CHAPTER - 5

STUDY ON VARIABILITY OF D20 IN THE INDIAN OCEAN

5.1 Introduction

Ocean General Circulation Models (OGCMs) are useful to determine the thermodynamic characteristics of the ocean. In chapter 2, model in use and data used in forcing the model as well as for validating the model outputs were described. In the subsequent chapters, usefulness of altimeter data and scatterometer data in modeling the depth of 20 °C isotherm (D20) were assessed. Impact of altimeter data was studied by assimilating this information in the ocean model using Cooper-Haines scheme (Cooper and Haines, 1996). One of the main objectives of the present work was to study the impact of scatterometer wind data on D20. It was found that surface wind stress is one of the most important surface boundary forcings for accurately simulating the D20 using OGCMs.

The objective is to understand D20 variabilities in the Indian Ocean (IO) with OGCM as a diagnostic tool. Several studies have been performed earlier by researchers where the ocean models have been used as tools to understand many important features. Indian summer monsoon is one of the very unique phenomenon during which ocean has very regular response at different scales, ranging from intraseasonal, seasonal to inter annual. Several other studies, both observational and modeling based, have discussed the variability of various oceanic parameters in the Indian Ocean on different temporal scales. Scott and McCreary (2001) reviewed the work in the Indian Ocean circulation at different scales. There have been studies related to variability of
surface and subsurface temperature and currents in the IO (McCreary and Kundu 1989, Rao and Sivakumar 1996, 2000). Rao and Sivakumar (2000) studied the seasonal cycle of surface and sub-surface temperature using the observation based climatology of the IO. Study of seasonal cycle and inter-annual variability of temperature (on different temporal scales) has been carried out in details using numerical models. (McCreary and Kundu 1989, McCreary et. al.1993, Behera et. al. 2000, Perigaud et. al. 2003). Indian Ocean dipole (IOD) has been found to be the most dominant mode of the inter-annual variability in the IO (Saji et. al. 1999, Webster et. al. 1999). Numerical modeling studies of the IOD have been carried out by various researchers (Vinaychandran et. al., 2002, Rao et. al., 2002 Feng and Meyers 2003). They discussed the structure, evolution, possible cause and the changes associated with the IOD mode. Apart from seasonal and inter-annual variability, the IO is characterized by intraseasonal oscillations (ISOs) in various parameters like the SST (Sengupta and Ravichandran, 2001) and ocean currents (Sengupta et. al. 2004).

In one of the pioneer work by Krishnamurthy and Bhalme (1976), they reported that the intra-seasonal variability (ISV) favored two spans of periodicity (30-60 day and 10-20 day). These periodicities have dominant role to play in the summer monsoon performance. They play an important role in shaping the average summer monsoon performance, it is essential to explore the physical mechanism associated with it. Many studies have reported that Bay of Bengal (BOB) plays a very significant role in monsoon ISO and there is a strong feedback to atmosphere at this scale. Thus ISV over the BOB during the summer monsoon is very phenomenal processes. It is a manifestation of coherent response of ocean to the atmospheric intra-seasonal variability (Sengupta et al., 2001, Agarwal et al., 2007; Bhat et al., 1999). There have been few studies on the SST ISOs in the IO using OGCMs (Schiller and Godfrey,
2003; Waliser et al., 2004). Extensive modeling studies have been carried by Sengupta et al. (2001, 2004), in which the mechanisms behind the intraseasonal variabilities in equatorial Indian Ocean currents have been explained. However, there are not many studies related to intraseasonal variability of D20 in the Indian Ocean and many issues are still unresolved at these scales.

Considering the importance of studying the variability of D20 at different scales in the Indian Ocean, the ocean state spanning 5 years, from 2004-2008 has been prepared. Types of simulations used in this study are:

(i) NCEP-R in which the OGCM is forced by daily analyzed wind fields and fluxes from NCEP/NCAR reanalysis

(ii) QS-R, using a combination of NCEP/NCAR Reanalysis and satellite QuikSCAT wind data and,

(iii) OSCAT-R, in which daily analyzed OSCAT winds generated in house for the period 1st January, 2011 till 31st December, 2011 have been used in the model to simulate ocean parameters. In this run once again, other parameters (heat and fresh water fluxes) were used from NCEP/NCAR reanalysis.

Later two experiments were conducted, realizing the importance of scatterometer derived wind data in faithfully simulating the D20. The simulated variables were stored on daily basis. The ocean states (NCEP-R, QS-R and OSCAT-R) so generated will now be utilized to study the D20 variability at different time scales. The scales of variability range from intra seasonal (occurring within 30-90 days) to intra annual (found during 60-360 day period) and even inter annual (existing from year to year). An attempt has been made to dwell upon the factors causing this variability. To begin
with, mean and seasonal behavior of D20 has been studied. The first two sections discuss the annual mean and seasonal characteristics oceanic parameters simulated by the model. Interannual variability of the above parameters with special emphasis on IOD is discussed in section-5.3, followed by intra-seasonal variability of SST in section-5.4.

5.2 Annual mean and seasonal variability of D20

To study the mean features of D20, we have utilized 1°×1° gridded products of all the conductivity temperature depth (CTD) data measured by ARGO in the Arabian Sea at 10-day intervals. The data were provided by the Indian National Centre for Ocean Information Services (INCOIS). The gridding was done by the objective analysis, the details of which are available in Udaya Bhaskar et al. (2007). Only the temperature profiles were used in this study to estimate observed D20 (ARGOD20) from ARGO profiles. The average values ARGOD20, NCD20 from NCEP-R and QSD20 from QS-R are plotted in figure 5.1. It can be seen from the plot that most of the features of D20 are captured in model-simulated D20s. However, scatterometer over-estimates the Argo observations along 20°S. In the north Arabian Sea, along the coast, NCD20 exhibits a high value (240m), which is almost 60m less in case of ARGOD20 and 40m less for QSD20.

Annual mean picture shows a prominent band of deep D20 (~200m) in the region between 15°S-25°S. This is due to the convergence of westward flowing south equatorial current (SEC) in the north and eastward flowing south IO currents. D20 is also deep in the East Equatorial Indian Ocean (EEIO), Bay of Bengal (BOB) and near Somali. However in BOB, model simulated D20 appears to be deeper than
observations (Rao & Sivakumar. 1996). While D20 deepening in the EEIO is due to mass convergence caused by the eastward flowing Wyrtki jet, near Somali, it is due to clockwise monsoon circulation. Coastal Somali and Arabian Sea (AS) regions exhibit shallow D20 due to upwelling.

Figure 5.1: Annual average (2004-2008) distribution of D20 (m) in the tropical Indian Ocean from ARGO (top), NCEP-R (middle) and QS-R (bottom).
Next we study the seasonal variability (figure 5.2) in the D20 simulations (NCEP-R and QS-R) by computing the monthly means. The comparison for the even numbered months has been depicted in figure 5.2. Note that, these monthly climatological means are prepared from 5 years (2004-2008) of D20 obtained from each of the runs. During February, QSD20 over estimates NCD20 along 20°S. As the year progresses, the same scenario is mostly found in this region. Since the only difference is in the wind products, this overestimation could be the result of scatterometer wind forcing. During April, along 10°S, QSD20 exhibits a wide patch extending from 55°E to 85°E with an average depth of 80m, which persists till the end of June and vanishes during August. This shallow feature is totally absent in NCD20. During August, a shoe-shaped feature is developed in the Arabian Sea, which is found to be deep in case of NCD20 than for QSD20. Also, there is a feature along Somali, which is prominent (200-220m) for NCD20 during most of the time of the year. In the Bay of Bengal, both the runs show moderate depths (100m-160m), which remain consistent throughout the year. Thus, it can be said that, D20 in the Bay of Bengal is highly stable and remains unperturbed for most of the part of the year.

However central and western Arabian Sea regions exhibit large seasonal variations. Deepest D20 can be seen in the month of August in the western AS, which is due to Ekman divergence owing to strong SW monsoon winds. In the south-east Arabian Sea (SEAS), a much deeper D20 can be seen during January in both the runs. This is due to the convergence which is also responsible for the warm pool generation in this region. The downwelling taking place in this region also generates westward propagating Rossby waves in the Arabian Sea.
Figure 5.2: Seasonal distribution of D20 (m) for the months of February, April, June, August, October and December computed from NCEP-R (left panel) and QS-R (right panel)
5.3 Inter-annual variability of D20

Next we study the variability explained by each of the products, the standard deviations of both NCD20 and QSD20. These variability maps are shown year-wise in figure 5.3 with some sort of similarity, every year, QSD20 exhibits high variability than NCD20, especially along 10°S and in the Equatorial Indian Ocean. During the years 2005, 2006 and 2008, the variability in QSD20 is as high as 40m in these regions, which is about 28m in case of NCD20. In the Bay, less variability is observed every year. These points to the fact that Bay region is highly stratified and hence not much mixing takes place between mixed layer and region below this. This is quite expected as due to fresh water impact at the surface (precipitation and river discharge), the region is highly stratified. In the southwest Indian Ocean (SWIO), QSD20 shows a high variability feature (36m) during 2004. Also, in the Arabian Sea, a small patch of high variability is detected in both QSD20 and NCD20. This variability is found to occur every year. During 2006, QSD20 depicts a high variability (40m) feature in the southern Indian Ocean (SIO), which could be the result of Indian Ocean Dipole (IOD). The same is not captured well by NCD20, it lacks magnitude and width both. The same signal is found to reappear in 2008, of course the signal is not very strong and wide-spread. For every year and almost everywhere, QSD20 explains higher variability than NCD20. Maximum variability of D20 (figure-5.3, bottom panel) can be seen in the southern ocean between 10°S-20°S and 60°E-80°E which is also the region of maximum wind variability (Figure 5.3).

Rossby wave activity near the SEAS up to Somali coast results in variability of around 20-30m in D20. Apart from this, moderate variability exists in the East Equatorial Indian Ocean (EEIO).
Figure 5.3: Standard deviation distribution of NCD20 (m) and QSD20 (m) for 2004, 2005, 2006, 2007 and 2008
Since QSD20 explains more variability and is closer to observations than NCD20, QSD20 has been considered for further analysis. Accordingly, seasonal cycle has been removed, so as to compute D20 anomaly. This anomaly is obtained month-wise and the root mean square values of D20 anomaly is shown in figure 5.4 for the month of October every year as per the study period.

**Figure 5.4:** Root mean square of QSD20 anomalies (m) in the month of October for the years (from top to bottom) 2004 to 2008
The reason for taking into account the month of October is the occurrence of IOD during October 2006. A strong anomaly is found in the Equatorial Indian Ocean during October 2006, it is of the order 60m. This was earlier found in 2004 also, but with a lesser value as compared to 2006. Everywhere else, the anomalies are moderate and uniform every year in the month of October.

To study the time-longitude varying features of D20, especially for studying the impact of IOD on D20 or vice-versa, we restrict our study to the equatorial belt averaged from 10°S to equator (figure 5.5). This Hovmuller plot averaged along 10°S to equator, shows the propagating features of QSD20 anomaly. A strong negative anomaly in D20 can be seen in the EEIO region towards the end of 2006. This is due to the anomalous upwelling associated with the IOD leading to shallow D20 in this part of the IO. One can see this feature propagating from west to east from the sloping isolines of D20 anomaly. Another interesting feature (positive D20 anomaly) can be seen between 60°E to 80°E. This is suggestive of the downwelling in this region. Hence there is a east-west see-saw pattern in the D20 anomaly during IOD year. This pattern leads to warming in the upper layer towards west and cooling of the upper layer towards EEIO region. A slight negative anomaly in D20 can also be seen in the year 2004 in this region. In general EEIO region exhibits large interannual and seasonal variability as compared to western equatorial region which is much unwavering.

We further compress the high variability box by taking two boxes in its neighborhood, where box-1 is on the east (90°E-100°E, 10°S-Equator) and box-2 is on the west.
(60°E-80°E, 5°S-5°N) of this feature. QSD20 anomalies are averaged in each of the boxes and then corresponding monthly time series is plotted.

![Figure 5.5: Longitude v/s time plot of QSD20 anomalies (m) averaged from 10°S to equator in the Tropical Indian Ocean.](image)

Time series of the D20 anomalies in these two boxes are shown in figure 5.6. One obvious feature one can observe is that the two series are exactly opposite in pattern to each other. Normally there is deepening in D20 every year during September to November in box-1 due to downwelling associated with the Wyrtki jet (Wyrtki, 1976). In the anomalous year like 2006 associated with the IOD, a large negative D20 anomaly of the order of 30 m is observed from the time series. This negative peak in box-1 is complemented by positive D20 anomaly in box-2. A detailed study carried out by Sharma et al. (2007) for the 1997 Indian Ocean dipole event suggested Reverse Wyrtki Jet (RWJ) partly responsible for the saltier upper layer due to the
upwelling in the EEIO. This upwelling caused by the anomalous easterlies leads to upward movement of the isotherms and hence shallow D20, as seen from figure 5.6 during 2006 IOD event.

![Figure 5.6: Time series plots of QSD20 anomalies (m) averaged in the two boxes (box-1: 90°E-100°E, 10°S-Equator and box-2:60°E-80°E, 5°S-5°N)](image)

5.4 Intra seasonal variability of D20

It has been known from quite some time that oscillations with 30-60 day and 90 day periodicities are important features of circulation in the equatorial Indian Ocean. Observed sea surface temperature (SST) in the Bay of Bengal (BOB) exhibits strong low period oscillations during summer monsoon [Sengupta and Ravichandran, 2001]. These oscillations, known as intraseasonal oscillations (ISOs) are very closely linked to the large scale atmospheric convection associated with the summer monsoon.
activity [Yasunari, 1979; Sikka and Gadgil, 1980; Webster et al., 1998]. Later, the intraseasonal variability in barrier layer thickness was investigated in the south central Bay of Bengal using Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA) buoy. Although these periodicities were discovered in observations of various oceanic parameters, there had been several modeling studies to reveal the origin of these oscillations. The modeling studies by Han et al. (2001) and Han (2005) are almost exclusively focused on sea level anomaly fields and currents. Fu (2007) has also focused exclusively on surface variables, namely the sea surface height, sea surface wind and sea surface temperature. The intraseasonal variability of the thermocline has not been investigated so far. It is of course worth mentioning that there has been a study which investigated the correlation between zonal surface wind stress and depth of the $20^\circ$C isotherm, a reasonable proxy for the thermocline depth in the tropical Indian Ocean. However, the primary focus was on the semiannual variability and not on the intraseasonal one.

In this study such an analysis has been carried out using primarily the data from a buoy. However, other auxiliary data like altimeter derived sea level anomaly and scatterometer winds have also been used. Ocean model simulations have also been used to study the intraseasonal variability. Spectral analysis of current, thermocline depth and sea level anomaly from simulations also supports the existence of the mentioned periodicities.

5.4.1 Various data sets and methodology used

There is a RAMA buoy deployed at (1.5°S 90°E) by JAMSTEC. Daily subsurface temperatures and near-surface current from this buoy for the period 1st January 2004
till 3rd July 2007 have been used in the study. D20 have been computed from the subsurface profiles. Apart from buoy data, sea level anomaly (SLA), which is a merged product of several altimeters, available from Archiving, Validation, and Interpretation of Satellite Oceanographic data (AVISO) has also been used. The period of this data is from 1st January 2004 till 31st December 2008. The method used is the spectral analysis using Fast Fourier Transform. Before carrying out spectral analysis, the seasonal cycle has been removed from the data. This cycle removal has been done subsequently for all other parameters. All those periodicities which are being discussed below are significant at 95% confidence level.

5.4.2 Variance Spectra Analysis

A strong peak is observed at 90 day (Fig. 5.7) in the altimeter data of SLA. The same is however, quite weak in the model simulated SLA. This is because the model simulation is primarily wind-forced response. It is quite well known that the wind amplitude at the 90-day period is weaker than that for the 30-60 day period, suggesting that equatorial Indian Ocean selectively responds to the 90-day winds. This selective response is due to the resonant excitation of the second-mode baroclinic waves by the 90-day winds. The Rossby waves, reflected from the eastern ocean boundary, enhance the directly forced response in the ocean interior. There is also a secondary peak at 60 day as expected. The peaks at same periods have been well simulated by the OGCM MOM-3. However, the peaks are much weaker than those of observations.
Figure 5.7: Variance spectra of SLA at 1.5°S 90°E

Figure 5.8: Variance spectra of depth of 20 °C isotherm at 1.5°S 90°E
In Fig. 5.8 we show the spectra of D20 at the buoy location. The spectra have been computed from observations as well as from model simulations of the same quantity. Here the simulated peaks, although still weaker than the peaks in observations, are more prominent. In this case, i.e., in the case of D20, the excitation of the 90-day model is not only a direct response. Here both the directly forced response and reflected waves associated with the first two baroclinic modes contribute to the 90-day variation.

Once it was observed that SLA and D20 exhibit intraseasonal variability, we tried to isolate these intraseasonal variabilities using band pass filter. Time series data of simulated and observed D20 were subjected to band pass filter at the RAMA buoy location. The intraseasonal fluctuations of the mentioned periodicities have been clearly brought out after this band pass filtering (Figure 5.9). The time cut-off (lower and upper) chosen is 30-100 day. It can be seen that there is an unusually strong negative peak during August –September of 2006 (Mankad et al., 2012a). This is present in both observations and model simulations. This is a manifestation of anomalous dipole event, which occurred in late 2006. During this event there was a strong upwelling and shallowing of the thermocline in the eastern equatorial Indian Ocean, which left its signature in this unusually strong anomaly.

This is suggestive of the fact that IOD event, which is an interannual variability also impacts the intraseasonal variability.
Figure 5.9: The 30-100 day bandpass-filtered D20 (m) at 1.5°S 90°E from observations and simulations.

We further carried out a spectrum analysis of near-surface zonal current at the above location to check whether similar intraseasonal periodicities exist for zonal current. The 60-day peak has been picked up nicely in both the spectra (Fig. 5.10). In order to see the cause of this variability both in D20 and zonal current, we also did the spectrum analysis of scatterometer wind at the same location (figure 5.11).

It can be seen that there is a clear 60-day peak in the wind spectrum. Hence it can be concluded that 60-day periodicity in zonal current and D20 are probably a direct wind-forced response of the equatorial Indian Ocean.
Figure 5.10: Variance spectra of simulated and observed zonal current at 1.5°S 90°E

Figure 5.11: Variance spectra of QuikSCAT zonal wind at 1.5°S 90°E
5.4.3 Intra seasonal variability of simulated (OSCAT-R and NCEP-R) and observed D20

With the availability of OSCAT winds, the experiment has been conducted for the year 2011. Fast Fourier Transforms of simulated and observed D20 have been carried out at three locations because of the availability of continuous data (Figure 5.12). These locations are 0°N 90°E, 1.5°S 90°E and 1.5°N 90°E. At the locations 0°N 90°E and 1.5°S 90°E, 30-60 day peaks are found in cases of BUOY D20 and OSCAT D20. At 1.5°N 90°E, a 90 day peak is observed for BUOY D20 and OSCAT D20. These observed peaks in D20 are better captured by OSCAT-R than by the NCEP-R. There are several observed low period variabilities in D20. Almost at all the three buoy locations, OSCAT-R simulates these variabilities quite faithfully. The reason why these low periodicities are absent in NCEP-R could be due to the coarse grid size of the NCEP/NCAR Reanalysis winds (1.875° x 1.875°) as compared to the OSCAT winds that are available at 0.5° x 0.5° grid size. 40-day peak in D20 is quite prominently seen at 1.5°S 90°E (buoy, NCEP-R and OSCAT-R), which is absent at other two buoys. Many research studies have addressed wind to be one of the factors causing D20 variability. To study the cause of this variability and to find which component of the wind (zonal or meridional) has larger influence, FFTs of zonal and meridional winds are shown in the figures 5.13 and 5.14 respectively. The peaks more so of the 90-day found in D20 are also seen in zonal wind. In case of meridional winds, these peaks are not clearly seen. This suggests that zonal wind dominates D20 variability and hence D20 variabilities in the EEIO region is largely wind driven (Mankad et al, 2012b). Some of the other intraseasonal peaks in D20 in observations and in simulations, that are not directly correlated with the wind peaks can be due to remote effect and not due to the local wind effect.
Figure 5.12: Amplitudes of the different periodicities of observed and simulated D20s (NCEP D20 and OSCAT D20) obtained using Fast Fourier Transform at (top) $1.5^\circ$N $90^\circ$E (middle) $0^\circ$N $90^\circ$E (bottom) $1.5^\circ$S $90^\circ$E
Figure 5.13: Amplitudes of the different periodicities of buoy, NCEP and OSCAT zonal winds obtained using Fast Fourier Transform at 1.5°N 90°E (top), 0°N 90°E (middle) and 1.5°S 90°E (bottom)
Figure 5.14: Amplitudes of the different periodicities of buoy, NCEP and OSCAT meridional winds obtained using Fast Fourier Transform at 1.5°N 90°E (top), 0°N 90°E (middle) and 1.5°S 90°E (bottom)