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Alan Pearce

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A BRIEF INTRODUCTION TO DESCRIPTIVE PHYSICAL OCEANOGRAPHY

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INTRODUCTION

This report was originally prepared as an introductory lecture in descriptive physical oceanography for a group of Asian technicians at an IOC-sponsored course held in Townsville in June 1980. Because the students had had little background in oceanography, and because of language difficulties, the presentation was kept as simple as possible, with many illustrations. The explanations and diagrams have been simplified to illustrate concepts, and it is hoped that the simplification is not misleading.

The topics have been selected to cover a wide range of physical oceanographic features – the choice has been subjective, and the coverage of the topics is not uniform. To illustrate the desired principles, examples from the South Pacific Ocean, the Tasman Sea, the East Australian Current system, and the New South Wales continental shelf, have been chosen where possible. Greater emphasis has been placed on studies on the continental shelf rather than on the deep ocean.

A reading list and glossary are appended for reference. The subject material has been taken (or adapted) from many sources, and individual references are not named to avoid disrupting the text – I gratefully acknowledge all sources used.

OCEAN BASINS AND THE SEABED

1. *The Oceans*

Water covers about 71% of the earth's surface, and the five main divisions of this water body are the Pacific Ocean (by far the largest), Atlantic Ocean, Indian Ocean, Southern (or Antarctic) Ocean, and the Arctic Ocean. Linked with, or forming part of, these main oceans are smaller seas, which are usually defined by submarine ridges, island areas, or local basins; the Tasman Sea off East Australia is a typical example (Figure 1).

The average depth of the sea is about 3800m, compared with the 250m average height of the land, but this is still small compared with the radius of the earth or the width of the main oceans. Using Pickard's analogy, "the relative dimensions of the Pacific Ocean.. are much the same as a sheet of.. paper". This is true even on the regional scale: the average depth of the continental shelf is say 100m and a typical width might be 50 km, so the ratio of depth to width is only 1/500.

For this reason, pictures of the temperature (for example) between the sea surface and the seabed must be drawn on a distorted scale, where the water depth is greatly exaggerated. It is important to remember this when studying temperature or salinity sections where the slopes of the seabed or of isotherms are drawn very much greater than they really are.

All maps in this report have been drawn on a mercator projection, which is probably the most widely used for general purposes. It has the important property that a direct course between any two points is a straight line on the chart.

2. *Shape of the Seabed*

The main divisions of the seabed and their names are shown in Figure 2.

The continental shelf is the relatively shallow platform around the continents. While in different areas of the world it varies greatly in terms of its depth, width and shape, in general it is some tens of kilometres wide and the shelf-break (which is the region where the seabed suddenly slopes more steeply into the deeper oceanic basin) is typically 100 to 200m deep. The average slope of the seabed on the continental shelf is very small, about 1 in 500 (or 7 minutes of arc). The continental shelf is economically very important, as most fisheries are concentrated on the shelf, oil may be found there, minerals can be mined, etc. The Australian continental shelf has an area of about 2,600,000 km^2.

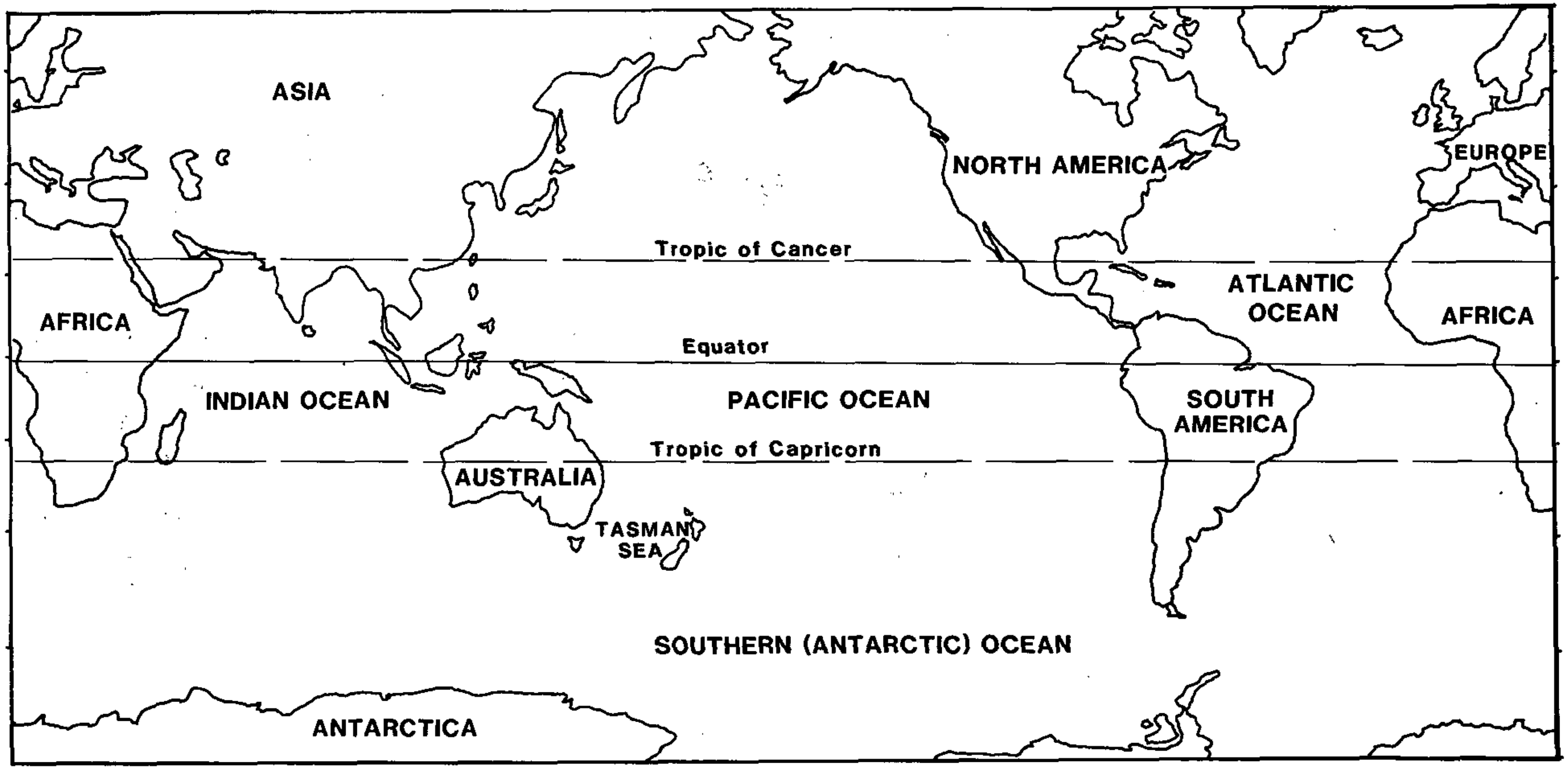


Fig. 1. The world's oceans and continents.

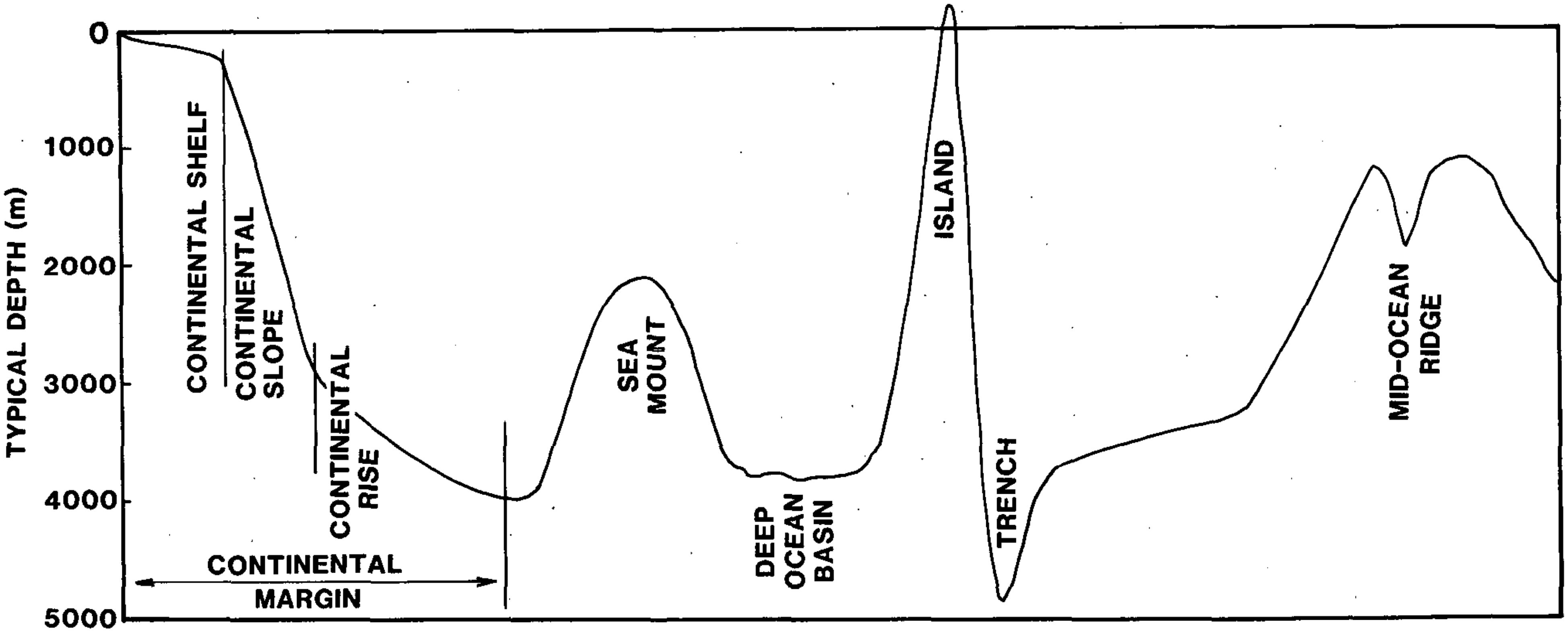


Fig. 2. Typical seabed features shown diagrammatically.

Beyond the shelf-break lie the continental slope, which has an average gradient of about 4°, or 1 in 14, and the continental rise, which has a gentler gradient. These two zones (the continental slope and rise) link the shallow shelf with the deep ocean bed. The shelf, rise and slope form the continental margin. In certain areas, the continental slope is cut by submarine canyons running down the slope (such as on the NSW south coast), and these may carry slumps of sediment down to the deeper basins.

In the deep ocean are found other features such as seamounts (which may rise to the surface to form islands) and the deep trenches. In the middle of the oceans, particularly the Atlantic and Indian Oceans, lies the mid-ocean ridge, a major submarine mountain chain extending for thousands of miles.

A simplified map of the bottom topography of the Tasman Sea is shown in Figure 3, together with a vertical section showing the main features between Coffs Harbour and the northern tip of New Zealand — note the exaggerated vertical scale. The continental margin on the east coast of Australia is narrow and very steep. The greatest depth in the Tasman Sea is about 4500m, and Lord Howe Island rises from such depths to the surface.

3. *Effect on Currents*

It is important to know the shape of the seabed because topographic features can have a large effect on the currents. It has been found that currents near the coast tend to flow along the isobaths, and that strong currents can occur near the shelf-break. Therefore sudden changes in the seabed can lead to the meandering of currents or the formation of eddies. Near submarine canyons, the currents may flow into or out of the canyon.

LARGE-SCALE PROCESSES

1. *Atmospheric Pressure and Wind*

On the global scale, the major oceanic surface circulations are largely driven by the permanent wind systems, which in turn are related to the large-scale pressure belts around the world. The ultimate source of energy for the earth (and therefore for the winds and currents) is the sun, which heats the equatorial regions more than the poles and sets up the atmospheric pressure distribution. As a result of the earth's rotation, the surface wind does not blow simply from the poles to the equator, but is deflected to flow more east-west, and the actual pressure distribution is as shown diagrammatically in Figure 4. There are belts of low pressure at the equator (where the warm air rises) and at about 60° latitude, and high pressure bands around 30° and near the poles. The presence of the continents alters this simple pattern to some extent, but the main ocean basins on each side of the equator have high pressure regions centred between roughly 20° and 40° latitude. The northern hemisphere is more affected by the land masses than is the southern hemisphere, and the reversing wind system (monsoon) in the northern Indian Ocean is well known.

Resulting from this basic atmospheric pressure field, the semi-permanent wind systems are as illustrated diagrammatically in Figure 5. The air tends to flow from the high pressure centres to the low pressure regions, but because of the "Coriolis effect" (i.e. the deflection of moving bodies of air or water caused by the rotation of the earth — a deflection to the left in the southern hemisphere and to the right north of the equator) the wind curves and in fact flows almost along the isobars. Thus the NE and SE trade

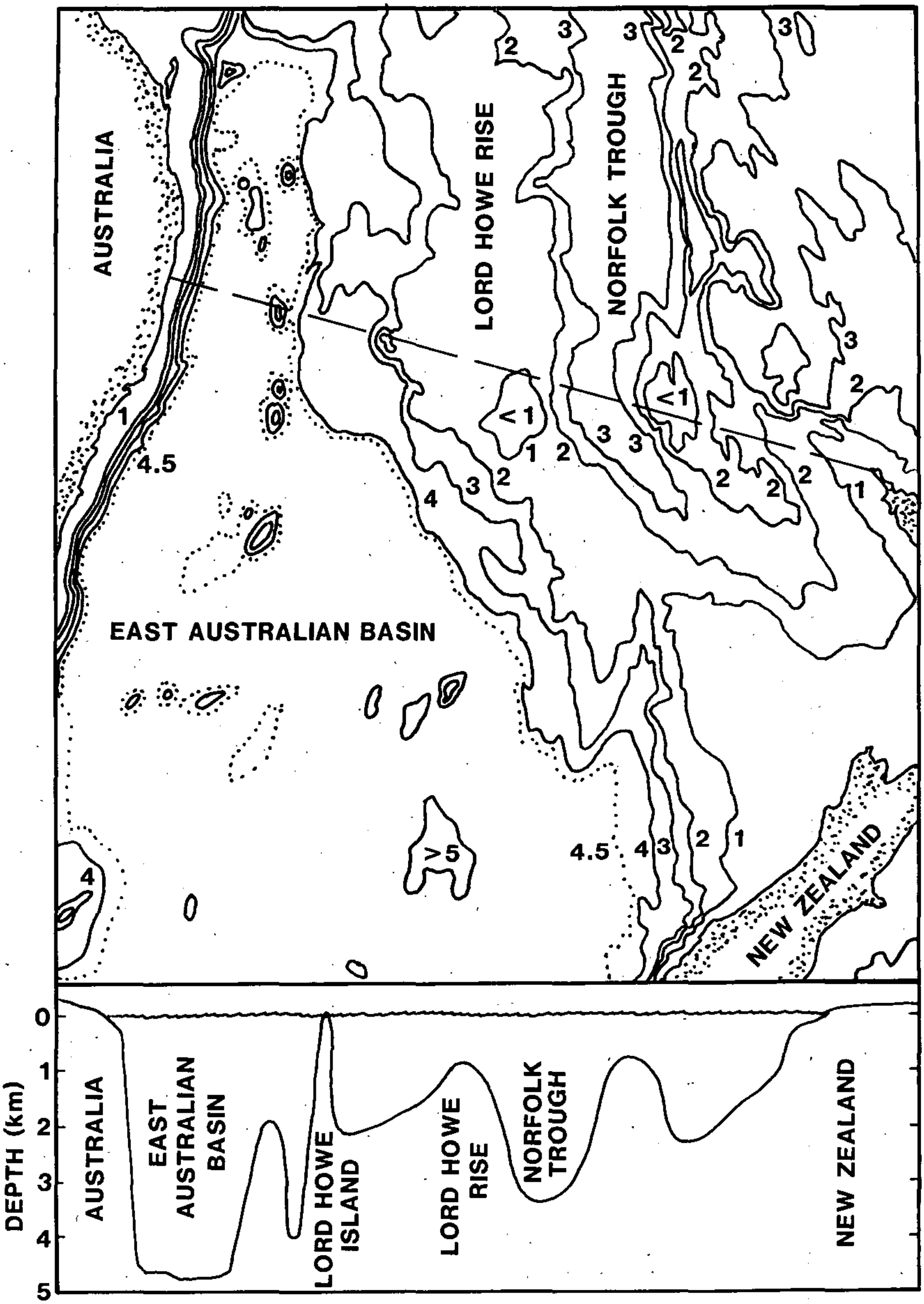


Fig. 3. Bathymetry of the Tasman Sea; contours are in kilometres (1000 m), and the dotted contour is 4.5 km. The lower diagram is a vertical section along the dashed line.

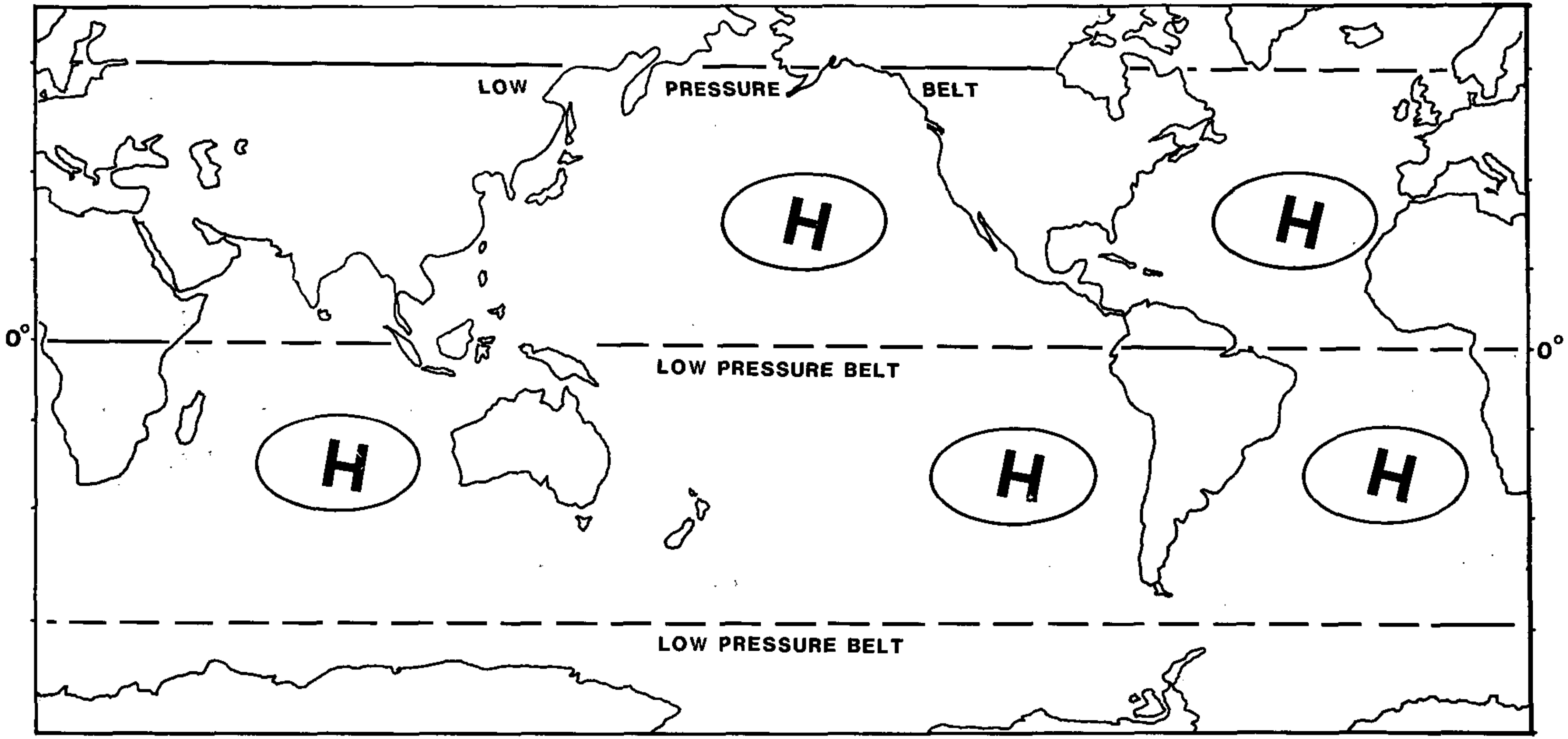


Fig. 4. Simplified global pressure distribution; "H" signifies high pressure zones.

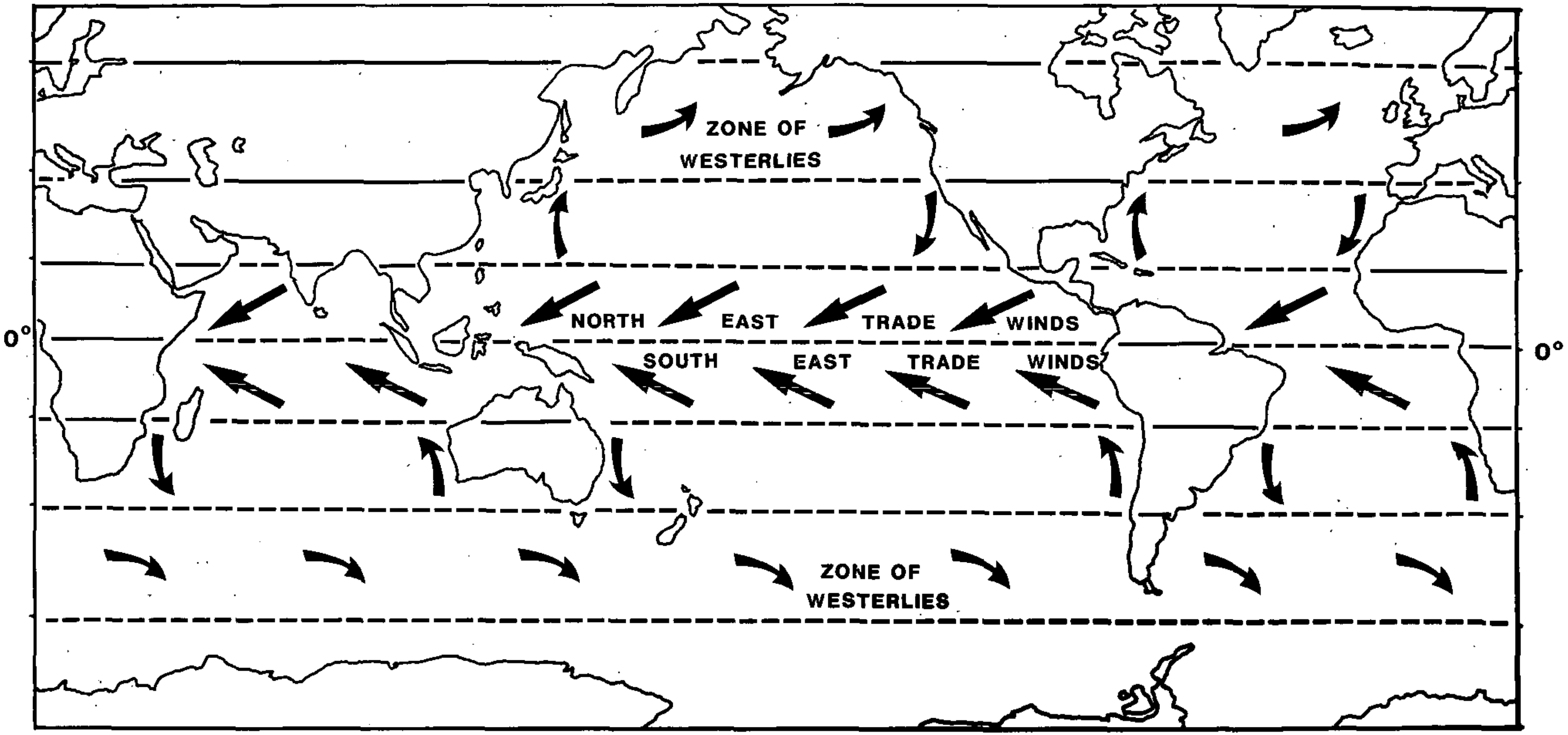


Fig. 5. The main global wind systems.

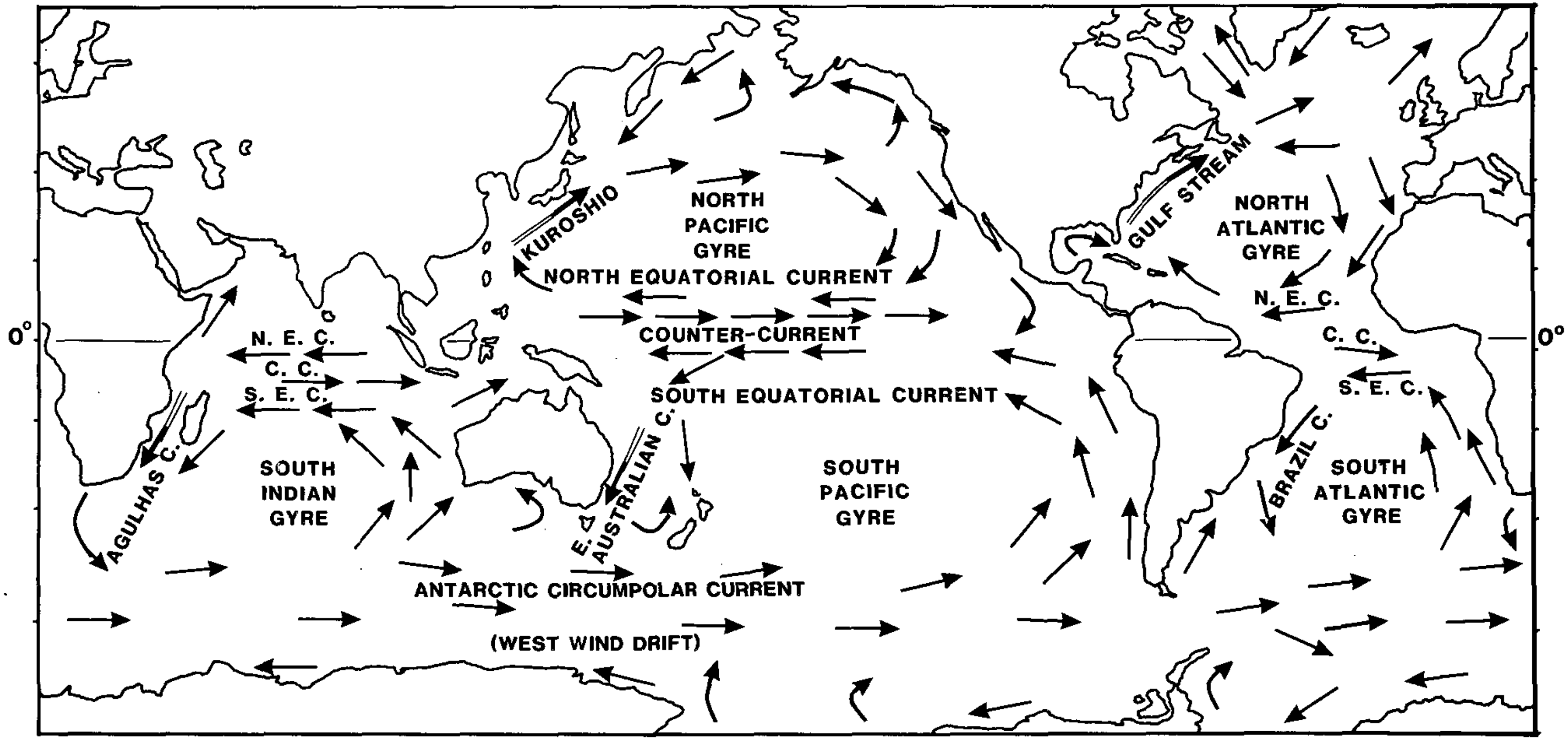


Fig. 6. Global current systems (only the major currents are shown).

winds blow steadily from the high pressure belts westwards towards the equator, and (particularly in the southern hemisphere) strong westerly winds blow between 40° and 60° — the notorious "roaring forties" of the Southern Ocean. (The term "geostrophic" is applied to winds and currents which flow along the isobars, as they are in balance between the pressure gradient and the Coriolis effect.).

2. *Large-scale Ocean Currents*

It is immediately clear by comparing Figures 5 and 6 that the large-scale ocean current systems are closely related to the wind fields. In each of the five half-oceans (i.e. North and South Pacific, North and South Atlantic, and South Indian — the North Indian Ocean is an exception as it is so limited in size and because of the reversing wind pattern) there exists a large gyre or circulation — anticlockwise in the southern hemisphere and clockwise in the northern hemisphere. The trade winds at the equator drive the south and north equatorial currents by the steady wind stress on the sea surface, and the bands of westerly winds similarly cause eastward currents in latitudes of 40° to 60°. Partly due to the Coriolis effect and partly because of the presence of the continents, there is an equatorward current along the eastern edge of each ocean, and a poleward current along the western edge.

It will also be seen in Figure 6 that the poleward current along the western side of each ocean is much narrower and stronger than the corresponding stream on the other side. This is caused by certain effects which lead to a strengthening of the current on the western boundary of the ocean, hence the term "western boundary currents". These are some of the strongest currents in the ocean, and include the Kuroshio, Gulf Stream and Agulhas Current. The East Australian Current does not exhibit the same behaviour, for reasons as yet unknown (see page 16).

3. *Temperature and Salinity in the Pacific Ocean*

In equatorial regions, the surface water is warmed by energy from the sun, and the surface temperature decreases towards the poles (Figures 7 and 9a). Generally the isotherms lie east-west (i.e. zonal), although near the continents they are distorted either by the horizontal boundary currents or by coastal upwelling processes (see page 24). Although not shown by the mean temperatures in Figure 7, there are two "convergence" zones where the surface temperature changes quite rapidly, due to water flowing together and sinking there — the positions of the Subtropical Convergence and Antarctic Convergence are at about 40°S and 55°S respectively. These convergence zones are important because water masses (see next Section 4) are formed there, and may be traced for thousands of kilometres northwards in all the oceans. This process is called "thermohaline" circulation because it is caused by differences in the density of the water (which depends on its temperature and salinity and which determines the depth at which that water mass will move). Figure 9c shows a simplified diagram of the formation of Antarctic Bottom Water by cooling at the Antarctic Continent, and Antarctic Intermediate Water by mixing and sinking at the Antarctic Convergence. Between these two north flowing water masses lies a southerly flow of Pacific Deep Water (which consists basically of water from the depths of the Indian and Atlantic Oceans).

The surface salinity pattern in the southern Pacific Ocean is shown in Figure 8, and is more complex than the temperature pattern. Over the equator (or in fact just north of it), there is a band of low salinity because of heavy rainfall there. Around 20°S there is much less rain,

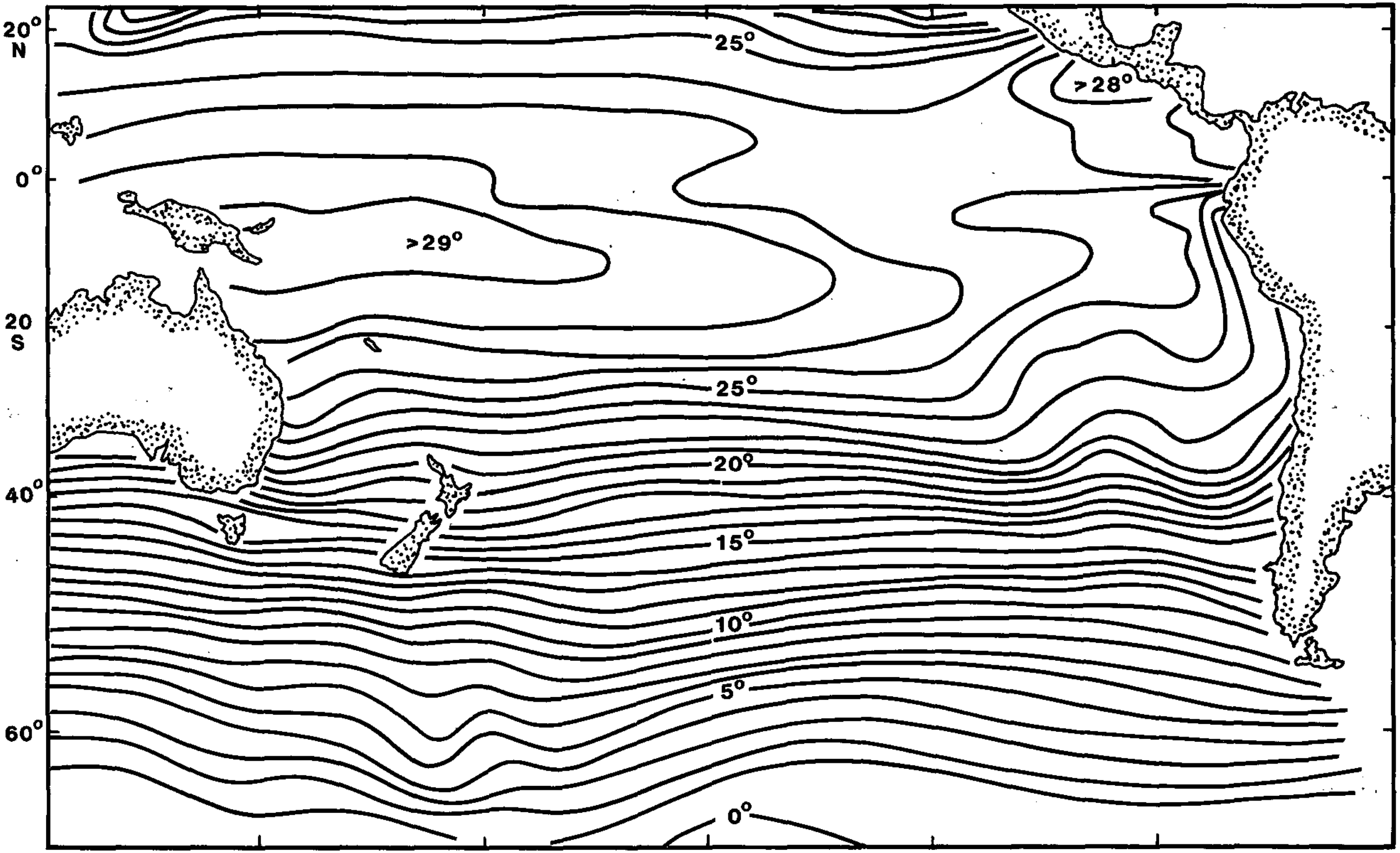


Fig. 7. Surface temperature in the South Pacific Ocean (February).

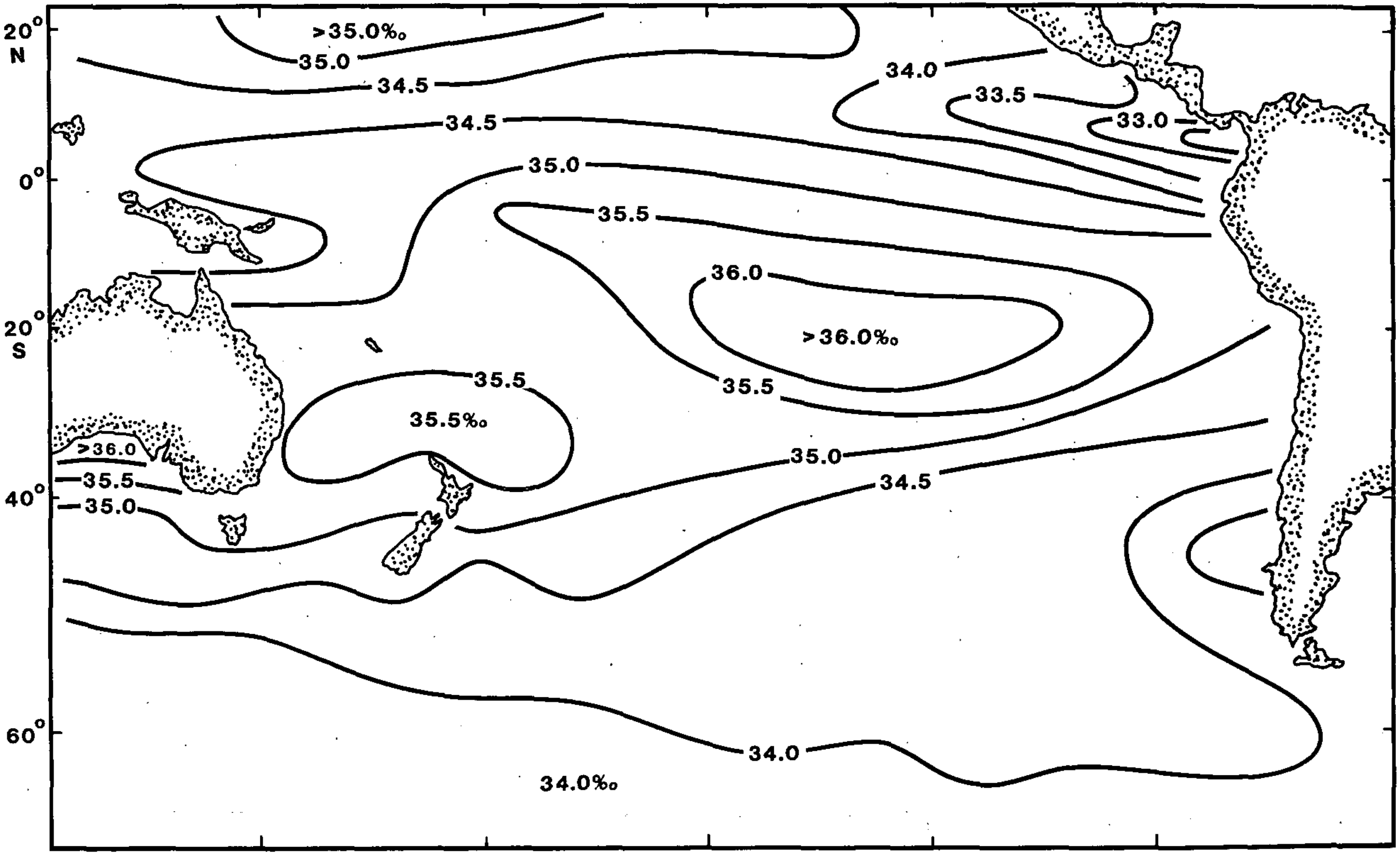


Fig. 8. Surface salinity in the South Pacific Ocean (February).

and evaporation from the sea surface is great, so the salinity is higher. The salinity then drops again towards the south because of increasing rainfall and decreasing evaporation (Figure 9b). These overall temperature and salinity patterns are not greatly altered by season, although the zones of highest and lowest temperature and salinity shift slightly north or south with the season (Figure 9a and b). There may also be a local drop in surface salinity in some coastal regions in the rainy season due to runoff of freshwater from large rivers.

4. *Water Masses and Vertical Distribution of Properties*

Vertical profiles of temperature and salinity from the Tasman Sea are shown in Figure 10a. The temperature was constant down to about 80m, and this zone is called the surface mixed layer because surface processes (such as wave action and heating or cooling or evaporation) bring about vertical mixing of the water in this layer. There is then a rapid decrease of temperature with depth down to a few hundred metres; this zone of large change is called the thermocline. Thereafter the temperature continues to fall slowly to the deep seabed.

The salinity profile is basically similar, with constant salinity in the mixed layer, the halocline where it decreased rapidly, but below 1000m the salinity begins rising again because of a higher-salinity water mass below that level.

As mentioned earlier, the density of seawater depends on its temperature and salinity, as well as the pressure (or depth below the sea surface). The density of seawater (about 1.025 g/cm^3) is only slightly greater than that of freshwater (1.00 g/cm^3), so it is convenient to use a new name sigma, which is calculated:

$$\text{sigma} = (\text{density}-1) \times 1000.$$

Thus a density of 1.0253 will have a sigma (σ) value of 25.3. For most purposes, the effect of pressure can be ignored, and the sigma value is then called sigma-t (σ_t). In Figure 10a the density (or σ_t) is seen to be constant in the surface mixed layer, then there is the pycnocline (corresponding to the thermocline and halocline), and the density increases steadily with depth to the seabed. On a small scale, density inversions may occur with local decrease in density with depth, but such a situation is unstable and results in vertical mixing.

Seasonal changes in temperature and salinity are restricted to the upper 200m or so, with the deeper water being largely unaffected. In summer, the surface temperature increases and a summer thermocline forms; in winter the surface temperature decreases and the mixed layer deepens.

If the temperature and salinity data of Figure 10a are replotted with temperature against salinity, as in Figure 10b, the points lie on a smooth curve known as a TS diagram ("Temperature-Salinity diagram"). The points must be joined in depth order. Water masses are bodies of water which have specific temperature and salinity characteristics, and which therefore appear in a particular part of the TS diagram. If the TS value of a water mass is very clearly defined so that it can be shown by a single point on the TS diagram, it is called a water type; some authors consider water masses to be formed by mixing of different water types. Near the sea surface, water masses may have variable TS characteristics due to changes at the surface (such as heating, cooling, rainfall, and evaporation) but in deeper water the TS value can be closely specified. For the Tasman Sea, the water in the upper 1000m or so consists of various central, equatorial or subtropical water masses. Below this, Antarctic Intermediate Water is characterized by a salinity minimum (at about

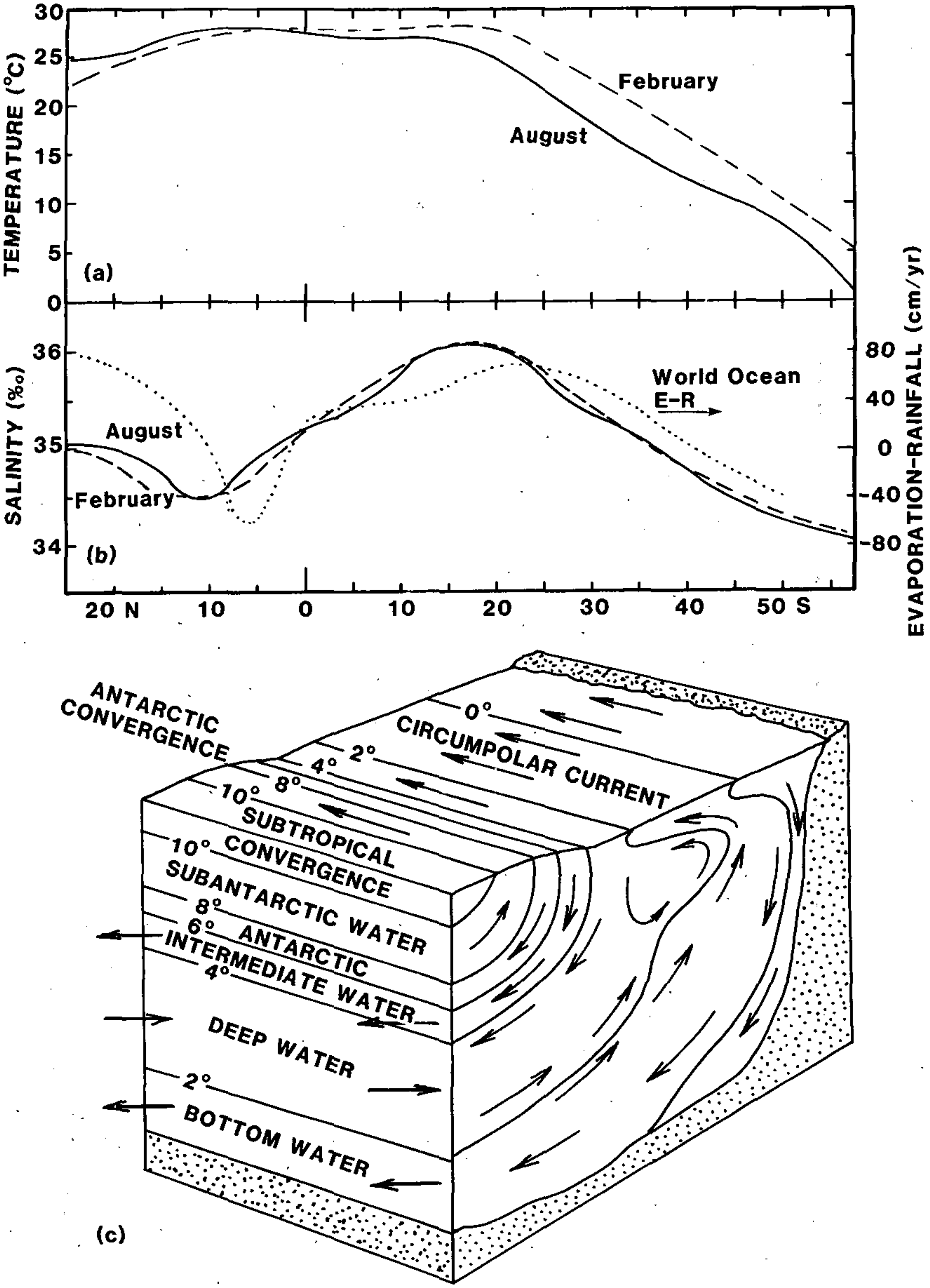


Fig. 9(a). Surface temperature in the Pacific Ocean.
(b). Surface salinity in the Pacific Ocean.
(c). Water masses in the Southern Ocean.

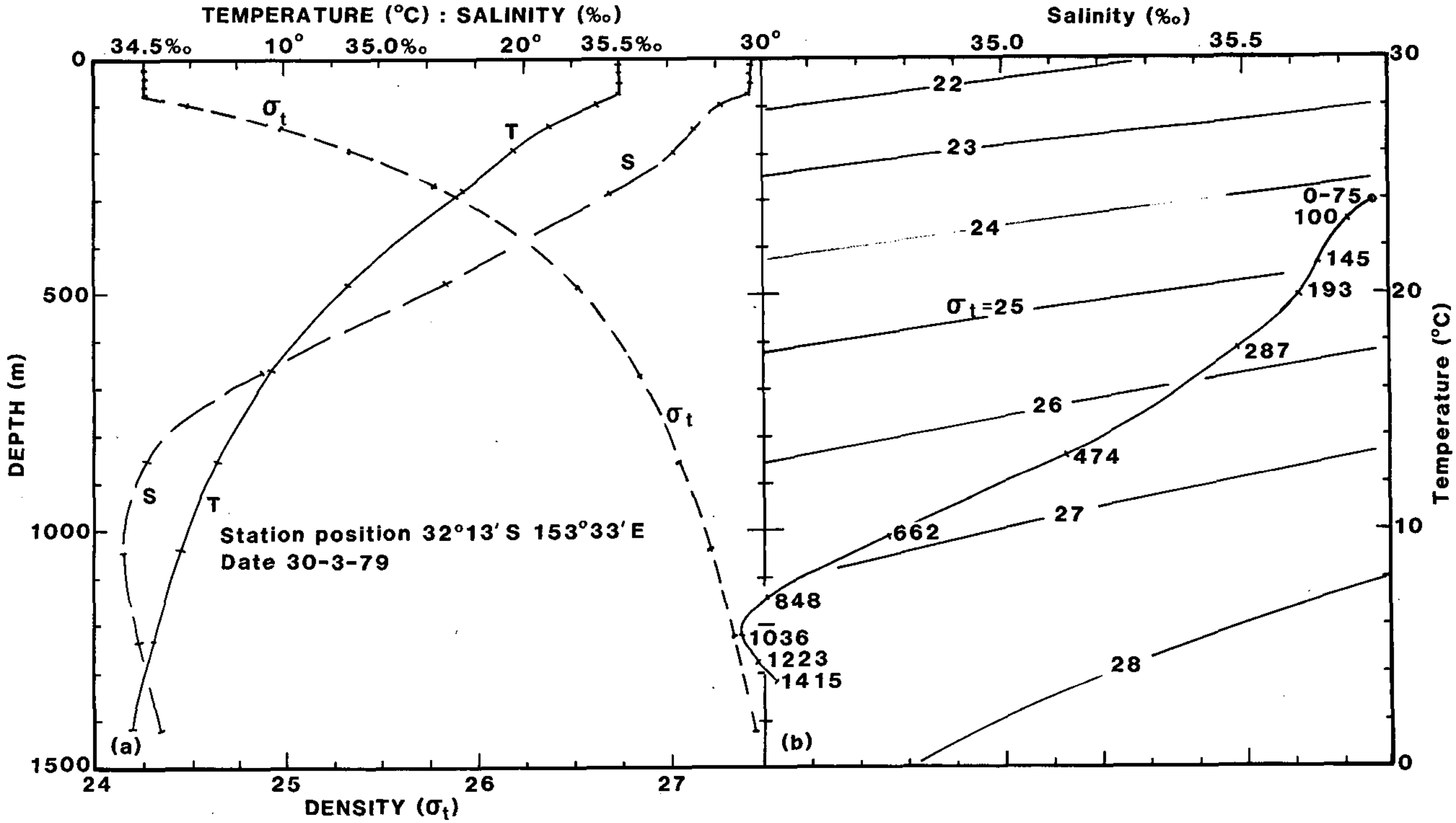


Fig. 10(a). Vertical temperature, salinity, and density (σ_t) profiles in the Tasman Sea.
(b). Temperature-salinity diagram for the station (the numbers are the depths of the samples in metres).

5.5°C, 34.46‰, depth about 1000m in Figure 10b, Deep Water has a salinity maximum of about 34.7‰ at a temperature of just under 2°C, and Antarctic Bottom Water has a lower salinity and a temperature of less than 0°C. As these water masses spread through the ocean (Figure 9c), they gradually mix with adjacent water and their TS characteristics are modified.

5. *Western Boundary Currents — the East Australian Current*

As mentioned above, the poleward currents on the western edge of each ocean are very intense (such as the Kuroshio or the Gulf Stream), and are known as western boundary currents. These boundary currents are warm and fast-flowing, and show up clearly in atlases produced from ship-drift data as well as classical hydrology surveys. However, the smooth steady stream shown in atlases is false as the currents are in fact highly variable. The "East Australian Current" (EAC) may not even exist at times, but may consist merely of a series of large eddies.

A typical atlas-type picture of the EAC is given in Figure 11, which is based on thousands of ship's estimates of the currents over a long period. (The ship gets a rough estimate of the surface current by noting how much it is carried off its course between fixes by the current). Such a chart gives an "average" picture of the EAC, and shows it as a stream of water coming from the east (the South Equatorial Current — see Figure 6) in latitudes of 10° to 20°S, sweeping down the Australian coast in a narrow stream, and then returning eastwards between 30° and 40°S. There is some re-circulation in an eddy at about 25°S.

At any particular time, however, there is great variability in the position, speed and shape of the EAC. The current system can be studied in an indirect way by using the "geostrophic relationship" (mentioned earlier) in which the horizontal pressure gradients caused by changes in the water density produce currents which flow parallel to the isobars because of Coriolis effects. If it is assumed that there is no current at say 1300m depth (which may not be entirely true although the current speed there will probably be very small), then changes in the density of the water at different places will lead to differences in the height of the sea surface. These sealevel differences are only about 50 cm across tens of kilometres of water, but can be estimated by measuring the temperature and salinity of the water at all depths to 1300m, and calculating its density. The resulting height of the water column (relative to that of a standard ocean) is called the dynamic height and these are plotted on a chart such as Figure 12. Contouring the dynamic heights shows the dynamic topography of the current system; the current direction is such that the sealevel is always highest on the left side of the current in the southern hemisphere (S.H.) or on the right side in the northern. The current speed can be estimated from the spacing between the contours, being swiftest where the contours are closely spaced. Figure 12a shows an occasion when there was a strong EAC down the shelfbreak for a few hundred kilometres, then it turned eastwards out to sea; an anticyclonic or warm-core eddy (i.e. anticlockwise in the S.H., clockwise in the N.H.) was situated at 35°S, and a few weaker cyclonic eddies (i.e. clockwise in the S.H.) can also be seen. In Figure 12b, however, the current system consisted almost entirely of eddies and there was no evidence of an East Australian Current. It should be noted that the surface temperature does not always show the eddies, but that at say 250m does.

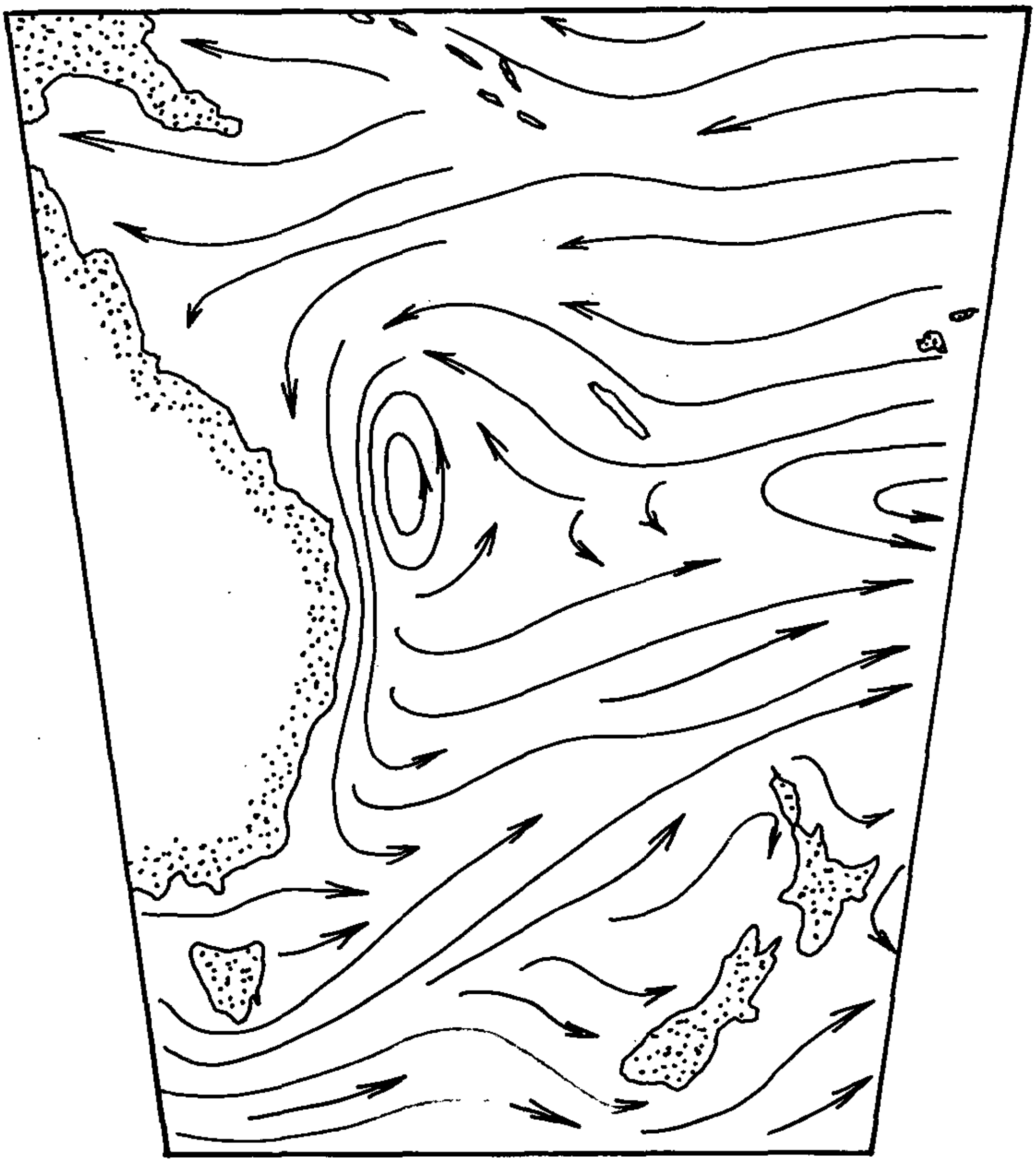


Fig. 11. The average surface currents in the Tasman Sea, using data from an atlas (for July).

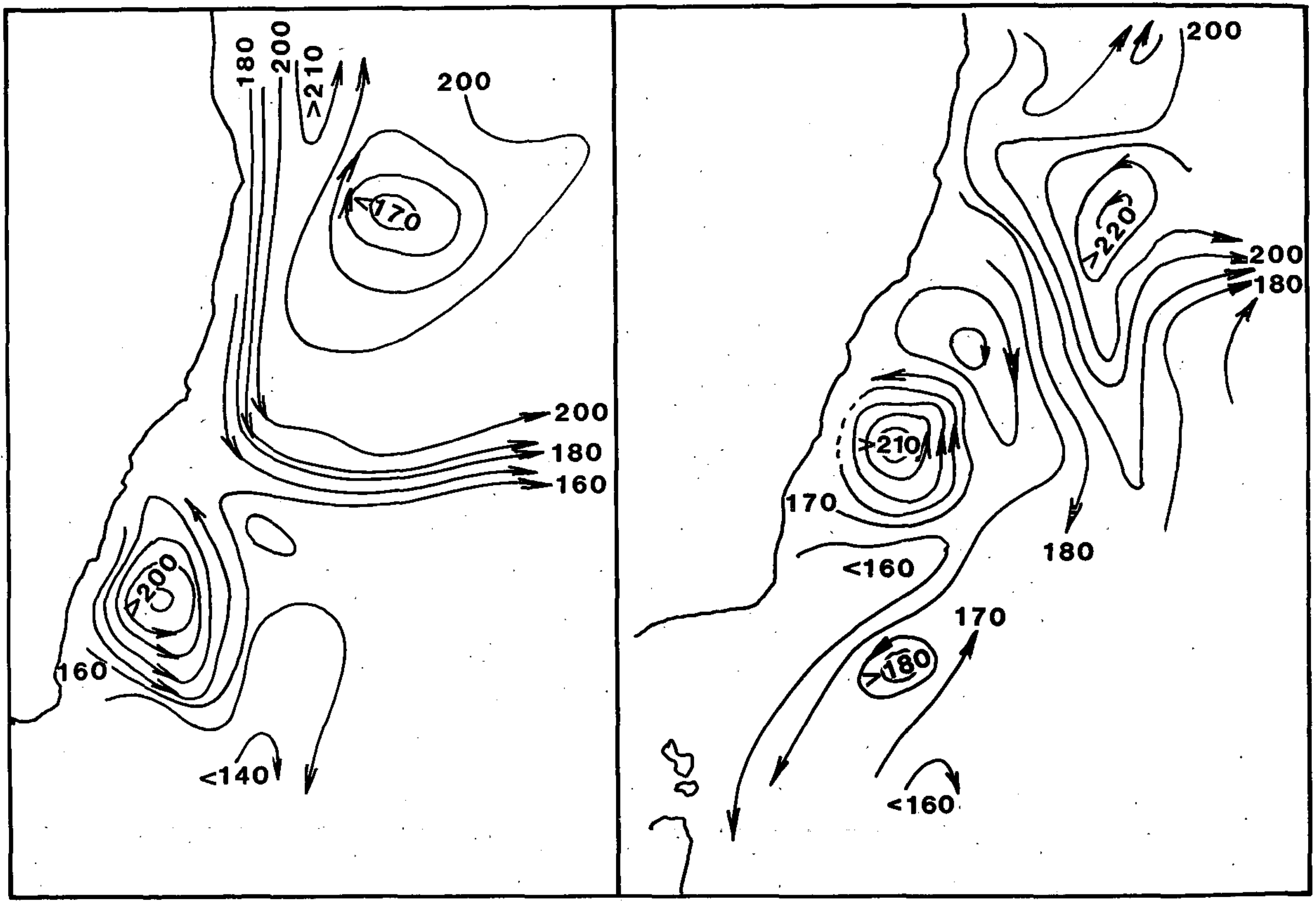
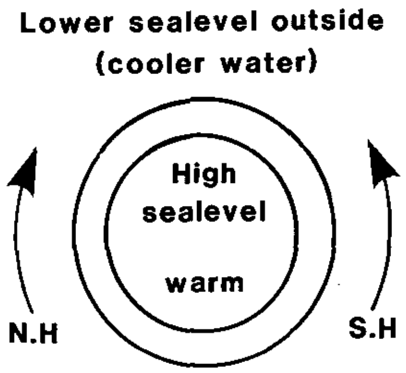


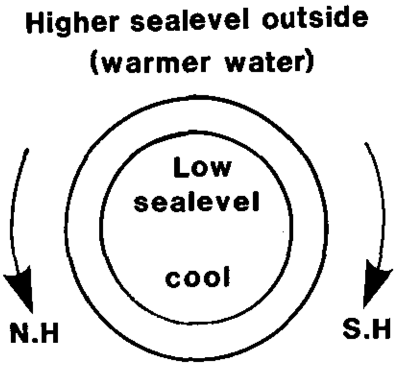
Fig. 12. Eddies in the Tasman Sea, shown by dynamic height contours (cm).

The rotation around eddies can be summarized as follows, being analogous to the flow around atmospheric highs and lows:



Anticyclonic flow

High sealevel in eddy.
Anticlockwise in S.H.
Clockwise in N.H.



Cyclonic flow

Low sea level in eddy.
Clockwise in S.H.
Anticlockwise in N.H.

Although it is difficult to measure directly the slope of the sea surface, it is relatively easy to determine the density of the water column by measuring the temperature and salinity. The isopycnals (and therefore usually the isotherms as well) slope in the opposite sense to the sea surface, and these isotherms slope far more steeply than the sea surface. Thus, for example, in a southern hemisphere anticyclonic eddy where the sea surface in the eddy is slightly raised, the isotherms dip steeply downwards towards the centre, as will be seen below. In the S.H., if one is moving with the current, the isotherms will slope up from left to right.

Examples of the vertical structure through the EAC and through an anticyclonic eddy are shown in Figure 13. When it exists, the EAC (Figure 13a) has a structure similar to that of the other western boundary currents, i.e. a warm surface layer, isotherms (and isopycnals) sloping downwards away from the coast, strong current shear (or change) across the inshore edge of the current, and peak surface speeds of over 1 m/s (2 knots) — highest speeds of over 2 m/s (4 knots) have been measured. Often, but not always, there is a strong surface temperature front of 1° to 5°C at the inshore edge of the current. In an anticyclonic eddy (Figure 13b), there is a warm mixed layer extending down to 200m or more, and the bowl shape is characteristic of these warm-core eddies. The speed of the current around the eddy is also of the order of 1 to 2 m/s.

One of the most recent methods of studying eddies involves tracking of free-drifting buoys by satellite. The resulting map (Figure 14) clearly shows how variable and complex the current system is over a year, but also how stable the eddies can be for many months at a time.

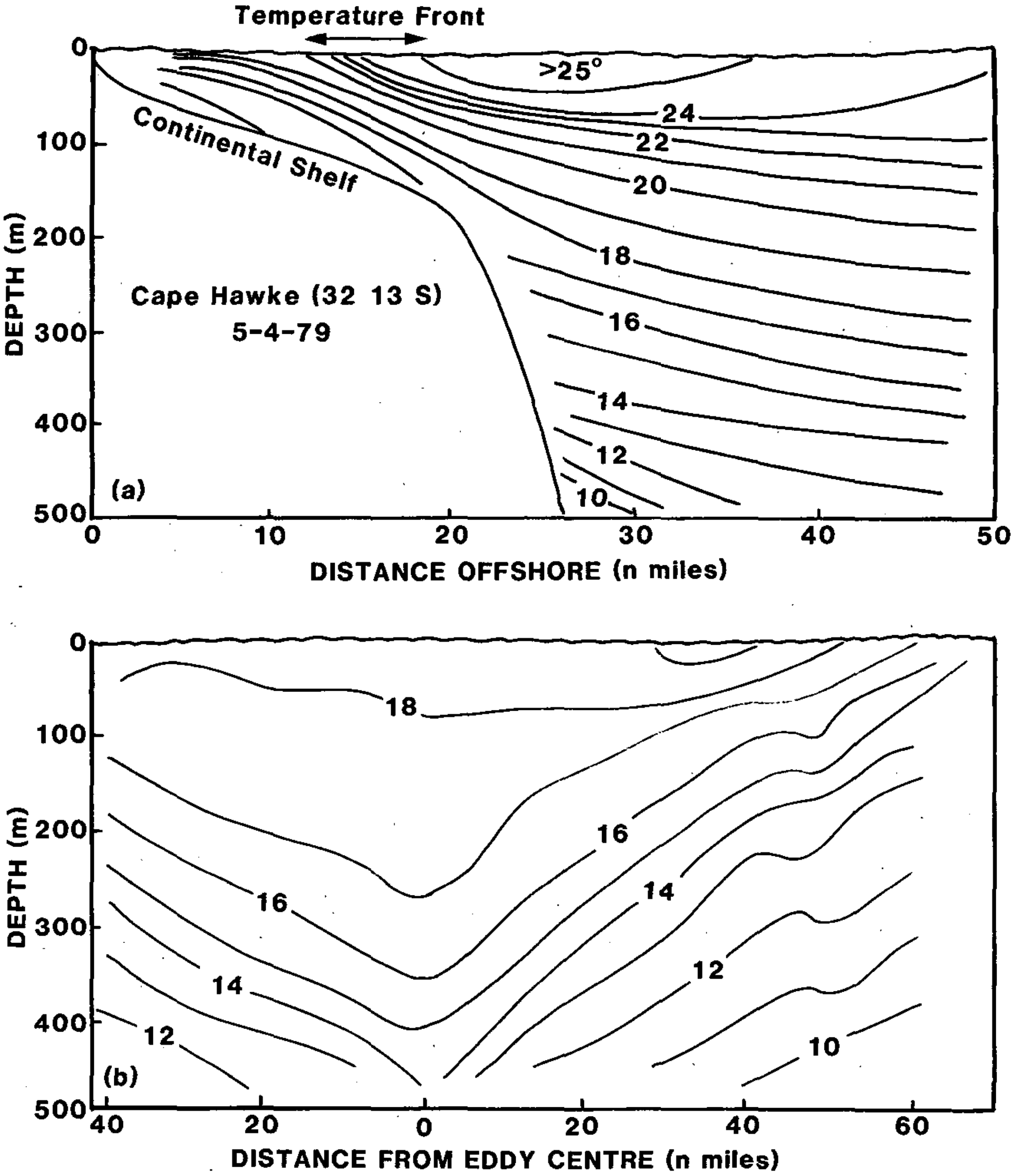


Fig. 13(a). Temperature section through the East Australian Current.
(b). Temperature section through Eddy F, centred on 36°30'S, 151°30'E, December 1978.

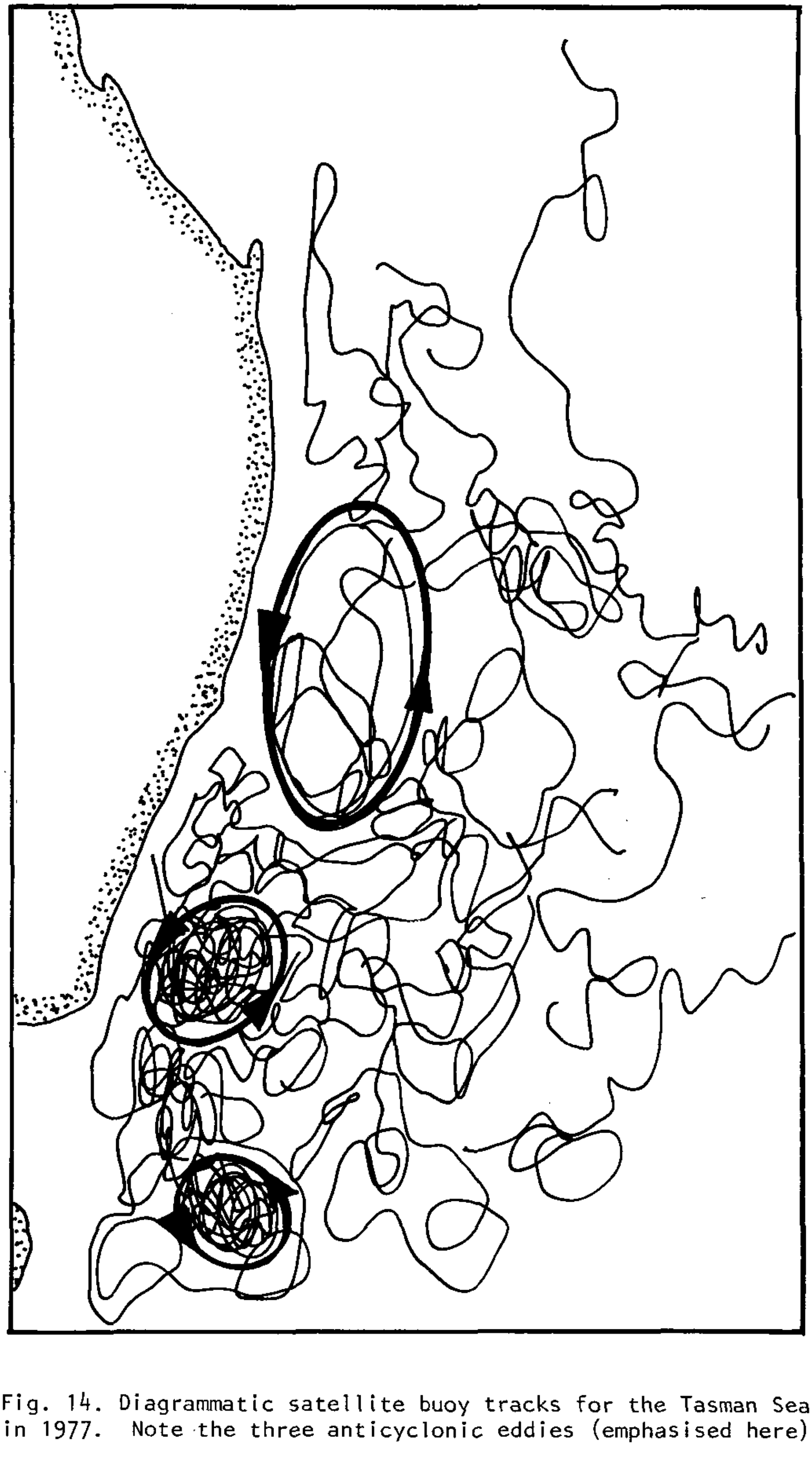


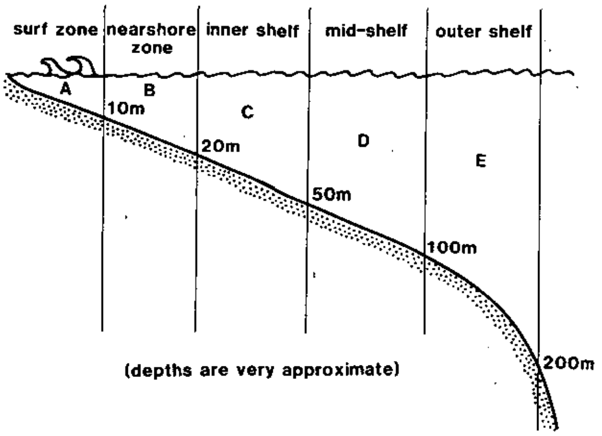
Fig. 14. Diagrammatic satellite buoy tracks for the Tasman Sea in 1977. Note the three anticyclonic eddies (emphasised here).

PROCESSES ON THE CONTINENTAL SHELF

The temperature, salinity and currents on the continental shelf are far more variable than in the open ocean, with large changes occurring in a relatively short time. It is only recently, in fact, that currents on the shelf have been studied in sufficient detail for the main features to be identified; this is partly due to increasing world-wide interest in continental shelf waters, as well as to the availability of better instruments. (Coastal engineers have studied the surf zone for many years in connection with sediment transport, but the currents there are very different from those on the open shelf).

1. Currents

For convenience, the continental shelf can be roughly divided into zones (which overlap to some extent) where the currents are dominated by different factors:



(depths are very approximate)

These zones are:

A Zone of shoaling and breaking waves (to about 10m depth) — characterized by wave-driven longshore currents.

B Nearshore zone (to 20 or 30m depth) — wave-induced currents near the seabed, and friction-damped coastal boundary layer flow; may have strong tidal currents.

C Inner shelf zone (to say 50m) — vertically mixed in winter, stratified (layered) in summer, currents in geostrophic balance.

D Mid shelf zone (to 100 or 150m) — generally stratified; often surface fronts and coastal "jets" (swift narrow currents) occur; currents are geostrophic.

E Outer shelf/slope zone (to 250m) — shelf and oceanic waters interact, with eddies, boundary currents, fronts; currents are geostrophic.

Wave-induced currents

The main current-generating factor in the water of the surf and nearshore zones is the transport due to incoming waves (swell). In this shallow water, the waves carry water towards the beach over a wide area, and "pile it up" over the beach; this causes an alongshore current to be formed in the breaker zone. If the waves are at a large angle to the coast, and the beach is straight, the alongshore current can continue for long distances (Figure 15a). The volume of water in the alongshore current increases for higher waves, and also with distance along the beach. If, on the other hand, the waves are approaching parallel to the beach as in Figure 15b, the mass of water at the beach only flows a short distance along the beach before returning out to sea in a narrow rapid rip current, often at a headland. In this way,

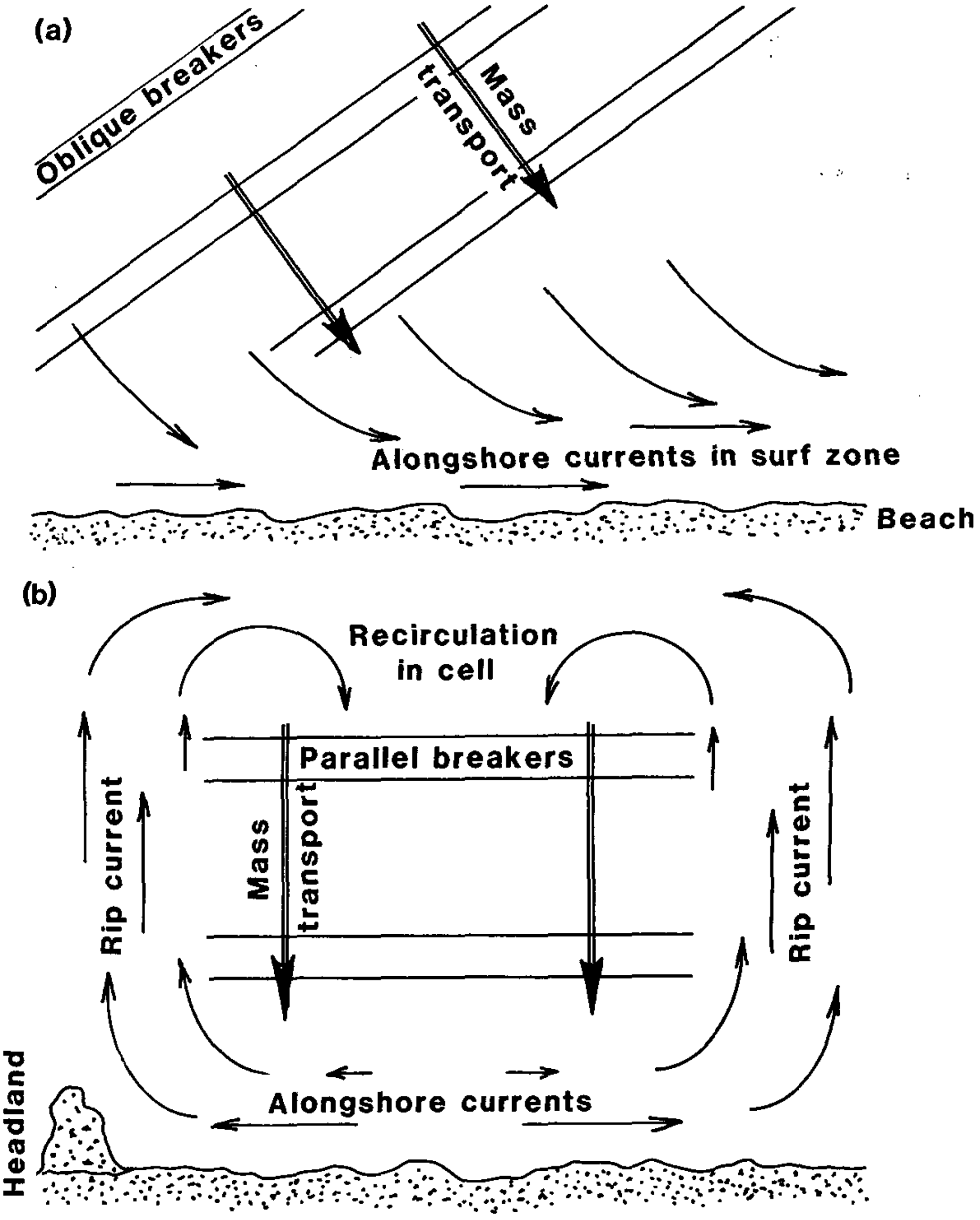


Fig. 15. Water circulation in the surf zone (and nearshore zone) due to (a) oblique swell, and (b) normal swell.

"cells" of circulation are formed. The rip currents are say 50m wide, have speeds of over 1 m/s at times, and may be intermittent (operate in bursts). If an alongshore coastal current is flowing in deeper water beyond the nearshore zone, the rip currents may be deflected to some extent, and there also may be an exchange of water between the rip current and the coastal current. The transport of sediment along beaches is largely due to wave-induced alongshore currents.

Wind-driven currents

Winds play an important part in driving surface currents, and along the inner shelf region can be the dominant cause of the currents. In general terms, the surface current moves at 2 to 3% of the wind speed, and subsurface currents are slower. The surface current direction is (theoretically) about 45° to the left of the wind direction in the southern hemisphere (to the right in the N.H.), and because of friction in the water the subsurface currents progressively rotate anticlockwise (or clockwise in the N.H.). At a particular depth of some tens of metres, known as the Ekman layer depth, the current speed is only about 4% of the surface speed and the current direction is opposite to that at the surface — this rotation of the currents is the well-known Ekman spiral (Figure 16a). Of great importance is the fact that the depth-averaged current in the Ekman layer is at 90° to the wind direction, to the left in the S.H. and to the right in the N.H.

In simple terms, this Ekman transport is responsible for coastal upwelling when the wind is blowing in the correct direction. In the southern hemisphere, a wind blowing with the coast on its right (e.g. a wind from the north on the Australian east coast) causes an offshore movement in the surface layer of water, and a compensating onshore flow along the seabed. This bottom flow is cool and usually nutrient-rich, bringing up nutrients from deeper water off the shelf (Figure 16b) and resulting in high biological productivity on the shelf. The cooler water close inshore sets up a seasurface slope as shown, which results in a general coastal current in the same direction as the wind.

This wind-driven upwelling is well-known off the Oregon coast (where it has been studied in great detail), off Peru, off northwest Africa and off southwest Africa; these are regions where some of the world's richest fisheries are found.

As described above, alongshore winds can drive coastal currents both by direct wind stress on the water and by setting up sea surface slopes, and the relationship can be very close. Figure 17 shows current and wind data from the South African east coast: atmospheric pressure "lows" move along the coast at intervals of a few days, causing northerly/ southerly wind reversals which in turn result in current reversals as measured near the seabed in about 20m of water.

It should be noted that, by convention, a northerly wind blows from the north, while a northerly current flows to the north.

Thermohaline currents

Thermohaline circulation is that brought about by changes in the water density, due to changes in the temperature or salinity of the water. A good example is the alongshore current resulting from the upwelling of cool water onto the inner shelf, as described above; because of the greater density of the upwelled water, sealevel slopes upwards away from the coast and this causes a southerly shelf flow (in the S.H.).

The opposite effect results from freshwater discharge from major rivers. River plumes gradually mix with the inner shelf water, lowering the salinity and hence the density, so that sealevel at the coast rises.

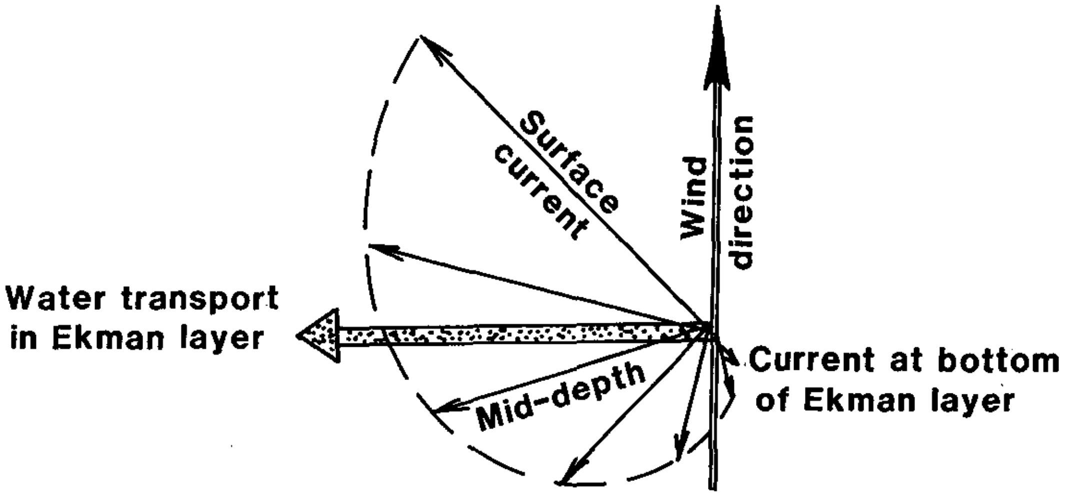


Fig. 16(a). Ekman spiral.

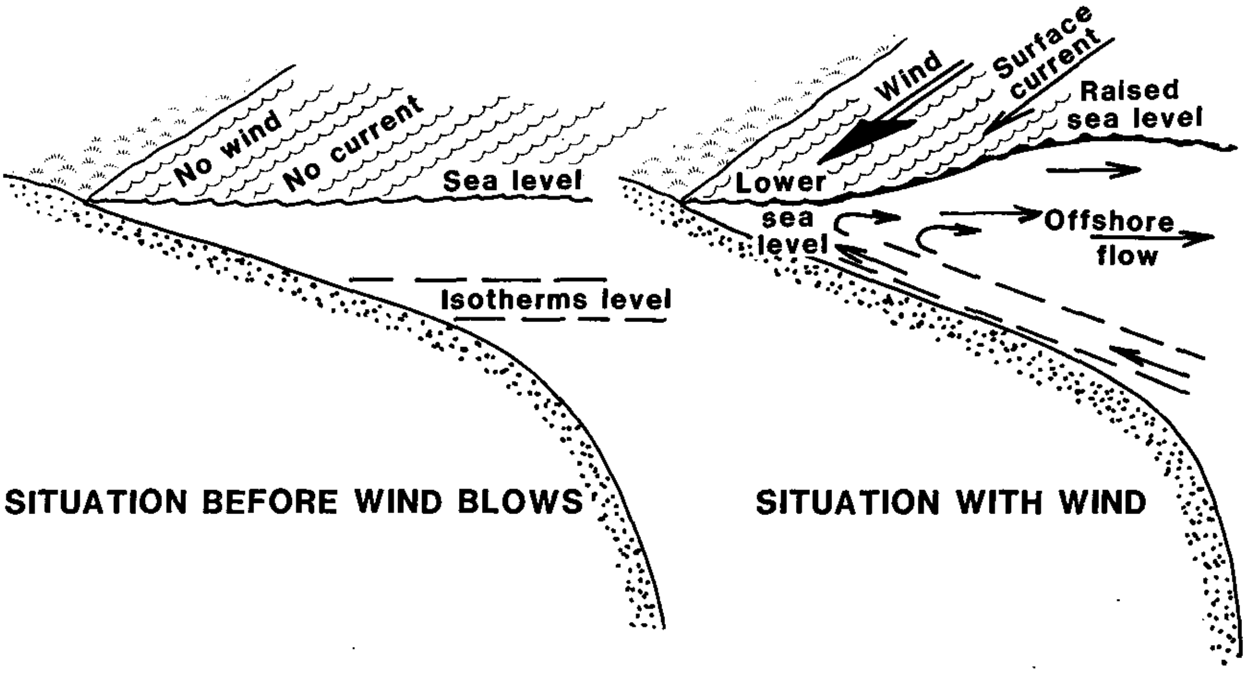


Fig. 16(b). Wind-driven coastal upwelling, in the southern hemisphere.

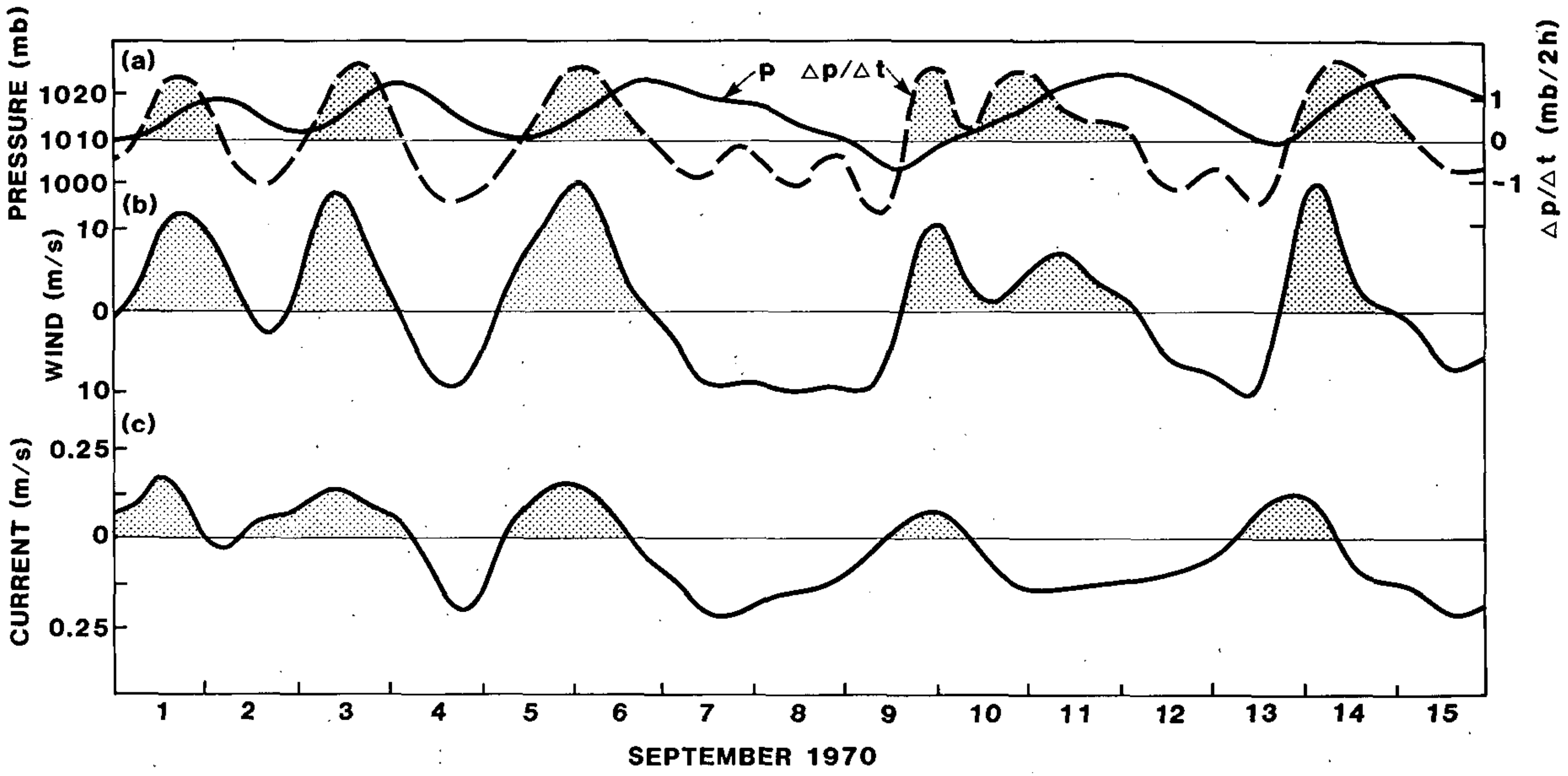


Fig. 17. Atmospheric pressure, wind and currents in 20m water on east coast of South Africa.
(a) Atmospheric pressure (p) and gradient (Δp/Δt).
(b) Alongshore wind component (shaded areas are winds towards north).
(c) Alongshore current component (shaded areas are currents towards north).

A northerly coastal current (on a S.H. east coast) then follows (Figure 18). In the northern hemisphere, the Davidson current flows northwards along the U.S. west coast in winter (only) as a result of large rainfall over the coast during the winter months.

Tidal currents

The rise and fall of sealevel due to tides is dealt with in the next section, but a brief mention of tidal streams or currents is appropriate here. Associated with the passage of the tidal wave are tidal currents, which in the open ocean (away from coasts and islands) rotate with the changes in sealevel – generally clockwise in the N.H. and anticlockwise in the S.H. (Figure 19a). Near a coast, the rotary nature of the tidal current may still be seen, but the currents will vary greatly in different localities due to varying coastlines and seabed topography. However, at any particular locality the flow resulting from the tidal cycle should be regular and predictable. In some regions, the tidal current follows a simple reversing pattern rather than a rotation; the flood current is when the sealevel is rising and the tide is coming into the coast, and the ebb current is when the tide recedes again. Between flood and ebb the current may be slack (Figure 19b).

On the east coast of Australia, tidal currents are rather weak in most places and are usually obscured by stronger currents resulting from wind effects, etc. On the other hand, there are places in the world where the tidal currents are very strong and dominate other types of currents.

Shelf-edge currents

Along the outer shelf and upper slope, interactions occur between the shelf water and that in the deeper ocean. These interactions are very complex and incompletely understood at present, but a few examples are given here.

On the east Australian coast north of 32°S current patterns at the edge of the shelf move towards the coast, so that the currents at midshelf are basically similar to (but weaker than) those occurring a few days earlier at the shelf break, as shown in Figure 20. These patterns migrate southwards at speeds of about 9km/day. The period of some of these fluctuations is of the order of 100 days, and they are probably related to the eddy movements offshore.

At times the East Australian Current comes very close inshore (Figure 21a), and on other occasions it is far out to sea (or perhaps even non-existent), as in Figure 21b. Because of this meandering process, the currents along the outer shelf can vary from strong southerly to northerly over a few days (Figure 22), and it appears that the local wind has little influence on such processes. When there is a strong southerly current along the outer shelf, shear processes in the bottom Ekman layer cause an onshore veering of the near-bottom flow and therefore an upwelling of cool nutrient-rich water from the upper slope onto the inner shelf area. (This process is different from the wind-driven upwelling described earlier, where surface stress drives the upwelling, but the two processes may act together).

On the east coast of the U.S.A., the strong Florida Current meanders in the straits of Florida, and as it moves northwards along the coast "spin-off eddies" are generated by shear processes (strong velocity changes) along the inshore edge of the current. These anticlockwise eddies are relatively small-scale (5 to 10 km wide), drift northwards with the current, and lead to current reversals on the shelf (Figure 23). They are also responsible for exchanging shelf and open ocean waters, and thus "flushing" the shelf.

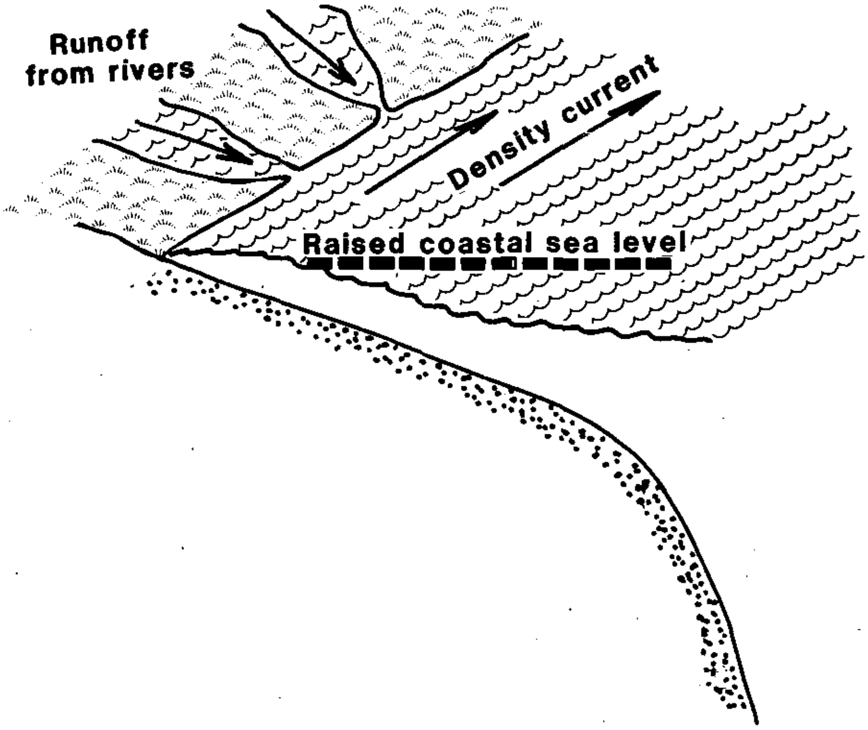


Fig. 18. Example of coastal currents resulting from low-salinity water near the coast (southern hemisphere).

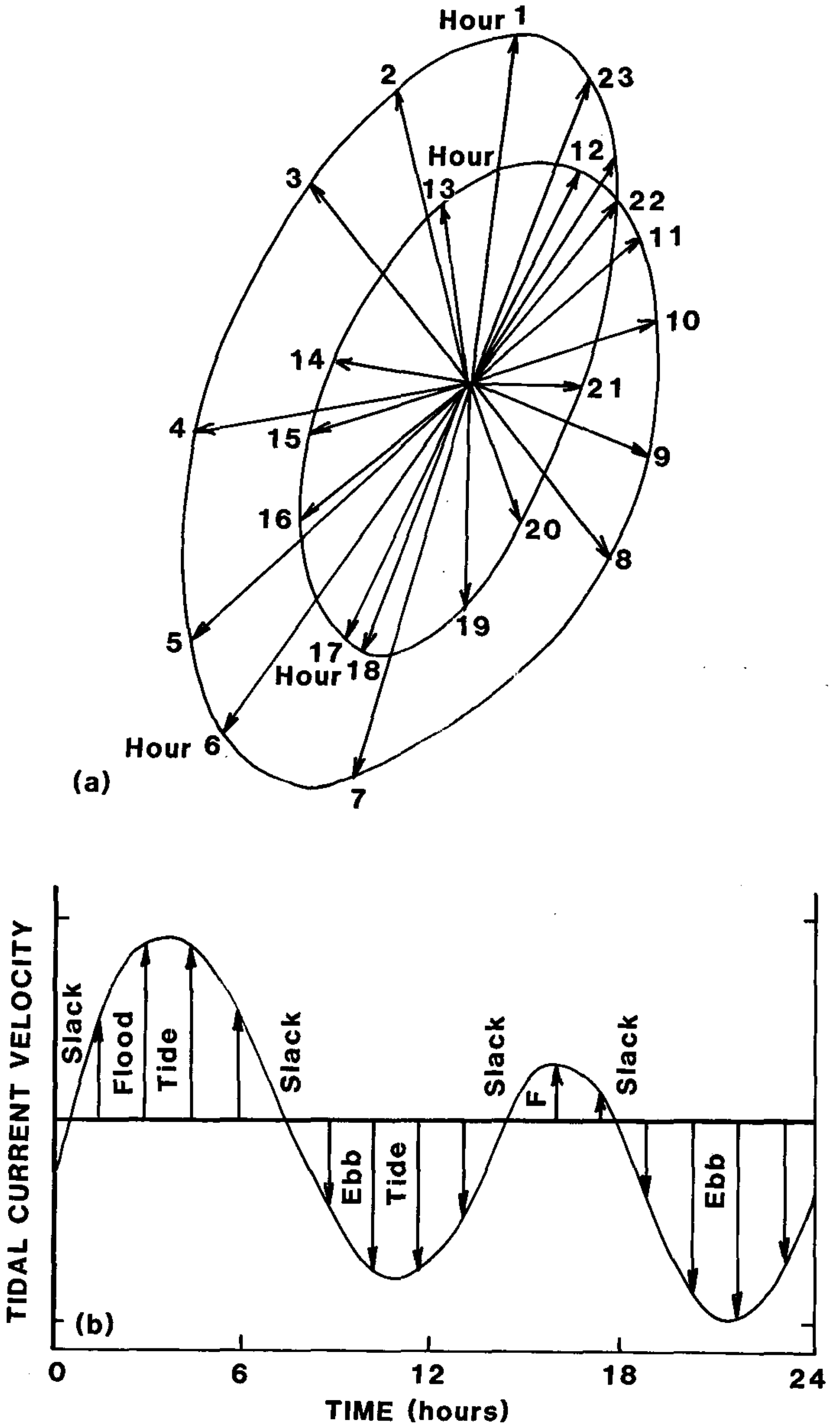


Fig. 19(a). Rotary tidal currents over a day (southern hemisphere).
(b). Oscillating tidal currents, such as in a harbour entrance.

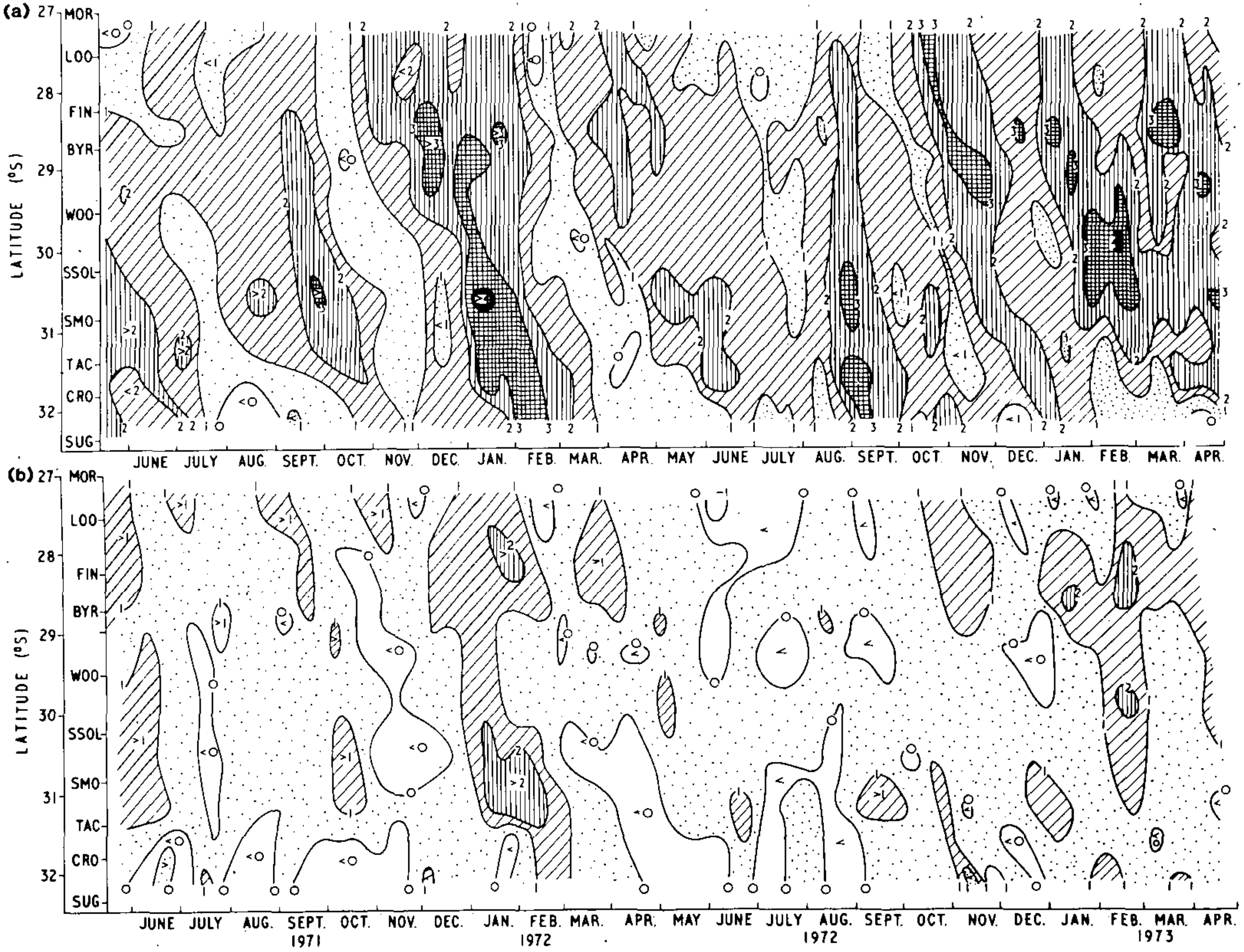


Fig. 20. Along-track currents on the east Australian coast, at (a) mid-shelf and (b) shelf-edge, as a function of latitude and time. Contour interval 1 knot. Currents are towards the south except in parts marked '<0', where the currents are between 0 and 1 knot to the north. The darkest shading shows periods of strong currents to the south.

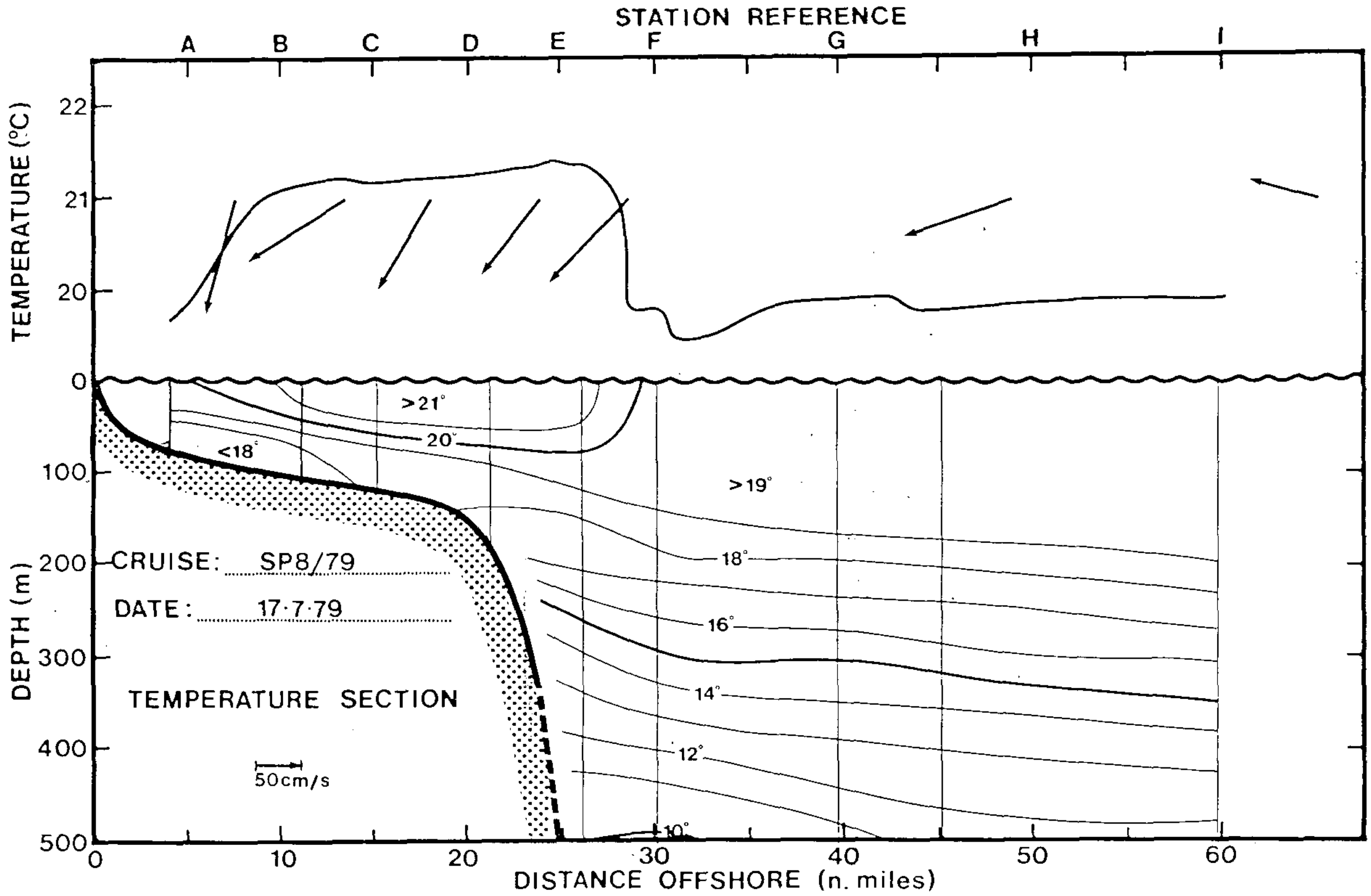


Fig. 21(a). Vertical temperature section through the East Australian Current off Cape Hawke. The solid line at the top is the sea surface temperature, and the arrows are current vectors.

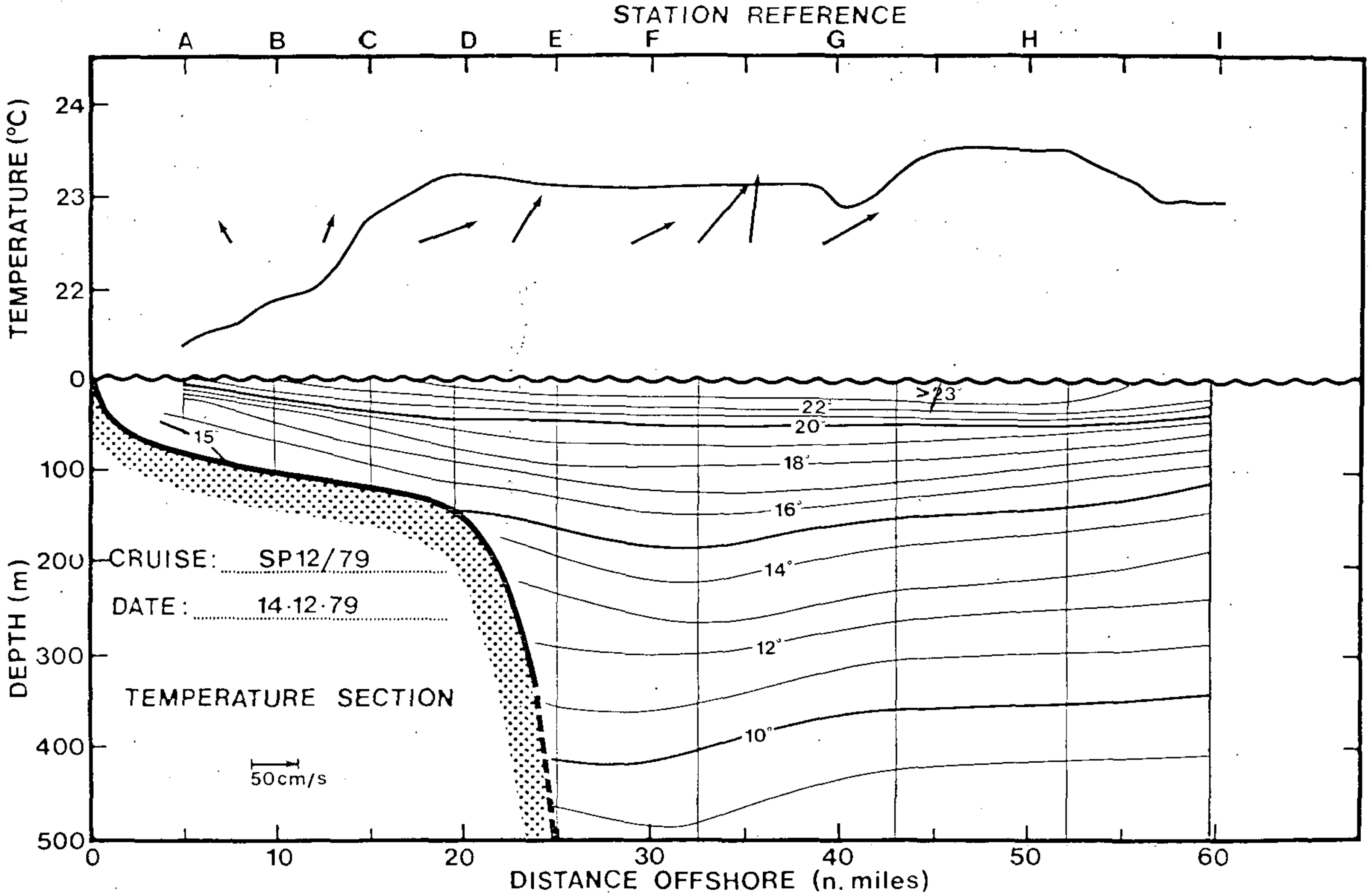


Fig. 21(b). Vertical temperature section off Cape Hawke, showing northerly currents out to 60 miles offshore. The solid line at the top is the sea surface temperature, and the arrows are current vectors.

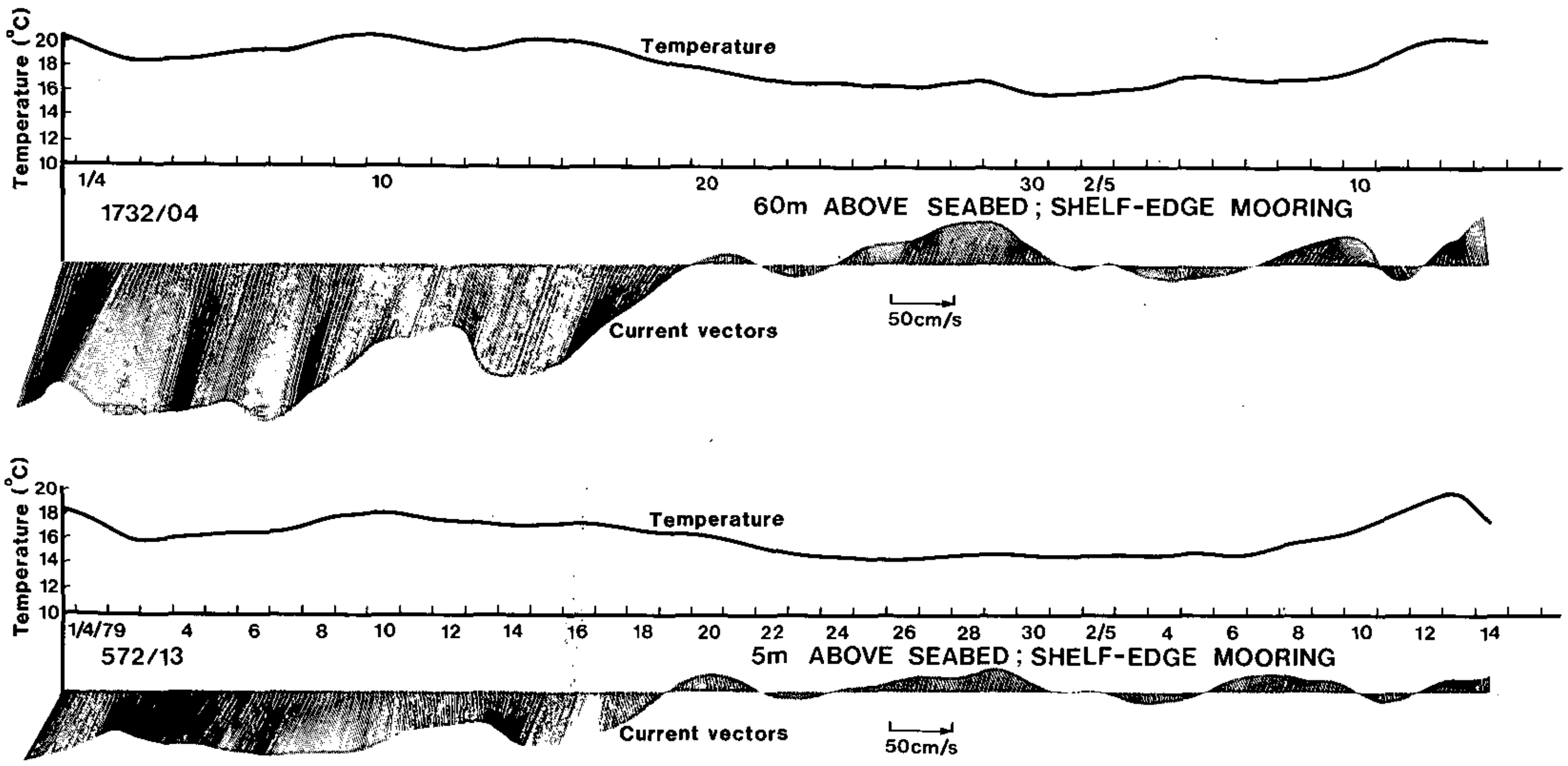


Fig. 22. Hourly current vectors and water temperature from two current meters moored at the shelfbreak off Cape Hawke. Each time-mark represents a day. The East Australian Current was over the shelfbreak for the first two weeks, then swung offshore.

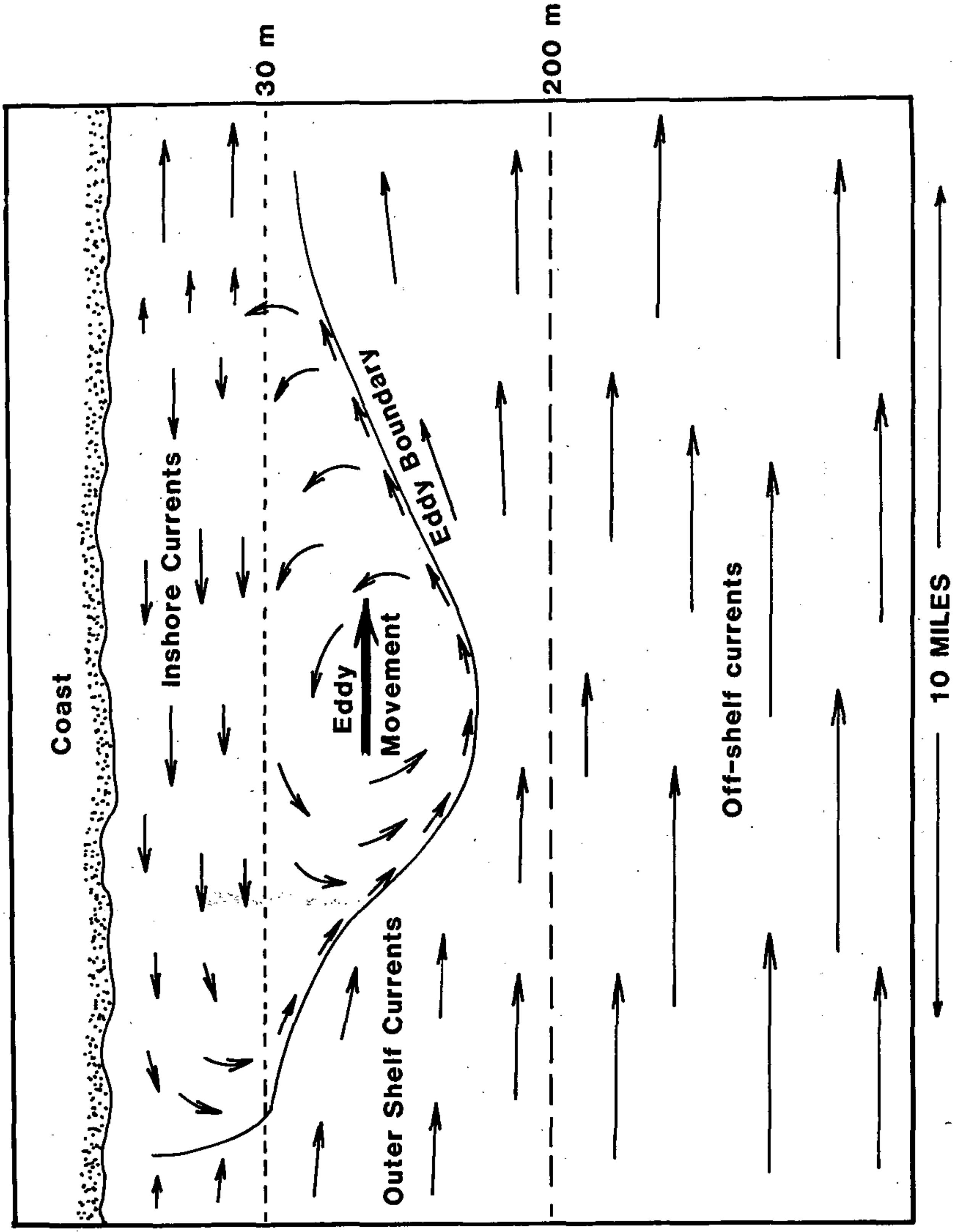


Fig. 23. Diagram of a 'spin-off' eddy from the Florida Current causing current reversals on the shelf.

2. *Temperature and Salinity*

Large changes in temperature and salinity can occur on the continental shelf, over a variety of time and length scales.

Seasonal scale

Ignoring fluctuations with a period longer than a year, seasonal changes in both temperature and salinity are evident right across the shelf. Measurements at 29°S off the east coast of South Africa have shown the seasonal pattern in both temperature and salinity clearly. Along the inner shelf, in 30m of water (Figure 24), the monthly mean temperature was 24° to 25°C in mid-summer (January to March) with the winter minimum being less than 21°C. Because of the shallow water, mixing over the whole water column resulted in isothermal conditions there. At the shelf break, the surface water was 1°C warmer (due to the warm Agulhas Current offshore) but the same pattern was evident. However, the average mixed layer in summer was only 20 to 30m deep, with a summer thermocline down to 50m; in winter the mixed layer was 50m deep. Below this the seasonal pattern becomes obscured, and the patches of warmer and cooler water are related to changes in the currents over the shelf break rather than to true seasonal effects. Of particular interest are the periods when cold water (16°C) appeared along the seabed.

The monthly salinity pattern is similar (Figure 25), with the seasonal changes mainly in the upper 50 to 70m. Near the coast, the reduced salinities in summer were due to increased river flow following summer rains over the coastal region. The lowest salinities were in the top few metres only, indicating that a local river or heavy rainfall on the sea were largely responsible.

Few-day scale

Less regular are the variations which occur on a time-scale of days to weeks. During the winter months when the water on the inner shelf (at least) is vertically mixed, the only mechanisms for temperature changes are such processes as meandering of warm boundary currents onto the shelf, spin-off eddies, surface heating or cooling (probably a minor effect even under slack water conditions), and upwelling of cool water onto the shelf. In summer when the shelf water is stratified, the propagation of long waves along the shelf can result in oscillations of the thermocline over a few-day period. In many inshore coastal areas, such as off east Australia, river run-off is likely to be the major cause of salinity variations, although the processes discussed above for temperature will also apply.

The only factor of any importance in causing salinity or temperature changes over a period of hours is internal wave activity (see next section), in which oscillations of the thermocline with a period of minutes to a day will result in temperature changes at a fixed depth. The changes will be greatest when the thermocline or halocline gradient is greatest and the internal wave-height is largest.

Fronts

The presence of temperature or salinity "fronts" on the shelf should be mentioned. Fronts are regions where the temperature or salinity changes very rapidly, and generally separate water bodies of different types. The processes operating at surface fronts are complex but usually some convergence (or flowing together) of water is involved. Typical fronts include the edge of a freshwater plume discharged from a river, and the temperature front at

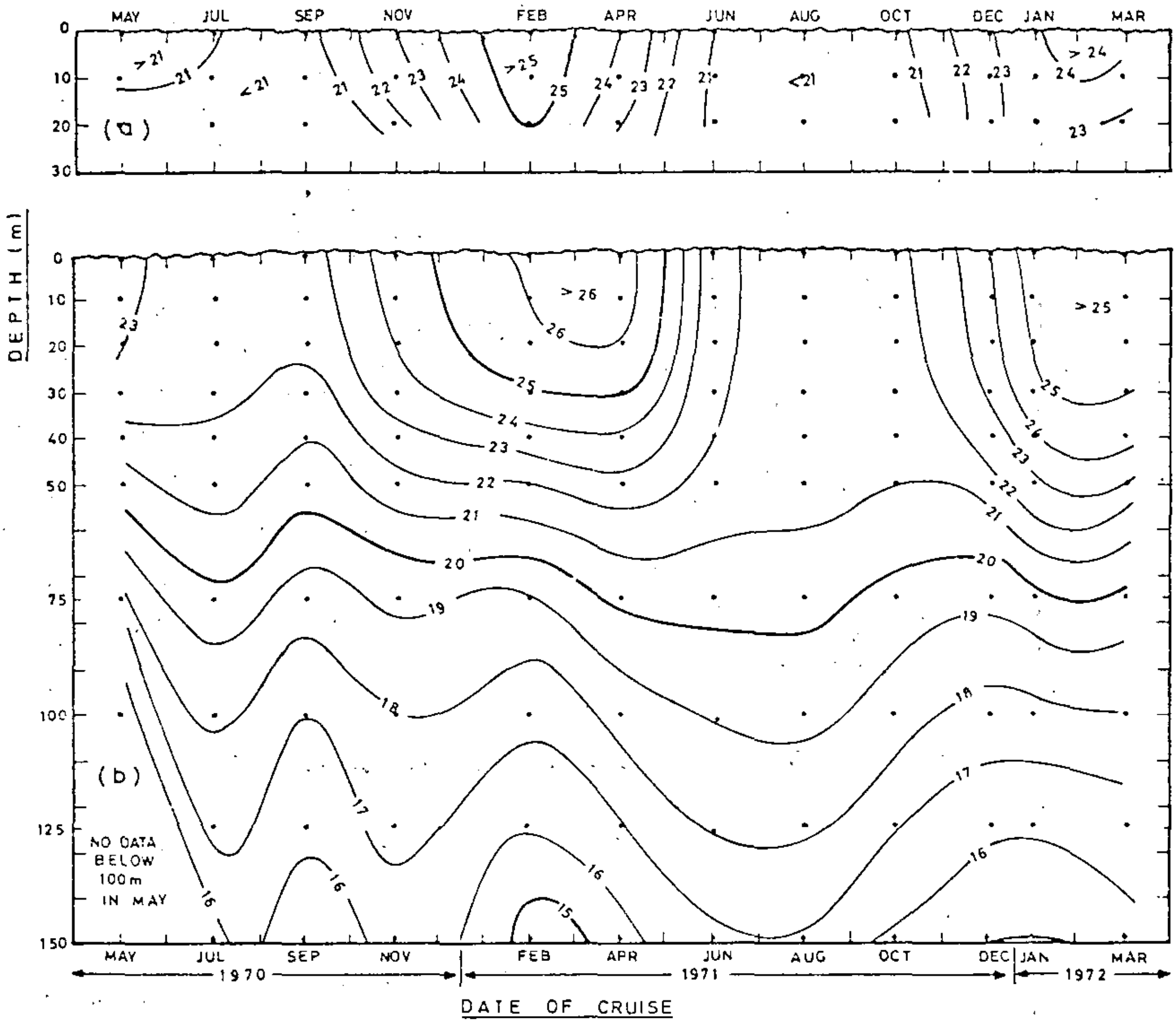


Fig. 24. Time-sections of mean monthly temperatures (°C) for (a) the inner and (b) outer shelf regions, off the east coast of South Africa. (From Pearce, A.F. "Seasonal variations of temperature...". S.A. Geographical Journal, Vol. 60, No. 2, pp. 135-143. Fig. 3. Reprinted with permission).

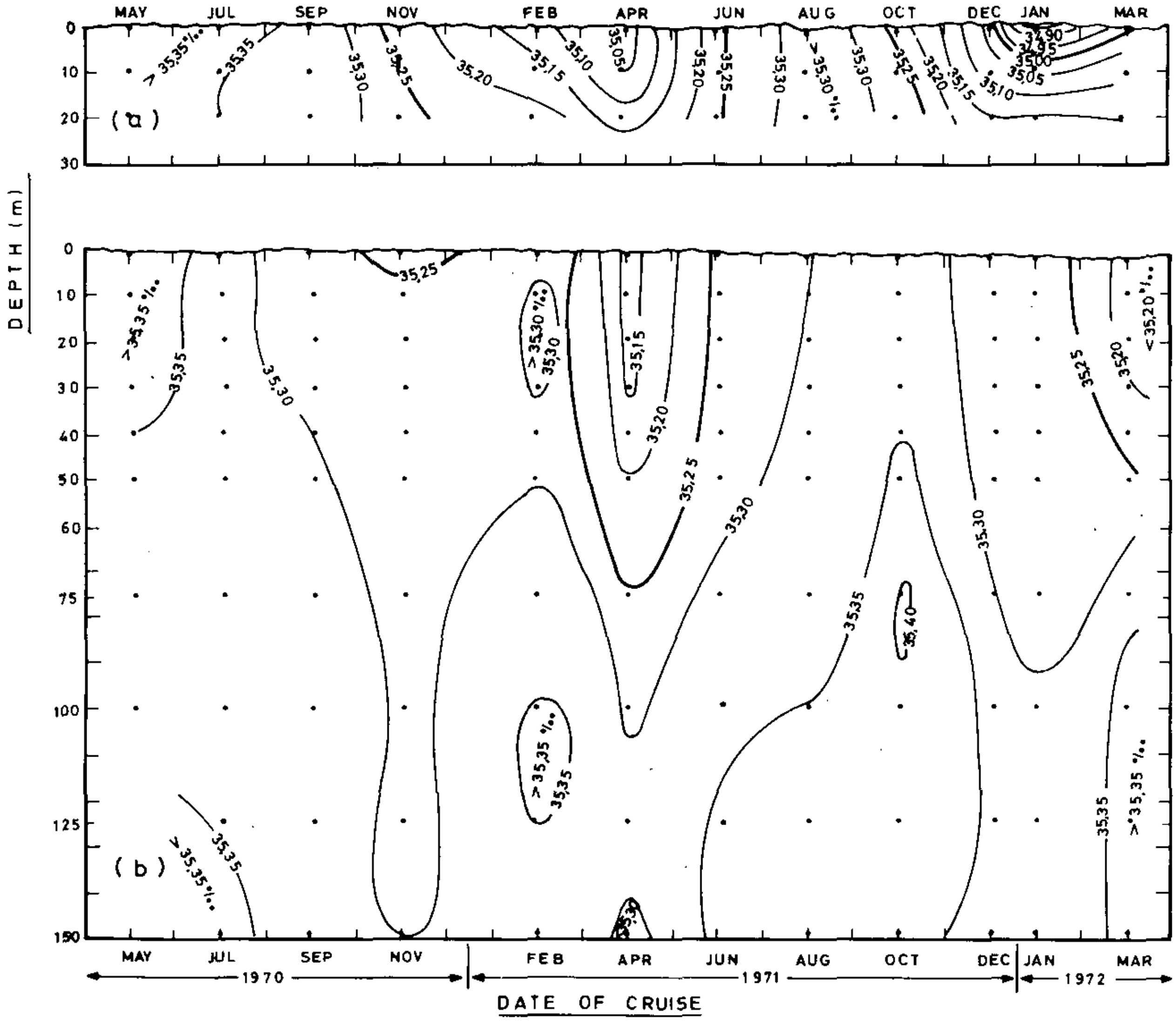


Fig. 25. Time-sections of mean monthly salinities (‰) for (a) the inner and (b) outer shelf regions off the east coast of South Africa. (From Pearce, A.F. "Seasonal variations of temperature...". S.A. Geographical Journal, Vol. 60, No. 2, pp. 135-143. Fig. 5. Reprinted with permission).

the boundary of an eddy or a western boundary current (as in Figure 21a and b). Fronts are often found near the edge of the continental shelf, and in certain areas tidal mixing can result in the formation of strong fronts.

WAVES AND TIDES

1. *Surface Waves*

Surface waves are the most obvious motion of the sea. Wind blowing over the water forms small wavelets, which gradually grow in size as the wind continues to blow, and the resulting choppy surface is called "sea" while it is still being acted upon by the wind. However, the "sea" moves away from the windy area, and the rather irregular surface slowly changes to a much more regular shape called "swell", which can travel for many hundreds of kilometres across the sea before breaking upon distant beaches.

The height of sea waves is anything from a few centimetres to more than 30m in a severe storm, and the period is generally of the order of say 5 to 20s. Some of the terms used in defining the characteristics of a surface swell are illustrated in Figure 26, which also shows the "orbital motion" (or paths of water particles) below the surface of waves in shallow and in deep water. This particle velocity is of great importance because it can affect the readings of some kinds of current meters, particularly near the sea surface.

From Figure 26a, the wave crest is the highest part of the wave and the trough is the lowest, the frequency is the number of crests (or troughs) passing a fixed point in a specified time interval, and the wave speed or celerity is the velocity of movement of a wave. For other definitions, see the glossary.

The properties of surface waves are different if they are in shallow or deep water. For deep water waves (where the water depth is more than half the wavelength — Figure 26b), the wavelength depends purely on the wave period, according to the approximate relationships:

wavelength L(m) = $1.56\ T^2$
(period T in seconds)

wave celerity C(m/s) = $1.56\ T$

since celerity C = L/T.

In this case, the wave particle orbits are circular, and decrease with depth below the surface so that at a depth of half the wavelength the motion is negligible.

For shallow water waves, where the water depth is less than 1/20 of the wavelength, wavelength and celerity depend on the water depth:

wavelength L(m) = $3.1\ T\sqrt{D}$
(period T in seconds, water depth D in metres)

celerity C(m/s) = $3.1\ \sqrt{D}$.

Beneath shallow water waves, the particle orbits are elliptical, with the vertical motion decreasing with depth while the horizontal particle velocity is constant down to the seabed (Figure 26 c).

For intermediate cases between deep-water and shallow-water waves, the relationships are considerably more complicated. As waves move into shallow water, the wavelength and wave speed will change, but the wave period remains constant.

An interesting feature of surface waves approaching a beach is the refraction of the waves. This is the gradual curving of the wave crests as they enter the shallower water, so that they become more parallel to the beach (Figure 27). When the depth contours are complicated, such as near headlands or over valleys, this refraction can cause focussing or dispersion of the wave energy, with

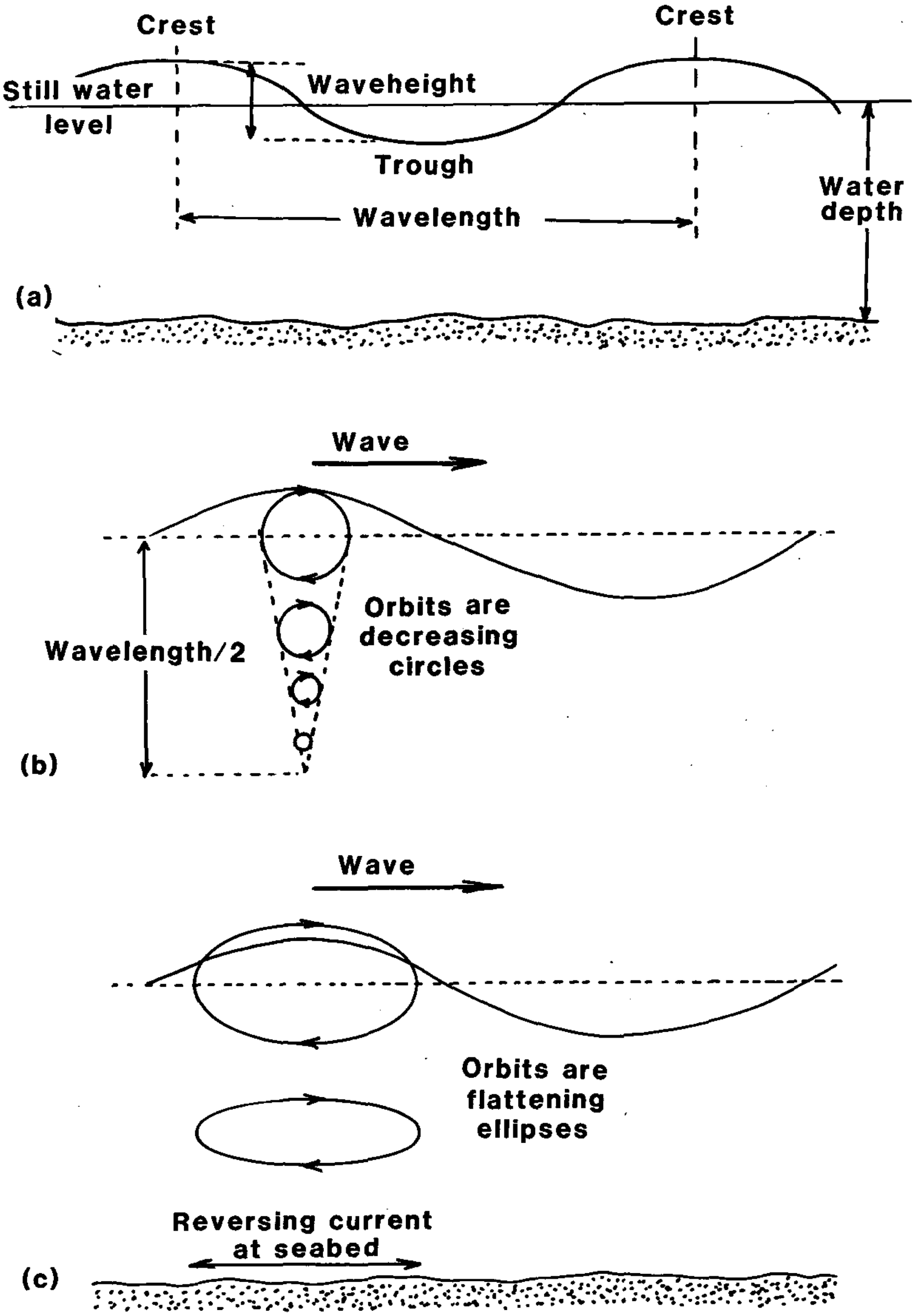


Fig. 26(a). Diagram of a simple seawave.
(b) and (c). Orbital motions in deep water and shallow water.

resulting variable effects on the beaches. The refraction can be easily explained from the shallow-water equation above ($C = 3.1\sqrt{D}$). As the water becomes shallower, the speed is decreased and the wave slows down, thus gradually bending towards the beach.

2. *Tides*

Astronomical tides

The regular rise and fall of sealevel over a period of a day or half-a-day is the tide, caused by the gravitational attractions of the moon and the sun on the oceans. If the earth were completely water covered at an even depth, the tides would be predictable from theory. However, with the presence of the land masses and with variable ocean depths, the actual movement of the tidal waves over the earth is complex. At any particular place, however, a sufficiently long tidal record from a sealevel recorder will yield the *tidal constants* enabling the tidal characteristics of that place to be predicted quite accurately.

In some places, a diurnal tide exists, i.e. a single high and low water cycle each day (or actually just under 25 hours) — Figure 28a. In other places, there are two highs and two lows of approximately equal size each day, i.e. a semi-diurnal tide, as in Figure 28b. Yet other areas may have a mixed tide, an example being in Figure 28c.

In addition to the above daily cycles, the relative motions of the sun and moon cause a monthly cycle. Every two weeks, the sun's and moon's effects act together to cause relatively higher and lower tides known as spring tides. Between spring tides, the sun and moon act at right-angles, in which case the tidal ranges are less than usual, and these are called neap tides.

Typical tidal ranges (i.e. from low to high tide) are of the order of 1 to 2m, such as on the east Australian coast. However, in some parts of the world the tidal range can exceed 15m, particularly in gulfs and bays.

The tidal currents associated with tides have been discussed briefly in a previous section.

The tides caused by the attractions of the sun and moon are very regular in nature and are known as *astronomical tides*. Two other kinds of sealevel changes which are mistakenly called tides are wind-generated storm surges, and geologically caused waves, both of which are highly irregular.

Meteorological (wind) tides

When a very strong wind blows along a coastline, and the atmospheric pressure is very high or very low due to a storm, exceptionally high or low sealevels can occur when such effects coincide with the usual (especially spring) tides. These are known as *meteorological tides* or *storm surges*, and have been responsible for major coastal catastrophies in some parts of the world. The worst effect will of course be when there is a high spring tide, an unusually low atmospheric pressure, and a strong wind blowing towards the coast or with the coast on its left in the southern hemisphere (or on its right in the N.H.). The resulting extra set-up of sealevel along the coast can be many tens of centimetres, and the high surface waves associated with the wind can then overtop coastal walls and cause tremendous damage.

Tsunamis

Tsunami is a Japanese term used to describe sea waves caused by geological disturbances or earthquakes under the sea (the term "tidal wave" is a misnomer). The resulting sudden water displacements move outwards away from the fault zone at high speeds (about 600 km/hour) but relatively low waveheights in the

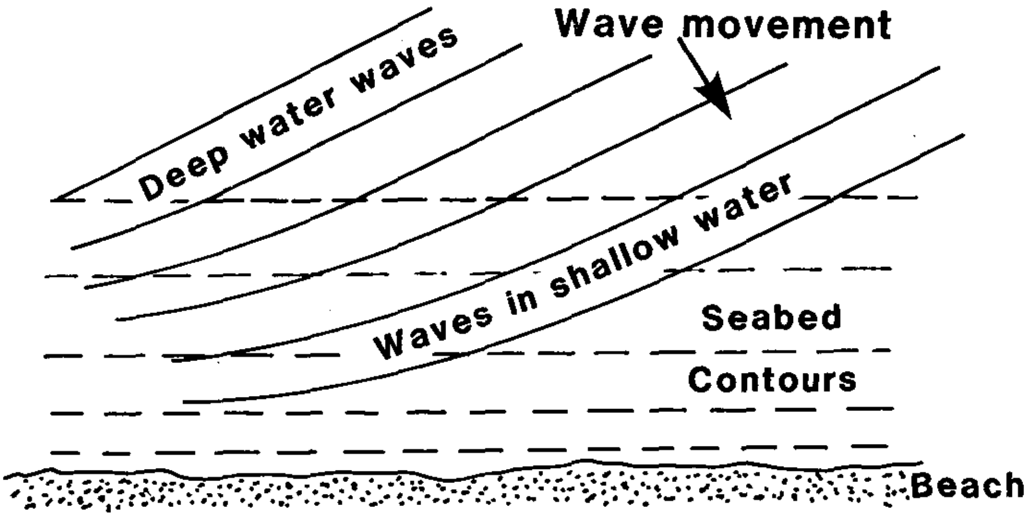


Fig. 27. Refraction of waves entering shallower water.

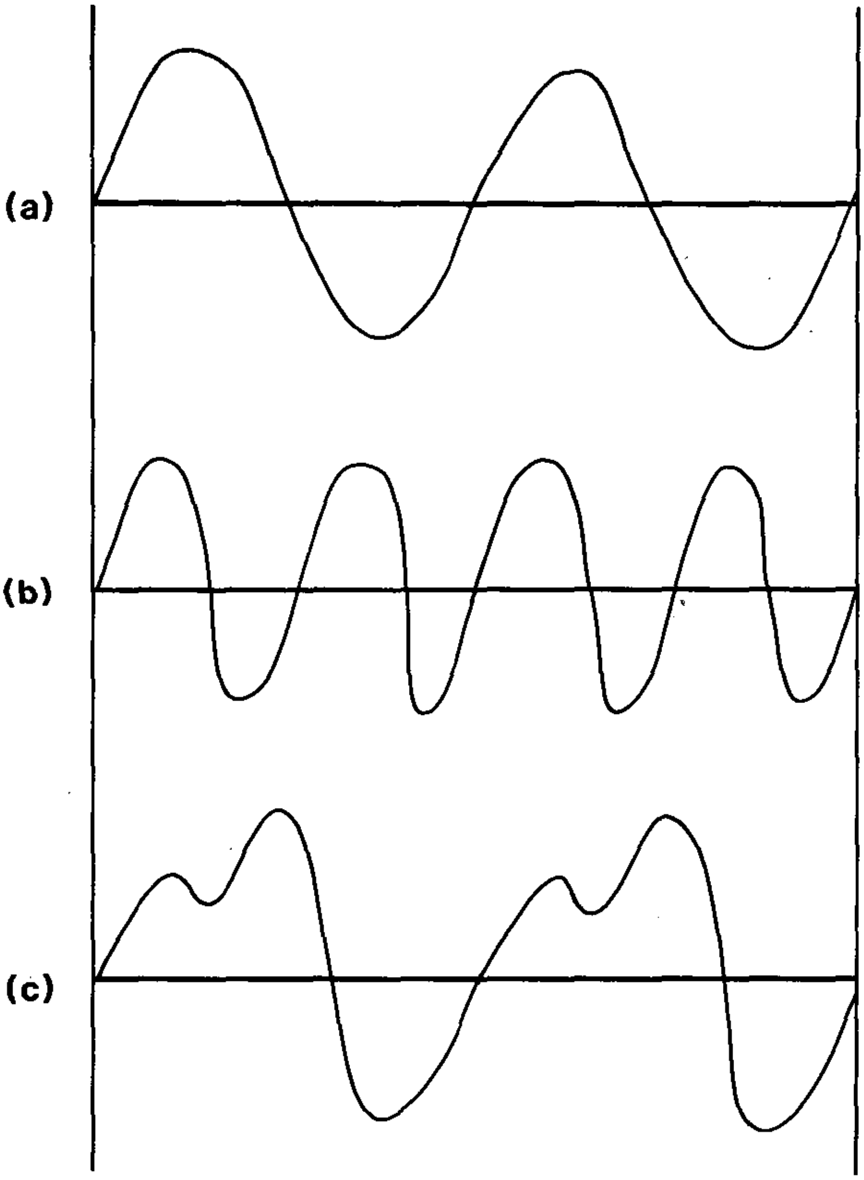


Fig. 28. Types of tides.
(a) Diurnal (i.e. daily).
(b) Semi-diurnal (twice-daily).
(c) Mixed.

deep sea. On nearing a coast, the energy in the wave causes it to grow in height, and the tremendous speed of the wave causes it to run up the coast sometimes to heights of tens of metres. Tsunamis can sometimes be predicted from earthquake measurements, allowing the time of arrival of the waves at a particular place to be forecast.

3. *Internal waves*

If a strong thermocline exists, waves can move along such a density change, and are called *internal* waves because they are below the sea surface. Basically their structure is very like that of a surface wave, but because of the relatively small density difference across the interface, internal waves usually have greater waveheights, wavelengths and periods than surface waves, and move far more slowly. They can be observed by a periodic rise and fall of the thermocline with a period of minutes to hours; if they have a period equal to the tidal period, they are called *internal tides*.

An important aspect of internal waves is their interaction with the continental shelf, as there is evidence of exceptionally strong shelf break currents apparently being caused by internal waves breaking near the edge of the shelf; this can enrich coastal water by bringing up nutrients from deeper layers. Internal waves can occasionally be observed as a series of surface slicks or bands moving towards the coast.

Internal waves are illustrated diagrammatically in Figure 29.

APPLICATIONS OF COASTAL PHYSICAL OCEANOGRAPHY

An understanding of some of the processes discussed above is of great importance to man's activities in the coastal sea.

1. *Effluent Dispersion*

For economic reasons, it is becoming common for coastal cities to dispose of their sewage and other effluents by discharging them through a long pipe (or outfall) into the sea; usually the pipe outlet (or outlets) are in water depths of 20m to 100m, where it is hoped that currents will carry the effluent away from the coast and so avoid pollution of the beaches. As the effluent (which is usually less dense than seawater) emerges from the pipe it mixes with the surrounding seawater as it slowly rises because of the density difference. If there is a strong thermocline, the effluent plume may be trapped there without reaching the surface. The partly diluted effluent "field" is now at the mercy of the currents, which will carry it away from the outfall, and further dilution occurs due to eddy mixing processes. In a reversing current system, the effluent field may simply move backwards and forwards over the area instead of being transported away. If the current is moving towards the coast, pollution of the beaches may occur.

2. *Other Pollution*

Other forms of pollution can cause damage to coastal communities. A major oil spill, for example, can result in tremendous problems in coastal areas if the surface current carries it inshore, and expensive detergent is then sprayed onto the oil while it is still out at sea to try and disperse it. However, the detergent is often toxic to marine life, and if the oil will be carried out to sea by the currents it would be better not to spray it.

3. *Shipping*

In coastal areas, and particularly regions where strong boundary currents and eddies occur, there are great

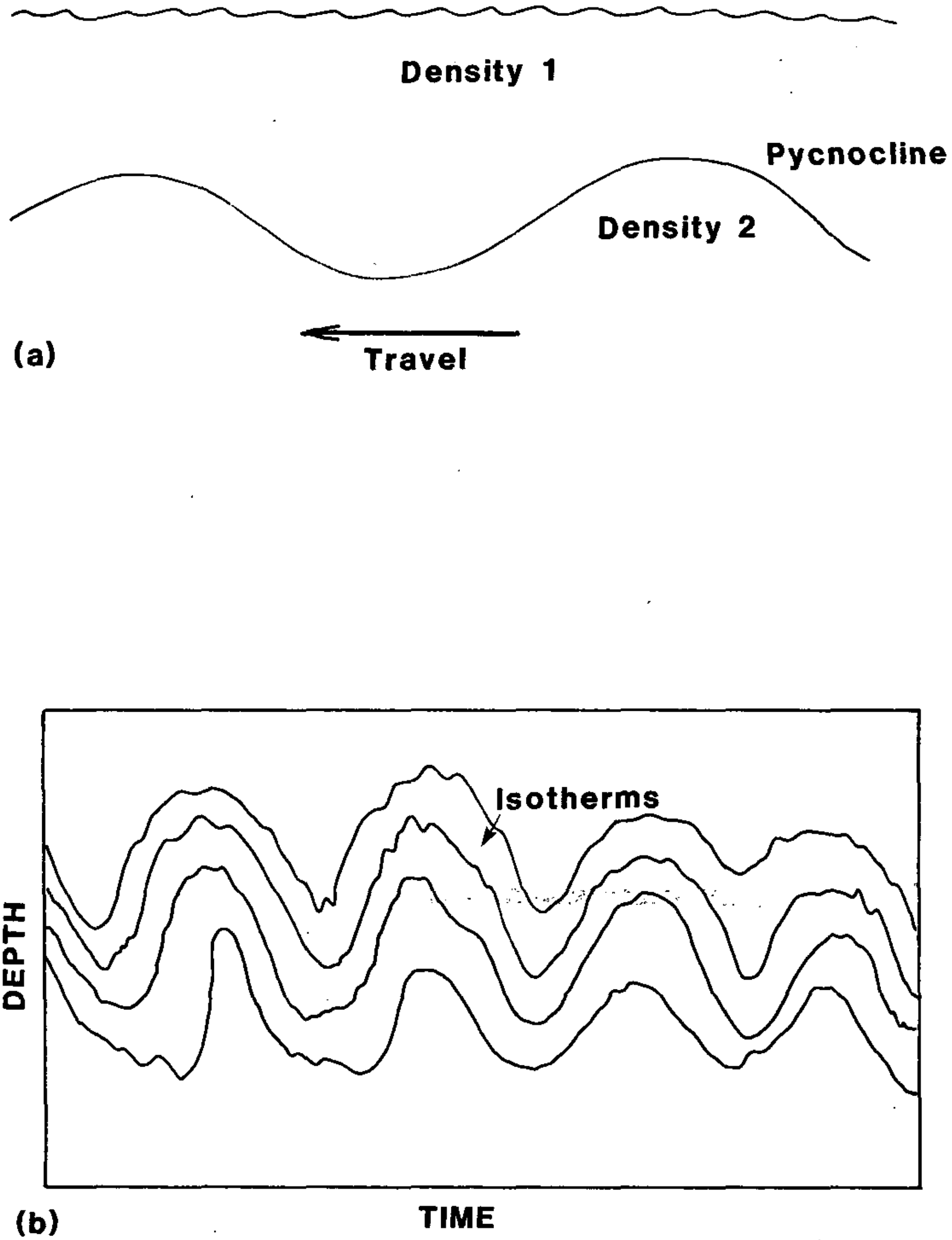


Fig. 29(a). Diagram of an internal wave.
(b). Time series of temperature at a station showing the periodic rise and fall of the thermocline associated with internal waves.

savings in time and money if the currents can be sufficiently well forecast for ships to find favourable currents (i.e. flowing with them) and avoid strong head currents. Further, if a ship breaks down, or a yacht is missing, a knowledge of the currents will enable the search for the vessel to be concentrated in the most likely areas, thus saving expense and perhaps lives.

Dangerous waves ("freak" waves) occur in some parts of the world when gale-force winds blow against a strong current, and there is evidence that this effect is most severe where there are large velocity gradients or changes. Ships should attempt to avoid such areas in adverse weather conditions and thus reduce the risk of major disasters as have occurred (for example) off the east coast of South Africa.

4. *Sediment Transport*

The erosion of beaches and the silting up of harbours and bays are problems related to the transport of sediment along a coast. The important factors involved are the wave climate (which depends to some extent on the wind patterns), the bottom topography, and currents in the nearshore region and possibly in the inner shelf zone. A better understanding of these factors would enable the correct defensive structures to be built.

5. *Coastal Structures*

Engineering works, such as submarine outfalls, long jetties, harbour breakwaters and oil rigs, are greatly influenced by the currents and waves. For design purposes, it is vital to know the strongest currents and the highest waves which may be encountered, while the ability to forecast calm conditions for the construction of such works would be invaluable.

6. *Coastal Climates*

It has been found that there is often a relationship between the coastal climate and oceanographic features, a good example being higher rainfall in Sydney associated with higher sea temperatures on the continental shelf. It appears that the large warm ocean eddies may also play a part in influencing the local climate.

7. *Marine Life*

The planktonic stages of many marine organisms which exist in coastal waters are at the mercy of the currents. For economic species such as lobsters, it is useful to know how and where the currents carry the larvae, and where the various stages of the growth and development of these animals occur. At present, some biological studies are hampered by a lack of knowledge of the current system.

It has also been shown that such factors as sea temperature are important in the distribution of marine organisms. Tuna, for example, tend to congregate along oceanic fronts such as on the edges of eddies, so commercial fisheries would like to know more about the formation and movement of these fronts.

APPENDIX 1 CONSTANTS AND CONVERSION FACTORS

For convenience, various numerical constants (not all of which are referred to in the text) and conversion factors are listed here.

1. Constants

$\pi = 3.14159$

1 radian = 57.3°

Earth mean radius = 6371 km

Earth angular velocity = 7.29×10^{-5} rad/s

1° latitude = 60 n miles = 111 km

Gravity $g = 980$ cm/s^2

Mean density of seawater $\simeq 1.025$ g/cm^3 ($\sigma = 25$)

Mean density of air $\simeq 0.0012$ g/cm^3

Standard atmospheric pressure = 1013 mbar = 760 mm mercury

Velocity of sound in seawater $\simeq 1500$ m/s

2. Conversion factors

1 nautical mile = 6076 feet = 1852m

1 fathom = 6 feet = 1.829m

1 m = 3.281 feet = 39.37 inches

1m^2 = 10.76 feet^2

1 knot = 1 nautical mile/hour = 0.514 m/s

APPENDIX 2 READING LIST Lecture 1

The following publications and books are suggested for further reading, to widen the scope of the material in this report. They are publications which were found to be useful in compiling these notes, and selection has obviously been subjective. Material has been taken from many sources, including technical papers in journals or unpublished institutional reports, and as many of these may not be readily available they have not been included here — this section is therefore not a "Reference List".

Admiralty (1969). Tides and tidal streams. Admiralty manual of hydrographic surveying. Volume 2, Chapter 2. HMSO, 119 p. (excellent introduction to tidal theory, observation. analysis, and tidal streams).

Bank of NSW (1979). Offshore resources: Australia's continental shelf and beyond. Bank of New South Wales, 78 p. (Description of Australia's shelf area, and mineral resources (oil in particular)).

Deacon, G.E.R. (ed) (1968). Oceans. An atlas-history of man's exploration of the deep. Paul Hamlyn, 297 p. (Interesting and popular-level account of marine activities and oceanography).

Defant, A. (1958). Ebb and flow. The tides of earth, air and water. Ann Arbor, 121 p. (Elementary discussion on tides in all aspects).

Duxbury, A.C. (1971). The earth and its oceans. Addison-Wesley Publ. Co., 381 p. (Good introductory text; includes geology, biology, chemistry. Some elementary mathematics (high school level)).

Gross, M.G. (1971). Oceanography. Merrill Physical Science Series, 150 p. (Elementary descriptive text. No mathematics).

McIntosh, D.H., and Thom, A.S. (1972). Essentials of meteorology. Wykeham Science Series, 238 p. (Useful elementary text, some mathematics mainly high-school level).

McLellan, H.J. (1975). Elements of physical oceanography. Pergamon Press, 151 p. (Concise, but clear explanations. University level mathematics. Very useful book).

Miller, A. (1971). Meteorology. Merrill Physical Sciences Series, 154 p. (Non-mathematical elementary general text, concise).

Mitchell Beazley (Pub.) (1977). Atlas of the oceans. Mitchell Beazley, London, 208 p. (Profusely illustrated atlas of oceanography and marine resources of the world oceans).

Neumann, G., and Pierson, W.J. (1966). Principles of physical oceanography. Prentice-Hall, 545 p. (Comprehensive text in physical oceanography; University level mathematics. Recommended for more advanced students).

Pickard, G.L. (1963). Descriptive physical oceanography - an introduction. Pergamon Press, 199 p. (Very good elementary text, at the descriptive level. Recommended for general reading. No mathematics).

Shepard, F.P. (1971). The earth beneath the sea. Atheneum Press, 242 p. (Popular-level account of seabed topography and processes).

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APPENDIX 3: GLOSSARY (WORD-LIST)

Some of the terms used in the text are briefly and simply explained here. The page numbers indicate where each term is discussed.

ANTICYCLONIC FLOW:	Anticlockwise flow (Southern Hemisphere), or clockwise flow (Northern Hemisphere). Page 19.
BATHYMETRY:	The depth and shape of the seabed. Page 2, 5.
BOUNDARY CURRENT:	Usually fast-flowing ocean current concentrated near the edge of the ocean. Page 10, 16.
CAPILLARY WAVE:	Wave whose characteristics depend on the surface tension of the water, usually having wavelengths less than about 3 cm.
CELERITY:	Speed (e.g. of a wave). Page 38.
CONTINENTAL MARGIN:	The true edge of the continent, consisting of the continental shelf, slope and rise. Figure 2.
CONTINENTAL RISE:	The rise from the deep ocean bed up to the continental slope. Figure 2.
CONTINENTAL SHELF:	The shallow water region (to 100 m or 200 m depth) around the continent, out to the shelfbreak where the seabed slopes more steeply. Figure 2.
CONTINENTAL SLOPE:	The relatively steep slope between the shelfbreak and the continental rise. Figure 2.
CONVERGENCE:	Flowing together of two water bodies, with sinking of water at their meeting point. Page 10.
CORIOLIS EFFECT:	Arises from the relative motion of an object over the rotating earth, causing the object to deflect to the left in the Southern Hemisphere (or the right in the Northern Hemisphere). Page 5.
CREST OF WAVE:	The highest part of a wave (opposite to "trough"). Figure 26.
CURRENT SHEAR:	Change of current speed with distance or depth. Page 19.
CYCLONIC FLOW:	Clockwise flow (in the Southern Hemisphere), or anticlockwise flow (Northern Hemisphere). Page 19.
DEEP WATER WAVES:	Waves whose wavelength is less than half of the water depth. Page 38.
DECIBAR:	Unit of pressure in the sea. Roughly, a depth change of one metre gives a pressure change of one decibar.

DIURNAL TIDES:	Tidal cycle with one high and one low sea level per day. Page 40.
DYNAMIC HEIGHT:	In practical terms, this is the height of the sea surface relative to that of a "standard ocean" whose temperature is 0°C and salinity 35‰, both of these being relative to some reference depth. Page 16.
EDDY:	Circular movement of water, on scales ranging from very small to a few hundred kilometres. Page 16,19.
EKMAN SPIRAL:	The gradual rotation of current vectors with depth (the velocity decreasing with depth), resulting from wind stress on the sea surface and internal friction in the water. Page 24 ; Figure 16.
FIX:	An estimate of the position of a ship or buoy at sea.
FRONT:	A region in the sea where the horizontal temperature or salinity gradient is much greater than on either side. Page 35,38.
GEOSTROPHIC FLOW:	The current or wind resulting when the Coriolis effect balances the pressure gradient causing the motion, so that the water or air flows parallel to the pressure contours. Page 10,16.
GRAVITY WAVE:	Wave whose characteristics are governed by gravity; surface water waves with wavelengths greater than about 5 cm are gravity waves. Page 38.
GYRE:	Large oceanic-scale circulation of water. Page 10 Figure 6.
HALOCLINE:	The layer of water where there is a rapid change of salinity with depth; often associated with the thermocline. Page 13.
INTERNAL WAVE:	A wave in the pycnocline, i.e. the interface between water layers of different density. Page 42; Figure 29.
ISOBAR:	Contour line joining points of equal pressure.
ISOBATH:	Contour line joining points of equal depth on the seabed.
ISOHALINE:	Contour line joining points of equal salinity.
ISOPYCNAL:	Contour line joining points of equal density (or sigma-t).
ISOTHERM:	Contour line joining points of equal temperature.
ISOTHERMAL	Constant temperature.

MASS TRANSPORT: (by waves)	The forward transport of water in the wave. Figure 15.
MEANDERING:	The process of a current slowly swinging from side to side. Page 27.
MEAN SEALEVEL:	Sealevel averaged over a long period of time to eliminate wave and tidal effects.
MERIDIAN:	Line of longitude on the globe, i.e. north-south.
MERIDIONAL FLOW:	Flow along a meridian, i.e. north-south.
MIXED LAYER:	A region in the sea where the water is vertically mixed and (usually) has a constant temperature. Page 13.
MIXED TIDE:	Tidal cycle with two high and two low sealevels per day, but they are of different ranges. Page 40.
OSCILLATION:	Fluctuation, or periodic rise and fall.
PYCNOCLINE:	The layer of water where the density suddenly increases with depth; usually associated with the thermocline. Page 13.
REFRACTION OF WAVES:	The change in direction of waves as they move into water of varying depth. Page 38 , Figure 27.
RIP CURRENTS:	The narrow jet-like currents carrying water from the breaker zone back out into deeper water. Page 22,24 Figure 15.
SALINITY:	The salt concentration (or amount of salt per unit volume) of seawater; usually about 35 g/kg (or ‰, parts per thousand).
SEASONAL CHANGES:	Changes on the time-scale of the seasons, i.e. spring, summer, autumn and winter. Page 35.
SEDIMENT:	Sand, mud, shell fragments, etc., on the seabed.
SEMIDIURNAL TIDE:	Tidal cycle with two high and two low sealevels per day, of roughly equal ranges. Page 40.
SIGMA (σ):	A density parameter: sigma = (density-1) x 1000. Page 13.
SIGMA-t (σ_t):	Sigma value at zero pressure, i.e. depends on temperature and salinity but not depth. Page 13.
STORM SURGE:	A rise above normal sealevel on a coast due to wind (storm) effects. Page 40.
STRATIFICATION:	Layering of the water, shown by vertical temperature or salinity gradients. Stratified water is the opposite of vertically-mixed water. Page 13.

SURF (BREAKER) ZONE:	The coastal region where the incoming swell breaks. Page 22
THERMOCLINE:	The layer of water where there is a rapid decrease of temperature with depth; usually occurs at the base of the surface mixed layer. Page 13.
THERMOHALINE PROCESSES:	Those which depend on variations in temperature and salinity (and hence in density). Page 24.
TIDAL RANGE:	The vertical distance between high tide and low tide.
TOPOGRAPHY:	The physical features and shape of the seabed. Page 2,5.
TROUGH OF WAVE:	The lowest part of a wave (opposite to "crest"). Page 38 , Figure 26.
TS DIAGRAM:	Temperature-salinity diagram, where temperature is plotted against salinity on a graph and the points are joined in order of depth. Page 13, Figure 10.
TSUNAMI:	Long period wave caused by underwater geological disturbances; commonly misnamed "tidal wave". Page 40.
UPWELLING:	The raising of water from moderate depths to shallower depths; usually signifies cool, nutrient-rich water being raised from about 100 m depth to the surface, often as a result of surface wind stress. Page 24.
WATER MASS:	A body of water having specific temperature and salinity characteristics. Page 13.
WAVE DIRECTION:	The direction from which a wave approaches.
WAVE GROUP:	A series of waves of similar direction and wavelength.
WAVE HEIGHT:	Vertical distance between a crest and a trough. Page 38.
WAVELENGTH:	Horizontal distance between two successive wave crests (or troughs). Page 38.
WAVE PERIOD:	The time for 2 successive wave crests to pass a fixed point. Page 38.
WIND STRESS:	The stress caused by the wind on the sea surface. Page 10.
ZONAL FLOW:	Flow along a line of latitude, i.e. east-west.

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