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CURRENT SYSTEMS IN THE INDIAN OCEAN

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doi:10.1006/rwos.2001.0363

Introduction

The Indian Ocean is the smallest of all the oceans and is in several respects quite different from the others. In particular, it is bounded by the Asian continent to the north. This meridional land–sea contrast has a strong influence on the winds, resulting in a complete seasonal reversal of the winds known as the monsoon system. The characteristics of the basin and of the wind regime are determinant for the currents, and will be described first in this article. The description of the currents has been separated into two main sections: the first for the southern part of the Indian Ocean which is not affected by the monsoons and is more akin to the other subtropical oceans; and the second for the northern part which undergoes forcing through the reversal of the monsoon winds. Some information on the deep circulation and a short conclusion are then provided.

Characteristics of the Indian Ocean Basin

The Indian Ocean basin is the smallest of the five great subdivisions of the world ocean with $49.10^6\,km^2$ out of the $361.10^6\,km^2$ of the global ocean (**Figure 1**). It is closed to the north around the latitude of the Tropic of Cancer by the Asian continent, which has important consequences on the ocean circulation. South of the equator, its western boundary is modified by the presence of the island of Madagascar. In the east, the basin is connected with the equatorial Pacific Ocean through the deep passages of the Indonesian Seas. The north of the Indian Ocean is made up of the large basins on either side of the Indian peninsula, the Arabian Sea in the west and the Bay of Bengal in the east which drains most of the river runoff from the Himalayas and the Indian subcontinent. The Arabian Sea is connected directly to the shallow Persian Gulf, and through the sill of Bab-el-Mandeb (110 m) to the deep Red Sea basin where high salinity waters are formed. In the south, the basin is largely open to the Antarctic Ocean between South Africa and Australia. The Indian Ocean limit to the south is the Subtropical Convergence, a hydrological limit where the meridional surface temperature gradient is maximum. At depth, the complicated system of ridges separates the Indian Ocean in many deep basins (**Figure 1**).

The Overlying Atmosphere

Due to the presence of the Asiatic continent to the north, the atmospheric circulation is quite different from the Pacific Ocean and the Atlantic Ocean, particularly north of 10°S. Seasonal heating and cooling of the atmosphere over Asia induces a seasonally varying monsoon circulation (**Figure 2**). For centuries it has been known that the winds north of around 10°S reverse with the seasons. A long time ago the Arabic traders along the east African coast made use of the fair currents and winds during their voyages. The word 'monsoon' comes from the Arabic word 'mawsin' meaning season. As the winds are the main driver of the currents, in particular near the surface, the main characteristics of the wind seasonal variability will be described below.

The wind seasonal variability over the ocean can be separated in four periods: the winter monsoon period, the summer monsoon period, and the two transition periods between the two monsoons.

Between December and March–April, north of the equator, the winter (NE) monsoon blows from the north east with a moderate strength. At the

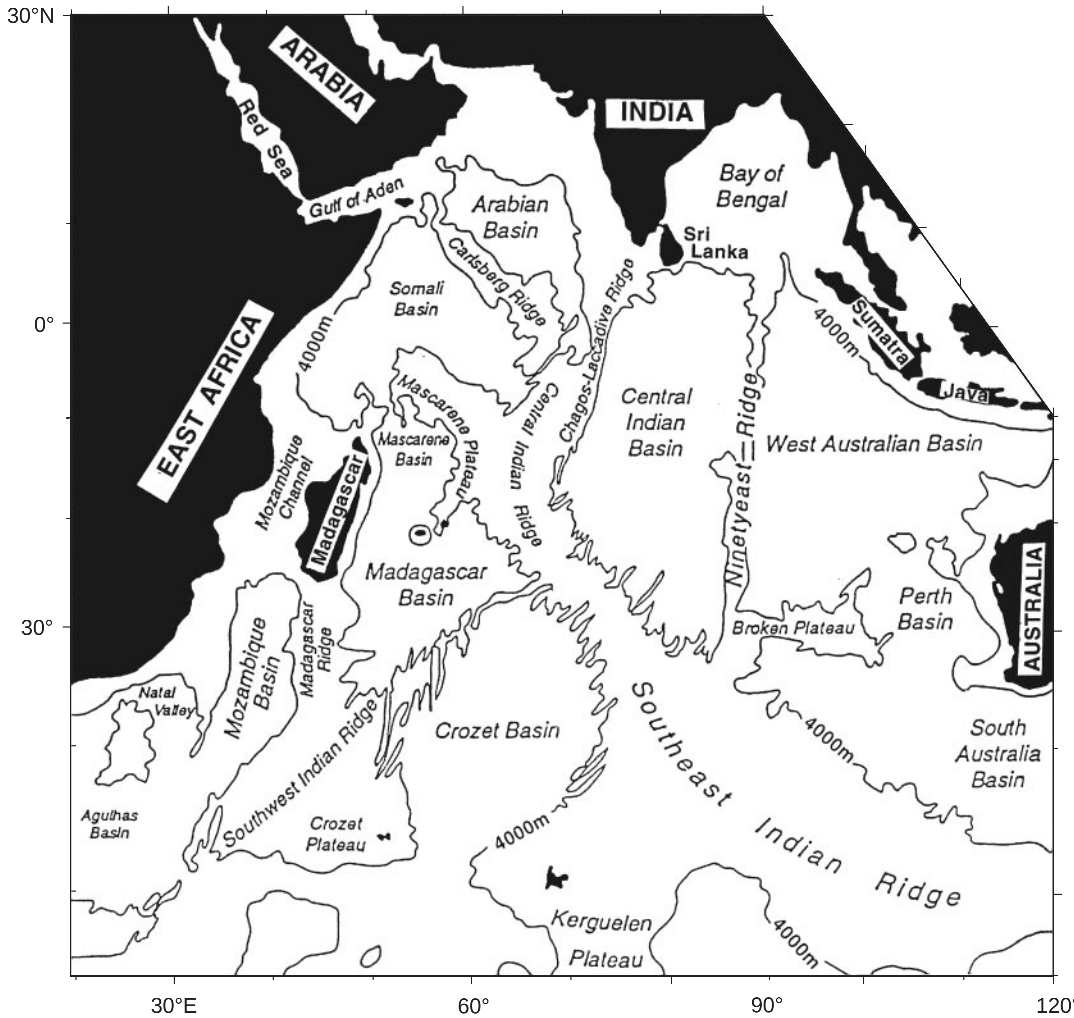

Figure 1 Map of the Indian Ocean with the different basins.

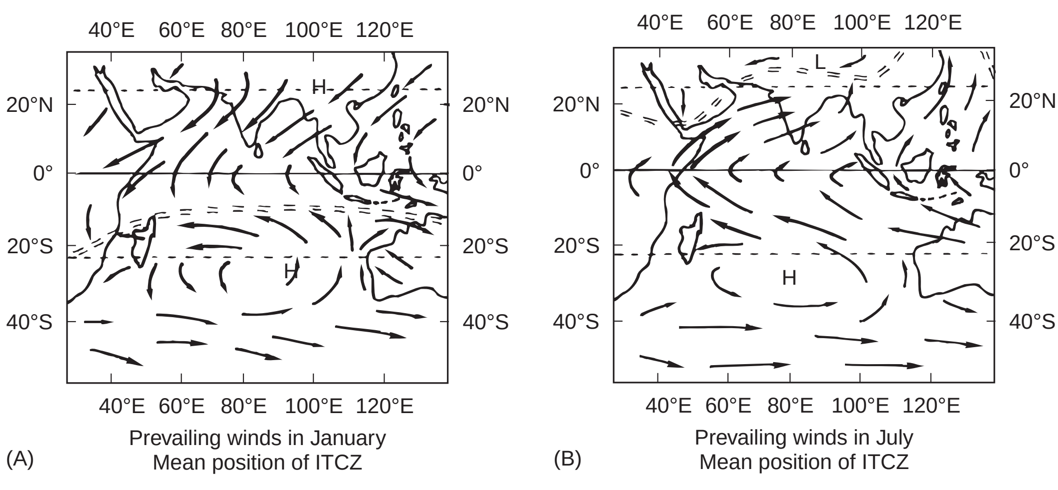

Figure 2 Prevailing winds during (A) the northern monsoon (January); (B) the southern monsoon (July); double dashed lines indicate the ITCZ.

equator the winds are weak and usually from the north. Between the equator and the Intertropical Convergence Zone (ITCZ) which stretches zonally near 10°S between north Madagascar and south Sumatra, it blows from the north west. During that season (southern summer), the atmospheric pressure decreases over Australia and South Africa and the subtropical high pressure over the ocean, around 35°S, is weaker – as are the south-east trade winds during that season.

In April–May, during the transition period between the end of the NE monsoon and the beginning of the SW monsoon, the winds north of the equator calm down. At the equator moderate eastward winds blow, which contrasts with the westward winds over the equatorial Pacific and Atlantic Oceans.

From June to September–October during the SW monsoon, the winds reverse completely and north of the equator the summer monsoon blows steadily from the south west. The SW summer monsoon is much stronger than the NE winter monsoon. A wind jet, also called the Finlater jet, develops along the high orography of the east African coast. As a consequence, the winds are the strongest on the western side of the Indian Ocean along the Somali coast towards the Arabian Sea, particularly northeast of Cape Guardafui (the horn of Africa) where the mean July wind speed is $12\,\mathrm{m\,s^{-1}}$ with peaks exceeding $20\,\mathrm{m\,s^{-1}}$. They are the strongest and the steadiest wind flow in the world. At the equator, the winds are moderate from the south and decrease eastward. In the southern Indian Ocean, the subtropical high pressure center intensifies and covers the whole width of the southern Indian Ocean during the southern winter (July) and the SE trades penetrate farther north than during the southern summer (January); they reach the equator in the western part of the ocean and are the strongest among the three oceans. During that season the air masses transported by the SE trade winds cross the equator in the west and continue, loaded with moisture, towards the Asian continent where they bring the awaited monsoon rainfall.

October–November corresponds to the second transition period between the end of the SW monsoon and the beginning of the NE monsoon. North of the Equator, the winds vanish and the sea surface temperature can exceed 30°C. At the equator moderate eastward winds blow again as during the first transition period, although they are usually slightly stronger.

This particular wind regime implies that at the equator, the zonal wind is dominated by a semiannual period associated with the westerly winds of the transition periods, while the meridional wind presents a strongly annual period associated with the monsoon reversals. The winds off the equator also present a strong annual period.

Along the western Australian coast the northward winds, favorable for upwelling, are much weaker than in the eastern Pacific and Atlantic Oceans. They even drop down during the SW monsoon season. This is due to the different land–ocean distribution.

The seasonal changes of the winds south of latitude 10°S are smaller than to the north, and therefore the variability in the ocean circulation will also be smaller there. The next section will describe the currents in this area, before presenting the currents in the northern area.

The Currents in the Southern Part of the Indian Ocean

The strong anticyclonic subtropical gyre of the southern Indian Ocean is the result of the large wind stress curl between the Antarctic westerlies and the SE trade winds. Its northern branch is the westward-flowing South Equatorial Current (SEC) centered between 12°S and 20°S, fed in its northern part by the throughflow waters originating from the Indonesian Seas and corresponding to lower salinity waters (**Figure 3**). The SEC is the limit of the influence of the monsoon system. Its mean transport relative to the 1000 dbar level varies from 39 Sv in July–August to 33 Sv in January–February. Its latitudinal range varies between 8°S and 22°S in July–August and 10°S–20°S in January–February.

The SEC impinges on both the east coast of Madagascar and on the east African coast, resulting in several intensified boundary currents along these coasts. The SEC splits into a northward flow and a southward flow east of Madagascar near 17°S. The southern branch continues as the East Madagascar Current (EMC) carrying of the order of 20 Sv (0–1100 m), which ultimately joins the Mozambique Current and the Agulhas Current (AC) to the south west, besides some recirculation to the east into the subtropical gyre. The northern branch of the SEC splits again east of the African coast near cape Delgado (11°S) into the southward-flowing Mozambique Current (MC) and the northward-flowing East African Coastal Current (EACC). The Mozambique Current presents intense recirculation in the northern Mozambique Channel, but ultimately feeds roughly 20 Sv into the Agulhas Current which is the strongest western boundary current in the south Indian Ocean, transporting nearly 70 Sv.

The eastward-flowing south branch of the anticyclonic subtropical gyre of the southern Indian

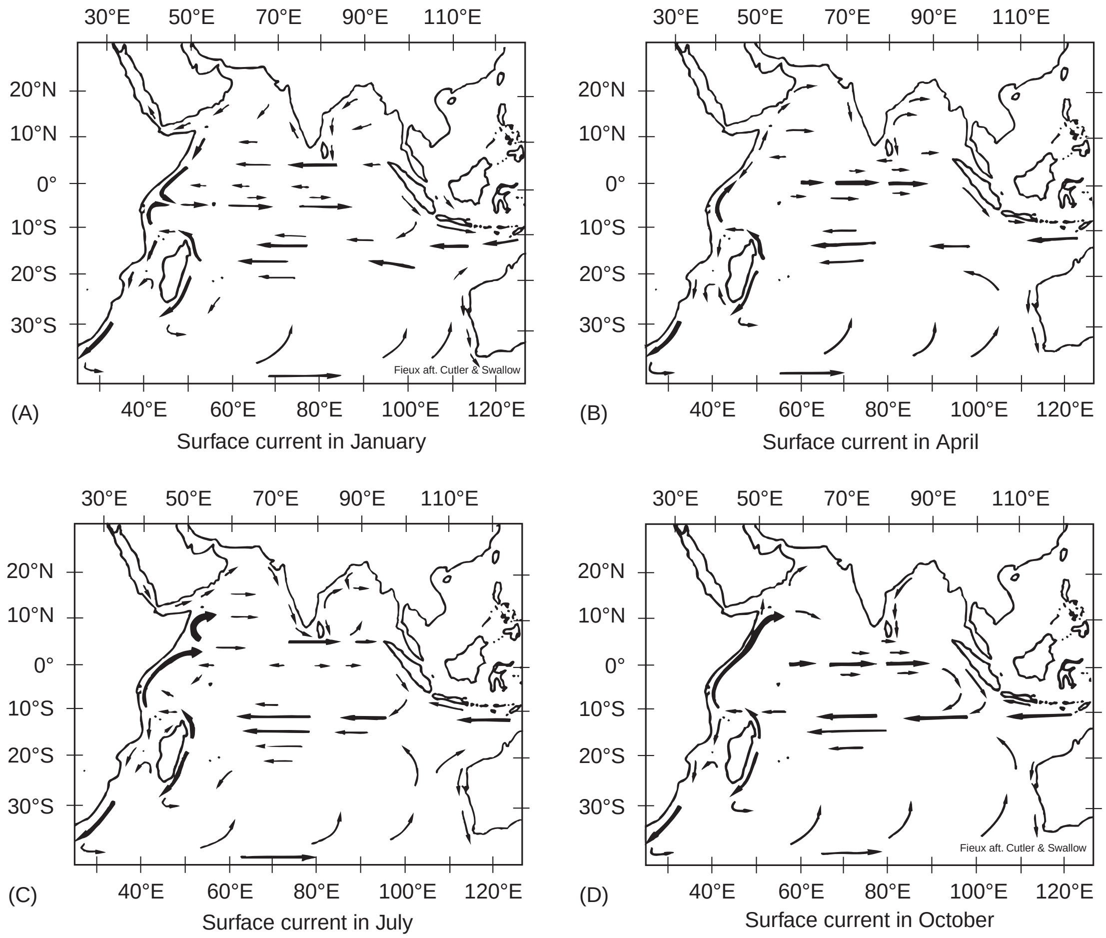

Figure 3 General surface circulation in the Indian Ocean: (A) during the NE monsoon; (B) during the transition period in April; (C) during the SW monsoon; (D) during the transition period in October. (Adapted from Cutler AN and Swallow JC (1984) *Surface Currents of the Indian Ocean* (to 25°S, 100°E): compiled from historical data archived by the Meteorological Office, Bracknell, UK. Institute of Oceanographic Sciences, Wormley, UK Rep. 187, 8pp and 36 charts.)

Ocean is part of the Antarctic Circumpolar Current (ACC). Nevertheless, north of the ACC, a South Indian Ocean Current (SIC) can be differentiated from the different cores of the ACC. The SIC comprises the eastward flow recirculating part of the Agulhas Current off South Africa and at depth transports North Atlantic Deep Water. The ACC transports Antarctic circumpolar waters with lower salinity than in the South Indian Ocean Current.

The eastern Indian Ocean is connected with the Pacific Ocean through channels in the Indonesian Archipelago. This has large consequences on the eastern Indian Ocean circulation and is expected to be one of the causes for the southward flow west of Australia, the Leeuwin Current, which flows opposite to the wind. The mean sea level, higher on the Pacific side than on the Indian Ocean side of the Indonesian Seas, drives a throughflow towards the Indian Ocean transporting warmer and fresher waters contributing to a high dynamic height in the north of the western Australian coast. This induces an alongshore pressure gradient off western Australia which drives the Leeuwin Current to the south and can even overwhelm the counteracting effect of the coastal upwelling induced by the weak southerly winds. At 22°S, the Leeuwin current is a 30–50 km wide and shallow (150–200 m) poleward jet close to the coast (max in May–June) with large intraseasonal to interannual variability which is associated to an equatorward undercurrent.

Response of the Indian Ocean Circulation to the Wind Variability in the Northern Part

North of 10°S, the ocean circulation responds to the seasonally varying monsoon winds and as a consequence presents well defined seasonal characteristics. It is necessary to distinguish the circulations near the western boundaries, near the equator, in the northern ocean interior, and the eastern boundary current systems, which have different dynamics. They will be described successively, on the basis of observations as well as numerical or analytical modeling studies.

The Western Boundary Current System

As in the other oceans, the strongest currents are close to the western shores of the ocean as a result of the direction in which the earth rotates and the variation of the Coriolis parameter with latitude. North of 10°S (which is the limit of the monsoon influence), there are two western boundary currents: the East African Coastal Current (EACC) which always flows northward and the Somali Current which is the most intense and the most variable.

The EACC flows in continuity with the branch of the SEC which passes north of Madagascar and splits around 11°S. It runs northward throughout the year between latitudes 11°S and 3°S. Its surface speed can exceed $1\,m\,s^{-1}$ during northern summer and its transport amounts to 20 Sv in the upper 500 m. Its northern end depends on the season. In northern winter, the EACC converges around 3°S–4°S with the south-going Somali Current to form the eastward South Equatorial Countercurrent. During the northern summer, the EACC merges into the north-going Somali Current.

The Somali Current is the most intense, but unlike the other western boundary currents it is highly variable due to the complete seasonal reversal of the winds. It was first studied during the International Indian Ocean Experiment in the 1960s, during INDEX (INDian ocean EXperiment which started in the 1970s) and during SINODE in the 1980s. Recently (1990–96), during WOCE (World Ocean Circulation Experiment) considerable amounts of new data were collected over the whole Indian Ocean. The Somali current develops in different phases in response to the winds.

During the transition period after the NE monsoon, in April, the Somali current flows south-westward along the coast south of 5°N, merging near the equator with the northward-flowing EACC. This feeds a south-eastward flow towards the ocean interior.

In early May, the Somali current responds rapidly to the onset of the local southerly winds and reverses northward in continuity with the northward EACC near the equator. By mid-May, the SW wind onset propagates northward and the current turns offshore towards the east at 4°N. North of that branch an upwelling wedge spreads out, bringing cold and enriched waters at the surface. Further to the north, the current flows northward from March onwards. When the onset of the strong summer monsoon winds occurs at these latitudes in June, the southern branch increases in strength and a strong anticyclonic gyre, called 'the great whirl' develops between 5°N and 10°N. Between the Somali coast and the northern branch of the great whirl a second upwelling wedge forms. Numerical models have shown that the location and motion of these structures are influenced by the distribution and strength of the wind forcing.

In August–September, when the winds decrease, the southern cold wedge propagates northward along the coast and meets with the northern one (although the latter probably also moves). It is only at that time that the Somali current is continuous from the equator up to 10°N and brings fresher waters into the Arabian Sea.

During the transition period in October–November, the northward Somali circulation decreases.

In December–February, during the NE winter monsoon, the Somali Current reverses southward from 10°N to 5°S where it converges with the northward EACC to form the South Equatorial Counter Current (SECC) flowing eastward. This countercurrent exists only during the NE winter monsoon and could be compared to the other Equatorial Counter Currents in the Atlantic Ocean and in the Pacific Ocean. It develops just north of the intertropical convergence zone (ITCZ) where the winds have an eastward component.

At the equator near Africa, the reversal affects only a thin surface layer below which (between 120 m and 400 m) there is a northward undercurrent, remnant of the SW monsoon season, followed again by a southward current below 400 m.

There are also western boundary currents in the Gulf of Bengal off the coasts of Sri Lanka and India.

From September to January, the currents are southward along the whole eastern coast of India and Sri Lanka, bringing fresh Bengal Bay water to low latitudes (6°N). In February–March the currents reverse to flow to the north along these coasts with a separation from the coast in the northern Bay of Bengal (19°N) in March. From April to August, the current reverses along the eastern coast of Sri Lanka where it flows to the south. Further north, from May to July, the separation from the coast of the northward current takes place around 16°N instead of 19°N. In July, north of 16°N, reversal to the south takes place. This seasonal cycle is markedly different from the one off the Somali coast. Modeling studies show that it is a response both to local winds, to the curl of the wind stress over the

Bay of Bengal, with other contributions propagating along the coast from further east, and from the vicinity of the equator.

Equatorial Currents System

The winds at the equator are profoundly different in the Indian Ocean from the mostly westward winds in the Atlantic and the Pacific tropical oceans. Instead, in the Indian Ocean, there is a strong semi-annual cycle in the zonal winds and the mean zonal wind is westerly.

During the two transition periods between the monsoons, a strong eastward jet (called 'Wyrtki jet') occurs in a narrow band, trapped within 2°–3° of the equator, mostly in the central and eastern parts, driven by the equatorial westerly winds. Due to the efficiency with which zonal winds can accelerate zonal currents at the equator where the Coriolis force vanishes, the current speeds can rapidly reach $> 1\,\mathrm{m\,s^{-1}}$. The jet usually peaks in November with velocities which can reach $1.5\,\mathrm{m\,s^{-1}}$; it could also reach these values in May as there is large intra-seasonal and interannual variability.

At the equator, in the middle of the Indian Ocean near Gan Island (73°E), measurements show currents throughout the upper 100 m in phase with local winds, which reverse four times a year. The associated change of current direction produces semi-annual variations in the thermocline depth and sea level. During periods of eastward flow the thermocline rises off Africa and falls off Sumatra corresponding to opposite displacements of the sea level. The set up of the jet is apparently triggered by the westerly winds during the transition periods. This forces a local response as well as waves propagating the response further to the east (Kelvin waves) and west (Rossby waves). The stopping of the jet seems to happen progressively from east to west, as it has been observed with drifting buoys. This is interpreted dynamically as westward propagating decelerating Rossby waves which are generated when the eastward jet reaches the coast of Sumatra.

During the fully developed SW monsoon in July–August, along the equator – aside from the extreme west where the strong north-eastward Somali Current occurs – the winds are southerly and light, and currents at the equator are weak and variable.

An eastward equatorial undercurrent embedded in the thermocline along the Indian Ocean equator exists only during January–June and is strongest in March at the end of the NE monsoon. It is confined between 2°30N and 2°30S and is weak east of 80°E. During the NE monsoon, it flows under a weak westward current until the eastward Wyrtki jet starts, then the whole upper layer flows eastward.

The Northern Interior Current System

During the NE monsoon in December–February, the northern Indian Ocean presents a current structure similar to those found in the other oceans. In the northern Arabian Sea, the circulation is not well defined during this season. There is a general westward flow south of 10°N, the North-east Monsoon Current (NMC), extending south to about 2°S, with speeds between 0.3 and $0.8\,\mathrm{m\,s^{-1}}$. South of Sri Lanka, the current splits into a branch continuing westward and a branch which tends to follow the western coast of India, possibly after meandering in eddies off south-west India.

Further south between 2°S and 8°S the eastward South Equatorial Counter Current (SECC) flows eastward starting at the convergence of the southward Somali Current with the northward EACC (see above).

During the SW monsoon in the Arabian Sea, there is a general eastward flow in the South-west Monsoon Current (SMC), with more intense veins near 15°N as well as near 9–10°N (although the latter might be more developed in April–June) and near 5°N. In the Arabian Sea, there is some anticyclonic recirculation to the south of the northern eastward vein, very likely forced by the curl of the wind stress, and some indication of cyclonic eddies to the north of this circulation. The flow along the western coast of India is southward during the SW monsoon associated with a poleward undercurrent along the shelf which sometimes could reach the surface. In the northern Bay of Bengal, north of 15°N, the eastward currents are already set in April–May, which last until August (in particular near 15°N–17°N). Eastward currents also exist south of 8°N in the Bay of Bengal from April to September.

The currents are intensified south of Sri Lanka during both monsoons, resulting in particularly large eastward SMC and westward NMC. Numerous eddies are also present, especially in the western parts of the Arabian Sea and Bay of Bengal, associated with upwellings that are particularly strong off the Arabian coast during the SW monsoon.

The Eastern Boundary Current System Affected by the Monsoons

Along the eastern boundary the currents are also seasonally variable, except along Sumatra, south of the equator, where it is always south-eastward and flows against the winds in June–September. During the transition periods the Kelvin waves associated with the Wyrtki jet continue north-westward and south-eastward as coastal trapped Kelvin waves along the Indonesian islands. South of Java they reinforce the NE monsoon-driven south-eastward Java current, but work against the response of the Java boundary current to the SE monsoon onset in May–June. So when the equatorial Kelvin waves arrive along the Java coast in October–November, the reversal is faster than in May–June. In July–September when the Java current is north-westward, there is a convergence with the south-eastward Sumatra current south of Sumatra. It is also during that season that large-scale wind-driven upwelling occurs along the coast of Java.

The open eastern boundary of the Indian Ocean allows exchanges with the Pacific Ocean through the channels of the Indonesian Archipelago. This flow is called the Indonesian throughflow. It transports waters from the surface down to 1300–1400 m which are principally drawn from the northern Pacific and modified in the Indonesian archipelago under both effects of exchanges with the atmosphere and dynamical mixing. The resulting water entering the Indian Ocean is a well characterized Indonesian Water. The principal route of the throughflow goes through Makassar Strait then through Lombok Strait (350 m deep between Lombok and Bali), and north and south of Timor Island (mean sills depth around 1350 m). The few partial direct measurements show strong interannual, seasonal, and intra-seasonal variability. This throughflow is entrained westward into the SEC bringing fresh and warm water to the Indian Ocean. It is also part of the source waters of the southward Leeuwin current which brings fresh and warm waters to the south along the west Australian coast.

The surface flow along the western coast of India is usually south-eastward with a north-westward subsurface undercurrent, in particular during the SW monsoon with upwelling favorable winds. However, the currents reverse at the end of the year bringing a pulse of fresher Bay of Bengal water along the coast.

Deep Circulation

Most of the circulation described here concerns the upper part of the ocean. The deep circulation is relatively unknown. The Indian Ocean is separated into numerous deep basins connected through narrow passages (**Figure 1**). As a consequence, the Antarctic Bottom Water cannot reach the northern ocean basins. Recent long-term direct measurements were carried in the Crozet-Kerguelen Gap of the South-west Indian Ridge, one of the major channels through which Antarctic Bottom Water can move equatorwards. The annual northward transport of Antarctic Water at depth greater than 1600 m amounts to 11.5 Sv which, because it has undergone large dilution through mixing, corresponds to an initial volume of Antarctic Bottom Water of 2.5–3 Sv deduced from CFC distribution. By contrast, further north, in the Amirante Passage connecting at depth the Mascarene Basin and the Somali Basin, the flow of bottom water flowing northward has been estimated to be 2.5–3.8 Sv.

From the characteristics of the water masses, an intensification of the deep flow is found as deep western boundary currents against the eastern flanks of each meridional ridge separating the numerous deep basins. Some of this deep, intermediate, and subsurface water flowing northward in the Indian Ocean is upwelled and contributed to the cooling of the surface waters.

Conclusion

The northern Indian Ocean is a natural laboratory to study the effect of the wind on the oceanic circulation, as regularly twice a year the winds change direction rapidly and are particularly strong in the western boundary. The highest variability as well as the highest current speed of the world ocean are found in the Somali current.

At the equator, particularly between the two monsoon seasons, westerly wind bursts entrain a strong eastward equatorial jet twice a year which could have an effect on the strength of the transport coming from the Pacific Ocean. Some of the variability of these wind bursts seems to be related to the El Niño–La Niña climatic variability. Comparing the width and the external forcing of the Pacific and Indian oceans, the Indian Ocean at semi-annual frequency should behave dynamically like the Pacific at annual frequency.

See also

Agulhas Current. Antarctic Circumpolar Current. Elemental Distribution: Overview. El Niño Southern Oscillation (ENSO). Indian Ocean Equatorial Currents. Indonesian Throughflow and Leeuwin Current. Pacific Ocean Equatorial Currents. Somali Current. Thermohaline Circulation. Water Types and Water Masses. Wind Driven Circulation.

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