

Variability of Surface Circulation of the Indian Ocean

V.S.N. Murty

National Institute of Oceanography, Dona Paula, Goa – 403 004



Dr. Vadlamani Surya Narayana Murty is an M.Sc. (1979) in the interdisciplinary Marine Sciences with Physical oceanography as a special subject and a Ph.D. from the Andhra University. Soon after his M.Sc., he joined N.I.O., Goa as Junior Scientific Assistant and rose to become Scientist F. His main interests have been large scale and meso scale circulation and air-sea interaction. He conducted Monsoon Experiments in the Bay of Bengal (BOBMEX) and Arabian Sea (ARMEX) and at the monsoon trough boundary layer (MONTBLEX). Presently, he is leading the equatorial Indian Ocean studies as part of Ocean Observing System (OOS) programme of the MoES and Equatorial Indian Ocean processes on the Climate Variability (EIO-CLIVAR) of the NIO. Cooperating at the global level as is necessary in oceanographic studies, he

has been responsible and takes leading role in collaborations with Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Pacific Marine Environmental Laboratory (PMEL), National Oceanic and Atmospheric Administration (NOAA) and NSFC (China). Dr. Murty has over 45 publications in international and national journals. He is a Member of the International Time-series Science Team and the CLIVAR./GOOS Indian Ocean Panel (IOP). Dr. Murty is a Life Member to the Indian Meteorological Society, New Delhi.

At the forthcoming 'Brain Storming Session on Carbon Sequestration', I have been given the topic on 'How to benefit most from ocean circulation?', to address the regional and global importance and the challenging scientific issue of Carbon Sequestration. In my presentation, I will highlight the 'variability of surface circulation in the Indian Ocean' what we have known so far and how best this knowledge could be useful to identify the suitable oceanic region to plan and set up a desired experiment. I will also put forward the already initiated observational plan with moored buoy array in the Indian Ocean for climate studies under the Indian Ocean Observing System (IndOOS) (Fig. 1), with a possibility of using this moored buoy array to measure the net transfer of carbon, through international collaborations. The schematic experimental plans for Carbon Sequestration proposed by the Inter-governmental Panel for Climate Change (IPCC) will be used for discussion at the meeting.

The tropical waters receive enormous amount of heat energy from the Sun and give birth to ocean currents that carry heat along their path from the tropical areas to polar region. The tropics thus act as the heat engine in Earth's Climate machine. Besides the exchange of heat back and forth between ocean and atmosphere, huge amounts of carbon dioxide dissolves into the ocean from the atmosphere.

It is now realized that the Indian Ocean Sea Surface Temperature (SST) shows warming trend since 1970's (Fig. 2), the fact that has been attributed to the global warming. This warming trend is also observed in many global models. It is believed that global warming is resulting from the accumulation of greenhouse gasses such as the Carbon dioxide in the atmosphere. While both the Antarctic and the Arctic regions absorb the carbon dioxide (CO₂) from the atmosphere, the entire equatorial Pacific acts as the source for the CO₂ to the overlying atmosphere. In the Indian Ocean, however, the western Arabian Sea particularly, the Oman coast, also acts as the source for the CO₂. When CO₂ sinks out of the air and dissolves in the ocean, it curtails greenhouse warming. But, the ocean circulation

constantly brings in CO₂ rich deep water to the surface, where it gives away the gas back into the air. Besides dissolving into the ocean water, CO₂ also enters the ocean when tiny plants and animals use the carbon to grow. As the plants and animals die, the carbon in their bodies sinks to the sea floor, where it may lie for centuries. Measurements of plankton growth at a number of stations are a crucial point to assess the prospects of commercial fisheries. The surface warming of the IO in the last few decades has also raised some questions about the response of the IO to anthropogenic activities and its impact on global climate variability.

The Indian Ocean has a unique character of lying within the tropics to the north and the seasonally reversing monsoons – the Southwest monsoon (June – September) and Northeast monsoon (November – March). The annual mean surface winds are from the west in the equatorial region and leads to the absence of equatorial upwelling, compared to that prevails in the equatorial Pacific and Atlantic. Since the northern Indian Ocean is not connected to the polar region, significant ventilation is absent followed by a lack of bottom water mass formation in the north. However, the northwestern Indian Ocean is connected to two marginal seas – the Persian Gulf and the Red Sea – from which very high salinity water enters the Arabian Sea in the depth ranges of 200-300 m and 500- 800 m respectively and spread out over longer distances in the interior of the Indian Ocean. The vertical mixing between the Red Sea water and the Bottom Water leads to the formation of North Indian Deep Water. The Persian Gulf Water and the Red Sea Water together form the high salinity North Indian Intermediate Water.

In the north Indian Ocean, the Arabian Sea and Bay of Bengal are located in the same latitudinal belt and are subjected to the similar reversing monsoon forcing, but experience drastically different freshwater fluxes. While the Arabian Sea experiences net evaporation, the Bay of Bengal experiences the net precipitation augmented by voluminous influx of riverine waters. This unique physical set up makes the Bay of Bengal waters are of low saline and the Arabian Sea waters are of high salinity. This contrasting difference further makes the Bay of Bengal waters more stratified and warmer compared to the Arabian Sea, with atmospheric convection dominating over the former oceanic region. However, winter convection is dominant in the northern Arabian Sea during boreal winter, and intense coastal upwelling is dominant off Somalia, Oman and southwest coast of India during the southwest monsoon period. Coastal upwelling from shallow depths in the Bay of Bengal is limited to the southern part of the east coast of India during southwest monsoon. The meso-scale cyclonic eddies are the potential source of the open-ocean upwelling for the nutrient-enrichment in the euphotic layer.

The surface circulation set up by the monsoonal winds is also unique to the northern Indian Ocean, while the surface circulation pattern in the southern Indian Ocean is a near-permanent currents system. In the north Indian Ocean, the wind driven circulation is characterized with the Somali Current along the Somali coast and a single large anticyclonic eddy (Great Whirl) during the southwest monsoon. In the interior of the Arabian Sea, the surface circulation is towards southeast feeding the southwest monsoon current in the equatorial region. Along the coast of India, the West India Coastal Current (WICC) on the west and East India Coastal Current (EICC) on the east are the dominant coastal currents whose flow direction reverses with season. The equatorial region is dominated by the semi-annual occurrence of equatorial jets during the monsoon transition periods (April – May and October – November). Besides the seasonal variation, there exists considerable intraseasonal and interannual variability in the wind forcing resulting in similar variability in the currents. The well-documented 10-20 day period intraseasonal variability in the observed and model currents is associated with the Mixed Rossby-Gravity Waves. These waves

generate alternating upwelling and sinking on either side of the equator and may have an impact on the biogeochemistry of the equatorial Indian Ocean. The Indian Ocean Dipole/zonal mode (IODZM) is the known dominant mode for the observed interannual variability in the tropical Indian Ocean. The IODZM has far reaching impacts on the regional climate. The IODZM, with the near-biennial mode variability, is characterized with lower SST off Sumatra coast during October – December. The large drop in SST off Sumatra coast is the result of air-sea interaction and the oceanic process of upwelling. The impact of this climatic event on the biogeochemistry of eastern equatorial Indian Ocean is yet to be studied.

The monsoon regime extends south of the equator up to 10°S. The reversing monsoons generate wind stress curl and the associated Ekman pumping in the southern tropical Indian Ocean leads to the 'doming of isotherms', known as the thermocline ridge between 5°S and 8°S, slightly north/northeast of the Madagascar. This thermocline ridge has the strongest impact on the SST, mixed layer depth and biogeochemical characteristics in the region.

In the Indian Ocean, the wind driven shallow meridional overturning cells have been identified. These overturning cells and mixed layer thickness variability affect the biological activity. The overturning circulation cells supply the subsurface, nutrient-rich water that surfaces in upwelling regions. The mixed layer thickness variation influences the nutrient supply in the euphotic zone. The shallow overturning cells consist of downwelling (subduction) at the southern mid-latitudes, northward flow within the thermocline, near-surface southward flow, and upwelling in the tropics. The cross equatorial cell (CEC) is closed by upwelling off Somalia, Oman, and the southern tip of India. The sub-tropical Cell (STC) is closed by upwelling from 5°-10°S in the western and central ocean. A third cell resembles the Atlantic and Pacific cells in that it is closed by upwelling in the eastern, near-equatorial ocean off Sumatra/Java, however, it is typically weaker than CEC and STC, attaining appreciable amplitudes only during the IODZM events. The biological impact of the mixed layer thickness is apparent in the Arabian Sea, where the mixed layer is thin (~10 m) during intermonsoon periods and very thick (~100 m or more) during the monsoons.

South of 15°S, the surface circulation is characterized by the subtropical anticyclonic gyre with an eastward flowing Antarctic Circumpolar Current on the south (40°S) and the westward flowing South Equatorial Current on the north. A subduction zone is identified in the southeastern Indian Ocean at the outer edge of the subtropical anticyclonic gyre. The air-sea heat exchange is negative in the subduction zone (Fig. 4). Under its influence the subtropical high salinity water sinks off western Australia and spreads equatorward to form the subtropical high salinity watermass. This high salinity watermass can be identified at 10°S in the 100-200 m depth range. Outcropping of isopycnals (constant density surfaces) is noticed south (40°S) of the Antarctic Circumpolar Current. At these higher southern latitudes, cold, less saline subantarctic waters sink to deeper depths to form the intermediate waters and mode waters. The Antarctic Intermediate Water (AIW), characterized by low salinity core, is one example and can be traced up to the western Arabian Sea. Mode waters, with a characteristic pycnostad or low potential vorticity, occur above the intermediate waters and their density progressively increases in the eastward direction.

Researchers identified the Indian Central Water (ICW) and Subantarctic Mode Water (SAMW) as the two major sources for the ventilation of the permanent thermocline in the Indian Ocean. ICW is formed by subduction in the region of negative wind stress curl in the southwestern Indian Ocean (30-40°S). The SAMW is formed by convective overturning in winter at the Subantarctic Front in the region southwest of the Australia.

The revised estimate of the strength of meridional overturning circulation at 32°S is $11.9 \pm 2.7 \times 10^9$ kgs⁻¹. This transport is composed of northward flowing deep waters returning south at shallower levels. The bulk of the northward flowing bottom and lower deep water is converted to intermediate and upper deep water, which exits the basin as southward flow across 32°S. A one-third of the northward flowing deep waters upwells into the thermocline.

The oceanic overturning circulation has a central role in the Earth's climate system and in biogeochemical cycling, as it transports heat, carbon and nutrients around the globe and regulates their storage in the deep ocean. Mixing processes in the Antarctic Circumpolar Current are key to this circulation, because they control the rate at which water sinking at high latitudes returns to the surface in the Southern Ocean.

The characteristics of the deep and bottom waters of the Indian Ocean, when illustrated on potential-density anomaly surfaces, indicate that the waters enter from both the Atlantic and Pacific Oceans. The paths of spreading are constrained by the complex topography, and characteristics are altered by exchange with the overlying and underlying water and with the sediments, especially in the northern Indian Ocean. Contact with the sediments increases the silica content of the bottom water in the Southern Ocean. In the northern Indian Ocean the sediments alter the silica of the water at the bottom and, together with enhanced salinity from diffusion of saline overflows from the marginal seas above, imprint unique markers to the deep water that flows back to the south. At mid-depths the series of ridges between Madagascar and Australia confine the flow to a series of gyres that carry characteristics from the circumpolar current equatorward and the northern Indian Ocean characteristics southward.

Studies on the large scale Indian Ocean circulation from a global hydrographic inverse geostrophic box model with a focus on the meridional overturning circulation (MOC) reveals a deep inflow into the Indian Basin of 11 ± 4 Sv, which is in the lower range of previous estimates, but consistent with conservation requirements and the global data set. The Indonesian Throughflow (ITF) is estimated at 15 ± 5 Sv.

The Indo-Pacific model run simulated 15 year mean annual surface circulation in the tropical Indian Ocean largely identifies the features of surface circulation during the southwest monsoon (boreal summer) north of the equator and during boreal winter season south of the equator. North of the equator, the identified features are the 1) poleward flowing Somali current and the associated anticyclonic eddy (Great Whirl) circulation, 2) poleward flowing current along the Oman coast, 3) a southeasterly flow in the interior Arabian Sea splitting into westward flow and eastward flow (Fig. 5). The westward flow feeds the Somali eddy circulation and the eastward flow forms the monsoon current along the equator, 4) a large cyclonic eddy off Sri Lanka feeding an equatorward current, 5) a large anticyclonic eddy between 12°N and 18°N feeding an equatorward flow in the eastern Bay. South of the equator, the eastward flowing South Equatorial Counter Current (SECC) between 4° S and 8°S joining the poleward coastal current off Indonesia/Java, the westward flowing South Equatorial Current (SEC) between 10°S and 15°S. The SEC appears to broaden towards west and feeds the poleward flowing Madagascar current and the East African Coastal Current.

The model simulated 15 year mean Sea Surface Temperature (SST) also shows the largest impact of the southwest monsoon wind forcing and wind driven circulation on the SST. A large warm pool is confined to the equatorial region and lower SSTs in the Somali and Oman upwelling regions. South of equator, SST decreases towards southern latitudes. Lowest SST is located in the subduction zone of the southeastern Indian Ocean. The

model simulated 15 year mean Sea Surface Salinity shows high salinity waters in the Arabian Sea and very low salinity waters in the Bay of Bengal. Between 5°N and 20°S, the surface salinity decreases eastward under the influence of the Indonesian Throughflow into the Indian Ocean. In the southeastern Indian Ocean, the sea surface salinity is very high in the subduction zone.

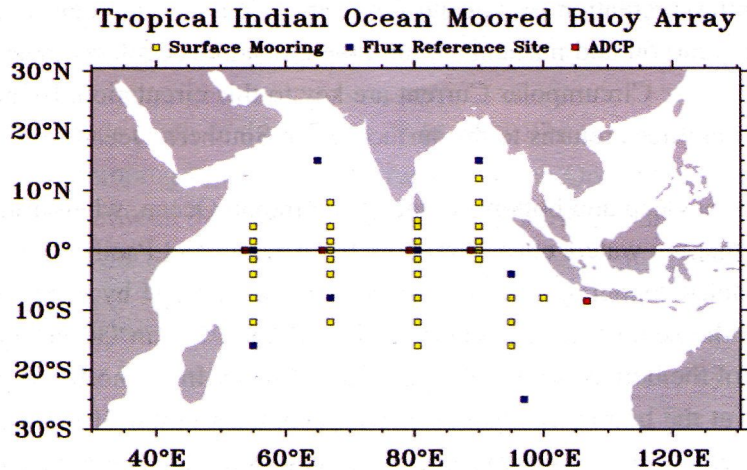


Figure 1: Draft plan for an Indian Ocean moored buoy array as part of a sustained and integrated ocean observing system. [Courtesy: <http://www.oceansites.org>]

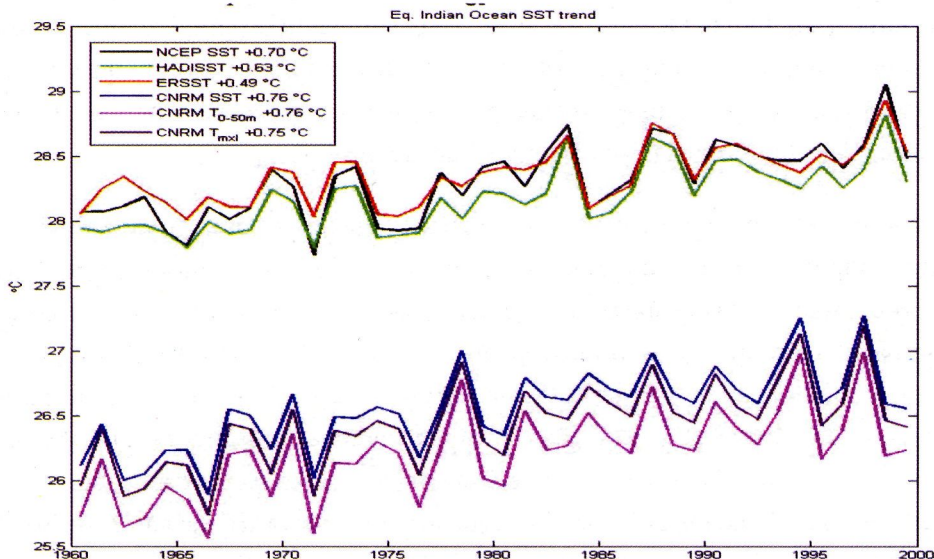


Figure 2. SST time series and trend values averaged over the equatorial Indian Ocean (9°S-6°N) for observations and CNRM model. [Courtesy : Mr. Gael Alory, CSIRO, Hobart, Australia]

Modelling of the Indian Ocean biogeochemistry and observations in the Arabian Sea during US JGOFS point out the spatial gradients and temporal variation in iron limitation patterns and the Arabian Sea ecosystem is highly sensitive to the spatio-temporal distribution of aeolian iron deposition. A 10% reduction in basinwide export from the euphotic zone is indicated during the Indian Ocean Dipole Zonal Mode events in 1990s. Largest reductions up to 20% occurred in the western half of the equatorial and southern tropical region (the Thermocline ridge). Therefore,

a pertinent question to be thought of by the participants is that whether the iron limitation is a factor for primary productivity and export production in the Arabian Sea during southwest monsoon. May be that Arabian Sea and Bay of Bengal are not as productive as they can be! An observational experiment is necessary for precise measurements of the biogeochemical parameters and carbon fluxes.

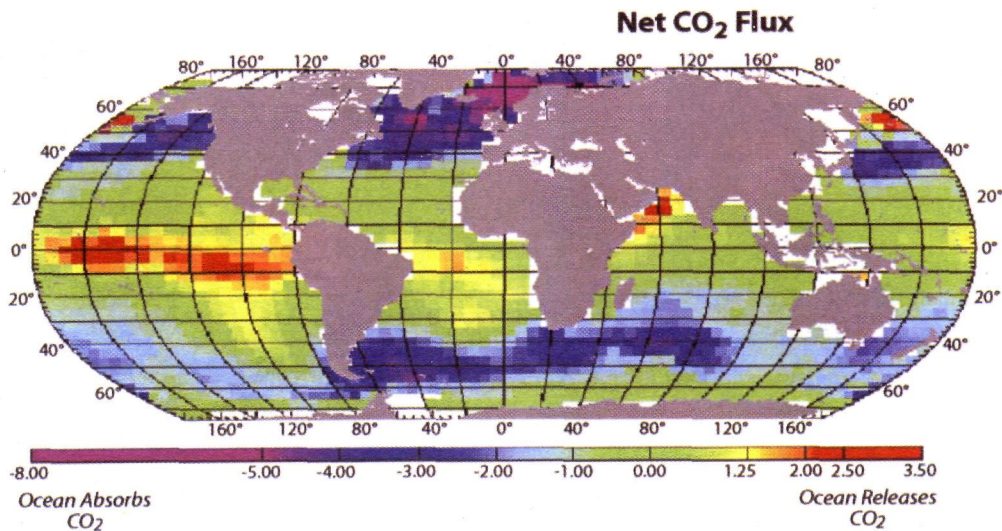


Figure 3. Distribution of net CO₂ in the global ocean. In this map, blue indicates strong absorption of CO₂ from the air; red areas show where the ocean puts CO₂ back into the atmosphere. [Courtesy: <http://www.oceansites.org>]

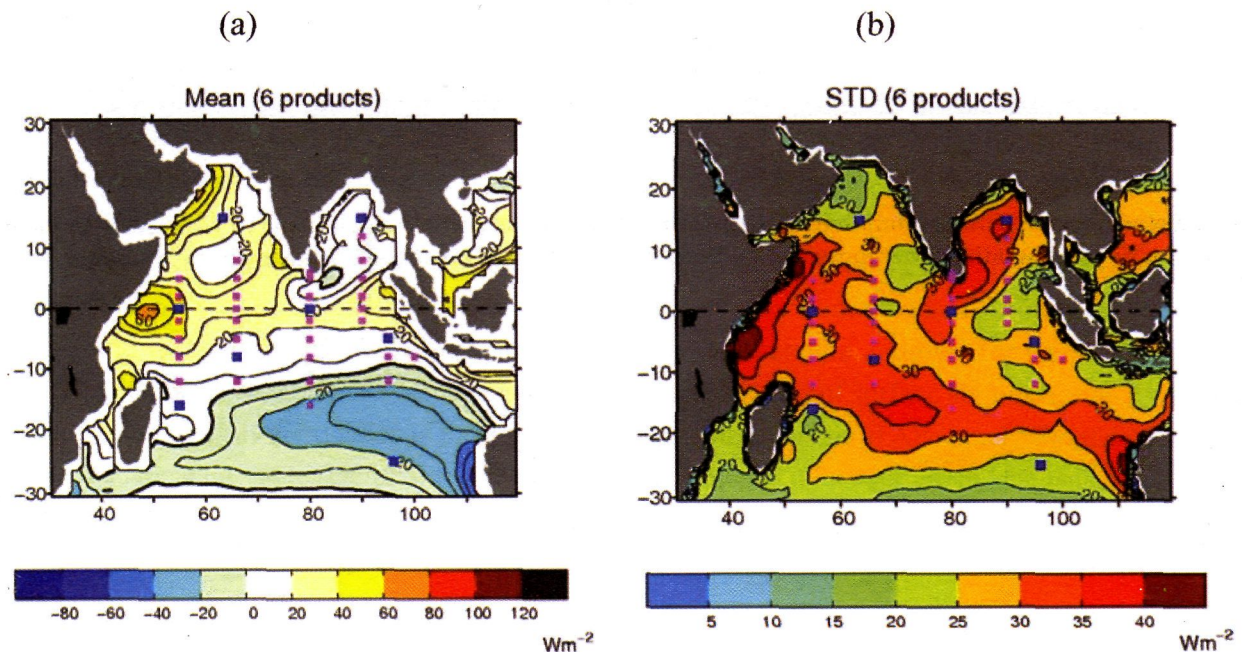


Figure 4: (a) Mean and (b) standard deviation of record length means from an ensemble of six surface heat flux products in the tropical Indian Ocean. The six products are OFA+ISSCP (WHOI), NCEP/NCAR reanalysis (NCEP1), NCEP/DOE reanalysis (NCEP2), ECMWF operational analysis, ECMWF reanalysis (ERA-40), and Southampton Oceanography Centre (SOC) analysis. (Courtesy of L. Yu, WHOI, US). Subduction Zone (25°S, 97°E): Located in the southeast subtropical Indian Ocean where mixed layer water masses are subducted into the subtropical pycnocline. This is also a region of large mean oceanic heat loss to the atmosphere.

15 year mean annual surface circulation in the Indian Ocean

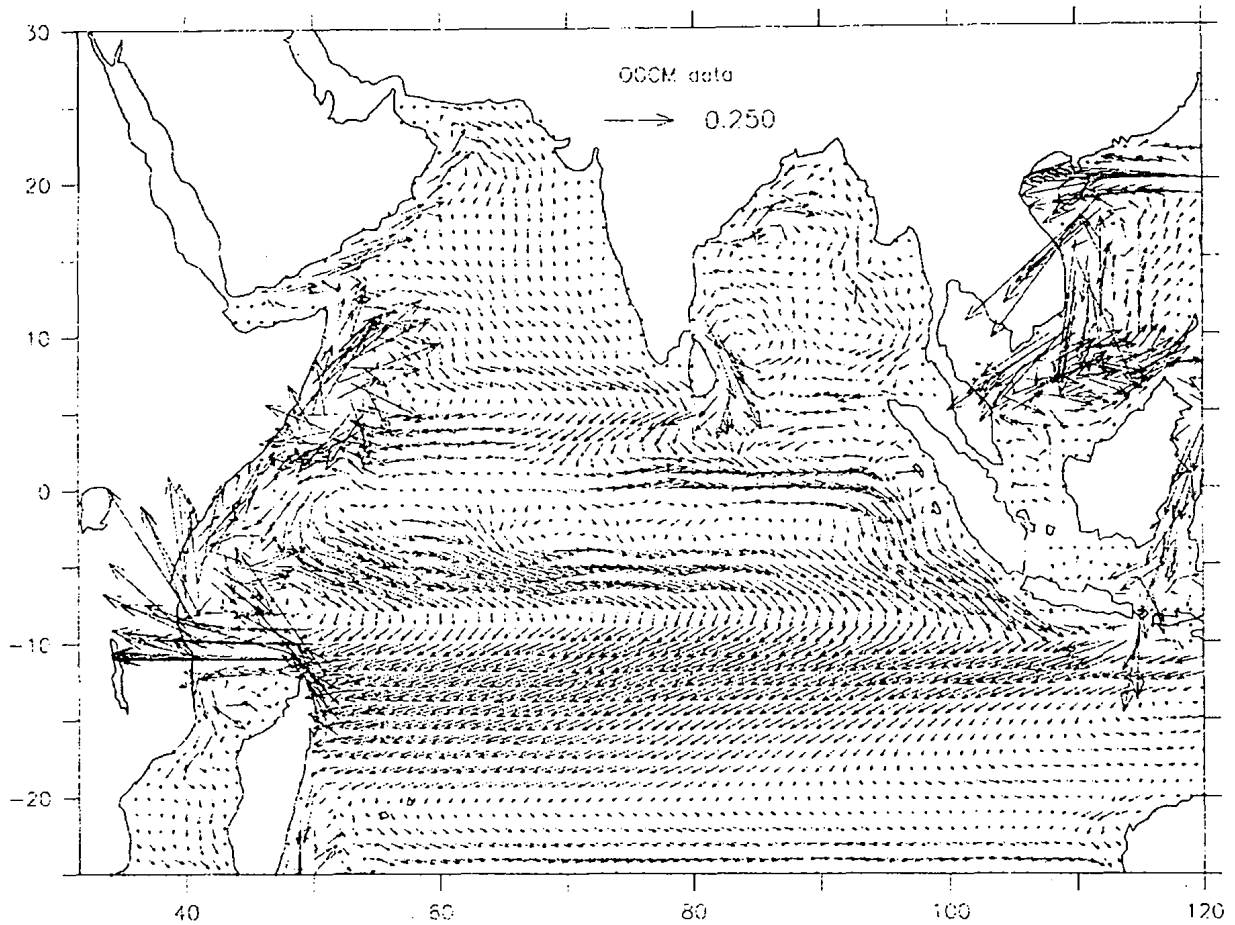


Figure 5. Ocean General Circulation Model (OGCM) simulated annual surface circulation (15 year mean) in the Indian Ocean. Model simulations were provided by Prof. Raghu Murtugudde, ESSIC, University of Maryland, US.