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Full Length Research Paper

Numerical simulation of seasonal variations in circulations of the Bay of Bengal

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The seasonal variations in circulation at different layers of the Bay of Bengal (BOB) basin have been studied using multilayered regional ocean modeling system (ROMS). The model is simulated with climatological comprehensive ocean-atmospheric data set (COADS) wind and thermal forcing until annual cycle is reached. The northward flowing western boundary current (WBC) during spring and southward flowing east India coastal current (EICC) during autumn are developed due to the formation of anticyclonic and cyclonic Eddies respectively. The influence of Malacca Strait is prominent during winter season. The north equatorial current in the southern basin during winter to spring and southwesterly monsoon current (SMC) during summer are well simulated by the model. At 100 m depth current pattern along the Indian coast is similar to surface pattern in all the seasons. The 500 m depth current depicts the western boundary current in the winter season only. Many Eddies are simulated along the western coast of the basin during summer. The 1000 m current pattern indicates the existence of different Eddies in the basin for longer time. A strong anticyclonic Eddy persists near the head of Sri Lanka for almost every season. Andaman Sea is driven generally by one Eddy in the north and another in the south.

Key words: Comprehensive ocean-atmospheric data set (COADS), western boundary current (WBC), east India coastal current (EICC), Bay of Bengal (BOB), regional ocean modeling system (ROMS), southwesterly monsoon current (SMC).

INTRODUCTION

The Bay of Bengal (BOB) is a three side bounded tropical small ocean basin situated in the northern part of the Indian Ocean and highly influenced by semiannually reversing monsoon winds. A number of studies mentioned that the geographical location and the unique wind forcing make the circulation very complex. Using ship drift data, Cutler and Swallow (1984) showed the reversibility of this surface current, that is there is clockwise circulation from February to July and reverse for the rest of the year. Then, the complex circulation was analyzed by researchers with hydrographic, satellite observation and numerical model as well. Legeckis (1987) first showed the existence of western boundary current (WBC) from satellite infrared image of sea surface temperature in the BOB. He found the similarities of this current with the well-known Gulf Stream as it carries warm water along the east coast of India during February. Sanilkumar et al. (1997) showed existence of WBC using MICOM STC profiles. Shetye et al. (1993) showed the western boundary current of the seasonal subtropical gyre in the BOB. Suryanarayana et al. (1993), Shetye et al. (1996) and Babu et al. (2003) investigated the circulation feature using hydrographic dataset. Somayajulu et al. (2003) and Gopalan et al. (2000) showed the seasonal and interannual variations of surface circulation of the BOB using satellite observations. Potemra et al. (1991) with Isopycnic layered model, Yu et al. (1991) with linear reduced-gravity model, McCreary et al. (1993) with two and half layer thermo-dynamics model and Paul et al. (2009) using multilayered modular ocean model showed the semi-annual variability of the upper layer circulation.

As a result of the typical wind forcing and geographical location they suggested that higher resolution numerical model study is required to understand the mesoscale feature of the BOB. In order to accomplish this, a high resolution-modeling setup has been done for the BOB (4 to 24°N and 76 to 100°E) using regional ocean modeling system (ROMS) to analyze the circulation features for the basin (Figure 1a), which has very shallow coastline and there is sharp slope in bathymetry from south to north. The coastal

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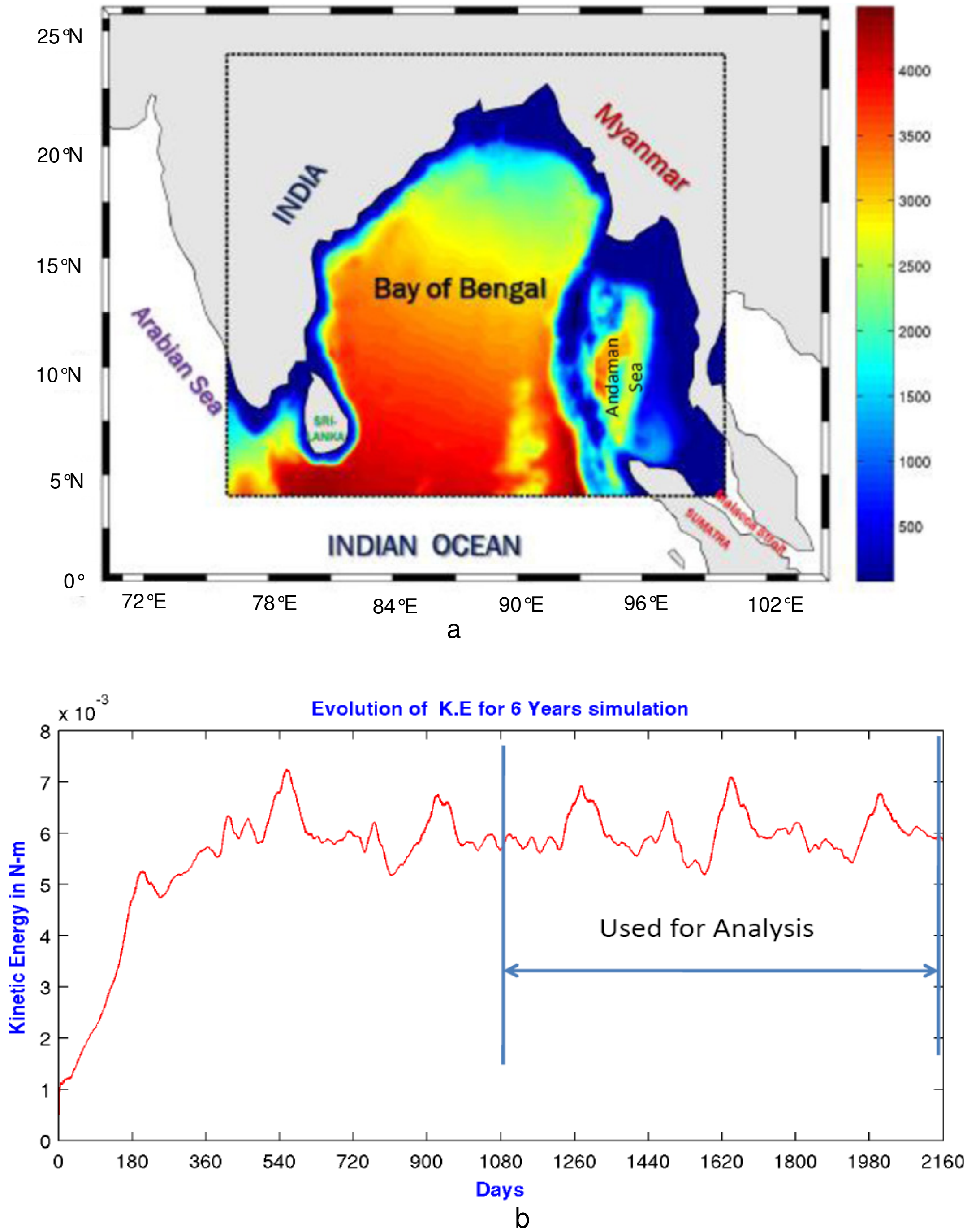

Figure 1. (a) Domain of study with its bathymetry (in m). Western side of the basin is deeper compared to AnS. Being shallower around the AnS, the area seems like a trench. (b) Evolution of kinetic energy (N-m) with time (days). Last three years are used for analysis.

region is very shallow (<100 m) while the southern part is very deep (>3500 m). The Palk Strait (PS) between Sri Lanka and India is shallower than 100 m. The Malacca Strait (MS) is also very shallow which connects the BOB and the South China Sea. The eastern part of the BOB basin is known as the Andaman Sea (AnS) which looks like a trench with shallow surroundings and very deep center. Chakraborty and Gangopadhyay (2010) showed that the difference of water mass characteristics of the AnS and the rest of the BOB is due to its bathymetry. The circulation feature of the AnS is not yet studied due to non-availability of datasets, but the model simulation can provide some idea about the circulation feature in this region. In this paper, study on the circulation pattern for different seasons from

Table 1. Parameters with their values used for model configuration.

Model parameter	Value
Depth	0-5500 m
s-coordinate surface control parameter (theta_s)	7.0
s-coordinate bottom control parameter (theta_b)	0.1
Thermocline depth (Tcline)	10 m
Mean density	1025 kgm^{-3}
Lateral harmonic constant mixing coefficient for momentum	4000 m^2s^{-1}
Lateral biharmonic constant mixing coefficient for momentum	100 m^4s^{-1}
Lateral harmonic constant mixing coefficient for tracer	1000 m^2s^{-1}
Linear bottom drag coefficient	10^{-4} ms^{-1}
Quadratic bottom drag coefficient	0 ms^{-1}
Slipperiness variable	1(no slip)
Sponge Layer Thickness	10^5m
Viscosity in sponge layer	800 m^2s^{-1}

ROMS simulation is presented. A materials and methods section is given. The validation of the model with observational datasets was performed by Sil et al. (2010) and Sil and Chakraborty (2011). The models simulating currents for different seasons and for different levels are discussed as results and discussion and finally conclusions.

MATERIALS AND METHODS

Brief description of the model

ROMS is a free-surface; terrain-following, primitive equations ocean model widely used by the scientific community for a diverse range of applications (Haidvogel et al., 2000; Lermusiaux et al., 2001; Wilkin et al., 2005; Chakraborty and Gangopadhyay, 2010; Sil et al., 2010; Sil and Chakraborty, 2011). The model is discretized in the vertical over variable topography using a stretched terrain-following coordinate and can be used for water bodies like coastal basin, estuary, river, sea and open ocean. The primitive equations are evaluated using boundary-fitted orthogonal, curvilinear coordinates on a staggered Arakawa C grid.

There are 287 and 248 grid points in zonal and meridional directions respectively corresponding to 10 km resolution with 32 vertical levels in the model. The northern, eastern and most of the western boundary are closed. The southern boundary and part of the western boundary are open. On the open boundaries, the temperature and salinity values are relaxed to match the Levitus monthly climatology. Vertical turbulent mixing is based on the K-profile parameterization (KPP) vertical mixing scheme. Chakraborty and Gangopadhyay (2010) showed from Brunt-Vaisala frequency distribution that the vertical level should be discretized with more levels in the mixed layer region. Therefore, the model parameters are chosen accordingly (Table 1).

Description of experiment and data used

Bathymetry data was derived from the ETOPO2 (2 min) gridded dataset (National Geophysics Data Center, 1988). Surface forcing functions were drawn from the comprehensive ocean-atmosphere data set (COADS) climatology of Da Silva et al. (1994). These forcing fields included surface wind stresses, heat and freshwater fluxes, and heat flux sensitivity to sea surface temperature. The latter is used to represent the feedback between model SST and the surface heat flux (Da Silva et al., 1994). In the open boundary (east, west and south) temperature and salinity are relaxed to Levitus monthly climatology.

The earlier defined climatological forcing parameters are used for interannual model simulation. The surface seasonal wind forcing transfers the energy to the deeper layers through the vertical advection term in the momentum equations of the model. This vertical advection along with the vertical mixing (KPP) is the main contributor to the deeper circulation in the model. The volume integrated kinetic energy shows that annual cycle is reached after three years of simulation (Sil et al., 2010; Sil and Chakraborty, 2011). The seasonal climatological features are studied for the next three years simulation (Figure 1b).

RESULTS AND DISCUSSION

Seasonal wind pattern over the BOB

Similar to Somayajulu et al. (2003), the seasons are selected on the basis of wind pattern as shown in Figure 2. The northeasterly winds during the winter (Figure 2a) and southwesterly winds during the summer (Figure 2c) flow over the BOB with maximum intensity between 5 to 14°N. Clockwise wind pattern with maximum intensity along the western boundary of the basin during the spring (Figure 2b) and anticlockwise wind circulation in the southern BOB but clockwise wind circulation in the northern BOB (north to 14°N) during the autumn (Figure 2d) prevail over this region. Although the model has 32 terrain following layers but for our analysis we have discussed only three layers; 10 m representing surface, 500 m representing the bottom of the thermocline and deep zone as 1000 m.

Circulation at 10 m

In the winter, the model simulating 10 m current shows that strong north equatorial current flows westward (Figure 3a). The current which enter to BOB basin from MS joins with the above current system and form a jet. This strong north equatorial jet at around 6°N reflects at the Sri Lankan coast

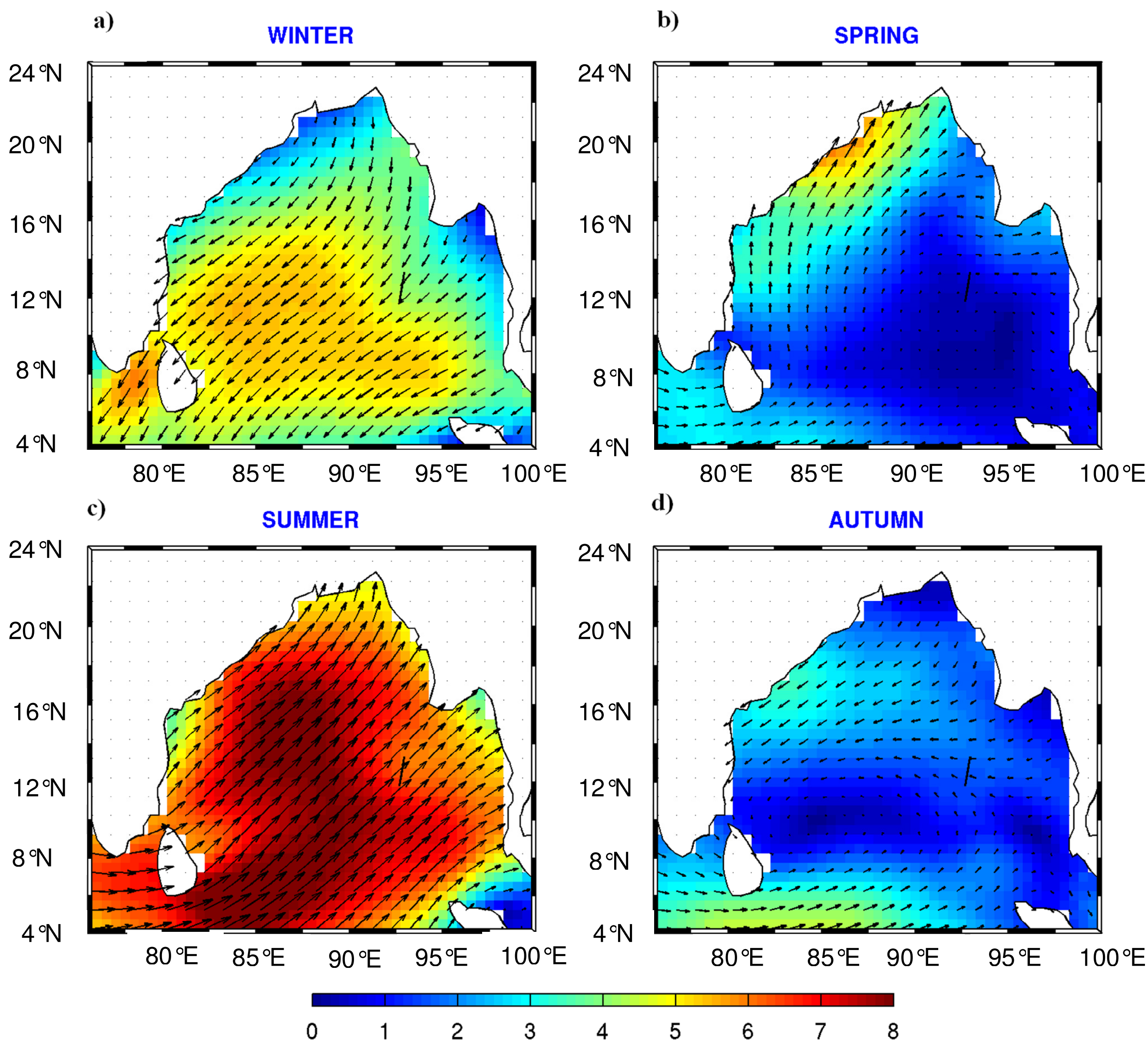

Figure 2. Seasonal wind pattern with magnitude in shaded background for (a) Winter: northeast monsoon (December, January and February), (b) Spring: transition (March, April and May), (c) Summer: southeast monsoon (June, July, August and September) and (d) Autumn: transition (October and November).

and then flows along the west coast of the basin. The bifurcation of this jet is found along 90°E to form an anticyclonic gyre at around 92°E; 10°N with other part to flow northward that may be due to the ridge along 90°E. The northward component deviates westward around 12°N due to anticyclonic gyre in the head of the BOB. But in this anticyclonic gyre, two cyclonic Eddies with centers at around 88°E; 16.5°N and 92°E; 18°N are observed. A small cyclonic Eddy is found with center at around 90°E; 21°N above the anticyclonic gyre. Two anticyclonic Eddies are found in the AnS with centers at around 96°E; 13°N in the north and 96°E; 9°N in the south.

Figure 3b shows that in the spring northward propagating western boundary current is found to develop due to intensification of consecutive anticyclonic Eddies along the boundary (Legeckis, 1987; Johns and Ali, 1992; Somayajulu, 2003; Sil et al., 2010; Sil and Chakraborty, 2011). The cyclonic and anticyclonic Eddies in the head BOB are shifted southward. The equatorial jet also shifts southward to the south of Sri Lanka. The circulation in the AnS is separated to two anticyclonic Eddies; one in the south and another in the north. Due to these two anticyclonic Eddies southward flowing eastern boundary is observed in the BOB. This time flow through the MS is from the BOB to the South China Sea with very less intensity. In the summer, the western boundary current is found to be disorganized due to formation

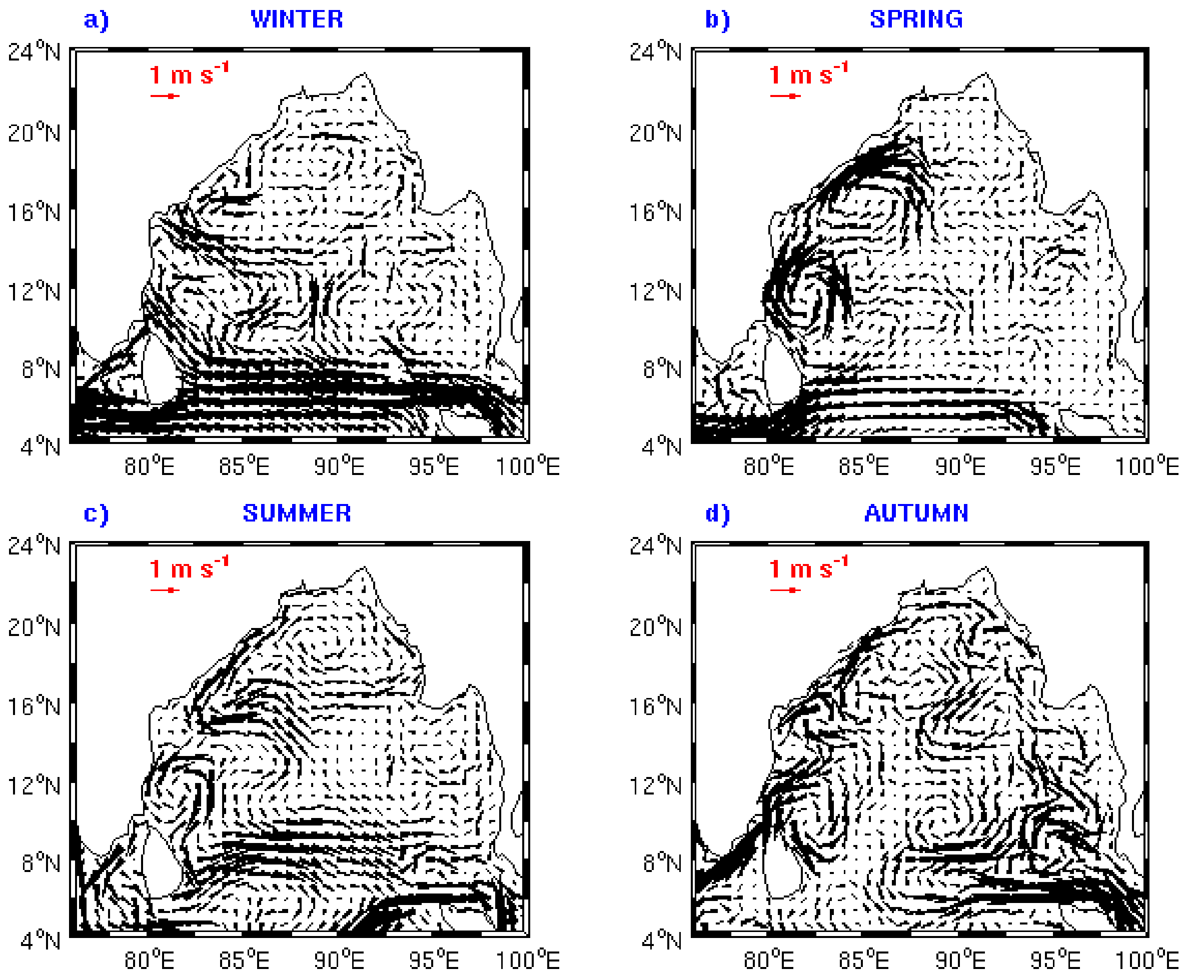

Figure 3. Model simulated current pattern at 10 m depth for (a) Winter, (b) Spring, (c) Summer and (d) Autumn. Western boundary currents during Spring and EICC during Autumn are two important boundary current systems of this basin.

of cyclonic (in the northern coast) and anticyclonic (near the head of Sri Lanka) Eddies along the coast (Figure 3c). This time a cyclonic gyre is found in the head BOB with centers at around 90°E; 19°N. The southwest monsoon current (SMC) is found to flow in the BOB between 80°E and 90°E (Potemra et al., 1991; Suryanarayana et al., 1993; Vinayachandran et al., 1999). This helps to produce anticyclonic Eddies in the head of the Sri Lanka (Vinayachandran and Yamagata, 1998). A cyclonic Eddy is formed at around 95°E; 14°N in the north of AnS.

This time the eastern boundary current is northward being influenced by SMC. It traverses along the coast and then meets with SMC. A flow from the MS does not directly enter the BOB as it is opposed by the SMC to divert around Sumatra. Figure 3d shows that in the autumn the east India coastal current (EICC) flow southward along the coast due to formation of cyclonic Eddies along the coast (Shankar et al., 1996). This time the flow from the MS is found to be strong along the AnS towards head BOB. Due to bathymetry of the AnS, an anticyclonic Eddy is found in the south of the AnS at around 95°E; 8°N. In broad view, a basin wise cyclonic gyre is found in the BOB (Potemra et al., 1991). But the mesoscale features are also obtained from the model simulation. The cyclonic Eddies are found at the central BOB at around 90°E; 9°N; near the Sri Lankan coast, it is found at around 84°E; 10°N; along the coastline at around 85°E; 18°N and 83°E; 17°N.

Circulation at 100 m

In the winter, the current pattern at 100 m depth is similar to the pattern of 10 m in the western pattern of the BOB but it is in opposite sense compared to the 10 m depth current in the AnS (Figure 4a). This time prominent eastern boundary current is found to flow southward. This eastern boundary current meets with the north equatorial jet which attend western boundary current being bifurcated at the Sri Lankan coast. Therefore, a basin wise anticyclonic current pattern is found from the model simulation. At this depth, effect from the MS is not there as depth is less than 100 m. In the spring, the dumbbell shaped current pattern with strong

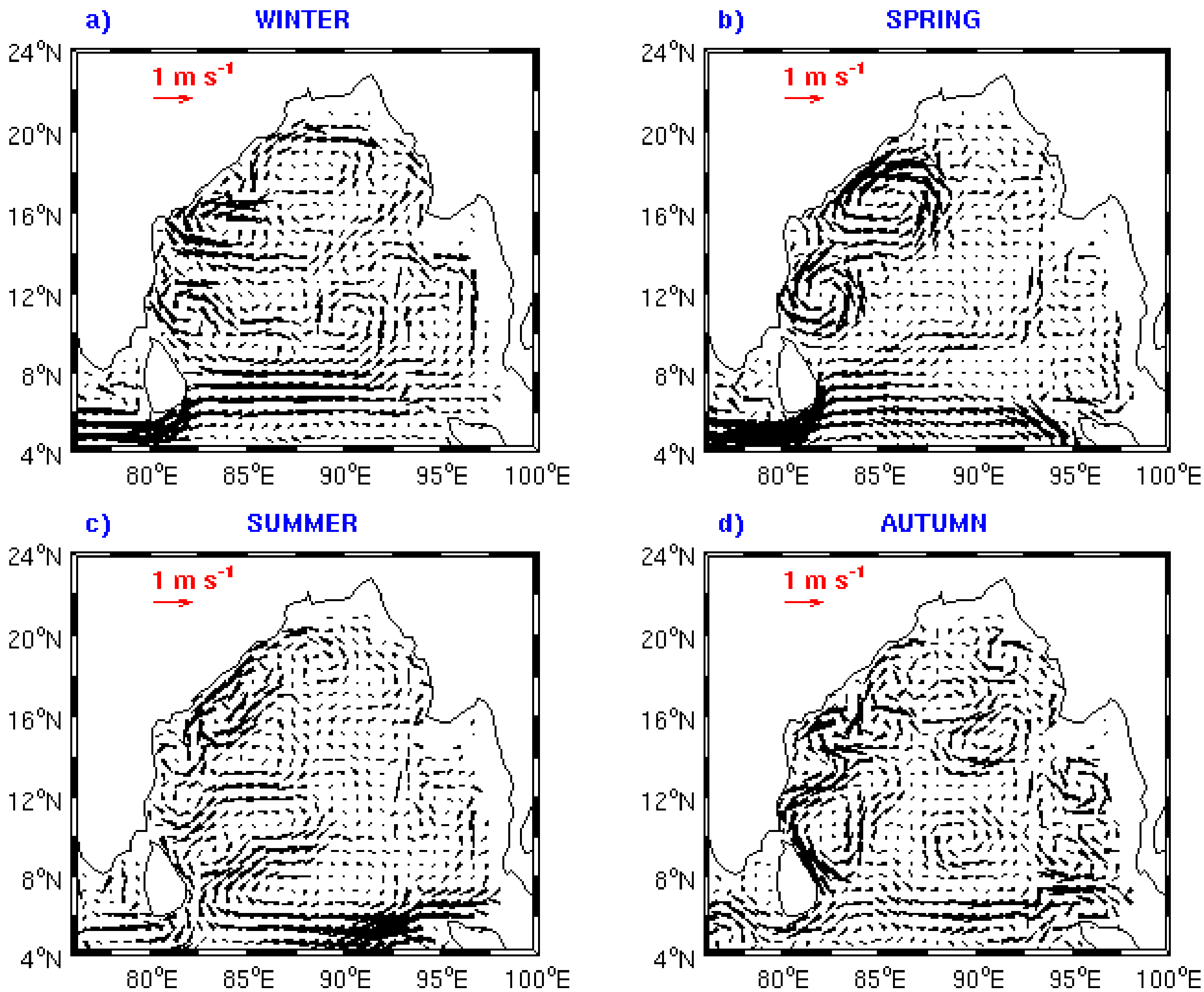

Figure 4. Model simulated current pattern at 100 m depth for (a) Winter, (b) Spring, (c) Summer and (d) Autumn.

boundary current is found in the western boundary similar to the current system at the 10 m depth (Figure 4b). In the AnS, the current pattern is similar to 10 m current. But during this time, a strong current is found to flow southwest from west of AnS which meets the north equatorial current which may be due to the bathymetry of the basin (Figure 1a).

In the summer, the western boundary current is found not well recognized like 10 m current. The eastern boundary current flows southward (Figure 4c). But the SMC is not observed in the south of the basin at this depth like surface. But north equatorial current is found to be reflected at the Sri Lankan coast and enter in the interior BOB. In the head of the BOB, cyclonic Eddies are observed with center at around 91°E; 17°N and 88°E; 18°N. In the autumn, the southward flowing EICC due to formation of cyclonic Eddies along the western coast of the basin is found like 10 m depth current (Figure 4d). The north equatorial current is present at this depth which is not present at the 10 m. This current meets with the EICC and flows towards southwest of the BOB. One cyclonic Eddy is found at around 89°E; 9°N and another two anticyclonic Eddies with centers at around 90°E; 14°N and 91°E; 18°N are observed in the northeast BOB from the model simulation. In the AnS two anticyclonic Eddies are found with centers at around 95°E; 14°N and 84°E; 9°N.

Circulation at 500 m

The current pattern at 500 m in the winter shows WBC is very much deep and strong (Figure 5a). This indicates that strong north equatorial current in the BOB cannot produce WBC in the upper surface due to other surface forcing like river discharge in the head BOB and western coast of the BOB. This WBC is found to form in the upper layer in the spring, but in 500 m depth it is found in the winter. Another thing to observe is that a strong current from west of the AnS to the southwest BOB which was found in the spring at 100 m depth is found at 500 m depth in the winter. Then, this current meets with the counter north equatorial current. The two anticyclonic Eddies in the AnS are also observed at 500

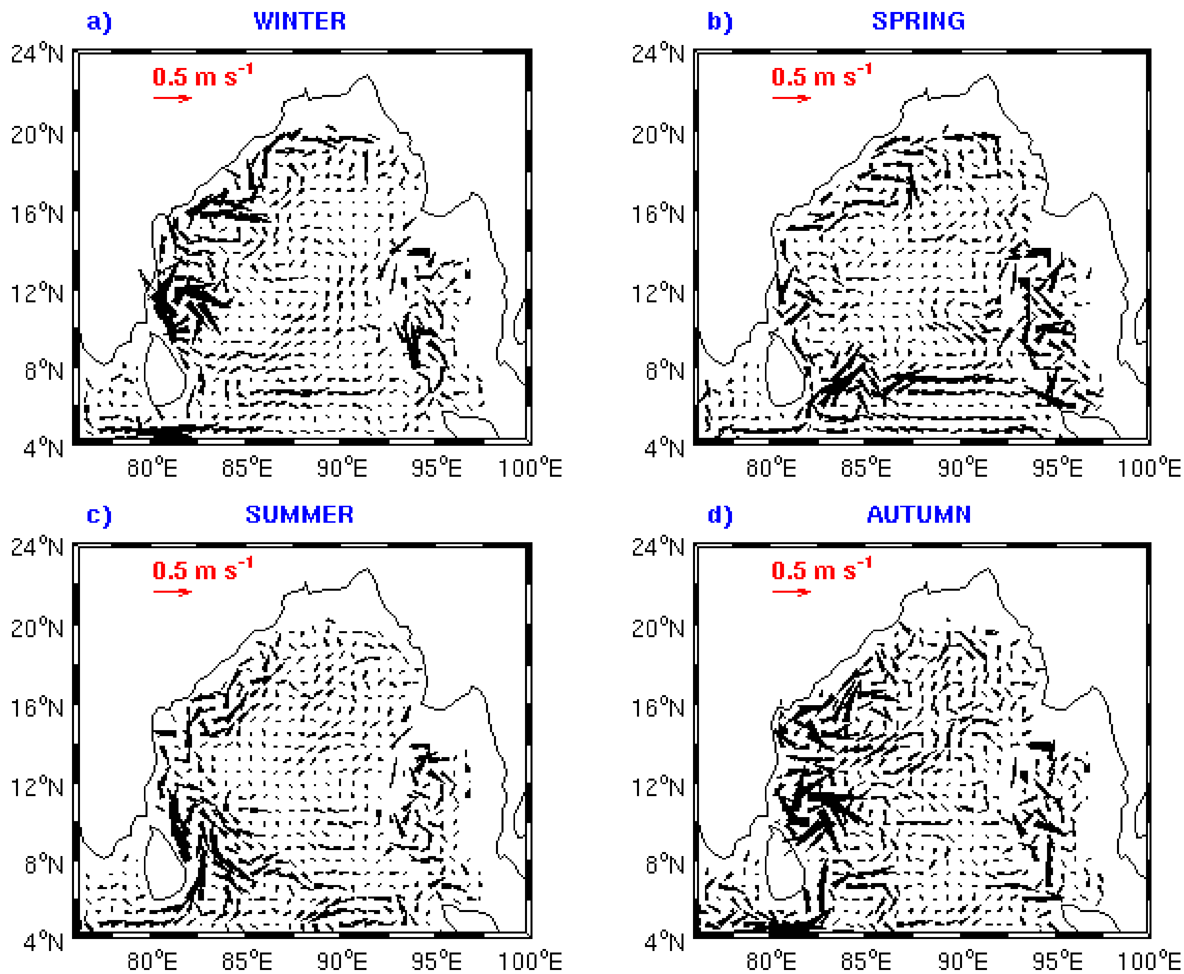

Figure 5. Model simulated current pattern at 500 m depth for (a)Winter, (b) Spring, (c) Summer and (d) Autumn.

m circulation. The current pattern in the spring at 500 m shows that the WBC is not well organized due to formation of cyclonic Eddy at the northern coast and an anticyclonic Eddy at the head of Sri Lanka (Figure 5b). But the dumbbell shaped anticyclonic gyre which is found in the upper 100 m does not appear at this depth; it breaks into two Eddies and they shift towards coast. In the southern BOB, currents from two opposite directions are found at around 6°N to form an anticyclonic Eddy in the southeast of the Sri Lanka. The eastern boundary current is found to flow northward through AnS to the head BOB. The circulation in the AnS is similar to that of winter but the northern Eddy is found to be cyclonic in nature.

In the summer, the current pattern shows the influence of AS to the BOB. The current flows around the Sri Lankan coast and then along the Indian coast (Figure 5c). But it moves back at around 12°N due to the formation of cyclonic Eddies in the northern coast. This time four cyclonic Eddies are formed in the northwest and head of the BOB. In the AnS, two anticyclonic Eddies were found from the model. In the autumn, the EICC is not found to be continuous southward due to the formation of an anticyclonic Eddy at around 82°E; 11°N near the Sri Lankan coast and cyclonic Eddies at the northwestern coast (Figure 5d). This north equatorial current is observed from the model study. The two anticyclonic Eddies which are found in the summer in the AnS are also observed in this season but they close together towards the north.

Circulation at 1000 m

The current pattern shows that in the winter the WBC flows northward. It indicates that the WBC is much deep in this basin (Figure 6a). An anticyclonic gyre is observed in the north of 14°N. Similarly, another anticyclonic gyre was found between 8 and 14°N. In the north of AnS, the anticyclonic Eddy is still there which can be found in the upper depths also. This is due to the bathymetry of this region. It cannot mix with the surroundings once it is formed. But current formed in the southern side of the AnS is observed to meet with the equatorial current. In the spring, the northward propagating WBC is found to flow continuously southward (Figure 6b). This is in opposite direction compared to the

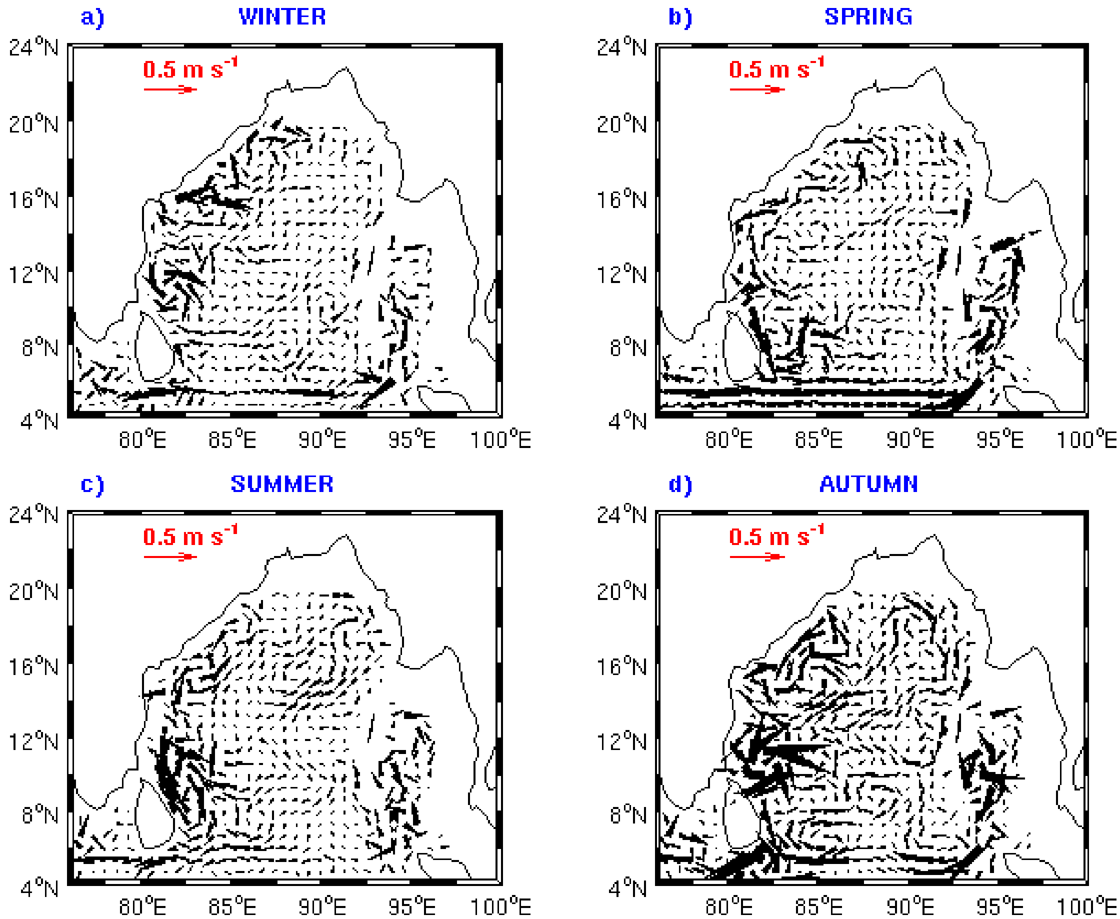

Figure 6. Model simulated current pattern at 1000 m depth for (a) Winter, (b) Spring, (c) Summer and (d) Autumn.

upper depths. The flow from the southern AnS to the southern BOB can also be observed here. The anticyclonic flow also persists at this depth there.

Figure 6c shows that the current along the western boundary is not well organized as the current pattern in summer during the summer. An anticyclonic Eddy is found near the Sri Lankan coast where cyclonic Eddy is found in the northwest coast of the BOB. In the head BOB, an anticyclonic gyre was found from this model simulation. In the AnS, three anticyclonic Eddies were formed in the model simulation. They are due to bathymetry effect of the AnS. In autumn, EICC flows southward in the upper BOB (Figure 6d). But at 1000 m it is not continuous along the western boundary due to formation of consecutive Eddies of opposite sense along the coast line. An anticyclonic Eddy was found at 82°E; 11°N which exists at 500 m also and a cyclonic gyre at 85°E; 14°N.

Conclusions

The seasonal variations in circulation for the BOB has been investigated using high resolution ROMS, driven by the climatological forcing. The outcome of the study are given as follows:

Circulation at 10 m: The formation of WBC at the upper layer and reversal of coastal current are well simulated by the model. The influence of the MS is prominent during the winter season at the 10 m depth. The model simulating north equatorial current and the SMC are quite comparable with previous studies. But the high resolution model is able to detect many more mesoscale features in the BOB basin. Most of the season, the circulation at 10 m depth in the Andaman Sea is driven by two Eddies; one in the north and the other in the south. These two Eddies are very deep.

Circulation at 100 m: The circulations in all seasons at 100 m depth are found to be similar like that at 10 m depth. The winter time influence from the MS is not present here due to its bathymetry which is less than 100 m. But the SMC in the summer and the north equatorial current in the autumn are not found at this depth like the 10 m depth.

Circulation at 500 m: The existence of the WBC at this depth in the winter confirms this current to be deep and strong. But spring time anticyclonic gyre in the western boundary of the basin is not present at this depth. The influence from the AS in the BOB circulation is clear from the model study.

Circulation at 1000 m: The current along the western boundary in the spring in 1000 m current is opposite to that of the upper layer current. A strong anticyclonic Eddy persists near the head of the Sri Lanka at 1000 m depth for almost every season. The overall analysis of the BOB model simulation, using ROMS with climatological southern boundary condition is sufficient enough to simulate seasonal climatological features. In addition, many mesoscale features are also simulated by the model whose existence is also supported by the satellite observations. This model simulation provides the idea about the circulation pattern in deeper oceans of this basin.

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