Validation of a hybrid coordinate ocean model for the Indian Ocean

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An eddy-permitting Hybrid Coordinate Ocean Model (HYCOM) configured for the Indian Ocean has been validated using both in-situ and satellite observations. The present work focuses on a detailed study of the model’s capability to simulate the major surface and subsurface variables realistically. Weekly data from the model for eight years from 1994 to 2001 are used for the evaluation of the surface data. The model simulation of the circulation patterns in the Indian Ocean for both the monsoon seasons and the transition periods matches well with the observations. Comparisons between model and satellite observations for the sea surface temperature (SST) patterns and its temporal evolution showed that the model produces realistic SSTs. The sea level anomalies (SLA) from the model compared with those from the altimeter data confirmed that the model is in good agreement with the observed SLA. A detailed comparison of results from the daily data of the model with the Argo profiles, for the years from 2002 to 2004 showed that the model has a diffuse thermocline with warming in the subsurface waters, but overall, the model simulates the subsurface temperature and salinity patterns well. The validation of the model indicates that the model results are satisfactory and that with improvements in some of the model configurations, it can be implemented in an operational forecasting system for the Indian Ocean.
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along its western coastal zones. Thus in the earlier times, most of the observational cruises as well as modelling studies were focused on the monsoon seasons and the associated reversal of Somali Current (SC) along the coast of Somalia and Oman in the western part of the AS.\(^1,2\)

The International Indian Ocean Expedition (IOE) from 1964–66 carried out the first extensive study of the Indian Ocean and the resulting hydrographic atlas\(^3\) started a series of comprehensive studies on the Indian Ocean circulation. Schott and McCreary\(^4\) give an extensive review on the monsoon circulation of the Indian Ocean based on observations, theory and modelling studies.

Numerical modelling is a powerful tool to study the oceans, especially in regions like the Indian Ocean where the observational data are sparse. Even though modelling studies of the Indian Ocean are limited in number compared to other parts of the world’s oceans, there has been major progress in the past few years. The SC, the coastal currents along the east and west coasts of India and the associated hydrographic features have received much attention in the past and present. Many of the earlier modelling studies of the SC implemented reduced gravity models\(^1,4,5\) to study its dynamics and variability. Anderson et al\(^6\) modelled the SC during the southwest monsoon in a 16-level model and McCreary and Kundu\(^7\) used a 2-/1-layer model to analyse the characteristics of the SC during southwest monsoon. All these modelling studies aided in understanding the effects of local as well as remote forcing, in driving the SC during summer monsoon and the importance of a slanted boundary in the models for proper gyre formation in the western AS.

The anticyclonic eddy formations in the south eastern AS (SEAS) during northeast monsoon were analysed in detail by Bruce et al\(^8\) employing a three layer, reduced gravity model forced by the Hellerman & Rosenstein\(^9\) wind climatology. An associated high in sea surface is developed during the northeast monsoon and a low is formed during southwest monsoon period. The formation mechanisms of these high and low were examined in detail by Shankar and Shetye,\(^10\) using their reduced gravity model for the northern Indian Ocean. McCreary et al\(^11\) published a comprehensive study of the dynamics, thermodynamics and mixed-layer process of the circulation of Indian Ocean simulated in a 2-/1-layer thermodynamic numerical model. The influences of forcing by local and remote along shore winds on the coastal currents were discussed in this study. The dynamics of the cyclonic (anticyclonic) gyre formation east of Sri Lanka during summer (winter) monsoon termed as Sri Lankan Dome (Bay of Bengal Dome) are discussed by Vinayachandran & Yamagata.\(^12\)

In recent years many of the major oceanographic features in the Indian Ocean area have been investigated using various models. The barrier layer (BL) formations in the Indian Ocean have been modelled by Masson et al.\(^13,14\) They used a coupled model to evaluate the effect of BL on the sea surface temperature (SST) and on the monsoon onset in the SEAS and in another study studied the BL formation in the eastern equatorial Indian Ocean (EIO).\(^15\) The effect of salinity on the generation of the BL in the SEAS is analysed employing an ocean general circulation model by Durand et al.\(^16\) Numerous studies have been done about Indian Ocean warm pool and in one recent study the mechanisms and formation of Arabian Sea mini warm pool is discussed by Kurian and Vinayachandran.\(^17\) Most of the earlier models were based on reduced gravity model structure, while as many of the recent models are based on versions of Geophysical Fluid Dynamics Laboratory (GFDL), Modular Ocean Model (MOM).

Haugen et al\(^18\) implemented the Miami Isopycnic Coordinate Model (MICOM) to examine the variability of the Indian Ocean in response to the monsoons and to study the inter-annual signals in the Indian Ocean. They also discussed the seasonal circulation and coastal upwelling along the southwest Indian coast using a high resolution nested model for the region.\(^19\) As a continuation of the Nansen Center’s study using MICOM in the Indian Ocean\(^20,21\) the HYbrid Coordinate Ocean Model (HYCOM) has been implemented which allows a higher vertical resolution in the mixed layer and hence give an improved representation of the surface layers,\(^22\) contrasted to MICOM. Most of the previous models developed for the Indian Ocean have coarser horizontal resolutions. Here the model has been configured with higher resolution (model details in the next section) in the northern Indian Ocean, which is the focus area of the authors’ research. The final goal is to implement a forecasting system for the Indian Ocean; however, at present no data assimilation is used, this is planned as the next step.

Even though the models have been much improved a complete study on the validation of the models used in the Indian Ocean are less common. Haugen et al\(^18\) validated MICOM for the Indian Ocean. Kurian and Vinayachandran\(^17\) presents the results of comparisons of their model (based on MOM) with observations in the study about the AS mini warm pool region. Model results needed to be evaluated and validated before utilising them for analysing or addressing any scientific problem.

Thus in this study the authors present the preliminary results from the validation of the model using in-situ and satellite observations. To validate the model for surface features the climatology of model results for eight years (1994–2001) are used. The surface currents are compared with observations based on previously published results. The surface temperatures and anomalies of sea level are compared with satellite observations. The inter-annual variability of the surface temperatures and the anomalies of sea level are also compared and the differences between the model and observations have been quantified. For the evaluation of model in the subsurface, the temperature and salinity for three years (2002–2004) are compared with the Argo profiles. A detailed description of the model configuration is given in the next section, followed by the satellite and in-situ data used for the model evaluation. The results of validation are then discussed.

MODEL DESCRIPTION

HYCOM is a hybrid coordinate model based on MICOM and is able to interchange between different vertical coordinate schemes. It is a primitive equation general circulation model with vertical coordinates that remain isopycnic in the open stratified ocean. In the weakly stratified upper ocean, the isopycnal vertical coordinates smoothly transfer to z-coordinates. This hybrid formulation gives a better emulation of the surface mixed layer and the coastal shelf regions\(^23\) compared to MICOM. The terrain following coordinates are not used in
the present configuration. The model for the Indian Ocean is set up with horizontal resolution ranging from 14 to 42 km for the entire domain (Fig 1). The conformal mapping tool is used to enhance the horizontal resolution in the northern Indian Ocean. Thus the resolution in the northern part of the Indian Ocean is 14 to 26 km, which is sufficient to resolve the larger mesoscale features.

Towards the southern part of the domain, the resolution is gradually decreasing. The model uses 30 vertical hybrid layers. The vertical mixing scheme used is the K-Profile Parameterisation (KPP) scheme of Large et al. The topography used by the model is interpolated from the General Bathymetric Chart of the Oceans (GEBCO) one minute resolution dataset (http://www.gebco.net/). The model is initialised using Generalised Digital Environmental Model (GDEM) climatology. The open boundaries relaxation of temperature and salinities to the GDEM climatology is applied. For the surface temperature and salinity the model is relaxed using 50 days time scale. The model was spun up for eight years using climatological monthly means of atmospheric data from European Centre for Medium Range Weather Forecasts (ECMWF) Re-Analysis (ERA 40) data before transition to synoptic forcing.

Following the spin up, a 13-year model run was carried out during 1992–2004 using the synoptic forcing. The synoptic atmospheric fields such as winds, surface temperature and surface dew point temperature are taken from the ERA 40 year reanalysis for the years from 1994 up to 2001 and later the operational analysis from the European Centre for Medium Range Weather Forecasts (ECMWF) are used. The precipitation from the climatological dataset of Legates and Willmott is used. The Indonesian ThroughFlow (ITF) transfers warm saline waters from Pacific to the Indian Ocean and has an impact on the Indian Ocean circulation and the surface temperature and salinity distributions in the eastern EIO.

The ITF transport to the Indian Ocean alters with season and fluctuates between 4 to 12 Sv. Gordon reports a total transport of 8–14 Sv and hence an average of ~10 Sv of ITF (with interannual modulation by ENSO) through the different passages in the Indonesian seas to the Indian Ocean. Lately Wijffles et al. estimated the mean ITF transport to be 8.9 ± 1.7 Sv, based on 20 years of XBT data. Hence in the present model the ITF has been added as a constant 10 Sv barotropic flux between Indonesia and Australia. The flux is maintained constant with depth. The model does not include tides.

From the 13-year model run, the results from the years 1994–2004 are presented here. Weekly averages were archived from 1994–2001. From 2002 daily files were stored for comparison with Argo float data (which are available...
from 2002 onwards). For some of the analysis, the results are averaged over the three major water bodies in the northern Indian Ocean; the AS, BoB and the EIO (Fig 1). The AS box is from 56ºE–75ºE and 8ºN–21ºN, the BoB from 80ºE–100ºE and 8ºN–21ºN and the EIO from 50ºE–95ºE and 7ºS–7ºN (Fig 1).

OBSERVATIONAL DATA

For validating the model, several observational datasets were used. The results discussed in this paper are validation of the model surface currents, the comparisons of sea surface temperature (SST) from the model with that derived from satellites, sea level anomaly (SLA) comparisons with altimeter data and the comparisons of temperature and salinity structure of the 1000m water column with the data obtained from the Argo profiling floats.

The dataset used for the SST comparison is the NOAA Optimum Interpolation (OI) SST V2 (version 2) data (http://www.cdc.noaa.gov). The dataset renders weekly OI SST analysis produced on a one-degree grid. The analysis uses both in-situ and satellite derived SSTs, with the satellite data adjusted for biases. The weekly data are centred on Wednesday and are available from 1989 to the present. The gridded SLA data are obtained from the multission altimeter products of Ssalto/Duacs system (http://www.aviso.oceanobs.com). The dataset is the merged gridded sea surface heights computed with respect to a seven-year mean from the multiple altimeter missions of Topex/Poseidon, ERS-1/2 + Jason-1, Envisat. The maps of SLA available for weekly intervals are used in this study. The gridded data are provided in delayed mode with a high horizontal resolution of 1/3 deg on a Mercator grid. The data are available for the time period of October 1992 to the present. From both datasets, the SST and SLA data from 1994 to 2001 are used for the comparisons.

Argo is a global drifting array of temperature-salinity profiling floats, which started operating in 2000. As of now 3000 floats have been deployed in the world’s oceans and in the Indian Ocean more than 600 floats have been deployed since the end of 2002. The Argo programme is an international collaboration and is a part of the Global Climate Observing System/Global Ocean Observing System (GCOS/GOOS). The Argo floats are designed to collect high quality temperature and salinity profiles of the upper 2000m of the world’s oceans. Thus the Argo data makes it feasible to carry out a three-dimensional validation of model results. The Argo dataset used for the present study are the gridded data available from the Indian National Centre for Ocean Information Services (INCOIS) live access server (http://las.incois.gov.in/las/getUI.do). The data from years 2002 to 2004 are used for the daily comparisons.

STATISTICAL ANALYSIS

In addition to the qualitative analysis some quantitative analysis has also been carried out for the validation. The Cost Function (CF) is a non-dimensional value which quantifies the difference between the model values and satellite data, thus indicating the goodness of fit between the two datasets. It is given by:

$$ CF = \frac{1}{N} \sum_{n=1}^{N} \frac{|D_n - M_n|}{\sigma_D} $$

where \( N \) is the total number of observations, \( n \) is the \( n \)th comparison, \( D \) is observed value, \( M \) is the model value and \( \sigma_D \) is the standard deviation of the observations. \( \bar{D} \) denotes the mean of observations. The performance criteria used here is CF <1 very good, 1–2 good, 2–3 reasonable, >3 poor. The CF values for the SST and SLA are calculated for the northern Indian Ocean for the present study.

VALIDATION RESULTS AND DISCUSSION

Surface circulation

In the first part of the validation the main focus is on the surface current patterns in response to the monsoon system. Over the northern Indian Ocean, winds blow from southwest during May–September and from northeast during November–February. In this paper, we refer to May–September as SouthWest (SW) period or summer monsoon and November–February as NorthEast (NE) period or winter monsoon. The winds are stronger during the summer monsoon than the winter monsoon. The transition periods with weak winds are in the months of March–April and October. This seasonal reversal of winds has great influence on the circulation pattern of the Indian Ocean, in particular the northern Indian Ocean. Fig 2 shows the climatology (averaged for the eight years from 1994–2001) of the surface circulation simulated by the model for the months of January (NE period), April (transition period), July (SW period) and October (transition period).

The South Equatorial Current (SEC) is the westward flow present within the latitudes 12–25ºS throughout the year. The observations from ship drifts and buoy data reports the speed of SEC as 0.4m/s and 0.3m/s respectively. The model simulates the SEC throughout the year within 10ºS to 15ºS (Fig 2). The flow peaks during the summer monsoon time (Fig 2c) with the speeds reaching up to 0.4m/s, which is in agreement with the observations. East of Madagascar it splits into two, one branch flowing northwards as the Southeast Madagascar Current (SEMC). The other branch flows northwards forming the Northeast Madagascar Current (NEMC) that feeds into the East African Coastal Current (EACC).

This branching of the SEC is clearly observed in the circulation patterns simulated by the model. The East African Coastal Current (EACC) flows northward along the African coast. The model simulates the EACC along the coast of Africa (Fig 2c). During the summer monsoon, along with the SEC it feeds water into the SC. In the western part of the Indian Ocean the strong northward flowing SC is simulated during the summer monsoon with the monthly averaged speeds of 1.7m/s. During the peak summer monsoon, a part of the SC turns offshore at around 4ºS and the Southern Gyre (SG) is formed, while the other part continues northward and forms another gyre, the Great Whirl (GW). Both these gyres
are present in the model when the data for individual years are evaluated. However in the climatology of eight years (Fig 2c) these gyres are smoothed. The southward flowing West Indian Coastal Current (WICC)\textsuperscript{33} is simulated in the model from May to September (Fig 2c). The model simulates the Summer Monsoon Current (SMC) flowing eastwards (Fig 2c) between 10ºN and the equator. The southwards flowing WICC also feed into the SMC. In the BoB (Bay of Bengal) the East Indian Coastal Current (EICC) flows northeastward from February with a fully developed phase during March–April and later reverses its direction after the withdrawal of summer monsoon.\textsuperscript{34} The poleward flow of EICC is present in the model from March–August (Fig 2b & c).

During the winter monsoon the flow along the Somali coast reverses its direction and forms a gyre with the South Equatorial Counter Current (SECC) (Fig 2a). The WICC flows northwards during the winter monsoon.\textsuperscript{35} The EACC, at around 4ºS, meets with the southward flowing SC and flows towards east as the SECC. The EICC in the BoB changes direction during this time and flow southwestward from November to January\textsuperscript{36} (Fig 2a). The modelled Winter Monsoon Current (WMC) is situated between 8ºN and the equator as the westward flowing current south of Sri Lanka. A part of the flow supplies into the WICC. The WMC flows westwards and joins the southward flowing SC (Fig 2a).

During the transition seasons, from April to June (Fig 2b) and October to December (Fig 2d) the eastward flowing strong surface jets – the Wyrtki Equatorial Jet (EJ) – is well simulated. The jet is formed due to the semiannual eastwards wind along the equator.\textsuperscript{36} The strongest part of the jet is between 70ºE and 90ºE, with averaged speeds up to 0.6m/s. In general it is concluded that the simulation of the surface circulation compares well with the observed surface circulation pattern.

**Sea surface temperatures**

Comparisons with SST (Fig 3) show that the model simulates the SST patterns for the month of January (Fig 3a, c, i) well. In general the colder waters in the northeast AS and in the northern BoB are reproduced with approximately the same temperatures. During April (Fig 3b, f, j) the warm waters that spread throughout the AS are clearly seen in the model. The tropical Indian Ocean surface waters are warm throughout the year. The building up of Indian Ocean Warm Pool (IOWP) in the southwest AS from the month of February to May\textsuperscript{37} and its collapse after the onset of summer monsoon in April and July are simulated (Fig 3b & c). The region with surface temperatures exceeding 30ºC, in the southeast AS, off the west coast of India is the warmest region – mini warm pool – during the months of April and May.\textsuperscript{17, 38, 39} This can be also seen in the modelled SST pattern (Fig 3b).

The coastal areas of the AS, especially the Arabian coast are the major zones of upwelling during the summer monsoon.\textsuperscript{17, 40} Here upwelling is observed to extend up to 400km

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**Fig 2:** The surface currents simulated by HYCOM (average of eight years; 1994–2001). The results for both the monsoon months (January and July) and the transition months (April and October) are shown. The speeds in m/s are denoted in the colour bar. Every 6th vector in X and Y direction is plotted.
offshore and run parallel to the coast. The upwelling replaces the warm surface waters with relatively colder subsurface water and the upwelling zones associated with lower SSTs along the western coast of the AS can also be seen in the model and satellite images (Fig 3c, g). During July the colder upwelling waters are found in the model (Fig 3c) and the mini cold pool which appears during the summer monsoon season near the southern tip of India and its intrusion into the BoB is clearly visible in the model but not observed in the satellite measurements (Fig 3g).

The intrusion of warmer waters along the eastern equatorial ocean during July is not as apparent in the model. During October much of the equatorial waters are warmer than the model by 1°C (Fig 3d & h). The model is generally colder in the equatorial region especially in the region that is influenced by the ITF waters (Fig 3i–l). The temperature differences are typically around 1°C. In the northern part of AS the model is warmer than the satellite by up to 1.5°C. In general the modelled SST patterns in the Indian Ocean region are in good agreement with those of the satellite measurements.

A time series of the temperature evolution (Fig 4) was made for the AS and BoB and the EIO. The differences between the observed and modelled SST for the three different regions are shown in Fig 4d. For this, both the model data and the satellite data were averaged over the AS (56°E–75E; 8°N–21°N), the BoB (80°E–100°E; 8°N–21°N) and the EIO (50°E–95°E; 7°S–7°N) (Figs 1 & 4) for the time period from January 1994 to December 2001. The temporal variations of the SSTs in the model for the AS region match with that of the satellite derived SSTs, however with slightly higher temperatures, in particular during the summer monsoon. The mean difference between the satellite observations and the model is –0.5°C. The SST plots for the BoB region show that the model is in good agreement with the satellite SSTs. Throughout the eight years the model is able to simulate the seasonal pattern of SST clearly, but again with the largest difference during the summer monsoon after 1997. For this region the mean difference between the satellite data and model is around +0.1°C. The SST patterns for the EIO show that the model performs well during 1994–1997, after which the differences increase up to 0.6°C and the mean difference between the observations and the model is +0.45°C. The increase in the differences both in the BoB and equatorial region is prominent after the extreme El Niño event and the dipole mode during the 1997–1998 period. There was an anomalous Indian Ocean warming reported during this time. Comparatively higher differences between observations and model results could be explained by the fact that the ITF is constant in the model, where as in reality, the ITF has seasonal variations. The inter-annual variability of the ITF is
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Fig 4: Time series plots of the SSTs (°C) for the period 1994–2001, from HYCOM (red) and the satellite (black) for the regions of (a) Arabian Sea, (b) Bay of Bengal and (c) Equatorial Indian Ocean. The difference (satellite minus model) for the three regions is shown in (d).

Fig 5: Statistics of model performance for SST, (a) the mean of differences (°C) between observations and the model (satellite minus model), (b) standard deviations of the differences (°C) and (c) cost function. The values are averaged for the eight years from 1994–2001.

correlated to the ENSO and Indian Ocean Dipole (IOD), the former was very strong in 1998.

In general the model is slightly warmer than the satellite measurements, which is seen in Fig 4i and k, particularly in the northernmost part of AS. The BoB shows better agreement with observations than the AS. In both regions the model reproduces the seasonal patterns well. Fig 4b shows a considerable change in the pattern for the BoB after the El Niño event and the IOD of 1997–1998. Before 1997, the model is warmer than the satellite measurements during the monsoon time and after the monsoon of 1997 the model is colder than the observations. The results from the EIO region show that the model is slightly colder than the satellite observations. In this region there is also a sudden increase in the differences in the years following 1997. In general the model agrees with the observed SST in all the three regions for the eight year simulations.
Along with the above comparisons a quantitative analysis of the SST is also carried out by calculating the CF for the northern Indian Ocean. The mean difference between the observation and the simulated values and the standard deviation of these differences are also calculated. Fig 5 shows the results. The values are averaged for the eight years (1994 to 2001) of the weekly simulation.

The modelled surface temperatures are warmer in the AS than the satellite SST, specially towards the northern coast (Fig 5a). In the BoB and in the EIO region the mean difference in temperature is less than 0.5°C. Towards the eastern side of the EIO the differences reach up to 1°C. In general the mean temperature differences do not exceed 1°C, except for the northern coastal regions of the AS. Standard deviations from the mean (Fig 5b) shows that for most parts of the northern Indian Ocean the deviations are less than 0.5°C. Towards the western part of the AS there is much more variability compared to the rest of the Indian Ocean. This could be attributed to the seasonal changes in SST along the coast, where the seasonal upwelling of colder waters occur during the summer monsoon33 and also to the mesoscale activities in the area. Higher standard deviations are also seen in the southwest coast of India (Fig 5b) which is also a region of upwelling19, 47 during the monsoon time. The CF values in the northern Indian Ocean (Fig 5c) are less than one (CF < 1 is very good) for a major part of the region. Only a part of the EIO has CF values higher than one, reaching up to 1.6 (CF between 1–2 is good). This could be from the slight offset in the temperatures of the region from 1997, as seen in the time series (Fig 4c). The CF values indicate that the model performance is very good, giving CF values of less than one for most of the northern Indian Ocean. The values also indicate that the BoB SSTs show the least differences from the observations.

Sea level anomalies

The sea level anomalies (SLA) computed from the model have been compared to the altimeter data (Fig 6). The results are shown for the two monsoon seasons, January (winter, Fig 6a,c) and July (summer, Fig 6b,d). The monthly means are averaged from eight years of model results. Since the model is not eddy resolving, the altimeter data are smoothed using the boxcar smoothing method in the Ferret software. The radius of the moving average is two degrees. During January there is low sea level near the Arabian coast associated with the upwelling,33 which is clearly present in the model. The SLA in the SEAS has a characteristic high during the winter monsoon, which is known as the Laccadive high.11 This high sea level pattern is simulated well by the model with comparable amplitudes to the altimeter data.
The high sea level along 12°S of the eastern Indian Ocean is also seen clearly in the model. The SLA along the central BoB in the model is not as high as in the satellite measurements. During summer monsoon there is a low sea level pattern observed in the southeastern AS. This low sea level is also reproduced well by the model (Fig 6b). The high sea level associated with the summer monsoon (July) in the African coast is also present in the model. In general HYCOM is able to simulate both the spatial and temporal sea level variations well and with comparable amplitude to the altimeter observations.

Time series plots for the SLA of the three regions of AS, BoB and EIO and their differences, are shown in Fig 7. The seasonal pattern of the SLA in the AS is clearly simulated by

Fig 7: Time series plots of SLA (cm) for the period of 1994–2001, from HYCOM (red) and altimeter measurements (black), for the regions of (a) Arabian Sea, (b) Bay of Bengal and (c) the Equatorial Indian Ocean. The differences in SLA (satellite minus model) for the three regions are shown in (d)

Fig 8: Statistics of model performance for SLA, (a) the mean of differences (cm) between observations and the model (satellite minus model) (b) standard deviations of the differences (cm) and (c) cost function. The values are averaged for the eight years from 1994–2001
the model as shown by the altimeter. However, the simulated SLA values for the BoB region (Fig 7b) show deviation from that of the altimeter even though the model simulates the high and low sea level patterns correctly. These differences are most prominent towards the end of 1997 and beginning of 1998, coinciding with the El Niño of 1997. After 1998 the differences are much less and the simulated sea levels are comparable in amplitudes to that of altimeter. In the EIO (Fig 7c) the model is able to simulate the seasonal variations of SLA clearly and the patterns match well throughout the time series. The differences between the simulated and altimeter sea levels for the three regions are shown in Fig 7d. The BoB shows the maximum variation in general. Even then the differences do not go beyond 6cm. The EIO SLA shows fewer differences between the model and the altimeter observations. The model also reproduces the AS SLAs well.

The statistical analyses for the SLA are presented in Fig 8, which shows the mean differences, standard deviations and CF averaged over the eight years from 1994 to 2001 for the northern Indian Ocean. The mean differences between the observations and the model SLA (Fig 8a) remain less than 0.15cm, which shows that the model could simulate realistic SLA for all the three regions. Since the satellite data do not have measurements near to the coast the statistical calculations also lack results close to the coast. However, the mean differences for the whole region show that the model results are in agreement with the altimeter data. The standard deviations from the mean (Fig 8b) have values below 8cm for most of the Indian Ocean except in two regions – near to the western part of the AS and in the BoB near to the Indian coast.

The long term comparison of temporal evolution of SLA (Fig 7) shows that the model simulates SLA that matches the altimeter observations. So the variations from the mean that is seen in the averaged standard deviations (Fig 8b) must be arising from the seasonal mesoscale activities and eddy formations occurring in these particular regions. The CF values calculated to test the goodness of fit between the observations and model SLA are shown in Fig 8c. The CF values for the whole northern Indian Ocean are less than one, thus indicating that the model is very good in simulating the SLA realistically.

Validation with Argo float data
In parts of the world’s oceans where only the surface data from the satellites and very limited hydrographic data from cruises are available, the Argo floats provide information with relatively high spatial and temporal resolution. In the Indian Ocean, there are around 600 floats deployed until now. Most of the deployments in the Indian Ocean started in 2002. The data for three years from year 2002 until 2004 are used for the validation. The Argo dataset provides daily data for the Indian Ocean, so for comparison studies, from the year 2002 the model stored daily averages.

The number of floats deployed in the Indian Ocean was very few in the beginning of 2002, especially in the BoB. But from 2003 onwards the deployment of floats increased and hence more data became available. The Argo dataset used here is from the live access server of INCOIS, which gives the gridded Argo float data produced by objective analysis. The dataset provided by INCOIS has values in the Indian Ocean in the gridded form (with one degree spatial resolution) with temperature and salinities down to 1000m depth. The data for three years from 2002 to 2004 are used for the analysis. For the analysis, the differences are calculated for the three different geographic areas shown in Fig 1. The model data are remapped in vertical using cubic spline interpolation and, from this data, the model temperatures and salinities at the location of the floats are extracted and the differences between the Argo and model data are calculated at the grid points of the float data. From these differences, the mean errors and the root mean square of errors (RMSE) are calculated for temperature and salinity and the results averaged over the three years from 2002 to 2004 are presented in Fig 9.

The temperature difference patterns at the surface level indicate that at the surface the model produces similar temperatures as those measured by the floats in all the three regions (Fig 9a,c). The deviations from the observations are more pronounced in the AS (Fig 9a). The mean differences for the AS show that the model is slightly warmer in the surface waters. In the subsurface, the model simulates much warmer water compared than observed values. The difference in the subsurface waters reaches up to 6°C. The RMSE are also at their maximum in the subsurface with values reaching up to 1.5°C. This subsurface warming is in the depth range of 100m to 300m. Below 400m the model simulates slightly cooler water temperatures than measured temperatures but the differences are less than 2°C at most of the depth levels.

The BoB (Fig 9b) agree better with the observations than the two other regions. The mean differences and RMSE also show that the model agrees well with the Argo data for the surface waters of the area. The subsurface warming is present up to an extent in this area too, with the model showing a mean 3–5°C increase in temperature in the same depth range of 100m to 300m. The mean differences below 400m are less than 2°C and shows that the model temperatures do not vary much from the measured values.

The differences between the model and the Argo temperatures are close to zero in the EIO for the surface waters (Fig 9c). For the waters in the deeper levels (below 400m), the temperatures from the model are close to those measured by the floats, whereas in the subsurface the temperatures simulated by the model are warmer than the measurements. The main feature that stands out in the comparisons is the subsurface warming. But this problem is not just specific to this particular model set-up. Most of the numerical models have problems in simulating a sharp thermocline. The simulation of diffuse thermoclines are seen in other models too.

The HYCOM model used by Winther et al45 for the North Sea and Skagerrak region to test the skills of the model in coastal shelf areas, reports a diffuse thermocline. Lee et al46 also reports a similar weakly stratified and warmer thermoclines in their simulations. The experiments performed with the present model by changing target densities did not have a prominent effect on the diffuse thermocline formation. It is assumed this could be more of an algorithmic problem/treatment of hybrid coordinate layers. A more recent version of
HYCOM has improved behaviour at the base of the mixed layer and will be used in further studies.

The comparisons of model salinities with Argo float data are also done for the upper 1000m water column of the three geographic regions selected in the northern Indian Ocean. In the AS (Fig 9d) the surface salinity differences are around 0.2 psu, with model simulating fresher waters. The subsurface waters in the model are more saline than the measured data, with the differences reaching up to 0.3 psu. Below 300m the model produces fresher waters again, but the differences do not go beyond 0.3 psu. The RMSE values show more deviations in the surface waters. The RMSE values are also less than +0.3 psu.

The mean salinity differences in the BoB (Fig 9e) are low below 400m. The surface mean errors also show that the model simulates the surface salinities close to observations for the region. However, for the subsurface level the model is much fresher compared to the other two regions. The mean differences reach up to 0.9 psu at 100m. The RMSE values show larger variations in the surface waters compared to the
subsurface values, which could be attributed to the freshwater input fluctuations to the region. This could be improved by providing more realistic river inputs in the next version. The mean differences between the model and Argo salinity values in deeper water levels are lower than 0.1 psu with not much deviation from the mean values. The EIO salinities (Fig 9f) from the model agree well with the salinities from the Argo floats almost throughout the water column, with mean differences below 0.2 psu, except around 100 m where it reaches around 0.3 psu. The deviations from the mean calculated for the region are also small.

SUMMARY AND CONCLUSIONS

In this study, we have validated a HYCOM model for the Indian Ocean region. An extensive comparison of model results with in-situ and satellite observations has been conducted and the results presented. Weekly data from eight years (1994–2001) are validated for the surface features of currents, SSTs, and SLA. For the next three years (2002–2004) the model is compared with the Argo float data to test how the model produces the temperature and salinity structure in the upper 1000 m water column.

The weekly surface currents from the eight-year run are compared with the known circulation features of the area gathered from previously published results. The model simulates the surface current in the study region remarkably well. It is able to produce the major surface current patterns with realistic speeds. The spatial comparison of SST patterns for the eight-year averages and its temporal evaluation during this time for the entire region shows that the model is able to produce accurate SSTs for the northern Indian Ocean. The differences between the model and observations after 1997 could be because the ITF is given as a constant flux into the model. The ITF is correlated with the ENSO and IOD and hence the changes in the flow during the anomalous events could not have been simulated in the model as it is kept constant.

This could be taken care of in the next version by using a seasonal cycle of the ITF rather than the mean value or by nesting a validated global model. The mean error, standard deviation, and CF are calculated to quantify the model performance. The mean error is around 1 °C in most parts of the northern Indian Ocean except for the northern coastal region of AS. The maximum deviations from the mean are associated with the upwelling regions in the Indian Ocean. The CF values for SST remain less than one for a major part of the northern Indian Ocean, which shows a very good level of performance by the model.

The SLA comparisons also give satisfactory results with the model reproducing the major sea surface height features and their temporal variability. The temporal evolution of SLA for the eight years also shows that the model compares well with the observations, especially in the AS and EIO region. The mean differences between observations and the model results are lesser than 0.15 cm. The standard deviations calculated shows that the model has more variability in the regions near to the western coast of the Arabian Sea (AS) near to the Somali coast and in the western coast of the Bay of Bengal (BoB), which are regions of seasonal eddy formations. The CF values of SLA remain less than one for the entire Indian Ocean indicating that the model produces the SLA remarkably well.

The validation with the Argo float dataset has been carried out for the three regions (AS, BoB, EIO) for the years 2002 to 2004. The differences between observations and model (mean error) and the RMSE values were calculated at common depths down to 1000 m. The results show that in all the three areas of the Indian Ocean, the model is able to reproduce the surface temperatures and salinities realistically. BoB shows the maximum salinity differences and RMSE compared to AS and EIO. This will be taken care of by introducing more realistic river fluxes in the next version.

In the subsurface waters, the model shows considerable differences in temperatures between the observations and the model, especially in the thermocline region. The model is warmer than the observations here. The warming, however, is not just a problem in this present configuration, but a common problem in numerical ocean models as stated in different modelling studies.46, 48 Using a more advanced vertical interpolation might bring an improvement in the new version. Further studies with sensitivity experiments should be done to verify this. Elsewhere in the intermediate and deep waters, the model produces the temperature and salinity pattern that is very much similar to that measured by the Argo floats.

It is concluded from the validation results that the model gives a good comparison with the in-situ and satellite data. The model is developed with the objective of making a forecasting system for the Indian Ocean. It is concluded that with the suggested improvements included, the model can further be used to study the major oceanographic features of the Indian Ocean and can be developed into a forecasting tool for the region.

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REFERENCES


Validation of a hybrid coordinate ocean model for the Indian Ocean


