

### Summary and Conclusions

The 3-D circulation of Indian Ocean is very complex and is controlled by both local and remote forcings because of the peculiar geographical and climatological setting. Identification of these forcing functions that control the large scale variability of circulation and numerical simulation of highly time-dependent 3-D circulation should be the objective of any modeling study. To determine the physical and dynamical mechanism underlying the variability of circulation of the Indian Ocean, a variety of ocean circulation models such as diagnostic, semi-diagnostic and prognostic types should be developed for the Indian Ocean area. 3-D circulation models that could be run in diagnostic, semi-diagnostic and prognostic models are the best for the study of circulation in the Indian Ocean. There have been many studies, both observational and modeling, on the circulation and watermass characteristics of the tropical Indian Ocean. Detailed literature survey shows that practically all studies were focused on the theoretical or modeling aspects of a particular current or on a particular basin of the Indian Ocean such as Arabian Sea or Bay of Bengal. These existing models mainly deal with upper layer circulation, and there is hardly any information on the circulation in the intermediate, deep and bottom waters.

One of the main objectives of this thesis is to adapt and configure a fully non-linear, primitive equation type, sigma co-ordinate, 3-dimensional circulation model to the entire Indian Ocean area which can be run on diagnostic, semi-diagnostic and prognostic modes. Such a model could identify both local and remote forcings and also could simulate the highly time-varying circulation of the Indian Ocean.

The thesis basically contains six chapters including the introductory chapter. In the introductory chapter of the thesis, boundaries of Indian Ocean and some of the unique features of Indian Ocean and its seasonal

reversing currents because of its peculiar geological, geographical and climatic settings are presented. This chapter also contains information on the various observational and mathematical modeling studies conducted since last five decades.

In chapter-II, a detailed description of the state of art 3-dimensional, sigma co-ordinate model that has been adapted to the tropical Indian Ocean is given. The model description includes details such as boundary and initial conditions, numerical solution procedure and some unique features and parameters of the model including the forcing parameters such as wind field, heat and fresh water fluxes.

Chapter-III addresses the problem of understanding the relative roles of steady local forcing of wind and internal density field in driving the circulation of the Indian Ocean by running the model in semi-diagnostic mode. The primitive equation type, sigma co-ordinate, 3-dimensional model developed at the Institute of Numerical Mathematics, Russia, has been adapted and configured to the Indian Ocean area between the latitudes  $36^{\circ}\text{S}$  -  $29.5^{\circ}\text{N}$  and longitudes  $22^{\circ}\text{E}$  –  $142^{\circ}\text{E}$  . The peculiarities of sigma co-ordinate model in semi-diagnostic mode, forcing parameters of the model, results of calculation of steady state currents and circulation were presented. The spatial variability of mean currents in the upper layers of Arabian Sea, Bay of Bengal, equatorial and southern tropical Indian Ocean were presented under separate headings.

#### **(i) Circulation in the Arabian Sea**

Model calculations for the month of January showed that the westward flowing North Equatorial Current (North East Monsoon Current) was present in the latitudinal belt ( $2^{\circ}\text{N}$  –  $6^{\circ}\text{N}$  ), and it impinged on the Somali coast with one branch flowing towards north-northeast and the other branch flowing southwestwards along the coast as Somali Current (SC). The model reproduced the northward flowing East African Coastal Current

(EACC), the West India Coastal Current (WICC) present during the winter season. All the major surface currents were discernable at 50m. depth also, but the strength of the current was considerably reduced.

Model calculations on mean currents in the upper layers of Arabian Sea for the month of April showed that the westward flowing Northeast Monsoon Current (NMC) was present in the latitudinal belt 5°N -10°N, its intensity was considerably reduced as compared to January month. Model reproduced a weak equatorward flowing WICC all along the west coast of India in the upper 50m. water column.

Model calculation for the month of July showed the presence of northeastward flowing Somali Current, the Southern Gyre (SG) and the Great Whirl (GW). The Somali Current was found to be an extension of the EACC which flows northward across the equator. It was found that the Somali Current system was mainly forced by the alongshore wind associated with the Findlater Jet and the internal density field. The South West Monsoon Current (SMC) was found to be primarily wind-driven, although the influence of density gradient on its strength and direction could be seen to a certain extent. The model calculation showed the presence of WICC along the west coast of India during July.

## **(ii) Circulation in the Bay of Bengal**

Model calculations for the month of January showed that large anticyclonic gyre was formed in the entire Bay of Bengal north of 8°N. The East India Coastal Current (EICC) associated with the wind-driven anticyclonic gyre in the Bay of Bengal flowed poleward all along the east coast of India. It was inferred that the combined effect of local wind forcing and thermal structure are responsible for the observed circulation in the Bay of Bengal during January. The EICC flowed poleward along the east coast of India during April and the model computed EICC features fully match with the

ship-drift data. Both the thermohaline forcing and wind stress fields are responsible for the formation of poleward flowing EICC during April.

During July, the EICC does not flow poleward as expected along the east coast of India. Model results showed that there was a northward flow north of 10°N and southward flow south of it. The probable reasons for the northward surface EICC north of 10°N and southward EICC south of it can be explained in terms of the prevailing wind stress curl pattern. During summer, the wind stress curl is cyclonic in the south western part of Bay of Bengal and this cyclonic curl could drive a southward flow south of 10°N. Signatures of the poleward flowing EICC could be seen at 50m. and 150m. depths. During the month of October, a weak southward flowing EICC was reproduced by the semi-diagnostic model very near to the coastline. Small cyclonic type of circulation cells were observed in the western Bay of Bengal, while southerly flows were observed in the central Bay of Bengal.

### **(iii) Mean currents in the equatorial and southern tropical Indian Ocean**

The semi-diagnostic model calculations for the month of January showed that the South Equatorial Current (SEC) flowed primarily west with a magnitude of approximately 30 cm/s between 10°S and 20°S. The computed results fully agree with the ship drift data compiled by Cutler and Swallow (1984). The equatorial circulation at 150m. depth and 300 m. depth was dominated by the presence of a strong eastward flowing Equatorial Under Current (EUC) between 5°N and 5°S.

During the month of April, the Wyrтки Jet could be traced across the equatorial regions between 2°S and 2°N and its magnitude varied between 20 cm/s and 30 cm/s. All the permanent currents in the southern tropical Indian Ocean such as SEC, EACC, NEMC and SEMC during April were reproduced by the model.

One important finding during the month of August was the appearance of EUC that flowed eastward in the equatorial belt at 150m. and 300m. depths. The semi-diagnostic model has been successful in reproducing all the permanent current systems in the Indian Ocean including the undercurrents over the entire annual cycle.

Chapter-IV deals with the simulation of the climatic currents in the Indian Ocean. Better understanding of the ocean dynamics can be achieved only by using state-of-art simulation models. The time-varying circulation of the Indian Ocean is controlled by both the local forcing and remote forcing by long waves. The main goal of this chapter is to study the large scale, time dependent, 3-dimensional circulation of the Indian Ocean and to understand the dynamical mechanism responsible for the observed circulation. Like semi-diagnostic model, the simulation model has been adapted and configured to the Indian Ocean area between the latitudinal belt 36°S - 29.5°N and longitude belt 22°E – 142°E with a resolution of 1° x 0.5° in longitude and latitude directions respectively. The model was integrated forward with a time step of 3 hours for 10 years using surface climatological forcing which were applied with cyclic condition in time. The solution attained semi-stationary by the 10th year of simulation. The 10th year simulation results were compared with existing observations and with results from SODA (Simple Ocean Data Assimilation).

The circulation obtained from the simulation model are in agreement with the SODA results and also with available observations. All the current systems in the Indian Ocean were well reproduced in the model along with their under currents and gyres. The volume transport of major currents were computed and compared with the transport estimates available in the literature. The volume transport was found to be comparable with the existing estimates for different currents. The dynamics of each of the current systems were explained by comparing the simulation model results with the semi-diagnostic model results. Thus the role of local verses

remote forcing on the computed circulation of the Indian Ocean has been brought out in this chapter.

Results of circulation models vary depending on its dynamics, spatial resolution, numerical scheme, the parameterization of physical processes and the forcing parameters of which the later, forcing parameters have significant effect on the model results. Wind stress is the main mechanical forcing term that influences significantly the upper layer circulation. One sensitivity experiment was carried out by forcing the simulation model with the winds derived from the Quikscat Scatterometer. Results of the response of the tropical Indian Ocean to Quikscat winds and NCEP/NCAR wind field are presented in chapter-V.

Large scale zonal wind stress difference was observed between the two wind data sets over the equatorial Indian Ocean. The monthly mean response of the model to two wind data sets were compared for mass transport stream function, and surface velocity for the month of January, July, April and October representing the four seasons. The model driven with Quikscat winds reproduced equatorial circulation features more realistically than the NCEP forcing. The current system in the equatorial Indian Ocean was intensified when the model was driven with Quikscat wind forcing. The Equatorial Jets (EJ's) of the Indian Ocean were strengthened by about 20 cm/s during the month of April and October when the model was driven with Quikscat wind forcing. The sensitivity experiment revealed that the surface circulation was mainly controlled by wind stress forcing and hence the thermodynamic forcing play minor role at the upper levels.

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