The physical oceanography of Australian waters—a review*

P. G. Baines
President, Australian Meteorological and Oceanographic Society
CSIRO Division of Atmospheric Research
Aspendale, Australia

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Introduction

The achievements in Australian oceanography over the past fifteen years have seen it reach a level of world prominence which greatly exceeds its reputation in the past. The principal objectives of this review are, first, to give a feeling for the flavour of modern Australian oceanography and what makes it interesting and even exciting, and second, to give some idea of the variety of phenomena involved. The article attempts to cover the whole region but is limited because of its length; the topics covered should be regarded as a personal selection. I must apologise in advance to those people whose work is not adequately represented, referenced, or properly acknowledged. The review is intended for a wide audience, with no particular knowledge of physical oceanography being assumed.

The Australian environment contains a rich variety of oceanographic features which are peculiar to the region, or which are much more pronounced here than elsewhere. The bottom topography of the region is very varied, as may be seen in Fig. 1. The nearshore region contains long coastlines which run north-south and east-west, with both broad and narrow continental shelves, vast coral reef environments, extensive shallow tropical seas and the unique environment of Bass Strait. This diversity gives rise to a corresponding diversity in physical phenomena, many of which are as yet poorly understood.

Fig. 1 Bathymetry of the Australian marine environment. Depth contours are marked in fathoms.

We may divide the subject up into three main areas: (a) surrounding ocean currents, (b) tides, and (c) coastal oceanography, and we will deal with these in turn.

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Surrounding ocean currents

These surface (i.e. upper ocean) currents are mostly driven by the winds acting over the whole of the relevant ocean basin. Figure 2, which is part of a world chart printed in Hamburg in 1943, shows a chart of the surface currents in the Australian region obtained from ship drift data for the summer season. The Leeuwin Current (see below) is conspicuously absent, but otherwise no significant corrections from more recent observations seem to be necessary. This is a statement of how little we know about our surrounding oceans, and how little detail has been added to the deep sea in the past 50 years, rather than that we know it all. For example, the chart represents summer mean conditions, but we are not aware of what the seasonal variations are with any confidence, even for the East Australian Current.

Fig. 2 Ocean currents in the Australian region in summer. From 'Weltkarte zur übersicht der Meereströmungen', Deutschen Seewarte, 1942. Longer arrows imply steadier currents, thicker arrows imply stronger currents. Dashed lines denote lines of convergence and divergence.

The Tasman Sea

As shown in Fig. 2, the inflow from the South Equatorial Current bifurcates at the middle of the Great Barrier Reef region, with the southward flowing portion accumulating to form the East Australian Current (EAC). The transport and variability of the EAC are uncertain, but the mean appears to be about 15 Sverdrup, or 15 x 10^6 m^3 s^-1 (Godfrey and Golding 1981). The current reaches its maximum transport just before it separates from the coast, which usually happens a little to the north of Sydney. Most of this warm water flows back northward further offshore, or flows eastward along the mid-Tasman front to pass north of New Zealand. Eddies form where the current recirculates and 'pinches off'; examples are shown in Fig. 3. These deep anticyclonic warm-core eddies may drift around the southern Tasman Sea, and then rejoin the current by merging with it or possibly escape into the circumpolar current to the south. There is no evidence of a substantial mean flux through the Tasman Sea in either direction and the bottom topography (principally the Lord Howe Ridge) ensures that the deep water is closed off. Figure 4 shows another example of the Tasman Sea EAC pattern taken nine days after Fig. 3, and a comparison between the two gives some indication of the variability. This pattern of behaviour of the EAC is different in detail from that found in any other ocean basin. The influence of New Zealand, to the east, may be a significant factor in this difference, and may control the mean location where the current separates from the coast.

Fig. 3 The East Australian Current system on 11 December 1980, showing two eddies (Maria and Leo). Dark shades indicate warm water (from Cresswell and Legeckis 1986).
Fig. 4 Same as for Fig. 3 but for 20 December 1980. Note the extent of the change from Fig. 3 in just 9 days.

The Indian Ocean
Here the circulation in the deep water in the Australian region has hardly been observed at all, and a broad northward flow as shown in Fig. 2 is largely inferred from ship drift and indirect considerations. No significant variability in the flow has been detected in this area by satellite altimetry, except quite close to shore where it is associated with the Leeuwin Current.

An important and as yet undetermined quantity for global ocean circulation is the ‘Indonesian throughflow’, which is the quantity of fluid which flows into the Indian Ocean north of New Guinea and through the Indonesian archipelago from the Pacific (the flow through Torres Strait is negligible). This flux is important for global ocean budget and climate calculations as well as for regional oceanography, but attempts to measure it have so far been frustrated by political and bureaucratic factors. The best estimate to date, based on circumstantial evidence, is about 15 Sverdrup.

Tides
The oceanic tides are forced by the differential gravitational attraction of the sea waters by each of the sun and the moon. The effect on currents is generally small except in shallow regions such as near coasts, where it may be the dominant cause of fluid motions. The overall effect of tidal forcing may be represented as the forcing of a rather complex oscillator (the oceans) at a number of discrete frequencies, mostly concentrated around a 12-hour period (semi-diurnal) and a 24-hour period (diurnal), with a few at much longer periods. The two most significant of these constituents are the $M_2$ (period 12.42 hours) due to the moon, and the $S_2$ (period 12.00 hours) due to the sun, with the former having the larger amplitude in nearly all locations. The beating between these two components gives the familiar fortnightly pattern of spring and neap tides.

Figure 5 (from Schwiderski 1979) shows the pattern of amplitudes (a) and phases (b) of the $M_2$ constituent in the Australian region, including the amphidromic points which are certain points of zero amplitude. Large amplitudes may occur in certain regions because the local geometry may be close to resonance for a particular frequency. A good analogy is an
Fig. 5 The M2 tides in the Australian region. (a) Amplitudes in cm, and (b) Greenwich phases in degrees. From the numerical interpolation model of Schwiderski (1979).

organ pipe which is closed at one end and open at the other; this pipe resonates for sound waves which have a wavelength equal to four times the length of the pipe. In the same way, surface waves in the ocean travel at a speed \((gd)^{1/2}\) which varies from place to place with the local depth \(d\); waves propagating over a continental shelf towards the coast (the closed end) may resonate if their wavelength is equal to four times the distance between the coast and the shelf-break or edge (the open end). This is just one common example of resonance and, in general, local geometry and depth variations result in considerable variation in the amplitude of each tidal constituent in coastal regions. Tides are essentially linear phenomena, but in these shallow regions they may become non-linear if their amplitude is large enough, and bores may form in narrowing shallow regions close to the shore. There are two main regions of large amplitude for semi-diurnal tides (and the M2 in particular) around Australia, namely the northwest shelf and the southern Great Barrier Reef region.

The patterns of amplitudes and phases for \(S_2\) are very similar to those for \(M_2\) (which is not surprising because the frequencies are similar), with the amplitudes being typically smaller by about 50 per cent. This ratio is not constant; in Spencer Gulf, for example, the two amplitudes are equal, so that there is a large amplitude at spring tide, but at neap tide there is virtually no tide at all.

We may 'zoom in' on the two regions where the \(M_2\) is large. Figure 6 (Griffin et al. 1987) shows the cotidal chart for \(M_2\) for the Great Barrier Reef south of Broad Sound (the big 'kink' in the Queensland coast, visible in Fig. 1) which is the region of largest tides on the Queensland coast. The geometry here is affected by dense coral reefs offshore which act as a barrier to the tidal flow so that it approaches Broad Sound along the shelf from the north and the south, as shown in Fig. 6. This channelling gives rise to a local resonance which magnifies the tidal amplitude by a factor of 4 (Middleton et al. 1984). The local estuarine geometry of Broad Sound is itself close to resonance, giving a further magnification of 1.5. When the effects of the other constituents (principally \(S_2\)) are added, the tidal range at Broad Sound can be 35 feet, or 10.7 m (Flinders 1814).

Figure 7 (from Schwiderski (1979), drawn by Holloway (1983)) shows cotidal lines for \(M_2\) for the northwest shelf; here the 1/4 wave resonance mechanism applies, and the tides are the most significant part of the local current pattern. Some further effects of the tides in this region will be mentioned later. The largest tides in Australia are found at Secure Bay (near Broome) where the range can reach 40 feet, or 12.2 m (Easton 1970).

Coastal oceanography

Most of the interesting work in recent years has been done in coastal oceanography. We will start with the south coast of New South Wales and move anticlockwise around the country.
Fig. 6 M2 tidal height in (a) cm and (b) Greenwich phase lag for the region directly south of Broad Sound from a numerical model (from Griffin et al. 1987).

South coast of New South Wales
Perhaps the most significant development in coastal oceanography anywhere in the last thirty years has been the discovery and comprehensive study of coarsely trapped waves. These waves may be regarded as topographic Rossby waves over the continent slope, with the restoring force due to potential vorticity variation related to the bottom slope. An outline of the essential mechanism is illustrated in Fig. 8. If the density stratification of the ocean is neglected, a vertical column of water over the continental slope satisfies the vorticity equation.

$$\frac{D}{Dt} \left( \xi + \frac{f}{H} \right) = 0,$$

where $\xi$ is the relative vorticity (that is, relative to the local earth) of the fluid column, $f$ the Coriolis parameter, and $H$ the local fluid depth. A column of fluid at middle-level depth with no relative vorticity ($\xi = 0$) will develop anticyclonic relative vorticity if it is displaced toward the shore, owing to compression of the water column, and cyclonic vorticity if displaced toward deep water. If, as shown in the plan view, an along-coast variation in on-off shore displacements is established, the pattern of vorticity implies an associated fluid motion which causes the pattern to move to the right for an observer facing the shore in the southern hemisphere. In general, the shape of the topography and stratification are very important, and there are several modes with different horizontal and vertical structure, but the same physical principles apply. These waves may be of paramount importance for coastal upwelling, for coastal currents and their variations, for sea level changes, and for associated processes such as sediment movement, pollutant dispersal and fisheries.

Fig. 7 Amplitude in metres (solid lines) and Greenwich phase (dashed) for the M2 constituent for the northwest shelf, drawn by Holloway (1983) from the results of Schwiderski (1979).
These waves were in fact first discovered (or more accurately, observed) on the NSW coast by Bruce Hamon in the early 1960s (Hamon 1962, 1966), who noticed that variations in sea level progressed slowly northward along the coast; they have been the subject of much theoretical and observational study ever since. CTWs have now been observed in a variety of locations around the world.

To return to the southern NSW coast, this now historic stretch of coastline was chosen by Australians from the CSIRO Division of Oceanography and some participating Americans and Canadians as an ideal location for an experiment to test the theory of coastally trapped wave (CTW) generation and propagation; it is sufficiently long, straight and uniform, without complicating currents. This Australian Coastal Experiment (ACE) took place over a period of seven months in 1983 and 1984. The design of the experiment consisted of three main sections of instruments to observe the CTWs, together with meteorological observing stations. A plan of the experiment is shown in Fig. 9 and a schematic perspective in Fig. 10. Figure 11 shows the modal structure of the CTWs observed at the three main lines. They are quite consistent with each other and, generally speaking, the CTW theoretical modes fitted the observations quite well, except for effects attributed to East Australian Current eddies which moved into the arrays. The only major discrepancy was that the CTW energy flux through each of the three main arrays was approximately the same, so that instead of being generated on the NSW coast as originally expected, the wave energy was entering the region somewhere between Tasmania (where there was little energy on the east coast) and Gabo Island. We will return to this point later.

Fig. 10 A perspective view of the instrument arrays deployed in the ACE experiment (from Freeland et al. 1986).
Fig. 11 Vertical/offshore structure of the first three coastally trapped wave modes at each of the three principal mooring lines, and the phase speed associated with each mode. Contours represent constant longshore velocity, with dashed lines representing the opposite directions to the solid lines. Dots represent instrument sites (from Freeland et al. 1986).

Great Barrier Reef
The north Queensland continental shelf is unusual because of the numerous coral reefs which are present throughout the region, and which are concentrated at the edge of the shelf. Understanding the effects of these reefs and constrictions on the flow on the shelf, and their complex effects on the biology of the region, has been tackled by scientists from the Australian Institute of Marine Science near Townsville. In particular, these reefs tend to produce small-scale fronts where sediments, zooplankton, eggs from spawning coral, and predators tend to concentrate (Wolanski and Hamner 1988). One example is shown in Fig. 12. Shallow flow (20-50 m deep) past reefs and islands produces large separated eddies (the size of the island, which may be several kilometres long as here) on the lee side, where fronts marking sharp changes in water properties occur at the boundaries of these eddies. This is only one of several types of frontogenetic processes which have been identified, and much work remains to be done in this area.
Gulf of Carpentaria
In this unusual broad and shallow area, the mean currents and the semi-durnal tides are both weak. The tidal currents are mainly diurnal and are not strong, and local winds and storms seem to be significant for water movement, with bottom friction being important because of the shallow depth (20-60 metres), particularly in the south. Evaporation from the region is very significant for atmospheric processes.

Northwest shelf
This is a very large and remote area and its physical phenomena have not yet been very well explored, although some extensive measurements have been made in specific locations because of the presence of oil and gas fields in the region. The tides are quite substantial, as noted earlier, and the wind-driven and other currents are generally weak, apart from the occasional effects of tropical cyclones. Consequently, the principal dynamical phenomena in the area seem to be governed by the tides.

An example which is visible from satellites is shown in Fig. 13. Large tidal motions across the edge of the continental shelf generate large amplitude internal tides (internal waves of tidal period). These typically have wavelengths of 20 to 40 km, but they often steepen to form undular internal bores with wavelengths of about 700 m or more. These features are dynamically similar to the 'morning glories' observed in the atmosphere in the Gulf of Carpentaria region and elsewhere. They may be seen from above the surface because of the effect of the flow convergence and divergence of the internal waves on the surface roughness. Hence they are visible in this Landsat picture which shows packets of waves from up to four tidal cycles. Internal waves with this character have been seen in satellite imagery from many parts of the world but this particular picture is remarkable because it contains more of these waves than any other that I have seen—apart from the semicircular bands in the centre, most of the right-hand (shallow water) part of the picture is covered with them! Internal tides are important because they may substantially increase the maximum tidal currents experienced at a particular location, and this may be very significant for oil and gas platforms, for example.

The region is also significant because it is the source region for the Leeuwin Current (Fig. 14). This warm current flows southward against the offshore flow and the prevailing winds at speeds of about 1/2 to 1 m s\(^{-1}\) and is strongest in autumn and winter. It is situated over the continental slope with a width of about 40 km and continues, intermittently and for different reasons, all the way to southern Tasmania. This makes it one of the longest narrow streams in the world, possibly even longer than the Nile (although the comparison is facetious). Its properties have only recently been fully recognised (e.g. Cresswell and Golding 1980), although the existence of warm water offshore for swimming in winter has been well-known to the residents of Perth for many years. The transport is about 2-3 Sverdrups and the factors causing it are not yet certain. Two suggestions have been made: first, that it is primarily fed by the Indonesian throughflow, and second, that it is fed by inflow from the Indian Ocean, as shown in Fig. 14.

The structure of the Leeuwin Current varies substantially with time along its entire
length. It often has a convoluted eddy character as illustrated in Fig. 15. These eddies are presumably due to dynamical instabilities (Griffiths and Pearce 1985) and may result in the transfer of warm water offshore. It seems likely that these eddies may play an important part in the life-cycle of the rock lobster in the southwest region.

**Fig. 13** Northwest shelf. (a) Landsat image (29 December 1972) showing internal wave trains of the region shown in (b). The principal wave trains and the shelf break (the 183 m depth contour) are also shown in the latter. The large shoal in the northwest corner is Ashmore Reef (from Baines 1981).

**Fig. 14** Schematic diagram of the Leeuwin Current (courtesy of F. Prata).

**Fig. 15** Satellite image of the Leeuwin Current, showing the temperature anomaly at each latitude (courtesy of F. Prata).

**Inverse estuaries**
Flow close to the shore around much of the Australian coast to the north, west and south is influenced by the "inverse estuary phenomenon". In the Australian coastal environment fresh water run-off is generally small or non-existent. On the other hand, evaporation in coastal shallows is high due to the persistent solar heating and this causes an accumulation of dense salty water which flows downhill out to sea. This in turn causes inflow towards the coast at the surface. This circulation is the
reverse of the usual estuarine pattern, where fresh water outflow occurs at the surface due to river run-off, with entrainment causing salt water inflow below. This contrast is illustrated schematically in Fig. 16 (although the processes involved are greatly simplified—this 'normal' estuarine circulation is only one of several types). This 'inverse estuarine' circulation is not restricted to estuaries although it is more pronounced there, and the best examples (perhaps) are those of Spencer and St Vincent Gulfs (Nunes and Lennon 1986). Very salty water emerges from the gulfs and is found subsequently (diluted) further east in Bass Strait.

Fig. 16 Simplified schematic diagrams showing the comparison between a 'normal' estuary with circulation driven by river inflow entraining salt water from below, and an 'inverse' estuary, driven by evaporation in shallow water.

Coastally trapped waves on the southern shelf
The Australian southern coastline is unusual in that it is a region which supports coastally trapped waves which propagate in the same direction as the weather systems which force them. Resonance is therefore possible, giving rise to quite large amplitudes. To date, these systems have (mostly) only been observed through their effects on sea level variations, as recorded by tide gauges. Figure 17 (from Church and Freeland 1987) shows disturbances propagating and growing from west to east. The typical propagation speed is \( \sim 10 \text{ m s}^{-1} \), which is the same as that for weather systems. These coastally trapped waves show a significant degree of correlation with the CTWs observed on the NSW coast in the ACE. If the CTWs on the NSW coast are caused by the CTWs on the south coast, their effect must pass through Bass Strait since they are not observed to pass around Tasmania.

Fig. 17 Subsurface pressure (sea level plus atmospheric) of low frequency disturbances at a number of south coast locations showing eastward propagation during the ACE experiment, and compared with CTW mode 2 at Cape Howe (from Church and Freeland 1987).

Bass Strait
Bass Strait itself has a number of interesting features. The geometry is unique, it being the only region of continental shelf in the world with broad openings on two sides to very deep water (although there are some similarities with Cook Strait in New Zealand). One important quantity related to the southern coast CTWs is the flux of water through Bass Strait. Recent observations (Baines, Hubbert and Power 1989, personal communication) have shown that flow through Bass Strait in winter occurs in eastward surges lasting 2 to 3 days, which coincide with southwesterly airstreams following the passage of cold fronts across the region.

These same southwesterly airstreams generate CTWs on the southern coast; an analysis of the data and the dynamics of the region
shows that these CTWs split into two when they encounter Bass Strait. The first part passes through Bass Strait in the form of a special CTW termed a Kelvin wave, and the remainder passes down the west side of Tasmania to the southern extremity where it disappears, presumably because the bend in the coastal waveguide is too sharp to be negotiated by the waves. The flow through Bass Strait is associated with these Kelvin waves; about three quarters of this flux is due to CTWs generated west of Bass Strait, and about one quarter is due to Kelvin waves generated inside it.

The water in these wintertime surges leaves Bass Strait in the form of a giant underwater waterfall (Godfrey et al. 1980, Tomczak 1985) which descends to 400 m; the water then moves northward into the Tasman Sea.

This completes our circuit around the continent. There is much that we still don’t know and another review in 10 to 15 years time may well highlight a completely different range of subjects, or some of those only touched on here.

References


