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Assessment of an ocean-ecosystem model in simulating the Indian coastal marine ecosystem dynamics

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ABSTRACT

This study describes an assessment of an ocean-ecosystem model in simulating marine ecosystem dynamics in the Indian coastal waters. Long-term sustained *in-situ* observations of temperature, salinity, chlorophyll-*a* and dissolved oxygen (DO) collected in the coastal waters of India, and ship-based observations are used for this assessment. The model captures observed trend of temperature, salinity and chlorophyll-*a* with high correlation in both eastern and western shelf waters except for salinity and DO along west and DO along east coast. The model performs very well in simulating the Indian coastal shelf ecosystem dynamics. The seasonal occurrence of prominent phytoplankton bloom in the central-east coast during pre-monsoon, south-west coast during monsoon and north-west coast during post-monsoon is realistically reproduced by the model. The model also reproduces the seasonal presence of significantly low DO content in the upwelled water at a shallow depth leading to coastal hypoxia in the south-west and central-east coast of India during summer monsoon. A fine-tuned model is useful in understanding better Indian coastal shelf ecosystem and predicting future changes in time and space, like the occurrence of coastal hypoxia or anticipating phytoplankton blooms. Such information is useful for predicting potential fishing grounds in coastal waters and fisheries management.

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Indian coastal waters; ROMS; SATCORE; phytoplankton bloom; coastal hypoxia

Introduction

The geographical setting of the north Indian Ocean makes it a unique ecosystem. The Indian Ocean is land-locked in the tropical north and west, connected to the low latitude western Pacific in the east and open to the Southern Ocean in the south. Although in the same geographical regime, the two components of the north Indian Ocean i.e. Arabian Sea (AS) and Bay of Bengal (BoB), exhibit different physical processes and associated biogeochemistry. The circulation patterns of both seas are driven by the seasonally varying monsoon. The water mass mixing process is comparatively higher in the AS than in the BoB. In general, the AS plays a major role in the onset of monsoon while the BoB has an important role in retreating monsoons (Murty et al. 1992; Raju et al. 2005). The coastal processes, monsoonal forcing and land runoff have a greater impact on the physical as well as biogeochemical conditions of both basins (Ramesh Kumar and Prasad 1997). In the context of the BoB, seasonally reversing East India Coastal Current (EICC) plays an important

role in controlling the biogeochemistry of coastal waters (Shetye et al. 1996; Chaitanya et al. 2014). The coastal areas of the AS are major zones of upwelling during the southwest monsoon (Smitha et al. 2008). The coastal upwelling is a major oceanographic process that influences nutrient concentration both in the AS and BoB.

A large population in the Indian sub-continent resides in the coastal areas and depends on the coastal ocean for their food and economy. Local factors such as changes in land use, particularly agricultural activities, urbanisation and industrialisation, construction of new ports all along the Indian coast, etc. make the Indian coastal waters especially vulnerable to anthropogenic perturbations (Rani et al. 2015; Bhavya et al. 2016). Human interference and large-scale climate-related changes significantly impact the ocean for the last couple of decades leading to modifications in the water column chemistry and the plankton ecosystem. Additionally, the changes in natural climate events such as an increase in intensification of tropical cyclones, heavy precipitation events, El Nino/IOD, etc. leading to alterations in ocean mixing and transport

processes. These changes influence nutrient supplies to the photic zone leading to modifications in the ecosystem structuring which is subsequently impacting the fisheries (Madhupratap et al. 1996; Murty et al. 2000; Sarma et al. 2006; Kumar et al. 2007; Vinayachandran, 2010; Nuncio and Kumar 2012; Currie et al. 2013; Gupta et al. 2016; Lotliker et al. 2020).

The coastal marine ecosystem is particularly vulnerable by virtue of the possible changes in ocean mixing due to increased ocean stratification and in the intensity of coastal upwelling. These changes are expected to reduce overall primary productivity and alter the biomass and composition of lower trophic levels, leading to changes in the structure of food webs that support marine living resources, which has a direct impact on the lives and livelihoods of coastal communities.

The load of nutrients significantly increases to the coastal ocean in the last three decades. Excessive nutrient loadings in coastal waters have become a serious environmental issue causing eutrophication and unusual phytoplankton blooms. The phytoplankton bloom is an environmental phenomenon resulting due to the rapid multiplication of phytoplankton species over a small period of time. The phytoplankton blooms are regarded as harmful when it exerts deleterious effects on the flora and fauna as well as on the environment. The spatio-temporal occurrence of Harmful Algal Blooms (HAB) is of major ecological concern in the present time. Anthropogenic impacts and a multitude of natural phenomena are frequently triggering HABs in different coastal areas of the globe (Harrison et al. 2011; D'Silva et al. 2012; do Rosário Gomes et al. 2014; Dwivedi et al. 2015; Baliarsingh et al. 2016; Lotliker et al. 2018).

In the same line, the change in watershed properties through coastal eutrophication (e.g. freshwater influx together with land-source nutrients, marine and terrestrial organic materials) can potentially lead to the coastal hypoxia. Additionally, the possible changes in the surface layer heat budget, wind-induced turbulent mixing and stratification resulting from the changes in global forcing are also considered as the potential cause in increasing the number of coastal hypoxic zones. The incidence and extent of coastal hypoxia have risen over the last century from ~ 20 sites before 1950 to ≥ 400 sites at the beginning of this century, mainly as a result of increasing human derived discharges of nutrients and organic matter. The natural hypoxic zone that develops seasonally over the western Indian continental shelf appears to have intensified over the last three decades (Naqvi et al. 2000, 2006; Piontkovski and Al-Oufi 2015; Shenoy et al. 2020). The

intensification of coastal hypoxia is also expected to have a large impact on food resources. It may potentially affect the entire food-web structure and species' movements, productivity, etc. important for the sustainability of marine ecosystems.

The complex dynamic nature of the coastal marine ecosystem makes it less predictable. Ecosystem modelling is a key scientific technique by which one can elucidate the mechanism of the marine system and predict its evolution in both the short and long term. Thus, the fundamental modelling technology for operational forecast, climate change science and environmental risk assessment is of high strategic importance. These models are designed to identify specific physical, chemical and biological processes, and to determine the relative influence of major environmental forcing functions. Despite some limitations and problems of initialisation, calibration and validation, the model output has been successfully used to study coastal processes and their impact on the biogeochemistry of coastal waters (Gruber et al. 2006; Travers et al. 2009; Fiechter et al. 2011; Marta-Almeida et al. 2012).

Based on the above backdrop, a high resolution, coupled ocean-ecosystem model has been configured using Regional Ocean Modeling System (ROMS) for the Indian Ocean to meet the operational and scientific needs of the Indian National Centre for Ocean Information Services (INCOIS). The present study is carried out to make an assessment of the model in simulating coastal ecosystem dynamics of Indian shelf waters. The validation has been performed against long-term sustained *in situ* observations collected as a part of SATellite Coastal and Oceanographic Research (SATCORE) and ship-based observations. Subsequently, the model is utilised to study coastal ecosystem dynamics associated with seasonally varying monsoon in the Indian coastal waters. The rest of the paper is organised as follows. The observations used in this study and a state-of-the-art high resolution, coupled, regional ocean-ecosystem model are introduced in Section-2. Major results and discussions are presented in Section-3 followed by conclusions in Section-4.

2. Data and methods

2.1. Long-term sustained observational network

A long-term sustained observation network consisting of eight time series sampling stations in Indian coastal waters (off Okha, Goa, Mangalore and Kochi along the west coast and off Parangipettai, Chennai,

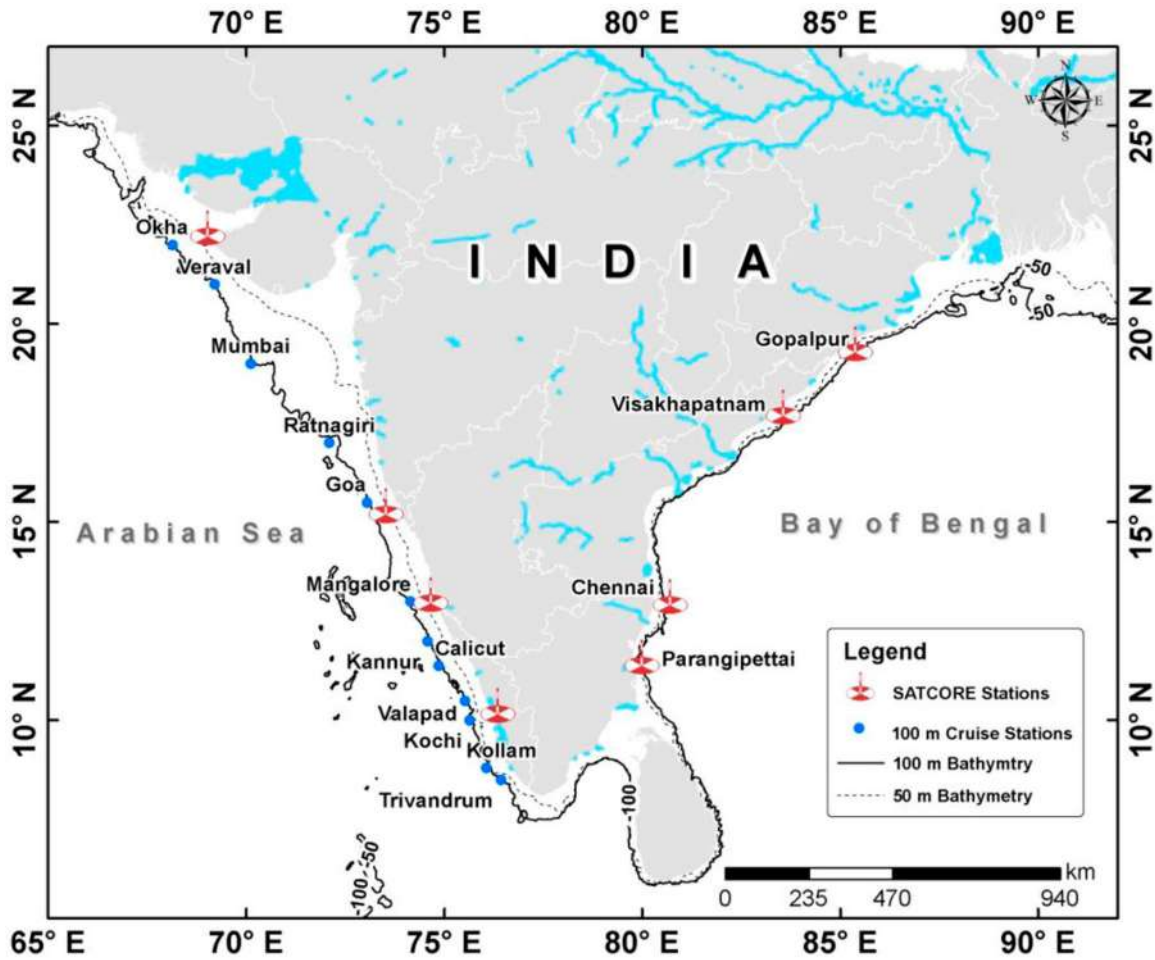


Figure 1. Schematic showing the study area. Long-term sustained time-series stations established under SATCORE project are shown as (★). Blue dots are depicting the cruise stations along 100 m depth contour in the western continental shelf of India.

Visakhapatnam and Gopalpur along the east coast) was established by the Indian National Centre for Ocean Information Services (INCOIS) as a part of its SATellite Coastal and Oceanographic REsearch (SATCORE) programme (Figure 1). A comprehensive dataset of water temperature, salinity, chlorophyll-a (chl-a) and dissolved oxygen (DO) generated during 2008–2017 is used for model validation in this study. At all SATCORE stations, monthly time series samples were collected up to a maximum water depth of 50 m. *In situ* data collected across the water column are used for model validation. The water temperature was measured using a centigrade thermometer. Knudsen's argentometric titration method was adopted for determination of salinity and Winkler's titration method was used for estimation of DO (Grasshoff et al. 1999). Chl-a concentration was estimated spectrophotometrically following 90% acetone extraction method (Strickland and Parson 1965). To ensure the accuracy of the parameters measured at various laboratories at different time-series locations, SATCORE Inter-comparison

Exercises (SICOME) were also conducted during 2014 and 2015 (Lotlikar et al. 2016).

2.2. Ship-based observations

A cruise was conducted onboard FORV Sagar Sampada to study the physical characteristics and associated biogeochemical response of the eastern AS during late summer monsoon (September–October) of 2014. The intense study on physico-chemical state of the ocean was carried out along 12 transects across the shelf waters of the west coast of India. The physical variables (temperature, salinity and DO) were collected using a CTD (SBE Model 11 PLUS, Sea-Bird Inc.) in 1 m bin intervals. The DO profiles obtained from the CTD casts were calibrated against the measured concentrations of samples (Winkler method, Grasshoff et al. 1999) collected from discrete depths ($R^2 = 0.98$). The data collected from 100 m stations (blue dots in Figure 1) were used here to make an assessment of the capability of model in reproducing the physical and

biogeochemical state of the coastal ocean over the western continental shelf of India across latitudes.

2.3. Ocean-ecosystem model

The ocean general circulation model used in this study is the ROMS (version 3.7). ROMS is a free-surface, terrain-following, primitive equations ocean model widely used by the scientific community for a diverse range of applications (Song and Haidvogel 1994; Haidvogel and Beckmann 1999; Haidvogel et al. 2000; Marchesiello et al. 2003; Shchepetkin and McWilliams 2003, 2005; Wilkin et al. 2005; Fennel et al. 2006, 2008, 2013; Haidvogel et al. 2008; Chakraborty et al. 2016, 2017, 2018, 2019a, 2019b). A fully coupled high-resolution ocean-ecosystem model has been configured using ROMS for the Indian Ocean basin (30°E to 120°E; 30°S to 30°N).

This physical model is configured with a horizontal grid resolution of 1/12° and it carries 40 vertical layers in a terrain-following s -coordinate system. The narrow channel between India and Sri Lanka is kept as closed and isolated land mask points were removed. The shallow Malacca strait and the part of the South China Sea are also removed from the model grid. The vertical profile has a resolution of 0.7 m near shore. Off the shelf with a 5000 m bottom depth, the vertical resolution ranges from 15 m at the surface to 500 m at the bottom. Bathymetry is supplied by Sindhu et al. (2007). The vertical stretching parameters are chosen in such a way that a finer vertical resolution is ensured in the upper part of the ocean. There are approximately 26 levels in the top 200 m of the water column in the deep ocean (with depth more than 3500 m). In the shallow regions, the number of levels in the given depth of water column is more. The K-Profile Parameterization (KPP; Large et al. 1994) vertical mixing scheme is used for parameterisation and biharmonic viscosity and diffusion schemes are chosen for horizontal mixing (Griffies and Hallberg 2000). The lateral boundaries in the east and south are treated as open. The western and the northern boundaries are solid walls.

The biological component of the coupled setup uses the nitrogen cycle model with parameterised sediment denitrification as described by Fennel et al. (2006). The nitrogen cycle model includes seven state variables, namely, phytoplankton, zooplankton, nitrate, ammonium, detritus classes (large and small) with nitrogen concentration and phytoplankton chlorophyll. The time rate of change of concentration of each state variable describes the balance of advection-diffusion and source-sink terms among the related state variables of the nitrogen cycle (Fennel et al. 2006). The biological model also resolves the full carbon cycle. The model carbonate

chemistry in the biological model is described following Zeebe and Wolf-Gladrow (2001) and Fennel et al. (2008). The full carbon cycle is represented in the model using four state variables, namely, alkalinity, dissolved inorganic carbon, detritus class (large and small) with carbon concentration. The dynamics of dissolved inorganic carbon include the primary production and respiration as sinking and source processes respectively following Redfield stoichiometry besides gas exchange at the air-sea interface. The biogeochemical processes, such as calcite formation and dissolution, nitrate uptake and regeneration, and sulphate reduction are represented in the dynamics of alkalinity. Oxygen is included as model tracer and biogeochemical dynamics of oxygen is described in the model following Fennel et al. (2013).

The one-way nested modelling approach in which a global ocean general circulation model provides boundary data to a regional model that is further coupled with an ecosystem model has been used in the present model set up (Shulman et al. 2004). In this approach, we make use of Global Ocean Data Assimilation System (GODAS) configured and operationalised at INCOIS using Modular Ocean Model-4.0 (Ravichandran et al. 2013). The GODAS has 1/2° resolution in zonal and meridional direction, however the meridional resolution is 1/4° within 10°S–10°N and it carries 40 vertical levels. In order to simulate the true state of the ocean, the model is forced with realistic atmospheric forcing in inter-annual timescales. The tracer fields (temperature and salinity), sea surface height and the components of momentum are initialised with the state of the ocean as available in the GODAS on 01-Jan-2003. The biological variables are initialised using the climatological state of January generated during climatological run of the coupled set up. The weekly averaged boundary on inter-annual time scale derived from the GODAS is prescribed for the tracers, sea surface height and momentum fields along the east and south lateral boundary, however for the biological state variables, nitrogen, oxygen, alkalinity and dissolved inorganic carbon climatological boundary conditions derived from the World Ocean Atlas (WOA; Boyer et al. 2013) are kept. The model is forced with National Centre for Medium Range Weather Forecast's (NCMRWF, New Delhi, India) winds, precipitation and radiation fluxes (Prasad et al. 2014). Six-hourly analysed atmospheric forcing fields include air pressure at 2 m, air temperature at 2 m, net shortwave and longwave flux, rainfall rate and wind velocity. Surface heat and momentum fluxes are internally calculated by ROMS using the bulk parameterisations (Liu et al. 1979; Fairall et al. 1996a, 1996b). The climatology of monthly river discharge has been implemented as a freshwater flux

using the global river flow and continental discharges estimated by Dai et al. (2009). The point-source method is used to distribute freshwater discharge volume of all the rivers individually in the model grids. The distribution of total volume flux of the river takes place in single or multiple horizontal grid points identified at the river drainage points and the corresponding vertical levels. The prevailing surface circulation advects the riverine freshwater.

An inter-annual run of the model has been carried out from the year 2003 to 2017. Daily averaged output is stored from 2003 to 2017, but to ensure that the model has reached its equilibrium state, daily averaged outputs from 2006 have been used for the analysis. The detailed description and validation of the Indian Ocean ROMS model have been presented in Chakraborty et al. (2018, 2019a, 2019b).

2.4. Statistical analysis

The model-simulated water temperature, salinity, chl-a and DO were validated against available *in situ* observations made in the continental shelf waters of India under the SATCORE programme. Initially, the model-simulated spatially box-averaged temperature, salinity, chl-a and DO for the corresponding date and location of *in situ* sampling was extracted for validation. The dimension of each box around *in situ* sampling station was $0.4^\circ \times 0.4^\circ$. Although a significant trend was observed between *in situ* and modelled variables, there was a large scatter around the trend. In the process of data quality control, the outliers were eliminated by filtering based on the absolute percentage difference (APD) of *in situ* and modelled data. The scatter plot showing relationship between *in situ* measured and model-simulated temperature, salinity chl-a and DO is shown in Figure 2. Although on the same latitude, AS and BoB exhibit different physical processes influencing the water column biogeochemistry. Therefore, the validation is performed separately for western (West Coast) and eastern (East Coast) continental shelf waters of India. The detailed account of statistics is described in Table 1. Statistical indices such as slope, intercept, correlation coefficient (R^2), mean ratio of measured to estimated values (r), root mean squared error (RMSE), absolute (APD), relative (RPD) and unbiased percentage difference (UPD) are used to determine the accuracy of the model.

3. Results and discussion

Understanding the spatial-temporal dynamics of the coastal ocean is a long-standing challenge. We have

configured a very high resolution, regional, coupled ocean-ecosystem model to understand the coastal ecosystem dynamics associated with physical mechanisms. The results of extensive validation of the model to establish its capability in simulating open ocean dynamics of the Indian Ocean against available remote sensing and *in situ* observations have been reported in our earlier studies (Chakraborty et al. 2018, 2019a, 2019b).

In this study, an assessment of the capability of the model in simulating coastal ecosystem dynamics of the Indian continental shelf waters has been carried out against long-term sustained observations made in the coastal waters of India along with ship-based observations. The capability of the model in simulating coastal ecosystem dynamics is presented here to avoid redundancy.

3.1. Validation of temperature, salinity, chlorophyll-a and dissolved oxygen against SATCORE stations

The capability of model in simulating water temperature, salinity, chl-a and DO is assessed by comparing with the *in situ* data generated at SATCORE time series stations. The assessment is based on the statistical indicators provided in Table 1.

In general, model is able to capture the trend ($R^2 > 0.78$) in both eastern and western shelf waters except for salinity ($R^2 = 0.44$) and DO ($R^2 = 0.50$) along west coast and DO ($R^2 = 0.53$) along east coast. The validation statistics for temperature showed slope close to unity ($=1.04$ along West and 0.91 along East Coast), lower RMSE ($=0.89^\circ\text{C}$ along West and 0.79°C along East Coast), lower percentage error ($<2.67^\circ\text{C}$ along west and $<2.38^\circ\text{C}$ along east Coast), moderate bias ($= -0.77$) along west coast and high bias ($=2.9^\circ\text{C}$) along east coast.

In the case of salinity, slope ($= 0.49$) and correlation coefficient ($= 0.44$) are relatively less for west coast as compared to east coast ($S = 0.84$ and $R^2 = 0.86$). The intercept is also large for west coast ($=17.87$ PSU) as compared to east coast ($= 5.10$ PSU). However, the percentage error is less (<1.52 PSU) for both west and east coast.

The chl-a is well simulated by the model with a slope value of 0.73 along west coast and 0.82 along east coast. Although higher APD is observed for both West ($= 41.57\%$) and East ($=34.64\%$) Coast, low RMSE (<0.75 $\text{mg}\cdot\text{m}^{-3}$ for west and east coast) and high correlation ($R^2 = 0.89$ along west and $= 0.84$ along east coast) is observed. The intercept is also lower (<0.08 $\text{mg}\cdot\text{m}^{-3}$) for both west and east coast.

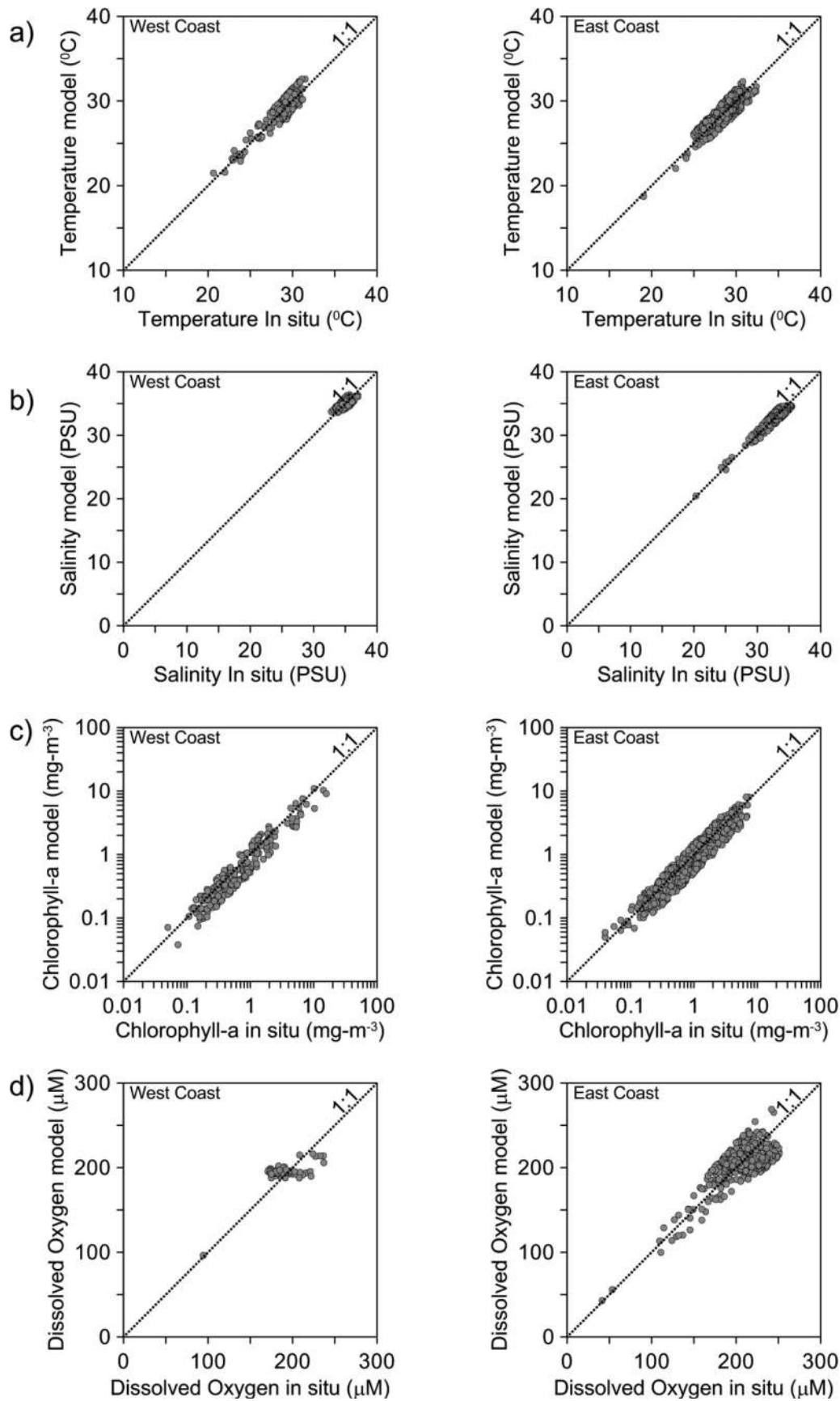


Figure 2. Scatter plot showing the relationship between *in situ* measured and model-simulated (a) temperature, (b) salinity, (c) chlorophyll-a and (d) dissolved oxygen in the western (left panel) and eastern (right panel) continental shelf waters of India. The dotted line represents 1:1.

Table 1. Statistical performance indicators between model-simulated and *in situ* measured variables (temperature, salinity, chl-a and DO) from SATCORE stations.

Variable	Coast	N	S	I	R^2	r	RMSE	APD	RPD	UPD	Fmin	Fmed	Fmax
Temperature	West	293	1.04	−0.77	0.82	0.99	0.89	2.67	−1.4	−1.4	0.06	0.38	2.33
	East	582	0.91	2.90	0.78	0.99	0.79	2.38	−0.8	−0.7	0.11	0.62	3.58
Salinity	West	134	0.49	17.87	0.44	1.00	0.61	1.52	0.11	0.12	0.27	1.11	4.59
	East	608	0.84	5.10	0.86	1.00	0.56	1.45	0.21	0.23	0.33	1.21	4.35
Chl-a	West	259	0.73	0.08	0.89	1.31	0.75	41.57	15.41	21.51	0.32	1.65	8.60
	East	516	0.82	0.06	0.84	1.224	0.603	34.64	10.03	15.01	0.420	1.57	5.836
DO	West	63	0.46	106.81	0.50	0.970	16.02	7.15	−3.66	−3.31	0.000	0.00	-
	East	581	0.62	78.38	0.53	1.006	16.93	7.00	−0.02	0.31	0.000	11.00	-

The performance of model in simulating DO is relatively poor as compared to other parameters. The correlation coefficient is moderate ($R^2 = 0.50$ along west and $= 0.53$ along east coast). The bias and RMSE are also large for both west ($I = 106.81 \mu\text{M}$ and $\text{RMSE} = 16.02 \mu\text{M}$) and east ($I = 78.38$ and $\text{RMSE} = 16.93 \mu\text{M}$) coast.

The F values refer to the inverse transform ratios between measured and estimated values of mean (F_{med}), addition of mean and standard deviation (F_{max}) and subtraction of standard deviation from mean (F_{min}). The ratio closer to unity provides the accuracy of the estimated parameter in lower (F_{min}), middle (F_{med}) and higher range (F_{max}). The F values indicate better accuracy of model-simulated parameters at median scale (Campbell et al. 2002).

3.2. Validation of model temperature, salinity and dissolved oxygen against ship-based observations

Upwelling is a major mechanism along the eastern AS during summer monsoon (June–September) which brings cool, oxygen-depleted and nutrient-rich offshore waters to the shelf and enhances the biological production (Naqvi et al. 2006; Gupta et al. 2016). The intra-annual variation over the southeastern AS shelf showed that the upwelling is discernible at depths during January–March, peaked to surface during summer monsoon (June–September) and thereafter abruptly recessed (Gupta et al. 2016). The late summer monsoon (September–October 2014) cruise observations all along 100 m depth contour of eastern AS showed the presence of much cooler, saline and oxygen-depleted waters in the central region (12–17°N) due to sustained upwelling. The north and south of this region were relatively warmer and oxic, as the upwelling over the former is weak while it is already under the withdrawing phase (Gupta et al. 2016) in the latter. Highly saline (>36.2) and relatively oxygenated waters have occupied the entire water column of northern region. It has been shown recently

by Sudheesh et al. (2016) that the central shelf of eastern AS exhibits intense upwelling during late summer monsoon. Our model has very well captured this late phase upwelling over the central shelf and withdrawal phase in the south, albeit the model has simulated intense cooling (by $\sim 2^\circ\text{C}$) below 25 m (Figure 3). Similarly, the model-simulated salinity distribution in the central and southern regions well agreed with the observations, but it underperformed in the north where Arabian Sea High Salinity Water mass (ASHSW, >35.6) occupied. Although DO simulation corroborated with the observations, the intense cooling simulated by model in the subsurface layers of central region was associated with relatively more oxygen (by $\sim 10 \mu\text{M}$). The difference is more serious in the bottom layers where the model has simulated hypoxic conditions ($>20 \mu\text{M}$) as against observed sub-oxic conditions ($<10 \mu\text{M}$), a condition in which the benthic-pelagic coupled ecosystem generally undergoes large-scale biogeochemical and biological changes (Naqvi et al. 2006; Abdul Jaleel et al. 2015; Sivadas et al. 2016; Sudheesh et al. 2016). The greatest difference between model results and observations was noticed in the north where oxygen concentrations at >50 m are depleted by $\sim 30 \mu\text{M}$. This degree of error in model-simulated deoxygenation could be due to the offset in capturing the ASHSW in this region. Overall, the model performed very well against the observations and captured the varying phases of upwelling and deoxygenation over the eastern AS. However, the present ocean-ecosystem model needs further refinement to better represent the ecosystem at below threshold conditions (suboxia).

3.3. Variation of temperature, salinity, dissolved oxygen and chlorophyll across latitudes

The model-simulated multi-year average (2006–2017) monthly composite outputs of temperature, salinity, chl-a and DO are used to understand a comprehensive view of the seasonal variability of coastal ecosystem across latitudes in the continental shelf waters of

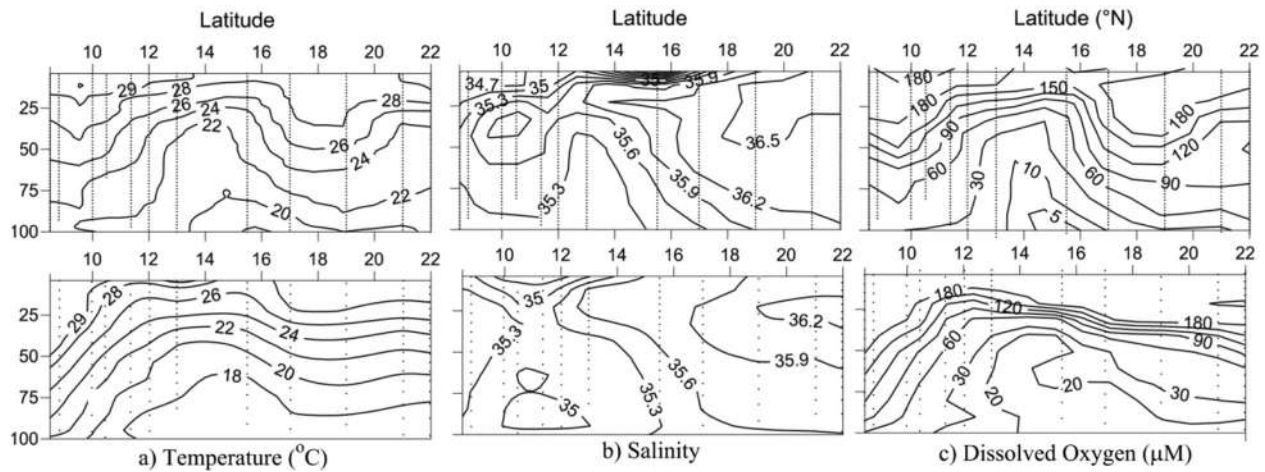


Figure 3. Comparison of model-simulated (lower panel) temperature (°C), salinity and dissolved oxygen (μM) against ship-based observations along 100 m depth contour (upper panel) in the western continental shelf of India.

India. The model in the AS has captured intense cooling with a deep mixed layer (~70 m) in the north during January–February due to winter convective mixing

(Figure 4), after its culmination by March the mixed layer depth (MLD) gradually shoaled to 30 m by June, sustained there till October and deepened thereafter to

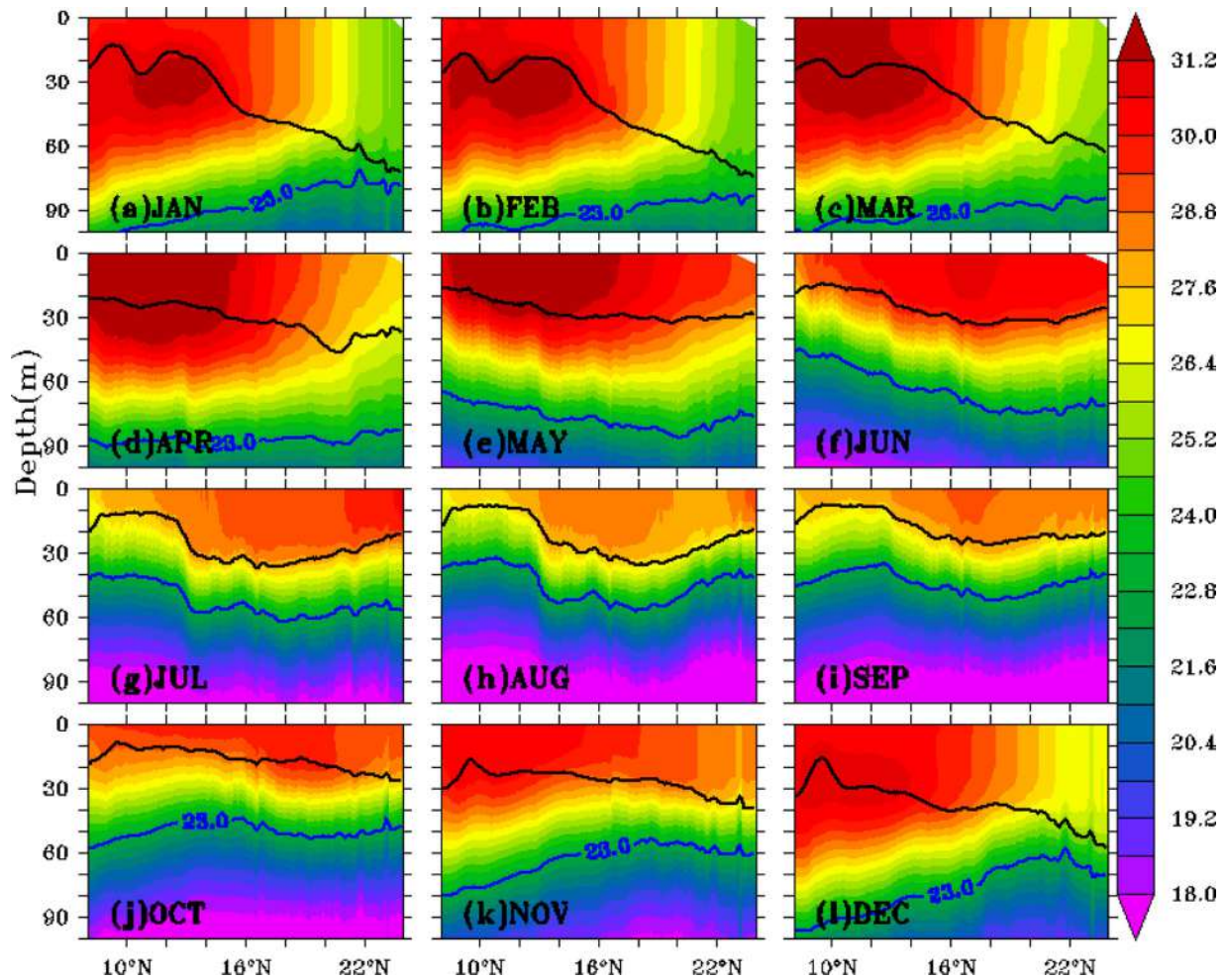


Figure 4. Multi-year average (2006–2017) monthly composite of model-simulated temperature (°C) across latitudes along the 100 m depth contour in the western continental shelf of India. Black line represents MLD (m) and blue line represents 23°C isotherm (m).

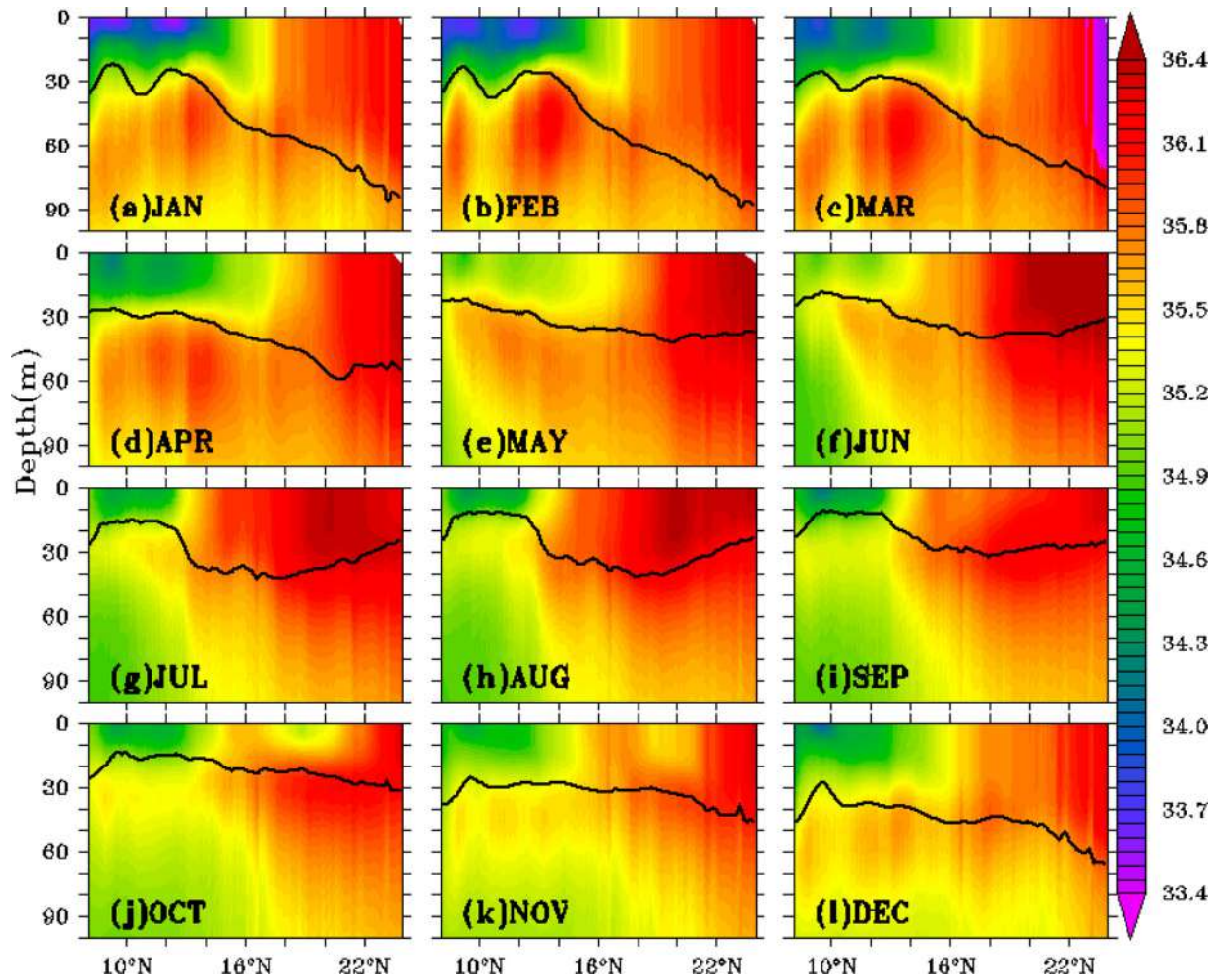


Figure 5. Multi-year average (2006–2017) monthly composite of model-simulated salinity across latitudes along the 100 m depth contour in the western continental shelf of India. Black line represents MLD (m).

60 m by December, making the onset of winter cooling. MLD is defined as the depth where the density is equal to the sea surface density plus the increment in density equivalent to 0.15 kg.m^{-3} (Girishkumar et al. 2017). The thermocline (depth of 23°C isotherm; Girishkumar et al. 2013) located at 90–100 m all along the eastern AS between January–April started shoaling May onwards in the south due to upwelling of cooler waters, peaked to ~ 40 m in July–August, and deepened to 100 m by December. This cooling in the bottom layers (>50 m) on account of upwelling has a clear impact through ingress of hypoxic waters in the south from May onwards, which sustained till October. Salinity distribution clearly depicts the progression of BoB low saline waters in the south during January–March and ASHSW in the north on account of evaporative cooling of winter convective mixing (Figure 5). The nutrients brought to the surface layers due to convective mixing in the north during December–February and upwelling in the south during May–October resulted in multi-fold

enhancement of phytoplankton production which is clearly reflected with high chl-a concentrations (Figure 6). The surface chl-a increases northwards with a prominent presence of subsurface chl-a maximum at approximately 50 m depth. However, the presence of subsurface chl-a maximum, a characteristic feature in the northern Indian Ocean, has shifted to the surface during the convective mixing in winter monsoon and upwelling in the summer monsoon. The strong coastal upwelling is observed along 14°N – 16°N even during the waning phase (September–October) of the summer monsoon and it appeared as a barrier to the southward transport of high saline water from the north. The eastern AS experiences oxygen deficiency primarily due to upwelled water. In the late 90s, hypoxia was reported in Indian coastal waters (Naqvi et al. 2000). Annual occurrence of hypoxia during September–October has been reported in the western continental shelf of India (Naqvi et al. 2006). It is observed that the upwelled water is significantly low in its DO content and is

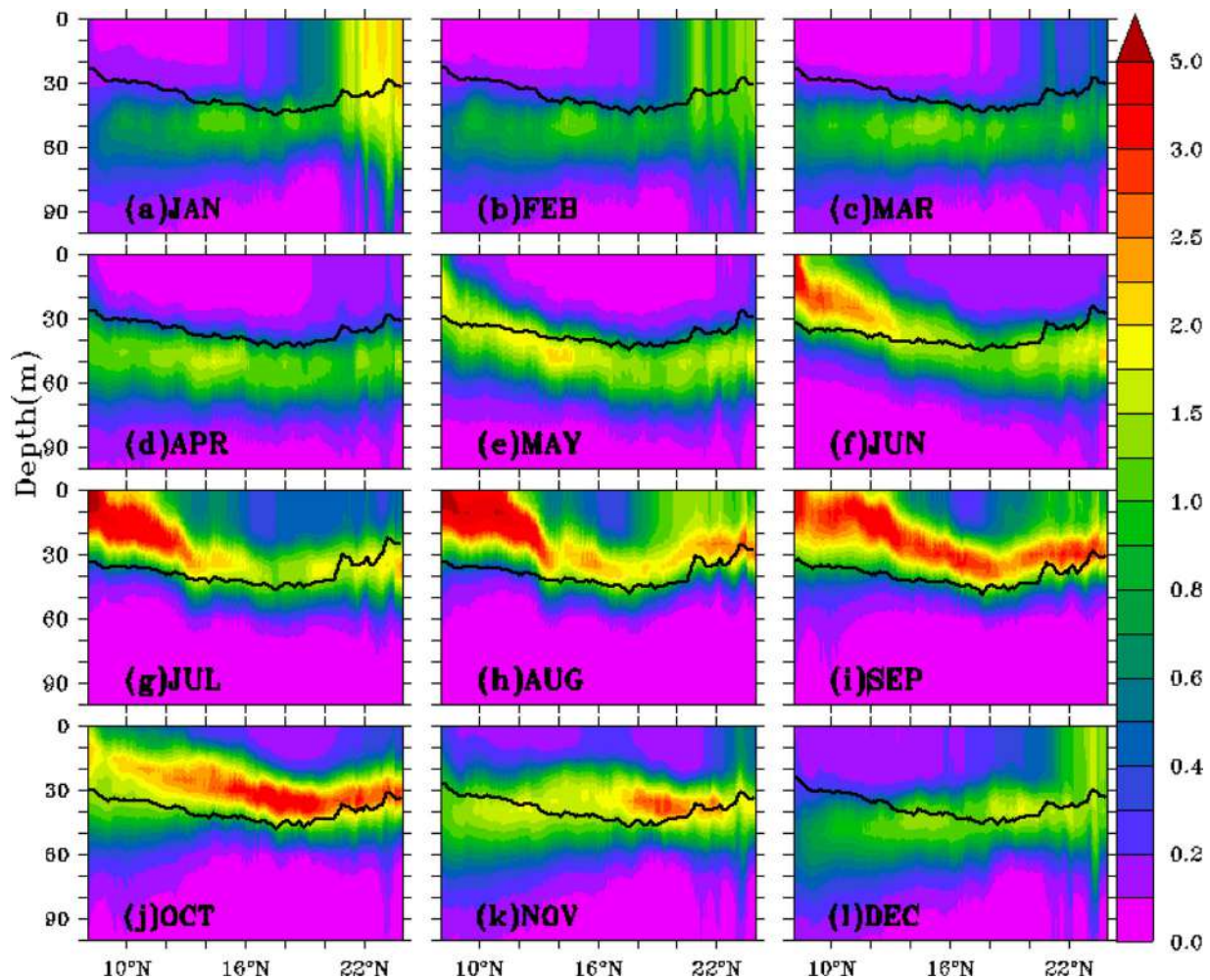


Figure 6. Multi-year average (2006–2017) monthly composite of model-simulated chlorophyll-a (mg/m^3) across latitudes along the 100 m depth contour in the western continental shelf of India. Black line represents depth of subsurface chlorophyll maximum (m).

present at a shallow depth of 20 m below the surface (Figure 7).

Unlike in the AS, the BoB depicts a completely different latitudinal distribution throughout the year as the winter convective process is completely absent and upwelling is insignificant in the latter region. Due to immense freshwater discharge from the Ganges-Brahmaputra rivers at the head Bay and also from major perennial rivers, namely, Mahanadi, Godavari, Krishna, Cauvery, etc. all along the east coast of India (Krishna et al. 2016), the BoB is more a freshwater dominated system with strong stratification regulating its physics and biogeochemistry. The warmer and low saline waters in the upper 20 m from June onwards in the northern Bay and its southward propagation till January through EICC as reported earlier (Sarma et al. 2013a, 2016) has been well captured by the model (Figures 8 and 9). Unlike the AS, the deoxygenation of bottom layers in the BoB is highly unorganised with space and time due to the effect of relatively higher quantum of river

discharge. The cold core eddies are considered an important source of nutrients that promote phytoplankton blooms in the BoB. The nutrients exported from these rivers in the presence of eddies stimulate the biological production, which is evident from the elevated upper column chl-a concentrations in their proximate shelf regions (Figure 10). These periods of enhanced production stimulates the shallowing of oxycline (characterised with $<50 \mu\text{M}$ DO concentration; Ravichandran et al. 2012) due to the decomposition of sinking surface production (Figure 11). So, there seems to be a trending relationship between the intensity of production and depth of oxycline. The seasonal variability of oxygen indicates the existence of coastal hypoxia in the central-east coast of India during the late phase of summer monsoon. The hypoxia has been reported to prevail in several places across the eastern continental shelf of India, such as 11°N – 13°N off Tamil Nadu coast and 16°N – 18°N off Visakhapatnam, spreading from shelf break to the inner shelf (Satpathy et al.

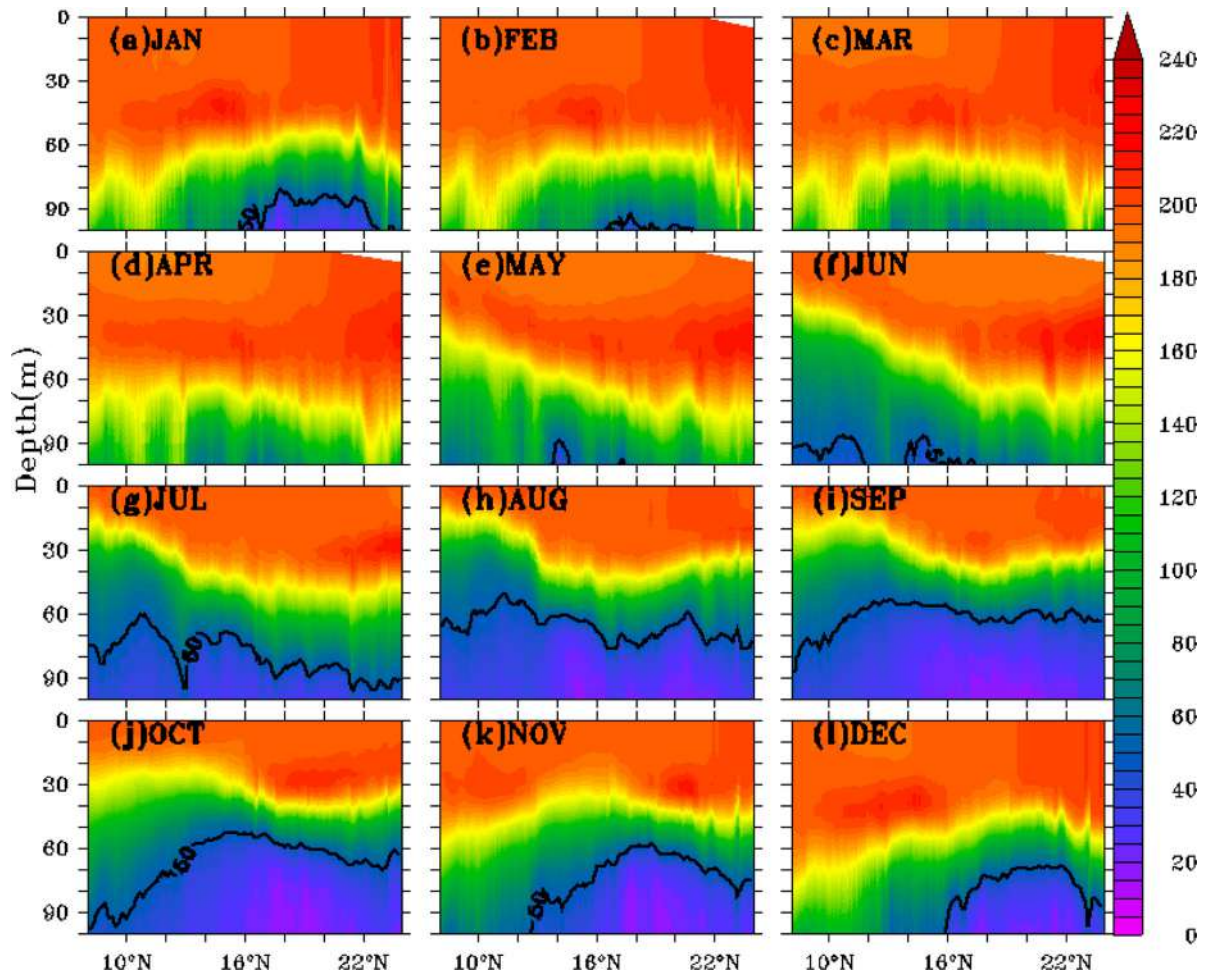


Figure 7. Multi-year average (2006–2017) monthly composite of model-simulated dissolved oxygen (μM) across latitudes along the 100 m depth contour in the western continental shelf of India. Black line represents depth of oxycline (m) characterised as $<50 \mu\text{mol}\cdot\text{l}^{-1}$ oxygen concentration.

2013; Sarma et al. 2013a). Nonetheless, it has been shown recently that the variation in the depth of oxycline and intensity of surface production are influenced by the cyclonic and anticyclonic eddies (Sarma et al. 2018) which are more rampant and systematic in the BoB than in the AS.

Overall, the two basins display contrasting seasonality governed by different processes. While the AS is highly regulated by upwelling and winter convective mixing, its counterpart is controlled largely by the spatially distributed rivers discharge and eddies. The exchange of these two basins waters is far clearly visible through penetration of BoB low salinity waters through EICC into the AS and advection of ASHSW waters through WICC into the BoB. The model has performed very well in capturing the contrasting controlling factors and associated biogeochemical dynamics in these two ocean basins.

The model faithfully reproduces seasonal variability of temperature, salinity, chl-a and DO in the coastal

waters around India across latitudes (Figures 4–11). The model is capable of simulating the physical mechanisms governing the seasonal variability of MLD resulting surface cooling in different part of the coastal ocean across latitudes (Fischer et al. 2002; Jayaram et al. 2010). The physical processes lead to the entrainment of high saline water to surface in the eastern AS and freshening of salinity in the western BoB across latitudes are well captured by the model (Vinayachandran et al. 2013; Akhil et al. 2014). However, the extent of cooling and magnitude of salinity are underestimated by the model in few regions across latitudes.

The model-simulated subsurface chl-a clearly indicates that the model is adequately simulating its seasonal, inter-regional variability and a persistent occurrence of deep chlorophyll maximum in the Indian coastal waters (Hanson et al. 2007; Ravichandran et al. 2012; Chakraborty et al. 2016; Gupta et al. 2016; Bharathi and Sarma 2019; Chakraborty et al. 2019b). Lotlikar et al. (2020) studied long-term trend of chl-a off

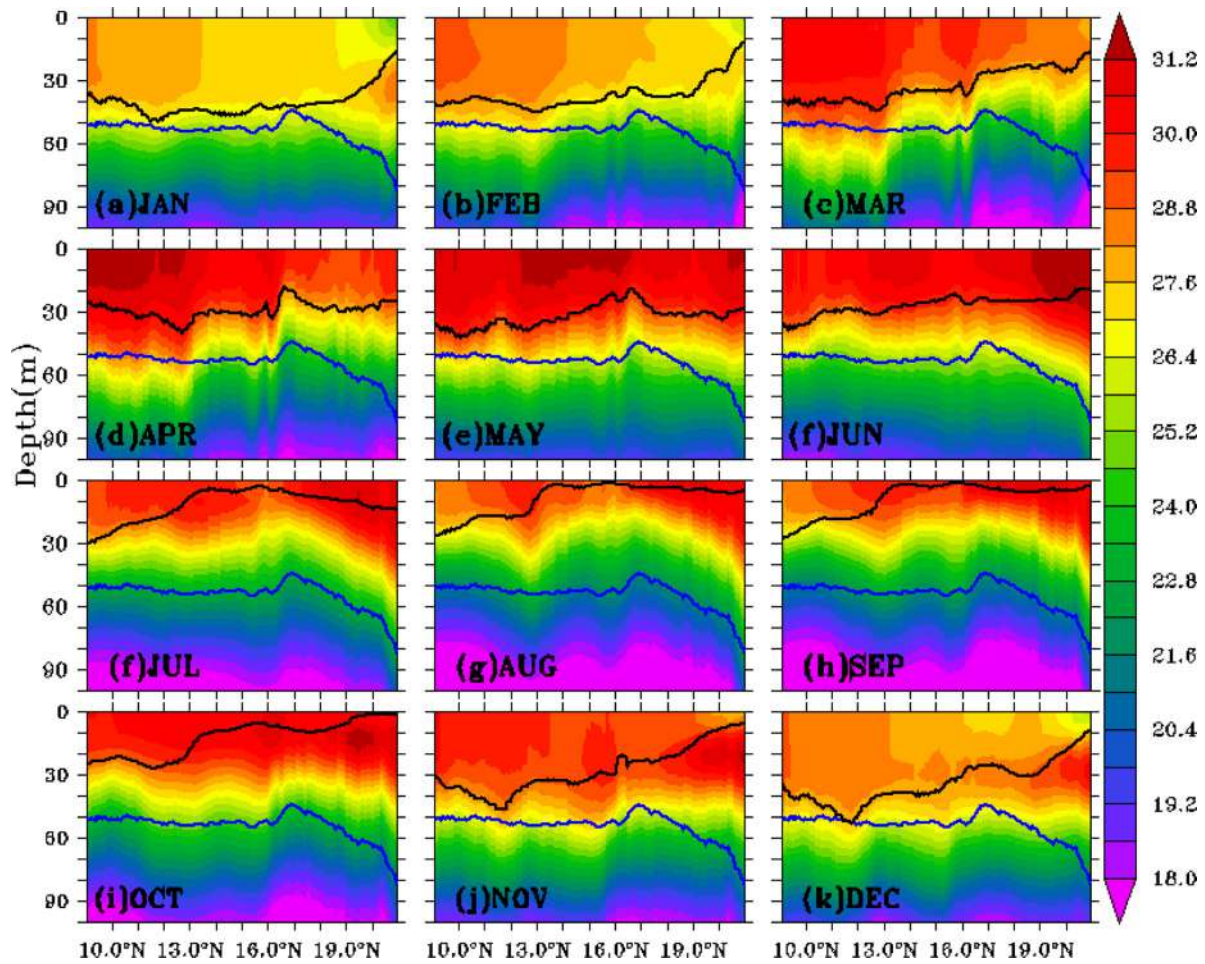


Figure 8. Multi-year average (2006–2017) monthly composite of model-simulated temperature ($^{\circ}\text{C}$) across latitudes along the 100 m depth contour in the eastern continental shelf of India. Black line represents MLD (m) and blue line represents 23°C isotherm (m).

Gopalpur in the BoB using satellite data. They reported a bi-modal distribution of chl-a with a primary peak during pre-southwest monsoon attributed to recurrent phytoplankton bloom that is mostly confined to near shore waters whereas, the secondary peak in chl-a can be seen during the end of southwest monsoon which spreads far offshore. The model reproduces both the peaks of chl-a off Gopalpur, though the model overestimates the magnitude of chl-a. The seasonally reversing monsoons, (winter and summer), trigger high biological productivity off Gujarat in the AS associated with two different physical processes (winter convective mixing and upwelling) resulting in two peaks of chl-a. The model does reasonably well in capturing two peaks of chl-a off Gujarat in the AS with an overestimation in the magnitude of chl-a in the winter season. Sarma et al. (2013b) examined the influence of physical and atmospheric processes on water column nutrient biogeochemistry using time series observations in the central west coast of BoB. They found that high nutrient and chl-a concentrations are associated with extreme

atmospheric events. The atmospheric chemistry module is not integrated in the model described in this study. As the atmospheric aerosols which are significant source of major and minor nutrients, it is expected that there is an underestimation in the model-simulated concentration of nutrients and chl-a and it will be significant during extreme atmospheric events. The model has very well captured intensive upwelling in the southeastern AS. The upwelling brings nutrient rich but oxygen deficient water from deeper layers to a very shallow depth during the southwest monsoon which leads to a hypoxic condition. The transport of nutrient rich water fuels high surface productivity. The modelling of chlorophyll is also in agreement with the observations; maxima at surface and sub-surface depths during monsoon and non-monsoon months, respectively with the former several folds higher than the latter (Gupta et al. 2016). However, the presence of low oxygen water at a very shallow depth have cascading effect on the local fisheries as they tend to migrate away from the oxygen stressed condition.

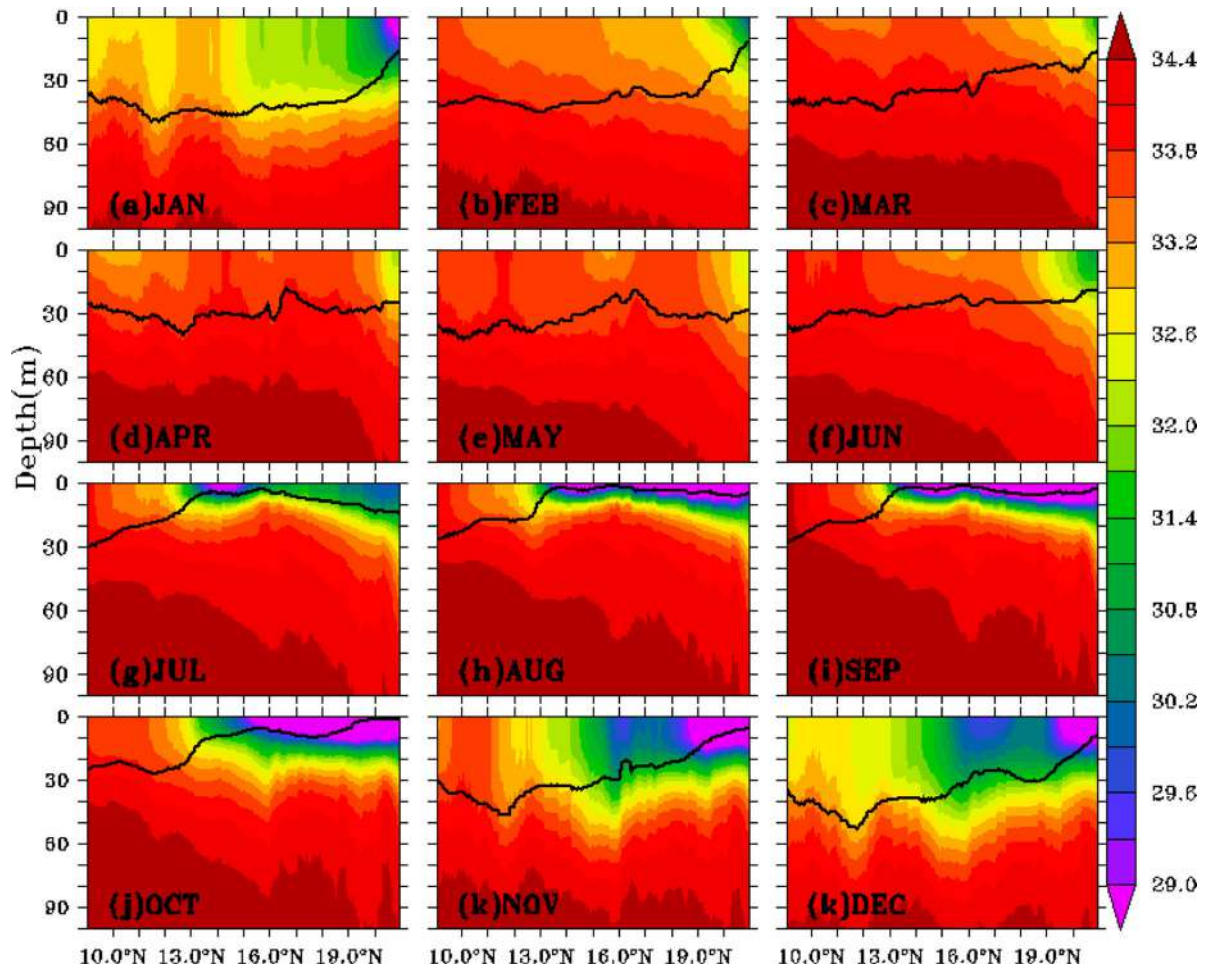


Figure 9. Multi-year average (2006–2017) monthly composite of model-simulated salinity across latitudes along the 100 m depth contour in the eastern continental shelf of India. Black line represents MLD (m).

Marine ecosystem modelling depends inherently upon field data. The data sets from the field observations and time series programmes, together with products derived from satellite-based observations, are invaluable in two ways. They serve as the basis not only for new and improved mechanistic parameterisations of specific biogeochemical processes but also indispensable for the preparation of initial as well as boundary conditions of physical and biogeochemical state variables. They also provide a resource for evaluating the overall skill of integrated system models through detailed model-data comparisons. The number of biogeochemical observations in and around the Indian Ocean is limited. Therefore, the boundary information of all biogeochemical state variables except nitrate and oxygen is set to a small constant positive number. This results in an absence of spatio-temporal variabilities at the boundaries of biogeochemical state variables leading to a non-realistic simulation particularly close to the boundaries. Therefore, it is essential to increase the number of biogeochemical observations so that better boundary

information can be prescribed to get a more realistic simulation. The biogeochemical processes are extremely sensitive to vertical mixing. We make use of the KPP mixing scheme for our simulation. As such, there is no mixing scheme available exclusively for the Indian Ocean. The KPP scheme was tuned for the Pacific Ocean whereas the Indian Ocean is known to respond differently to the fluxes. Therefore, an attempt should be made towards developing a vertical mixing scheme exclusively for the Indian Ocean.

4. Conclusions and summary

The assessment of the capability of an ocean-ecosystem model in simulating coastal ecosystem dynamics in the waters around India is carried out using long-term sustained *in situ* observations during 2008–2017 and ship-based measurements made in 2014. The model is capable of capturing observed trend of temperature, salinity and chl-a with high correlation ($R^2 > 0.78$) in both eastern and western shelf waters except for salinity

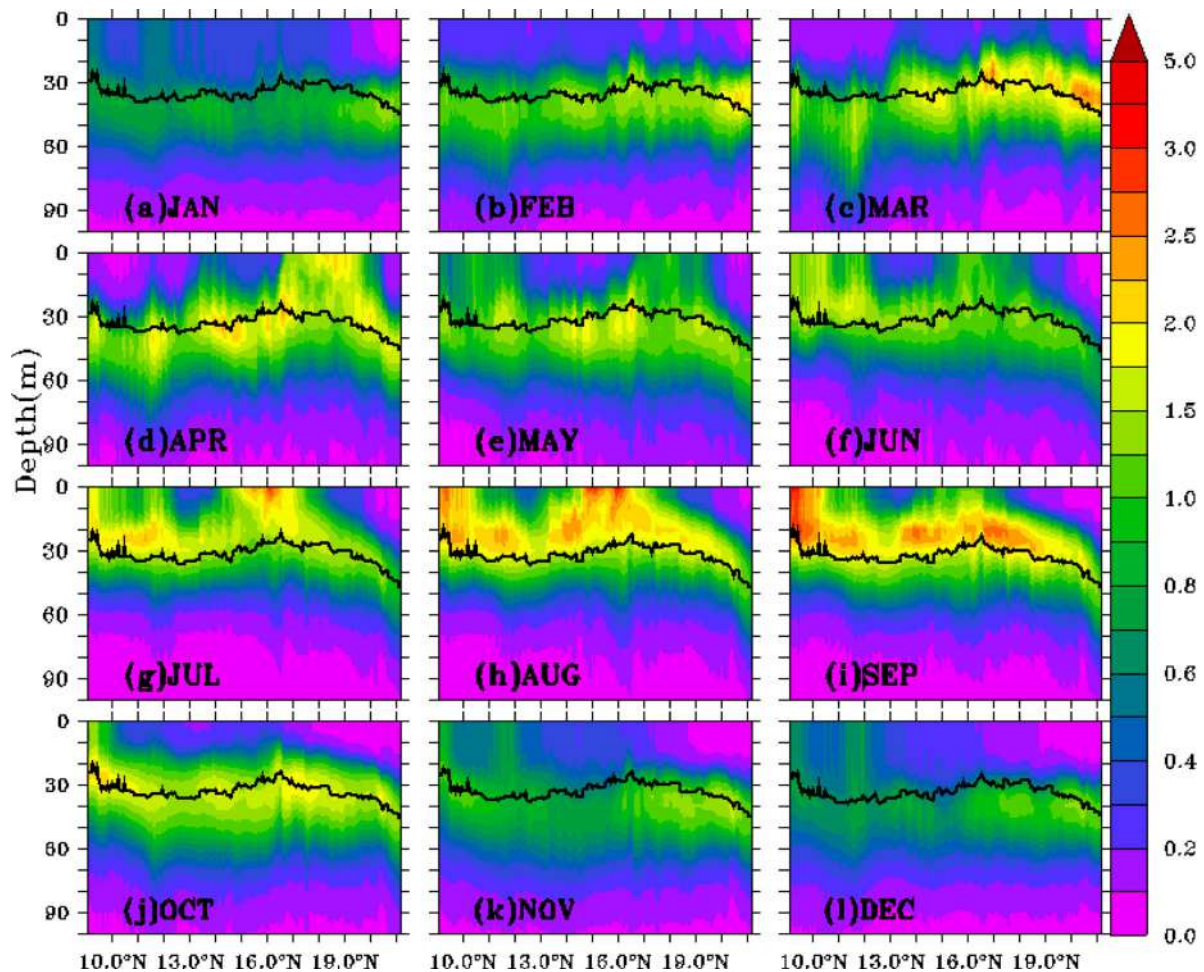


Figure 10. Multi-year average (2006–2017) monthly composite of model-simulated chlorophyll-a (mg/m^3) across latitudes along the 100 m depth contour in the eastern continental shelf of India. Black line represents depth of subsurface chlorophyll maximum (m).

($R^2=0.44$) and DO ($R^2=0.50$) along west coast and DO ($R^2=0.53$) along east coast. The capability of the model in simulating upwelling dynamics along the west coast of India during summer monsoon is established when it is compared with ship-based observations. The model is in well agreement with observed seasonal, inter-regional variability of physical and biogeochemical state of the Indian coastal waters across latitudes. The enrichment of inorganic nutrients into the near-surface ocean, associated with different physical processes governed by the seasonal reversal of monsoon, controls the variability of chl-a concentration in the upper ocean. In the presence of favourable environmental conditions, phytoplankton concentration often elevates resulting in bloom in different part of the Indian continental shelf waters (central-east coast during pre-monsoon, south-west coast during monsoon and north-west coast during post-monsoon). The presence of lower level of DO content in shallow waters indicates the existence of coastal hypoxia in the south-west and central-east coast of India during summer

monsoon. The model faithfully resolves the physical processes governing the seasonal occurrence of phytoplankton bloom and coastal hypoxia in different locations of the continental shelf waters of India across latitudes.

5. Implications and future scope

The dynamics associated with the growth and decay of biological state variables make ecosystem modeling more complex and distinctive compared to the modelling of physical variables. A high-resolution numerical model provides an insightful understanding of the physical–biological coupling processes across the water column. The capability of ocean models to provide accurate predictions of physical variables enables the use of model output to drive in the direction of ecological forecasts. In order to understand the biophysical coupling in the Indian coastal waters, which are fundamental to the structure and functioning of marine ecosystems, the coupled physical–

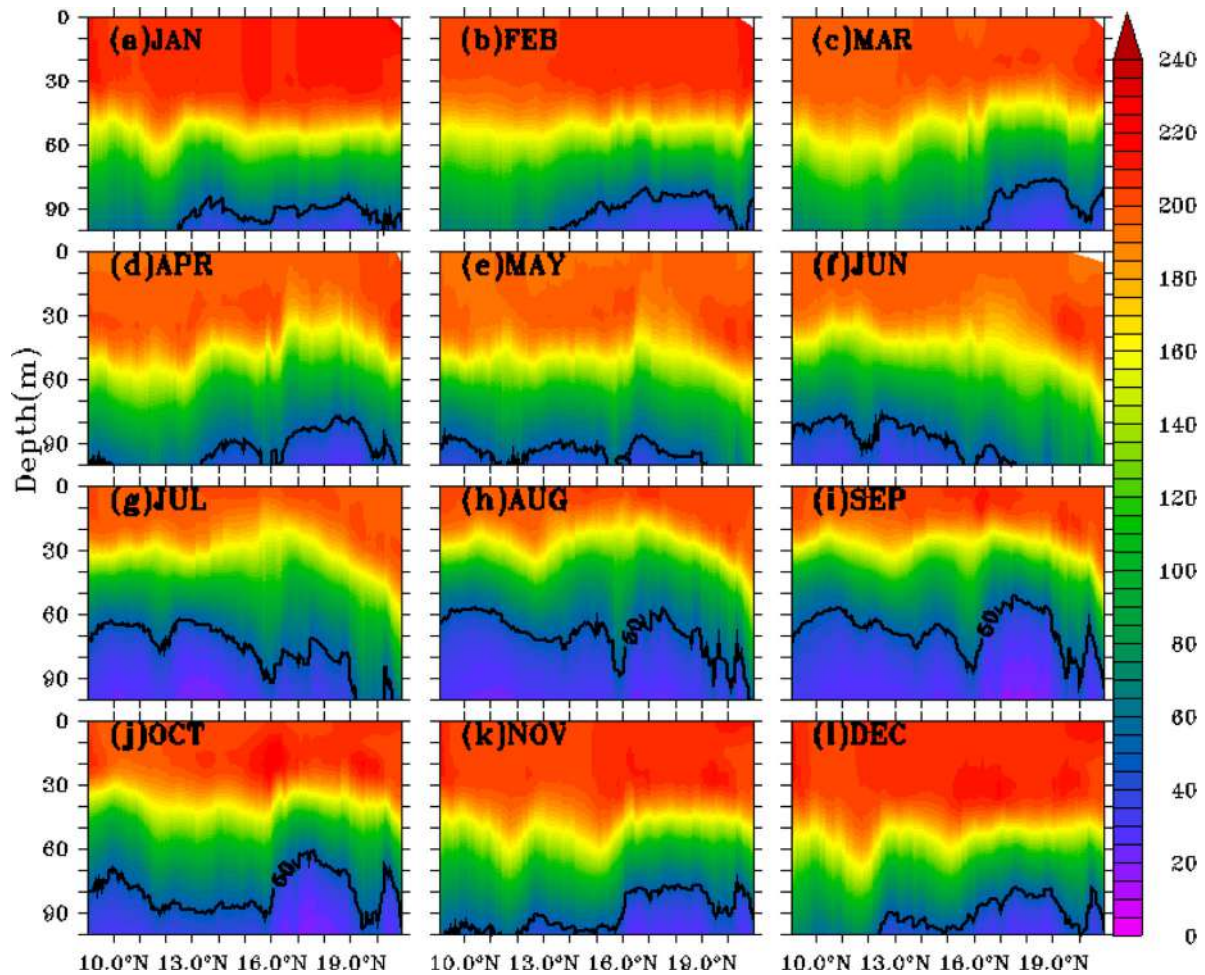


Figure 11. Multi-year average (2006–2017) monthly composite of model-simulated dissolved oxygen (μM) across latitudes along the 100 m depth contour in the eastern continental shelf of India. Black line represents depth of oxycline (m) characterised as $<50 \mu\text{mol l}^{-1}$ oxygen concentration.

biological modelling system described in this study is evidently a useful tool. It can also be effectively used to study biogeochemical and ecological responses to physical forcing.

With increasing economic activity in and around the coastal oceans, the sustainable development and environmental conservation of the coastal ocean become a major concern. The focus is to find sustainable means to utilise ocean resources without causing damage to the oceans and their marine life in line with Goal 14 in the United Nations Sustainable Development. Therefore, it is very important to monitor various biogeochemical properties over a longer period of time to assess the change and understand the processes responsible for the observed changes. The *in situ* data collected during 2008–2017 helped us to understand the health of coastal waters to a certain extent and flagged the vulnerability of our coastal zones to adverse human impacts and industrialisation. However, a numerical model-simulated data are extremely useful

to study long-term trends of environmental variables in hindcast as well as forecast mode. In order to assess the health of the coastal marine ecosystem, the model outputs can be efficiently used with direct measurements to derive environmental health indicators.

In the recent past, there has been an increase in the intensities of algal bloom in coastal waters which may also lead to coastal hypoxia. The deterioration of the water quality due to anthropogenic influx may be the major reason for such events. The manual *in situ* samplings has limitations in terms of efforts whereas the other observation systems like remote sensing can provide only surface data. However, the numerical model has the ability to simulate water quality parameters for the surface as well as for sub-surface. Therefore, the model can be potentially used to better understand the coastal marine ecosystem in the waters around India and predicting its future changes in time and space, like the occurrence of coastal hypoxia or anticipating phytoplankton blooms. Another possible use of the

model is that its prediction can be used to identify potential fishing grounds in the coastal waters of India. The high resolution, regional model-simulated outputs are useful towards monitoring the coastal ecosystem, and subsequently developing strategies to manage coastal resources in a changing environment.

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No potential conflict of interest was reported by the author(s).

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