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Influence of Bathymetry on the Performance of Regional Scale Model

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ABSTRACT

A three dimensional ocean circulation model (Princeton Ocean Model) is utilised to study the thermohaline variability of the eastern Arabian Sea associated with changes in the three input bathymetry data sets, viz. ETOPO5 (E5), Modified ETOPO5 (ME5) and ME5 further modified based on actual fine resolution data collected using Multibeam echo-sounder (MEN5). The temperature and salinity measurements made onboard INS Sagardhwani for the period July 2000 is utilised to validate the model. Simulations of temperature using Princeton Ocean Model show good improvement in the coastal region with MEN5 bathymetry data (RMS error of 0.71 °C and correlation coefficient of 0.98). The study highlights the choice of fine resolution bathymetry data in the simulation of nearshore processes, where bathymetry is very complex.

Keywords: Ocean modelling; Eastern Arabian Sea; Bathymetry

1. INTRODUCTION

The seasonally reversing monsoon winds make the Northern Indian Ocean (NIO) one of the most complex oceanic systems of the world oceans. Over the NIO, the winds blow from southwest during May to September and from the northeast during November to January. The NIO splits into two parts, the Arabian Sea (AS) and the Bay of Bengal (BoB) because of the presence of Indian subcontinent. Even though both the AS and BoB are semi-enclosed basins located in the same latitude belt and opening into the equatorial Indian Ocean, their oceanographic and meteorological characteristics are quite different. The winds over the AS are more than twice stronger than the winds over the BoB. Also, the precipitation exceeds evaporation in the BoB whereas in the AS, the evaporation exceeds precipitation. Consequently, the surface layers of the AS is characterised by high salinity (>35.5 psu) whereas the BoB has a much lower salinity. The occurrence of upwelling during the summer monsoon season along the eastern and western boundary of the Indian coast is well known[1-5]. During the summer monsoon, the southward flowing West India Coastal Current (WICC) together with the strong (~8 m/s) westerly / north westerly wind in the eastern Arabian Sea and northward flowing East India Coastal Current (EICC) together with southwesterly winds in the western BoB trigger the upwelling to the maximum extent. The topography off the east coast and southwest coast of India is characterised by a narrow shelf bounded by a steep continental slope and a wider shelf in the north-west coast of India. This variable topography also has an important effect on the circulation pattern and thermo-haline fields.

To investigate various aspects of circulation over the NIO, in particular to gain an understanding of the various processes, an ocean general circulation model is very much essential. For the AS and BoB, the efficacy of Princeton Ocean Model (POM) has been demonstrated by many researchers[1,6-7]. The accuracy of ocean simulations depends on factors like uncertainties in the input parameters and atmospheric forcing, approximations in the governing equations, and errors introduced by the numerical scheme. The surface forcing by winds, heat and salt water fluxes must be incorporated on time scales which adequately represent the variation of these forcing fields. In addition, the model parameters like bathymetry smoothing coefficient, number of sigma-levels, etc. also define the model's capability to resolve the desired features. Willebrand[8] *et al*. clearly highlighted the importance of grid resolution in a model. The choice of sigma levels for the water column is very crucial in determining the resolution of the model as the layer thicknesses vary with the bottom depth. So, for a better simulation of the ocean features especially in the coastal regions we require accurate bathymetry information.

Most of the ocean models use ETOPO-5 (E5) as the input bathymetry data[9]. However, E5 contains comparatively less data from the shallow waters. Hence, National Institute of Oceanography, Goa derived an improved shelf bathymetry for the Indian Ocean[10] utilising the shallow water bathymetry data for the Indian ocean collected by various agencies including National Hydrographic Office and combining it with the E5 data (ME5). They also assessed the improvements of this bathymetric data with the performance of existing tidal circulation and tsunami propagation models. Naval Physical and Oceanographic Laboratory, Kochi has collected fine resolution multi-beam echo-sounder data from the southeastern

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Arabian Sea (SEAS). In the present work, the fine resolution bathymetric data collected from the nearshore regions of the SEAS is blended with ME5 (MEN5) to make the coastal data robust and more accurate. Also, a series of numerical experiments is conducted in the SEAS using the POM model to investigate the improvements in the ocean simulation with the MEN5 data.

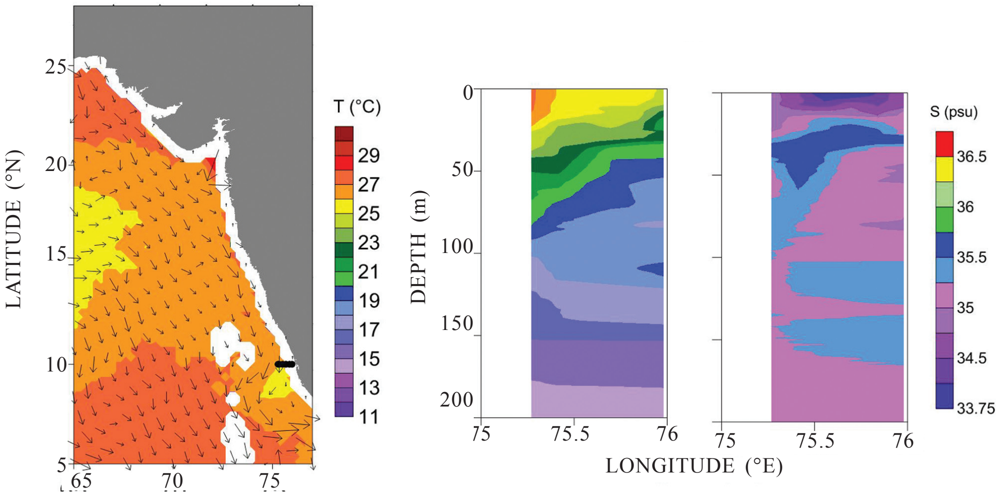
2. OCEANOGRAPHY OF THE REGION

Temperature and salinity data collected from pre-designated locations in the southeastern Arabian Sea (SEAS) during July 2000 onboard INS Sagardhwani (Observational track plotted in Fig. 1(a)) shows signatures upwelling during the active period of summer monsoon (Fig. 1(b)). The upwelling in the SEAS is driven by the offshore Ekman transport associated with the west-northwesterly winds and the southward flowing WICC[11] (Fig. 1(a)). During this period, the signatures of upwelling are evident from a depth of 80 m on the shelf and slope (Fig. 1(b)). Consequently, the 25 °C isotherm, representing the thermocline, undergoes an upward displacement of 30 m over a distance of ~70 km, i.e., from around 30 m depth at 75.25 °E to surface around 75.9 °E. As a result of upwelling, the coastal waters cools to less than 25 °C, while in the offshore, the observed surface temperature is in excess of 26 °C. The sea surface temperature (SST) obtained from tropical rainfall measuring mission microwave imager (TMI) also indicates warmer waters in the offshore (>27 °C) and drops to <26 °C in the nearshore regions, supporting coastal upwelling (Fig 1(a)). The cooler water as observed in the observations is not evident in the TMI SST because of its poor resolution in the nearshore. The downsloping of isolines below 80 m depth suggests the existence of a poleward flowing undercurrent[6,12], which is typical during the periods of western boundary upwelling. In the salinity field, the upwelling signal is reflected in the uplifting of the subsurface salinity maxima (~35.5 psu) associated with the Arabian Sea Watermass (ASW). The core of ASW observed around 60 m in the offshore shoals to 25 m centered at 75.75 °E. The upward movement of this subsurface maxima towards surface is inhibited by the presence of fresher water (<34 psu) in the upper 15 m of the water column.

3. MODEL DESCRIPTION

The Princeton Ocean Model, POM is a three-dimensional primitive equation finite difference model[13] that has been widely used for modelling different oceanic regions of the world ocean. The terrain following ocean models is best in the smooth depiction of topography and their ability to simulate the interactions between currents and bottom topography. The model used here is the same as that used in Kumar[7], *et al.* and Kumar & Anand[1] for the study of warm pool dynamics and coastal upwelling in the SEAS respectively. Hence, only brief description is given here.

The model domain covers the region between 65° to 78 °E and 5° to 27 °N covering the eastern Arabian Sea. More details of the model for the Indian Ocean scenario are given in Rao[6], *et al.* and Kumar[7], *et al*. There are 150 x 250 grid points in the horizontal computational plane and 26 levels in the vertical. Resolution in the zonal and meridional direction is ~10 km (5 nautical miles). In the vertical, a terrain following sigma coordinate is used with fine resolution of 0.5 m and 15 m, respectively near the surface and the bottom, while a relatively coarse grid of about 30 m is used at the mid-depths. The horizontal time differencing is an explicit scheme, whereas the vertical time differencing is an implicit scheme. It uses a mode splitting technique with barotropic (20 s) and baroclinic (400 s) mode. The horizontal boundary conditions over the land are implemented by a land mask, which ensured that the velocity over the land and the normal velocity along the coastline were zero. Along the open boundaries, radiation conditions are used. The bathymetry was acquired from three different data sets with 5 nautical mile resolution from E5, ME5 and MEN5 database. The initial fields of temperature[14] and salinity[15] were extracted from the World Ocean Atlas Database. This data is supplemented with daily QuickSCAT winds estimated at a standard height of 10 m at 0.25° grid horizontal resolution (ftp.ifremer.fr/products/gridded/ mwfquiskcat/data), heat flux



(a)

(b)

Figure 1. (a) TMI SST overlaid with OSCAR currents with station locations marked as black line and (b) Vertical section of temperature and salinity during July 2000 (Color scale for SST and vertical section of temperature is kept same).

and solar radiation data at 1° grid horizontal resolution from Hastenrath and Lamb[16] atlas. To eliminate effect of wetting and drying, the numerical calculations were performed in the regions deeper than 20 m. The models simulations are initialised from the restart files produced by geostrophic runs, allowing the geostrophic currents to spin up without losing initial temperature and salinity field. The data collected onboard INS Sagardhwani along 9.5 °N latitude off the southwest coast of India during July 2000 is utilised for model validation.

In this work, there are three parts of numerical experiments, namely:

(i) To investigate the efficacy of the model in simulating the thermohaline and currents in the SEAS during an upwelling regime using E5 bathymetry data with all the forcing including monthly heat flux and daily winds
(ii) Same scenario as in (i) except E5 is replaced by ME5
(iii) Same scenario as in (i) except E5 is replaced by MEN5.

4. RESULTS AND DISCUSSIONS

4.1 Bathymetry Data

Figure 2(a) depicts the bathymetry of the SEAS (8.5 °N to 10.5 °N and 74.5 °E to 77 °E) using the data sets E5, ME5 and MEN5 (upper panel). The bottom topography derived from MEN5 shows a flat region (with depth around 350 m) between 8.6 °N and 9.2 °N and 75.5 °E and 76 °E covering an area of ~3700 km^2. This flat region is referred to as the Quilon Mount in the literature[1]. Westward of the Mount, i.e., west of 75.5 °E, the depth increases very rapidly resulting in very steep gradients. On the other hand, the gradients are very weak east of 76 °E. Several studies[1,17-18] have showed that such bathymetric features are capable of modifying the ocean circulation (Fig. 1(a)).

The bottom topography derived from E5 and ME5 show significant deviations from MEN5, especially around the Quilon Mount and in the nearshore regions of the southwest coast of India. Between 200 m and 2000 m depths, where the Quilon Mount is present, E5 and ME5 shows more or less similar pattern of variation. However, in the offshore beyond 2000 m depth there are no appreciable changes in the bottom topography of all the three datasets. As mentioned earlier, the flat region of the Quilon Mount is very well depicted in MEN5 and covers an area of ~3700 km^2, while such a well defined flat region is clearly visible in E5 and ME5. Similarly, the steep gradient observed on the west of the Quilon Mount is comparatively weak and exhibits a different pattern. Similarly, the comparatively strong gradients observed in MEN5 is absent in the other two datasets. In the nearshore region also, the MEN5 exhibits a totally different pattern compared to the other two datasets. For example, the 100 m depth contour is confine closer to the coast in E5 while it extends to farther offshore in the other two datasets. Similarly the observed pattern of variation of the 50 m depth contour is totally different in the E5 and ME5. Possibly the fine resolution data in this region might capture the small scale variability in the bottom topography. This is more visible from Fig. 2(b), where the differences in ocean depth between the three data sets (E5-ME5, E5-MEN5, and ME5-MEN5) are plotted. In the case of E5-ME5, the variability is primarily confined to the coastal region. The maximum difference is about 100 m off 9.75°N while it is less than 25-50 m in other regions. In the case of E5-MEN5, the variability is very conspicuous upto 2000 m depth contour. The maximum variability (>400 m) is noticed centered at 8.75 °N and 75.5 °E. From Fig. 2(b), it is evident that, in the offshore the bottom depth from the three data is more or less similar pattern of variation whereas it departs significantly in the coastal region, where the bottom topography is more complex. This clearly stress the need for modifying the existing databases including fine resolution bathymetry observations, especially from the coastal regions to improve the quality of bathymetry databases as stated by Sindhu[10], *et al.*

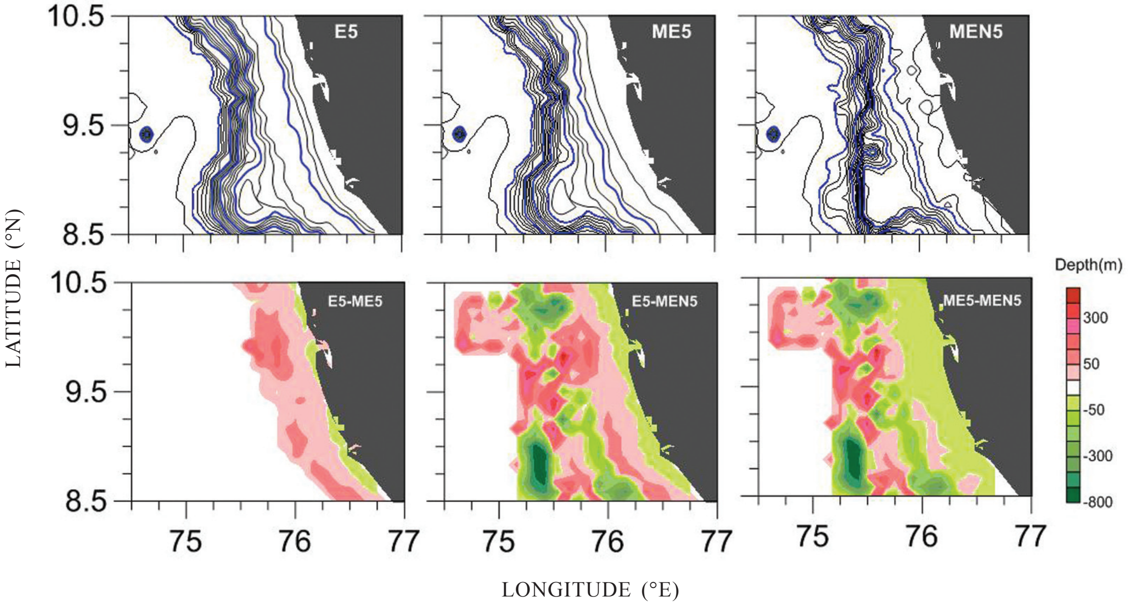


Figure 2. (a) Bottom topography of the study regions using E5, ME5 and MEN5 bathymetry datasets and (b) Difference between the bathymetry data sets (marked in each figure).

Further, the bottom depth along 9.5 °N is extracted from the three databases and plotted against the longitudes (Fig. 3(a)). To have more clarity on the bottom depth variability in the coastal and deep waters, the bathymetry data is presented separately for these two zones (<200 m in left panel and >200 m in right panel of Fig. 3). One of the interesting observations is that MEN5 lies in between E5 and ME5 in the coastal regions where water column depth is less than 150 m. In other words, in the nearshore regions, E5 overestimates by ~40 m and ME5 underestimates by ~10-20 m when compared with actual observation (MEN5). Here, it is worth mentioning that in a water column of 0-150 m, a difference of 20-40 m in the total depth (~25 per cent of total depth) is quite substantial. Beyond 150 m and upto around 1000 m depths, both E5 and ME5 underestimate (even upto 200 m) compared to actual observations. Interestingly, this region coincides with the location of Quilon Mount. Beyond 1000 m depth, the sign reverses and bottom depth values from both the datasets overestimate MEN5 by more than 100 m.

4.2 Simulation Experiments

The impact of accuracy of the bathymetry dataset is seen in the simulation of the temperature and salinity of the water column (Figs. 4 and 5). The surface temperature simulated using the three bathymetry datasets (Fig. 4) show significant changes in the coastal region than in the offshore. The simulation with MEN5 show cooler (<25 °C) and fresher (<35 psu) surface water near the coast and it increases towards the offshore (Figs. 4 and 5(a)). In the nearshore region, the simulated SST is found to be cooler by 0.5 °C when compared with the simulation using the other two data sets. Moreover, the temperature less than 25 °C is absent in the simulation using E5 and ME5. Near to the region of Quilon Mount also, the simulation using these two datasets causes warmer surface layers. However, in the offshore, the differences are not appreciable in the simulated SST among the three different data sets.

Figure 5 depicts the simulation results with the MEN5 bathymetry data along 9.5°N. In the vertical, isotherms show

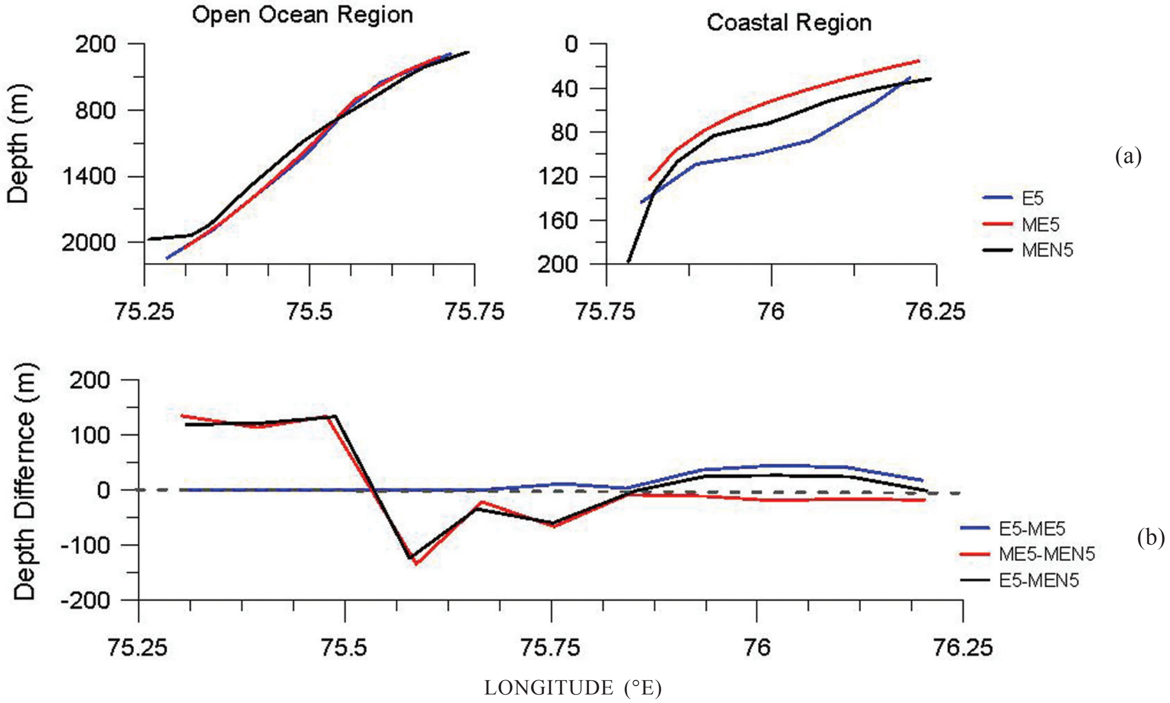


Figure 3. (a) Bottom topography along 9.5 °N (i) open ocean region (2000 m > Depth > 200 m), (ii) coastal region (Depth < 200 m) and (b) Depth difference between the three data sets along 9.5 °N.

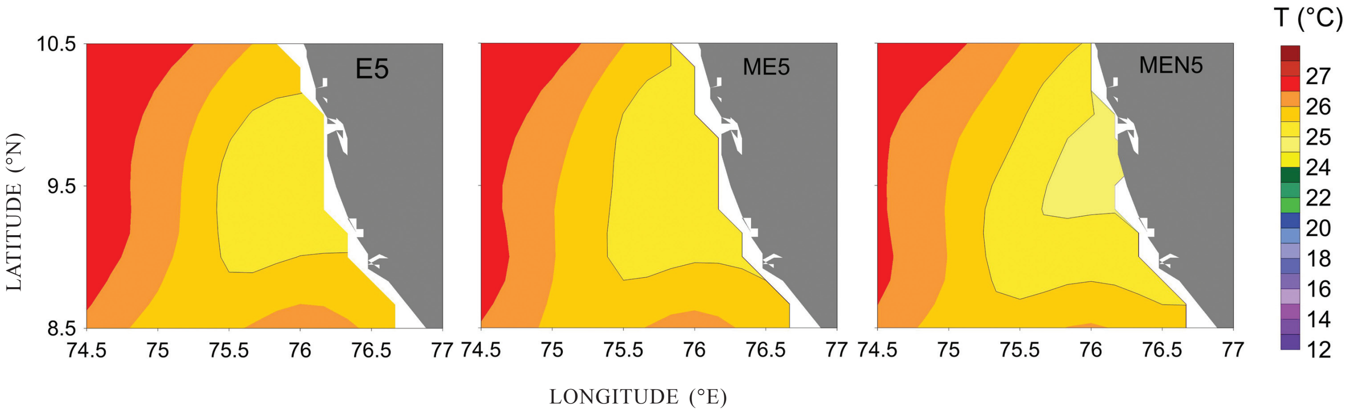


Figure 4. Simulated SST using E5, ME5 and MEN5 bathymetry.

upsloping towards the coast resulting cooler waters in the nearshore, indicting the presence of upwelling. However, with E5 and ME5 bathymetry, the model simulate (Fig. 6) slightly warmer water in the surface layer of the nearshore regions (>0.3°C). Further, a difference of 0.2 °C is noticed in the simulated temperature using MEN5 and ME5 while the difference exceeds 0.3 °C when ME5 is replaced with E5. Also, with MEN5, the simulation shows that, the 25 °C isotherm reached surface from a depth of 70 m which is in agreement with the observation (Fig 1(b)). The cooler water resolved in the surface and subsurface levels of the nearshore regions are the result of the accurate bathymetry gradient especially in the nearshore. The offshore spreading of the cold upwelled water results in the formation of an upwelling front in the nearshore. The downward bending of isotherms at the subsurface depths close to the slope indicate poleward flowing undercurrent. The computed RMSE (0.93 °C, 076 °C, and 0.71°C for E5, ME5 and MEN5 respectively) and correlation coefficient (0.95, 0.96, and 0.98 for E5, ME5 and MEN5 respectively) between different simulations and corresponding observations also suggest improvement in the simulation with MEN5 bathymetry. In the salinity field, the freshening of the surface layers in the nearshore regions and the subsurface salinity maxima associated with ASW is also well depicted in the simulation.

The simulation shows the WICC flows southward along the coast with speeds of ~40 cm/s (Fig. 5). South of 11°N, the current turns away from the coast and flow in a southwestward direction, changes its direction towards the coast around 8 °N and flows towards southeastward, thus creating a cyclonic pattern nearer to the Quilon Mount. This variability in the WICC is in agreement with the satellite derived geostrophic current (Fig. 1). Therefore, it can be concluded that there is a clear benefit of using the accurate and realistic bathymetry data for the simulation of the hydrographic properties of the SEAS.

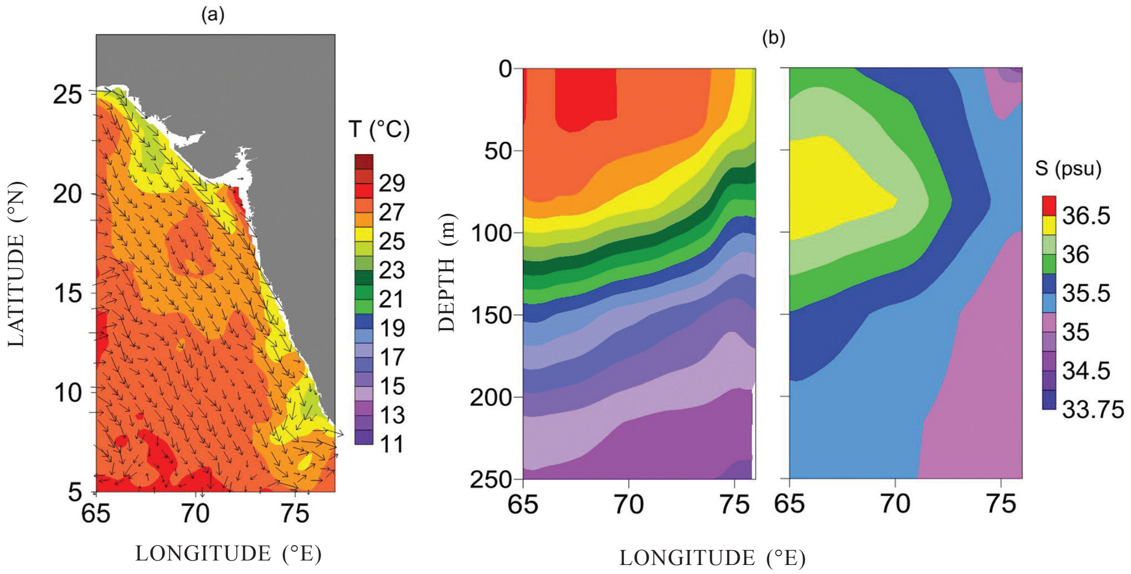


Figure 5. Simulation results, (a) SST overlaid with currents and (b) Vertical section of simulated temperature and salinity during July 2000 (Color scale for SST and vertical section of temperature is kept same).

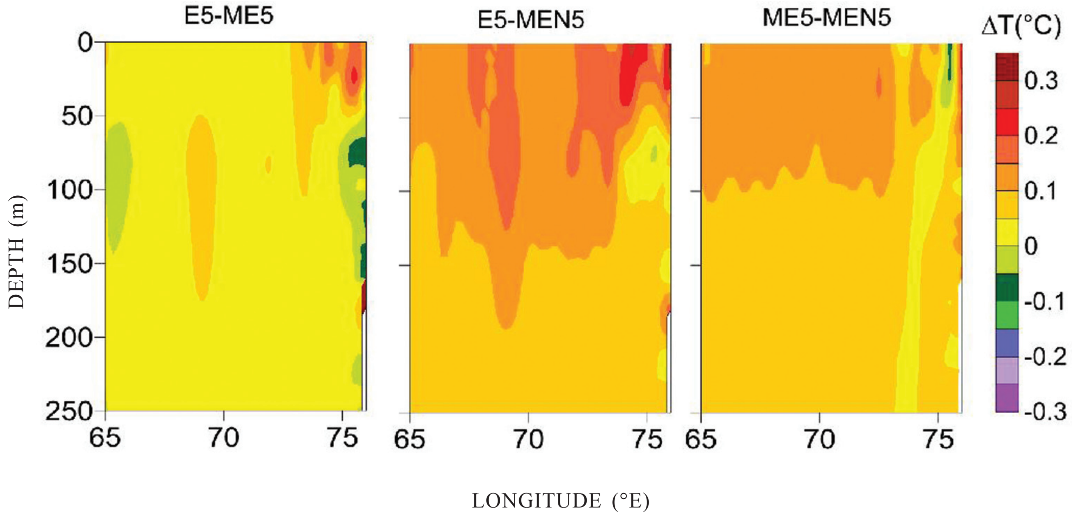


Figure 6. Difference between simulated temperature fields using E5, ME5 and MEN5 bathymetry (marked in each figure).

5. CONCLUSIONS

Princeton Ocean Model (POM) is a 3-D, free surface, time-dependent, bottom following σ-coordinate coastal ocean circulation model. The model domain covers the eastern Arabian Sea between 65° to 78 °E and 5° to 27 °N. As a first step, the fine resolution multibeam data collected by NPOL is blended with the modified ETOPO5 to develop a new bathymetry dataset. The sensitivity of three different bathymetry datasets in the simulation of hydrographic features off the southwest coast of India during the summer monsoon is evaluated utilising the POM model. In addition, the efficacy of POM in simulating the upwelling characteristics with a realistic bathymetry is also studied. The numerical experiments using three different bathymetry datasets suggests the efficiency of this newly developed dataset. The study highlights the improvements in the simulation of nearshore processes, where bathymetry is very complex, with the choice of fine resolution bathymetry data. Using the newly developed bathymetry dataset, the POM model is able to capture the coastal variability with a higher degree of accuracy (RMS error of 0.71°C and correlation coefficient of 0.98) compared to simulation with other two datasets.

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He initiated the idea and provided guidance work throughout the course of this work.