INDONESIAN THROUGHFLOW AND LEEUWIN CURRENT

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Introduction

Ocean currents along the eastern boundary of the Indian Ocean are markedly different from those found in the eastern Pacific and Atlantic. There are several reasons why this should be so: the unique, monsoon-reversing character of the winds; the complex topography of the coastline; and especially the gap from the Pacific to the Indian Ocean that permits warm west Pacific water to flow through to the Indian Ocean (the 'Indonesian Throughflow'). Proceeding from north to south along the boundary, one finds (**Figure 1**): the eastern boundary current of the Bay of Bengal (referred to below as the Andaman Current, though it as yet has no official name); the South Java Current, which flows eastward along the south coasts of Sumatra and Java twice each year; the Indonesian Throughflow; the Leeuwin Current, flowing south along the western coast of Australia; the 'West Wind Drift', flowing east along the south coast of Australia; and the Zeehan Current, flowing south-east along the Tasmanian coast.

We first discuss the unusual character of this set of eastern boundary currents as an ensemble. Then we consider the better-known of these currents in more detail. However, it must be appreciated that our knowledge of the entire eastern boundary current system of the eastern Indian Ocean is still quite limited, especially for the Undercurrents below about 200 m, and for the flows along the coasts of Indonesia and the Andamans. Strong tidal flows also make detection of mean currents difficult, over the wide continental shelf northwest of Australia.

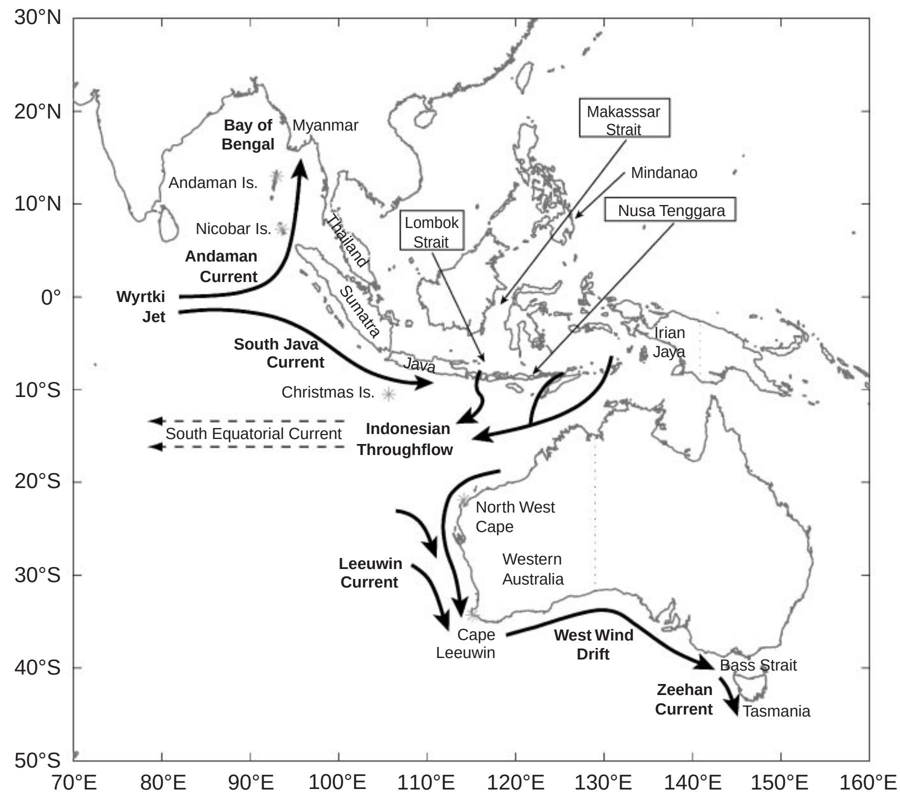

Figure 1 Location map.

The Unique Character of the Indian Ocean's Eastern Boundary

In the Pacific and Atlantic, steady easterly winds blow along the Equator. Ocean pressure gradients develop along the Equator to balance these winds, and as a result average near-equatorial water temperatures at depths of about 100 m are typically 6–10°C lower on the eastern than the western side of both oceans. This is the primary cause of the cold, nutrient-rich water found near the eastern boundaries of the Pacific and Atlantic Oceans. By contrast, coastal-trapped waves pass south-westward from the Pacific, along the west coasts of Irian Jaya and Australia; they tend strongly to make temperatures along the north-west coast of western Australia equal to those in the western equatorial Pacific, i.e., much warmer than those in the tropical eastern Pacific. Such high ocean temperatures cannot be sustained in the colder climate of south-western Australia. Hence, as a further consequence, longshore temperature and density gradients develop along the Australian coast south of 20°S. These gradients in turn drive a density current southward, into the prevailing wind – the Leeuwin Current. This flow follows the continental shelf edge, reaching maximum strength near Cape Leeuwin, at the south-west corner of the continent. The longshore temperature and pressure gradients disappear along Australia's south coast, a short distance east from Cape Leeuwin. Nevertheless, mean flow continues westward as the 'West Wind Drift'. The name is apt, since this flow indeed appears to be driven along the shelf edge mainly by the strong westerlies of austral winter, which drives onshore Ekman transports and coastal downwelling at the shelf edge. Mean wind stresses and longshore pressure gradients both favor the Zeehan Current – another shelf-edge flow. Wind-driven upwelling (and the associated rich fisheries) are essentially absent along this entire coastal region, though weak coastal upwelling is observed in summer, inshore from the West Wind Drift.

A strong discontinuity in eastern boundary behavior occurs across the gap from Australia to Indonesia, with much lower temperatures off southern Indonesia. The resulting pressure drop across the Indonesia–Australia gap holds the Indonesian Throughflow in geostrophic balance, while the drop from the Pacific to southern Indonesia along the west side of the Throughflow drives this current along Makassar Strait as a western boundary current, into the Indian Ocean. During the austral winter, when south-east Trade Winds blow along Indonesia's south coast, quite strong upwelling develops: for this reason, Indonesia has the richest fisheries found anywhere along the eastern boundary of the Indian Ocean. It is the spawning ground of the Southern Bluefin Tuna, a particularly prized commercial fish species. The Throughflow joins the westward-flowing South Equatorial Current, just south of Indonesia. Near May and again near November, i.e., between the two monsoons, a narrow east-flowing current (the South Java Current) develops between the coast and the South Equatorial Current.

A further difference between the Indian Ocean and the other two is that mean wind stresses along the equatorial Indian Ocean are in fact slightly westerly. This is due primarily to strong equatorial westerlies in April and October, between the two monsoons. These winds drive the 'Wyrtki Jets' – rapid flows along the Equator peaking in May and November. The Jets impinge on Sumatra, driving the thermocline down and splitting northward and southward into flows along the boundaries. The southern arm is responsible for the strong semi-annual character of the South Java Current, while the northern arm does the same for the Andaman Current. Buoy tracks and satellite altimetry show that similar phenomena occur along the west coast of Thailand and Maianmar.

The Indonesian Throughflow

It has been estimated that about one-quarter of the heat absorbed by the Pacific Ocean i.e., $\sim 0.5 \times 10^{15}$ is carried into the Indian Ocean by the Indonesian Throughflow. (Mass balance is preserved by a flow of much colder water, flowing back to the Pacific south of Tasmania.) Because of its major role in the global heat budget, substantial efforts have been put into measuring the strength of the Throughflow. However, it has until recently proved quite difficult to measure its strength with sufficient accuracy, for several reasons. The most important of these is that it has very large interannual variability: it is only since several years' data came available from sampling by bathythermographs (expendable temperature profilers dropped from Volunteer Observing Ships) that the strength of this variability became known. For example, two precise flow measurements were made in August 1988 and February 1922; flow strength from the Pacific was 18 ± 7 Sv and -2 ± 9 Sv, respectively, at these times.

When the Throughflow is strong/weak (in La Niña/El Niño conditions), sea level along the entire northern, western and southern Australian coast is relatively high/low. A strong relationship of the

Throughflow magnitude to the Southern Oscillation Index (a simple measure of the state of the ENSO (El Niño–Southern Oscillation) phenomenon) is apparent. A winter (August) maximum is also discernible; the winter Trade Winds along the Sumatra and Java coast not only generate upwelling, they raise the thermocline at the east end of Java, lowering pressures there and thus increasing the Throughflow magnitude. Recent current meter measurements in a constriction of Makassar Strait suggest that the average magnitude of the Indonesian Throughflow is close to 10 Sv.

The Indonesian Throughflow enters Indonesia south of Mindanao; water mass properties at entry indicate a North Pacific source, though originally the water must come from the South Pacific. It exits through Lombok Strait, between Lombok and Bali (**Figure 2**) to the Indian Ocean via a large number of channels (further complicating the measurement problem). About 1–2 Sv exits through Lombok Strait, between Bali and Lombok; most of the rest exits in roughly equal amounts on either side of Timor Island. The flow strength through some smaller channels along the Nusa Tenggara Island chain is at present not known. After leaving Indonesia, the Throughflow joins a strong westward-flowing jet. Vigorous eddies develop along this jet. These are not seen in SST, but are clear in altimeter data (**Figure 3**, eddies 1–3), further modulating the Throughflow and the South Java Current.

Water masses change their properties substantially at all depths as they flow along the Throughflow from the Pacific to the Indian Ocean. Mixing by the strong tidal currents found in several parts of Indonesia is thought to be responsible, though the exact mechanism has not yet been identified. This mixing process may also contribute to the relatively high near-surface nutrients and rich fisheries found in the region, and to the substantial absorption of heat observed there.

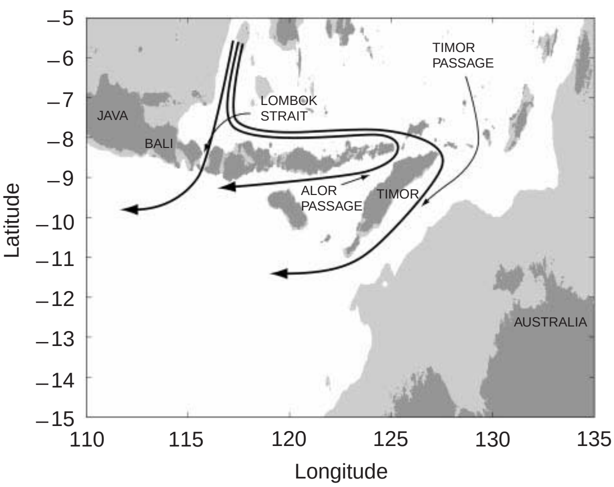

Figure 2 The Indonesian Throughflow.

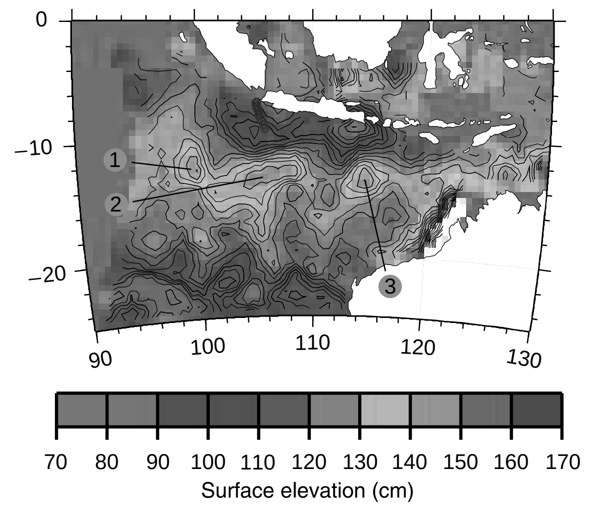

Figure 3 Map of sea level, showing an eddy south of Indonesia. Courtesy S Wijffels.

The Leeuwin Current

The first recorded suggestion that there might be a strong, warm poleward-flowing current along the western Australian coast was made in the 1890s, based on the observation that tropical corals grow on the Abrolhos Islands, only 40 km west of Geraldton at 29°S. This is well south of the latitudes at which coral is usually found. Turtles are sometimes carried into the West Wind Drift. However, direct observation of the Leeuwin Current did not take place until the 1970s, when an investigation was commissioned into the life cycle of the Western Rock Lobster. (This is the major shelf fishery between Northwest Cape and Cape Leeuwin; the upwelling-dependent pilchards and anchovy found at similar latitudes off the west coasts of America and Africa are minor features of the biota off Western Australia.) Satellite-tracked buoys released near the shelf break were often trapped in vigorous eddies just beyond the break; on leaving the eddies they would then frequently travel southward at speeds of up to 1.5 m s^{-1}, following the shelf break closely. Maximum speeds were attained near Cape Leeuwin, but the buoys quickly decelerated after rounding the Cape. It was this discovery that alerted researchers to the unusual nature of the flow regime off Western Australia. The drifters showed that the Current is strongest (about 5 Sv) in about May, falling to near zero in September, though there is strong interannual variability associated with the ENSO phenomenon in the same sense as that of the Indonesian Throughflow.

Investigation of hydrographic data collected over the preceding decades revealed that surface geostrophic flow in the adjacent ocean is strongly eastward; that is, it flows toward the coast, overwhelming the offshore Ekman transport. Consequently, there is coastal downwelling; the Leeuwin Current is in geostrophic balance with the downward-sloping isopycnals that result. Interestingly, there is a north-flowing Leeuwin Undercurrent between about 200 m and 1000 m, directly beneath the surface current, whose northward transport roughly compensates the southward transport of the Leeuwin Current above it (this compensation is typical of a density-driven flow). The vigorous eddies found just beyond the continental shelf edge appear to be generated by instability of the shelf-edge current system both west and south of Australia, as is clearly seen in SST imagery (e.g. **Figure 4**).

The continental shelf is several hundred kilometers wide off Australia's northwest coast, but it narrows markedly as one moves southwestward towards Northwest Cape (**Figure 1**). The southwest flowing Leeuwin Current (strongest in May) starts along this shelf; at first it is dominated by strong tidal currents. However, the Leeuwin Current narrows as it moves southwestwards, and accelerates to speeds of about $0.5\,\mathrm{m\,s^{-1}}$ off Northwest Cape, while tidal flows decrease. The flow is augmented at Northwest Cape and further south by inflow from the east, to reach maximum transport at Cape Leeuwin.

The warm Leeuwin Current is an important mechanism for carrying some of the excess heat of the Indonesian Throughflow southward.

The South Java Current and Andaman Current

As noted above, the two Wyrtki Jets feed into coastal currents that flow northward and southward from the Equator. South of the Equator, sea level rises along the south coasts of Sumatra and Java, generating eastward currents there around each May and November. It is these eastward flows that define the 'South Java Current'; they reach a strength of about 6 Sv in May, and 3 Sv in November. The warm, fresh South Java Current waters suppress upwelling at these times, which is strongest around August. It is not yet known how much of these currents penetrate beyond Lombok Passage, the first deep channel encountered along the southeastward flow. South Java and Christmas Island are home for a prolific bird life; the birds feed on fish within the upwelling zone south of Java.

Similar semiannual currents occur north of the equator when the Wyrtki Jets impinge on the region. However, it is not yet known how this current system splits after passing the northern tip of Sumatra; the topography of the Andaman and Nicobar

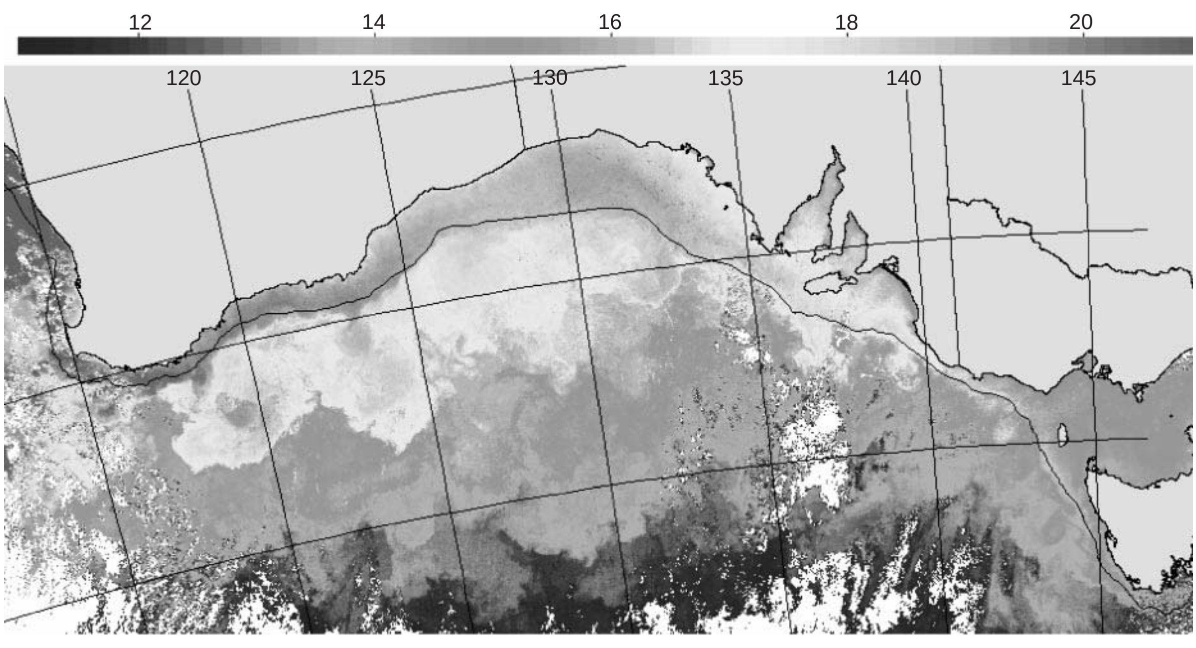

Figure 4 SST map of the south coast of Australia. Courtesy G Cresswell.

Islands appear to generate much complexity. Furthermore, intense tidal flows make this a region of turbulent mixing.

The West Wind Drift and Zeehan Current

The continental shelf south of Australia is nearly 200 km wide along much of its length. Circulation north of the shelf break is generally quite slow; the West Wind Drift is strongest in a narrow jet along the shelf break, particularly in winter where speeds reach $1\ \mathrm{m\,s^{-1}}$. Strong eddy formation also occurs at the south edge of the Leeuwin Current/West Wind Drift south of Australia (**Figure 4**). Similar eddies occur in the Leeuwin Current off Australia's west coast (not shown). Strong evaporation occurs in the Great Australian Bight in summer. Much of the salty water so generated flows eastward in winter, through Bass Strait; it sinks some 400 m on encountering the warm, light waters of the East Australian Current in eastern Bass Strait. However, satellite-tracked buoys frequently arc south-eastward to join the Zeehan Current, usually staying close to the shelf break in the process. These flows are slower than those found off Cape Leeuwin, but current meter moorings in the Zeehan Current show it to be much deeper than the Leeuwin Current. The Zeehan Current extends down to 1000 m in winter. The summer upwelling referred to earlier appears to be mainly confined to the narrow continental shelf region off western Victoria; it occurs during bursts of easterly wind.

See also

East Australian Current. El Niño Southern Oscillation (ENSO). Indian Ocean Equatorial Currents.

Further Reading

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INHERENT OPTICAL PROPERTIES AND IRRADIANCE

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Introduction

Light is of great importance for the physics, chemistry, and biology of the oceans. In this article, a brief introduction is provided to the two subdisciplines focusing on light in the ocean: ocean optics and bio-optics. A few of the problems addressed by these subdisciplines are described. Several of the *in situ* sensors and systems used for observing the subsurface light field and optical properties are introduced along with general explanations of the operating principles for measuring optical variability in the ocean. Some of the more commonly used ocean platforms and optical systems are also discussed. Finally, some examples of oceanographic optical data sets are illustrated.

Solar radiation, which includes visible radiation or light, impinges on the surface of the ocean. On average, a small fraction or percentage is reflected back into the atmosphere (roughly 6% on average) while a high fraction penetrates into the ocean. This fraction (or percentage), defined as the albedo, varies in time and space as a function of several factors including solar elevation, wave state, surface roughness, foam, and whitecaps. Radiative transfer is a branch of oceanography termed 'ocean optics,' a term that denotes studies of light and its propagation through the ocean medium. Radiative transfer processes depend on the optical properties of the components lying between the radiant source (e.g., the sun) and the radiation sink (the ocean and its constituents). Another commonly used term is 'bio-optics,' which invokes the notion of biological effects on optical properties and light