# CMFRI

## *Winter School on*

# Impact of Climate Change on Indian Marine Fisheries

## *Lecture Notes*

**Part 2**

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**(18.01.2008 - 07.02.2008)**

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## Physical Processes and wind-driven circulation in the Northern Indian Ocean

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The vast expanses of oceanic waters are continuously in motion and one wonders what makes ocean waters in a state of perpetual restlessness. Ocean currents are important as they redistribute heat, salt, nutrients, and biological organisms. As they transport heat from tropics to poles they are capable of influencing the climate. There are two physical processes that drive the ocean circulation and they are (1) transfer of momentum from wind to the ocean (tangential stress) and (2) convection driven by buoyancy changes due to heating and cooling or addition or removal of salt. The motion of the ocean due to the first process is known as the wind-driven circulation in which winds impart momentum to the ocean. The motion due to the second process is known as the thermohaline circulation in which the cooling in the Polar Regions result in loss of buoyancy and causes water to sink to deep ocean. The above separation of circulation into two components, though provides a conceptual simplification of circulation, is somewhat artificial in the real world. In this presentation we will focus on the wind-driven global ocean circulation and then try to understand the circulation of the northern Indian Ocean.

The transfer of energy from wind to ocean surface takes place through frictional coupling or surface wind stress which can be related to the wind velocity through the following relationship (known as a 'bulk formula'):

Wind-stress $\tau = P_{air}\, C_D W^2$

where pair is the density of air at the surface $C_D$ is a bulk transfer coefficient for momentum (typically $C_D = 1.5 \times 10^{-3}$), and W is the speed of the wind.

The wind blowing across the ocean surface moves its waters because of its frictional drag on the surface. If Earth did not rotate, frictional coupling between moving air and the ocean surface would push a thin layer of water in the same direction as the wind. This surface layer in turn would drag the layer beneath it, putting it into motion. This interaction would propagate downward through successive ocean layers, each moving forward at a slower speed than the layer above. However, because of the rotation of the Earth the shallow layer of surface water set in motion by the wind is deflected to the right of the wind direction in the Northern Hemisphere and to the left of the wind direction in the Southern Hemisphere. This deflection is known as the Coriolis effect. Except at the equator, where the Coriolis effect is zero, each layer of water put into motion by the layer above shifts direction because of Earth's rotation. The figure 1 illustrates this phenomenon of motion of water at different layer acted upon by the wind. The surface current moves at an angle $45^0$ to the right (left) direction of the wind in the northern (southern) hemisphere while the net transport of water through the entire wind-driven column is $90^0$ to the right (left) of the wind in the northern (southern) hemisphere. This is known as the Ekman spiral named after the Swedish physicist Walfrid Ekman who first described it mathematically in 1905. It may be kept in mind that the real ocean does not quite match the idealized conditions of the Ekman spiral. In shallow water if the depth is not sufficient for full spiral to develop the angle between the horizontal wind direction and surface water movements can be as small as $15^0$.

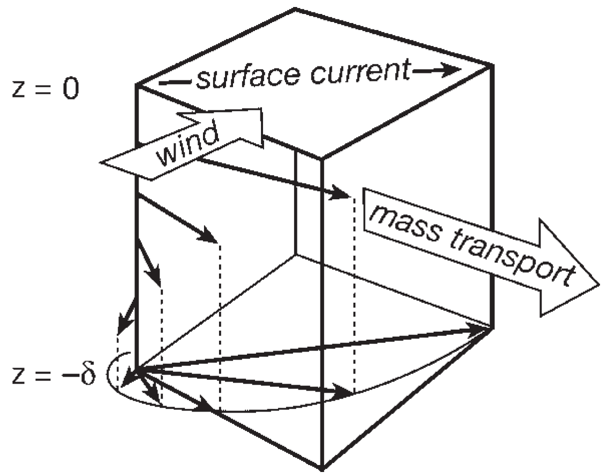


Figure 1. Schematic picture depicting the motion of upper layers of the ocean under the action of wind forcing and development of Ekman spiral.

The depth of the upper layer over which the above mentioned wind-driven currents will be active, known as the Ekman layer depth DE, is given by a simple relation

$$D_E = \frac{7.6 \times W}{(\text{Sin }\theta)^{1/2}}$$

Where ? is the latitude and W is the wind speed. Also there is a simple relationship between the wind speed and the speed of the surface currents (VO)

$$V_O = \frac{0.0127 \times W}{(\text{Sin }\theta)^{1/2}}$$

Thus, the surface distribution of winds is what drives the global ocean circulation and hence it is important understand it. The figure 2 below depicts the global distribution of the surface winds which are symmetrical about equator. Broadly, they are the tropical easterlies (trade winds) between equator and $30^{o}$, subtropical westerlies between $30^0$ to $60^0$, and Polar easterlies between $60^0$ to Poles.

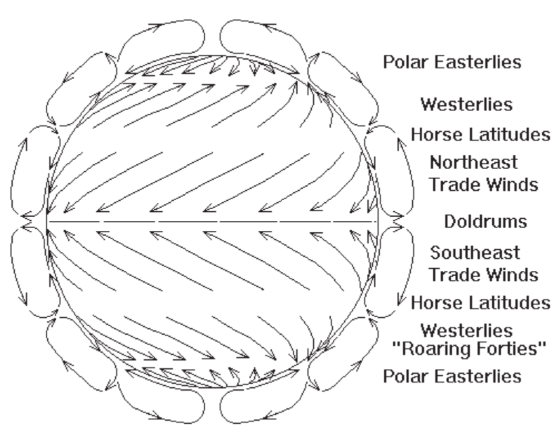


Figure 2. Global distribution of surface winds.

The northeasterly winds north of the equator drive the equator the north equatorial current (NEC) while the southeasterly winds south of the equator drives south equatorial current (SEC). These NEC and SEC when encounters land mass they turn and move along the coast forming the gyres. Thus, the large-scale winds set-up basin-scale ocean currents called gyres and they are sub-tropical gyre and sub-polar gyre as shown in figure 3.

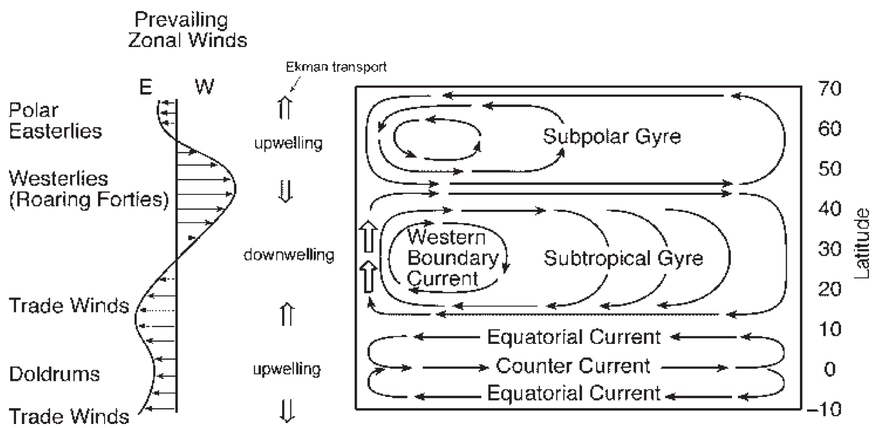


Figure 3. Schematic diagram showing the ocean gyres in relation to the prevailing zonal winds. The pattern of Ekman transport and regions of upwelling and downwelling are also shown.

The major gyres of the world ocean are shown in figure 4. The red colour indicates the warm current while blue colour indicates the cold currents. Thus, we see two gyre systems in the Pacific and Atlantic oceans, but in the Indian Ocean we have only one gyre and that is in the southern Indian Ocean.

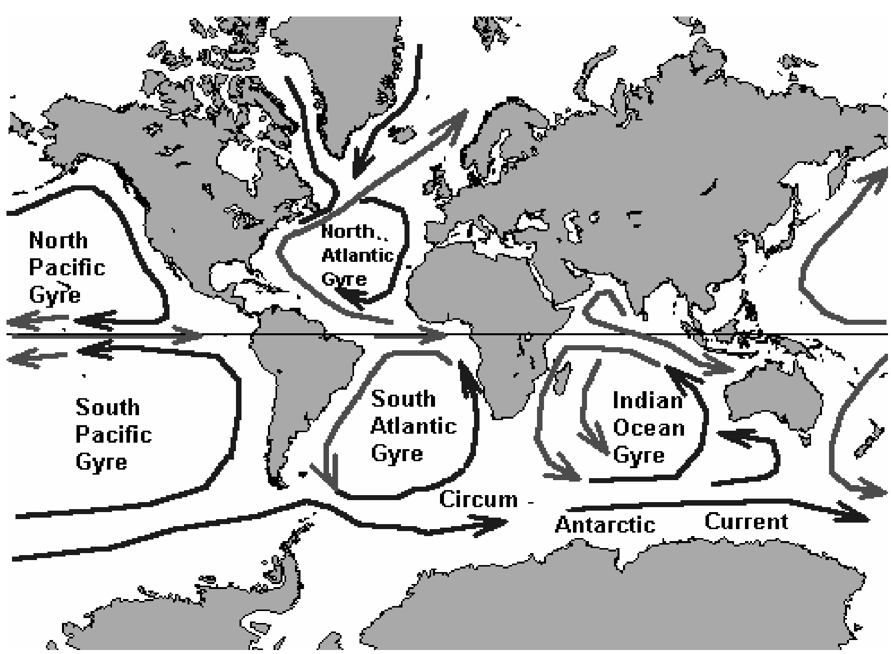


Figure 4. Major gyres of the world ocean.

The reason for this lies in the characteristics of the wind system. The wind system in the Pacific and Atlantic do not change within a year. Unlike this, the winds over the northern Indian Ocean (north of 10$^{O}$S) changes two times a year (semi-annually). In addition to this the northern Indian Ocean is land-locked in the north and Indian peninsula divides it into two basins – the Arabian Sea to the west and the Bay of Bengal to the east. During winter (northeast) monsoon (November-February) weak (~5m/s) northeast trade winds bring cool and dry continental air into the northern Indian Ocean and cool the upper ocean. In contrast during summer (southwest) monsoon (June-September) strong (~15m/s) southwest trade winds bring humid maritime air into the northern Indian Ocean. The winds during spring (March-May) and fall (October) intermonsoons are weak (~1-3m/s) and variable. Consistent with the wind reversal the surface circulation also undergoes seasonal changes in both the basins as depicted in figure 5.

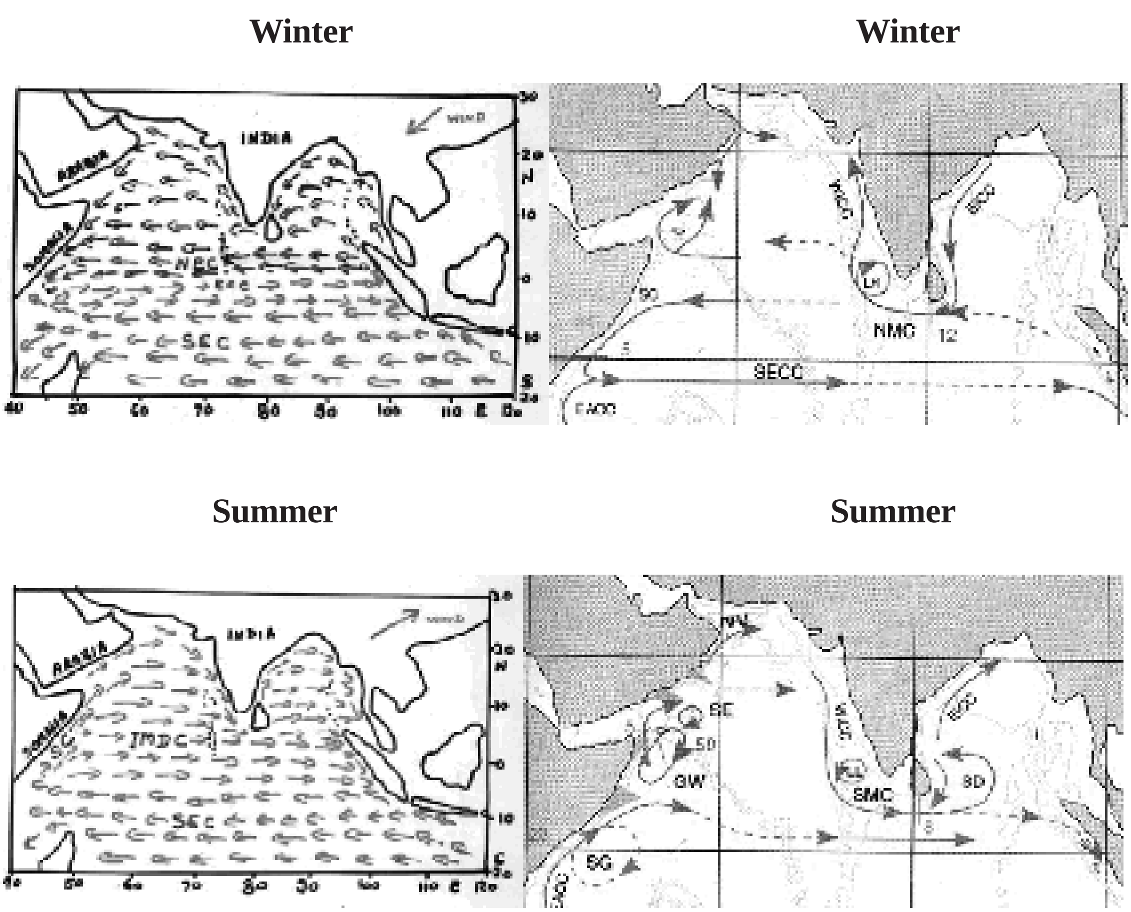


Figure 5. Schematic picture of North Indian Ocean circulation during winter (upper panels) and summer (lower panels).

It is during winter that the north Indian Ocean circulation most resembles the other world ocean circulation. During winter the NEC as well as SEC flows from east to west. Between NEC and SEC there is a zonal current moving from west to east known as the equatorial counter current (ECC). The NEC brings the low salinity waters from the eastern equatorial region as well as the Bay of Bengal into the western Indian Ocean. The circulation in the Bay of Bengal as well as Arabian Sea is cyclonic. In the Bay of Bengal, the East India Coastal Current (EICC) flows southward along the east coast of India and transports warm (~29$^{o}$C) and low salinity waters (~ 34 psu) from the Bay of Bengal into

the Arabian Sea. In the Arabian Sea, the West India Coastal Current (WICC) transports the warm and low salinity waters fed by the EICC along the west coast of India towards the north. The WICC flows against the prevailing northeasterly winds in the Arabian Sea.

At this time of the year, due to reduced incoming solar radiation, the sea surface temperature (SST) of both the basins, the Arabian Sea and the Bay of Bengal, fall below

25$^{o}$C. In addition, the cold and dry continental air brought by the northeast trade winds further reduces the SST due to evaporative cooling. In the Arabian Sea, as the ambient salinity is in excess of 36 psu, the winter cooling increases the density of the surface waters above the critical value and drives convection. Thus, the winter cooling and convection in the Arabian Sea leads to the formation of Arabian Sea high salinity water mass (ASHSW). In addition to this, the convective mixing also brings nutrients from the subsurface waters to the upper layers and triggers winter phytoplankton bloom. However, in the Bay of Bengal though the winter cooling occurs, the low salinity ambient waters do to support the winter convection.

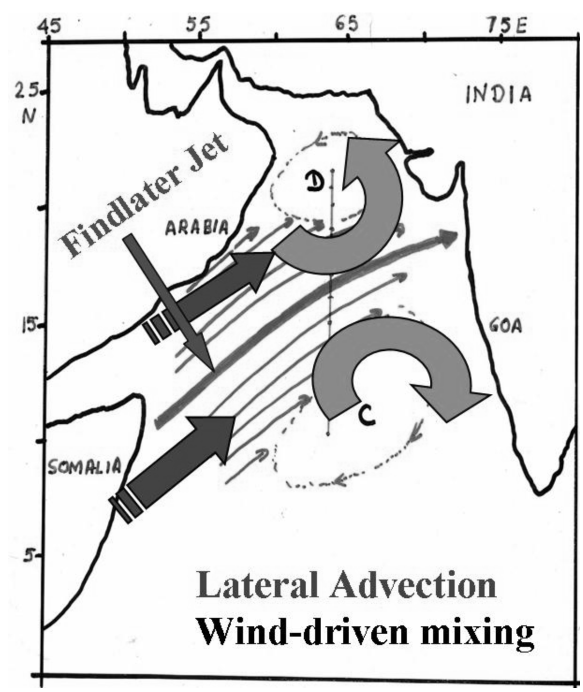


Figure 6. Schematic picture showing the axis of the Findlater Jet. Note the cyclonic (anti-cyclonic) wind-stress curl and the divergence (convergence) of surface waters north (south) of the Findlater Jet axis.

In summer monsoon the NEC in the northern Indian Ocean is replaced by the strong Indian Monsoon Current (IMC) which merges with the ECC and flows from the western Indian Ocean towards the east. This current carries the high salinity Arabian Sea waters into the eastern parts. The circulation in both the basins, the Arabian Sea and the Bay of Bengal, now changes to anti-cyclonic. Along the western Arabian Sea the strong western boundary current, the Somali current, moves north ward. Along the west coast of India, the WICC changes its direction and now flows towards south. The currents in the open Arabian Sea is zonal and eastward. Strong upwelling takes place along the coast of Somalia, Arabia and southern part of the west coast of India. In addition to the coastal upwelling, Open Ocean upwelling also takes place in the Arabian Sea. The Findlater Jet which is a strong and organized flow of wind that extends from the horn of Africa to the coast of Gujarat in India becomes active during summer as depicted in figure 6. North of the Findlater Jet, the cyclonic wind-stress curl drives divergence of water and upwelling, while in the south the anti-cyclonic curl drives convergence of surface water and downwelling. Both the open ocean as well as coastal upwelling has implications to biological productivity and biogeochemistry.

The IMC brings high salinity Arabian Sea waters into the Bay of Bengal during summer. At this time of the year the EICC along the east coast of India flows towards north. The circulation in the Bay of Bengal is characterized by several eddies, both cyclonic and anti-cyclonic. The cyclonic eddies that occur in the Bay of Bengal are capable of enhancing the biological productivity through upward Ekman-pumping of nutrients to the euphotic zone. Unlike in the Arabian Sea no major upwelling regions are noticed in the Bay of Bengal during summer except few places very close to the shore. However, east of Sri Lanka, the cyclonic wind-stress curl and associated Ekman-pumping moves the thermocline close to the sea surface and leads to the formation of Sri Lankan dome.

During the spring Intermonsoon (March-May) and fall Intermonsoon (October) the winds are weak and variable. Accordingly, the currents in the northern Indian Ocean also are weak. However, in the Bay of Bengal, during spring Intermonsoon a comparatively strong western boundary current (northward flowing EICC) develops and flows northwards along the east coast of India. This current cannot be explained solely based on wind-forcing and recent studies using circulation model attribute this to a combination of local and remote forcing.

In the equatorial Indian Ocean, during the spring and fall intermonsoons a strong narrow flow of water, known as Wyrtki Jet, occurs from west to east.

**Acknowledgements**

Figures 1 to 4 and part of the figure 5 (right panels of top and bottom) are taken from internet resources.