shown that even moderate amounts of turbulent mixing can actually inhibit the growth of certain dinoflagellates. The effect seems to be that of preventing cell division, since other cellular processes (e.g., photosynthesis, pigment synthesis, nucleic acid synthesis) appear to continue as usual. If the period of turbulent mixing is short-lived, the cells recover and quickly begin dividing, possibly going on to form a bloom. If, however, the turbulence continues for longer periods, the cells will be prevented from dividing, or they may even die. Of particular interest is that the growth of at least two dinoflagellate species that form harmful algal blooms *(Lingulodinium polyedrum* and *Heterosigma carterae*) seems to be inhibited by turbulence.

Conclusions

Although our basic view of plankton as being organisms that 'go with the flow' still holds true, over the past 20 years we have also learned that interactions between plankton and their physical environment can be quite complex. Perhaps the most important result of this research has been the realization that small-scale physical processes affect so many different aspects of plankton ecology including feeding, predator–prey interactions, swimming and buoyancy, nutrient diffusion, mate selection, and even patterns of community composition. That many of these discoveries are rather new is largely due to the fact that, until relatively recently, oceanographers were simply unable to conduct experiments and observe plankton at appropriately small scales. Now that we have that capability, however, the challenge in the coming years will be to find ways to integrate what has been learned about the behavior of individual plankton to further develop our understanding of population-level processes. Are population-level processes merely the sum of innumerable individual interactions, or are there other physical processes that affect populations at larger space and timescales? Alas, we do not yet know the answer to this question. However, finding new ways to extend what has been learned in the laboratory into more realistic field settings may prove one step in the right direction.

See also

Fish Larvae. Plankton.

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SOMALI CURRENT

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Introduction

The western Indian Ocean is the only region of the world where a large boundary current, as strong as the Gulf Stream, reverses twice a year in response to the wind reversals during the north-east winter monsoon and the south-west summer monsoon. This region of the Somali current is known to undergo the highest variability of the world ocean circulation.

Along the Somali coast, the reversals of winds and currents, known for many centuries, have been used by the Arabic traders for their navigation along the African coast and towards India. The term 'monsoon' comes from the Arabic word 'mawsin', which means seasonal.

Far from the large oceanographic research centers, the Indian Ocean used to be relatively poorly observed. The first large-scale international experiment was set up during the 1960s: the International Indian Ocean Experiment (IIOE), whose results were gathered into the Oceanographic IIOE Atlas. Until recently, the Somali current was known to reverse just twice a year with the direction of the monsoon, flowing south-westward during the NE monsoon and north-eastward during the SW monsoon. It is only with the international 'INDEX' experiment in 1979, under the initiative of Henry Stommel, that a careful survey of the response of the Somali current to the onset of the SW monsoon has been carried out.

Winds

The winds are the main driver of currents, in particular near the surface; therefore, we first recall their main characteristics. Their seasonal variability over the western boundary of the Indian Ocean can be described in four periods: the winter monsoon period, the summer monsoon period, and the two transition periods between the two monsoons (*see* Figure 2 of **Current Systems in the Indian Ocean**).

North of the Equator, the winter (NE) monsoon blows from the north east, with moderate strength, between December to March–April. At the Equator the winds are weak and usually from the north.

During the transition period between the end of the NE monsoon and the beginning of the SW monsoon, in April–May, the winds north of the Equator calm down. At the Equator moderate eastward winds blow, which contrast with the westward winds over the equatorial Pacific and Atlantic Oceans. As early as the end of March or early April, the SE monsoon starts south of the Equator, between the ITCZ (Inter-Tropical Convergence Zone) about 10°S and the Equator, with southerly winds along the East African Coast.

In most years, north of the Equator, the onset of the SW monsoon develops in two phases. The onset of the SW monsoon involves a reversal of the winds, which reach the Equator in early May as weak winds and progress northward along the Somali coast. Then a strong increase in wind occurs typically in late May to mid-June. In some years the onset can be gradual with no intermediate decrease between the first phase and the full-strength winds. They reach their full strength over the Arabian Sea usually in June–July. The summer (SW) monsoon blows steadily from the south west from June to September–October and is much stronger than the winter monsoon. Along the high orography of the east African coast, a low-level wind jet, called the Findlater jet (a kind of atmospheric western boundary flow) develops, bringing the strongest winds along the Somali coast toward the Arabian Sea, particularly north-east of Cape Guardafui (the horn of Africa). These are the strongest steady surface wind flows in the world, with mean July wind speed of $12\,\mathrm{m\,s^{-1}}$ and peaks exceeding $20\,\mathrm{m\,s^{-1}}$. At the Equator, the winds are moderate from the south and decrease eastward. In the southern Indian Ocean, during the southern winter (July), the SE Trades intensify and penetrate farther north than during the southern summer (January); they reach the Equator in the western part of the ocean and are the strongest in the three oceans. During that season the air masses transported by the SE Trade Winds cross the Equator in the west and flow, loaded with moisture, toward the Asian continent where they bring the awaited monsoon rainfall (for the Indian subcontinent, 'monsoon' means the wet monsoon, i.e., the SW monsoon).

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.

This particular wind regime is dominated off the Equator by a strong annual period. At the Equator, the zonal wind component is dominated by a semiannual period associated with the transition westerly winds, while the meridional wind component has a strongly annual periodicity associated with the monsoon reversals (*see* Figure 1 of **Indian Ocean Equatorial Currents**).

The Western Boundary Current System

As in the other oceans, the strongest currents are found close to the western shores of the ocean and are called the western boundary current system. In the western boundary region influenced by the monsoonal winds, i.e., north of 10°S, there are two western boundary currents: the East African Coastal Current (EACC), also called the Zanzibar current, which always flows north-eastward; and the Somali Current (SC), which is highly variable in contrast to other western boundary currents (*see* Figure 3 of **Current Systems in the Indian Ocean**). The Somali Current is the more intense, and reverses twice a year owing to the complete seasonal reversal of

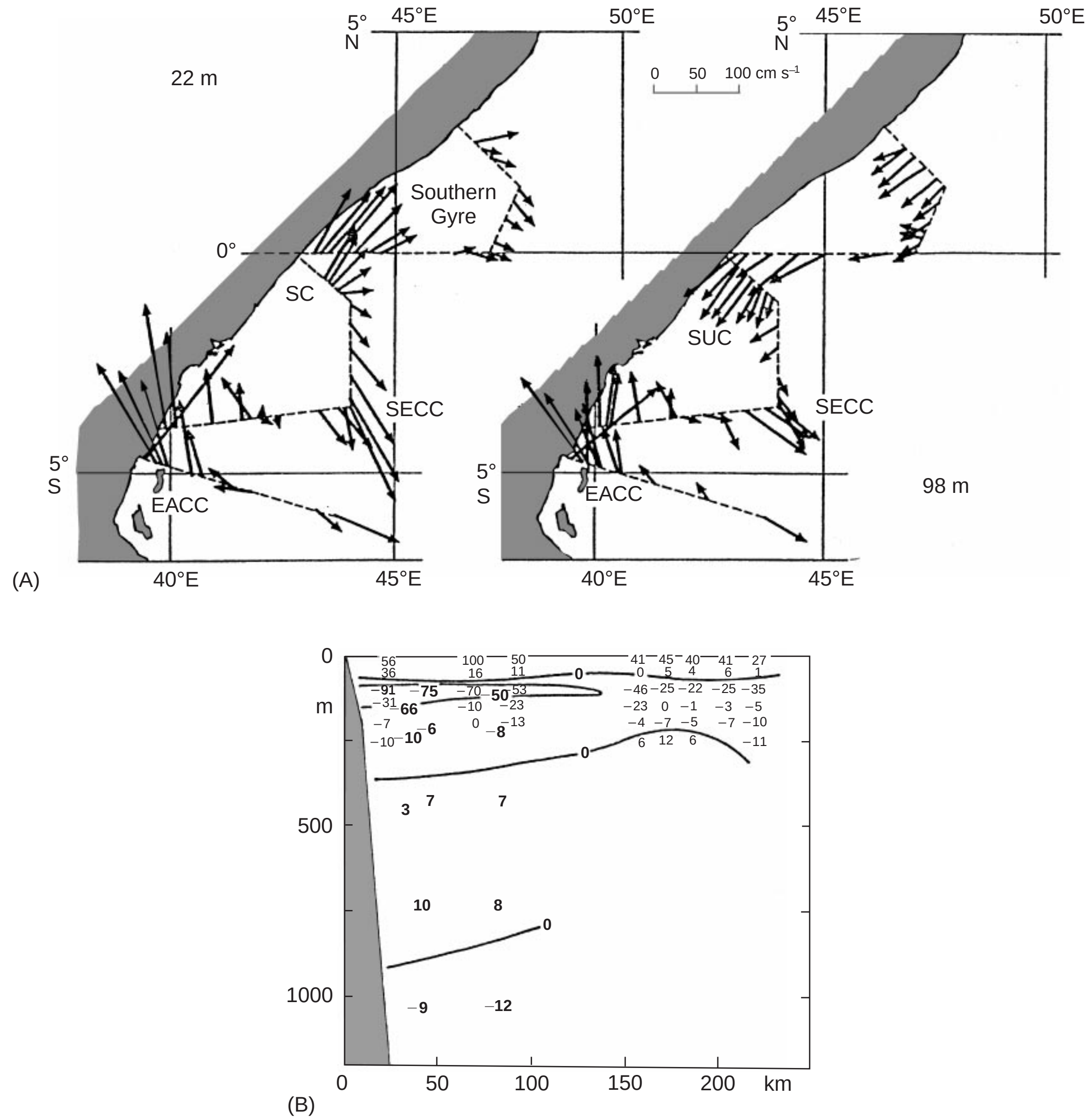

Figure 1 (A) Circulation along the East African Coast in April 1985 at 22 m and at 98 m depth, measured by shipboard Acoustic Doppler Current Profiler (ADCP). showing the EACC, the SECC, the reversal to the north at the equator of the Somali Current (SC), the Southern Gyre (SG) and the southward undercurrent (SUC) at the Equator. (B) Northward component of current along the equator in April 1985, from shipboard ADCP, in cm s^{-1}. Bold figures are mean northward components from moored currentmeters for the same period. (From Swallow et al., 1991, Structure and transport of the East African Coastal Current, *Journal of Geophysical Research* 96, C12, 22 245-22 257, 1991, copyright by the American Geophysical Union.)

the winds. It has been particularly studied during the Indian Ocean Experiment (INDEX) that started in the 1970s and the SINODE (Surface Indian Ocean Dynamic Experiment) in the 1980s. In 1990–1996, during the WOCE (World Ocean Circulation Experiment), a large number of new data were collected over the whole Indian Ocean and particularly in the Somali Basin.

The East African Coastal Current (Also Called the Zanzibar Current)

The EACC is fed by the branch of the South Equatorial Current (SEC) that passes north of Madagascar and splits northward around 11°S. It runs northward throughout the year between latitudes 11°S and 4°S. The location of its northern end depends on the season. In the northern winter, during the NE monsoon, the EACC converges around 3°–4°S with the south-going Somali Current to form the eastward South Equatorial Counter Current (SECC). It flows against light winds and is then the weakest (**Figure 1A**).

Direct current measurements at 2°S during March–April 1970 and 1971 indicated that the current reversed to the north at least one month before the onset of the SW monsoon over the interior of the north Indian Ocean, immediately after the southerly winds began along the East African coast at the beginning of April (15–20 knots) and the onset of the SE monsoon to the south. At that time, the current is very sensitive to small variations in the local wind direction. The boundary between the northward (EACC) and the southward (SC) flow was distinctly marked by changes in fauna and water properties with lower salinities in the EACC and higher salinities in the south-westward Somali Current. At that time the EACC is strengthened by the winds. By the end of April, at 2°S, the current was about 100 nautical miles wide with peak speeds of 2 m s^{-1} within few miles offshore.

In April 1985, of the 10 Sv passing northward at 5°S between 0 and 100 m, 4.5 Sv continued across the Equator and 5.5 Sv join the SECC from the south (**Figure 1A**). The total transport down to 300 m of the SECC was 23 Sv of which 17 Sv came from the EACC. Most of the subsurface transport of the SECC moved eastward between 2.5°S and 6°S across 45°E and most of the northward near surface boundary current crossing the Equator was turning eastward south of 1.5°N. At the Equator, within the layer 0–100 m, below the surface northward transport, 2.5 Sv still flowed south across the Equator (**Figure 1B**).

Under the onset of the SW monsoon, the EACC merges into the reversing Somali Current, which progresses northward. Its surface speed can then exceed 2 m s^{-1} and its transport amounts to 20 Sv in the upper 500 m with 14 Sv in the upper 100 m at 1°S. Below the surface, the deeper EACC current flows northward across the Equator at all seasons. During the NE monsoon, it becomes an undercurrent under the southward-flowing Somali current.

The Somali Current

North of the Equator, the Somali current develops in different phases in response to the onset of the monsoon winds. **Figure 2** shows the evolution of the circulation from the 1979 SW monsoon observations. **Figure 3** gives a schematic representation of the western boundary current system for the different seasons for the surface layer.

During the transition period at the end of the NE monsoon, in April–early May, the Somali current flows south-westward along the coast from 4°–5°N to the Equator, whereas south of the Equator the EACC flows north-eastward (see above). At that time, the two currents converge and turn offshore to the south east to form the SECC. North of 4°–5°N, the current is already north-eastward, fed by the NE monsoon current, which brings waters from the interior Arabian Sea driven by the wind stress curl, splitting into a northward boundary surface current between 5°N and 10°N associated with a southward subsurface current underneath, and a southward surface current towards the Equator.

During the early phase of the SW monsoon, in early May, the Somali current responds rapidly to the onset of the southerly winds at the Equator and reverses northward in continuity with the northward EACC, which crosses the Equator. It develops as a shallow cross-equatorial inertial current, turning offshore at about 3°N, where a cold upwelling wedge develops north of the turnoff latitude near the coast. As part of it recirculates southward across the Equator, it forms the anticyclonic Southern Gyre (**Figure 2**).

By mid-May, the SW wind onset propagates northward along the coast and the southern offshore-flowing branch, at 1°N to 3°N is strongly developed, with westward equatorial flow across 50°E indicating the recirculation of the Southern Gyre. North of that branch along the coast, the upwelling wedge spreads out bringing cold and enriched waters at the surface about 4°–5°N. Further to the north, the current is already northward from March. With southerly winds blowing parallel to the coast, a typical upwelling regime develops with northward surface flow, an undercurrent below and cold water along the coast.

When the onset of the strong summer monsoon winds occurs at these latitudes in June, the southern branch increases in strength and extends farther north (5°N) and a strong anticyclonic gyre, called the 'Great Whirl' develops between 5°N and 9°N with velocities at the surface higher than 2.5 m s^{-1} and transports around 90 Sv between the surface and 1000 m, where currents exceeding 0.1 m s^{-1} have been observed (**Figures 2** and **3**). Between the Somali coast and the northern branch of the Great Whirl a second strong upwelling wedge forms at its north-western flank where the flow turns offshore (**Figure 3**).

In August–September–October, depending on the year, when the winds decrease, it has been observed that the southern cold wedge propagates northward along the coast and coalesces with the northern one, which moves slightly northward (**Figure 4**). It is only at that time that the Somali current is continuous from the Equator up to the horn of Africa and brings fresher waters from the Southern Hemisphere into the Arabian Sea (**Figures 2, 5A–C, 6A,B**). The breakdown of the two-gyre system can occur at speeds of up to 1 m s^{-1}, replacing a100 m thick and 100 km wide band of high-salinity water with lower-salinity water from south of the Equator, which represents a transport of 10 Sv.

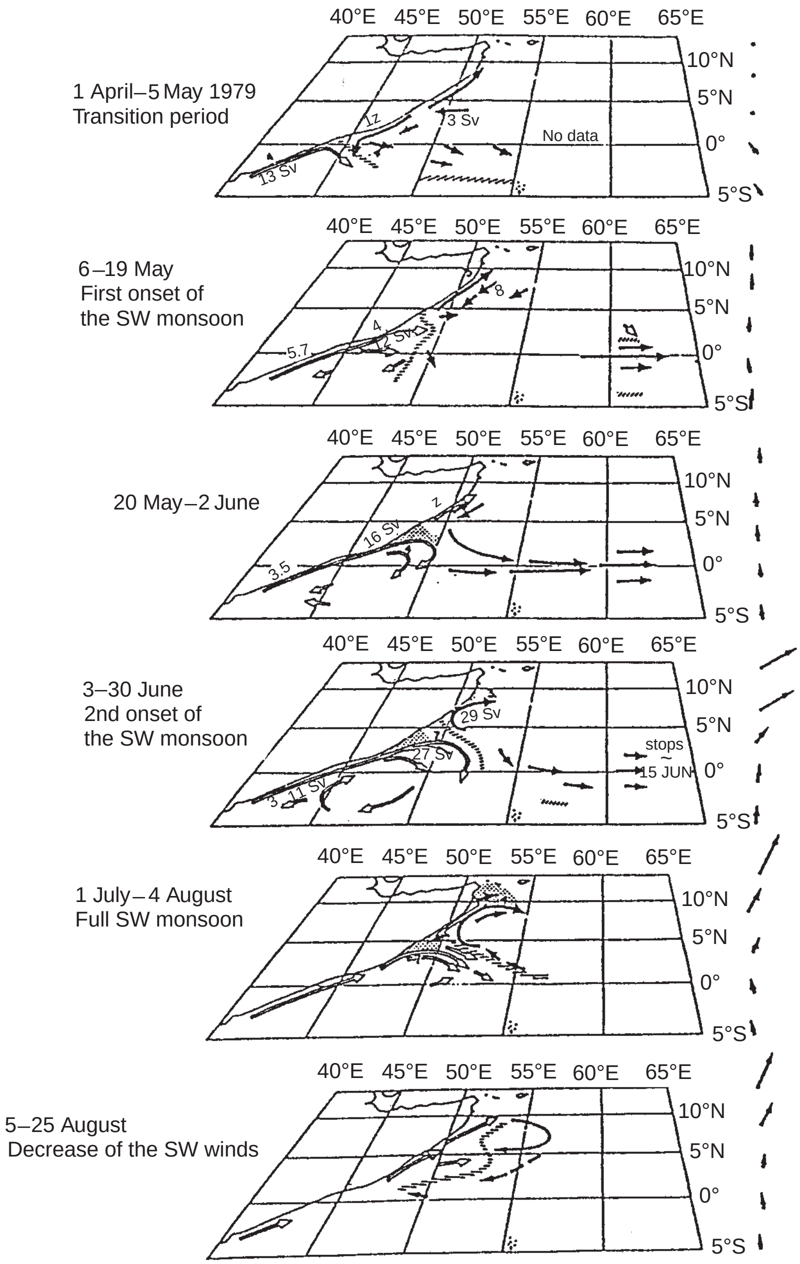

Figure 2 Evolution of the circulation during the onset of the SW monsoon from the 1979 observations during INDEX (speed in knots; transport in Sv $= 10^6\,m^3\,s^{-1}$; open arrow = low salinity, solid arrow = high salinity, front, upwelling). The arrows on the right of the figure represent the wind stress observed at different latitudes along the coast; the full strength of the SW monsoon is reached in June (From M. Fieux, 1987, Circulation dans l'océan Indien occidental, Actes Colloque sur la Recherche Française dans les Terres Australes, Strasbourg, unpublished manuscript).

At the end of the summer monsoon and during the transition to the winter monsoon, in October, the continuous Somali Current no longer exists; instead the cross-equatorial flow, characterized by low surface salinities (35–35.2) with a transport of 12 Sv in the upper 100 m, turns offshore south of 2.5°N. The northward current component through the equatorial section has a subsurface maximum of more than $1.50\,m\,s^{-1}$ near the coast at 40 m depth and velocities of more than $0.5\ m\,s^{-1}$ at 200 m depth. The cross-equatorial transport in the upper 100 m was comparable to the 14 Sv transport at 1°S in the period May–June 1979. This means that the cross-equatorial transport of the Somali current in late autumn is very similar to that during the onset of the SW monsoon. The local winds are quite

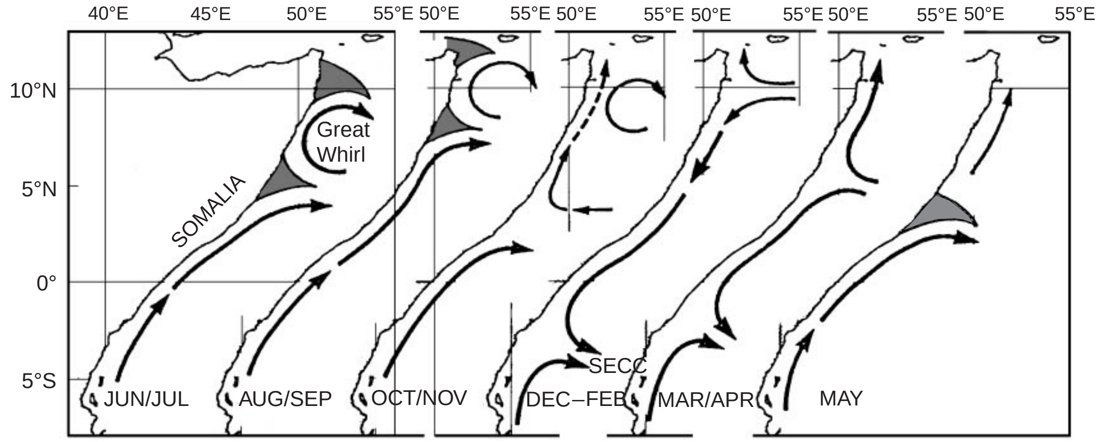

Figure 3 Somali Current flow patterns for the layer 0–100 m for different seasons with upwelling in grey (Reprinted from *Deep Sea Research*, 37(12), F. Schott et al., 1990, The Somali Current at the Equator: annual cycle of currents and transports in the upper 1000 m and connection to neighbouring latitudes, 1825–1848, copyright 1990, with permission from Elsevier Science).

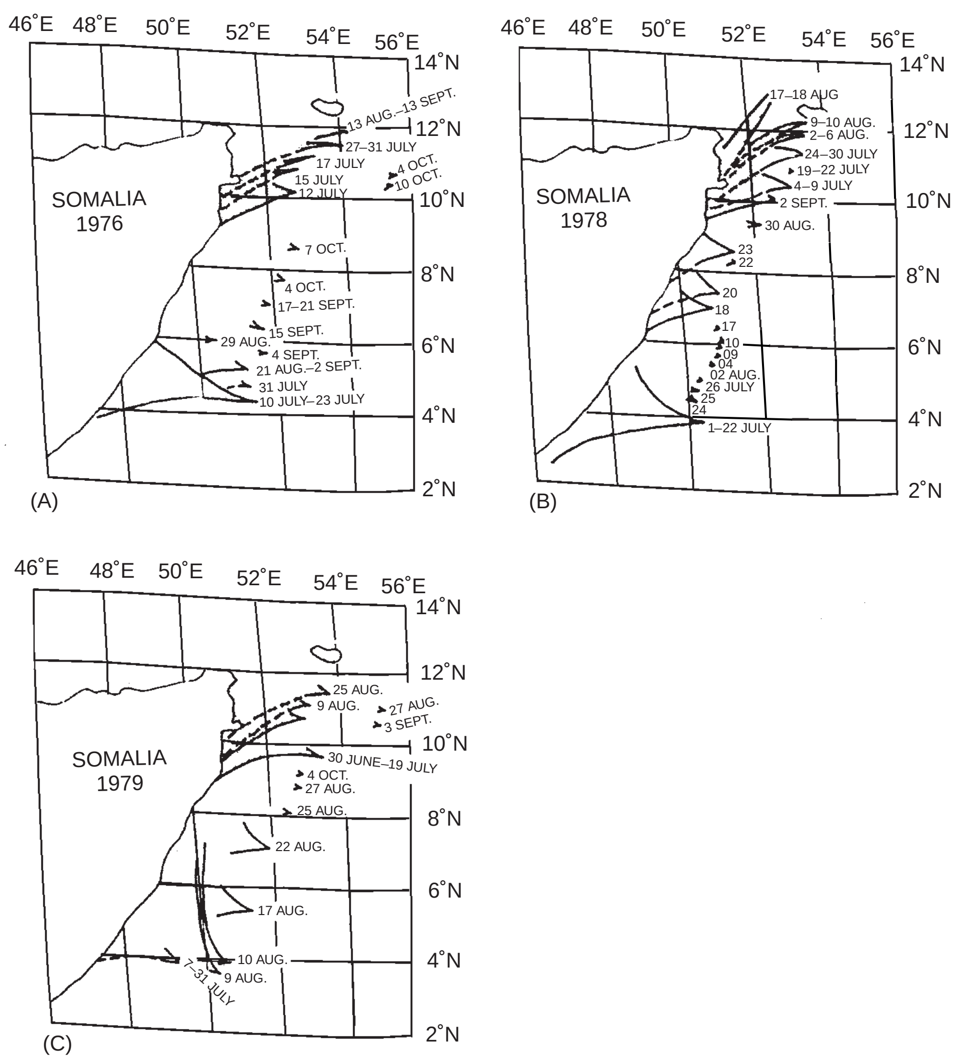

Figure 4 Propagation of upwelling wedges in 1976, 1978, and 1979, as seen in satellite infrared imagery (the northern one is in gray). (Reprinted from *Progress in Oceanography* 12, F. Schott, Monsoon response of the Somali Current and associated upwelling, 357–381, copyright 1983, with permission from Elsevier Science).

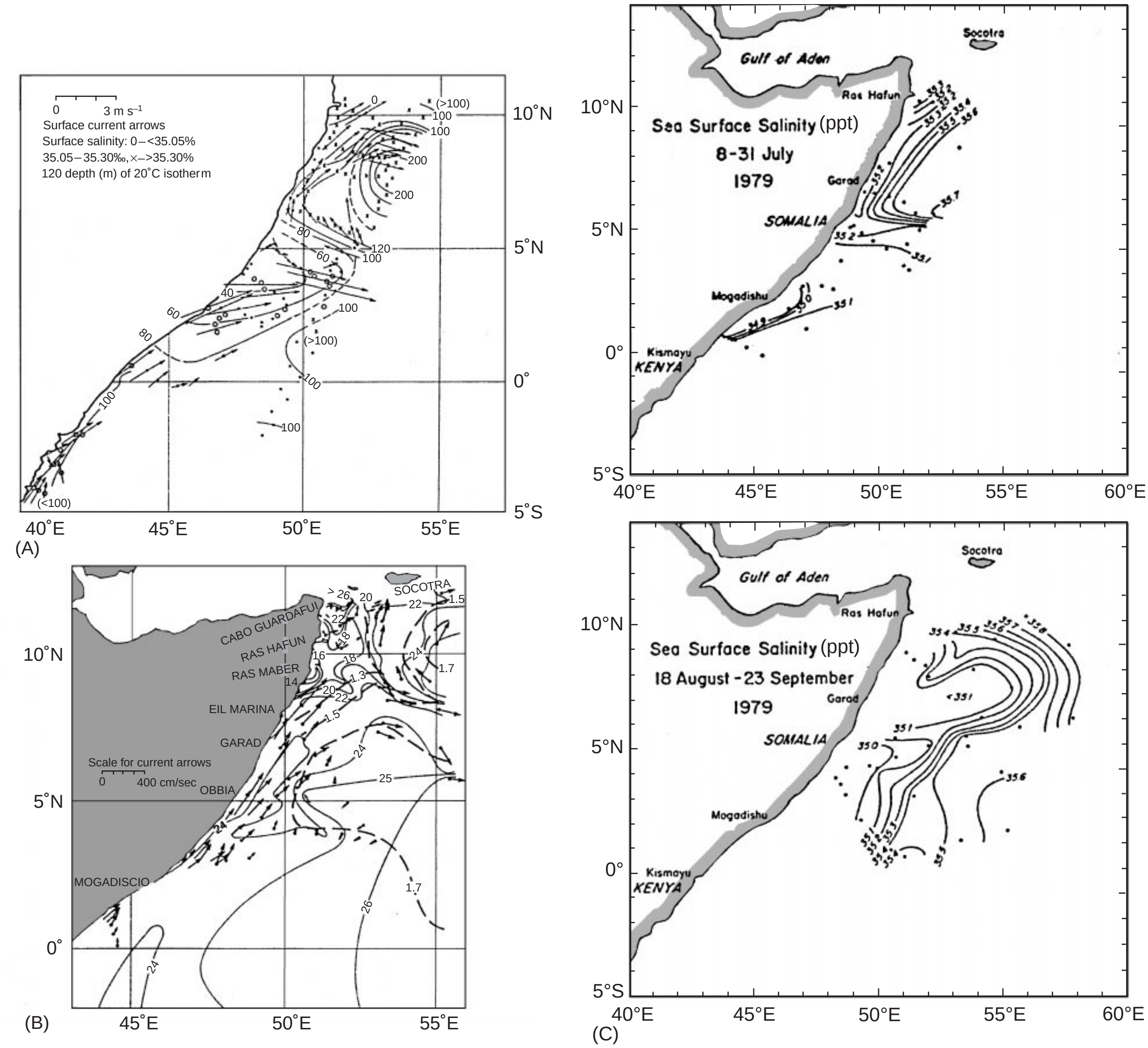

Figure 5 Variability of the circulation and salinity along the Somali coast. (A) 1 July–4 August 1979: surface currents (arrows), depth of the 20°C isotherm and surface salinity range (Reprinted from Swallow et al., 1983, Development of near-surface flow pattern and water mass distribution in the Somali Basin in response to the southwest monsoon of 1979, *Journal of Physical Oceanography*, 13, 1398–1415, with permission from American Meteorological Society). (B) 4 August–4 September 1964: currents at 10 m depth (arrows), dynamic heights of the sea surface relative to 1000 dbars in dyn. meters (heavy dashed) and sea surface temperatures in °C (solid) (Reprinted from *Progress in Oceanography*, 12, F. Schott, Monsoon response of the Somali Current and associated upwelling, 12, 357–381, copyright 1983, with permission from Elsevier Science (redrawn from J. C. Swallow and J. G. Bruce, 1966 and Warren et al., 1966)). (C) Surface salinities during the existence of the two gyre system, 8–31 July 1979, and during and after the northward propagation of the southern cold wedge, 18 August–23 September 1979 (Reprinted from Progress in Oceanography, 12, F. Schott, Monsoon response of the Somali Current and associated upwelling, 357–381, copyright 1983, with permission from Elsevier Science). At that time the Somali Current is continuous along the coast and brings fresher water from the south at the end of the SW monsoon season.

different during the two periods, whereas the Trade Winds over the subtropical south Indian ocean are similar, which suggests that, in October, the cross-equatorial flow is driven primarily by remote forcing through the inflow from the South Equatorial Current. Between 6°N and 11°N, the anticyclonic Great Whirl, marked by relatively high surface salinities (35.6–35.8), persists with transport of 33 Sv westward in the upper 250 m between 6°N and 8.5°N, and 32 Sv eastward between 8.5°N

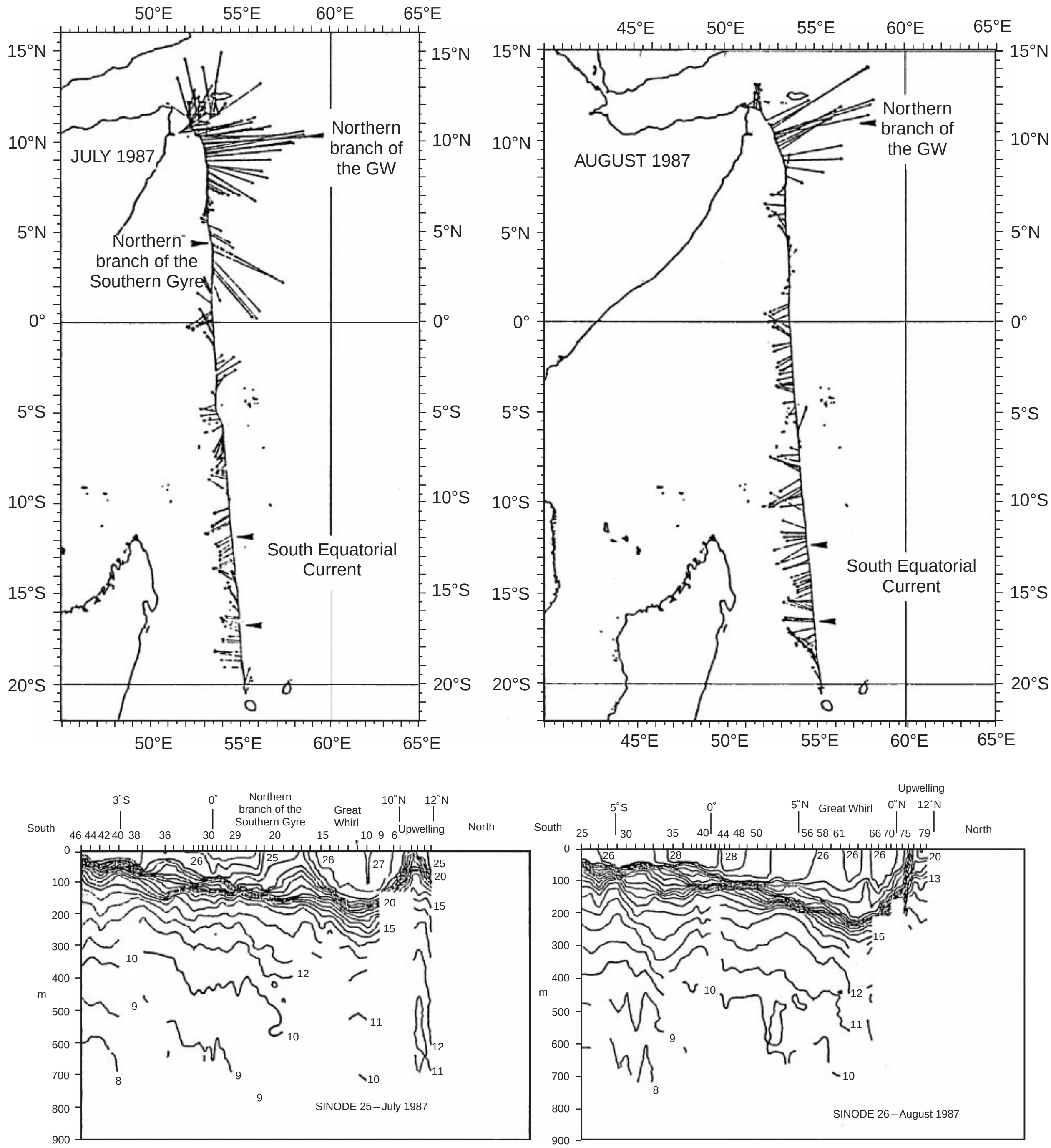

Figure 6 (A) Location of the section in July and August 1987 across the Great Whirl (GW) with corresponding surface drifts. (B) Corresponding temperature sections (°C) showing the strengthening of the northern front of the Great Whirl in August and the disappearance of the southern front in August compared to July at that longitude. (From M. Fieux, 1987, Circulation dans l'océan Indien occidental, Actes Colloque sur la Recherche Française dans les Terres Australes, Strasbourg, unpublished manuscript.)

and 11.5°N. Then a southward undercurrent is established during the transition period while the Great Whirl weakens.

The northern gyre is not symmetrical, as can be seen from the depth and slope of the 20°C isotherm, which is much steeper on the northern flank of the gyre (**Figure 6B**). This can be explained by the strong nonlinearity of that system, causing a shift of high currents into the northern corner.

The northern Somali Current was found to be disconnected from the interior of the Arabian Sea in the latitude range 4°–12°N in terms of both water mass properties and current fields. Communication predominantly occurs through the passages between Socotra and the horn of Africa.

During the late phase of the SW monsoon, a third anticyclonic gyre appears north-east of the island of Socotra that is called the Socotra Gyre (**Figure** 7).

In summer 1993, a significant northward flow of 13 Sv was observed through the passage between the island of Abd al Kuri (west of Socotra) and Cape Guardafui (the horn of Africa). East of the Great Whirl, a band of northward warm water flow that provided low-latitude waters to the Socotra Gyre and the Socotra Passage separated the Great Whirl and the interior of the Arabian Sea. The net transport through the Socotra Passage is northward throughout most of the year.

During the transition period in October–November, the northward Somali circulation decreases, with a branch turning offshore south of 2.5°N.

In December–February, during the NE winter monsoon, the Somali current reverses southward from 10°N to 4°–5°S, where it converges with the northward EACC to form the SECC flowing eastward (see above).

Nonlinear reduced gravity numerical models driven by observed monthly mean winds are very successful in simulating the observed features of the circulation in this region, such as the formation and decay of the two-gyre system of the Somali Current during the SW monsoon. With interannually varying winds they also simulate a large interannual variability in the circulation.

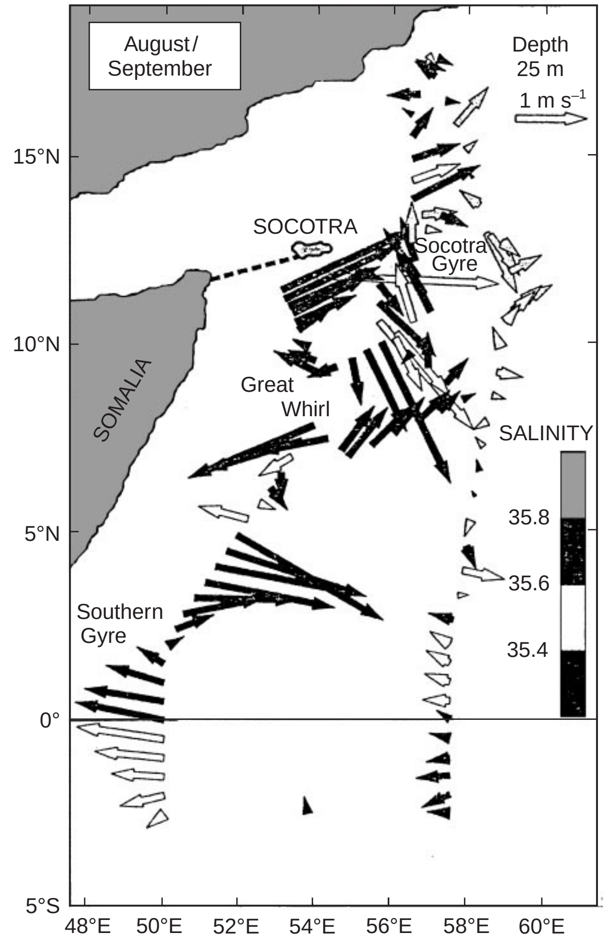

Figure 7 Near surface circulation at 25 m in August–September 1995, showing the Southern Gyre (SG), the Great Whirl (GW) and the Socotra Gyre (SG) together with surface salinities. (Reprinted from F. Schott et al., Summer monsoon response of the northern Somali Current, 1995, *Geophysical Research Letters*, 24(21), 2565–2568, 1997, copyright by the American Geophysical Union).

Currents at Depth

Direct measurements made in 1984–1986 at the Equator, near Africa, show that the southward reversal implies only a thin surface layer below which, between 120 m and 400 m, there is a northward undercurrent, remnant of the SW monsoon season circulation (**Figures 8** and **9**), followed again by a southward current below 400 m. It results in a large variability of the cross-equatorial transport, which amounts to 21 Sv for the upper 500 m during the summer monsoon season and is close to zero for the winter monsoon mean transport. The annual mean cross-equatorial transport in the upper 500 m is 10 Sv northward, with very little transport in either season in the depth range 500–1000 m (**Figure 9**). Comparison of current profiles at 4°S in the EACC, at the Equator, and at 5°N in the Somali Current in both seasons shows that at 4°S the subsurface profile stays fairly constant while at 5°N drastic changes occur between the seasons as well as at the Equator (**Figure 10**). North of 5°N, there is less variability at subsurface, with the presence of a southward coastal undercurrent during most of the year except during the full strength of the deep-reaching Great Whirl in July–August to more than 1000 m, involving large deep transports. The Somali Current flow patterns for the different seasons in the 100–400 m layers are shown in **Figure 8**.

Deeper, below the Somali current, at the Equator during October 1984 to October 1986 at 1000 m, 1500 m, 2000 m, and 3000 m depth, the measured mean currents were very small. However, the only clear seasonal signal was observed at the 3000 m level, with a seasonal current parallel to the coast

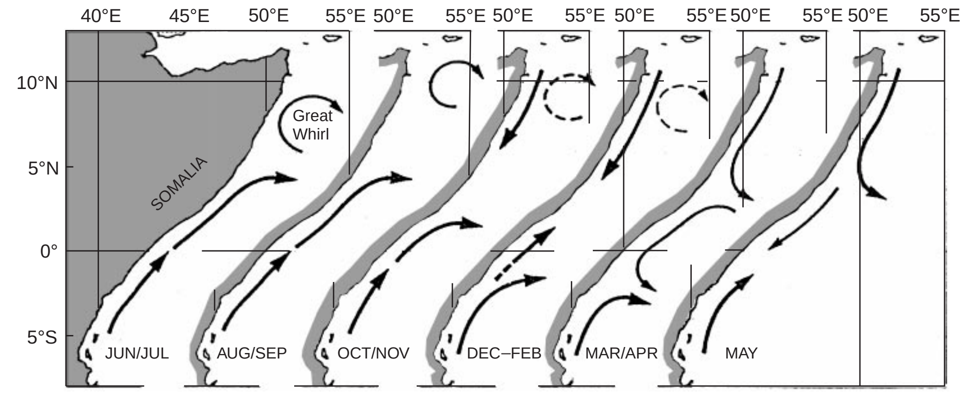

Figure 8 Schematic representation of Somali Current circulation patterns in the layer 100–400 m for different seasons. (Reprinted from *Deep Sea Research*, 37(12), F. Schott *et al.*, 1990, The Somali Current at the equator: annual cycle of currents and transports in the upper 1000 m and connection to neighbouring latitudes, 1825–1848, copyright 1990, with permission from Elsevier Science).

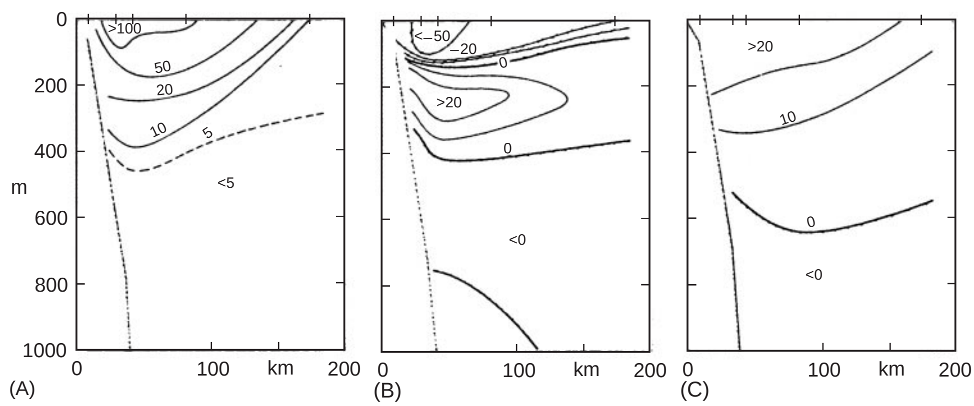

Figure 9 Mean sections of northward current component at the Equator (positive northward): (A) for winter monsoon (1 June–13 September); (B) for winter monsoon (15 December–15 February; (C) for overall mean, in cm s^{-1}. (Reprinted from *Deep Sea Research*, 37, (12), F. Schott *et al.*, 1990, The Somali Current at the equator: annual cycle of currents and transports in the upper 1000 m and connection to neighbouring latitudes, 1825–1848, copyright 1990, with permission from Elsevier Science).

approximately in phase with the local surface winds. This reached a north-eastward mean of $0.10\,m\,s^{-1}$ between June and September, and a south-westward mean of $0.06\,m\,s^{-1}$ between November and February. This variability seems in agreement with salinity distribution near that level along the coastal boundary, with slightly higher salinity at the end of the NE monsoon season and slightly lower salinity during the SW monsoon. Higher up, at 2000 m, 1500 m, and 1000 m, the currents are dominated by events of 1–2 months duration.

From the long-term current measurements, it seems that at the Equator the semiannual variability is stronger than the annual variability even near the coast. Off the equator, the annual component dominates.

Numerical models have shown that the location and motion of eddies are influenced by the distribution and strength of the wind forcing; an increase in the winds leads to a southward displacement of the offshore turning of the southern branch; the northward motion of eddies is very dependent upon the coastal geometry; and the onset of the northward Somali current depends on local winds forcing and on the wind forcing far out at sea. Baroclinic Rossby waves generated by the strong offshore anticyclonic windstress curl have been found to be the generation mechanism of the Great Whirl.

Conclusion

The western boundary of the northern Indian Ocean is a remarkable natural laboratory for studying the effect of the wind on the oceanic circulation, as regularly twice a year the winds change direction rapidly and are particularly strong. It is in the

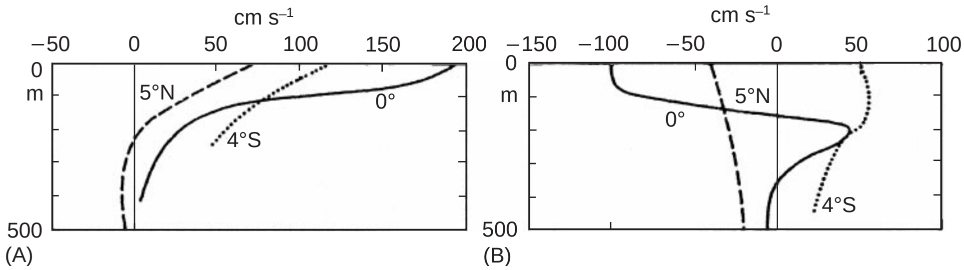

Figure 10 Current profiles for different seasons at 4°S, on the Equator, and at 5°N: (A) for summer monsoon; (B) for winter monsoon. (Reprinted from *Deep Sea Research*, 37(12), F. Schott *et al.*, 1990, The Somali Current at the equator: annual cycle of currents and transports in the upper 1000 m and connection to neighbouring latitudes, 1825–11848, copyright 1990, with permission from Elsevier Science).

Somali current that the highest variability as well as the highest current speeds in the world ocean are found.

See also

Current Systems in the Indian Ocean. Elemental Distribution: Overview. Indian Ocean Equatorial Currents. Thermohaline Circulation. Water Types and Water Masses. Wind Driven Circulation.

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SONAR SYSTEMS

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Introduction and Short History

Sonar (Sound Navigation and Ranging) systems are the primary method of imaging and communicating within the ocean. Electromagnetic energy does not propagate very far since it is attenuated by either absorption or scattering – visibility beyond 100 m is exceptional. Conversely, sound propagates very well in the ocean especially at low frequencies; consequently, sonars are by far the most important systems used by both man and marine life within the ocean for imaging and communication.

Sonars are classified as being either active or passive. In active systems an acoustic pulse, or more typically a sequence of pulses, is transmitted and a receiver processes them to form an 'image' or to decode a data message if operating as a communication system. The image can be as simple as the presence of a discrete echo or as complex as a visual picture. The receiver may be coincident with the transmitter – a monostatic system, or separate – a bistatic system. Both the waveform of the acoustic pulse and the beamwidths of both the transmitter and receiver are important and determine the