The Separation of the East Australian Current

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ABSTRACT

Oceanographic data from the last two decades show that the behavior of the East Australian Current system is qualitatively different on either side of a line extending south-southeast of Sugarloaf Point (32°30′S); to the north and east of the line, dynamic height contours and satellite buoy tracks are either open, or they consist of large eddies elongated in the north-south direction. South and west of the line, flow consists of relatively small, near-circular eddies. Just south of Sugarloaf Point, northward currents on the continental shelf appear to be common, suggesting entrainment toward a separation flow near Sugarloaf Point which may be topographically controlled. The oceanographic data suggest that the separation point is more closely defined in summer, when the current is strong, than in winter.

Merchant ship, current atlas and continental shelf sediment data generally support this description of the East Australian Current. However, current atlas data collected between 1854 and 1938 suggest that the separation near Sugarloaf Point is stronger in winter than in summer; this may be a real change from present conditions or it may be due to the unknown errors in the data. The distribution of fine sediments over the continental shelf suggests that the current separation near Sugarloaf Point is quite sharp and has been present for a considerable time.

1. Introduction

At least three of the world's western boundary currents separate from the continental shelf at well-defined locations. The Gulf Stream follows the North American continental shelf until the shelf takes a major bend at Cape Hatteras (35°N, 75°W); the current then flows straight out to sea, rather than following the bend (e.g., Stommel, 1966). The Boso Peninsula (35°N, 140°E) on the east coast of Honshu, plays a similar role for the Kuroshio (e.g., Teramoto, 1972). The Agulhas Current appears to separate at the southern tip of the Agulhas Bank at 37°S, 20°30′E (Harris *et al.*, 1978).

By contrast, the flow patterns in the East Australian Current are so complex and variable that it is often difficult even to decide whether a single, continuous current exists. In this paper, the term "East Australian Current" will simply mean the flow regime on the western side of the Tasman Sea. The dynamic height maps from some (but not all) cruises show a few contours that run parallel to the Australian coast for some hundreds of kilometers, as one would expect of a continuous current; but even when this occurs, the maps usually show several intense anticyclonic eddies just offshore (Hamon, 1965; Boland and Hamon, 1970). However, whether the current that separates is part of an eddy or part of a larger system, the evidence of the last two decades suggests that the current shows a clear tendency to separate between about 30 and 34°S, and especially near Sugarloaf Point (32°30′S). Two possible mechanisms have been proposed for this phenomenon.

First, Warren (1970) suggested that a zonal jet flowed from East Australia to New Zealand; he based his suggestion on the theories of Stommel and Aarons (1960) and their laboratory realization by Faller (1960). Essentially, the idea is that New Zealand blocks the westward propagation of Rossby waves: north of about 32°S these waves can propagate through to the Australian continent but south of 32°S they strike the New Zealand land mass and create a western boundary current there. The transport of the New Zealand current must flow as a zonal jet across the Tasman. Recent evidence partially supports this suggestion. Strong north–south gradients of dynamic height frequently have been observed near Wanganella Bank, a short distance northwest of New Zealand at 32°30′S, 167°40′E (Denham and Crook, 1976; Stanton, 1976). Between about 15°S and 15°N, a theory based on non-dispersive baroclinic Rossby waves and predicting movement of such features for large distances *due* westward has been very successful (e.g., Lighthill, 1969; Meyers,

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1975; White, 1977), though at the higher latitudes of interest here, barotropic effects may be important (Bye, Heath and Sag, personal communication). Evidence for westward movement of features was found near New Zealand by Stanton (1976) and near the Australian coast (north of 34°S) by Hamon (1965) and Boland (1979). The speed of motion was in all cases 0.01–0.03 m s^{-1}, while the predicted speed of a first-mode baroclinic Rossby wave in these latitudes is ~0.02–0.03 m s^{-1}.

Direct observational evidence for a zonal jet of the type proposed by Warren is rather contradictory. For example, Wyrtki (1962) shows a concentrated zonal outflow from Australia nearly to New Zealand. His data come from two lines of dynamic height measurements along 34°S and 30°S in January and April 1960. On the other hand, some recent dynamic height maps do not show such a feature (e.g., Wyrtki, 1975) and paths of satellite-tracked buoys drogued at 20 m show no obvious indication of a zonal jet in these latitudes in the latter half of 1977 [(Fig. 1); from Cresswell and Golding (1979)].

Fig. 1 also suggests that the current has a strong tendency to separate near Sugarloaf Point (32°27′S, 152°33′E), even though (in 1977) the buoys that came away from Sugarloaf Point did not go eastward along a zonal jet. This indicates the second possible separation mechanism: it may be a topographic effect, similar to the one that acts at Cape Hatteras and Boso Peninsula. An isobath map is shown in Fig. 2. There is a definite bend in the shoreline and continental margin near Sugarloaf Point, though it is not as pronounced as at Cape Hatteras or Boso Peninsula or at the tip of the Agulhas Bank. Such minor topographic features have been found to have an important influence on western boundary currents elsewhere (e.g., Brooks and Bane, 1978; Pearce *et al.*, 1978).

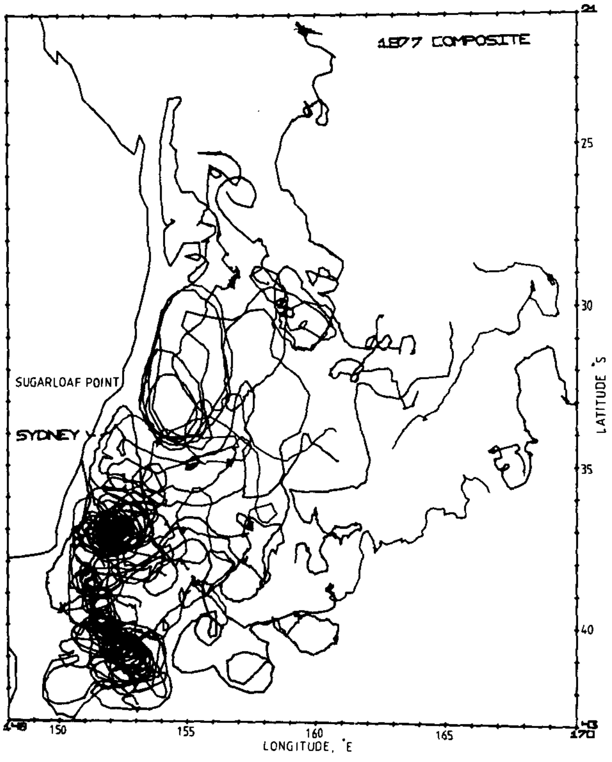

FIG. 1. Paths of all satellite-tracked buoys, 1977. Most of the tracks within 400 km of the shore were made in the first half of 1977; most of those more than 400 km from the shore in the second half (from Cresswell and Golding, 1979).

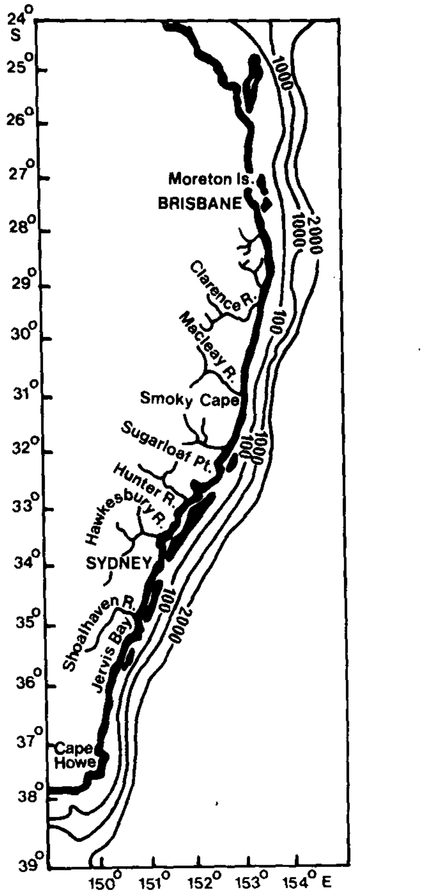

FIG. 2. Bottom topography near the east Australian coast; depths are in fathoms (1 fathom = 1.83 m). In the darkened patches over the continental shelf, mean sediment grain size is less than 0.125 mm.

In this paper, we summarize available evidence on the separation of the East Australian Current from the coast, from a variety of different sources.

2. Surface dynamic height patterns

a. Summer and winter averages

Hamon (1961, 1965) and Boland and Hamon (1970) reported the results of a number of oceanographic cruises in the East Australian region. The principal tool used in analyzing flow was the surface dynamic

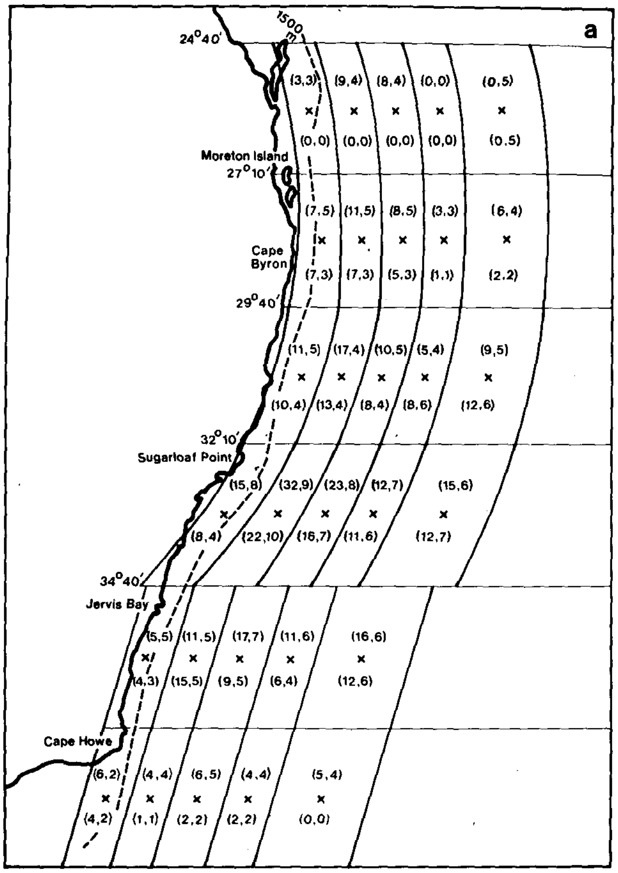

FIG. 3a. Grid arrangement used for averaging dynamic height data. A number pair (n,m) indicates that n Nansen stations were taken in the given box, on m separate cruises; the upper number pair refers to summer cruises (November–April), the lower to winter cruises (May–October). The dashed line is the approximate position of the 1500 m contour, west of which no Nansen stations were taken.

height relative to 1300 db, $D_{0/1300}$. In this section, we first consider the average of $D_{0/1300}$ values from these cruises, and a few others from the period 1950–68. Since the dynamic height field has strong gradients perpendicular to the coast, it is desirable to average the data within boxes whose sides are roughly parallel to the coast; Fig. 3a shows the boxes that were used. It also shows the number of Nansen stations that were taken within each box, and the number of different cruises on which they were taken, for the summer and winter half-years. In the following, the summer half-year will mean the period November–April, while the winter half-year will mean May–October. Figs. 3b and 3c are the average dynamic height maps for the summer and winter half-years, respectively. The system is very highly variable, so that within the dashed lines the root-mean-square (rms) deviations are > 0.2 dyn m; if the 95% confidence limits on the average dynamic height within a given box are taken as ±(2 × rms deviation)/(number of cruises)$^{1/2}$, then we can establish an individual average only to about ±(0.1–0.15 dyn m). However, the fact that the patterns for summer and winter are so smoothly contoured and so similar encourages the belief that both patterns are reasonable representations of the "average" East Australian Current.

In the summer half-year there is an elongated, closed eddy between 26 and 31°S, and an anticyclonic feature that nearly closes into an eddy at 36°S. There is a sharply defined outflow between 31 and 33°30′S, roughly centered on Sugarloaf Point; half this outflow passes around the southern edge of the northern eddy, while half passes around the southern eddy. In the winter half-year, the tendency to eddy formation is weaker but is apparently present, judging by the curved nature of the 2.0 and 1.7 dyn m dynamic height contours. However, the outflow now appears to be distributed uniformly along the whole coast.

In the summer, the region where the dynamic height variability is greatest, enclosed by the dotted line, lies just offshore from the Sugarloaf Point out-

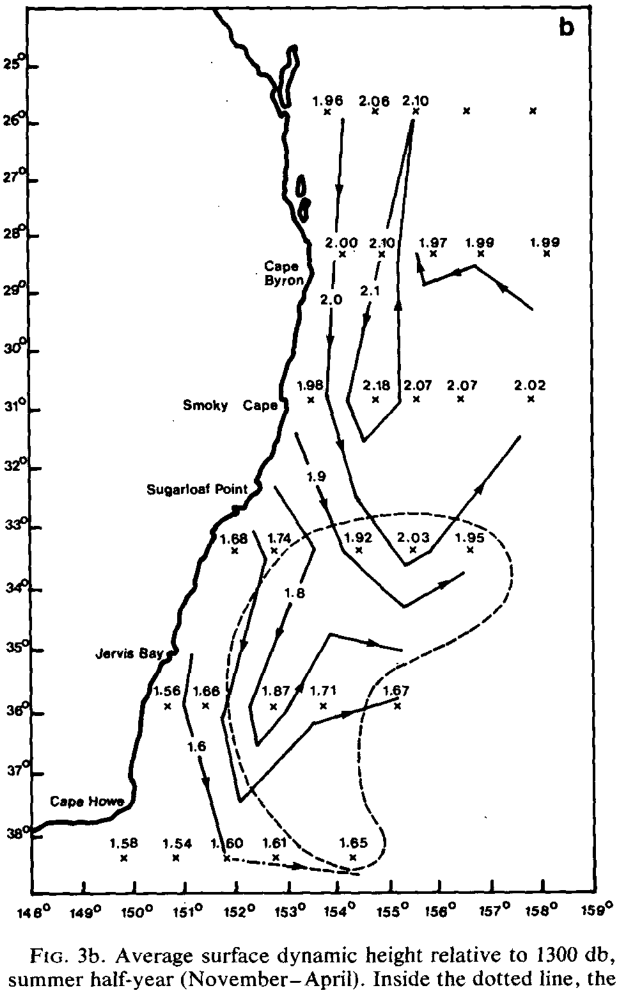

FIG. 3b. Average surface dynamic height relative to 1300 db, summer half-year (November–April). Inside the dotted line, the rms deviation of the dynamic height analysis is > 0.2 dyn m.

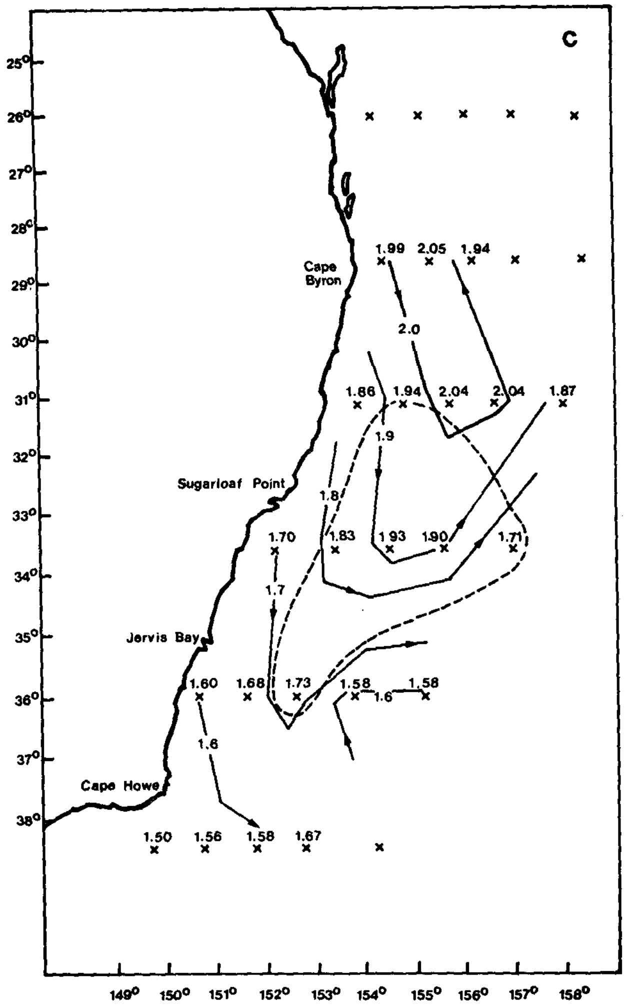

FIG. 3c. As in Fig. 3b except for winter half-year (May–October).

flow. One is reminded of the Gulf Stream and Kuroshio, which become much more variable just after they separate from the coast at Cape Hatteras and Boso Peninsula, respectively. In the winter, the region of maximum variability moves northward, suggesting that the current tends to separate further north in winter.

b. *Locations of current cores and paths of satellite-tracked buoys*

Hamon (1965) noted that the 1.9 dyn m contour of dynamic height almost always lay near the core of a region of strong current. He drew a composite picture of this contour from all cruises between 1960 and 1964, to indicate the average pattern of the East Australian Current. Figs. 4a and 4b show similar composite pictures for ten summer and seven winter cruises, respectively. The contours are taken from the papers of Hamon (1965), Boland and Hamon (1970), Nilsson *et al.* (1977), and Andrews and

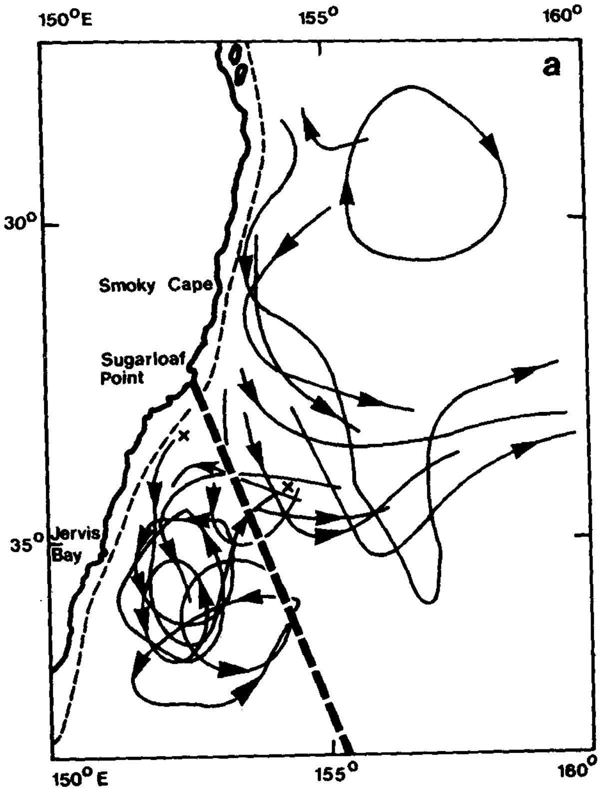

FIG. 4a. The 1.9 dyn m contour of surface dynamic height relative to 1300 db, for 10 cruises in the summer half-year.

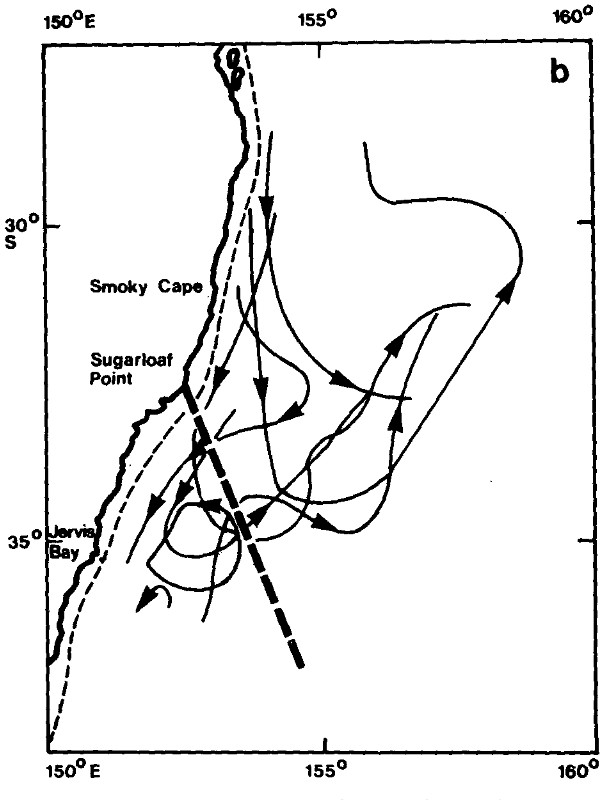

FIG. 4b. As in Fig. 4a except for the winter half-year.

Scully-Power (1976); in the latter two cases we have used the 15°C isotherm at 240 m as a current core indicator instead of the 1.9 dyn m dynamic height contour. The cruises covered different areas and each individual contour was drawn by hand, so we cannot make useful statistical statements about the figures. However, the similarities between Fig. 1 and (particularly) Fig. 4a are quite striking, despite the fact that the data were collected by quite different techniques in different time periods. Most of the satellite buoy tracks in Fig. 1 within 400 km of the shore were obtained in the first half of 1977, so it is reasonable that they should look like the 1.9 dyn m contour picture for the summer half-year.

In Figs. 4a and 4b, we have drawn a dotted line south-southeast from Sugarloaf Point. Broadly speaking, contours to the north of this line in Fig. 4a suggest a flow leaving the coast between Smoky Cape and Sugarloaf Point, and then turning eastward, while those to the south of the line suggest (and in five out of eight cases definitely form) closed anticyclonic eddies. On only one occasion (the contour with the × on its two ends) was the current core south of the dotted line definitely *not* suggestive of an anticyclonic eddy closed to the north. In this case, a cruise five weeks later showed that the tongue had already closed off to form a new eddy off Jervis Bay (Nilsson *et al.*, 1977).

There is a small "shadow zone" in Fig. 4a, just south of Sugarloaf Point which the 1.9 dyn m dynamic height contours tend to avoid: strong currents from the north generally leave the coast to the north of this region, while strong currents associated with the eddies pass to the south of it. The only exception is the special case just referred to, observed by Nilsson *et al.* (1977).

The winter picture (Fig. 4b) is somewhat similar to the summer picture, but eddies appear to be less frequent off Jervis Bay. However, this may simply reflect the fact that relatively fewer cruises occur south of Sydney in the winter. As anticipated in the previous section, the outflow does not show the same clear-cut tendency to flow seaward between Smoky Cape and Sugarloaf Point, that can be seen in the summer picture; the shadow zone south of Sugarloaf Point is also less obvious.

3. Current patterns on the continental shelf

Dynamic height measurements can only be made in deep water, so they cannot provide any information about flow patterns on the continental shelf: unfortunately, direct measurements of current are sparse over much of the shelf. In the present section, we discuss two different sources of information on currents over the shelf and slope, and try to relate them to the offshore patterns mentioned in the previous section. The first data set consists of geomagnetic electrokinetograph (GEK) and ship's drift measurements on some oceanographic cruises; the second is the distribution of ship's drifts from merchant ships along the coast.

a. Nearshore currents and temperature fronts observed on oceanographic cruises

On several cruises, currents have been measured on the shelf and slope using the GEK technique (CSIRO, 1963) or sometimes ship's drift. The magnitudes of the GEK current vectors may be incorrect by a factor of perhaps 2 because of varying bottom depth (and hence conductivity field in the neighborhood of the GEK cable), but the directions of these vectors are probably correct. There is a discernible pattern to these vectors that is best illustrated using results from one recent cruise.

Fig. 5 shows the contour map of $D_{0/1300}$ values obtained between 30 March and 11 April 1978, on *Sprightly* cruises Sp5/78 and Sp6/78; dynamic height values obtained from Nansen stations have been supplemented by use of expendable bathythermographs (XBT's), using a minor variation of Hamon's (1968) regression of dynamic height on water temperature at 240 m depth. The dynamic height pattern is typical of those for the summer half-year in Fig. 4a; a strong southward flow follows the continental shelf, then separates a little north of Sugarloaf Point. The northern end of what is probably an anticyclonic eddy can be seen off Jervis Bay; some of the Sugarloaf Point outflow appears to double back into the eddy.

We were fortunate in that two good satellite infrared photographs of the region occurred during these two cruises. The dominant feature on these photographs (taken on 3 and 11 April 1978) was a sharp temperature front, starting right at the shore near Crowdy Head and proceeding smoothly southward over the shelf edge. Cloud obscured the front south of 33°S in the photo of 3 April, but in the second photo, the front was slightly S-shaped; it has been drawn as a heavy dark line in Fig. 5 (for simplicity some other fronts, also visible on the photos, have not been drawn). On several crossings of the front by *Sprightly*, surface temperature rose 3–4°C from south to north. The full arrows in Fig. 5 are GEK vectors, while the dashed arrows are measurements of ship's drift, made during periods of light winds. The heavy full arrow off Crowdy Head is the average current at a current meter, at 50 m depth in 100 m of water, between 2 to 11 April 1978. Currents over the continental shelf at Crowdy Head clearly run parallel to the direction of the temperature front, rather than to the direction of the coast. The currents on the shelf to the south of the front, off Port Stephens, are substantially weaker.

Three previous cruises (CSIRO, unpublished data) have suggested a similar pattern. In other

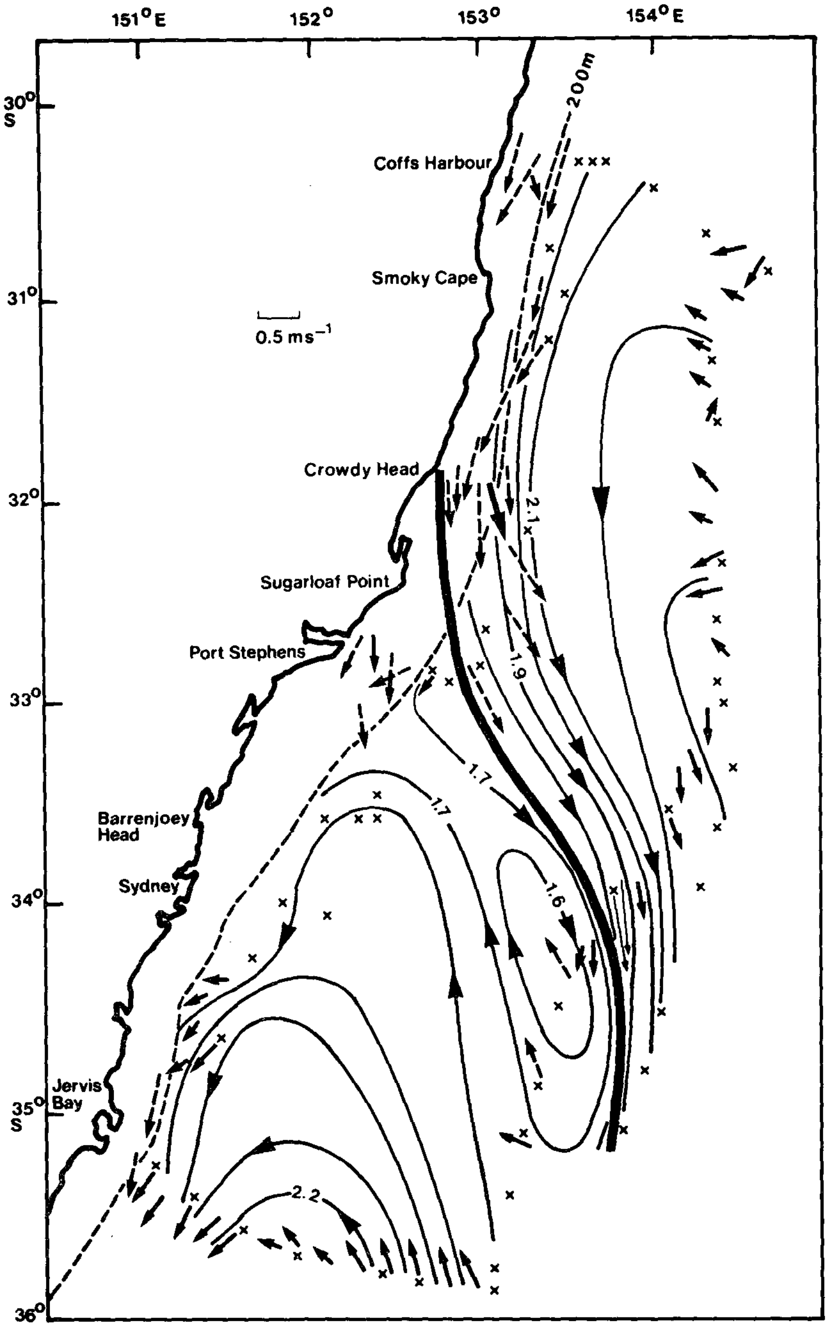

FIG. 5. Results of *Sprightly* cruises Sp5/78 and Sp6/78, 30 March–11 April 1978. Light full lines are contours of surface dynamic height relative to 1300 db. The heavy full line shows the position of a surface temperature front, from a satellite photo of 11 April. Full arrows are currents measured by GEK, dashed arrows currents measured by ship's drift. The heavy full arrow off Crowdy Head is the 11-day average of a current meter record.

words, they have shown a sharp temperature front leaving the continental shelf edge off Sugarloaf Point, with currents flowing rapidly southward and parallel to the front on the offshore (warm) side and with weak, non-parallel currents on its inshore (cold) side. Indeed, the pattern of Fig. 5 may be unrepresentative in that the currents are southward, inshore from the front; on earlier cruises, the currents on the inshore side were *northward* on two of three occasions, suggesting entrainment of cold water into the front.

If the separation point is often near Sugarloaf Point and entrainment is common, we might therefore expect northward flow to be rather frequent in

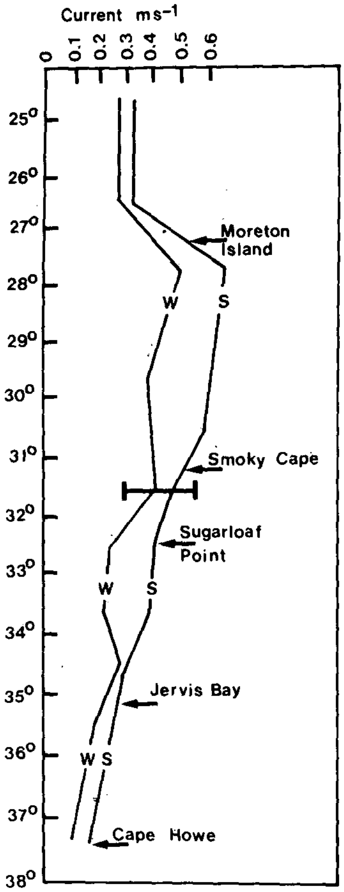

FIG. 6. Average longshore component of surface current, in the 1° square covering the 200 m isobath along the east Australian coast, for the summer (S) and winter (W) half-years. Positive currents flow southward. From data in the atlas *Sea Areas Around Australia* (K. Ned. Meteor. Inst., Rep. No. 124). Errors in the data are unknown (see text).

the shadow zone between Sydney and Sugarloaf Point. This is in fact supported by XBT data from 104 voyages of M. V. *Maheno* from Sydney to Auckland between 1969 and 1975 (Boland, personal communication). Currents inferred from XBT's dropped at 152° and 152°30'E, i.e., just off the Sydney shelf, were northward 35% of the time. Also, two out of five satellite-tracked buoys released near Sydney traveled north, to be entrained into an offshore flow near Sugarloaf Point (Cresswell, 1973, 1976; Cresswell and Wood, 1977).

b. Evidence for current separation from merchant ship data

The only long, thoroughly edited series of current measurements over the east Australian continental shelf comes from the drifts of 38 merchant ships, during the period May 1971 to April 1973 (Greig, 1974; Hamon *et al.*, 1975). The ships measured their drift between nine pairs of landmarks, from 27°S to 32°30'S; in this section of coast, southbound ships travel along the shelf edge, ~19 km offshore, to take maximum advantage of the current, while northbound ships stay ~6.5 km from shore to avoid the strongest currents. Time series of currents were developed from all northbound and from all southbound ships' reports. Unfortunately, south-bound ships no longer follow the shelf edge after passing Sugarloaf Point at 32°30'S, so we cannot tell from these data alone whether there is a complete separation of the East Australian Current north of Sydney (33°50'S). However, in combination with other data we can arrive at some reasonable conclusions.

From 30 to 32°30'S, average longshore ship's drift at the shelf edge dropped from 1.0 to 0.65 m s^{-1} in the summer half-year and from 0.9 to 0.5 m s^{-1} in the winter, indicating that a moderate degree of current separation was occurring between these latitudes in *both* seasons (Hamon *et al.*, 1975, Fig. 5). However, at the southernmost pair of landmarks used by the merchant ships (31°50'–32°30'S), northward currents were still rare at the shelf edge, occurring only 5% of the time; this is quite different from the situation off Sydney, where—as previously mentioned—the figure is ~35%. These results indicate that there is a large degree of separation of the East Australian Current between 30 and 34°S.

4. Historical data

The preceding sections have examined data from the last two decades, in an attempt to find an average signal buried beneath the noise of the East Australian Current eddies. However, the signal itself may change slowly with time. We have two sources of data on the East Australian Current in earlier times: the first is a current atlas, and the second is the distribution of fine sediments and certain minerals over the east Australian continental shelf.

a. Observations from a current atlas

Fig. 6 represents the longshore component of current, in the 1° square that covers the 200 m isobath, averaged for the summer and winter half-years, from the atlas *Sea Areas Around Australia* (K. Ned. Met. Inst., 1949); between 75 and 175 ship's drift observations, taken between 1854 and 1938, contribute to each point. Apart from statistical errors due to the large variability of the East Australian Current (the error bar shows the order of magnitude of the expected 95% confidence limits), the data may contain substantial systematic errors due to the fact that reporting ships are probably a different average distance offshore at different latitudes. The details of the data editing used in preparing the atlas are also unknown. With these cautions, the data are still useful for providing average currents in regions where no other data are available.

The main conclusions to be drawn from Fig. 6 are first that, after rising rapidly to a maximum off Moreton Island, the average current speed falls away rather steadily to the south, becoming almost zero at Cape Howe; and second, that the average current for the summer half-year is typically about 1½ times stronger than the winter average.

If Sugarloaf Point creates a shadow zone, we would expect a strong reduction of current just to the south of it, particularly (according to earlier sections) in summer. Fig. 6 shows some reduction relative to the general linear trend between 31.5 and 32.5°S, but it is mainly in winter rather than summer. This rather puzzling discrepancy may represent a real change between the period 1854–1938 and the present time, or it may simply reflect the scarcity of current observations off Sydney—both then and now.

b. Bottom sediments on the continental shelf

Distribution patterns of sediments on the sea floor may be used to describe the behavior of the current field responsible for their dispersal (e.g., Curray, 1960; Stanley and Wear, 1978). Fine sediments with mean grain size < 0.125 mm, smaller than fine sand, are a sensitive indicator of the energy environments at their sites of erosion and deposition. Such fine sediments are unlikely to be deposited by currents of velocity $> 0.1–0.15$ m s^{-1} or resuspended by currents $< 0.2–0.25$ m s^{-1}. Cohesion of the fine sediment particles due to compaction and dewatering increases with time and makes them progressively harder to resuspend.

Major deposits of fine sediment on the New South Wales (N.S.W.) continental shelf are restricted to areas south of 32°S (Fig. 2) and in particular to a belt stretching from Sugarloaf Point to Jervis Bay between depths of 50 and 130 m. This belt has been described by Shirley (1964) and Boyd (1974). It consists of very fine sand, silt and clay and is concentrated offshore from the mouths of the three major rivers (Hunter, Hawkesbury and Shoalhaven) on this section of the coast. No major fine sediment accumulations occur on the shelf north of 32°S (Davies, 1979) even though the rivers of the north coast of N.S.W. discharge greater quantities of fine sediment than their counterparts in the south.

Bottom current measurements on the shelf between 28°S and 29°S (Delft Hydraulics Laboratory, 1970; Gordon *et al.*, 1978) on the N.S.W. north coast have revealed strong currents with mean velocities of 0.15–0.3 m s^{-1} and peak velocities of 1 m s^{-1}, chiefly directed southward. Similar bottom current measurements conducted off the Sydney coast (Cresswell, 1974; MWSDB, 1976; Boyd, 1974) show weak currents with variable direction. Mean velocities for most records are in the range 0–0.15 m s^{-1} with peak values of 0.3 m s^{-1} and suggest that below 50 m depth on this section of the shelf is a relatively low-energy environment. Such energy conditions are favorable for the accumulation of fine sediment with many periods of velocity below the threshold of deposition but few above the threshold of resuspension. These data are consistent with the hypothesis that the East Australian Current is an important mechanism controlling the distribution of sediment on the N.S.W. shelf, and that a current separation in the general region indicated in earlier sections of the paper leads to sediment deposition near Sydney. However, there is further geological information that suggests a quite sharp separation of the current south of Sugarloaf Point.

Shepherd (1970) compared the heavy mineral assemblages of the Manning River, 80 km north of Sugarloaf Point and the Hunter River 100 km to the south with those from shelf sediments. He found that epidote is common in Manning River alluvial deposits but rare in those from the Hunter and could be used as an index mineral to trace shelf sediments derived from the Manning. The distribution of epidote over the shelf (Fig. 7a) shows that above-average accumulations (between 5 and 28% of the total heavy mineral fraction) lie directly offshore from the mouth of the Manning. This high concentration continues in a belt trending south across the shelf past Sugarloaf Point, passing onto the continental slope off Port Stephens. In the sediments south of Port Stephens epidote rarely constitutes more than 2% of the heavy mineral fraction.

Shepherd (1970) and Boyd (1974) have also reported contrasting distributions of fine sediment offshore from the Manning and Hunter estuaries (Fig. 7b). Major accumulations of silt and clay are absent north of Sugarloaf Point where they make up less than 20% of the total sediment. This minor silt and clay fraction is found mainly on the outer shelf east and southeast from the mouth of the Manning River. South of Sugarloaf Point silt and clay comprise up to 60% of the total sediment and are concentrated on the inner and mid shelf regions immediately offshore and to the north and south of the Hunter River mouth. Fine sediment and debris contained in Hunter River floodwater are commonly observed to travel north toward Port Stephens.

The dashed lines in Figs. 7a and 7b, running south from Sugarloaf Point, mark a fairly sharply defined border between different sediment types, presumably marking the southernmost limit of the separation of the East Australian Current. Note that this line runs south rather than south-southeast as in Fig. 4; this suggests that when the East Australian Current first separates at Sugarloaf Point it flows southward, then bends eastward.

These results indicate that the East Australian Current has had this flow pattern for some con-

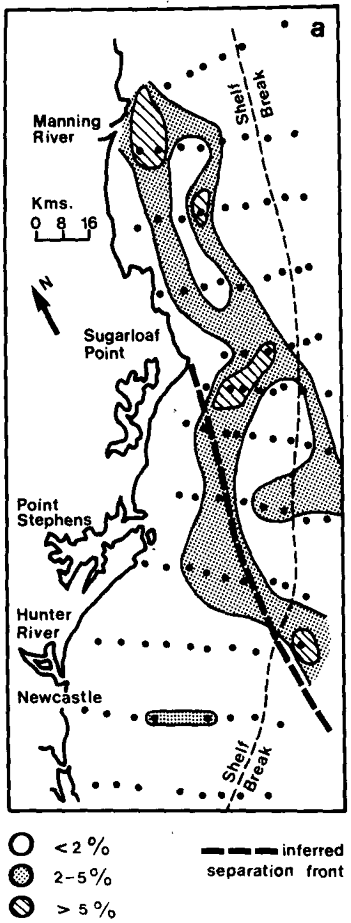

FIG. 7a. The percentage of epidote (a component of Manning River sediments) in total heavy minerals in bottom sediments from the N.S.W. continental shelf: heavy dots, station positions, stippled areas, 2–5% epidote; shaded areas, >5% epidote.

siderable time; other processes controlling sedimentation patterns on this part of the shelf, such as wave action and fine sediment input from coastal stream discharge, may be expected to have been maintained since sea level reached its present position some 5000 years ago.

5. Discussion

The East Australian Current seems to consist of strong anticyclonic eddies, which tend to move irregularly southward along the coast (Hamon, 1965; Hamon *et al.*, 1975; Wyrtki, 1962). The time-average pattern described here is not obvious from a few synoptic pictures of the current; thus, for example, the eddies south of Sugarloaf Point are not separate entities but probably form by the pinching off of current loops that start near Sugarloaf Point. A large volume of data is needed to identify the time-average pattern beneath the "noise" associated with these eddies: it appears that the data are not yet fully sufficient for this purpose, so that some contradictory conclusions regarding the mean pattern emerge from different sources of data, particularly as regards the difference between summer and winter conditions. It seems safe to say, however, that the East Australian Current tends to separate from the coast between 30 and 34°S, and that the circulation south of 34°S nearly always consists of a series of closed, nearly circular anticyclonic eddies. This is markedly different from the situation further north. The separation may be solely due to the influence of Rossby waves propagating westward from north of New Zealand—in other words, if the Australian coastline were completely straight, the separation might occur in the same latitude band of 30 to 34°S, because of fronts propagating due west from New Zealand. However, this seems unlikely for two reasons. First, the East Australian Current is simi-

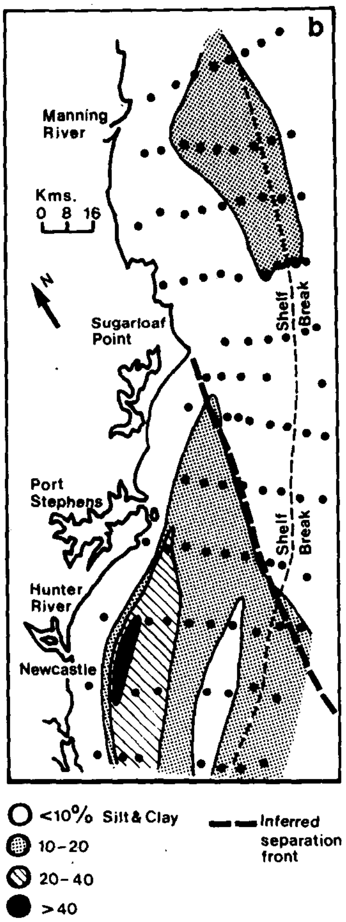

FIG. 7b. The percentage of silt and clay in sediments from the N.S.W. continental shelf, stippled areas, 10–20% silt and clay; shaded areas, 20–40%; darkened areas, >40%. The dashed lines in Figs. 7a and 7b show the inferred line of the East Australian Current.

lar to the western boundary flow in Bryan and Cox's (1968a, 1968b) numerical model (Godfrey, 1973a, 1973b); the model contained fluctuating anticyclonic eddies that were similar in length scale, vertical structure and in their pattern of poleward movement to those in the East Australian Current. In Bryan and Cox's model, separation of the average flow occurred a long distance poleward of where it was predicted from a linear model, due to the "inertial overshoot" phenomenon: one would expect the same phenomenon to carry the East Australian Current at least an eddy diameter (150 km) south of the latitude of Wanganella Bank (32°30′S), where linear Rossby wave theory predicts that the separation should occur. The second reason is that Sugarloaf Point does appear to define the separation point quite sharply a large part of the time, particularly in the bottom sediment data. It seems likely that, while westward propagation of Rossby waves from New Zealand may be important in determining the general locale of current separation, the exact location is determined by bottom topography—and in particular, by the bend in the coastline at Sugarloaf Point.

A further difference between the flow regimes on either side of the separation point is that, to the south of the separation, surface temperature is not a reliable guide to dynamic height (Hamon, 1965): anticyclonic eddies in this region are often no warmer at the surface than the areas outside the eddies. By contrast, north of the separation, experience indicates that strong currents are nearly always marked by surface temperature fronts. This difference is evidently important for interpreting satellite infrared photographs, such as those of Legeckis (1978).

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REFERENCES

Andrews, J. C., and P. Scully-Power, 1976: The structure of an East Australian Current anticyclonic eddy. *J. Phys. Oceanogr.*, **6**, 756–765.

Boland, F. M., 1979: A time series of expendable bathythermograph (XBT) sections across the East Australian Current. *Aust. J. Mar. Freshwater Res.*, **30**, 303–313.

——, and B. V. Hamon, 1970: The East Australian Current, 1965–1968. *Deep-Sea Res.*, **17**, 777–794.

Boyd, R., 1974: A marine geological investigation of the N.S.W. coast between Port Stephens and Norah Head. B.Sc. (Hons) thesis, University of Sydney, 115 pp.

Bryan, K., and M. D. Cox, 1968a: A nonlinear model of an ocean driven by wind and differential heating: Part I. Description of the three-dimensional velocity and density fields. *J. Meteor.*, **25**, 945–967.

——, and ——, 1968b: A nonlinear model of an ocean driven by wind and differential heating: Part II. An analysis of the heat, vorticity and energy balance. *J. Meteor.*, **25**, 968–978.

Brooks, D. A., and J. M. Bane, Jr., 1978: Gulf Stream deflection by a bottom feature off Charleston, South Carolina. *Science*, **201**, 1225–1226.

Cresswell, G. R., 1973: The French-Australian satellite-buoy experiment. *Aust. Meteor. Mag.*, **21**, 1–17.

——, 1974: Ocean current measured concurrently on and off the Sydney area continental shelf. *Aust. J. Mar. Freshwater Res.*, **25**, 427–428.

——, 1976: A drifting buoy tracked by satellite in the Tasman Sea. *Aust. J. Mar. Freshwater Res.*, **27**, 251–262.

——, and J. E. Wood, 1977: Satellite-tracked buoy data report II. Tasman Sea releases November 1976–July 1977. CSIRO Aust. Div. Fish. Oceanogr., Rep. 91.

Cresswell, G. R., and T. J. Golding, 1979: Satellite-tracked buoy data report III. Indian Ocean 1977. Tasman Sea July–December 1977. CSIRO Aust. Div. Fish. Oceanogr., Rep. 101.

CSIRO Aust., 1963: Oceanographical observations in the Pacific Ocean in 1960. H.M.A.S. *Gascoyne* cruise G3/60. CSIRO Aust. Oceanogr. Cruise, Rep. 6.

Curray, J. R., 1960: Sediments and history of holocene transgressions, continental shelf, N.W. Gulf of Mexico. *Recent Sediments, N.W. Gulf of Mexico,* F. P. Shepard, F. B. Pheger and T. J. H. Van Andel, Eds., Amer. Assoc. Petrol. Geol., 221–226.

Davies, P. J., 1979: Marine geology of the continental shelf off southeast Australia. *Aust. Bur. Min. Res. Geol. Geophys. Bull.*, **195**, 51 pp.

Delft Hydraulics Laboratory, 1970: Coastal erosion and related problems. Gold Coast, Queensland, Rep. 257.

Denham, R. N., and F. G. Crook, 1976: The Tasman Front. *N.Z. J. Mar. Freshwater Res.*, **10**, 15–30.

Faller, A. J., 1960: Further examples of stationary planetary flow patterns in bounded basins. *Tellus*, **12**, 159–171.

Godfrey, J. S., 1973a: On the dynamics of the western boundary current in Bryan and Cox's (1968) numerical model ocean. *Deep-Sea Res.*, **20**, 1043–1058.

——, 1973b: Comparison of the East Australian Current with the western boundary flow in Bryan and Cox's (1968) numerical model ocean. *Deep-Sea Res.*, **20**, 1059–1076.

Gordon, A., D. Lord, and M. Nolan, 1978: The Byron Bay-Hastings Point Erosion Study. N.S.W. Public Works Department, Rep. 78026.

Greig, M. A., 1974: The estimation of surface current from ship's set. CSIRO Aust. Div. Fish. Oceanogr., Rep. 54.

Hamon, B. V., 1961: Structure of the East Australian Current. CSIRO Aust. Div. Fish. Oceanogr., Tech. Pap. No. 11, 11 pp.

——, 1965: The East Australian Current, 1960–1964. *Deep-Sea Res.*, **12**, 899–921.

——, 1968: Temperature structure in the upper 250 metres in the East Australian Current area. *Aust. J. Mar. Freshwater Res.*, **19**, 91–99.

——, J. S. Godfrey and M. A. Greig, 1975: Relation between mean sea level, current and wind stress on the east coast of Australia. *Aust. J. Mar. Freshwater Res.*, **26**, 389–403.

Harris, T. F. W., R. Legeckis and D. Van Foreest, 1978: Satellite infra-red images in the Agulhas Current system. *Deep-Sea Res.*, **25**, 542–548.

Koninklijk Nederlands Meteorologisch Instituut, 1949: Sea Areas Around Australia: Oceanographic and Meteorological Data. K.N.M.I. Publ. 124.

Legeckis, R., 1978: A survey of worldwide sea surface temperature fronts detected by environmental satellites. *J. Geophys. Res.*, **83**, 4501–4521.

Lighthill, M. J., 1969: Dynamic response of the Indian Ocean to onset of the South-West Monsoon. *Phil. Trans. Roy. Soc. London*, **A265**, 45–92.

Metropolitan Water, Sewerage and Drainage Board, Sydney, 1976: Report on submarine outfall studies. 288 pp.

Meyers, G., 1975: Seasonal variation in transport of the Pacific North Equatorial Current relative to the wind field. *J. Phys. Oceanogr.*, **5**, 442–449.

Nilsson, C. S., J. C. Andrews and P. Scully-Power, 1977: Observations of eddy formation off east Australia. *J. Phys. Oceanogr.*, **7**, 659–669.

Pearce, A. F., E. H. Schumann and G. S. H. Lundie, 1978: Features of the shelf circulation off the Natal coast. *S. Afr. J. Sci.*, **74**, 328–331.

Shepherd, M. J., 1970: The geomorphology of the Myall Lakes region, New South Wales. Ph.D. thesis, University of Sydney, 344 pp.

Shirley, J., 1964: An investigation of the sediments on the continental shelf of New South Wales, Australia. *J. Geol. Soc. Aust.*, **2**, 331–341.

Stanley, D. J., and G. M. Wear, 1978: The "Mud Line": An erosion-deposition boundary on the upper continental slope. *Mar. Geol.*, **28**, M19–M29.

Stanton, B. R., 1976: An oceanic frontal jet near the Norfolk Ridge northwest of New Zealand. *Deep-Sea Res.*, **23**, 821–829.

Stommel, H., 1966: *The Gulf Stream, a Physical and Dynamical Description*. University of California Press, 248 pp.

——, and A. B. Aarons, 1960: On the abyssal circulation of the world ocean: I. Stationary planetary flow patterns on a sphere. *Deep-Sea Res.*, **6**, 140–154.

Teramoto, T., 1972: History of the Japanese observation program of the Kuroshio and adjacent regions. *Kuroshio, its Physical Aspects*. H. Stommel and K. Yoshida, Eds., University of Tokyo Press, 517 pp.

Warren, B. A., 1970: General circulation in the South Pacific. *Scientific Exploration of the South Pacific*, Warren S. Wooster, Ed., National Academy of Science, 33–49.

White, W. B., 1977: Anomalous forcing of baroclinic long waves in the tropical North Pacific Ocean. *J. Phys. Oceanogr.*, **7**, 50–61.

Wyrtki, K., 1962: Geopotential topographies and associated circulation in the Western South Pacific Ocean. *Aust. J. Mar. Freshwater Res.*, **13**, 89–105.

——, 1975: Fluctuations in the dynamic topography in the Pacific Ocean. *J. Phys. Oceanogr.*, **5**, 450–459.