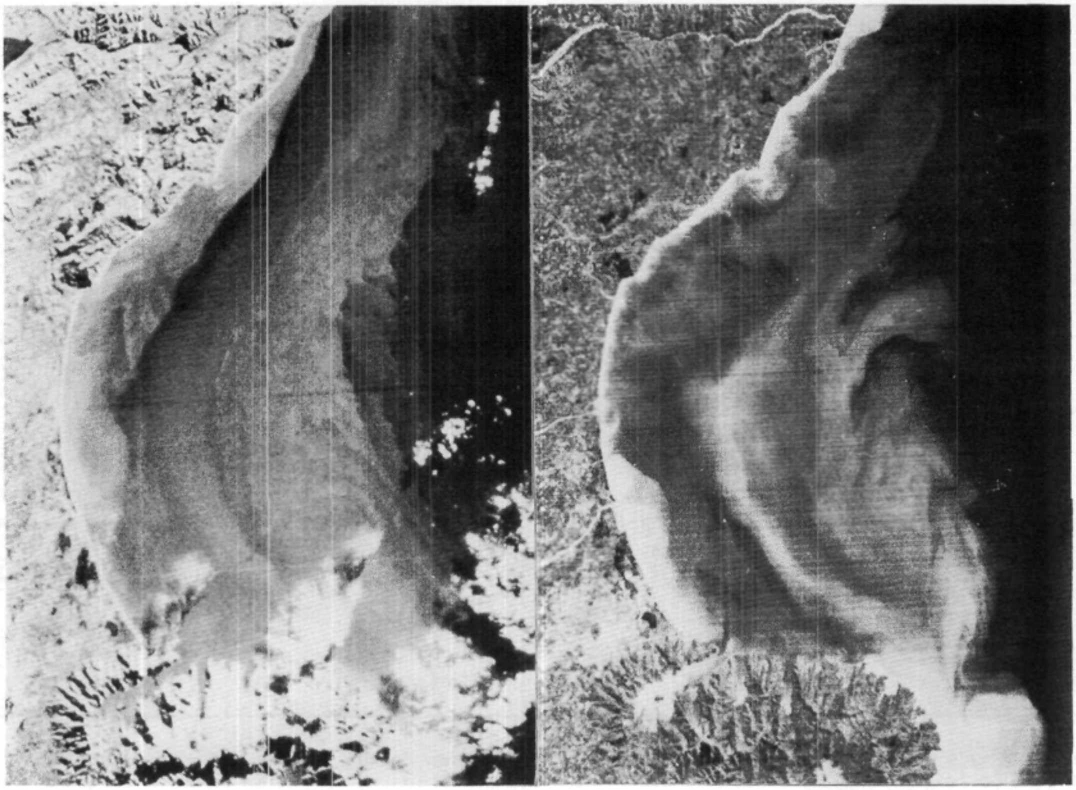

Fig. 6 *Landsat II* (Band 4) images featuring absence of anticlockwise gyre in Pegasus Bay at 0926 h NZST on 3 August 1975 (left), and subsequent presence at 0925 h NZST on 1 November 1975 (right). Reference: portions of ERTS E – 2192 – 21265 – 4 and E – 2282 – 21254 – 4, respectively. Imagery by courtesy of NASA; prepared by the Department of Lands and Survey in conjunction with Physics and Engineering Laboratory (Department of Scientific and Industrial Research), New Zealand.

extraordinary sighting at 41°30′S, 122°E on 17 August 1899 (Russell 1899), it is in the area for which we invoke the cold surge that bergs are known to reach farthest north. There are no records of them in the Tasman Sea.

The data discussed above serve to illustrate an important point—that the marked southward flexing of the STC during February 1981 is a summer rather than a winter phenomenon. The regional intrusion of cold surface water tends to restrict the STC zone to a position north of the Chatham Rise.

Some of the temperatures mentioned here are lower than others previously reported from the region. For example, the lowest surface temperature recorded by Jillett (1969) for Subantarctic Surface Water is 7.8°C (station D, Mu67/94: 18/8/67). Lower temperatures could be expected to occur in areas east and south of this Otago shelf-slope location, while remaining within the positive error bounds of the VHRR and AVHRR SST data mentioned above. However, the inshore SSTs are almost certainly too low to be explained in this manner.

The medial zone occupied by the Convergence east of New Zealand (see, e.g., Fig. 5) does not conform with some interpretations (Heath 1973a, 1975a, 1981) but is in agreement with those of Gilmour & Cole (1979) and Garner (1957, 1967a). Zoogeographical evidence (e.g., Young 1929, Moreland 1957, Dell 1960, Powell 1976) suggests that the Convergence lies generally, but not always, to the south of the Chatham Islands. The satellite-derived SST data suggest that the STC zone is in the region of the islands from mid-winter until October and at other times lies to the south. Furthermore, if the Deacon-Garner seasonal temperature minima for Subtropical Surface Water are adjusted downward for use in locating the Convergence, the certainty of this interpretation is further assured.

The common presence of Subtropical Surface Water around Chatham Island is indicated also by meteorological data. At Waitangi (altitude 48 m) the mean monthly air temperature, May 1976–December 1979, was 11.3°C. Adjusting at the dry adiabatic lapse rate, the sea level equivalent is

11.8°C and compares to a mean satellite-derived SST for the Chatham Island vicinity during the same period of 12.9°C. Heat transport from lower latitudes by eastward diffusion of western boundary currents is therefore indicated. Corresponding temperatures for February 1980 were 15.1°C and 17.1°C, suggesting that Subtropical Surface Water was advecting heat to the Chatham Islands area at the time of the Pegasus Bay strandings.

DRIFT FACTORS IN PEGASUS BAY

Meteorological records for locations within the Christchurch metropolitan area indicate a predominance of northeasterly winds on a percentage-time basis. Winds from this direction are typically associated with anticyclonic conditions, stable environmental lapse rates, and land-surface heating in summer. They are locally strengthened in southern Pegasus Bay by topographic influences. Moreover, onshore surface northeasterlies often prevail at the coast even when the general flow is from northwest. Although northeasterlies are, in general, a fair-weather phenomenon, they are frequently fresh to moderate in strength.

According to surface wind directions recorded at Christchurch during February 1981, northeast to east winds predominated on 24 of the 28 days. Brief spells of south to southwest wind occurred, but on no day did strong offshore winds predominate over the nearshore zone in Pegasus Bay. This wind pattern is likely to have superimposed short-period waves from the northeast upon the regional southerly swell and to have induced a shoreward surface drift for much of the time.

As Pickrill & Mitchell (1979) stress, this coast is a high-energy lee shore. It experiences a mixed wave-climate of southerly swells generated in the westerlies to the south together with locally-generated storm and lesser waves. Southerly swells tend to follow great circle paths, and arrive in the bay as deep-water waves 0.5–2.0 m high and of 6–9 seconds period. Further seaward, mean significant wave height is of the order of 2.4 m. Inshore these waves attenuate and are 0.5–1.5 m high and of 7–11 seconds period. According to shore-based observations, the mean significant wave height is approximately 1.0 m, while the mean zero crossing period is circa 8.6–8.8 seconds. The modal wave period is somewhat less than the latter.

The local wave directions manifest a bimodal distribution and include a peak at about northeast. Although wave height is uniform through the year, heights and periods associated with the northeast mode dominate the record in summer.

Heath's (1973c) representation of currents for Pegasus Bay suggests an anticlockwise gyre (Heath 1973a, 1975a) having surface velocities of 0.1–0.3 m s^{-1}, the weakest velocities occurring close inshore. This representation is confirmed by the streaming pattern of solids in suspension as illustrated in Fig. 6 for 1 November 1975, although the pattern shown in the same place for 3 August 1975 indicates that the circulation is not a permanent phenomenon.

From the foregoing we conclude that a local 'fencing' process was in operation during the period immediately preceding the strandings, and that the combined effect of wind, tide, and topography was to preferentially drive our drift bottles into Pegasus Bay once they had rounded Banks Peninsula.

CONCLUSIONS AND FUTURE WORK

1. Results of the drift-bottle experiment reported here are consistent with those previously attained in the region and serve to reinforce the pattern of oceanic circulation depicted around southern New Zealand by Heath (1973a, 1975a, 1981).
2. The high degree of coherence in the oceanic surface drift pattern indicated by the results would be explained by
    a) regularity of the STC in the southern Tasman Sea
    b) a pronounced southward flexing of the STC eastward of the South Island during February 1981, and
    c) the existence inshore from the STC of a regional, meridionally-converging flow.
3. There appears to have existed during February 1981 an augmented probability that items drifting with the Southland Current to latitude 43°10'S and beyond would strand preferentially around Pegasus Bay.
4. Finally, despite obvious limitations of the 100-km resolution data grid, and of the time-compositing procedure, satellite-derived SST data for the period of the experiment assisted us greatly with the intepretation of results. We therefore recommend consideration of this data source in future work. Recent introducton (24/11/81) of a multichannel technique using the 3 thermal IR channels (3.6, 10.8, and 12.0 μm) of the AVHRR on board the NOAA – 7 satellite has improved the coverage and accuracy of SST monitoring greatly, especially in cloudy regions e.g., tropical and subpolar latitudes. Better correction for atmospheric attenuation of the IR signal and improved data processing techniques have also enhanced data quality.

The enthusiastic response of people who returned our bottle-notes suggests that beachcombers are more likely to respond to requests in bottles than on drift cards, and we intend following this experiment up with continued use of drift bottles.

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APPENDIX 1 Sea-surface temperatures taken on the cruise of the M.V. *Nella Dan*, Macquarie Island to Melbourne, November 1980.

Latitude (°S)	Longitude (°E)	Day	G.M.T.	Temperature (°C)
52.9	158.4	01	2100	6.5
52.5	158.3	02	0000	7.0
52.1	157.8	02	0300	6.3
51.6	157.6	02	0600	6.7
51.2	157.1	02	0900	6.9
50.6	156.7	02	1200	8.0
50.1	156.3	02	1500	7.8
49.7	155.8	02	1800	8.8
49.4	155.3	02	2100	no data
48.8	155.5	03	0000	9.5
48.2	155.7	03	0300	9.9
47.6	155.6	03	0600	9.8
47.1	155.1	03	0900	10.0
46.7	154.6	03	1200	10.0
46.2	154.2	03	1500	10.0
45.7	153.7	03	1800	10.3
45.3	153.3	03	2100	11.2
44.8	152.7	04	0000	11.5
44.4	152.3	04	0300	12.8
44.0	151.8	04	0600	12.9
43.6	151.3	04	0900	12.6
43.1	150.8	04	1200	12.8
42.6	150.2	04	1500	13.0
42.0	149.7	04	1800	13.8