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High resolution numerical modeling of the Indian Ocean surface Hydrography and circulation

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ABSTRACT

High-resolution numerical ocean modeling has been performed to simulate the circulation features over the Indian Ocean with the help of Ocean General Circulation Model (MITgcm) in the domain [65E-95E; 5N-22N] for the years 1998-2014. The MITgcmis run with ahorizontal resolution of 10 km whereas the vertical resolution varies from 5 m near the surface to 500 m near the bottom of the ocean. The model uses the open boundary condition along all the sides. The initial condition is taken from the World Ocean Atlas 2013 (WOA13). The model is forced with NCEP/NCAR long wave radiation, short wave radiation, zonal and meridional winds, air temperature, precipitation, net latent heat flux and relative humidity. The seasonal variations of surface current, sea surface temperature (SST), sea surface salinity (SSS) and sea surface height anomaly (SSHA) are analyzed and compared with the available satellite in-situ and reanalysis observations. The modeled trends in the SST, SSS, and SSH are computed in the context of climate change. Interestingly, an increase is observed in these variables in recent years in the Arabian Sea and Bay of Bengal. The model mixed layer depth (MLD) matches fairly well with the observations. The seasonally varying cyclonic and anticyclonic patterns, eddies and other small-scale features of the surface current in the Bay of Bengal and Arabian Sea is also studied. The model currents are found to be in agreement with the observed variability of the OSCAR currents. The variability of the surface currents is also anaysed in relation to the changes in the Indian summer monsoon rainfall variability.

Keywords: SST, SSS, SSHA, MLD

1. INTRODUCTION

The Indian Ocean (NIO) has two main basins, namely the Arabian Sea (AS) and the Bay of Bengal (BoB). Both the basins strongly influence the climate over the Indian peninsula. The Indian Ocean displays a very clear seasonal variability with the Indian monsoon. The main feature of the Northern Indian Ocean is the seasonally reversing monsoon winds which are bounded by the land on its northern side. The study of Indian ocean surface circulation and air-sea interaction is necessary for understanding the monsoon and climate variability in the Indian Ocean. The upper ocean plays an important role in regulating the sea surface temperature (SST), sea surface salinity (SSS), sea surface height anomaly (SSHA), and mixed layer depth (MLD). Several studies have been carried out in order to understand the seasonal variability of these variables in the context of change in climate and monsoon. These studies involve both the observational as well as modeling studies. An eddy-resolving numerical modeling (Jochum et al 2005, Rajendran et al 2012) has been performed to study the relation between the variability of SST with rainfall. It was found that the low rainfall occurs over the cold regions whereas high rainfall occurs over the regions where the SST is greater than the threshold value (>28^0C). Bijoy Thompson et al. (2008) have simulated the long-term variability of the SST and sea level anomaly with MOM4. An increasing trend in the SST and sea level anomaly was found. The BoB is different from the AS in several aspects. Over the AS, the evaporation exceeds precipitation resulting in a highly saline water, whereas, in the BoB, the precipitation exceeds evaporation as a result of increased freshwater flux due to river discharge (Saheb et al. 2008, Suryanarayan et al. 1993) resulting in low salinity water. The salinity in upper layer is dominated by salinity gradient rather than temperature gradient (Shetye et al 1991). Chaitanya et al. (2015) have also studied the interannual variability of salinity over the BoB region. Shenoi et al. (2002) and Prasad (2004) have studied mixed-layer variability and various processes responsible for mixed layer heat budget in the AS and BoB. Keerthi et al (2013) and Rao et al. (1989) have studied the relationship of variability of the MLD with several known climate modes. The circulation patterns over the Indian Ocean are discussed in detail by Schott et al. (2001) and Shanker et al. (2002). In the present paper the seasonal variability of the Indian Ocean Surface Hydrography, mixed layer depth, and Circulation is studied. The surface variables during 1998-2014 are also analyzed in the context of changing climate.

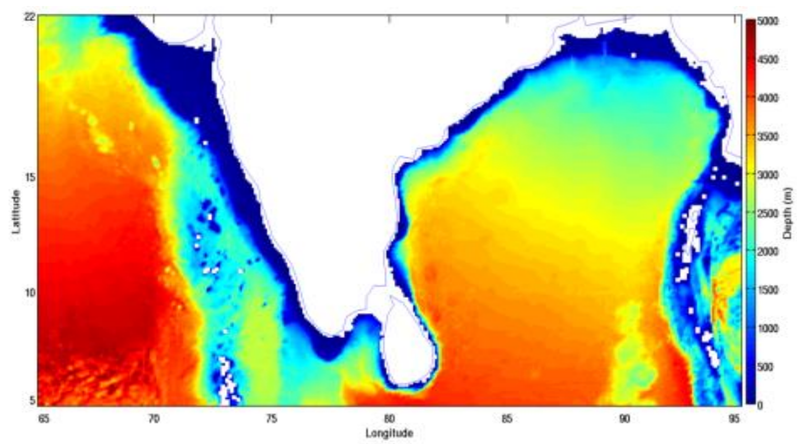

Figure 1
Bathymetry of region of interest in the Indian Ocean [65E-95E; 5N-22N]

2. METHODOLOGY

We use the MIT General Circulation Model (MITgcm) (Marshall et al. 1997) to perform different sensitivity study. The MITgcm is a z-coordinate model, which uses hydrostatic approximation. We configure the model at a high horizontal resolution of 10 km in the Indian Ocean region around [65E-95E; 5N-22N]. We used a total of 28 vertical levels with the highest vertical resolution of 5 m near the ocean surface and then gradually telescoping out to 500 m at depth. The model uses open boundary conditions on all four sides, which are taken from the ORAS4 reanalysis data. We used the KPP non-local vertical mixing scheme (Large et al. 1994) to resolve the sub-grid scale processes. The bottom frictional drag coefficient is taken as 0.001. A 3^{rd} order direct space-time advection scheme is employed for temperature and salinity. The eddy (harmonic) viscosity and diffusivity satisfying the CFL stability criterion is chosen in horizontal and vertical. We use no-slip condition on sides as well as bottom. The bathymetry of the region of interest (Figure 1) is taken from the Smith and Sandell (1997) 1′ bathymetry data. The nonlinear equation of state is used following the Jackett and McDougall (1995). The initial temperature and salinity are derived from the World Ocean Atlas 2013 (WOA13) data

(Locarnini et al. 2013). We used 6-hourly zonal and meridional winds at 10 m, 2 m air temperature, specific humidity, precipitation, evaporation, downward shortwave and long wave radiation flux from the NCEP/NCAR data to force the MITgcm. The model calculates the air-sea fluxes using the bulk formula (Large and Yeager 2004). The model is spun-up for a period of 5 years during 1 Jan 1993 - 31 Dec 1997. The production run is then carried out for a period of 17 years during 1 Jan 1998 – 31 Dec 2014.

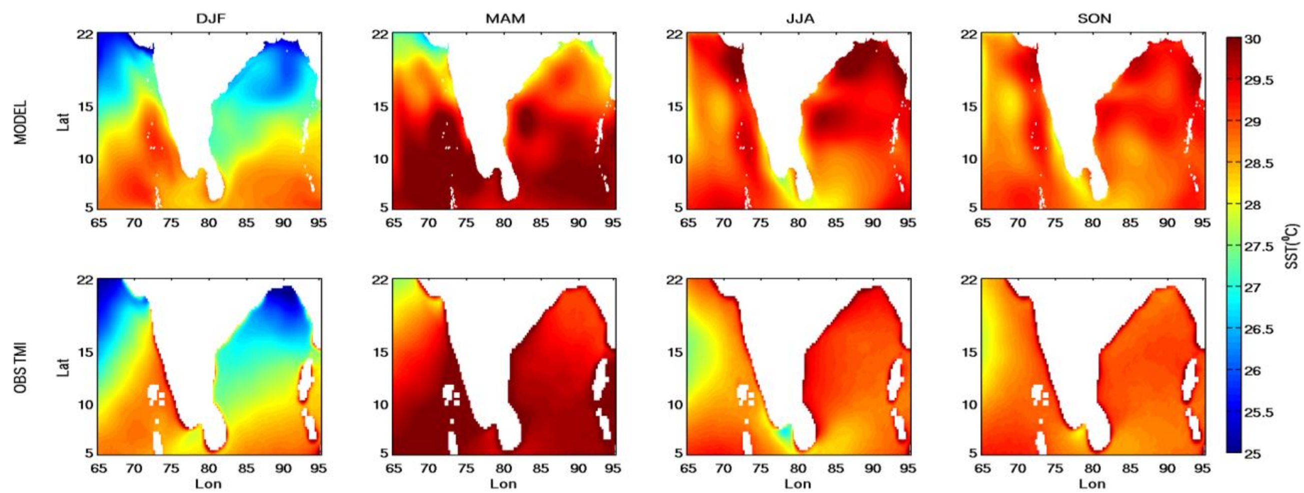

Figure 2

Sea surface temperature (SST) of the AS and BoB during DJF, MAM, JJA, and SON seasons of 1998-2014. The model simulated and observed TMI SST is shown in the upper and lower panels, respectively

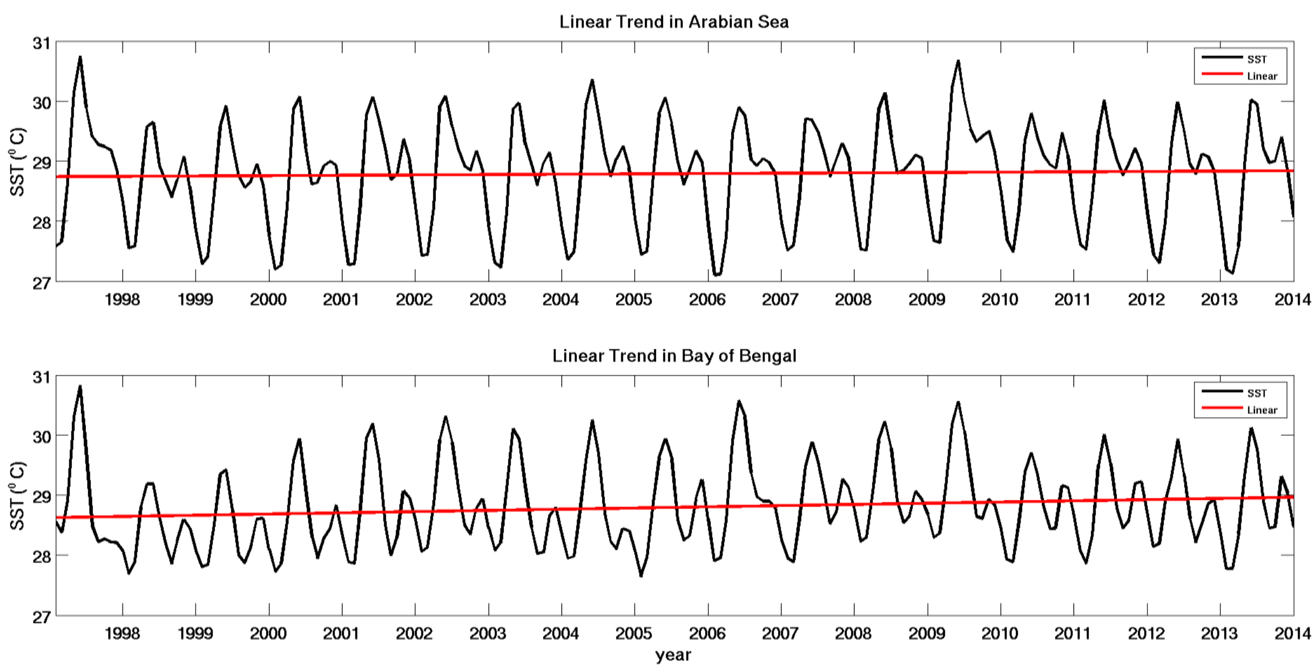

Figure 3

Area average monthly time series of the SST over the Arabian Sea (Upper panel) and the Bay of Bengal (lower panel) from 1998-2014

3. RESULTS

It is clear from Figure 2 that the seasonal variability of the SST simulated by the model matches very well with the observed TMI SST data. During winter season northeast winds starts flowing; as a result of which the coastal upwelling begins in the head Bay of Bengal and the east coast of India. The relatively cold SST region during December-January-February (DJF) extends from 10 N to 22 N in the BoB and 15 N to 22 N in the Arabian Sea. The difference of the extension of cold region in the AS and BoBis due to the freshwater influx in the BoB, which decreases the SST in the BoB while no such major source of freshwater exists in the Arabian Sea.

In the March-April-May (MAM) season, in the region south of 15N the entire ocean becomes warm due tothe trapping of Kelvin waves. In the JJA season, entire ocean basin becomes relatively warm thus making this region conducive for summer monsoon rainfall over India as a result of moisture generation and atmospheric convection. The SST becomes relatively cooler in SON as compared to JJA season.

Figure 3 shows the time series of monthly mean SST averaged over the AS and BoB region. The red line shows the linear trend. The SST fluctuations are near periodic with maximum in April-May and minimum in December-January. Secondary maxima (minima) are seen in July-August (September-October) months. We find that SST trend is almost absent in the Arabian Sea [0.02^{0}C/year]as well asBoB [0.008^{0}C/year]regions over the period of study 1998-2014.

In Figure 4, we compare the model sea surface salinity (SSS) with the observed NIO Atlas (Chatterjee et al. 2012). The surface salinity values over AS and BoB show large variations and very different nature. In the AS, salinity is very high mainly in the post monsoon season SON. A similar pattern is also found in the observation. This may be due to the intrusion of more saline water from the different straits to the AS. During the same time, the upperBoB and east coast of India show minimum salinity due to the freshwater influx from major rivers and winter precipitation. In monsoon season salinity is high over northern part of the AS due to high evaporation and less precipitation than the BoB region. The model is able to capture the seasonal variability in all the seasonsover the AS and BoB. In the DJF season, the low salinityis observed between 5N-8N at the interface of AS and BoB as a result offlow of low salinity water from the BoB to the AS.

Figure 5 shows the monthly SSS averaged over the AS and BoB. The SSS fluctuations are nearly periodic with maximum (minimum) in October-November (April-May) over the AS. We find that no significant increasing/decreasing trend exists in the SSS similar to SST during 1998-2014.

Figure 6 shows the comparison of seasonal sea surface height anomaly (SSHA) from the model and observation (AVISO). The model is able to correctly capture the SSHA variability over the AS and BoB. The figure shows the contrasting SSHA pattern in the AS and BoB. Most of the region in the BoB (AS) shows positive (negative)SSH anomaly. In the BoB region, minimum SSHA is found in DJF. SSHA shows maximum value in MAM and JJAS seasons. The minimum SSHA in winter is due to contraction of water caused by cold SST. In pre-monsoon season expansion of water takes place due to warm SST. During the summer seasons, high precipitation is the main cause for the increase in SSHA. The upwelling and down welling zones in different parts of the AS and BoB during different seasons are also correctly simulated by the model.

MLD is the upper portion of near Surface Ocean where temperature, salinity and density are uniform upto some vertical depths and where the coupling of ocean and atmosphere occurs. The MLD is calculated using shallowest extreme (Lorbacher et al. 2006) curvature of near surface temperature. From Figure 7 we see that model MLD matches well with the observations in all the season. Except during the DJF, the MLD in the BoB north of 16N is generally low (<40 m). In the AS north of 15 N, the MLD becomes 45-50m in the JJA and SON seasons. During theDJFseason, the MLD reaches to 70-100m in the AS. During MAM, the MLD is small (<30 m) in the entire AS and BoB regionsdue to weak wind intensity and increased incoming solar radiation. In monsoon region, the MLD over both the AS and BoB shows nearly similar pattern. The MLD of the northern BoB is generally less than 40 during the year due to incoming freshwater flux. The MLD along the coasts is generally low both in the AS and BoB, except in the DJF season.

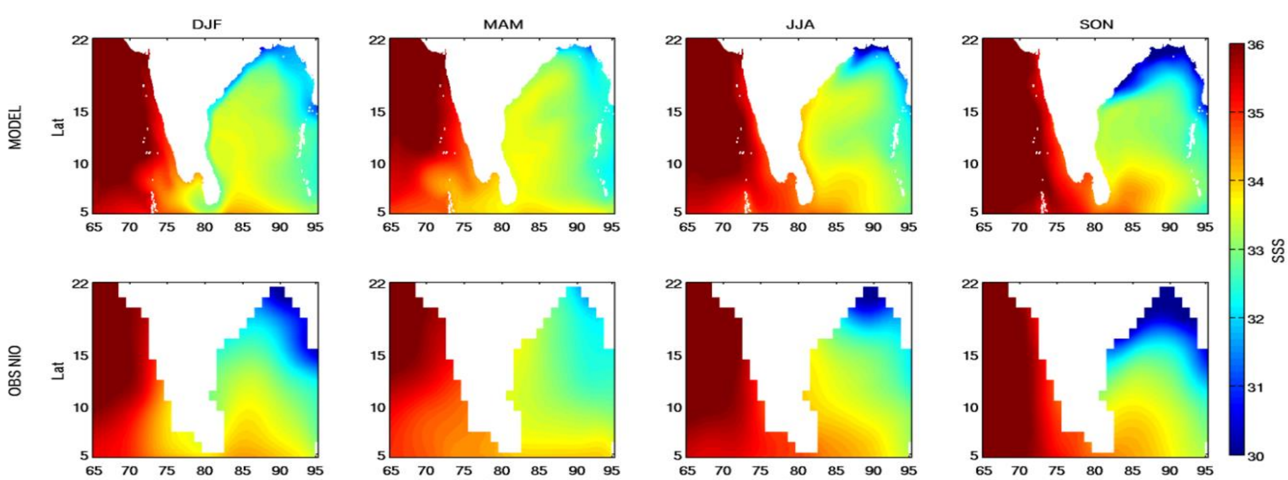

Figure 4

Sea surface salinity (SSS) of the AS and BoB during DJF, MAM, JJA, and SON. The model simulated and observed NIOA SSS is shown in the upper and lower panels, respectively

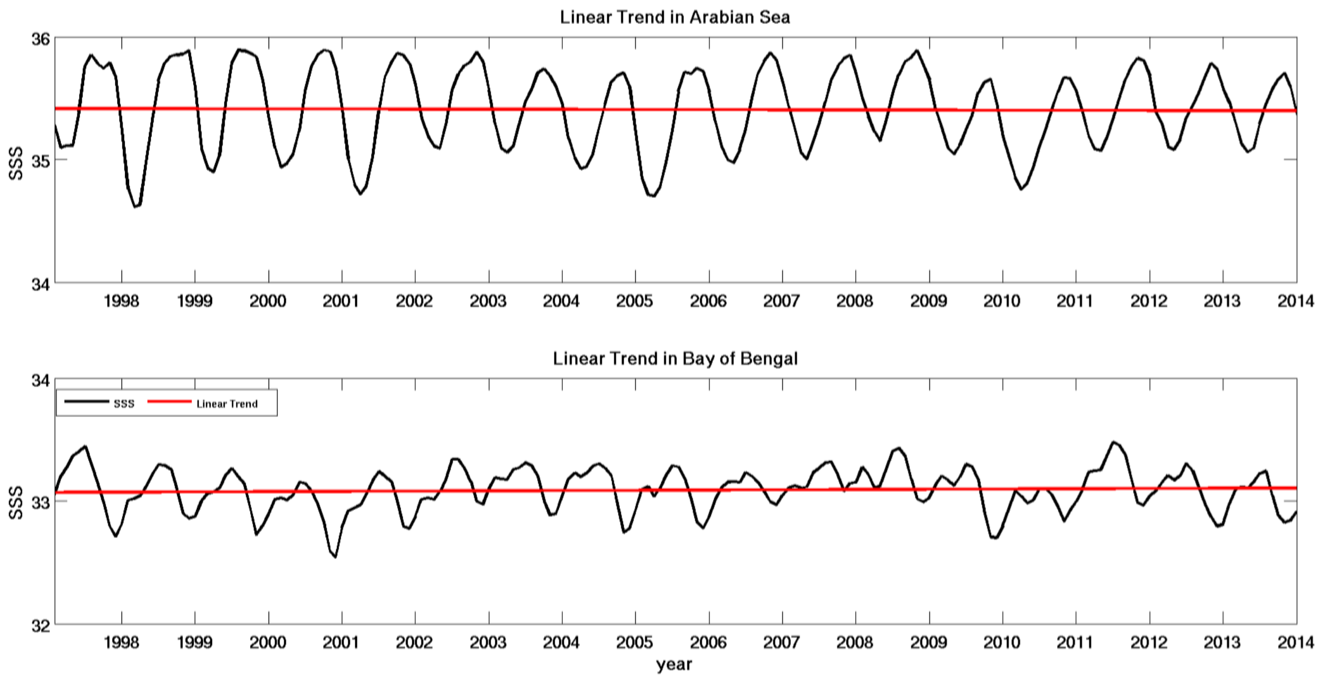

Figure 5

Area average monthly time series of the SSS over the Arabian Sea (Upper panel) and the Bay of Bengal (lower panel) from 1998-2014.

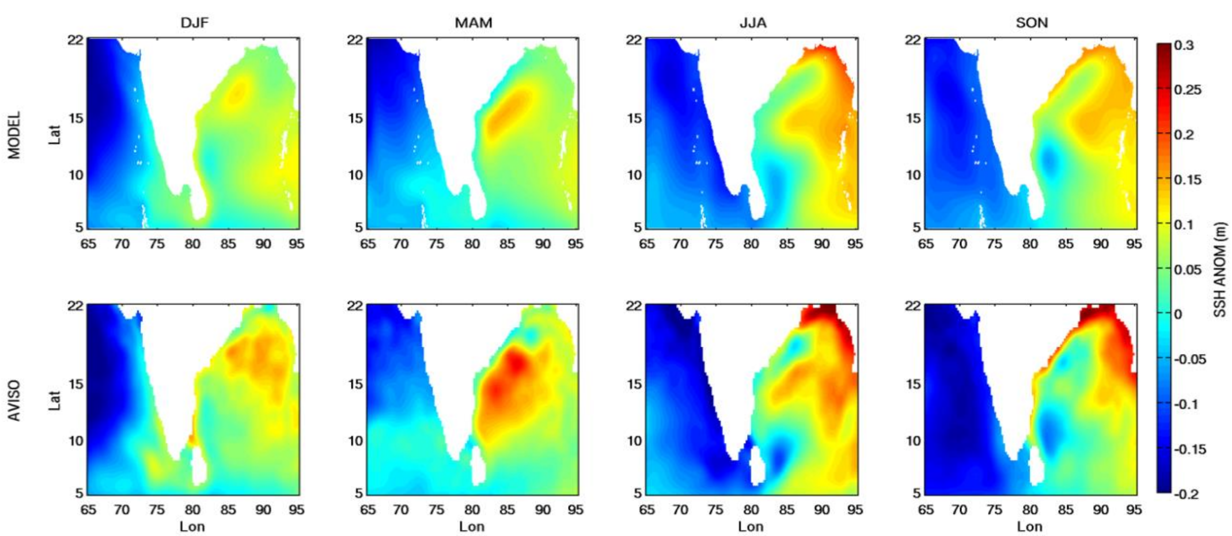

Figure 6

Sea surface height anomaly (SSHA) of the AS and BoB during DJF, MAM, JJA, and SON. The model simulated and observed AVISO SSHA is shown in the upper and lower panels, respectively

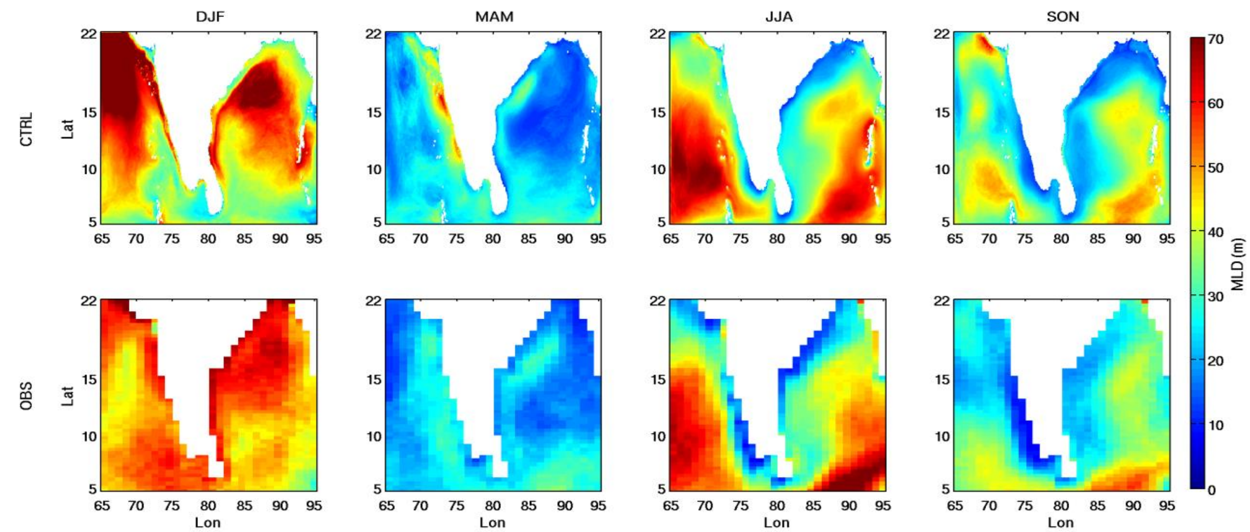

Figure 7
Mixed layer depth (MLD) of the AS and BoB during DJF, MAM, JJA, and SON. The model simulated and observed GODAS MLD is shown in the upper and lower panels, respectively

4. CONCLUSION

A high-resolution ocean circulation model is used to simulate the main features of the Indian Ocean surface hydrography, mixed layer depth, and sea surface height anomaly. The seasonal variability of these variables is studied in the context of changes associated with the summer monsoon rainfall. We find that the SST and SSS trend is absent over the BoB and AS regions over the period of study during 1998-2014. The sea surface height anomaly in the BoB region is generally more than the Arabian Sea during all the seasons. The highest MLD values are found in the winter DJF season.

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