Oceanic Circulation Patterns off the East Coast of Australia

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CSIRO DIVISION OF FISHERIES AND OCEANOGRAPHY

Information Circular

The Effect of Currents on Sea Level

The present study is being carried out by the Division with the assistance of many individual ships' officers and tide gauge attendants, and with the cooperation of a number of shipping companies. This account has been prepared for those participating in the work.

Cronulla, N.S.W.
July 1971

THE EFFECT OF CURRENTS ON SEA LEVEL

Scientists at the CSIRO Division of Fisheries and Oceanography are looking for evidence connecting variations in sea level along the east coast of Australia with the strong and variable currents in that area. The project should take two to three years to complete.

Sea Levels

Sea level measurements are obtained from tide gauge records. These records can be treated in a way that will average out the effects of the tides. The remaining changes in sea level are partly due to weather, atmospheric pressure, and to a lesser extent, wind. When these known sources of variation are allowed for, there are still changes in sea level of up to ten inches, which may last for weeks. It is believed that these remaining variations in sea level are related to variations in currents near the tide gauges. The variations are seldom large enough to attract comment or be economically important; however, in February 1969, tides in the Newcastle area were between 2 and 9 inches lower than predicted. This situation, which lasted for about three weeks, caused damage to oyster farms and interfered with ship loading operations. With the development of larger ships and the increasing number of supertankers of greater draft, entailing the dredging of deeper harbours, small variations in sea level will become more significant.

Currents from Ships' Deck Logs

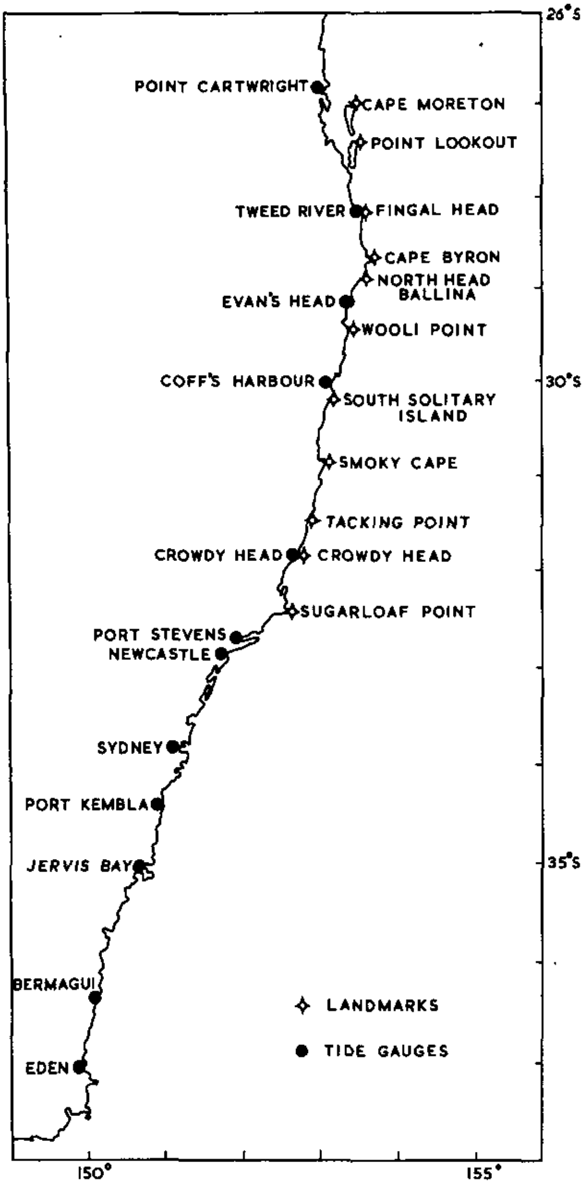
Tide gauges situated along the east coast (see Fig.) give continuous readings of sea level. These are relatively easy to obtain. It is much harder to assess the currents that may be affecting the sea level. It is especially difficult to get continuous records of current measurements over a long period of time. Currents reported by ships in their meteorological logs are averaged over a 24-hour period, and so these records are not detailed enough for this study.

The method of obtaining current data being used by the Division of Fisheries and Oceanography, is to extract from ships' deck logs the entries of fixes taken on specific coastal landmarks. The speed of the ship through the water, as recorded by towed or hull-mounted logs, is compared with the speed of the ship estimated from the fixes on the landmarks, the difference being the speed of the current. In this study, fixed sections with specified landmarks at either end are being used. The current velocities obtained in this manner are then compared with the sea levels of particular places.

For example, the mean of the sea level readings from all the selected stations on the coast is compared with the Coff's Harbour reading for the same time, and the difference noted. This difference in sea level is then compared with the estimated currents in the adjacent current section, in this case between Wooli Point and South Solitary Island.

The sections in which the currents are being measured lie between Moreton Bay and Sugarloaf Point (see Fig.). Similar current data for the region between Sugarloaf Point and Eden are less useful, as the ships' tracks are usually more to seaward, so few fixes are obtained.

Southbound passages usually give currents approximately on the 100 fathom line, however, some northbound ships stay much closer in to shore, so that information on the shoreward extensions of strong currents should be available.



The location of landmarks used in the study, and of tide gauges on the New South Wales coast.

Earlier Work on Currents

In an earlier study, currents from deck logs of A.N.L. and B.H.P. ships southbound from Brisbane were used. The main results, from one year of data, were:

> Strong southward currents near the 100 fm line at any given latitude tended to last for 10-15 days. After 30-40 days, there were sometimes weak currents or even

currents in the opposite direction (i.e. northward sets).

Strong currents at any given time extended only about 60 miles along the 100 fm line.

We could find no evidence of gradual drift of the current pattern in either direction - i.e., no evidence to support the idea that strong currents off one part of the coast would be likely to lead to strong currents further north or south, some days or weeks later.

The average current was about 1.5 knots to the south, and the range was between 1.3 knots to the north and about 4.8 knots to the south.

Other Information on Currents

Although ships' deck logs will be the main source of data on currents for this study, useful information can be obtained from other sources. Officers on Union Steamship Company's M.V.Maheno operating an expendable bathythermograph (XBT) for the Division on the passage towards Auckland every fortnight. This gives temperature in the upper 1500 feet of water, at stations about 35 miles apart. Average currents at right angles to the ship's track, can be computed from the measured temperatures. This will help to fill the gap in current observations south of Sugarloaf Point.

The Division has also been operating a recording current meter about five miles off Cronulla for the past year, and plans to extend this work to a station off Laurieton, at least for a few months.

This project started on 1st May, 1971. Its success will depend on the cooperation of ship owners and ships' officers, and the owners and operators of several tide gauges in N.S.W. and Queensland.

We would like to thank those whom we have already approached and who have so readily agreed to cooperate with us. The Division would be grateful for any additional information on currents that fishermen or yachtsmen might care to send in to us in the next two years. Even qualitative information ("strong" or "weak", with approximate direction and position) could be useful.

For further information, contact R.H. Austin, CSIRO, Box 21, Cronulla 2230 (phone 523-6222).

The East Australian Current

By B. V. HAMON and D. J. TRANTER
Research Scientists with the Division of Fisheries and Oceanography, CSIRO, Cronulla, New South Wales

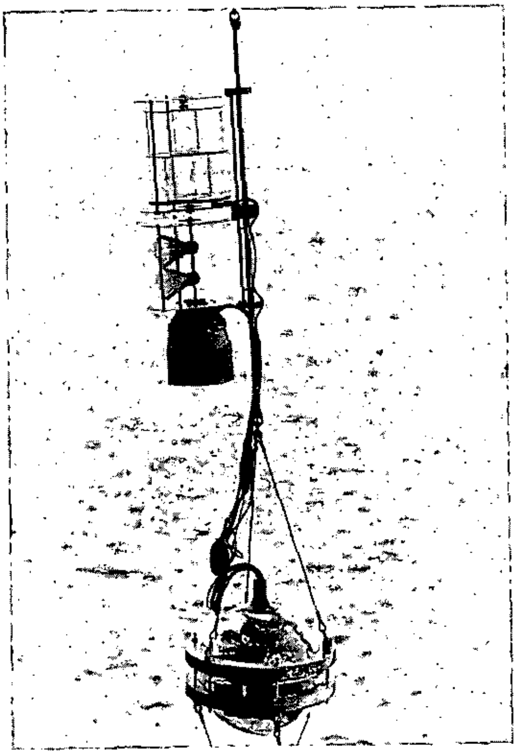
IN many and various ways the East Australian Current influences the entire southeastern seaboard of the Australian continent. We suspect that it determines the productivity of our fisheries and the nature of our climate. There seems little doubt that the tropical flora and fauna found in isolated pockets along the coast of New South Wales are maintained by this warm current from the north. The coral reefs of Lord Howe Island, 31½° S. latitude, are located much further south than other Pacific coral reefs, and it is thought that their continued existence depends on the current and its associated countercurrents and eddy systems.

Unlike the Gulf Stream of the north Atlantic and the Kuroshio Current of the north Pacific, the East Australian Current dissipates on leaving the coast. The pattern of this dissipation is constantly changing, and it is believed that the variations in the current system may play an important role in determining the variations in the rainfall in southeast Australia, the area where the greater part of the population is concentrated.

For these reasons the Division of Fisheries and Oceanography of CSIRO has carried out special studies on this oceanic system, a system whose complexity constitutes a challenge to Australian oceanography. These studies will be extended when oceanographic research ship facilities are provided.

Origin of the current

The East Australian Current is born in the region between the Great Barrier Reef and the Chesterfield Reefs of the Coral Sea. It is here that waters pile up under the influence of the trade winds and are constrained to flow southward by the land barriers of New Guinea and Australia. The current draws its water from the easterly Trade Drift for the greater part of the year. Between January and March, however, equatorial waters driven by the monsoon winds move southward around the northeast coast of New Guinea, enter the source area, and are caught up with the current. The stream narrows to the north of Fraser Island, and there draws further water from the lagoon of the Great Barrier Reef. Full velocity is reached in the area off Cape Byron; thence the current flows along the edge of the continental shelf, veering out to sea somewhere between Sydney and Eden.



A current meter used by the CSIRO in studies of the East Australian Current. [Photo: CSIRO, Cronulla.]

Early knowledge about the current came from mariners. They found a southerly "set" near the edge of the continental shelf (100-fathoms line), from off Rockhampton to off Sydney. The current was first charted from ships' logs accumulated for over a century, with the result shown in fig. 1.

But this is only an average picture. The detail, at any one time, is much more complex and interesting. Navigators have known for years that the current is variable; this is specially noticeable on southbound passages between Brisbane and Sydney, where frequent fixes against landmarks lead to a more detailed picture of current structure than can be found when navigating out of sight of land. Ships coming south, near the 100-fathoms line, are often in the curren for 100 miles or so, then suddenly they ar out of it. Many captains use wate temperature as an indicator; if th temperature drops suddenly, they assum they have lost the current, and may alte course away from the coast to pick it u again.

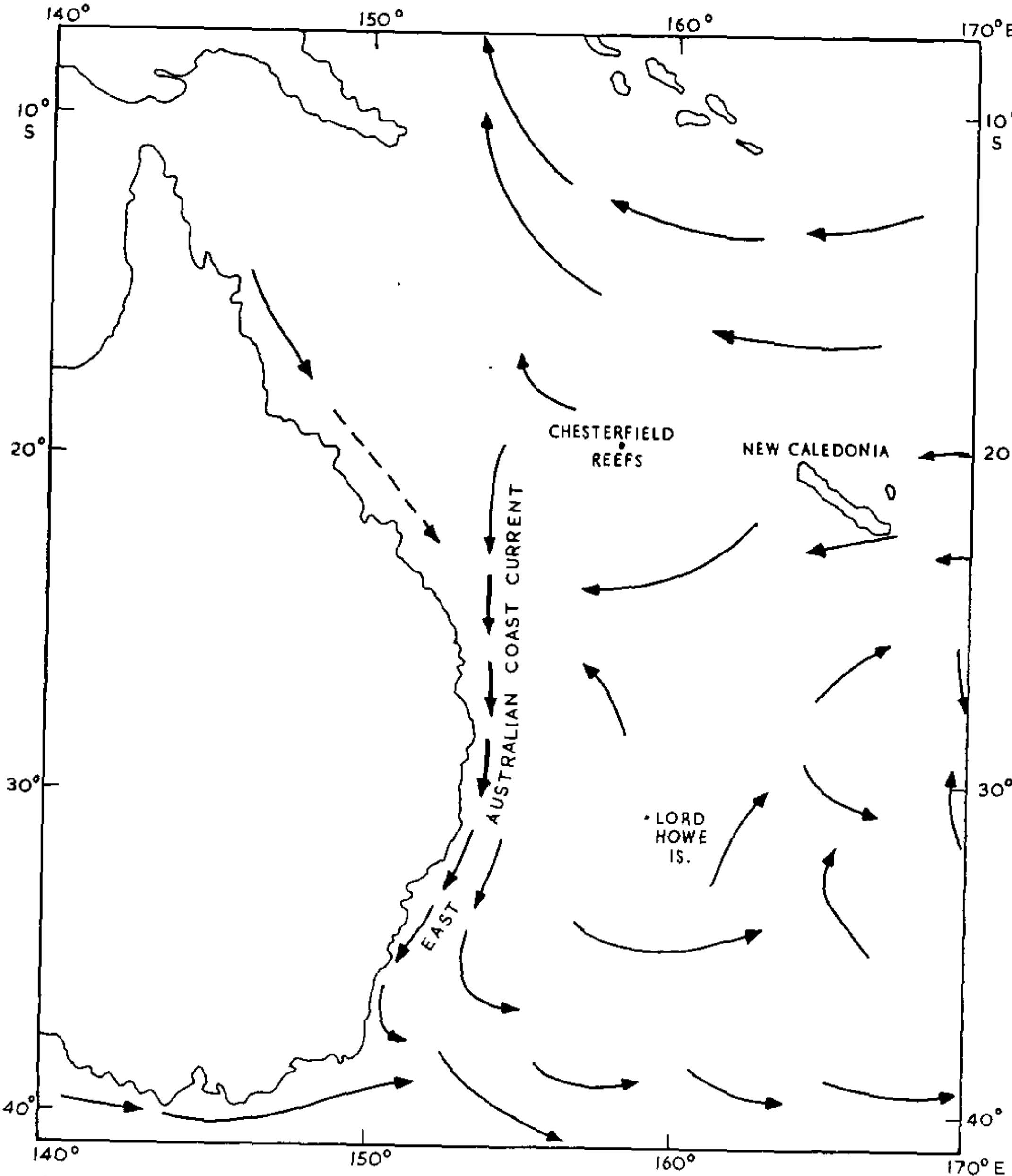


Fig. 1.—Surface circulation in the Coral and Tasman Seas, December–February, adapted from *Australia Pilot*, Vol. III (British Admiralty, 1960).

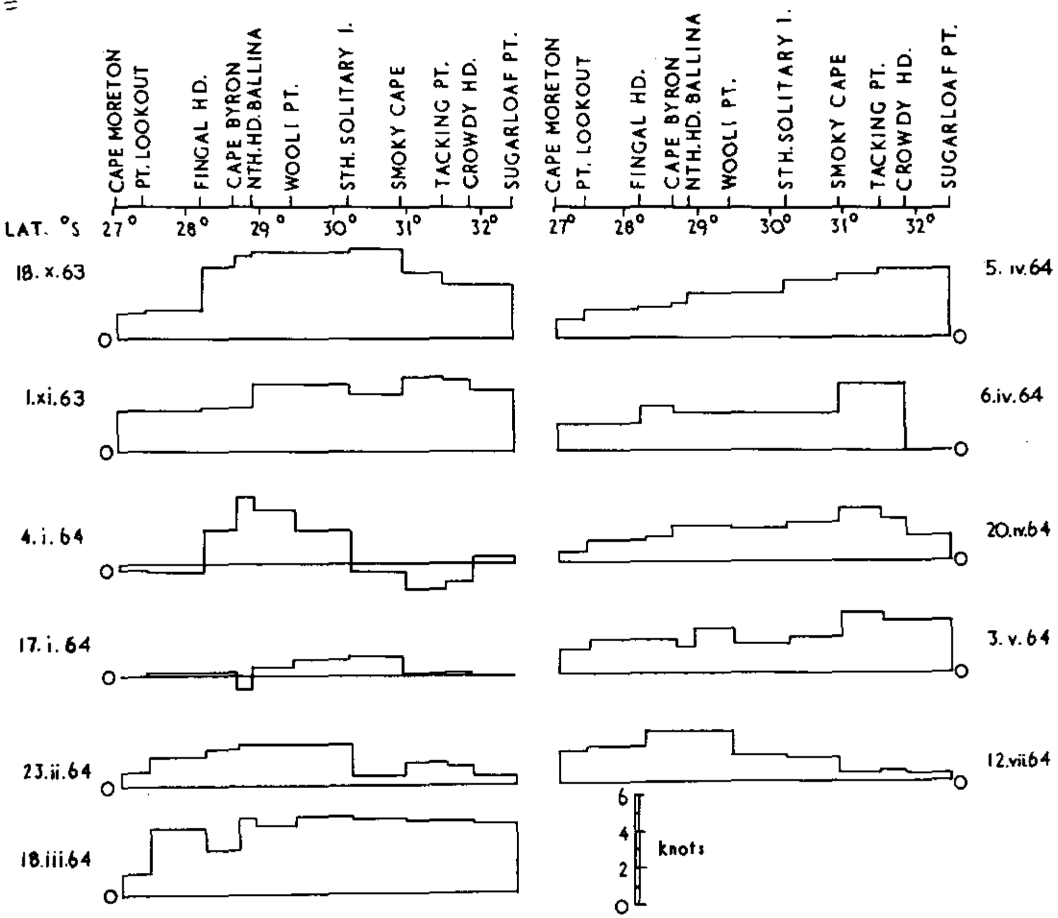


Fig. 2.—Currents near the 100-fathom line, between Cape Moreton and Sugarloaf Point, for 11 southward passages in 1963–64. Currents above zero line flow south, those below zero line flow north. [Diagram by the author.]

CSIRO recently collected ships' navigation logs for a year, to look at the current in more detail. Fig. 2 shows the currents between fixes from Cape Moreton (Brisbane) to Sugarloaf Point (near Port Stephens) for a number of passages down the 100-fathoms line; note how seldom the current looks anything like a steady stream over this distance.

The Division of Fisheries and Oceanography of CSIRO commenced its investigations in the East Australian Current area in 1954, working from a schooner, the Fisheries Research Vessel *Derwent Hunter*. This continued until 1959. Since 1960 the Division has been looking at the current in more detail, using H.M.A.S. *Gascoyne*, a frigate made available for oceanographic work by the Royal Australian Navy. This work led to our first coherent picture of the current away from the coast.

Assessing ocean surface height

On *Gascoyne*, we usually steamed a grid pattern, and measured temperature and salt concentration (salinity) down to 5,000 feet at stations 50 miles apart. Water density was worked out from temperature and salinity. We were then able to work out the height of the sea surface, since the average density is found to vary from station to station. "Light" (less dense) water stands higher than more dense water, just as kerosene stands higher in one limb of a U-tube if there is water in the other. The height differences found this way are up to about 2 feet. Knowing the heights at a grid of stations, we can draw contours of equal height, like isobars on a weather map. Fig. 3 shows an example.

What do these surface-height maps tell us? They have much more than a superficial resemblance to weather maps. Just as winds blow parallel to isobars on a weather map, we find that currents flow parallel to the contour lines in fig. 3. The arrows give the direction. Currents are stronger where the lines are close together. A few current strengths have been entered on the figure.

Eddies and countercurrents

Fig. 3, and a dozen or more similar charts from ten years' work on *Gascoyne*, show some surprising things. First, there is always a strong current to the north, if one goes far enough offshore. We have been calling this the "countercurrent". Second, there are often strong anti-clockwise eddies, about 150 miles in diameter. The near-shore edges of these must often be confused with the East Australian Current, and their eastward parts with the countercurrent—in fact, it is not clear if we should keep trying to attach separate meanings to the three terms "current", "countercurrent", and "eddy". It often appears to us that the so-called East Australian Current is really made up of a number of large anti-clockwise eddies. Third, the "shape" of the current at any time is often very complex (note the curious loops in fig. 3).

Transport of water by current system

There is good evidence that the current system brings water from the Coral Sea down along the east coast. In view of the countercurrents and eddies, how does this water get carried down, and at what rate? We are by no means sure of answers to these questions. At present we think the transport is by the bodily drift of complete eddies. We have some evidence that they move south, and even a little evidence about their speed—about 50 miles per month. But attempts so far to show that the water in an eddy is different from the water outside have failed. There is nothing to prevent an interchange of water between eddy and surrounding ocean.

Surface speeds go up to about 4 knots. Half the surface speed is found at 800–1,000 feet depth, and the current is still measurable at 5,000 feet.

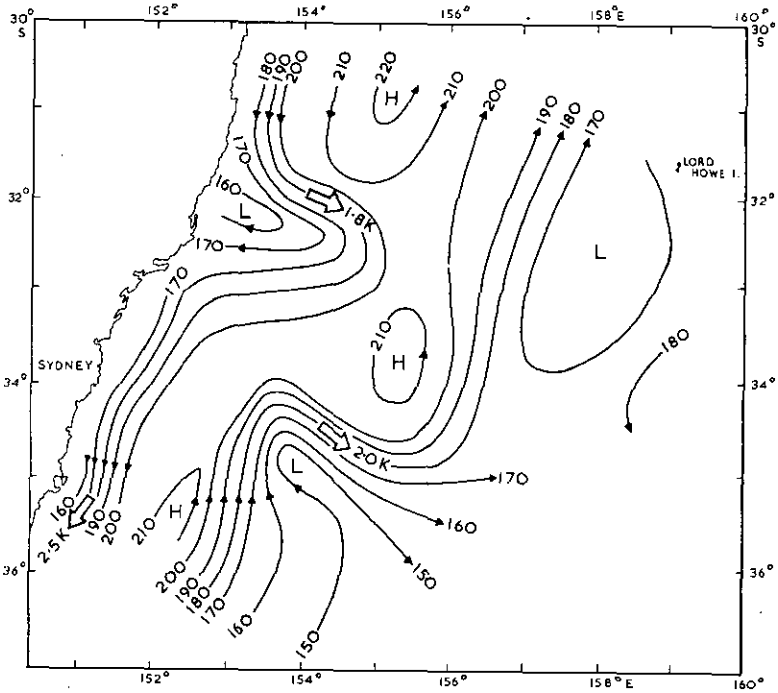


Fig. 3.—Contours of height of the sea surface, at 10-centimetre intervals, as worked out from water density. Height numbers are referred to an arbitrary zero. Some surface currents (in knots) estimated from the contour spacing are shown by the broad arrows. H, high sea-level; L, low sea-level. [Diagram by the author.]

The total flow of water around an eddy is about half that of the Gulf Stream. (It could fill Lake Eucumbene, New South Wales, in two minutes!) But the net southward transport would be much less than this, and has not yet been estimated.

Blooms of plankton

We have known for more than 30 years that there are blooms of plankton on the continental shelf of New South Wales in the spring of nearly every year. Spring blooms are well known in other regions of the world, but here they have a quite different origin. They appear, in some way that we do not yet fully comprehend, to be related to the East Australian Current. So far as we can determine, periodic changes in the velocity of the current and in its proximity to the coast allow cold deep water from the continental slope to penetrate the waters of the shelf. The mineral nutrients that these slope waters carry enrich the sunlit waters of the shelf and become available for the use of planktonic algae. Algal blooms are the inevitable result. These upwellings are better developed in some areas than in others. They are usually confined to the inner 10 miles of the shelf.

The details of this annual enrichment are not yet understood. Many questions remain unanswered. Which particular nutrient triggers off these algal blooms? Is it nitrate or is it silicate? Nitrate is sometimes used to exhaustion, but individual pulses of nitrate-rich water are not well-correlated with individual plankton blooms. Silicate levels fall very low during the spring, but remain both low and steady even though phytoplankton blooms come and go.

As Professor Dakin observed many years ago: "It is a difficult region, for we are probably sampling in a slow stream . . .". Maybe the algal blooms and swarms of zooplankton that we observe each spring off Sydney are the downstream consequence of upwellings further north. Maybe our coastal waters should be regarded as a river that changes speed, course, and direction in response to forces that we have yet to determine.

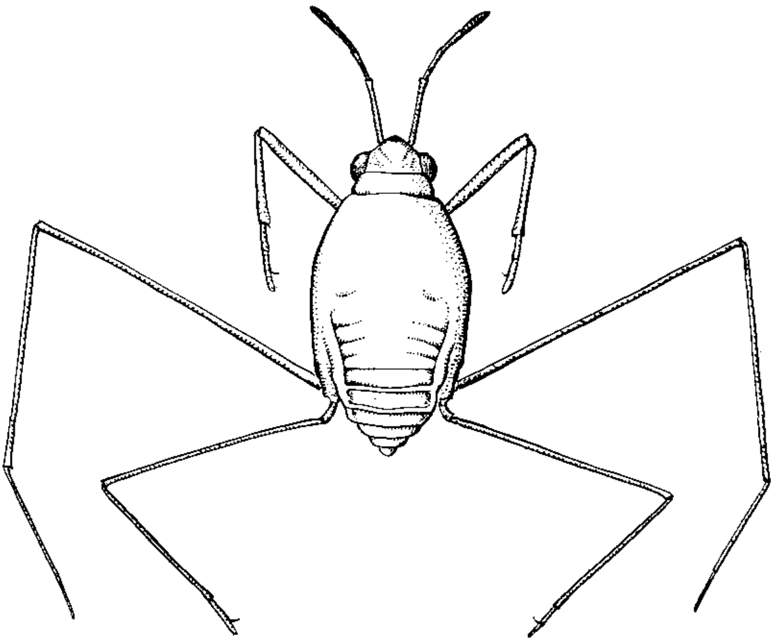
A strong upwelling is known to take place each year at Laurieton, near Port Macquarie, New South Wales. From August to October of this year (1971) the Laurieton upwelling was continually under observation. Moored current meters (see photo) recorded speed and direction of the current. At the same time a programme was carried out using ships which happened to be in the area. Commercial ships plying between Sydney and Brisbane noted changes in speed and track due to the prevailing current. Concurrent observations were made downstream of the upwelling in the area off Cronulla, near Sydney, to see whether the same body of water passed by, and, if so, what changes took place in the plankton community in the intervening period. We are trying to determine, in effect, whether the algal blooms and swarms of salps that characterize the Sydney area are the downstream consequence of upstream enrichment.

These are the sort of questions we are seeking to answer. In such a complex system as the East Australian Current there are sure to be many surprises.

FURTHER READING

Highley, E. (1967): "Oceanic Circulation Patterns off the East Coast of Australia". (CSIRO Division of Fisheries and Oceanography, Technical Paper, 23).

Wright, M. A. (1970): "Cook and the East Coast Current", in *Australian Fisheries*, 29, pp. 33–36.



The water-strider Halobates hayanus, from the Low Isles. [Drawing by S. R. Curtis.]

AUSTRALIAN MARINE INSECTS

By ELIZABETH N. MARKS
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THE saltwater coastal environment grades from estuaries and salt marshes through mangrove swamps and sandy beaches, rocky shores and coral reefs, to the open sea. We might class as *marine insects* those that spend all or most of their life-cycle in the intertidal zone or beyond it. However, when considering marine insects in relation to seas around Australia, one's mind turns to the rocky shores and coral reefs, pounded by violent waves, or to wide expanses rich in animal and plant life exposed at the lowest tides, and it is mainly with the insects of these habitats that I will deal.

On Australia's rocky shores insects of the orders Hemiptera, Coleoptera, Diptera, and Trichoptera occur, as well as the primitive hexapods Collembola (springtails), mites, and a spider; all but Trichoptera are recorded also from coral reefs.

I should like to trace with you my own introduction to marine insects, because this is how any observant naturalist might encounter them if he or she sets out deliberately to look for them.

In August 1954 Dr M. J. Mackerras and I were members of a scientific party organized by the Great Barrier Reef Committee, which spent 2 weeks on Low Isles, 9 miles northeast of Port Douglas. These are two small sandy islands near either end of a horseshoe-shaped reef opening to the northwest, where, in 1928, a scientific expedition led by Dr C. M. Yonge spent a year in intensive study of corals and the ecology of the reef. They recorded a marine spider, *Desis crosslandi*, but no marine insects. Marine biologists do not look for insects in marine habitats, and entomologists rarely seek them there.

We went to Low Isles armed with some literature, so that we knew a little of the types of insects we should look for and were usually able to identify them to family and sometimes to genus. We later identified the Diptera ourselves and obtained expert

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OCEANIC CIRCULATION PATTERNS OFF THE EAST COAST OF AUSTRALIA

By E. HIGHLEY*

[*Manuscript received December* 22, 1966]

Summary

Surface current atlases depict the East Australian Current as a north–south current between about Rockhampton and Bass Strait. Such atlases are based on ships' observations of currents on the sea surface. Data collected during oceanographical cruises off the east coast of Australia, and during coastal hydrological studies, have shown that the East Australian Current is one part only of a complex system of oceanic circulation. Information available on the characteristics of this system is reviewed.

I. INTRODUCTION

The East Australian Current is an important physical feature of the Australian environment, oceanic circulation off the east coast of Australia being dominated by a system, the main component of which is the East Australian Current. Information at present available about the flow characteristics of the East Australian Current comes from two main sources: observations made by ships' navigators, and more detailed data collected on oceanographical cruises. Such data have made it clear that the East Australian Current is not so much a single current as a component of a complex and variable current system. The factors responsible for formation of the system and variations in its flow characteristics at different times of the year are only partly known. The influence of prevailing winds is important, but it seems likely at present that other factors must also be important determinants of circulation in the area.

The aims here are to review briefly what is already known about circulation in the area and the methods used in acquisition of this knowledge, to note the various forms that future work might take, and to discuss the importance of a knowledge of circulation in the area to our general understanding of the Australian environment.

II. SURFACE CURRENT ATLASES

Ships' observations on currents off the east coast of Australia have been amalgamated into surface current atlases (British Admiralty 1960; Wyrtki 1960). These atlases depict the East Australian Current as a strong, narrow current flowing south, close to the edge of the continental shelf, between 27° and 37° S. (Rockhampton and Bass Strait).

Navigators are interested in currents only in so far as they are liable to affect a ship's course. Because of this specificity of interest, ships' observations are given in terms of an average effect of currents on a ship's course during a day's run. A ship might cross a number of different currents during its run, but the navigator's current

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assessment is always given as a net course deviation in one direction. Because of this method of assessment, surface current atlases tend to give only the general features of currents in an area, and the ships' observations from which they are compiled usually fail to bring to light any anomalies in current flow, or interesting specific features of a current pattern, that might from time to time exist. However, navigators of vessels plying coastal waters of eastern Australia are aware that currents in the area can be more complex than surface current atlases indicate.

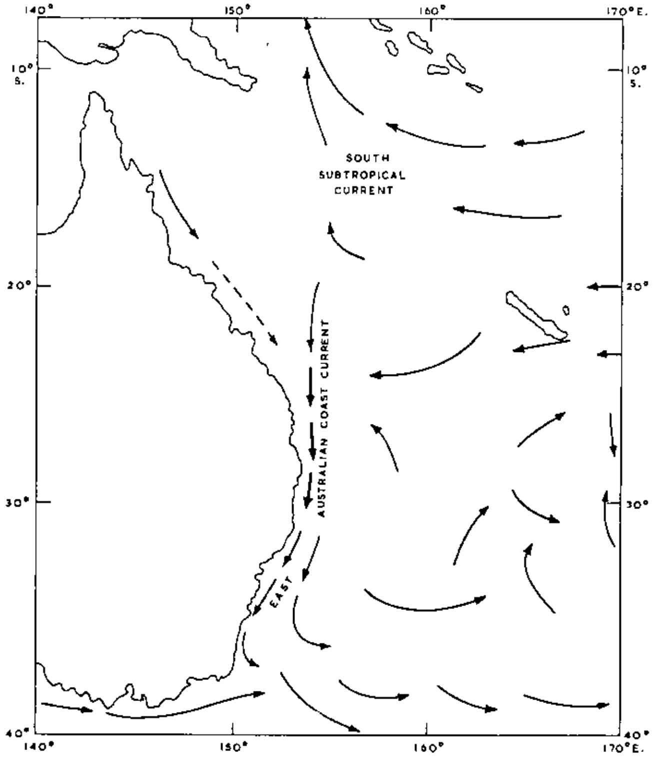

Fig. 1.—Surface circulation in the Coral and Tasman Seas, December–February, from "Australia Pilot", Vol. III (British Admiralty 1960).

The "Australia Pilot" (British Admiralty 1960) notes (Vol. III, p. 7)

> 'The flow of the East Australian Coast Current, which is mainly between south-east and south-west is not a very constant one; it is liable to interruption throughout the year by sets in other directions, notably reverse sets in a northerly direction. There is also considerable seasonal variation both in southerly and northerly flows. Between latitudes 26° S. and 34° S. the southerly currents are strongest from December to March, while during the southern winter, June to August, not only are the southerly currents weaker but the northerly ones reach their greatest strength and increase in frequency. This is due to the prevalence of south-easterly and southerly winds at this season. As the majority of northerly currents, however, do not reach or much exceed one knot, the net flow is still to the southward from June to August.'

Some hint is given here of the variability of currents in the area. The Australia Pilot's assessment is again based on ships' observations. The method of assessment is alluded to in the above quotation, which notes that even though there might be a number of strong northerly currents the net flow is still to the south. It should be noted that the northerly currents mentioned flow *between* the East Australian Current and the coast, i.e. on the continental shelf, and should not be confused with the "countercurrent" to be mentioned later.

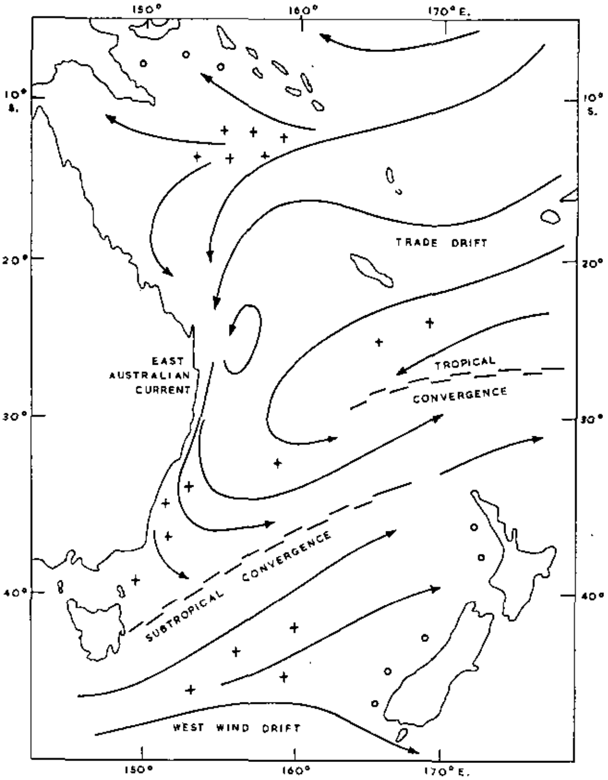

Fig. 2.—Surface circulation in the south-west Pacific (after Wyrtki 1960).
+ areas of divergence; ○ areas of convergence.

In general, the Australia Pilot describes the East Australian Current as occupying a belt from about 20 to 50 or 60 miles from the coast, its greatest strength being found near the 200 m line, this occurring near the edge of the continental shelf. Figure 1 shows, according to the Australia Pilot, the generalized current pattern in the south-west Pacific, for the December–February period. The East Australian Current is depicted as a southerly current turning away from the coast south of Sydney and flowing eastwards across the Tasman Sea in a diffuse manner.

Wyrtki (1960) analysed the surface current data for the south-west Pacific Ocean amassed by the United States Navy Hydrographic Office and the Royal Dutch Meteorological Office. Current vectors for 1° squares for each month were derived from ships' observations made over a number of years. From these vectors surface current atlases were plotted, the vectors being based upon a frequency factor and a strength factor for currents encountered within each particular square. Wyrtki (1960, p. 2), in noting the utility of his methods of interpretation of these data, said

> 'The representation of the surface currents of this region is not limited to the drawing of charts of the average current arrows for every month, but an analysis of the circulation is given in streamline charts. These streamline charts provide material for investigating the convergences and divergences of the water masses in the upper layer.'

In general, an area of convergence is where two streams of water from different sources come together. However, there is seldom complete confluence, and a transition zone at a convergence usually separates the two streams. The transition zone is formed by limited mixing of waters of different physical and chemical properties. Thus, the subtropical convergence (Fig. 2) is a region of interaction between waters from the north and colder sub-Antarctic waters. Conversely, divergence occurs when a stream is separated into a number of smaller streams flowing in different directions. Figure 2, which is a generalization of plotted streamlines for every month of the year, shows the East Australian Current as turning eastward south of Sydney and flowing along the northern side of the subtropical convergence over a wide area of the southern Pacific Ocean. Here Wyrtki has drawn in the likely effects of the interactions of the various water masses present in the region.

In his discussion Wyrtki (1960, p. 31) notes of the East Australian Current

> 'Along the east coast of Australia a comparatively strong but narrow current flows to the south. Its transports are estimated to vary between 10 and 25×10^6 m^3/sec. The current is an effect of the piling up of water in the Coral Sea by the trade winds, and it is forced by the configuration of the coast to flow southwards . . . . The East Australian Current has often been compared with the Gulf Stream and Kuroshio. However, it lacks the most important of the main features of these two large northern hemisphere systems; namely, it does not, like these, form a huge current system which extends eastwards over the whole ocean but disappears rapidly when departing from the coast.'

It is this last point in Wyrtki's discussion that has been the subject of most recent work on the East Australian Current. The dynamics of termination of the East Australian Current is the important question here. The large volume of water brought down by the Current must be dissipated or leave the area by some means or other. It is on this point, more than any other, that surface current atlases fail to give an adequate representation of circulation in the area.

III. OCEANOGRAPHICAL CRUISES

Oceanographical cruises off the east coast of Australia commenced in 1954, and data collected on these have made the greatest contribution to our present level of understanding of the dynamics of the East Australian Current. Of necessity, the methods used by the oceanographer in estimating current strengths and directions differ from those of the navigator. Whereas a navigator measures current characteristics more or less directly by their effects on his ship's course, data collected on oceanographical cruises allow current patterns in the area covered to be calculated and comprehensively plotted by indirect means. Data collected on oceanographical cruises apply solely to oceanic circulation, i.e. to water movements outside the continental shelf line. The oceanographer seeks to obtain an overall picture of oceanic circulation patterns. Moreover, currents at the surface might be only a small part of a circulating system, the movements of deeper waters playing an important role.

The method most commonly used by oceanographers collecting data about the East Australian Current, and by oceanographers in general, over the last 50 years or so is called the "dynamic" method. Current meters measuring currents directly are rarely used, owing to the fact that their results are liable to reflect small-scale phenomena, such as movements of the survey vessel, or small-scale transient currents, such as might result from local winds. The dynamic method allows currents in an area to be plotted on the basis of density differences existing from place to place in the waters of that area. In practice the method relies on much the same factors as those that allow the plotting of geostrophic winds from atmospheric pressure differences. Density differences make for differences in sea level from place to place, and, in the southern hemisphere, currents flow in an anticlockwise direction around areas of high sea level in the same way as winds blow anticlockwise around areas of high barometric pressure. The converse, of course, applies to areas of low sea level. In the application of the dynamic method density is not measured directly. Instead, it is computed from measurements of temperature and salinity, this allowing more precise density estimations. For operational purposes at least, temperature and salinity are the only variables that need to be taken into account in computing density. (In the dynamic method variations in density due to pressure differences cancel out.) Equipment at present in use allows temperature estimations accurate to within ±0·02 degC and salinity estimations accurate to within ±0·003 parts per thousand (see Hamon 1962*a*). In practice these orders of accuracy are necessary owing to the small density differences that are dealt with.

In collecting data for the application of the dynamic method the research vessel works a grid of stations in the area to be covered. Station spacing varies between 30 and 150 miles, dependent on either the suspected complexity of currents or the degree of detail sought. At each station, temperature and salinity are measured at about 20 predetermined depths from the surface down to 1000 m or more. (The method requires the selection of an arbitrary reference depth at which zero current is assumed. This level is usually between 1000 and 2000 m.) When densities for the various sampling depths have been computed from temperature–salinity observations, the average current between any pair of stations can be calculated, for intermediate depths as well as at the surface.

The great advantage of the dynamic method is that it averages over appreciable distances, thus eliminating distractions by small-scale phenomena. A three-dimensional picture of currents in the area covered is obtained.

Between 1954 and 1959, F.R.V. *Derwent Hunter* made several cruises in oceanic waters within about 500 miles of the east coast of Australia, between latitudes 30° and 37° S., and collected data suitable for measuring currents by the

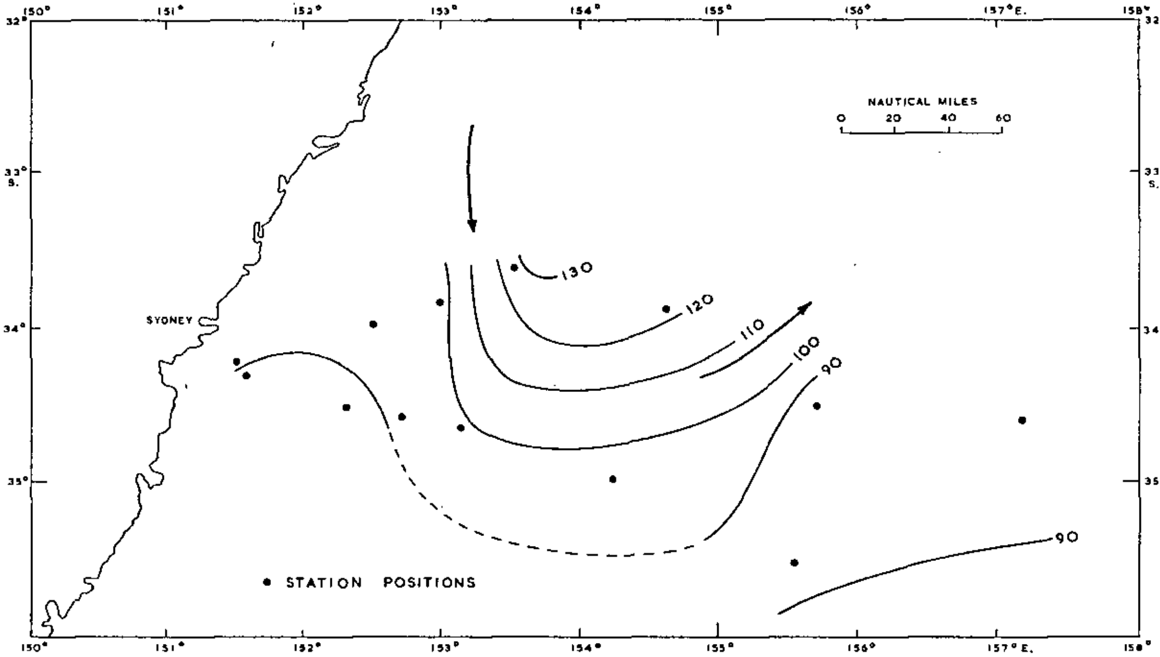

Fig. 3.—Surface circulation off Sydney, N.S.W., September 1957 (after Hamon 1961).

dynamic method. As a result of these cruises some important features of the East Australian Current were brought to light. Hamon (1961, p. 6), reporting on these data, noted

> 'The two main features of the surface circulation . . . are as follows:
>
> (1) A southerly or south-easterly current usually just beyond the edge of the continental shelf. In accordance with established usage this will be referred to as the "East Australian Current". . . . The current is usually within about 60 miles of the edge of the shelf but on two occasions was between 80 and 110 miles from the edge. On these occasions, there appeared to be a weak northward current between the East Australian Current and the edge of the shelf.
>
> (2) A northerly or north-easterly current, here called the "countercurrent", whose axis is from 70 to 200 miles east of the axis of the East Australian Current. Perhaps the most interesting result of this study is the demonstration of the magnitude and persistence of this countercurrent.'

The results of these cruises indicated that the East Australian Current is effective down to a depth of about 1500 m, currents at 250 m being about half those at the surface. The maximum volume transport noted occurred in December 1958, this being 35×10^6 m^3/sec. Values greater than 20×10^6 m^3/sec were found only between December and April, when the East Australian Current is known to be best developed due to the influx of tropical and subtropical waters from the north under the influence of the trade winds. The meaning of these volume transport values is appreciated when one considers that the estimated volume transport of the Mississippi River is $0{\cdot}06 \times 10^6$ m^3/sec. At certain times the East Australian Current is carrying at least 500 times as much water as the Mississippi River.

The results of the *Derwent Hunter* cruises suggest also that the East Australian Current, and the countercurrent noted above, are continuous and form a U-shaped current system. Water entering the area from the north is diverted east, then north to north-east, and leaves the area by the countercurrent. Figure 3 shows the East Australian Current and countercurrent off Sydney in September 1957. The arrows give direction of current flow. The lines are contours of equal sea-surface height, with contour values given in centimetres. A large change in sea-surface height over a short distance means that a strong current is flowing. Off Sydney a height change of 46 cm in 60 nautical miles represents an average surface current between stations of 1 kt.

Wyrtki (1960) suggested that the countercurrent is formed by strong southerly winds. However, Hamon (1961, p. 10), discussing the *Derwent Hunter* cruises, stated

> 'The evidence from the present study is that the countercurrent appears too frequently, and is too closely linked with the East Australian Current itself, to be due to local winds. . . . the main reason why the countercurrent appears so rarely in the current atlases is its narrowness and variability in position, and the fact that there are no regular north–south shipping routes through the region in which it occurs.'

Wyrtki (1962) discussed data collected off the east coast of Australia on three cruises by H.M.A.S. *Gascoyne* in 1960 and 1961 and by the Japanese research vessel *Umitaka Maru* on a cruise in 1959. Figure 4 (Wyrtki 1962, p. 90) shows surface circulation in the south-west Pacific area for the period January–April calculated by the dynamic method from data collected on these cruises. The East Australian Current and a well-developed countercurrent can be seen, the countercurrent flowing across the Tasman Sea, north of New Zealand. In discussing the dynamics of this system Wyrtki (1962, p. 96) said

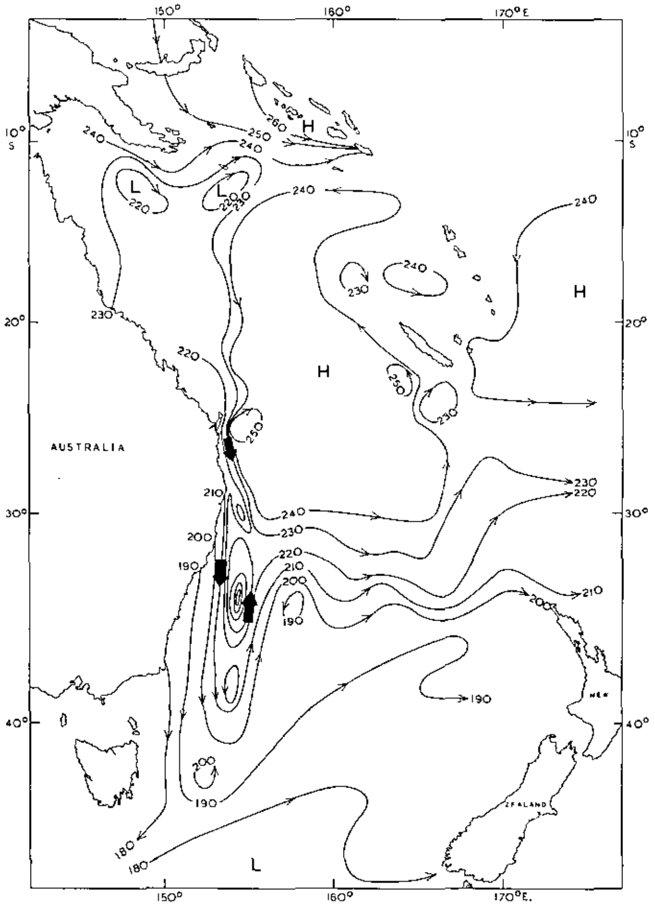

Fig. 4.—Surface circulation in the south-west Pacific, January–April (after Wyrtki 1962).

> 'The circulation pattern is governed by a high in the subtropical region. Along the west side of this high the East Australian Current flows south. Between 30° and 35° S. this current turns east, crosses the Tasman Sea, and leaves the area to the north of New Zealand. In the process of this turning large eddies are separated which probably drift south along the Australian coast.'

Hamon (1962*b*, p. 23), in discussing factors responsible for the formation of the East Australian Current, agreed in general with Wyrtki's earlier interpretation

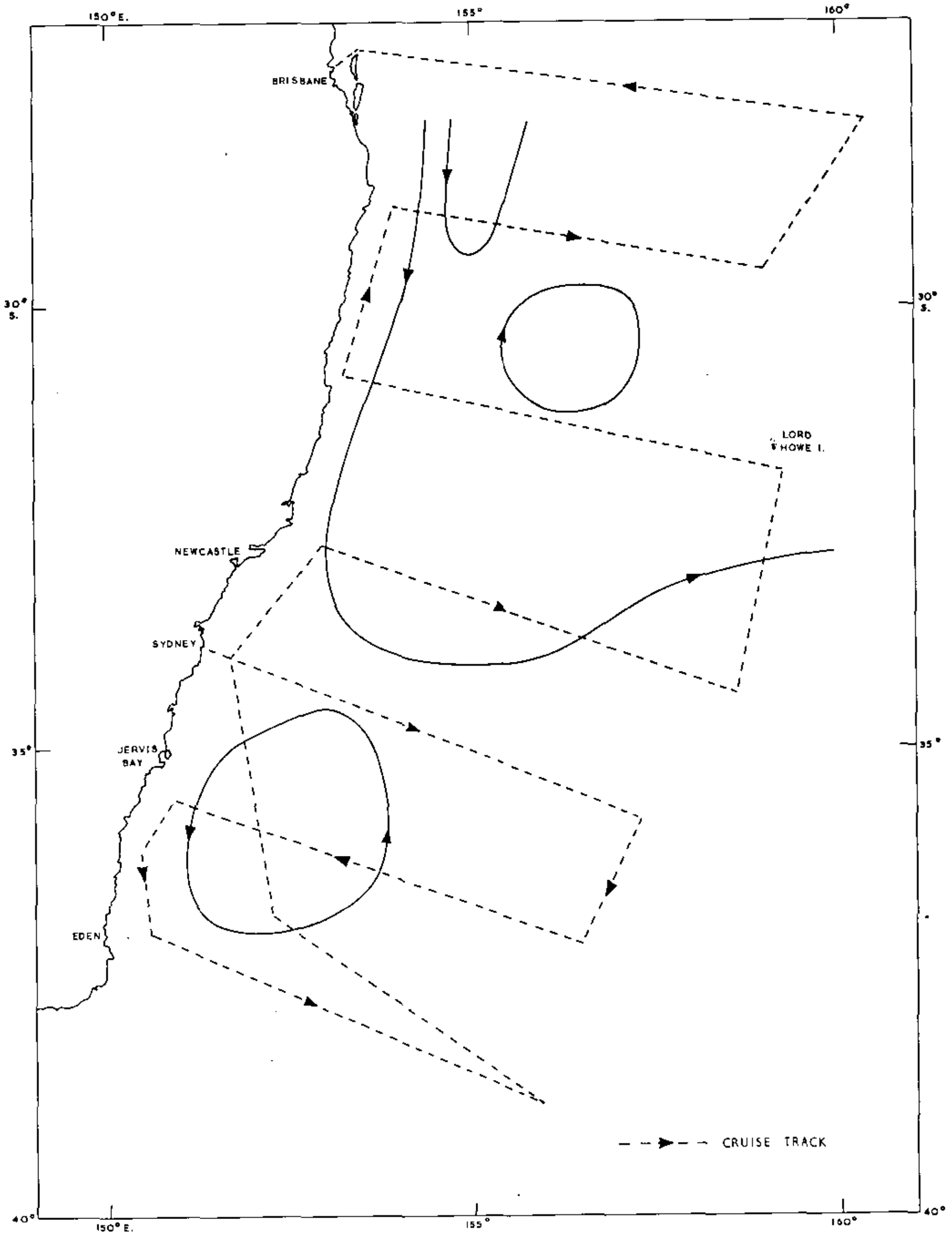

Fig. 5.—Main features of surface circulation in the Tasman Sea, November 1960 (from Hamon 1962*b*).

(1960). He noted, however, that the confirmation of the existence of the countercurrent necessitates some reframing of previous ideas.

> 'It (the East Australian Current) is probably a result of water being driven into the Coral Sea by the south-east trade winds, and escaping to the south. But this cannot be taken as a full explanation, since it does not account for the countercurrent . . . . The current atlases foster the idea that the East Australian Current brings a large quantity of warm water down from the Coral Sea, and 'discharges' this in the area off Sydney much as a flooded river discharges its muddy waters to be mixed with the salt water. This idea seems to be quite wrong, since the countercurrent takes the water out of the area again.'

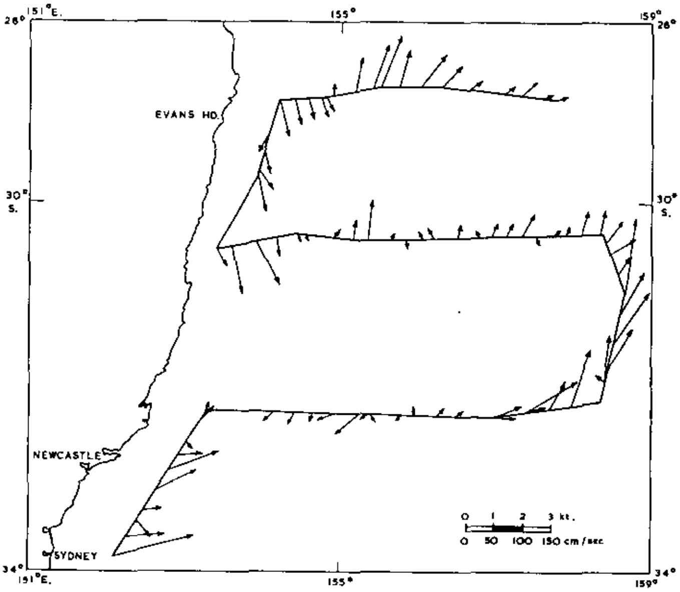

Fig. 6.—GEK surface currents in the Tasman Sea, August 1964 (after Hamon 1965).

The discovery of the countercurrent was an important step forward in the study of the East Australian Current. It was now possible to start working towards a reconciliation of the conflict between observed southward volume transports and the fate of this transported water at the southern extremity of the Current.

Figure 5 shows general features of the East Australian Current system in November 1960, as determined by the dynamic method from observations made on a cruise of H.M.A.S. *Gascoyne*. The Current turns east when about abreast of Sydney to form the countercurrent, which then flows across the Tasman Sea to the south of Lord Howe Island. In the process of turning, a large eddy has been broken off and is drifting down the east coast of Australia. The fate of such eddies is not completely clear at present, but water originally in the East Australian Current has been located as far south as Tasmania, and it seems probable that eddy systems are responsible for the transport of such water to this area.

Hamon (1965) analysed the data pertaining to the East Australian Current that had been collected on eight oceanographical cruises off the east coast of Australia between 1960 and 1964. In general, this analysis confirmed, and elaborated on, earlier results in so far as it shows again the complexity of currents in the area and the way in which flow characteristics of these markedly change from time to time during the year. On these cruises the dynamic method of estimating currents was supplemented by the towed electrode method (GEK) for measuring currents at the surface. To do this two electrodes, set about 100 m apart, are towed by electric cables behind the ship. When the ship (and electrodes) is set at right angles to its course, voltages are induced in the cable as it cuts the vertical component of the earth's magnetic field. If the towing vessel follows a zig-zag course a fairly complete picture of surface currents in the area covered is obtained. Figure 6 shows the GEK analysis of currents encountered during a cruise of H.M.A.S. *Gascoyne* in August 1964. The continuous line is the ship's track. Lengths of GEK vectors indicate current strengths. Figure 7 is the surface current representation by the dynamic method for the same cruise. The general agreement in current representation between the two methods can be seen. Between 155° E. and the coast southerly currents predominate, whereas east of 155° E. currents are mainly northerly. The westward swing of the countercurrent at about 30° S. (Fig. 7) suggests that it might

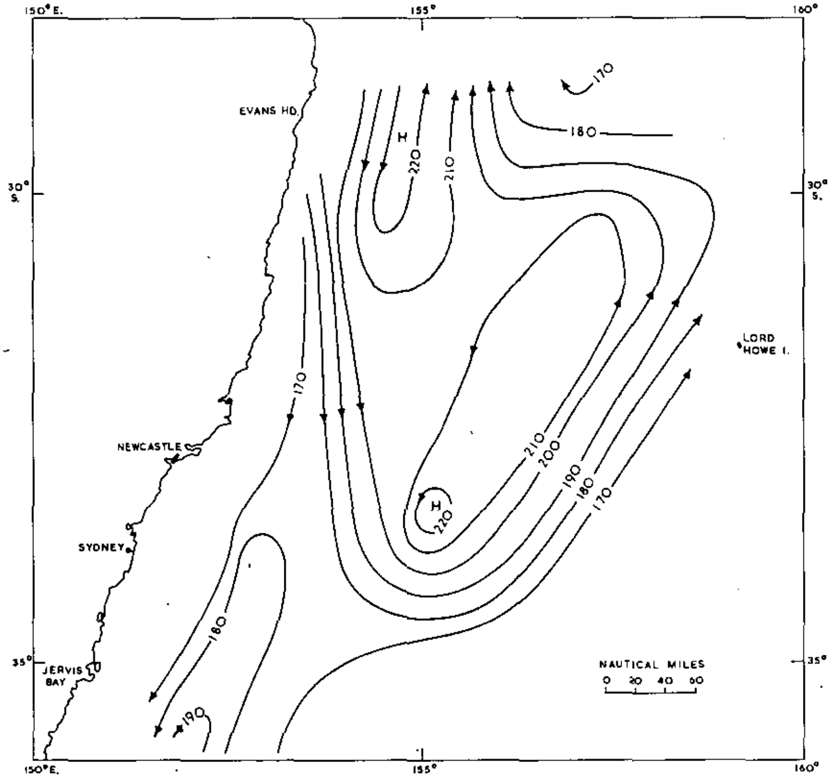

Fig. 7.—Dynamic surface currents in the Tasman Sea, August 1964 (after Hamon 1965).

be part of a closed eddy system, but the data are insufficient to confirm this. An interesting feature of the results of this particular cruise is the fact that north of 30° S. the countercurrent flows much closer to the coast than was previously encountered.

Figure 8 (Sept. 1964) gives a clear picture of the East Australian Current, and its swing, east of Sydney, to form the countercurrent. The data presented here elaborate on Figure 3. The contour values are markedly different between Figures 3 and 8 because different arbitrary reference depths for zero current were assumed.

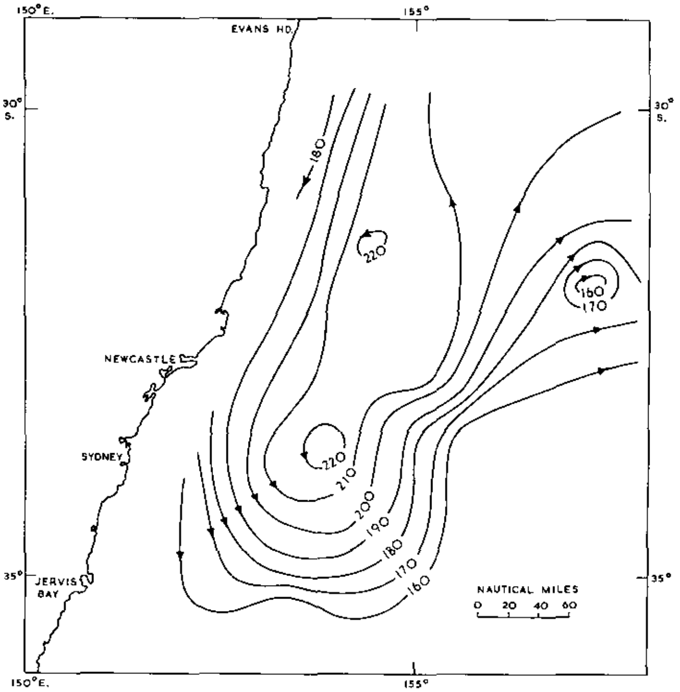

Fig. 8.—Dynamic surface currents in the Tasman Sea, September 1964 (after Hamon 1965).

The complex and variable circulation in the area studied on the 1960 to 1964 cruises is emphasized in Figure 9. This shows the East Australian Current leaving the coast at about 33° S. and flowing east or north-east in the form of the countercurrent. Eddies are shown forming at about 34° S., and these then appear to drift southwards along the coast. Hamon (1965, p. 921), in summing up the data from these cruises, noted

> 'If the East Australian Current is considered as the western boundary current for the whole South Pacific Ocean, its volume transport would be expected to be larger than that of the Gulf Stream, roughly in proportion to the areas of the two oceans, since the wind stresses appear to be comparable. Actually, the transport in the East Australian Current is not more than half that of the Gulf Stream. The discrepancy may be due to the circumpolar current, which must absorb some of the energy imparted by winds over the southern part of the Pacific Ocean, and thereby reduce the tendency to set up a large gyre in the South Pacific.'

IV. Coastal Studies

Although the East Australian Current flows outside the continental shelf, changes in its flow characteristics are reflected in changes occurring in the composition of shelf water. Because of this it seems evident, at present, that a wedding of oceanic and coastal data can provide useful information on variations in the flow characteristics of the East Australian Current.

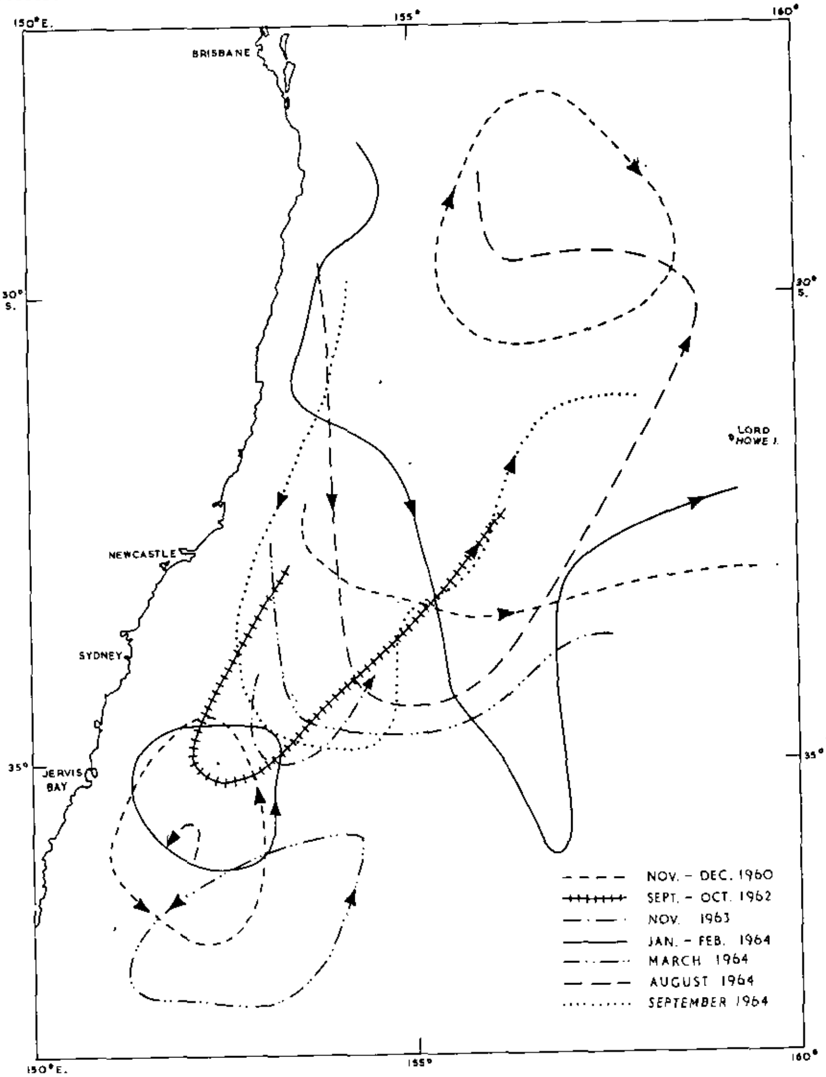

Fig. 9.—Variations in the pattern of surface circulation in the Tasman Sea, November 1960 to September 1964 (after Hamon 1965).

Newell (1966), working on coastal systems, analysed 10 years' data collected at the Port Hacking 100 m station located 7 miles off the coast near Sydney. He concluded that the characteristics of the marine environment off Sydney were determined basically by the East Australian Current. For example, in May the properties of shelf water are determined by high salinity water from the western

Pacific carried into coastal waters by the East Australian Current. Talking about the East Australian Current in general, Newell notes that surface velocities are maximal in February, the average net drift southwards at this time being 20 miles per day. Currents off Port Hacking are not uniform, in either magnitude or direction. Complex gyrals and countercurrents are present throughout the year.

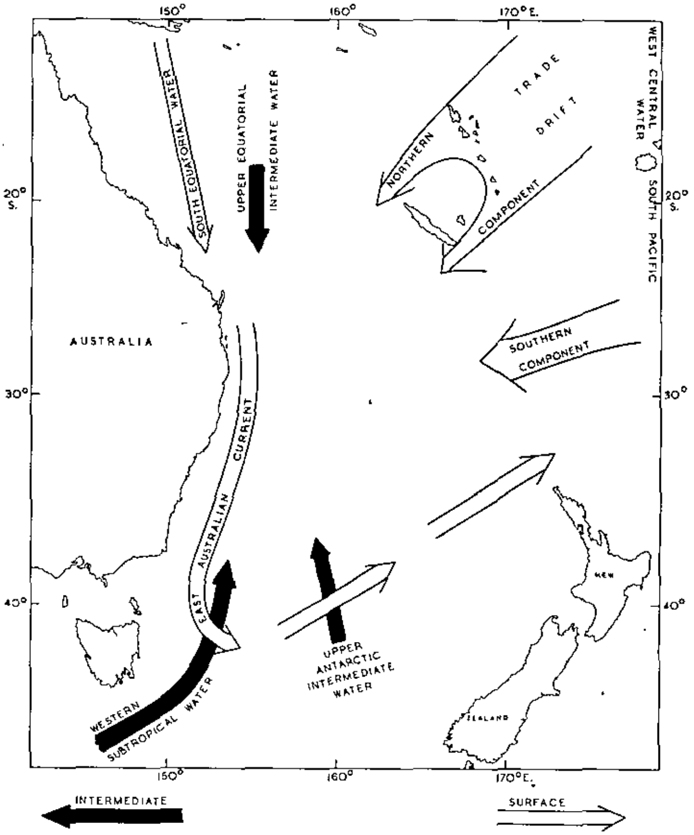

Fig. 10.—Components of surface (0–300 m) and intermediate (300–700 m) depth circulation in the Coral and Tasman Seas (from Newell 1966).

Figure 10 gives Newell's general scheme of the water masses influencing Australian coastal waters. In the light of work discussed earlier it seems that the East Australian Current, as a discrete entity, is extended too far south. However, owing to eddy formation, it seems clear that water from the Current can influence areas as far south as 45°.

Rochford (unpublished data) notes that one of the major problems in coastal hydrology is that of identifying, with some degree of confidence, features that owe their origin to shoreward movement of oceanic waters. An analysis of data collected over a number of years enabled him to identify two separate oceanic intrusions into waters on the continental shelf off Port Hacking and into New South Wales coastal waters in general. On the basis of oxygen–salinity structure these oceanic intrusions were traced to their origin, a region of poorly oxygenated subsurface (300 m) waters in the Coral Sea north-east of Brisbane. These waters were carried south by the East Australian Current and, by mixing with lower salinity coastal waters, formed identifiable oxygen minima in New South Wales coastal waters.

The above studies of Newell and of Rochford illustrate another means of tracking water movements, that is, on the basis of differing chemical and physical characteristics. More generally, these studies again show the importance of the role of the East Australian Current in determining circulation off the east coast of Australia.

V. CONCLUSIONS

Oceanographical data amassed on the East Australian Current have shown that the Current is a much more complex phenomenon than the older surface current atlases would have. It has become clear that we are dealing more with a current system than a single current, but, because characteristics of the system are liable to vary markedly over short time periods, more work is needed to formulate its precise dynamics.

Future work could take a number of forms—a continuation of oceanographical cruises in the area, the use of fixed buoys to record temperature and/or other features continuously, and the use of temperature–depth measuring devices dropped from the air and transmitting their measurements by radio or other means to the survey aircraft. Each of these methods of gathering information has its own particular merits. Oceanographical cruises allow the collection of more detailed data than the other methods but take a relatively long time to cover the required area of study. It might not be possible on cruises to assess the significance of short-term variations. Fixed buoys are useful in that they can provide a continuous record of changes occurring. Probably their greatest disadvantage is the expense that might be incurred in their maintenance; they are liable to be damaged, or even lost, in heavy weather. The aerial method is probably the most ambitious, but, as far as the East Australian Current is concerned, with its rapidly changing flow pattern, this method could provide information unavailable by other means. It is already known that a marked temperature gradient often occurs at the edges of the Current. An aircraft, dropping bathythermographs (temperature–depth sensors), could adequately cover a large area in a short time period and locate rapid changes in direction of current flow. An airborne infrared thermometer is already being used to measure sea-surface temperatures in connection with the tuna fishing industry. However, it is unlikely that this device could be of much use in studying the dynamics of the East Australian Current, as surface temperature alone is not a reliable indicator of the Current's position.

The location and formation of eddies is a problem most amenable to attack by the airborne method, and the mechanics of eddy formation is probably the most difficult of the questions about the East Australian Current still to be answered.

Increased knowledge of the dynamics of the East Australian Current is important for a number of reasons. It is important in the navigation of east Australian waters; however, future scientific work will probably have little bearing in this field since contact with the Current by navigators is usually limited to coastal vessels. The importance of water movements in the area to the tuna fishing industry is a relatively new field of study. Variations in flow of the East Australian Current at different times of the year make for changes in the physical and chemical characteristics of waters off the New South Wales coast. It seems probable at present that the Current may play a significant role in creating conditions favourable to schooling behaviour in tuna off the south coast of New South Wales. In this region catchable schools of tuna have been encountered only when surface temperatures lie between 62 and 68°F (16–20°C). The occurrence of water in this temperature range is largely dependent on southward transport of warmer waters by the East Australian Current.

Associated with these factors is the zooplankton abundance of the area. Zooplankton is an important link in the food chain that is terminated by the tunas. East Australian waters, in common with other subtropical waters, have a low zooplankton abundance due to the prevalence of a more or less permanent thermocline, which prevents the influx to surface layers of deeper nutrient-rich water. Tranter (1962, p. 123) notes

> 'In the words of King and Demond (1953) "one is inclined to speculate as to how the pelagic fish populations, particularly the relatively large population of tunas, are supported".'

Further work on the East Australian Current system, together with seasonal studies of zooplankton abundance and distribution off the New South Wales coast, in particular the south coast, might clear up much of the speculation about tuna behaviour in the area. In the subtropical convergence (Fig. 2) there is some interplay of differing water masses, and these might significantly affect the behaviour of the fauna of the area. Similarly, the eddies breaking off the main stream of the East Australian Current might make for nutrient upwelling and subsequent plankton blooms. A recent survey for southern bluefin tuna in Tasmanian waters failed to locate fishable schools even when surface temperatures indicated favourable conditions. The conclusion to be drawn is that factors other than surface temperature are involved.

It has become apparent that patterns of oceanic circulation off the east coast, and in particular the East Australian Current, play an important part in the meteorology of the mainland. Priestley (1964, p. 15) notes

> 'There are definite correlations between monthly anomalies in rainfall and sea surface temperatures in inshore waters along the coast of New South Wales . . . . Stronger and more definite relations could, it is argued, be established if adequate temperature data a hundred or so miles to sea were available . . . . The need for such investigations in the Australian region is apparent, even though the relative shortage of data subtracts from the expectation of immediate dividends.'

Priestley analysed sea-surface temperature data collected by CSIRO between 1942 and 1962 and monthly rainfall data for adjacent coastal regions. It should be noted that the temperature data applied to waters within the continental shelf line. Long-term sea temperature studies could elucidate further the relationship between sea-surface temperature and rainfall on the mainland. The transport of warmer tropical waters into southern areas by the East Australian Current probably yields a greater net evaporation from the sea surface than would otherwise be the case.

The East Australian Current then, and its associated system, is an important physical feature of the Australian environment. As such it is worthy of increased attention, and a complete understanding of its dynamics could bring benefits in many fields of Australian endeavour.

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