MARINE MANAGEMENT SUPPORT

OVERVIEW OF THE BROAD-SCALE CIRCULATION PATTERNS OF THE INDONESIAN-AUSTRALIAN BASIN AND SHELF REGION FROM NORTHWEST AUSTRALIA TO CAPE LEEUWIN

Technical Report: MMS-75/2003

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1. INTRODUCTION

GENERAL

This report presents a description of the broad-scale oceanic currents that occur off the northwest, west and southwest coasts of Western Australia. It has been prepared to assist in understanding the role of such currents in influencing nearshore hydrodynamic processes in State Coastal Waters, for which the Department of Conservation and Land Management (DCLM) has key jurisdictional responsibilities for natural resource management. The DCLM's management role focuses on marine protected areas (MPAs) under the *Conservation and Land Management Act 1984* and, more broadly, within and outside of MPAs under the *Wildlife Conservation Act 1950*. An effective understanding of Western Australia's nearshore hydrodynamic characteristics is reliant on an appropriate understanding of the adjacent broader scale oceanic currents, in terms of how they effect and interact with nearshore waters. The fundamental importance of understanding the hydrodynamics lies in its intrinsic role in ecological processes and in transporting and mixing waterborne substances that threaten the health of the State's marine ecological and social values.

OBJECTIVE

The aim of this report is to provide a broad-scale description of the major oceanic current systems off the northwest, west and southwest coasts of Western Australia.

2. DEFINITION OF AREAS COVERED

INDONESIAN-AUSTRALIAN BASIN

Bray *et al* (1997) defined the region between Indonesia and Australia as the Indonesian-Australian Basin (IAB), shown in Figure1.

SHELF REGION OF NORTHWEST AUSTRALIA

This region is defined here as the region off the northwest Australian coast where water depths are less than about 200 m (Figure 2).

SHELF REGION OFF THE WEST AND SOUTHWEST COASTS OF WESTERN AUSTRALIA

This region is defined here as the continental shelf region from Exmouth to Cape Leeuwin, where depths are less than about 200 m (Figure 3).

3. PRINCIPAL CURRENT SYSTEMS AFFECTING THE INDONESIAN-AUSTRALIAN BASIN

The broad-scale circulation patterns of the Indonesian-Australian Basin (IAB) have been summarised in a schematic by Wijffels *et al* (1996) and reproduced in Figure 4. The descriptions of the individual currents shown in Figure 4 are based on descriptions in Bray *et al* (1997), Buchan and Stroud (1993), Cresswell (1991), Cresswell *et al* (1993), Cresswell and Golding, (1980), Feng *et al* (in revision), Godfrey and Ridgeway (1985), Meyers (1996), Meyers *et al* (1995), Nof *et al* (2002), Pearce and Walker (1991), Scott (1997), Taylor and Pearce (1999) and Wijffels *et al* (1996).

INDIAN OCEAN GYRAL CIRCULATION

A persistent anti-clockwise Indian Ocean gyral circulation is generated by the semi-permanent high pressure system that spans the southern Indian Ocean, and for which the broad-scale wind field is characterised by the westerly winds of the 'Roaring Forties' and south-easterly winds of the South East Trade wind belt (Figure 5). The resulting oceanic scale circulation is comprised of four main systems (Figure 6), as follows:

- South Equatorial Current (SEC) (east to west, from NW Australia towards central Africa)
- Agulhas Current (AC) (north to south, off eastern Africa)
- West Wind Drift (WWD) (west to east, from southeast Africa towards southwest Australia)
- Western Australian Current (WAC) (south to north, off the continental slope of Western Australia)

SOUTH EQUATORIAL CURRENT

The westward flowing South Equatorial Current (SEC) (Figures 4 and 6) is generally confined to a latitudinal band of about 12-15 °S, although it is known to migrate within a latitudinal range of 5-15° S. It is maintained by the southeast trade winds and enhanced appreciably in the region of the IAB by the Pacific-Indian Throughflow (PIT). The PIT directs warm, tropical Pacific Ocean water into the northeastern region of the Indian Ocean via straits of the Indonesian Archipelago (the PIT is described further below).

To the north of the SEC is a semi-annual alongshore flow off the southern coasts of Sumatra and Java (namely, the South Java Current (SJC)) (Figure 4) which transports water eastward. Throughout the year, the semi-permanent high over the Indian Ocean migrates in its north-south position, centred at about 30° S in winter and about 40° S in summer (Figure 7). When the accompanying SE trades are at their northern-most latitudes (ie in winter/spring), the SEC is also situated within its northern-most latitudinal belt, thereby directing water to flow westward as far north as off the southern coasts of Sumatra and Java, effectively replacing the SJC for a short period. During this period (July to September) the SEC is strongest, carrying low salinity water (of approximately 34.2 to 34.6 psu).

SOUTH JAVA CURRENT

The South Java Current (SJC) flows eastward off the southern coasts of Sumatra and Java (Figure 4). It is fed by the remotely forced Equatorial Counter Current (ECC) and the locally forced Indian Monsoon Current (IMC) (Figure 4).

The ECC is driven remotely as a result of the large-scale wind systems in the North and East Trade wind belts over the central Indian Ocean, generating Wyrtki Jets. Wyrtki Jets propagate as equatorially-guided eastward currents in the equatorial zone until they encounter Sumatra and Java, thereby being constrained to flow as boundary currents, contributing to the flow of the SJC. The large scale wind systems associated with the southwest and northwest monsoons lead to an Ekman-induced elevation of sea-level in the equatorial latitudes of the Indian Ocean. When the Intertropical Convergence Zone (ITCZ) (Figure 8) is south of the equator, northwesterly monsoonal winds drive currents downwind which are quickly rotated clockwise (in the northern hemisphere) by the force of the Earth's rotation, thereby directing water towards the equator from the north of the equator. When the ITCZ is north of the equator, southwesterly monsoonal winds drive currents downwind which are quickly rotated counterclockwise (in the southern hemisphere) by the force of the Earth's rotation, again driving water towards the equator but this time from south of the equator. This build up of energy (expressed along the equator as a rise in water level) then radiates out (mainly eastward) and travels as the equatorially confined Wyrtki Jet towards the coast of Sumatra.

The ITCZ crosses the equator twice per year, at which time the Wyrtki Jet is at its greatest intensity (ie during April/May and October/November). Correspondingly, the SJC is at its strongest during April/May and October/November.

As discussed in the preceding section, a reverse (ie westward) flow is believed to replace the SJC between these periods, with the strongest westward flow believed to occur around September. This is a period when the PIT is at its strongest, and since it is this throughflow which acts as the principle driving force for the SEC in the IAB, the westward flow off Sumatra and Java that occurs at that time is considered by some researchers to indicate the arrival of the SEC in its strongest form.

The IMC contributes less to the net flow of the SJC when compared to the contribution of the EEC, however it is still an important contribution. The IMC is locally generated by winds of the Indian Monsoon.

The individual and relative strengths of the EEC and IMC change throughout the year according to the respective remote and local atmospheric systems that generate them.

On travelling south of Java the SJC turns clockwise and feeds into the SEC.

PACIFIC-INDIAN THROUGHFLOW

The Pacific-Indian Throughflow (PIT) floods the IAB with warm, low salinity tropical water, derived from both the southwestern Pacific Ocean region and freshwater runoff from the islands of the Indonesian Archipelago. It is driven by the sea-level difference set up between the Pacific and Indian oceans either side of the Indonesian Archipelago as a result of westward winds of the SE and NE Trades over the Pacific Ocean. These winds move warm Pacific Ocean surface water towards the archipelago, leading to a water level set-up, downwelling and associated accumulation of relatively warm water there (to a depth typically of about 400 m). This temperature differential across the archipelago has an associated sea-level height differential and the associated pressure gradient that is consequently set up drives the PIT. The PIT is strongest during the SE Monsoon (May to September) when the sea-level difference across the archipelago is at its maximum (up to 28 cm) and weakest during the NW Monsoon (November to March) when the sea level difference is at its minimum (less than about 10 cm). Most of the highly variable PIT transport takes place within the upper few hundred metres and is estimated to be 5-10 Sv ($Sv \equiv 10^6\ m^3\ s^{-1}$), with annual variability of approximately 5 Sv.

El Nino events result in a weakening of the wind field across the Pacific Ocean resulting in reduced sea level differences across the archipelago and relatively weak associated throughflows. The opposite, in terms of wind strengths, consequent sea level differences and throughflow rates, occurs during La Nina events, when the SE and/or NE Trade winds are at their strongest and sometimes replaced by westward winds. El Nino and La Nina events recur every 2 to 10 years (Figure 9). Interannually, El Nino events reduce PIT transport by approximately 5 Sv.

The Pacific-Indian ocean sea-level gradient drives a consequent throughflow from the Flores and Banda Seas which travels both around and through the Indonesian Archipelago. A major component of this throughflow enters the region off northwest Australia via the Timor Sea and, in doing so, effectively ‘branches’ out into two main streams, one via the Timor Strait feeding eastwards throughout the year almost directly into the SEC, the other via the Sahul shelf, heading southwestward closer to the Western Australian coastline, and feeding the region where the Leeuwin Current forms and begins its strong poleward journey (ie off the Pilbara coastline). It is believed that the flow over the Sahul Shelf reverses from being southwestward during March to September (driven by the SE Monsoon) to northeastward during September to January (driven by NW Monsoon), in response to changing wind fields (Cresswell *et al*, 1993) (see Figure 10). Most of the throughflow enters the Indian Ocean via the Timor Strait (~4-6 Sv) and the Lombok Strait (~1 Sv), with the Ombai Strait possibly at times providing an important conduit. The component of the PIT that passes southward via Lombok Strait feeds into the SEC.

EASTERN GYRAL CURRENT

The Eastern Gyral Current (EGC) is directed approximately eastward towards the Pilbara coast of Western Australia and runs below the SEC (Figure 4). It is generated by a geostrophic response (ie due to the rotation of the earth) of the southward flow that is initiated by north to south sea-level and temperature gradients in the IAB (see Godfrey and Ridgway, 1985 and Scott, 1997).

The PIT sets up a north-south (meridional) sea-level gradient in the waters between the Indonesian Archipelago and northwest Australia. This gradient is further enhanced with the north-south gradient in sea-level associated with the tail of the SEC in the IAB. In addition, during winter spatially differential cooling occurs between the relatively deep northern IAB areas and adjoining shallower shelf waters off northwest Australia. During this time the relatively shallow waters over the shelf cool at a greater rate than the waters to the north. This serves to strengthen the background north to south temperature gradient that is already set up in the IAB due to the introduction of warm tropical waters by the PIT.

The net north to south pressure gradient set up by the combined actions of the SEC, PIT and differential cooling drives a southward flow which must very quickly rotate counterclockwise (at 'inertial' time scales, which are less than one day in that region) due to the action of the earth's rotation. The resulting eastward flow manifests itself as the intense zonal current known as the EGC. En route to the Pilbara region the EGC splits into northward and southward flowing streams. The northward stream feeds back into the SEC and the southward stream contributes to the source region for the Leeuwin Current.

LEEUWIN CURRENT

Originating over the North West Shelf, the Leeuwin Current (LC) (see Pearce and Walker, 1991) can be described as "*…a poleward boundary current of warm, low salinity water that flows at the surface from near North West Cape down to Cape Leeuwin and thence towards the Great Australian Bight*" (Cresswell, 1991) (Figure 11). The LC is driven by a north to south steric height gradient set up by the mechanisms described above for the IAB (ie relating to the PIT, the SEC and the action of differential cooling over the IAB) and the density structure of the Indian Ocean. The north-south variation in the density structure (density increasing towards the south) has an associated north to south sea-level gradient. The net gradient between the northwest and southwest coastal regions off Western Australia has been estimated to be as much as about 50 cm (Cresswell and Golding, 1980).

The LC exhibits a seasonal behaviour, modulated by the seasonal variability in the local wind stress off Western Australia and changing steric height gradient. During the summer months the LC is at its weakest because it is opposed by the equatorward wind stress associated with south-southwesterly winds. During the winter months the LC is at its strongest because the poleward sea-level gradient is at its strongest and also because the equatorward wind stress is at its weakest. These modulating features apply from the southwest to northwest of Western Australia.

South of Exmouth the LC typically flows over the continental shelf and slope with maximum core speeds just beyond the shelf edge of 0.5 to 1.5 m s^{-1}. The LC is of order 50-100 km wide and up to about 300m deep. The LC has its maximum southward geostrophic speed of 45 cm s^{-1} during April-May, while the maximum southward volume transport of 5 Sv occurs in June-July. The annual mean poleward transport east of 110°E is 3.4 Sv. The Leeuwin Current is stronger during La Nina years and weaker during El Nino years, with the annual mean volume transports being 4.2 and 3.0 Sv, respectively (Feng *et al*, in revision). The LC frequently meanders and breaks out to sea forming warm anti-cyclonic eddies, up to about 200 km in diameter, separated by cold core cyclonic cells.

Over the North West Shelf the LC has a structure that is less well defined than that south of Exmouth.

The LC originates over the North West Shelf as water derived from a combination of the EGC, a 'funnelling' of the relatively warm, low salinity region of the IAB and from that which arrives in the direct flow of PIT water via the Sahul Shelf. Cresswell (1991) summarised Holloway and Nye's (1985) current meter data from the North West Shelf (collected approximately 100 km NW of Dampier Archipelago) during 1982/83 and stated that the data revealed "*…a contribution to the Leeuwin Current by NW Shelf waters. It was strongest from February to June reaching 0.2 m s^{-1} in March-April-May 1982.*" Cresswell (1991) also reported on the movement of satellite-tracked drifters released near and offshore of Holloway and Nye's (1985) moorings and described their movement to have the following seasonal behaviour.

- "*From November to late March the situation could best be described as quiescent, with the drifters moving slowly (~0.1 m s^{-1}) and following no consistent path.*
- *At the start of April, however, there was a dramatic move poleward at speeds of about 0.2 m s^{-1} on the shelf and up to 0.3 m s^{-1} off the shelf. A drifter that rounded NW Cape in late April accelerated to 0.5 m s^{-1}.*
- *May through August saw a predominantly poleward flow with an increasing tendency for the region to feed the South Equatorial Current.*"

4. SEASONAL FLOW REVERSALS ON THE NW SHELF

Buchan and Stroud (1993) have addressed the issue of flow reversals and interacting flows over the NW Shelf. They refer to current patterns presented in the US Navy's (1976) Climatic Atlas of the World. The following precis is taken directly from Buchan and Stroud (1993), with reference to their illustrative diagram (reproduced below as Figure 12).

"*The US Navy (1976) surface current patterns for the area show that the flow* (referring to the west-southwestward flow of Pacific Ocean water over the NW Shelf region via the Timor Sea) *is strongest during winter, originating from east of the Timor Sea, allowing an input of Pacific Ocean water into the Indian Ocean. This westward flow intersects with the northeasterly flowing West Australian Current in the region of Scott Reef, generating a series of confused eddies* (Figure 12A). *During the winter/summer transition the strength of the westward flow through the Timor Sea decreases and the West Australian Current extends northward beyond Scott Reef* (Figure 12B). *During the summer months* (Figure 12C) *the northward flowing West Australian Current branches at around latitude 20 °S with some of the flow moving northeast into the Timor Sea, providing an eastward current near Scott Reef and a reversal from the stronger winter flows. The South Equatorial Current is effectively displaced westward during summer. This summer picture is a result of the North West Monsoon. During the summer/winter transition, the West Australian Current ceases to flow northeast allowing the establishment of the westward flow from the Pacific Ocean past Scott Reef* (Figure 12D)."

This and the preceding descriptions of the dynamics of the LC over the NW Shelf points to the strong influence of the opposing wind stress that occurs along the Western Australian coast during the spring/summer months. This effectively leads to an offshore displacement of the current south of Exmouth and to an annulment of any strong poleward flows over the NW Shelf. In fact, Cresswell (1993) and Buchan and Stroud (1993) have highlighted the point that close to the Western Australian coastline off the Pilbara-Kimberley regions, the flow heads towards the northeast during spring-summer in response to NW Monsoon winds, a feature that is not inconsistent with Holloway and Nye's (1985) current measurements which revealed an absence of southward flows during this period.

Oceanographic researchers at the CSIRO Division of Marine Research have recently advanced the understanding of interacting flow patterns in the IAB through the complementary techniques of numerical hydrodynamic modelling, in-situ measurements of temperature, salinity and temperature structures and remotely sensed measurements (from satellites) of sea-surface temperature and water level. They have begun to elucidate on the presence of major semi-permanent eddy systems between the SJC, SEC and EGC (see Figure 13, which is as yet unpublished but reproduced with the permission of Dr Susan Wijffels, CSIRO Division of Marine Research). These anti-cyclonic eddies, containing PIT water, are now referred to as "teddies". Teddies have been recently identified to the west of Timor at 12°-14° S and tend to be intraseasonally forced. They are most common when the PIT reaches a maximum (July to September). Teddies propagate westward at 15-19 cm s^{-1}, have a radius of 100-150 km, orbital speed of 20-60 cm s^{-1} and a periodicity of 40 to 80 days. This eddy generation process explains why some of the PIT water forms the source of the Leeuwin Current (Nof *et al*, 2002).

5. SEASONAL FLOW REVERSALS ALONG THE WEST COAST OF WESTERN AUSTRALIA

The predominance of winds with a relatively strong northward component during spring-summer along the west coast results in wind stress that can overcome the steric height gradient over the upper continental shelf. This effectively forces the LC further offshore, being replaced closer to the coast by northward flows.

For example, the relatively cool Capes Current (CC) replaces the LC between Cape Naturalist and Cape Leeuwin from about mid-spring to mid-autumn (Pearce and Pattiaratchi, 1999; Gersbach *et al*, 1999), in response to the seasonal strengthening of the northward wind stress (Figure 14). The CC has been described as being narrow (<20 km wide) and restricted to the inner shelf between the two capes, but then broadening northwards past Perth. Pearce and Pattiaratchi (1999) suggest that the CC may even propagate to as far northwards as the Abrohlos Islands. The present understanding of its dynamics suggests that the CC originates as locally upwelled water from the coastal regions between Cape Leeuwin and Point D'Entrecasteaux and between Cape Naturaliste and Cape Leeuwin (Gersbach *et al*, 1999). The relative contributions of these two respective regions as sources for the CC are yet to be determined.

Studies have also shown that there is an inshore, wind-driven, northward counter-current near the Abrohlos Islands (Cresswell *et al*, 1989; Pearce, 1997). Whether the counter-current described by these authors is hydrodynamically connected to the Capes Current is unclear.

Taylor and Pearce (1999) suggest that there is a near-coastal flow of relatively cold water, named the Ningaloo Current (NC), which heads equatorward probably from as far south as Shark Bay to past North West Cape (Figure 15). Taylor and Pearce (1999) suggest that this near-shore counter-current operates from about September to mid-April, in response to the occurrence of relatively strong south-southwesterly winds. They used satellite imagery of sea-surface temperature (SST) to determine the NC's width, which ranged from about 30 km near the southern end of Ningaloo Reef, where the continental shelf is wide, to about 2 km or less north of Point Cloates where the seabed shelves more rapidly. Taylor and Pearce (1999) suggest that this relatively cold counter-current may at times extend eastwards past North West Cape, thereby forming a counter-clockwise re-circulation of water as it opposes the southward flowing LC. In addition, Taylor and Pearce (1999) believe that the prominence of Point Cloates is conducive to the formation of a topographic eddy in the LC, as observed from satellite images of SST, and that this re-circulation would be important in bringing warm water into the southern end of the Ningaloo Reef tract.

Taylor and Pearce's (1999) counter-current model for the Ningaloo Reef may help explain the cold water temperature anomalies recorded by Simpson and Masini (1986) in the lagoonal waters of the Ningaloo Reef region. The nearshore lagoonal dynamics of Ningaloo Reef have been reviewed by D'Adamo and Simpson (2001).

In summary, Taylor and Pearce (1999) suggest that "*…there are three current zones across the continental shelf off Ningaloo; the warm southward Leeuwin Current, flowing along the outer shelf/upper slope and driven by an alongshore pressure gradient (Godfrey and Ridgway, 1985); a seasonal wind-driven northward inner-shelf counter-current, the Ningaloo Current; and a wave/wind/tidally-driven flow within the nearshore reef system (Hearn et al, 1986).*"

The picture that may be emerging from the discovery of these major near-coastal counter-current systems (ie those off the southwest capes, Abrohlos Islands and Ningaloo Reef), is one of a series of locally generated counter-currents driven by wind stress (Alan Pearce, pers. comm.). These counter-currents periodically replace the southward flowing LC and evolve as the equatorward wind stress overwhelms the poleward steric height gradient over the continental shelf of Western Australia, particularly during the spring/summer months. During the times when these counter-currents are operating, the LC is effectively forced further offshore.

6. CONCLUSION

There is a complex array of currents that contribute to the broad-scale circulation off the Western Australian coast (Figure 16). Major current systems, including the currents of the Indian Ocean Gyre, the Pacific-Indian Throughflow, the South Java Current, the Eastern Gyral Current, the Leeuwin Current, and the seasonal Capes and Ningaloo Currents, all play important roles in carrying Pacific and Indian Ocean waters towards and away from the Indonesian-Australian Basin. The currents that comprise the circulation patterns off the Western Australian coast are crucial to the transport of the planktonic gametes and larvae of a multitude of marine species northward and southward during the year, thereby having a significant influence on the ecology of the Western Australian coastal and marine environments.

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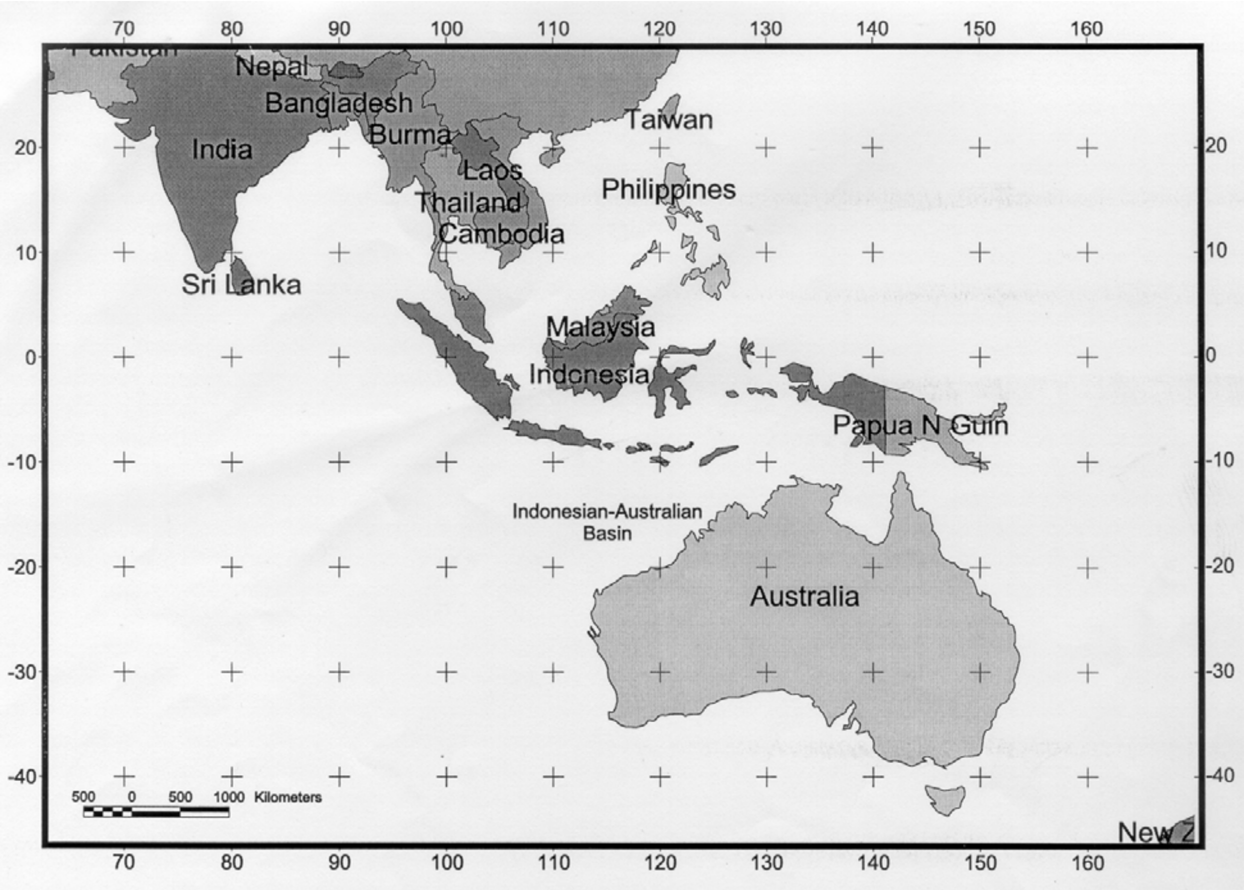

Figure 1: The Indonesian-Australian Basin.

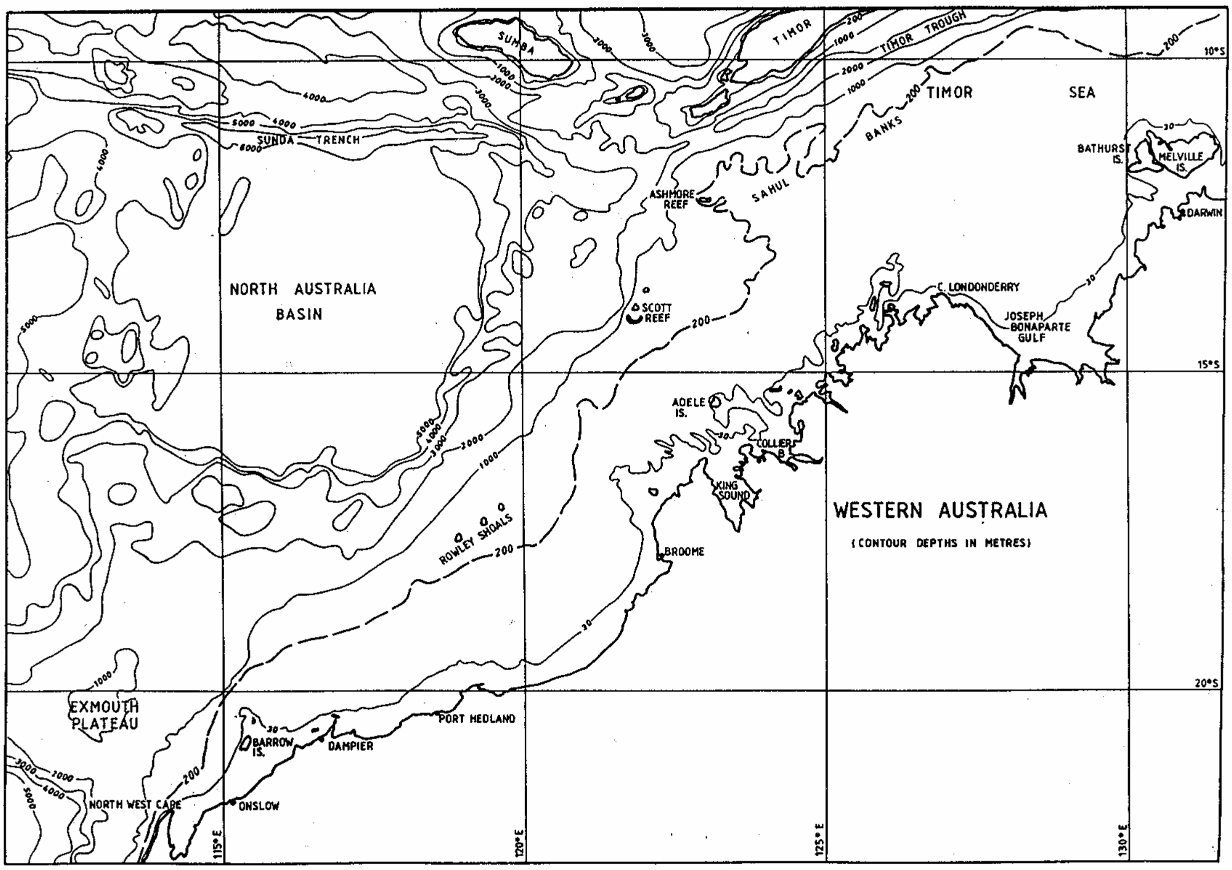

Figure 2: Australia's North West Shelf region.
(taken from Buchan and Stroud, 1993)

Figure 3: The shelf region off the west coast of Western Australia.

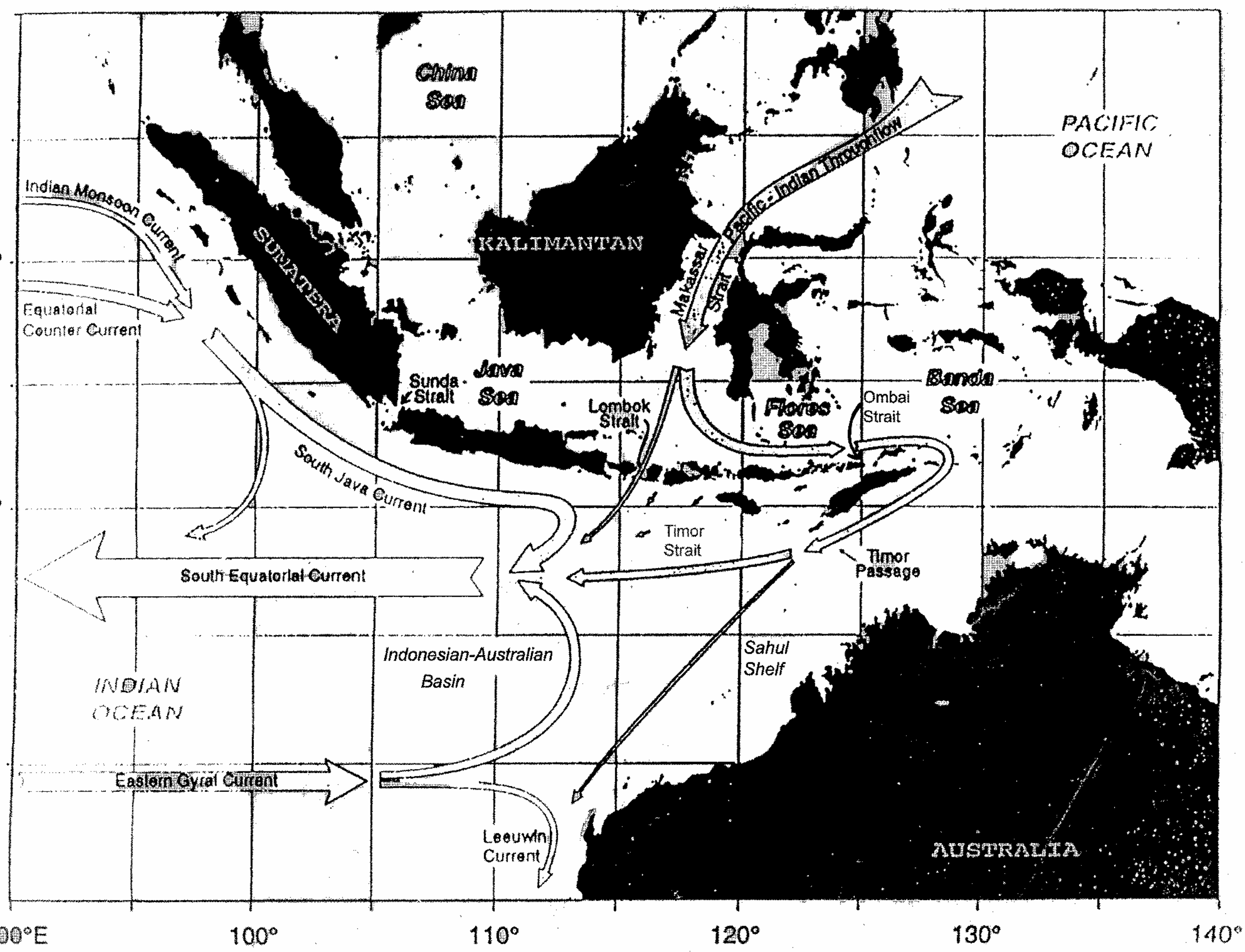

Figure 4: Broad-scale circulation patterns of the Indonesian-Australian Basin. (taken, with additions, from Wijffels *et al*, 1996)

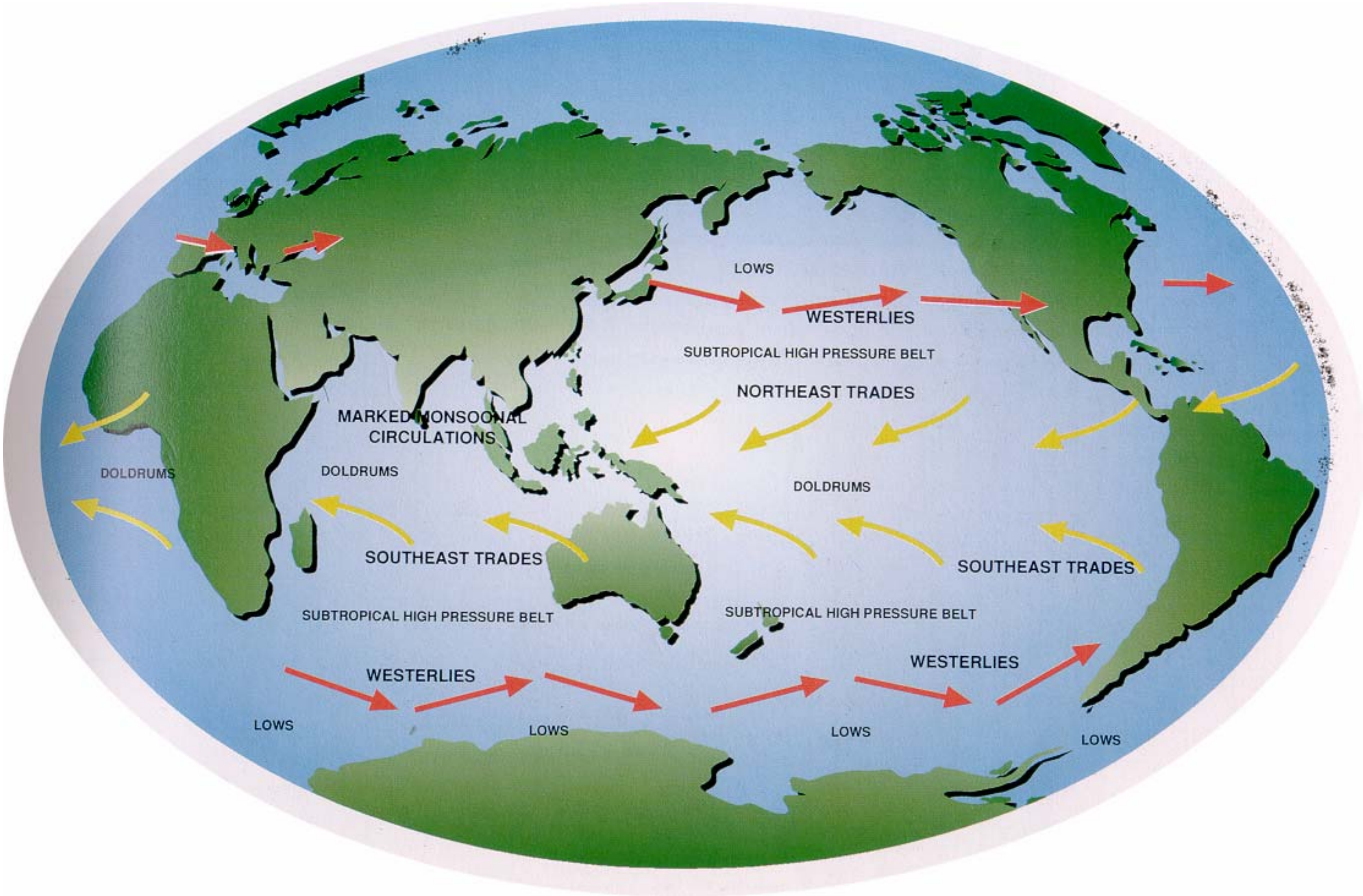

Figure 5: Major wind regimes of the world.
(taken from Crowder, 1995)

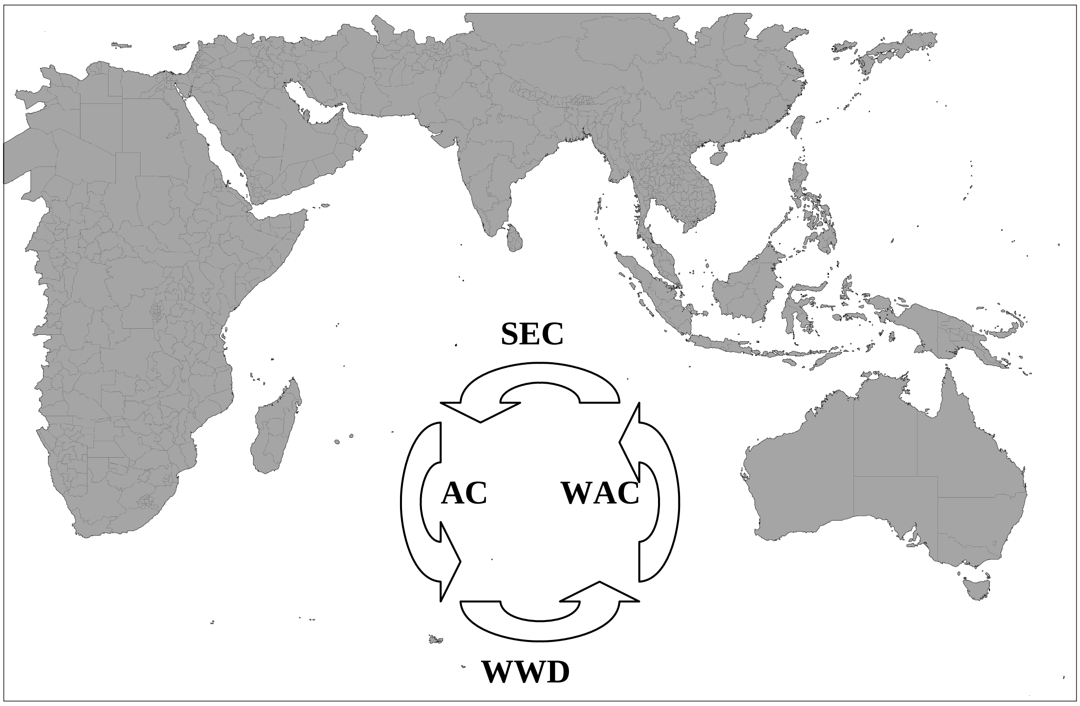

Figure 6: Currents comprising the Indian Ocean Gyre circulation (SEC: South Equatorial Current; AC: Aguhlas Current; WWD: West Wind Drift; WAC: West Australian Current).

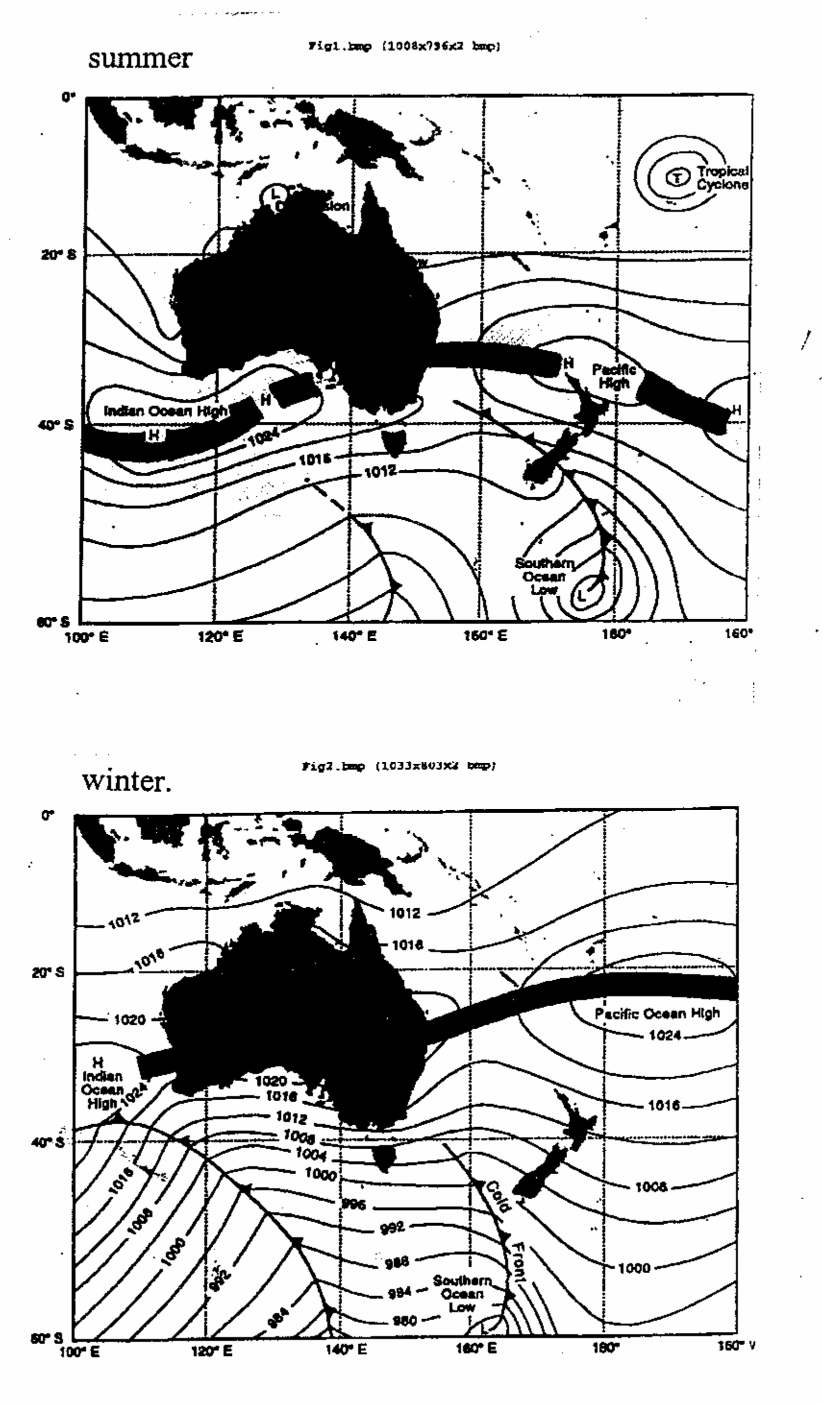

Figure 7: Representative examples of typical summer and winter isobaric weather charts over the Australian and western Pacific regions highlighting the latitudinal difference in the position of the Sub-tropical Ridge of high pressure (ie the anti-cyclonic belt) and associated synoptic scale systems. (The thick dark line indicates the approximate centreline of the 'ridge' in mid-summer and mid-winter respectively. (charts obtained from the Commonwealth Bureau of Meteorology)

a)
b)
c)

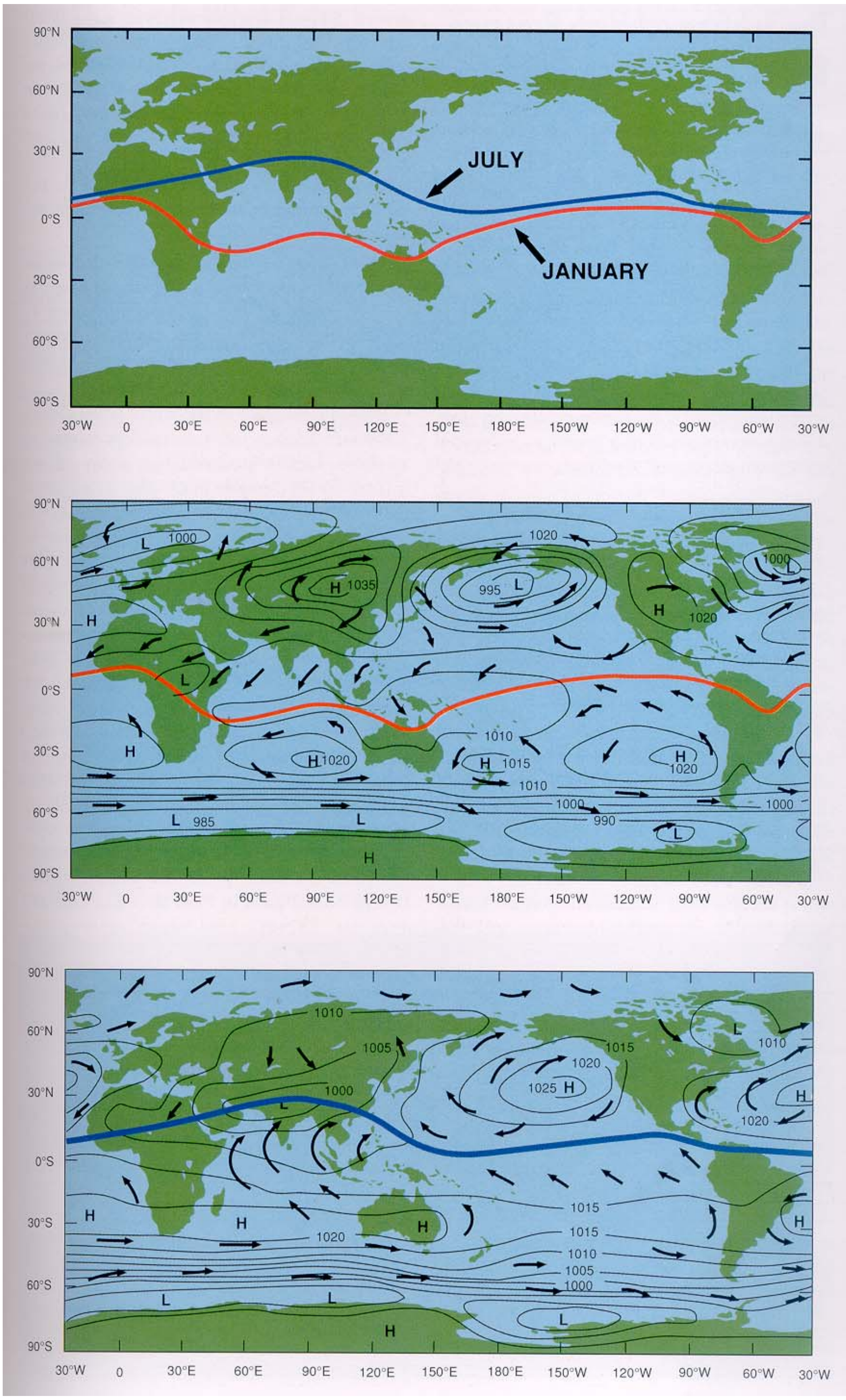

Figure 8: Positions of the Intertropical Convergence Zone (a) and average sea level pressure distribution and surface wind flow patterns in January (b) and July (c).
(taken from Crowder, 1995)

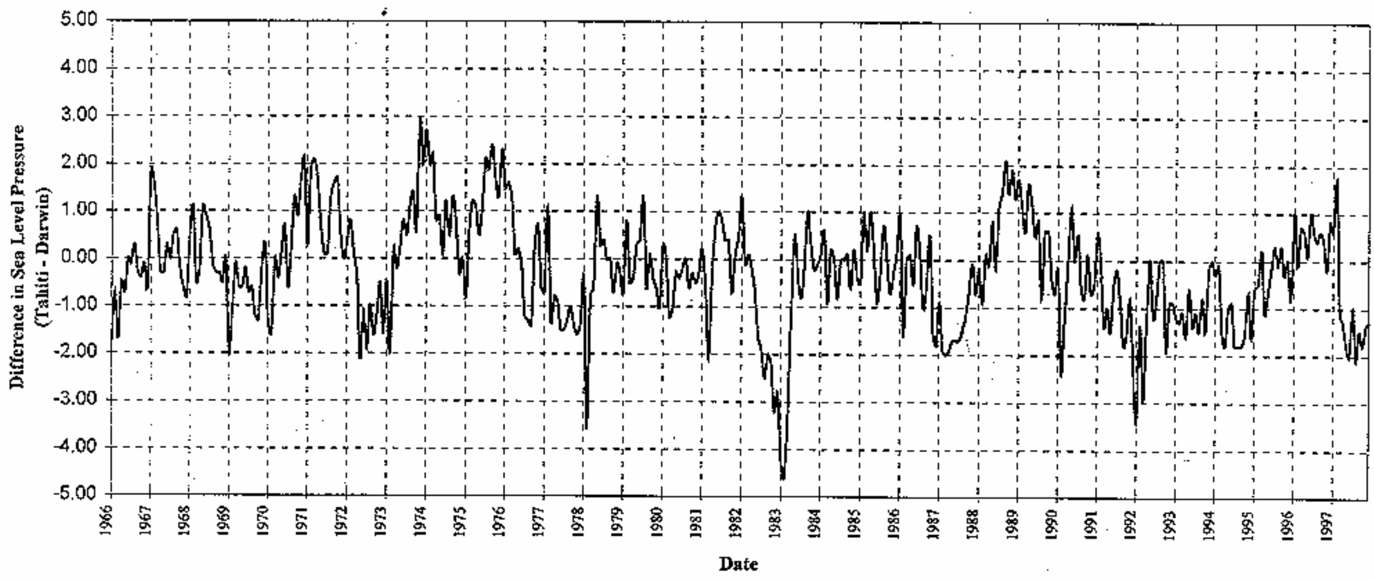

Figure 9: El Nino Southern Oscillation Index 1966 – 1997. (High Southern Oscillation Index (SOI) = La Nina event; Low SOI = El Nino event).
(information obtained from NOAA.USA internet site)

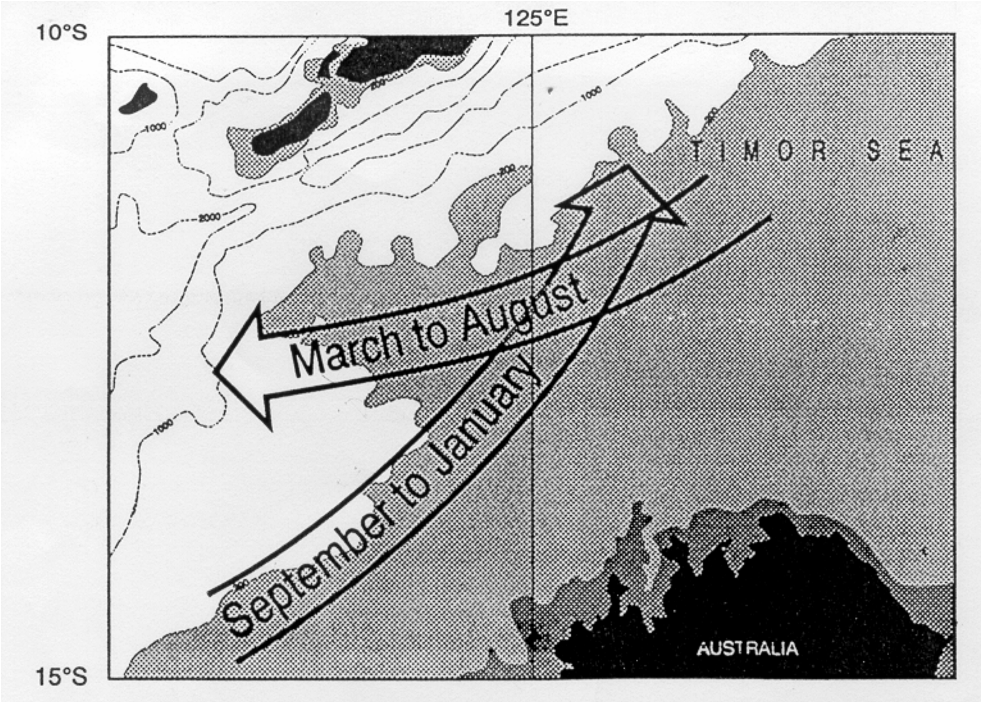

Figure 10: Near-surface circulation on the Sahul Shelf.
(taken from Cresswell *et al*, 1993)

a) b)

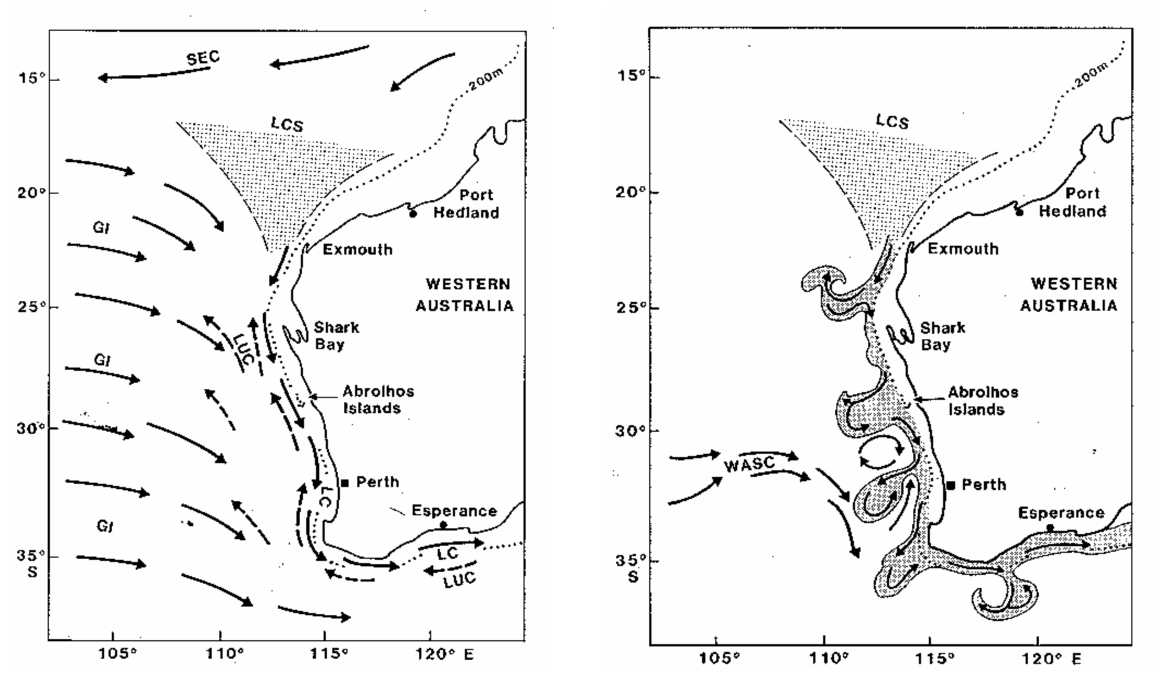

Figure 11: (a) Schematic diagram of the main features of the Leeuwin Current system. (GI = geostrophic inflow from the open ocean; LC = Leeuwin Current; LCS = Leeuwin Current source area; LUC = Leeuwin Undercurrent; SEC = South Equatorial Current). Solid arrows are surface currents, dashed arrows are subsurface currents. The dotted line shows the 200 m contour. (b) Schematic diagram of mesoscale features of the Leeuwin Current system, derived largely from satellite imagery. The Leeuwin Current itself is shaded, the solid arrows indicating the flow in the warm surface meanders and jets as well as the currents in the cooler offshore waters. (WASC = West Australian Summer Current). (taken from Pearce and Walker, 1991)

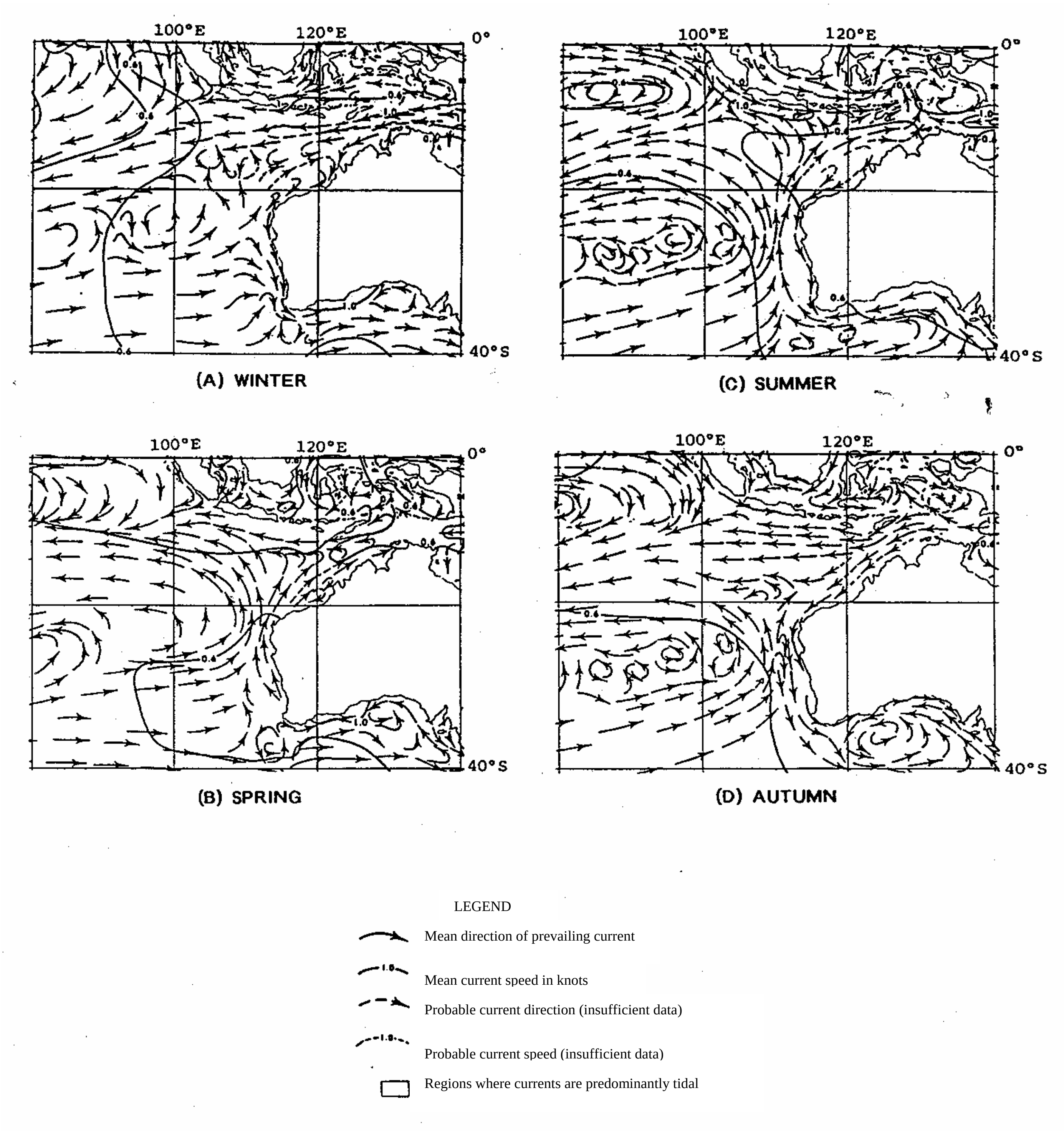

Figure 12: Illustrations of the surface current circulation of the eastern Indian Ocean during a) winter, b) spring, c) summer and d) autumn.
(taken from Buchan and Stroud, 1993)

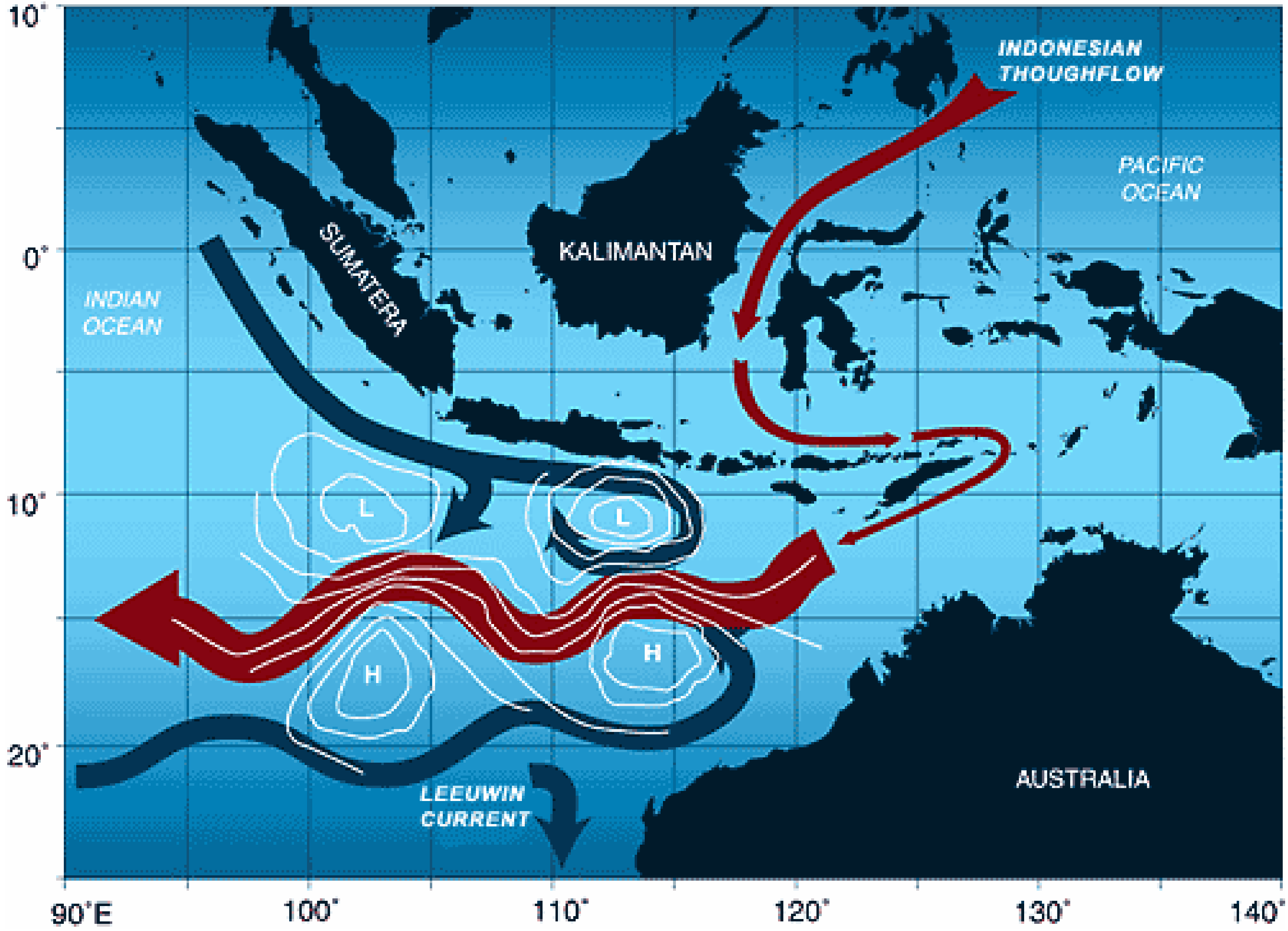

Figure 13: Semi-permanent eddy systems between the South Java Current (off Sumatra), the South Equatorial Current (between the eddies) and the Eastern Gyral Current in the northeast Indian Ocean. (taken, with permission, from Dr. Susan Wijffels, CSIRO Division of Marine Research (unpublished))

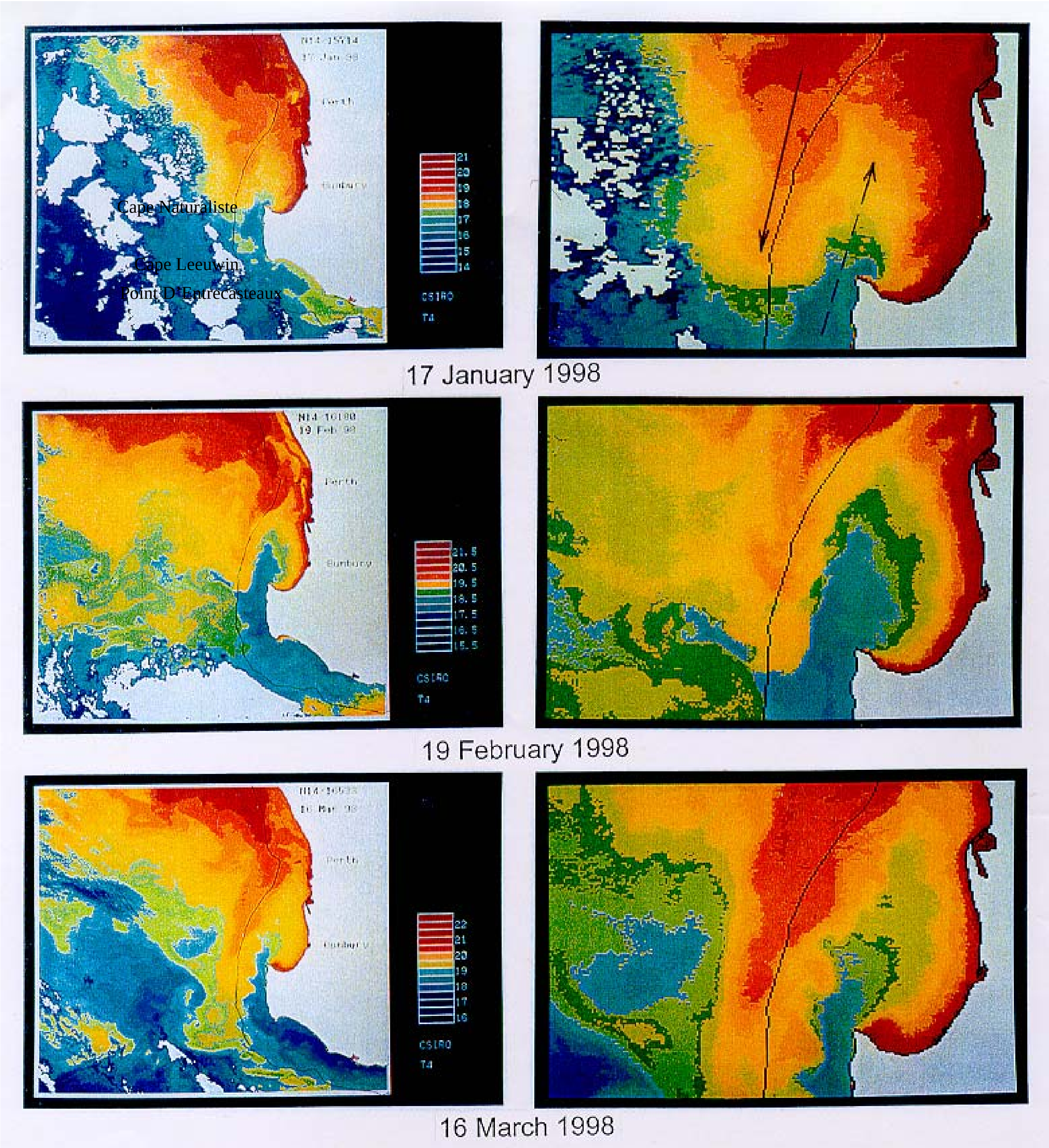

Figure 14: Monthly satellite sea-surface temperature images for southwestern Australia in 1998, as well as complementary enlarged images of the coastal region between Mandurah and Cape Mentelle. The colour scale shows the temperature in AVHRR Band 4, uncorrected for atmospheric absorption (and so reads 1 to 2 °C low). Warmest water is shown in red, cooling through orange, yellow and green to the coolest water in blue. The Capes Current is seen on the images as a wedge of cool (blue) water intruding into Geographe Bay, most prominently during February-March. Clouds are white or mottled blue. The black line marks the 200 m isobath, representing the approximate position of the continental shelf break. Different temperature/colour scales have been used to most clearly display the thermal features in each image, so there are no connections between the scales used.
(taken from Pearce and Cake, 1999)

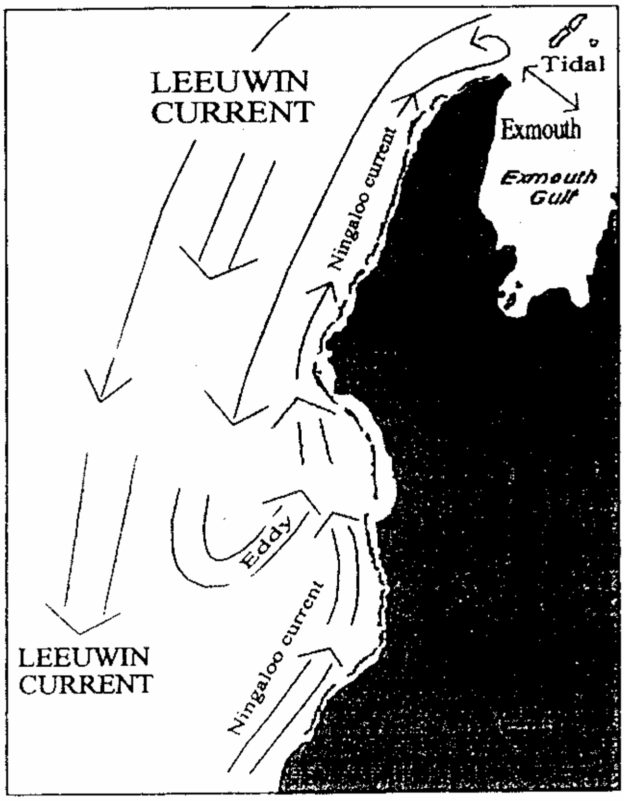

Figure 15: Proposed current mechanisms at Ningaloo Reef operating principally from September until mid-April.
(taken from Taylor and Pearce, 1999)

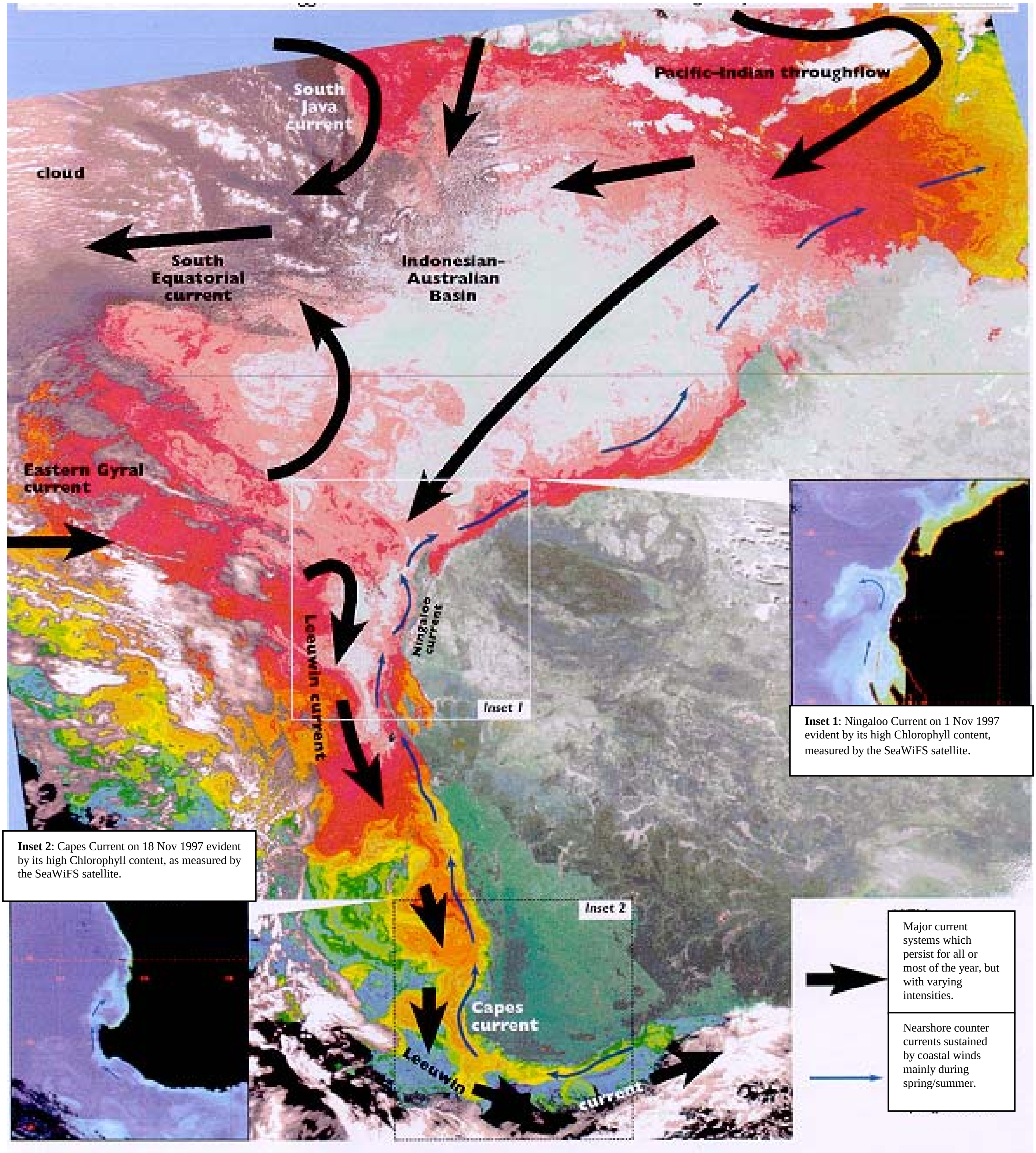

Figure 16: The broad-scale circulation off Western Australia. The background colour over the sea represents the surface temperature of the water as measured by a NOAA satellite on 15 August 1991. The warmest seawater is off northwest Australia (pink-white) and the coolest seawater is off southern Australia (blue). The Leeuwin Current and its meanders are clearly seen as the red/yellow band beginning off the Pilbara coast and running off the west and south coasts. The nearshore counter-currents, driven seasonally by winds, are indicated by the thin blue arrows.