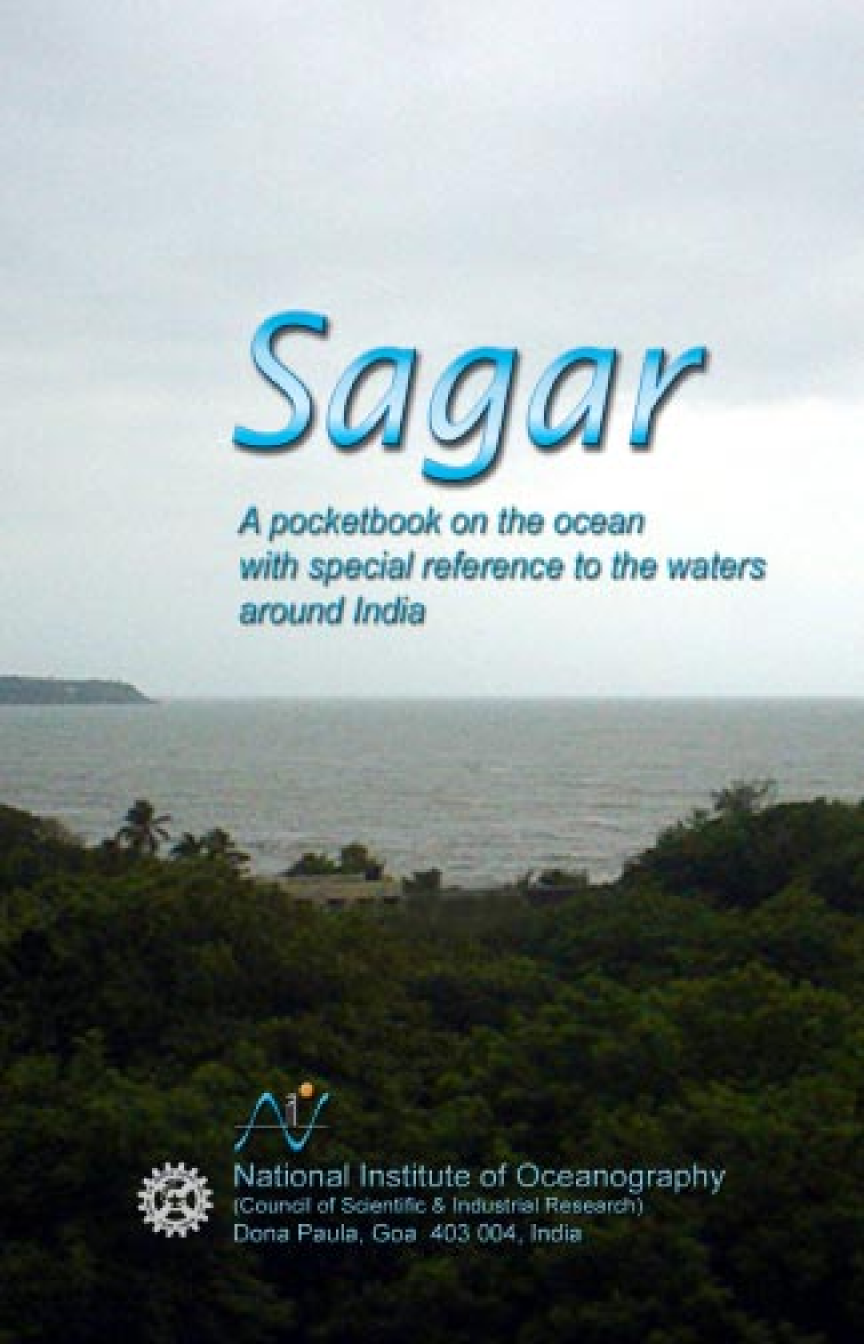

Sagar

A pocketbook on the ocean with special reference to the waters around India

National Institute of Oceanography
(Council of Scientific & Industrial Research)
Dona Paula, Goa 403 004, India

Preface

Dear Reader,

The National Institute of Oceanography, the largest and oldest institute dedicated to ocean research in this part of the world, attracts visitors, particularly students, who come to learn about oceanography. A short visit, however, can only provide a glimpse of the field. This pocketbook, *Sagar,* has been prepared to enable the visitor to pursue the fascinating world of the oceans even after the visit.

Sagar provides an overview of the oceans: their formation, characteristics, and the dynamics that determine their evolution. It also contains information on how the interested reader can pursue these topics further through books and websites.

We trust *Sagar* will serve as your companion as you learn more about the oceans.

With best compliments,

National Institute of Oceanography

Contributors:

M. Dileepkumar
K.S. Krishna
V. Krishnakumar
G.S. Michael
P.V. Narvekar
S. Prasannakumar
V. Purnachandra Rao
C. Raghukumar
S. Raghukumar
N. Ramaiah
D. Shankar
R. Sharma
S.R. Shetye
M.P. Tapaswi

We are grateful to Karl Banse, University of Washington, Seattle, USA, and Joaquim Goes, Bigelow Laboratories for Ocean Sciences, West Boothbay Harbor, USA, for their inputs.

Editing : S.P. Sharma and Sujal S. Bandodkar
Layout & Design : A.Y. Mahale
Graphics : P.J. Pawaskar, Sham Akerkar, R. Uchil and Shaikh Ali Karim

Cover: A view of the Arabian Sea from the campus of the National Institute of Oceanography, Dona Paula, Goa. The mouth of the Zuari estuary is on the left.

Sagar *A pocketbook on the ocean with special reference to the waters around India*

Contents

Sources of figures and data

- Fig. 4: http://pubs.usgs.gov/publications/text/inside.html
- Fig. 5: http://geology.er.usgs.gov/eastern/plates.html
- Fig. 6: http://pubs.usgs.gov/publications/text/Vigil.html
- Fig. 7: http://courses.missouristate.edu/ejm893f/creative/glg110/Cdrift-plates.html
- Fig. 8: http://pubs.usgs.gov/publications/text/himalaya.html ,The Himalayas: Two continents collide
- Fig. 10: From Geological-Geophysical Atlas of the Indian Ocean, Pergamon Press, Oxford U.K.,1975
- Fig. 11: AAPG Memoir 26, page 83, 1977
- Figs. 12, 20, and 22: Temperature data - S. Levitus and T.P. Boyer, NOAA Atlas NESDIS 4, 1994
- Fig. 13: Salinity data - S. Levitus, R. Burgett and T.P. Boyer, NOAA Atlas NESDIS 3, 1994
- Fig. 15: http://sealevel.jpl.nasa.gov/overview/climate-water.html
- Figs. 17 and 21: Wind data - US Navy
- Fig. 18: Current data - NOAA, USA
- Figs. 19 and 26: Sea level data - Survey of India, Dehradun, India
- Figs. 21 and 23: Rainfall data - P. Xie and P.A. Arkin, Bulletin of the American Meteorological Society, Vol. 78, pages 2539-2558, 1997
- Figs. 24 and 27: Adapted from Waves, tides, and shallow-water processes, The Oceanography Course Team, The Open University, Butterworth - Heinemann, Oxford U.K., 1999
- Fig. 29: http://www.mos.org/oceans/planet/cycle.html
- Fig. 33: Derived from satellite sensor SeaWiFS (NASA)

The Oceans : size, shape, and basins

The Earth's radius is approximately 6300 km. About 71% of the Earth's surface is covered by oceans. The average depth of the oceans is 3700 m, and they contain 97% of the Earth's water (Fig. 1). The remaining 3% is freshwater: of this, one-third is in liquid form, and the rest is frozen in glaciers and polar icecaps. The oceans form a rather unconventional tank of water: its horizontal dimension stretches to tens of thousands of kilometres, but its vertical dimension is generally less than 4 km. If we were to make an exact replica of the oceans on an Earth of one metre diameter, the depth of the oceans on it would be less than a millimetre.

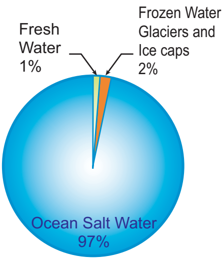

Fig. 1. Earth's water.

The oceans have been conveniently divided into the Indian, Atlantic, Pacific, Arctic, and Southern (Antarctic) Oceans (Fig. 2). The Indian Ocean extends between the continents of Africa (to the west) and Australia (to the east), and south Asia (to the north) and the Southern Ocean (to the south). The North Indian Ocean includes the Arabian Sea (to the west of India) and the Bay of Bengal (to the east).

Fig. 2. Earth's Oceans.

Countries with coastline have a fixed area earmarked exclusively for exploration and exploitation. This area is called its Exclusive Economic Zone (EEZ) (Fig. 3). Islands help increase a country's EEZ area. The Lakshadweep are a group of 36

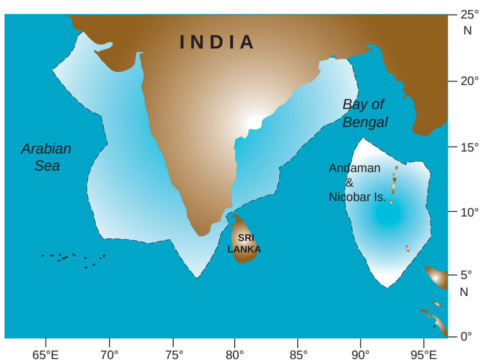

Fig. 3. North Indian Ocean with Arabian Sea and Bay of Bengal. The dashed lines demarcate India's EEZ, which covers about 2 million sq. km, which is roughly 60% of India's land area. India's coastline including islands is about 7000 km long.

low-lying coral islands, 10 of which are inhabited. At their highest point they are less than a few metres high. Another group of islands, the Andaman and Nicobar Archipelago in the Bay of Bengal, comprises 554 islands, some of which are merely large rocks. If these are excluded, the total number of islands is 294, of which 36 are inhabited. The Andaman and Nicobar islands owe their existence to plate tectonic processes (see below). These islands were formed as a result of geological processes associated with the destruction of the ocean floor.

Internal structure of the Earth and its outer plates

The universe formed with a big bang about 14 billion years ago. The Solar System and the Earth formed about 4.5 billion years ago and life on Earth began about 3.5 billion years ago. During the first billion years, the Earth experienced immense turbulence, with continuous bombardment by cosmic bodies that made this planet look like a fireball.

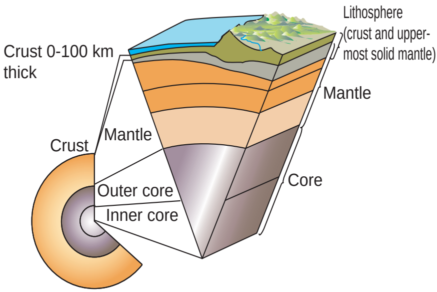

Fig. 4. Internal layers of the Earth.

The Earth is made up of three main layers: *crust, mantle,* and *core* (Fig. 4). Beneath the oceans, the crust generally extends to about 5 km. The thickness of the crust beneath the continents is thicker and averages about 30 km. Below the crust is the *mantle,* a dense, hot layer of semi-solid rock approximately 2900 km thick. At the center of the Earth lies the *core,* which is actually made up of two distinct parts, a 2200 km-thick *liquid* outer core and a 1250 km-thick *solid* inner core. As the Earth rotates, the liquid outer core spins and generates the Earth's magnetic field.

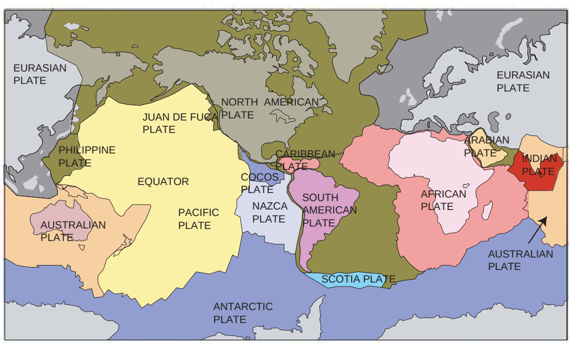

Fig. 5. Major lithospheric plates.

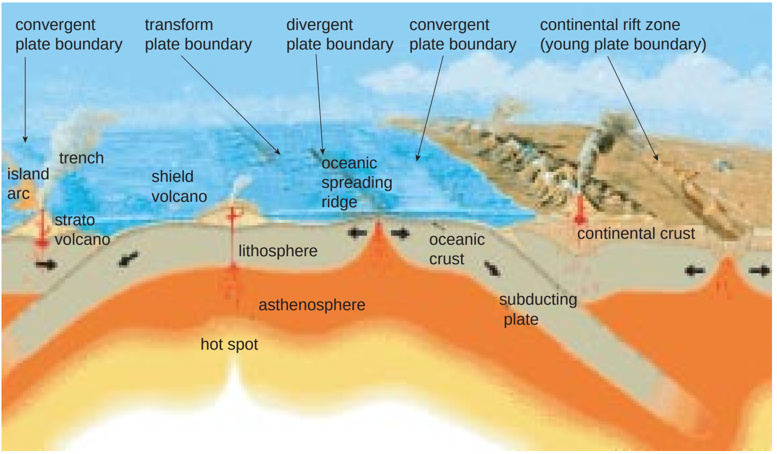

Fig. 6. Formation and destruction of lithospheric plates.

The outer rigid layer (about 70-100 km thick) of the Earth, comprising the crust and uppermost mantle, is divided into a number of plates. There are about 12 major plates such as North American, South American, African, Indian, Eurasian, etc., covering the entire surface of the Earth (Fig. 5). The lithospheric plates are bounded by one of the three main types of geological features: (1) mid-oceanic ridges, (2) subduction zones, and (3) transform faults. Boundaries are narrow deforming zones, which are accompanied by earthquake activity, but the plates' interiors are rigid. Each plate is in relative motion with respect to others on the surface of the Earth. The relative motion between the plates produces new crust at mid-oceanic ridges, consumes crust at subduction zones, and conserves crust along the transform faults (Fig. 6). Apart from the normal process of construction and destruction at plate boundaries, plates also undergo break-ups and unifications.

Fig. 7. Breaking up of continents in the geological past (~225 million years ago) near South Pole.

In the past, continental landmasses have undergone break-ups (Fig. 7), have collided with other continental masses, new oceans have formed, and some have perished. About 225 million years ago, India was a large island situated off the Australian coast, and a vast ocean called 'The Sea of Tethys' separated India from the Asian continent. The Indian subcontinent, moving northwards, collided with Asia about 40 million years ago, and set in motion a chain of events that led to the formation of the Tibetan Plateau and the Himalayan Mountain Range (Fig. 8). This is a spectacular demonstration of a head-on crash between two giant landmasses that began many millions of years ago and continues to date. As a result of this collision, mountain ranges such as the Himalayas and peaks such as Mt. Everest were formed. Mt. Everest has risen to a height of nearly 9 km. The Himalayas continue to rise more than 1 cm a year.

The ocean floor

The ocean floor can be divided into the continental margin and the deep-sea floor. The continental margin consists of the continental shelf, the continental slope, and the continental rise (Fig. 9). The continental shelves have a flat topography (0.1° gradient), the average depth being ~130 m. They are sites for the deposition of abundant land-derived sediments and biogenic carbonates. The continental shelf is separated from the continental slope by the shelf-edge or shelf-break at approximately 200 m depth. The gradient of the slope (4° on an average) is much higher than that of the continental rise (1°). The continental shelf and slope together cover ~15% of the total ocean floor, and the continental rise covers

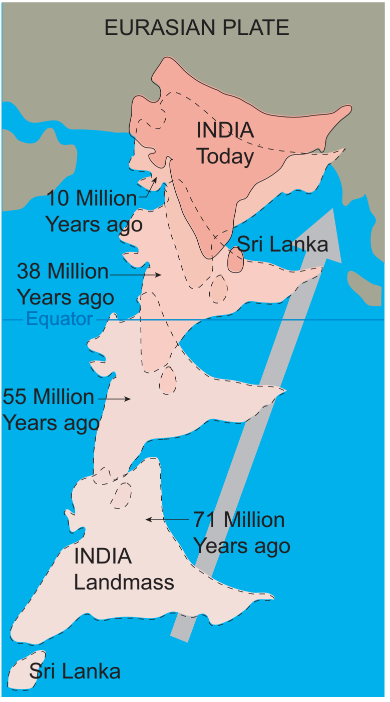

Fig. 8. Northward migration of the Indian subcontinent.

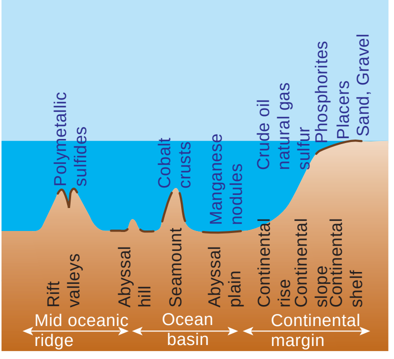

Fig. 9. Physiographic features of the ocean floor and associated mineral deposits.

about 5%. Abyssal plains are sea floors with a slope of only 0.001° for hundreds of kilometres. About 42% of the deep-sea floor area shows relatively gentle relief.

Seamounts are elevations on the deep-sea floor exceeding 1 km in height. Both flat-topped (guyot) and peaked seamounts are known to occur. Fossil corals, phosphorites, and cobalt-rich manganese crusts may be found at their summits. Mid-ocean ridges are elevated physiographic features of the ocean basins and are the sites of formation of new oceanic lithosphere. The mantle material upwells, and as a result of seafloor spreading and plate movement, seawater comes in contact with fresh magmatic material (Figs. 5 and 6). The seawater circulates within the newly formed hot rocks, and this forms 'hot springs' similar to those on land. Hot water, whose temperature can reach 400°C (in contrast to the ambient seawater temperature of 1-3°C), gushes out of the cracks. These are called hydrothermal vents. The global system of mid-ocean ridges is about 74000 km in length. Trenches are deep, V-shaped valleys on the ocean floor (below the continental slope). They generally occur at the subduction zones where oceanic crustal plates collide with continents or island arcs. Water depth in the famous Mariana Trench (~11 km) located in the Pacific Ocean exceeds the height of Mt. Everest.

The North Indian Ocean has two major submarine fans. These fans are the Bengal fan and the Indus fan (Fig. 10). The basins are filled with sediments that are mostly derived from the continents through river systems. The Bengal fan in the Bay of Bengal is the largest deep-sea fan in the world. Its total area is ~3.0 x 10^6 sq. km. It is ~3000 km in length, 1430 km at its maximum width, and 20 km at its maximum thickness. The sediments of the fan are largely eroded from the Himalayas and transported by the Ganga-Brahmaputra River system. The sediments making up this deep-sea fan at times were deposited at a rate of 35 cm /1000 yr, a rate comparable to that of deposition in shallow shelves (20-30 cm /1000 yr). By investigating the sediments of the Bengal fan it is possible to identify different phases of

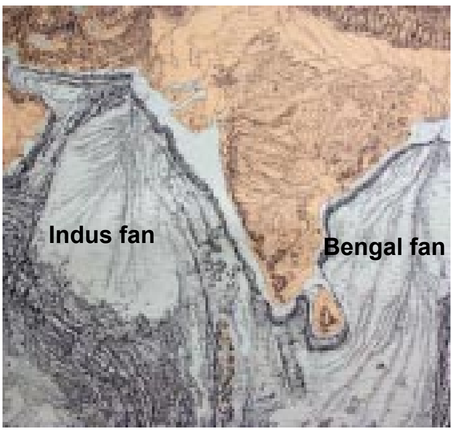

Fig. 10. Bengal fan and Indus fan.

the Himalayan uplift history. The Indus fan (1.1 x 10^6 sq. km area, 1500 km length, 960 km maximum width, >10 km maximum thickness) in the Arabian Sea not only receives sediments from the Himalayas, but also from the alluvial soils of Pakistan and the arid soils of Arabia.

Long-term sea level changes

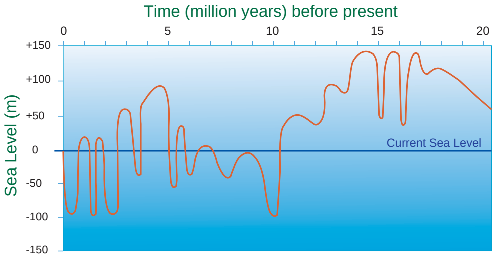

Fig. 11. Sea level fluctuations over last 20 million years.

In response to plate tectonics, volcanic activity, and climatic changes, sea level has risen above or fallen below the present sea level many times in the geological past (Fig.11). About 90 million years ago, the sea level was about 300-400 m higher than at present. Sea level rose by about 120 m during the last 18000 years, mostly because of the melting of glacial ice caps in the Polar Regions. The global average rate of rise of sea level is 1-2 mm/year. This is partly caused by continued melting of glaciers and ice caps as a result of warming of the globe, and partly by the expansion of near-surface water caused by the rise in average temperature.

During the most recent sea level minimum, ~120 m below the present level about 19000-15000 years ago, rivers began discharging their sediment load directly near the shelf edge. As a result, many deep channels, called submarine canyons, were cut into the outer shelf/slope by rivers or by turbid currents generated by the sediment-laden waters. In the Bay of Bengal, there are 16 major submarine canyons.

Seawater

The global ocean is filled with water whose average density is 1.03 g/cm^3. The density is not uniform: it varies in the vertical, with denser water always below lighter water. The temperature, the quantity of dissolved salts (also known as salinity), and the pressure to which a parcel of seawater is exposed determine its density. 75% of the water in the oceans has temperatures ranging between 0° and 6°C; the average temperature is 3.5°C. Water at depth and near the poles is cold. It gets warmer towards the surface and towards the equator (Fig. 12). Surface temperature in the Bay of Bengal is usually between 22°C and 31°C. It is cooler by 1-2°C in the Arabian Sea. This difference has major implications for the atmosphere above the two basins.

Salinity is measured as the ratio of weight of dissolved salts to total weight; the ratio is usually expressed as parts per thousand (ppt). 75% of seawater has a salinity ranging between 34-35 ppt (Fig. 13). The average salinity in the oceans is 34.7 ppt, i.e., on an average there is 34.7 g of salt in every kg of seawater. (see page 23).

Salinity near the surface in the northern Bay of Bengal can be as low as 31 ppt (Fig. 14) because the bay receives lots of freshwater in the form of rain and from runoff of surrounding rivers (Ganga, Brahmaputra, Irrawaddy, Godavari, and others). If all the freshwater that the bay receives during a year is accumulated and spread uniformly over its entire surface, it would form a layer over a metre thick. Salinity near the surface in the Arabian Sea is much higher than in the Bay of Bengal because evaporation over the Arabian Sea is much greater and it receives relatively less river runoff.

We live at 1 atmosphere pressure. In the ocean, pressure increases by 1 atmosphere for every 10 m increase in depth. This means that the pressure at the bottom of the ocean of an

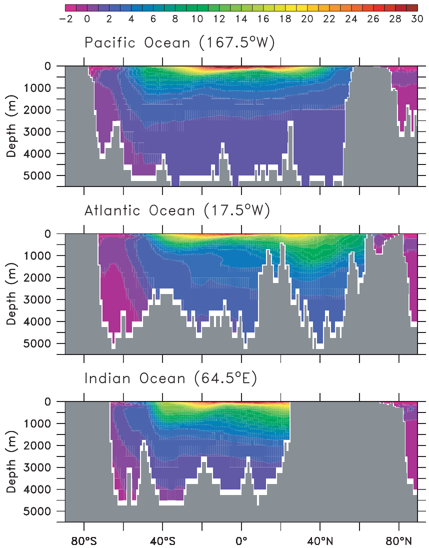

Fig. 12. North-south vertical sections of temperature (°C) in the Pacific, Atlantic, and Indian Oceans.

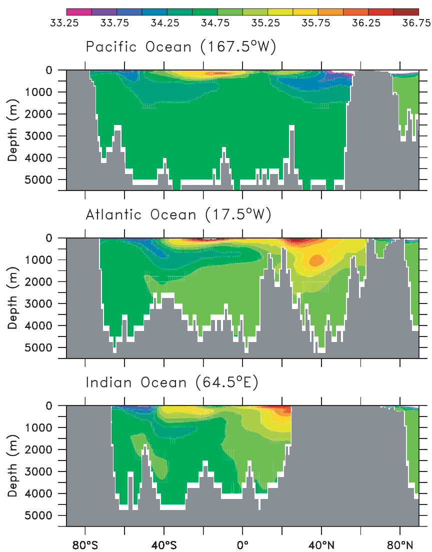

Fig. 13. North-south vertical sections of salinity (ppt) in the Pacific, Atlantic, and Indian Oceans.

average depth of 3700 m will be 370 atmospheres. Pressure has an influence on physical (density), chemical, and biological (decomposition of shells) properties of the ocean.

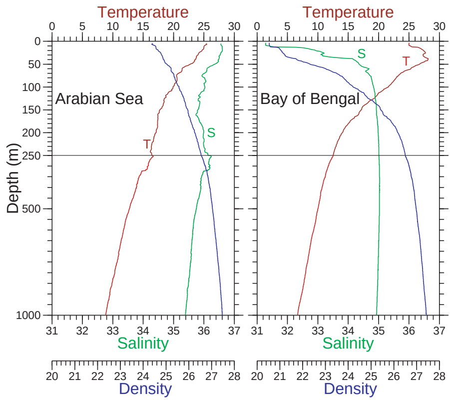

Fig. 14. Vertical profiles of temperature, salinity, and density in the northern Arabian Sea and Bay of Bengal. The much lower surface salinity in the latter leads to a strong near-surface density gradient (high stratification). Because of the small variability of density in the ocean, the scale marked density gives density in (g/cm^3-1) × 1000.

The restless ocean

The waters of the ocean move because of three main mechanisms: cooling near the Polar Regions and warming near the equatorial region, the force exerted by the winds on the ocean surface, and the tides arising from the gravitational pull of the Moon and the Sun. The rotation of the Earth (360 degrees in 24 hours from west to east) about an axis passing through its poles, the shape of the oceans (long horizontal dimension in comparison to vertical), and the stable stratification (lighter waters overlying denser waters) in the oceans influence the movement of waters in the oceans.

Water is cooled near the poles (Fig. 12). As a result, its density increases and it sinks to great depths, setting up a global scale circulation known as the conveyor belt or thermohaline circulation (Fig. 15). Water sinks in the north Atlantic and upwells (rises) in the Pacific and Indian Oceans. The velocity associated with this circulation is typically a small fraction of a cm/s and the time scale associated with it is a few centuries. Since it is difficult to measure directly, its existence must be inferred from analysis of the distribution of temperature,

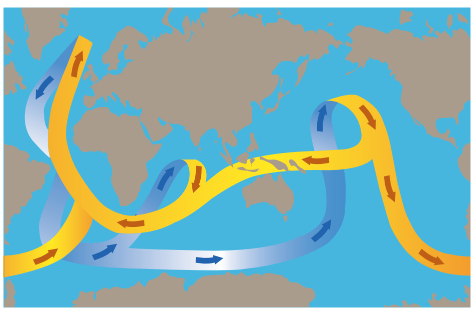

Fig. 15. The Global Ocean Conveyor Belt (red arrows warm, blue arrows cold).

salinity, and other fields.

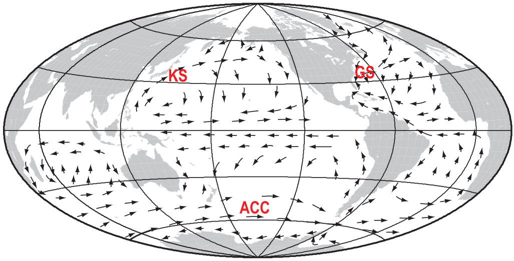

Fig. 16. Schematic of wind-forced surface circulation. Note the poleward currents near the western boundaries in the Pacific, Atlantic, and south Indian Oceans. (KS = Kuroshio, GS = Gulf Stream, ACC = Antarctic Circumpolar Current).

Motion forced by winds is most noticeable within the upper 1 km from the surface, but the strongest motions are in the uppermost few hundred metres. The nature of these currents is determined by the nature of the winds. The most striking feature of the wind-forced surface circulation is the sub-tropical gyre, in which a strong poleward (towards the pole) current near the western boundary (east coast of a continent) is balanced by a gentler equatorward drift over the rest of the basin (Fig. 16). In the Atlantic and Pacific Oceans, the strong western boundary currents are called the Gulf Stream and Kuroshio respectively. The strongest ocean current is the Antarctic Circumpolar Current, which flows all round the globe in the Southern (or Antarctic) Ocean.

The circulation in the north Indian Ocean is unique because it experiences strong seasonal winds called the monsoons (Fig. 17). Hence, unlike in much of the Pacific and Atlantic Oceans, the currents in the north Indian Ocean change with season (Fig. 18). Recent research shows that the Arabian Sea, the Bay of Bengal, and the equatorial Indian Ocean function

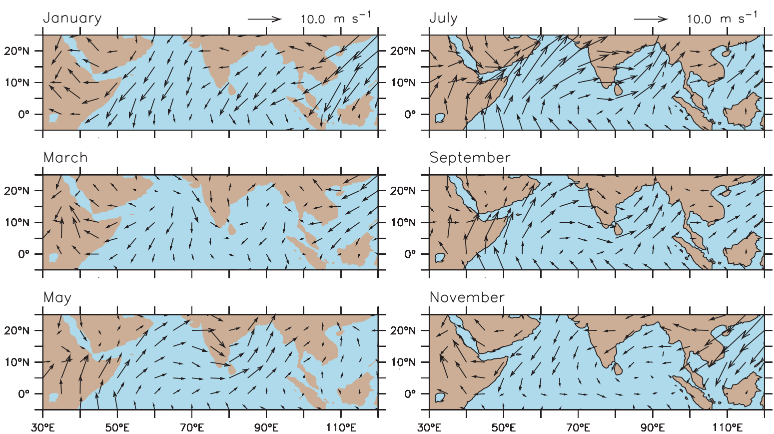

Fig. 17. The seasonally reversing winds (m/s) over the north Indian Ocean.

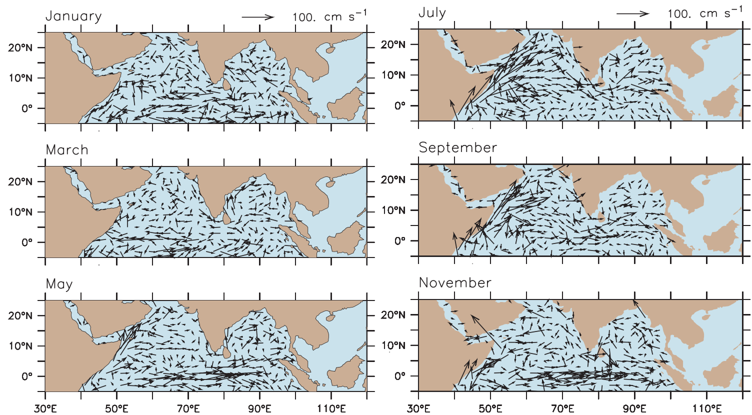

Fig. 18. The seasonally reversing surface currents (cm/s) in the north Indian Ocean.

as a single dynamical entity, making the current at any location in the basin a response not just to the local winds, but also to winds elsewhere in the basin. For example, the strongest currents along the east coast of India occur not only during the summer monsoon, when the winds are strongest, but during March-April, a period of weak winds.

Motion due to tides is strongly periodic and leads to upward and downward movement of the water surface. The up and down motion of the surface is accompanied by horizontal currents that are also periodic (Fig. 19). Tidal

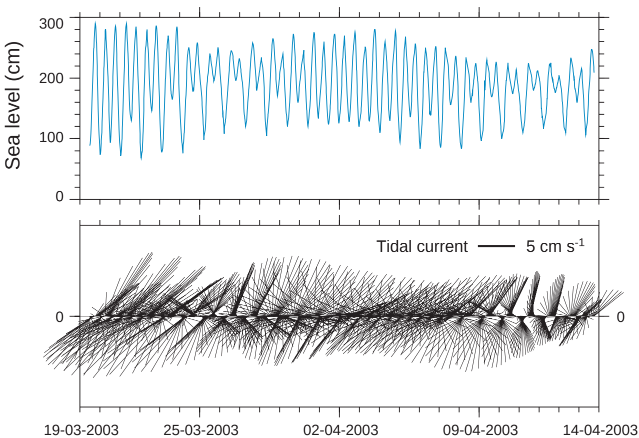

Fig. 19. Sea level (cm) measured by the tide gauge at Mormugao Port, and tidal currents (cm/s) off Mormugao. Note the rhythmic changes associated with the tides and how the tidal current vector rotates over a day.

motion is most conspicuous in shallow coastal areas. Its importance, in comparison to wind-driven circulation, reduces in deeper waters.

Oceans and climate

Solar heating is distributed unequally over the Earth's surface. Oceanic motion makes an important contribution to the transport of heat and reduces the equator-pole temperature gradient over the Earth. On an average, the ocean transports as much heat to the higher latitudes as does the atmosphere. The larger heat capacity of water compared to air makes it possible to do this with currents that are much weaker than the winds. Oceanic circulation therefore has a close relation to climate and affects it on a range of space and time scales. On long time scales, the oceans participate in determining climate through the global conveyor belt (Fig. 15), which is affected by changes intrinsic to the atmosphere and the ocean and by the changes in solar heating due to variations in the Earth's orbit around the Sun.

A more easily observable example of the ocean's role in climate is El Niño, a phenomenon that occurs in the equatorial Pacific Ocean. Under normal conditions, the easterly (from the east) trade winds maintain a reservoir of warm water in the western Pacific off Indonesia and Papua New Guinea (Fig. 20). This warm water supports strong atmospheric convection. As a result, rainfall in this region is among the highest in the world. During the summer monsoon this band of high rainfall extends into the Indian Ocean and over the Indian subcontinent (Fig. 21). The rising air that is responsible for this rainfall moves across the Pacific basin and sinks over the cool waters off Peru on the eastern side. When an El Niño occurs, the waters off Peru warm, and these warm waters spread westward, increasing the sea surface temperature across the eastern and central Pacific. This suppresses convection over Indonesia and the western Pacific. The effect of El Niños is not restricted to the equatorial Pacific. The large expanse of the basin, which covers almost half the globe, ensures that El Niño has a global impact on climate. During El Niño, with the atmospheric convection over the western Pacific

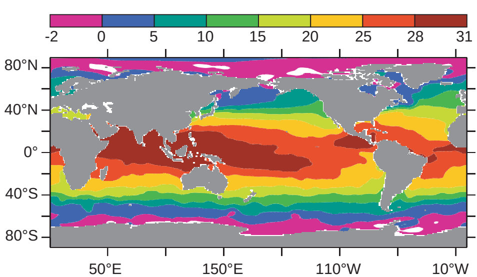

Fig. 20. Sea surface temperature (°C) during May. Note the 'warm pool' that spreads across the western Pacific and the north Indian Ocean.

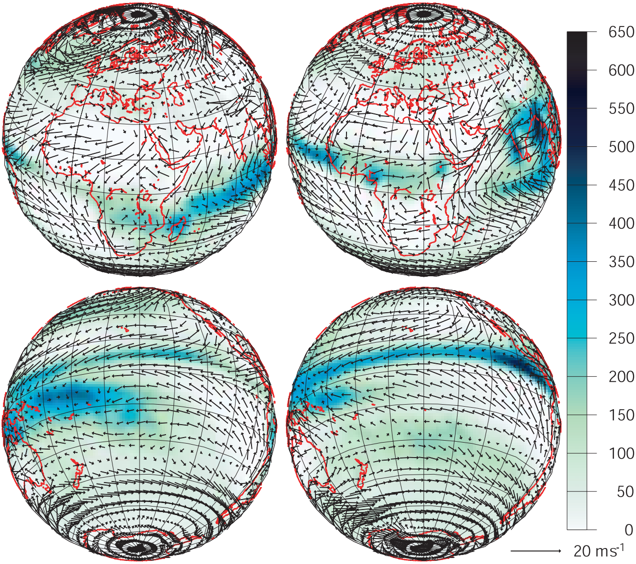

Fig. 21. Rainfall (colour, mm/month) and winds (vectors, m/s) during January (left) and July (right). Note the band of high rainfall in the vicinity of the equator during January; in the Indian Ocean, this band migrates northward over the Indian subcontinent during July. Also note that the western Pacific and eastern Indian Ocean are wetter than their eastern and western counterparts, respectively.

being suppressed and the band of high rainfall shifting eastward, there is a tendency for rainfall over India also to decrease.

Dramatic advances in satellite technology have led to the recent discovery of an El-Niño-like oscillation in the equatorial Indian Ocean. It has been called the Indian Ocean Dipole Mode. Under normal conditions, the band of warm waters in the western Pacific extends across the north Indian Ocean (Fig. 20). The eastern equatorial Indian Ocean is usually warmer than its western counterpart (Fig. 22). When the positive phase of the dipole occurs, as it did in 1997, sea surface temperature decreases in the east and increases in the west. Recent research suggests that the dipole has a significant influence on the rainfall over India.

The Arabian Sea and the Bay of Bengal also exercise a profound influence on climate. Though both are located in the same latitude band and receive the same amount of solar radiation from the Sun, the Bay of Bengal is much warmer than the Arabian Sea and many more storms brew over the bay. The depressions that form over the northern Bay of Bengal move northwestward across the Indo-Gangetic plains, bringing rain to most of northern India (Fig. 23). Over the Arabian Sea, rainfall is much less on an average. The ocean plays a major role in keeping the Arabian Sea relatively dry. Recent research shows that there are two causes. First, the winds over the Arabian Sea are stronger because of the presence of the mountains of East Africa. These strong winds force a much more vigorous oceanic circulation and the heat received at the surface is transported southward and into the deeper ocean. The winds over the Bay of Bengal, in contrast, are more sluggish and the bay is unable to remove the heat received at the surface. Second, the bay receives more rainfall; it also receives more freshwater from the large rivers, especially the Ganga and the Brahmaputra, that empty into it. This freshens the surface of the bay and stabilizes the water column, making it more difficult for the winds to mix the warm, stable surface layer with the cooler waters below (Fig. 14). In the Arabian Sea, there is no such stabilizing effect. As a consequence, the mixing with the cooler waters below is more vigorous. Since a sea surface temperature of about 28°C is necessary for convection to take place in the atmosphere,

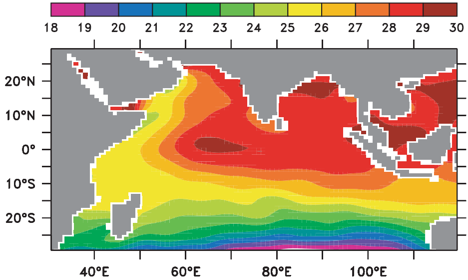

Fig. 22. Sea surface temperature (°C) during July in the Indian Ocean. Note that the Arabian Sea cools during the monsoon, but the Bay of Bengal remains warm.

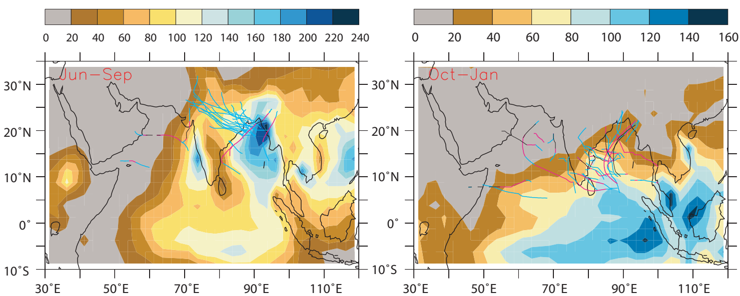

Fig. 23. Average cumulative rainfall (colour bar, cm) and storm tracks during June-September and October-January. Data for 1990-1997 have been used. The light blue (cyan) tracks are for depressions, the red tracks for cyclones (storms), and the black tracks for severe cyclones. Note the large number of depressions that form in the northern Bay of Bengal during June-September, when cyclones are fewer. These depressions move northwestward into the Gangetic plains and bring rain to much of northern India. During October-January, there are fewer depressions, but the number of cyclones is larger.

this condition is satisfied in the Bay of Bengal but not in much of the Arabian Sea (Fig. 22). Thus, in spite of their geographical similarities, the two arms of the north Indian Ocean are strikingly different when it comes to climate.

Storms in the Bay of Bengal

The Bay of Bengal is one of the major centres of the world for breeding of tropical storms. These storms are known as cyclones over the Indian Ocean and southwestern Pacific, as typhoons over the northwestern Pacific, and as hurricanes over the Atlantic. Cyclones over the Bay of Bengal usually move westward, northwestward, or northward and cross the east coast of India or Bangladesh (Fig. 23). When this happens, it brings strong winds and high rainfall to the coastal region, causing loss of life and damage to property.

Compounding the damage is the occurrence of a "storm surge" that often accompanies a storm. The surge is primarily piling up of water due to the strong storm winds. This raises the mean water level in the coastal zone, whose magnitude is dependent on the strength of the winds. It is not unusual for this rise to be a metre for many cyclones, and 2-3 metres for major cyclones. With mean water levels being elevated, and with strong winds generating high waves, storm surges lead to immense loss of life and property. The particularly strong cyclone (also called supercyclone) of October 1999 caused a loss of over 10000 lives and huge property loss in Orissa. Of the 34 reported storm surges with loss of life of 5000 or more around the world, 26 have occurred in the Bay of Bengal. A storm surge in 1970 in Bangladesh caused 500,000 deaths. The rather flat topography of Bangladesh makes it particularly vulnerable to storm surges.

Wind waves

The most visible manifestation of the dynamic nature of the ocean is its undulating surface. It is visible to anyone who watches the water while standing on a beach or travelling in a ship. The undulation is caused by the action of winds on the ocean surface, and hence is known as *wind waves*. Wind waves are the most common form of a class of waves called surface gravity waves. They are called gravity waves because the Earth's gravity pulls the water particles back to equilibrium once the wind disturbs the ocean surface and perturbs it from equilibrium by injecting kinetic energy into the water. Wind waves occur in water that is deeper than half their wavelength; hence, they are called deep-water waves. The momentum gained by the water decays with depth, and there is no motion due to

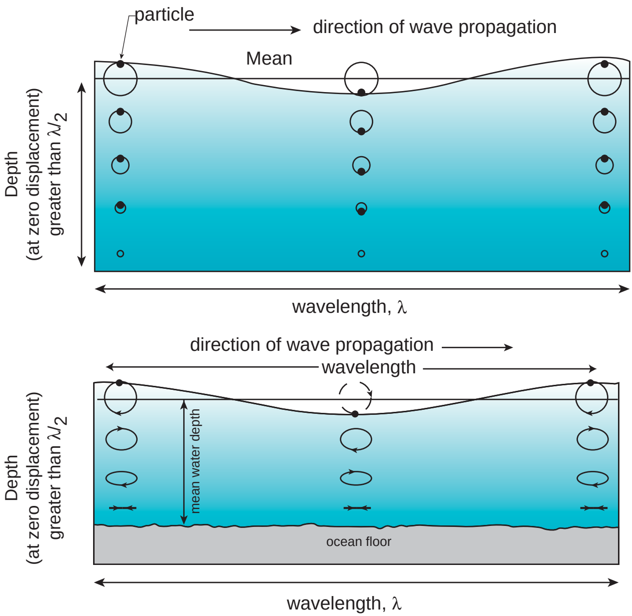

Fig. 24. Schematic showing deep-water waves (top) and shallow-water waves (bottom).

these waves in deeper water (Fig. 24). The pattern associated with these waves moves at speeds of 1-100 m/s, their wavelengths range from 1-1000 m, and their periods range from seconds to minutes.

At a given time, the link between the winds and waves is so strong that wind velocity can be inferred quite reliably from the characteristics of the waves. A scale, called the Beaufort scale, has been constructed for the measurement of waves.

The waves generated in the deep ocean travel thousands of kilometres (in the form of swells) across the oceans and reach the shore. The area where waves are generated in the open ocean is called 'fetch'. The size of a wind wave depends on wind speed, duration, and fetch.

Tides

Tides are another aspect of the restless ocean visible to a keen observer on a beach. Forced by the gravitational attraction of the Moon and the Sun, tides are periodic (Fig. 19) and highly predictable. Tide tables are prepared for major ports a year in advance. Tides are a special class of surface gravity waves: they are shallow-water waves, so called because they occur in water that is shallower than half their wavelength. The speed of shallow-water waves is given by $\sqrt{(gH)}$, where g is the Earth's gravitational acceleration and H is the ocean depth. In the open ocean, which is about 3700 m deep, these waves have a speed of 700 km/hr, which is the speed of a typical jet airplane. In shallow-water waves, momentum does not decay with depth and there is motion even at the bottom (Fig. 24).

Tides have wavelengths ranging from 100-10000 km, and periods of 12.5 (semi-diurnal tides) and 24 hours (diurnal tides). Along the Indian coast, the tides observed are a combination of both semi-diurnal and diurnal tides. The tides and tidal currents are weaker along the southern part of the Indian coast (current speeds of the order of a few tens of cm/s). The magnitude of tidal currents increases northward, and it reaches very high values in certain areas like the Gulf of Kutch and the Gulf of Khambhat, where the speeds can exceed 2 m/s.

Tsunamis

Tsunami is a Japanese word meaning "harbour wave(s)". Tsunamis are shallow-water waves, and therefore, like tides, they move in the open ocean at very high speeds. However, they have shorter wavelengths (ranging from 10-1000 km) and periods (100-3000 seconds). The surface perturbation due to a tsunami is small (usually less than half a metre) in the open sea and the particle (not wave) speed is a few cm/s, making them too insignificant for a passing ship to notice. When they approach a coast, however, tsunamis amplify owing to two changes. First, the decrease in depth implies that energy that was distributed over a larger depth in the open ocean now has to be squeezed into a smaller depth. Second, the decrease in depth leads to a decrease in the wave speed, and therefore in its wavelength. As a result, the energy has to be accommodated in a smaller horizontal distance too. This leads to an increase in wave height and particle velocity, which can exceed 7 m/s (~ 25 km/hr). The water level due to tsunamis rises and falls, and this goes on for about 2-3 days until the energy contained in the tsunami wave packet is exhausted and the ocean regains equilibrium.

Tsunamis are caused by a large-scale perturbation of the ocean floor. Three mechanisms can cause this: (1) earthquakes with epicentres located below the ocean floor can make it vibrate; (2) mudslides on the ocean floor, particularly on the continental slope (Fig. 9), can suddenly change its shape; and (3) volcanic eruptions, either on the ocean floor or on the nearby continent, can lead to a shaking of the ocean floor, or huge quantities of ash accompanying an explosion can flow rapidly on the ocean floor and displace a huge volume of water.

Tsunamis are rare in the Indian Ocean: only 0.8% of tsunamis are recorded in the Bay of Bengal. Most tsunamis have been recorded in the Pacific, and submarine earthquakes are the major cause.

On 26 December 2004, an earthquake of magnitude 9.3 (Richter scale) occurred at 0629 IST at 3.4°N, 95.7°E off the coast of Sumatra, Indonesia (Fig. 25). This triggered the devastating tsunami that killed over 300000 people in Indonesia, Sri Lanka, India, Thailand, Myanmar, and Somalia, making it the biggest killer tsunami on record. Signatures of the tsunami were recorded by tide gauges in India and in several other countries. The tsunami reached Chennai on the Indian east coast at 0905 IST, ~ 2.5 hours after the earthquake and perturbed the sea level from the normal rhythmic tidal variation (Fig. 26).

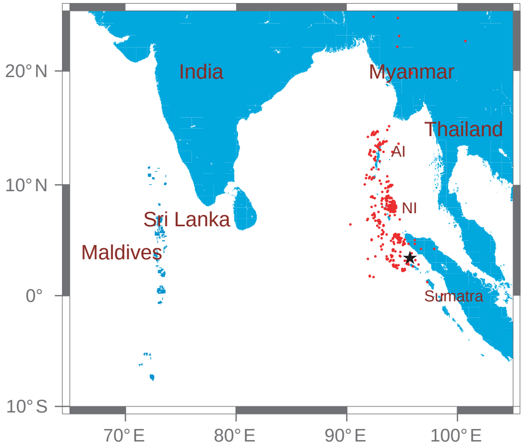

Fig. 25. The black star marks the epicentre of the 26 December 2004 earthquake; the red dots mark the aftershock locations till 10 February 2005. The aftershocks are spread over the region affected by the quake. AI: Andaman Islands, NI: Nicobar Islands.

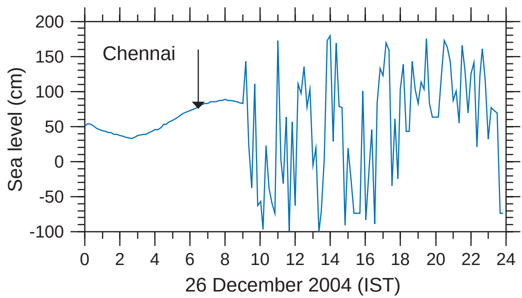

Fig. 26. Tide-gauge sea level at Chennai. The arrow marks the time of the earthquake.

Beaches

Being a unique boundary between land, water, and air, beaches are very dynamic forms of land. Waves continuously operate on the beach, putting beach material into motion. Winds and tides are also important forces acting directly on the beach and causing changes. Also altering the nature of the beach is human interference. Building of breakwaters, piers, jetties, and sea walls can disturb the natural movement of beach material and can cause profound changes.

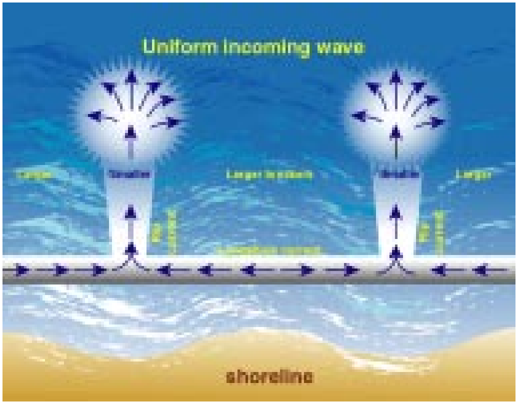

Fig. 27. Generation of nearshore rip currents.

During the monsoons, very high waves dissipate their energy, causing beach erosion and damage to nearshore landforms and property. During fair weather, low-energy waves help build up beaches by deposition or accretion of sand. One of the important features of wave action near the shore is the generation of nearshore currents (Fig. 27). These water movements, which can be longshore or offshore, are fundamental to the movement of beach material. Also to be noted is the increased intensity of these currents during the monsoon, which would be hazardous for those who venture into the sea for recreational activities. Strong currents directed towards the sea, perpendicular to shore, are called ‘rip currents’ or ‘killer currents’, and one should be careful of them.

Estuaries along the coast of India

An estuary is a channel that has the sea at one end and a river at the other; in an estuary, seawater is appreciably diluted. The complete salinity range from 0-35 ppt is seen from the head (river end) to the mouth (sea end) of an estuary. About 100 such channels of varying sizes and shapes occur along the coast of India. Each estuary receives its freshwater from drainage channels of a river basin. The major river basins of India are shown in Fig. 28 together with some of the major riverine/estuarine channels. The banks of estuarine channels form a favoured location for human settlements, which use the estuaries for fishing and commerce, but nowadays also for dumping civic and industrial waste. Estuaries are usually biologically highly productive zones. They also act as a filter for some dissolved constituents in river water; these precipitate in the zone where river water meets seawater. More important is the trapping of suspended mud and sand carried by rivers which leads to delta formations around estuaries. Major estuaries occur in the

Bay of Bengal. Many estuaries are locations of some of the major seaports. Most of the India's major estuaries occur on the east coast. In contrast, the estuaries on the west coast are smaller. Two typical examples of estuaries on the west coast are the Mandovi and Zuari estuaries located to the north and south of the main campus of the National Institute of Oceanography at Dona Paula, Goa.

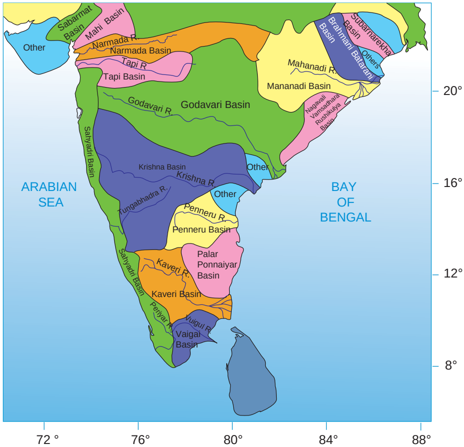

Fig. 28. Major river basins and estuaries of India.

Water cycle on planet Earth

The Earth is called the blue planet because it looks blue when seen from space. The blue color is due to water (oceans) that covers 71% of the surface of the Earth (Fig.1). Our watery planet holds about 1.5×10^{18} t (1 tonne = 1000 kg) of water, which in turn contains 0.05×10^{18} t of dissolved salts. This part of the hydrosphere interacts chemically with the Earth's rocks (geosphere), with the air (atmosphere), and with living things (biosphere).

Water evaporates from the oceans as water vapour, which condenses later in the atmosphere to fall as rain or snow, collectively called precipitation (Fig. 29). It is estimated that 0.42×10^{15} t of water circulates annually in this water cycle. Precipitated water finally returns to the oceans via streams and rivers and carries weathered and eroded material from the Earth's crust into the oceans. Each year, 8×10^{12} t of material is transported from the land into the oceans. About two-thirds of this consists of insoluble material (rocks, pebbles, sand, silt, etc.) and the rest remains in dissolved state.

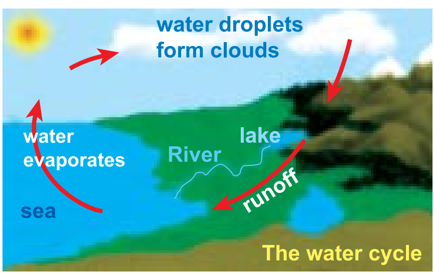

Fig. 29. Schematic of Earth's water cycle.

Where did the elements in seawater come from?

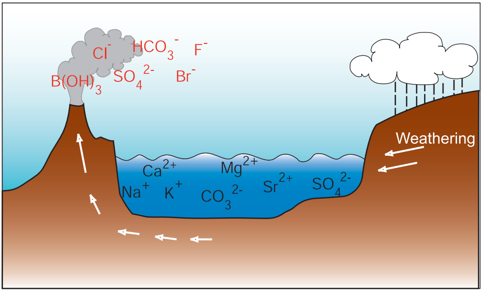

Fig. 30. Sources of different elements in seawater.

Most elements in seawater came from chemical weathering of minerals in the Earth's crust and other elements came from the atmosphere. The crust is made up mostly of silicates and aluminosilicates of metals in Groups 1 and 2 of the periodic table and of iron. The crust also contains carbonates of these metals. In weathering, acidic rainwater percolates through the soil and underlying rocks and acts on metal silicates and carbonates to dissolve them. Carbonates weather more rapidly. Rainwater is usually acidic because it reacts with carbon dioxide in the atmosphere and soil to form carbonic acid (H_2CO_3). The dissolved ions are ultimately washed into the sea (Fig. 30). At the air-sea interface, the atmospheric gases (nitrogen, oxygen, carbon dioxide, etc.) enter the seawater in which they dissolve. The atmosphere also contains small amounts of sulfuric and nitric acids produced when oxides of sulfur and nitrogen respectively react with rainwater.

The presence of fluoride, chloride, bromide, sulfate, and borate ions, which are present in insignificant levels in the Earth's crust, suggests that they probably originate from volcanic gases and are then dissolved in rainwater.

In spite of all the dissolved material that is transported by rivers (2.5×10^{12} t each year), the sea does not get saltier. We believe that the oceans reached their present level of saltiness quite rapidly in the early history of the Earth and since then they have maintained the same salt content. The salinity of the sea does vary from place to place. While the open ocean contains 35 ppt dissolved solids, the Mediterranean Sea (39 ppt) and the Red Sea (41 ppt) are much saltier.

Major elements in seawater

Elements present in amounts greater than 1 mg/litre are called major elements (Table 1). These elements determine the salinity of seawater. Their ratios with salinity or with each other are nearly constant. They are also known as conservative elements. Common salt (sodium chloride) is the principal ingredient of seawater that makes it salty. It exists in solution as separate hydrated sodium ions (Na^+) and hydrated chloride ions (Cl^-).

Minor elements in seawater

Most of the other elements of the Periodic Table are also present in seawater. They are called minor and trace elements. Among them, the micronutrient elements N, P, Si, and Fe are essential for biological production in the ocean. Their abundance is controlled by horizontal and vertical circulation and by biogeochemical processes of utilization and regeneration. Of other elements, even dissolved gold is found in the water of all oceans. Although present in very small concentrations (0.000004 mg/litre), there is 5.6 million t of gold in all the Earth's oceans, but the dilution is such that it cannot be extracted economically.

Table 1. Major elements, their ionic forms, concentrations in seawater of 35 ppt salinity and percentage levels.

Elements	*Concentration (mg/litre)*	*% by weight*
Cations		
Na^+	10762	30.61
Mg^{2+}	1290	3.67
Ca^{2+}	413	1.17
K^+	387	1.10
Sr^{2+}	7.75	0.02
Anions		
Cl^-	19374	55.10
SO_4^{2-}	2710	7.71
HCO_3^-	141	0.40
Br^-	68	0.19
$B(OH)_3$	4.50	0.02
F^-	1.30	0.01

Why seawater composition does not change?

Just as the salt content of seawater does not change, the concentration of its components also remains unchanged. To maintain the constant composition, it is necessary that dissolved ions are removed at the same rate as they are added. Processes by which ions are removed from seawater include the following:

1) Evaporative precipitation: In hot, dry climates where the sea is shallow and enclosed, solid deposits of salts such as rock salt (sodium chloride) and gypsum (calcium sulphate) are formed.
2) Chemical precipitation: When the concentration of a salt becomes too great, that salt forms a solid precipitate. For example, calcium ions and carbonate ions combine together to form insoluble limestone (calcium carbonate).
3) Biochemical removal: Organisms remove ions by scavenging them from seawater. Some animals like coral and bivalves make shells of calcium carbonate. Many organisms concentrate ions in their body tissues by a factor of 10^5 or more. For example, sea squirts concentrate vanadium,

other tunicates concentrate niobium, oysters concentrate zinc, lobsters concentrate copper, and other shellfish concentrate mercury.

Life in the oceans, especially the upper layers

The ocean is the cradle of life. Evolution of life in this aqueous environment has given rise to a wide variety of lifestyles. While some evolved into free-living plankton that drift passively in the water, others developed into nekton that swim about actively. Species that dwell on the sea bottom are called the benthos. These may be sessile and attached, or possess only weak mobility. Organisms in the sea are governed by its physical and chemical properties, such as temperature, salinity, nutrients, light, and hydrostatic pressure. All of them are adapted to cope with salinity. Intertidal and estuarine organisms thrive in salinities that vary from freshwater conditions to that in the adjoining sea. Temperature tolerance varies from near-freezing to tropical conditions, but, of course, any species is restricted only to a relatively narrow range of salinity and temperature.

Organisms require energy for growth and multiplication, which they acquire through photosynthesis (plants), chemosynthesis (autotrophic bacteria anywhere, and animals living in great profusion at the “hot springs” of the mid-oceanic ridges, Figs. 6 and 9) or uptake of organic matter as particles (most animals) or dissolved materials (heterotrophic bacteria). These different mechanisms can be broadly classified as ‘trophic levels’.

(1) The photosynthetic organisms that constitute the lowermost trophic level, both on land and in the sea, are called *primary producers*. In the water column, unicellular phytoplankton (Fig. 31) are responsible for photosynthetic fixation of carbon dioxide in the presence of sunlight and nutrient salts. This process of primary production takes place within the “euphotic zone“ or the upper sunlit zone. In clear tropical offshore waters the euphotic zone extends beyond 100 m, but is much shallower in near-shore waters because of increase in turbidity. Among the phytoplankton, the pico-plankton are less than two microns in size, the nano-plankton between 2-20 microns, and the micro-plankton 20-200 microns (human hair is about 80 microns thick).

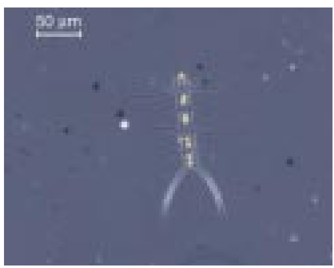

Fig. 31. Chain-forming phytoplankton Chaetoceros *sp.*

(2) The trophic level above that of the primary producers consists of the *primary consumers*, namely zooplankton, which graze upon the phytoplankton. Like their food, zooplankton are also classified as

nano- and micro-zooplankton. The meso-zooplankton, between 200 microns to 20 mm in size, are important inhabitants of the sea. Among these, the copepods are the most abundant.

(3) Animals (zooplankton, fish) that feed on the "herbivorous" zooplankton are the *secondary consumers* and, in theory, constitute the next higher trophic level.

(4) Carnivorous fish, squid and turtles constitute the top of the trophic level, and are sometimes are called *tertiary consumers*.

Since all trophic levels are connected, any attempt to understand fisheries should also take into consideration the other trophic levels (Fig. 32). Some 80-90% of organic matter or energy is lost during each feeding step, principally by incomplete digestion and the metabolism of the predator. Therefore, relatively little food can reach the top carnivores. The metabolism regenerates the nutrient salts and carbon dioxide, while some of the "lost" organic matter is in the form of organic secretions, faeces, and dead tissues. These are utilized by heterotrophic organisms such as bacteria and fungi. Every ml of seawater contains on an average a million cells of bacteria, which perform the important task of recycling nutrient salts . The bacteria are fed upon by many microscopic animals, such as the flagellates and ciliates, which in turn are eaten by the mesozooplankton.

Actually, the food relations in the water column do not constitute a chain as on land (grass - cattle - tiger), but a web in which much feeding is by size rather than kind. The mass of a phytoplankton cell of 200 micron is 1 million times that of a 2-micron cell, similar to the ratio between elephants and small mice: the ratio is very much larger between the small planktonic and the nektonic animals. Just as no net catches

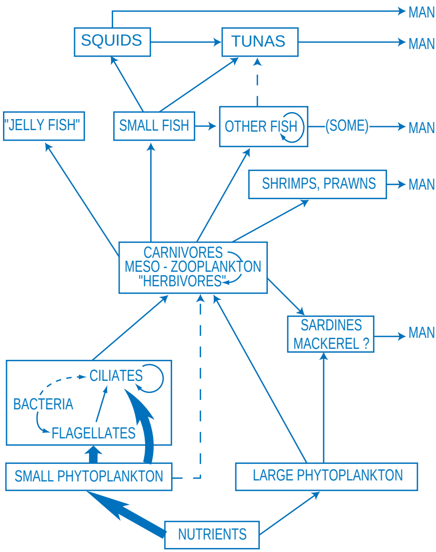

Fig. 32. Some aspects of an open-water food web: The circular arrows in boxes indicate feeding within the categories: "small fish" may be small species or juveniles of large fishes. Dissolved organic matter and the "feedback" of the nutrients liberated by metabolism are omitted.

elephants and mice, marine animals also can hunt only for limited size ranges. However, also in contrast to land, a large "goat" easily and commonly eats a young "wolf" and thus obliterates the trophic level concept, aside from the fact that many phytoplankton species can also eat particles (mixotrophs). We cannot predict fish yield from primary production rates alone because the uncertainty about the level(s) of the food web on which a particular species feeds, and because of our ignorance of how much food is available to the target species from competition with the other members of the web.

All organisms in the sea, to whichever trophic level they belong, are linked to each other in a complex food web, the structure of which is determined by the physics and chemistry of the ocean. The Arabian Sea and the Bay of Bengal, being tropical waters, provide congenial temperatures and light conditions throughout the year for sustained primary production. This, however, does not always happen because nutrients can often be seasonally limiting.

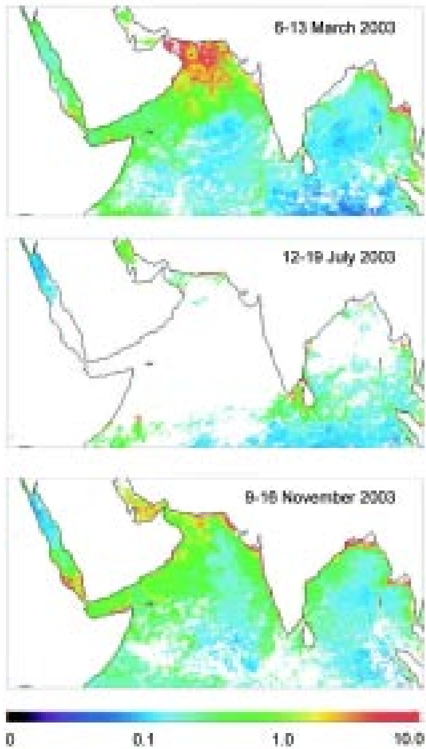

Fig. 33. Satellite images showing chlorophyll (mg/m³) concentrations in false colour in the North Indian Ocean. White patches are clouds.

Mineral nutrients (nitrate, ammonium, phosphate, silicate, and iron) are essential for phytoplankton growth and multiplication. Physical processes such as upwelling (a process in which cooler waters from below are brought up), hydrographic fronts (regions over which a property like temperature or salinity changes sharply in the horizontal), eddies, and cyclones are responsible for bringing up nutrients from deeper waters to the surface, thus stimulating primary production. The southwest monsoon along the west coast of India brings up nutrients from deeper waters through upwelling and is important for the high biological productivity. Cyclones are among the major cause of nutrient injection to the surface waters and elevated primary production in the Bay of Bengal. The fertility of the oceanic water column can be assessed by its chlorophyll content as a measure of phytoplankton. Ocean Colour Remote Sensing technology offers a real-time estimate of this fertility (Fig. 33).

Life in the deep sea

Life in the deep sea is sustained essentially by the biological production in sun-lit, top 50-100 m water column. Sinking of dead organisms, their faecal pellets, and calcium carbonate shells of various organisms transfer carbon to the deep sea in a process called the 'biological pump'. Life thrives in the deep sea in spite of the high hydrostatic pressure, low temperature, complete darkness, and total dependence on food from above. Hydrostatic pressure at the average ocean depth of 3700 m equals 370 atmospheres, but deep-sea organisms have evolved mechanisms to cope even with this extreme condition. Hydrothermal vents (see page 7) are a significant exception to the scarce deep-sea life elsewhere. In and around the vents, the high diversity of life and biomass is sustained purely by the bacteria as symbionts within the animals that thrive there. Chemosynthesis, not photosynthesis, is the process that sustains the food web in the hydrothermal vents.

The coastal marine environment

The coastal marine environment, consisting of intertidal regions, the estuaries, seaweed and seagrass beds, mangrove forests, and coral reefs has a direct impact on human society because it provides social and economic benefits. In addition to the phytoplankton in the water column, larger, multicellular intertidal and benthic algae are important primary producers in coastal ecosystems. Two of the major ecosystems that are important along the Indian coast are the mangroves and the coral reefs. Mangrove vegetations protect land against erosion (Fig. 34). Major mangrove forests are found on the Indian east coast: these include the Sunderbans in the Gangetic delta and the mangroves along the Krishna-Godavari delta. The west coast of India also had extensive mangroves, but many have been converted into rice paddies or shrimp culture lots.

Coral reefs are a virtual underwater paradise. The diversity of life in coral reefs is often comparable to that of tropical rain forests (Fig. 35). Fringing coral reefs are most abundant around the Andaman and Nicobar islands in the Bay of Bengal, while coral atolls occur in the Lakshadweep islands in the Arabian Sea (Fig. 36). High primary production and abundance of life in coral reef atolls, despite their location right in the middle of an ocean that is poor in essential mineral nutrients, reminds one of an oasis in the middle of a desert. This remarkable affluence of the ecosystem despite limiting resources is a result of its efficient functioning, nutrients being tightly conserved and recirculated without much loss to the surroundings. Thus, the functions of organisms in coral reefs are tightly coupled to one another.

Fig. 34. A mangrove vegetation at high tide.

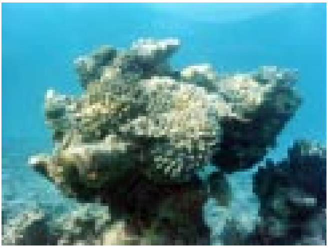

Fig. 35. Coral reef ecosystem.

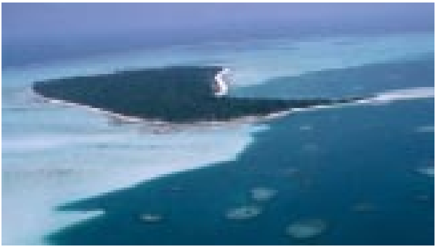

Fig. 36. An island in the Lakshadweep archipelago in the Arabian Sea.

Biodiversity of the oceans

Most of the biodiversity (number of species) of the oceans still remains a mystery. It is believed that less than 0.1% of bacterial plankton diversity has been documented. The deep-sea sediments are considered to be yet another source of undiscovered biodiversity. While the diversity of species is greater on land, the number of phyla is greater in the sea.

The sheer size and volume of the oceans makes it a major player in the global climate, and much of this can be attributed to its biology. Carbon dioxide is the major greenhouse gas and photosynthesis is the fundamental mechanism by which it is sequestered in tissues of living organisms and their dead matter. The oceans contain about 38 x 10^{12} tons of soluble carbon dioxide, which is ~60 times more than that in the atmosphere. The magnitude of primary production, export to the deep sea, and the production of calcium carbonate by marine organisms are the major biological factors in determining the role of the oceans in the global carbon cycle. Understanding details of these processes remains a major challenge in biological oceanography.

Minerals from the sea

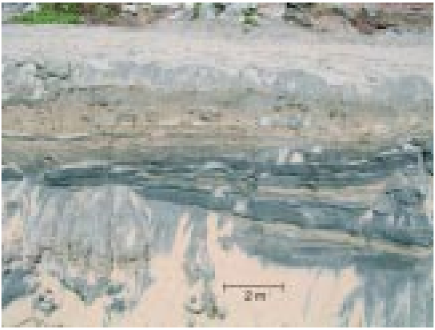

Fig. 37. Layers of placer minerals as seen in the vertical section dug on a beach.

The sea offers a variety of minerals, many of which are considered to be alternative sources of metals in the future. Among these are the placer deposits, which are mechanically concentrated minerals that originate from eroded onshore rocks. The near-shore waves separate the minerals brought by rivers and glaciers into heavy (sp. gravity >2.8) and light minerals, and concentrate heavy minerals on the beaches and estuaries (Fig. 37). Elements in native state (diamond, gold, and platinum) or minerals such as ilmenite, rutile, magnetite, zircon, monazite, garnet, and corundum are some examples of placer deposits. The ilmenite sands of Ratnagiri, monazite and zircon sands of Kerala, and garnet sands of Visakhapatnam are the better known placer deposits on the beaches of India.

Oolites are the inorganic chemical precipitates of calcium carbonate that form in hyper-saline, shallow marine environment (<10 m). Oolites are found on the continental shelf off Mumbai, Visakhapatnam, and Chennai. Phosphorites or sedimentary phosphate (>18% P_2O_5) deposits form on the continental shelf or upper continental slope by biogeochemical processes associated with organic-rich sediments (Fig. 38). Phosphorites occur both on the east and west coasts of India. The phosphorite deposits in Mussoorie and Udaipur in northern India were formed in marine conditions millions of years ago. Barite ($BaSO_4$) deposits occur in deep-sea sediments in association with organic and biogenic remains and/or with volcanic activity. Zeolites are the alteration products of the submarine volcanic rocks in the deep ocean floor. Phillipsite, analcime, harmotome, and clinoptilolite are some of the zeolite minerals.

Ferro-manganese deposits form in the deep ocean basins (4-5 km depth) in areas away from the influence of terrigenous (from land) fluxes (Fig. 39). They occur as nodules (round objects upto 10 cm in size) and encrustations (as layers on rocks exposed on the seafloor). These are valuable deposits not because they have a high iron and manganese content, but because of their copper, nickel, and cobalt (total 2.5%) content. Manganese nodules grow at a rate of 1-3 mm per million years and occur on the ocean floor or a few centimetres below it. Crusts with high cobalt content (0.25% - 1%) usually occur on seamounts, elevated marginal areas, and mid-ocean ridges.

Fig. 38. Phosphorite deposits from the eastern continental shelf of India.

Fig. 39. Ferromanganese nodules on the sea bed.

Hydrothermal deposits are formed by the interaction of seawater with submarine volcanic activity. They occur intermittently all along the mid-ocean ridge system (especially Mid-Atlantic Ridge and Central Indian Ocean Ridge) and in the Red Sea. The hydrothermal fluids that gush out of the vents on the seafloor deposit metal sulphides (iron, copper, and zinc) and sulphate (barium and calcium) minerals. The sediments close to the vent are enriched with high content of iron, manganese, silver, chromium, lead, and zinc.

Gas hydrates are compounds where gas molecules are physically trapped inside an expanded lattice of water molecules. They can be present below the ocean floor on the continental slopes and deeper areas of high rate of deposition of sediments with moderate organic content (0.5%). Seabed gas hydrates could be an energy source of the future. A potential gas hydrate province covering an area of 1400 sq. km has been identified in the Krishna-Godavari offshore basin.

Seawater can be evaporated to produce sodium and potassium chlorides. In countries like Saudi Arabia where fresh water is scarce, salts are separated from seawater (desalination) to provide pure water for drinking. Treating seawater with calcium hydroxide precipitates magnesium hydroxide, which is used in the manufacture of magnesium metal. Bromine and iodine are obtained by treating seawater with chlorine gas.

How do we explore the oceans?

The oceanographer addresses two questions: "What is going on in the oceans?" and "Why?" The former is answered by careful observations of the oceans, the latter by putting these observations in perspective with the help of an established theoretical framework.

Oceanographers use a variety of instruments to observe the oceans. A basic requirement for such observations is a platform that can support the equipment deployed in observations. At present there are three kinds of platforms in use. The first is a research ship. It is like a floating laboratory equipped with instruments (temperature and salinity profilers, bottles for collecting water samples at different depths, devices that can sense the

Fig. 40. Equipment used for exploring the oceans. (Top: a research ship towing an array of sensors and a net near the surface; Left to right: remotely operated vehicle, a sound pulse to measure depth, multiple sampler for seafloor sediments, conductivity - temperature - depth sensor with water samplers, boomerang grab for manganese nodules, underwater video and photo system, autonomous underwater vehicle, deep-sea mooring for deploying current meters and sediment traps for long duration of time).

ocean floor, etc.) to observe the ocean. It also has facilities (lodging, boarding, communication, etc.) for oceanographers to stay at sea for a few weeks. A research vessel is equipped with machinery to handle sampling equipment: nets for biological studies, autonomous and remotely-controlled underwater vehicles, profilers, photography, and video systems, etc. (Fig. 40).

The second kind of platform often utilised by oceanographers is called a "mooring". It consists of a wire that is attached to the ocean floor, and kept taut with the help of floats. Instruments (current meters, temperature recorders, etc.) are then attached to the wire.

The third kind of platform is one that is used by oil and gas companies in offshore petroleum production. These stable structures are often used for measuring meteorological variables, water level, currents, etc.

During the last 25 years there has been significant improvement in our ability to study the oceans with sensors that are stationed on satellites. These sensors provide information only on properties of the ocean surface, but their ability to cover a large spatial area and repeat the observations at regular intervals has proved useful in exploring the oceans.

Explore the oceans on the Internet and in books!

Internet

1. URL: http://www.mos.org/oceans/ . Learn about our global seas in Oceans ALIVE!
2. URL: http://www.onr.navy.mil/focus/ocean/default.htm . An Office of Naval Research (USA) site. Contains considerable information on oceans and oceanography.
3. URL: http://life.bio.sunysb.edu/marinebio/challenger.html . Brief history of the pioneering expedition of HMS *Challenger*, which gave birth to modern oceanography.
4. URL: http://www.epa.gov/owow/estuaries/kids/ . Explore the world of estuaries.
5. URL: http://www.mangroveindia.org/ . All about the mangroves found along the Indian coast.
6. URL: http://www.nio.org/jsp/tsunami.jsp . Information on the 26 December 2004 tsunami. Also contains links to other sites.

Books

1. *The ocean basins: Their structure and evolution.* Open University, U.K., 1998.
2. *Seawater: Its composition, properties and behaviour.* Open University, U.K., 2002.
3. *Ocean circulation*. Open University, U.K., 2001.
4. *Waves, tides and shallow-water processes*. Open University, U.K., 2002.
5. *Ocean chemistry and deep-sea sediments*. Open University, U.K., 2001.
6. *Biological oceanography: An introduction*. C.M. Lalli and T.R. Parsons. Open University, U.K., 1997.
7. *Planet Earth: Cosmology, geology and the evolution of life and environment.* C. Emiliani. Cambridge University Press, U.K., 1992.
8. *Our affair with El Nino*. S.G.H. Philander. Princeton University Press, U.S.A., 2004.
9. *Indian estuaries*. S.Z. Qasim. Allied Publishers, New Delhi, India, 2003.
10. *Tsunami: An underrated hazard*. E. Bryant. Cambridge University Press, U.K., 2001.
11. *The Oceans, their Physics, Chemistry, and General Biology.* H.U. Sverdrup, M.W. Johnson, R.H. Fleming. URL: http://ark.cdlib.org/ark:/13030/kt167nb66r/ . A classic book on oceanography. Technical.

Books 1-6 are published by Butterworth-Heinemann, Oxford, U.K. in association with the Open University.

About NIO

The National Institute of Oceanography (NIO), a constituent laboratory of the Council of Scientific and Industrial Research (CSIR) (www.csir.res.in), was founded in 1966. It has its headquarters at Goa and regional centres at Mumbai, Kochi, and Visakhapatnam. NIO has a staff strength of about 600, of whom 190 are scientists. Amongst them are about 115 PhDs working on different aspects of ocean sciences.

NIO has laboratories for oceanographic research, a well-equipped library and a coastal research vessel, *CRV Sagar Sukti*, which is equipped for coastal studies. NIO's researchers study virtually all the topics discussed in this pocketbook. In many of these studies, NIO uses two other research vessels, ORV *Sagar Kanya* and FORV *Sagar Sampada*; these are owned by the Department of Ocean Development (DOD), Government of India. The DOD funds a number of research projects at NIO.

NIO provides services to industrial organisations to address issues that concern marine waters. It offers training in the collection and processing of oceanographic data and in analytical methods. NIO conducts courses on topics in ocean science and technology. A number of students work on their doctoral research under the guidance of NIO researchers. The institute welcomes students at various levels (high school onwards) to use NIO's facilities in their studies. To know more about NIO's research and researchers (including how to contact them), visit www.nio.org.

Contact us at :

National Institute of Oceanography
Dona Paula, Goa - 403 004, India

Phone : 91(0)832-2450 450   Fax : 91(0)832-2450 602/603
e-mail : ocean@nio.org   URL : http://www.nio.org

Meena Arts, 9326100627

NIO/P&R/2006