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RESEARCH REPORT

Sea Surface Height and Upper Ocean Heat Content Variability in Bay of Bengal during Contrasting Monsoons 2009 and 2010

Anitha Gera, Mitra A.K, Mahapatra D.K
Imran Ali, Rajagopal E. N and Swati Basu

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National Centre for Medium Range Weather Forecasting
Ministry of Earth Sciences,

A-50, Sector 62, NOIDA – 201309, INDIA

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Sea Surface Height and Upper Ocean Heat Content Variability in Bay of Bengal during Contrasting monsoons 2009 and 2010

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Contents

List of Acronyms:

AISMR: All India Summer Monsoon Rainfall

Aviso :Archiving, Validation and Interpretation of Satellite Oceanographic data

BoB: Bay of Bengal

IOD: Indian Ocean Dipole

D20: Depth of 20^{0}C Isotherm

D23: Depth of 23^{0}C Isotherm

D26: Depth of 26^{0}C Isotherm

ECCO: Estimating the Circulation and Climate of the Ocean

EICC: East India Coastal Current

JJAS: June July August September

JPL: Jet propulsion Laboratory

LPS: Low Pressure System

NASA: National Aeronautics and Space Administration

NOAA: National Oceanic and Atmospheric Administration

NCEP: National Centres for Environmental Prediction

OSCAR: Ocean Surface Current Analysis

OLR: Outgoing Longwave Radiation

SMC: Southwest Monsoon Current

SSH: Sea Surface Height

SSHA: Sea Surface Height Anomaly

SST: Sea Surface Temperature

SSTA: Sea Surface Temperature Anomaly

TRMM: Tropical Rainfall Measuring Mission

TMI: TRMM Microwave Imager

UOHC: Upper Ocean Heat Content

Abstract

Over the Bay of Bengal (BoB), Monsoon Depressions (MDs) form and move westward resulting in heavy rainfall over the Indian sub-continent. Sea Surface Temperature over the BoB plays a crucial role in the convection and thereby on the rainfall over India. In addition to the above, upper ocean heat content (UOHC) (heat content above 26^0 C isotherm) over the ocean also plays an important role in the intensity and intensification of tropical systems. Satellite derived sea surface height anomalies (SSHA) give information on thermocline variations. Here we report the importance of UOHC over BoB and the influence on the rainfall over India using SSHA, model temperature profiles and satellite meteorological data. It is hypothesised that increased UOHC over BoB would enhance the convection and low pressure systems, modulating the monsoon circulation and hence the rainfall over India. In particular, two contrasting monsoon years 2009 (below normal) and 2010 (normal) are examined and the causes in the UOHC variability and the associated ocean atmosphere coupling during the two monsoons are investigated. The report gives an account of how equatorial and coastal Kelvin and Rossby waves cause upwelling and downwelling promoting changes in UOHC and thereby modulating convection during contrasting years 2009 and 2010.

1.0 Introduction

During Summer monsoon (June to September), monsoon depressions form over Bay of Bengal and move westward or northwestward causing much rainfall over the Indian land mass. Krishnamurthy and Ajayamohan (2010) indicated that the Low Pressure Systems (LPSs) play a major role in determining the rainfall in the central and northwest India. They have shown that over these areas the seasonal contribution of rain during the LPS days is 60 % during flood years and 30-40% during drought years. Goswami et al (2003) have studied the depressions forming in the BoB during active and break periods and found that the frequency of occurrence of LPS is nearly 3.5 times higher in the active phase than in break phase and that the tracks of these synoptic systems are also strongly spatially clustered along the monsoon trough during the active phase of the monsoon. The surface temperature of the BoB remains above 28 ^{0}C, the threshold for convection, during the entire summer monsoon period. Previous studies (Vecchi and Harrison, 2002; Shankar et al 2007; Joseph and Sabin, 2008) emphasized the role of Sea Surface Temperature (SST) in Bay of Bengal in relation to Indian monsoon rainfall. Rajeevan and McPhaden (2004) have studied the interannual variations of Pacific Ocean heat content and Indian summer monsoon rainfall. On the interannual scale, Loschnigg et al (2003) in their study have observed the role of ocean heat transport over the summer and winter hemispheres of the Indian Ocean and the monsoon. Sindu et al (2009) have studied the response of the mixed layer heat content on intraseasonal time scales in the BoB.

The upper ocean heat content is one of the key factors for the genesis and intensification of cyclone (Emmanuel, 1999). The ocean thermal energy is defined as tropical cyclone heat potential or the upper ocean heat content (Gray, 1979) and calculated as the integrated heat content till 26^{0}C isotherm. The tropical Indian Ocean is an active part of the tropical monsoon system and acts as a heat source. SSH is an indicator of the vertically integrated density changes in the entire water column. The density changes in the water column are due to changes of temperature and salinity. The contribution of the temperature is large and that due to salinity change is comparatively less in the global ocean. As temperature increases, the density decreases and the volume increases. Hence an increase/decrease in SSH represents a corresponding increase/decrease of the warm water/ heat content of the ocean. Tropical systems maintain their intensity or intensify rapidly in places where the sea surface height anomaly (SSHA) is relatively high. However there could be regional differences and salinity impacts on SSH could be significant in some regions. The changes in the upper ocean heat content in the BoB has been studied by many researchers with respect to cyclones (eg., Sadhuram et al, 2004; Yu and Mc Phaden, 2011; Wang et al 2012).

Sea Surface Height (SSH) is an important parameter to study and understand coupled ocean-atmosphere phenomena like, Monsoon, IOD, ElNino etc (Eg, Meyers,1996; Feng et al , 2001; Feng and Meyers, 2003). Variations of SSH provide information on the subsurface ocean and air-sea interaction parameters like thermocline and upper ocean heat content. Propagation of planetary Kelvin and Rossby waves can be observed using sea surface height anomaly (SSHA) (Chelton and Schlax, 1996; Polito and Cornillon, 1997; Fu, 2001). Sreenivas et al (2012) have studied the role of Kelvin waves in the cyclone heat potential over BoB and its interannual variability. Assimilation of SSHA into coupled ocean-atmosphere/ocean models produces better representation of the ocean as SSHA gives subsurface ocean information. Hence better forecasts could be made by realistic representation of SSHA. In the present study we report the influence of the variability of upper ocean heat content over Bay of Bengal on the Indian summer monsoon rainfall and demonstrate the usefulness of satellite altimetry to study the coupled tropical monsoon system. The study focuses on the SSHA and the associated UOHC variabilities in the BoB during two contrasting monsoon years 2009 (below normal) and 2010 (normal monsoon).

2.0 Data and Methods

Weekly merged altimeter derived SSHAs obtained from Aviso data are used in the study for analysis and computation of ocean heat content over the North Indian Ocean region. Altimeters observe the height of the satellite above the sea surface generally with a precision of ±2 cm and an accuracy of ±4 cm. SST used in the study is three day running mean of daily SST from TRMM/TMI (Wentz et al, 2000). NCEP reanalysis surface level winds are used to study how the remote and local winds influence the thermocline depth variations. The OLR data of NOAA are used as a proxy for convection. ECCO ocean analysed temperature obtained from JPL, NASA of 0.3^0 in latitude and 1^0 in longitude resolution and of weekly time resolution is used to obtain D23 and D26. Ocean temperature climatology of Chatterjee et al., (2012) is used to compute the thermocline depth anomalies in conjunction with the ECCO temperature data. This climatology is also used for deriving D20 and D26 climatology for computing heat content from SSHA. Merged rainfall data from rain gauge and TRMM TMPA satellite estimates is used for rainfall analysis in the study (Mitra et al, 2009). The heat content from the ECCO ocean temperature is derived using Leipper and Volgenau, (1972). The methodology used to compute heat content from the SSHA, SST, climatological D26 and D20 is Shay and Brewster (2010) which is based on a two-layer reduced gravity model. The relationship is given by equations 1, 2 and 3.

$$Q = \rho_1 c_p \int_{H_{26}}^{\eta'} [T(z) - 26^{\circ}\mathrm{C}]\, dz \qquad (1)$$

$$H_{26} = \frac{\overline{H_{26}}}{\overline{H_{20}}} H_{20} \qquad (2)$$

$$H_{20} = \overline{H_{20}} + \frac{g}{g'}\eta' \qquad (3)$$

The anomalies of UOHC, SST, surface winds and OLR are difference from climatology computed as mean of the years 1998 to 2010 for months June, July, August and September. The reason for taking this period is that the availability of TMI JJAS SST is from 1998 onwards. Ocean surface currents from Ocean Surface Current Analysis (OSCAR) data set (Johnson et al, 2007; Sikhakolli et al, 2013) are used to study the propagation of SMC. Monthly net heat flux data of TropFlux (Praveen Kumar et al, 2012) is used in the study.

3.0 Rainfall distribution over India during monsoons 2009 and 2010

Monsoon (JJAS) rainfall during 2009 and 2010 was contrasting. The monsoon period JJAS 2009 was 23% deficit (Monsoon 2009-A report, 2010), and recorded 77% of LPA whereas JJAS 2010 was 102% of the Long period average (LPA) (Monsoon 2009-A report, 2010 and Monsoon 2010-A report, 2011). The JJAS average precipitation for the years 2009 and 2010 is shown in figures 1a,b. During monsoon year 2009 the period 30th July to 11th August was a break period and Indian land region suffered drought conditions due to the rainfall deficit. The precipitation difference during the month of August in 2010 and 2009 indicated a large positive difference over most of the Indian sub-continent region except in the North east region and Bangladesh (figure not shown). The higher precipitation in August 2010 compared to August 2009 ranges from 2mm to 15mm per day. The AISMR from India meteorological department rainfall difference for August 2010 and August 2009 is 82mm.

The OLR anomalies for JJAS 2009 and JJAS 2010 (figure 1(c-d)) show that most of the BoB is occupied with positive anomalies during JJAS 2009 and negative anomalies during JJAS 2010 indicating increased convection over the south central BoB in 2010 and reduced convection in 2009. We examine the role of heat content of BoB in these contrasting years and its links to these anomalies. Francis and Gadgil (2009) have shown that the negative SST anomalies over Bay of Bengal are responsible for the drought during 2009. Chacko et al (2012) have studied the mixed layer budget in the Bay of Bengal during June 2009 and concluded that the BoB cooled as a mixed response to a cyclone in May 2009, SMC and rossby waves.

4.0 Mean SSHA Features over Bay of Bengal during Summer Monsoon

The satellite derived SSHA represents the dynamic topography of the ocean. Wind and thermohaline forcings influence the SSHA variability. The circulation of the Indian ocean is majorly influenced by seasonal wind, buoyancy and remote forcing through Ekman and geostrophic adjustments (Schott and McCreary, 2001; McCreary et al, 1993). The SSHA over Bay of Bengal is influenced by the strong reversing monsoons, the remote forcing by the equatorial winds and the density changes due to the large fresh water input. The sea level/SSHA varies in BoB over wide range of timescales (Han and Webster, 2002). The annual cycle of SSHA in the Tropical Indian Ocean has been documented by Subramanyam and Robinson (2000). The equatorial winds drive planetary waves, equatorial Kelvin and Rossby waves (Potemra et al 1991, McCreary et al , 1993). The equatorial Kelvin waves as they reach the east coast reflect as coastal Kelvin waves and split into two branches propagating poleward. One travels northward in the northern hemisphere and the other southward in the southern hemisphere. The northward branch travels along the eastern coast of the BoB. These coastal Kelvin waves in turn radiate westward propagating Rossby waves which move into the BoB interior (McCreary et al , 1993).

Figure 2 shows the SSHA from merged altimeter data averaged over the years 1993 to 2010 for the summer months June-July-August and September (JJAS). During the summer monsoon the basin wide circulation in the BoB is anti-cyclonic (Yu et al., 1991; Shetye et al., 1993, Somayajulu et al., 2003). Anti-cyclonic (cyclonic) circulations are associated with downwelling (upwelling) and hence positive (negative) SSHA represent anti-cyclonic (cyclonic) eddies. Similarly downwelling and upwelling Kelvin/Rossby waves are represented with positive and negative SSH anomalies respectively. SSHA variability along the eastern coast of Bay of Bengal is forced by a downwelling Kelvin wave during early summer and an upwelling Kelvin wave during the later part (Rao et al., 2010). The upwelling Kelvin wave during later part of summer is generally weak (figure 2d) and is limited to south-east coast of Bay of Bengal or the Sumatra-Java coast. The downwelling Kelvin wave generates downwelling Rossby waves which propagate into the BoB interior. Hence most of the central and northern Bay of Bengal is occupied with positive SSHA. The propagation of this downwelling Kelvin wave terminates near head BoB due to the opposing force from the poleward flowing EICC (Rao et al., 2010 and figure 2-c,d). The SMC intrudes into the BoB after flowing south of India and Srilanka and the flow is enhanced as the monsoon progresses (Vinayachandran et al.,1999). and brings salty waters into the BoB from Arabian Sea (Jensen, 2001). An anticyclonic eddy is embedded in the SMC east of Srilanka (Vinayachandran and Yamagata, 1998). In addition, anticyclonic mesoscale eddies from the western BoB propagate into the BoB. Hence the south west of BoB is occupied by negative SSHAs, increasing in extent as the monsoon progresses.

4.1 SSHA and D26 anomalies

Figures 3 and 4 show SSHA during summer months JJAS of 2009 and 2010. The positive and negative values are demarked by thick dark zero contour. From these figures it is clearly seen that the SSH anomalies were very high over the Bay of Bengal in 2010 compared to 2009. During June 2009 the SSHAs were positive over most part of the BoB exceeding 14cm but when compared to June 2010 the magnitudes of SSHA are lower over western part of the BoB. The positive SSHAs indicate a deep warm layer of the upper ocean. During July to September 2009, negative SSHAs occupied the western part of the BoB unlike July to September 2010. Over the eastern part of the BoB, the magnitudes were positive but lower during July to August 2009 compared to July to September 2010. The mechanisms governing these differences are discussed in the next section.

Variabilities in D26 are important because it is the depth to which the upper ocean heat content is integrated and proxy for middle of the thermocline. D23 is assumed as a proxy for bottom of the thermocline. Figures 5(a-d) show the D26 and D23 anomalies during JJAS 2009 and JJAS 2010. The spatial anomalies of D23 and D26 show negative values north of 10N in the BoB during 2009 indicating a shallow thermocline and cooler upper ocean. The

D23 and D26 anomalies are positive over most of the BoB during 2010 indicating deeper thermocline and a warmer upper ocean.

4.1 SST and Upper Ocean Heat Content anomalies

Climatologically, the surface temperature of the BoB remains above 28^{0}C, the threshold for convection, during the entire monsoon period. During JJAS 2009 the sea surface was cooler than normal by 0.2 to 0.6 ^{0}C and during JJAS 2010 the entire BoB was warmer than normal by 0.6^{0}C to 1^{0}C and over the eastern coast it is warmer by 1.6^{0}C (figure 6). Very contrasting anomalies of ocean heat content are observed over the BoB during JJAS 2009 and JJAS 2010 (figures 7 and 8). The BoB is entirely covered with positive anomalies during 2010 whereas most of the BoB is covered with negative anomalies during JJAS 2009. Wada and Usui (2007) have shown that the UOHC plays a more important role in tropical system intensity and intensification. During the summer monsoon (June-September) synoptic lows pressure systems form over the BoB and propagate west northwestward over the Indian land mass towards Rajasthan (Ding and Sikka, 2006) causing widespread rain over the Indian landmass. Goswami (1987) suggested feedback mechanism for west northwest movement of monsoon depressions. The warm anomalies over the BoB are favourable for formation of these low pressure systems by enhanced convection. Some of these systems are westward-propagating residual lows from the western pacific (Krishnamurti et al., 1977;saha et al, 1981; Chen and Weng 1999) enhanced by the warm anomalies over the BoB. On an average six to seven low pressure areas form over Bay of Bengal every JJAS. However, the LPS activity during JJAS 2009 was subdued and only six LPS formed over the Bay of Bengal with one each in June and August and two each in July and September. The duration of these systems was very short and did not produce persistent rainfall. One of them formed over northwest Bay of Bengal in early June 2009 dissipated over the BoB itself in the north east BoB without reaching the landmass (Monsoon 2009 report, 2010). During 1-24th Jun 2009 the life span of convective events over the BoB was never longer than 3-4 days, no northward movement was observed and no low pressure system generated over the head BoB and westward propagation across the monsoon zone did not occur. (Francis and Gadgil, 2009). During JJAS 2010 twelve low pressure /depressions systems formed over the Bay of Bengal with two each in June and September and four each in July and August. All these systems originated in the west central Bay of Bengal and eleven of them moved west northwestward towards Madhya Pradesh and Rajasthan producing active monsoon rainfall conditions over central, western and north peninsular India (Orissa, Andhra Pradesh, Chhattisgarh, Madhya Pradesh, Bihar, Rajasthan Haryana and Gujarat) (Monsoon 2010, 2011). Correspondingly the heat content anomalies over the BoB were negative in JJAS 2009 and positive in JJAS 2010 (figures 7 and 8). The heat content averaged over Bay of Bengal during JJAS 2009 was cooler than normal by 6 X 10^ 8 J/m^2 and during JJAS 2010 was warmer than normal by 8-15 X 10 ^ 8 J/m^2. Sadhuram et al(2004) showed that a threshold value of 60KJ/cm2 (equivalent to 6 X 10^ 8 J/m^2) may be necessary for genesis and intensification of cyclones during post monsoon season in BoB. The OLR anomalies over the BoB shown in figure 1-c,d exhibit negative anomalies over the BoB during JJAS 2010 and positive anomalies during JJAS 2009. This highlights the role of UOHC in enhancing convection and providing heat supply for the more number of LPS formed over the BoB during 2010 compared to 2009. In addition to providing rainfall, these systems transport heat and moisture upward and maintain the monsoon trough and the low level monsoon winds (Mooley, 1973). These systems contribute about 45%-55% of the total summer monsoon rain (Yoon and Chen, 2005; Krishnamurthy & Ajayamohan, 2010). Mooley (1973) based on data from six stations falling in the trough region, estimated 11-16% contribution to the seasonal rainfall.

5.0 Forcing Mechanisms

Figure 9 showing the net heat flux anomalies (convention is positive into ocean and negative out of ocean) for JJAS average for 2009 and 2010 over the BoB indicates that the heat flux anomaly over BoB is large and positive during 2009 while it is negative in 2010. Hence net heat flux would not be the reason for increased/positive SST and UOHC anomalies during JJAS 2010 and lower/negative anomalies during JJAS 2009. Shankar and Shetye (2001) have examined the wind and thermohaline forcings in BoB and Arabian Sea in a comparative study of coastal sea level differences. Prakash and Mitra (1988) have suggested that the seasonal cycle of SST in the monsoon region of Indian Ocean may be influenced by surface fluxes of fresh water. Anitha et al (2008) have analysed the annual cycle of surface buoyancy fluxes in Bay of Bengal and Arabian Sea and have shown the large influence of fresh water in the BoB. These studies emphasise the importance of fresh water on the upper ocean of BoB. The fresh water forcing could not be made due to lack of well distributed observational salinity data in the basin over coastal regions and could be a limitation of the study. However the correlation between SSHA and D26 in the domain of BoB (80E-90E and 5N to 20N) for JJAS of years 1993 to 2010 is 0.82 and the correlation between UOHC from ECCO and SSHA for the same time period is 0.85. This indicates good coupling between SSHA and

D26 & UOHC in this region. Now, the wind forcing mechanisms for the differences in SSHA, D26, D23 and heat content anomalies during summers of 2009 and 2010 are examined. The thermocline variability in the BoB depends on the three factors (Eg., Yu, 2003). The first one is the remote forcing by equatorial winds. The second factor is the along shore winds on the eastern rim of the Bay of Bengal and third one is the local wind stress curl. If all the three factors affect it to raise/lower the thermocline then the net result would be amplified, else the net effect would be that of the one that dominates.

5.0.1 Remote Forcing: Role of Rossby and Kelvin Waves

The remote forcing was different during 2009 and 2010. The equatorial zonal winds were strongly westerly during 2010 (**figure** 10e-h) and were responsible for driving a strong equatorial Kelvin wave which propagated into the BoB as coastal Kelvin Waves. Hence strongly positive SSHAs were observed along the equator and along the eastern rim of BoB during June, August and September 2010 with reduced positive amplitudes during July 2010 (figure 4). The thermocline was deeper as seen in D23 anomalies (**figure 5d**). Figure 11 shows winds along equator and SSHA along at equator from 80E to 92E (equatorial Kelvin Wave) , its northward progression (coastal Kelvin wave)along 92E from 0N to 14N and westward progression (as rossby wave) along 14N from 92E to 80E during march to October 2009 and 2010. The downwelling Kelvin wave along the east coast of BoB radiated downwelling rossby waves (**figures 4 & 11(e)-(f)**). These downwelling Rossby waves propagated westward into the BoB and gave rise to higher SSHAs(**figures 4 & 11**) and deeper D23 anomalies (figure 5d) resulting in higher heat content in the BoB interior. The propagation speed of the Rossby waves was found to be 9.5 cm/s (figure 11) at 14N close to the theoretical speed of first baroclinic rossby waves and to earlier studies (Yu and Mc Phaden 2011). Due the deeper thermocline, the upper ocean heat content was high (figure 8) during this period. Contrastingly, the zonal equatorial wind anomalies over western part during June 2009 and entire Indian ocean longitudes during July 2009, were negative (figure 10a-d). The anomalies were easterlies during June and July and were driving an upwelling Kelvin wave (figure 3 and 11). The anomalies were negative over the western and eastern longitudes in August 2009 and negative over central longitudes during September 2009. These winds produced an upwelling effect due to which negative D23 anomalies are observed during JJAS 2009 (figure 5c). However because of weak and discontinuous (figure not shown) equatorial easterly anomalies the SSHAs during July to September 2009 were not strongly negative but have reduced in amplitude compared to June. These winds generated westward propagating upwelling rossby wave (figure 11a-d). As a result, the thermocline (D23) anomalies and SSHA were negative.

5.0.2 Forcing from Local Wind Stress Curl and Alongshore Winds

The windstress curl (i.e., curl of τ / f) over the BoB is quite similar with respect to magnitude and sign during JJAS of both 2009 and 2010 over all the months June to September (figure 12). Both 2009 and 2010 show similar patterns and magnitudes. The eastern BoB is covered with negative curl τ / f forcing downwelling and western part of BoB shows positive values forcing upwelling. Hence the effect of local wind stress curl on the thermocline would be to raise it(D23 anomalies- figure 5) over the western part of BoB adjacent to the east coast of India, and depress it in the eastern part of the BoB adjacent to the west coasts of Andaman and the Myanmar (figure 5). The along shore wind during June to August of both the years 2009 and 2010 are northward (figures 10i-p). These northward winds give rise to downwelling rossby waves which propagate westward. Depressed the thermocline (figure 5) would be associated with these rossby waves.

5.0.3 Role of Southwest Monsoon Current (SMC) intrusion

Figure 13 shows the OSCAR near surface currents during June-August 2009 and June-August 2010.From the figure it is clear that during 2009 the Southwest Monsoon Current was stronger and intruded much into the BoB bringing saltier and cooler waters from the Arabian Sea. This may possibly be due to increased winds in June July 2009 compared June July 2010over the region (figure 10a,b,e,f,i,j,m,n). The SMC was associated with cyclonic circulation (figure 13) and hence upwelling. The SMC dominated and opposed the effect of downwelling rossby waves generated during June. The downwelling – high SSHA could not be sustained beyond June 2009. The SMC propagated negative SSHAs into the BoB. During 2009, the meridional wind anomalies (figure 10i) were positive along the west coast of Srilanka promoting the propagation of SMC into the BoB. Contrastingly in 2010, the meridional wind anomalies were negative and did not support the propagation of SMC into the BoB (figure 10m). Instead, the propagation of downwelling rossby waves dominated resulting in higher SSHA, deeper themocline and higher heat content.

5.0.4 Resultant of the wind forcings

During 2009, (1) the effect of local winds in terms of curl τ / f is to cause negative anomalies over the western BoB and positive anomalies over the eastern BoB (2) the effect of along shore winds is to generate downwelling rossby waves i.e positive SSHA and D23 anomalies (3) the effect of remote forcing is to cause upwelling and hence negative SSHA and negative D23 anomalies. In addition there is a downwelling rossby wave which left the east coast of BoB in April May reaching longitudes 80- 84 during August (figure 11a). The net D23 anomalies and the heat content over the BoB during June to August show overall negative anomalies spread over the BoB with a small patch of positive anomalies. Over the western BoB the upwelling effect due to remote forcing by equatorial winds and local winds stress curl dominated the downwelling due to along shore winds along eastern boundary of BoB. Over the eastern BoB, again the upwelling effect due to remote forcing dominated the downwelling due to local winds stress curl and along shore winds along eastern boundary of BoB. As a result the heat content anomalies were negative during 2009.The patch of positive anomalies may mainly be due to the downwelling rossby waves radiated from the coast during May, June (figure 11a). At 14N in the BoB strong westward propagating upwelling rossby waves were observed during 2009

During 2010, the effect of remote forcing, and along shore winds cause positive anomalies over the Bay of Bengal. But the local windstress curl has an upwelling component in the western BoB. Over the entire BoB positive heat content anomalies and D23 anomalies are observed, except in a small pocket adjacent to Srilanka. In addition to the effect of windstress upwelling, the along shore winds adjacent to srilanka might have caused the coastal upwelling. An upwelling rossby wave is radiated in jun 2010 which gave rise to negative anomalies near the Myanmar coast. At 14N in the BoB strong westward propagating downwelling rossby waves are observed in 2010 (Figure 11b).

6.0 Summary

The variability in SSHA and UOHC during contrasting monsoon years 2009 and 2010 are observed and analysed. Positive anomalies of SSH and UOHC over Bay of Bengal are found to occupy most of the BoB during JJAS 2010 (a normal monsoon year) and negative anomalies observed during JJAS 2009 (a below normal monsoon year). The forcing mechanisms for these differences in variability in the ocean are investigated. The thermal forcing was opposing the SST and heat content anomalies and hence could not be the driving the contrasting anomalies. The fresh water forcing could not be studied due to lack of data and stands a limitation of the study. Remote forcing by equatorial winds is found to be a major difference between the two contrasting years. During JJAS 2010, anomalous equatorial westerlies have driven downwelling Kelvin wave and as the Kelvin wave peaked, positive SSHA occupied major portion of the BoB whereas in JJAS 2009, the equatorial forcing was opposite with anomalous easterlies. This caused the differences in the SSHA and UOHC during the summers of these two years and possibly leading to enhanced convection and formation of lows and depression in the BoB during JJAS 2010 and subdued LPS activity during JJAS 2009. However modelling studies need to be conducted to confirm the hypothesis. The study brought out the importance of SSHA and the UOHC over the Indian Ocean especially over the Bay of Bengal and some aspects of coupled ocean atmosphere interactions in understanding the Indian summer monsoon. Hence realistic simulation of upper ocean and SSHA by coupled models would lead to better understanding and forecasting of Indian summer monsoon.

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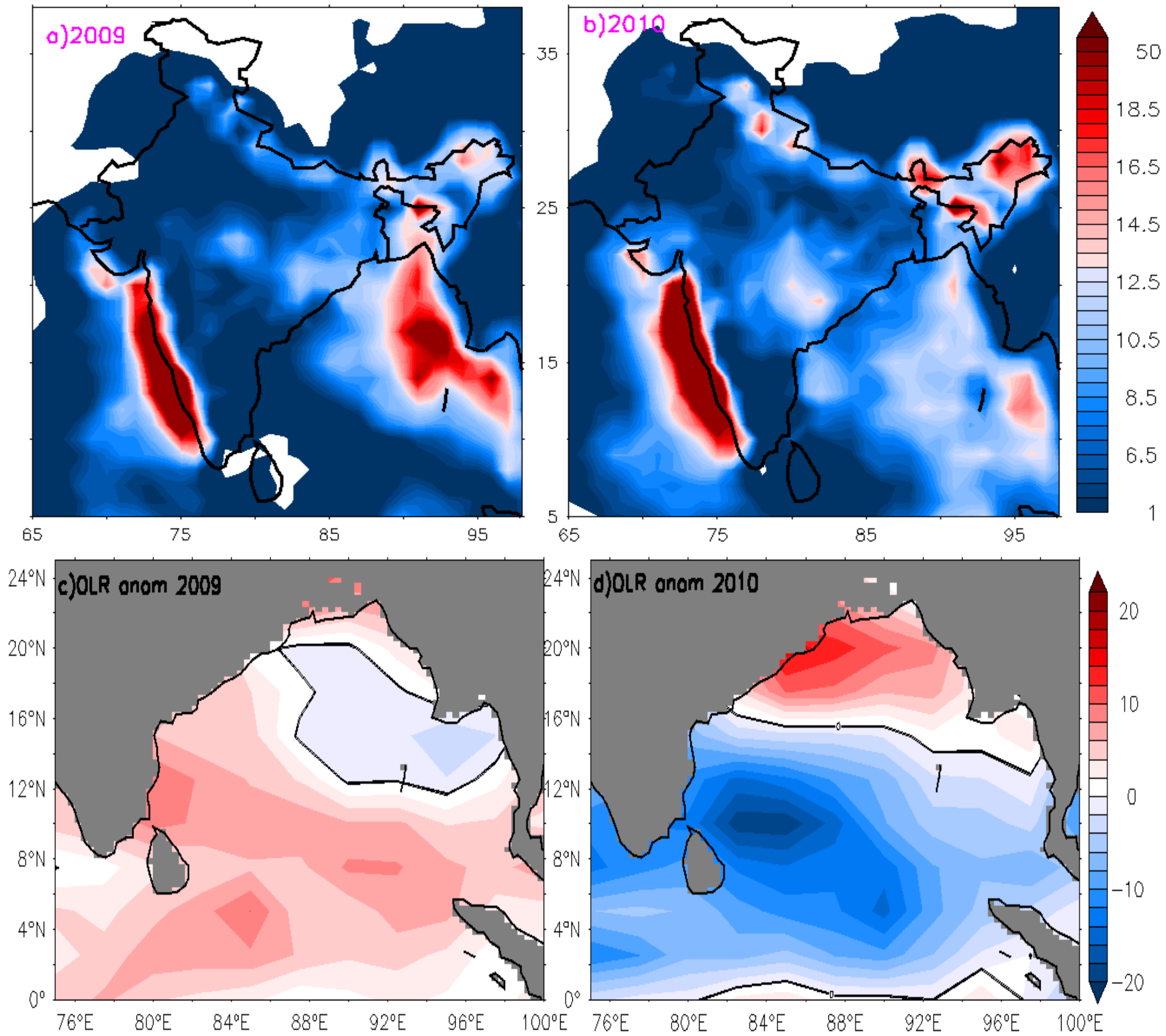

Figure 1. PCP (mm/day) JJAS average for (a) 2009 (b) 2010 and OLR anomaly (W/m^2) for JJAS (c) 2009 (d) 2010

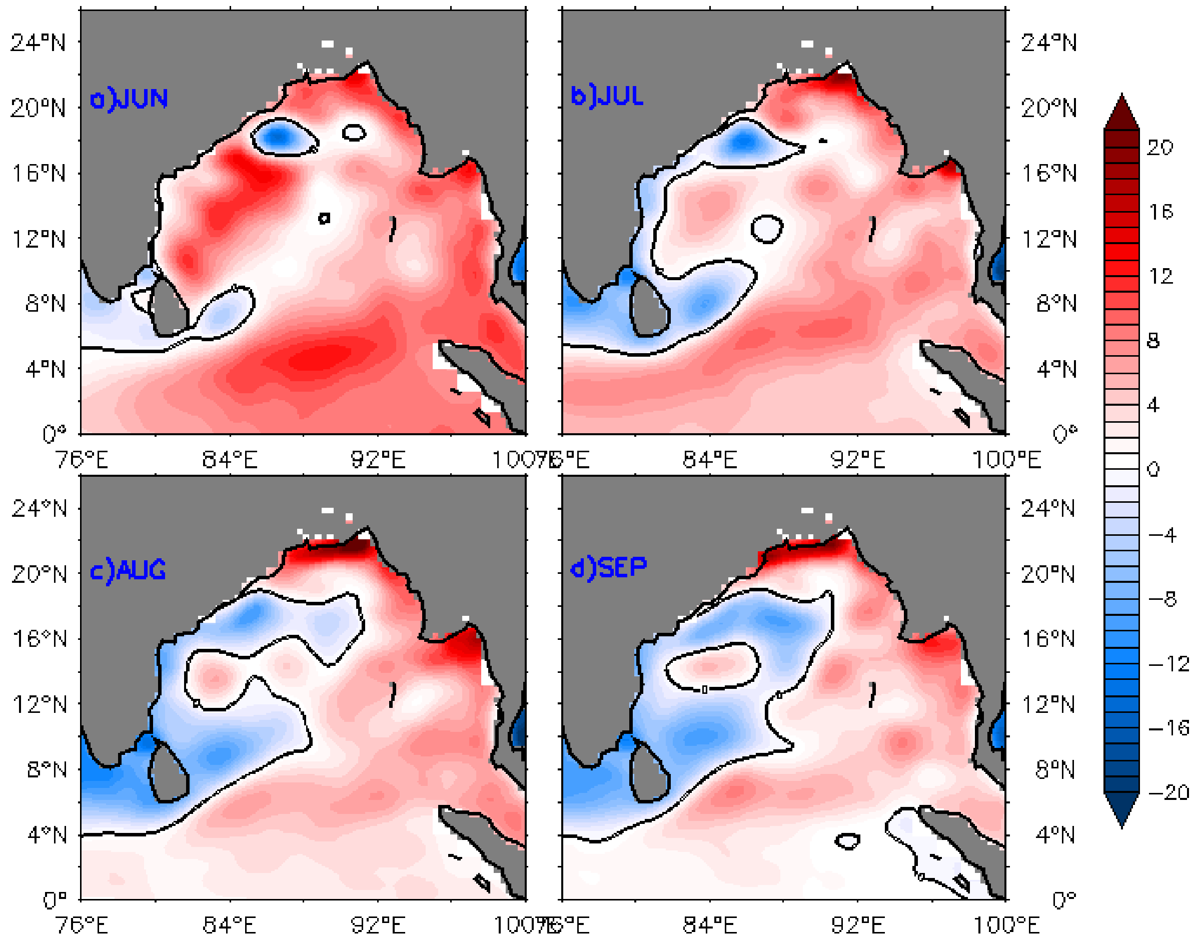

Figure 2: Climatological SSHA (cm) for a)June b)July c)August d)September

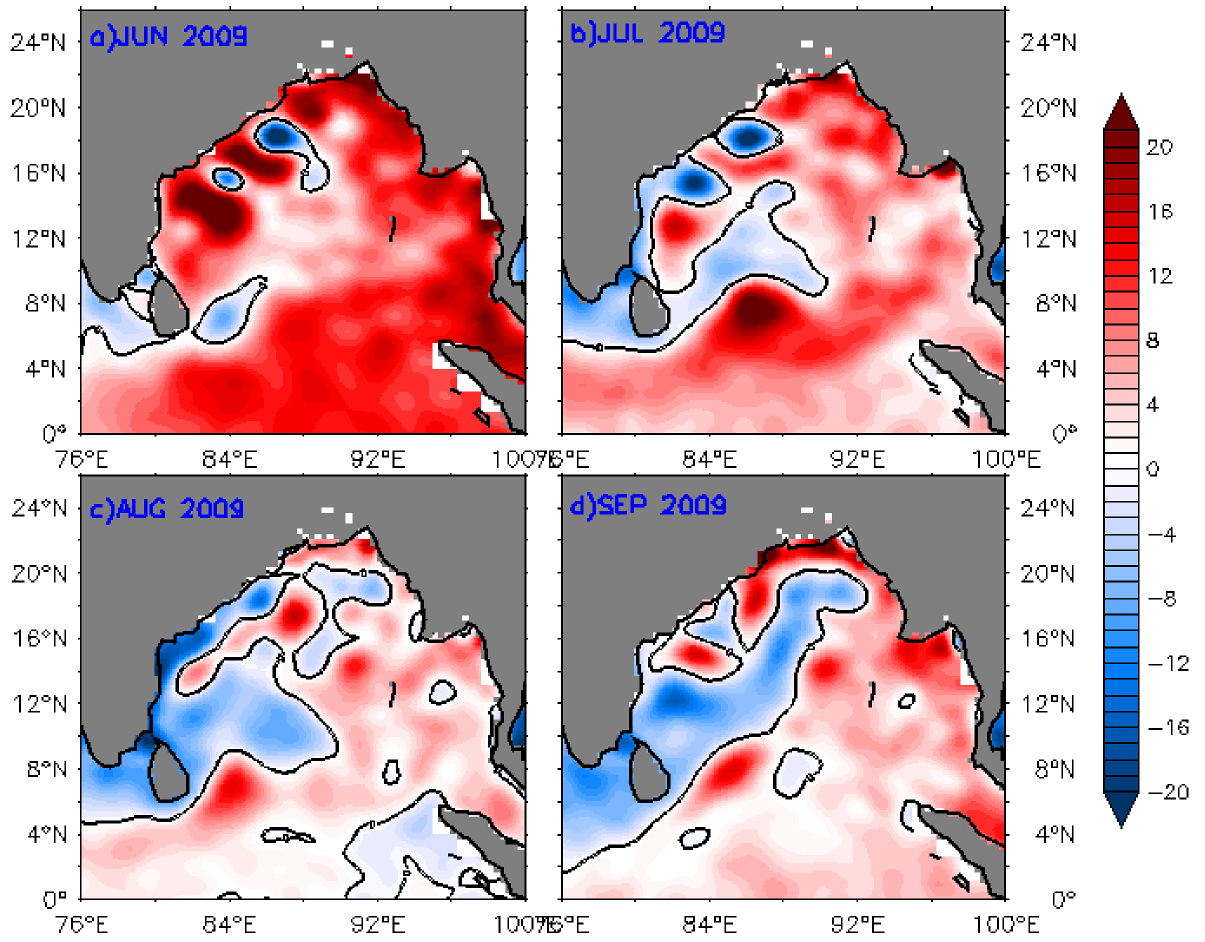

Figure 3: SSHA (cm) during 2009 (a)June (b)July (c)August (d)September

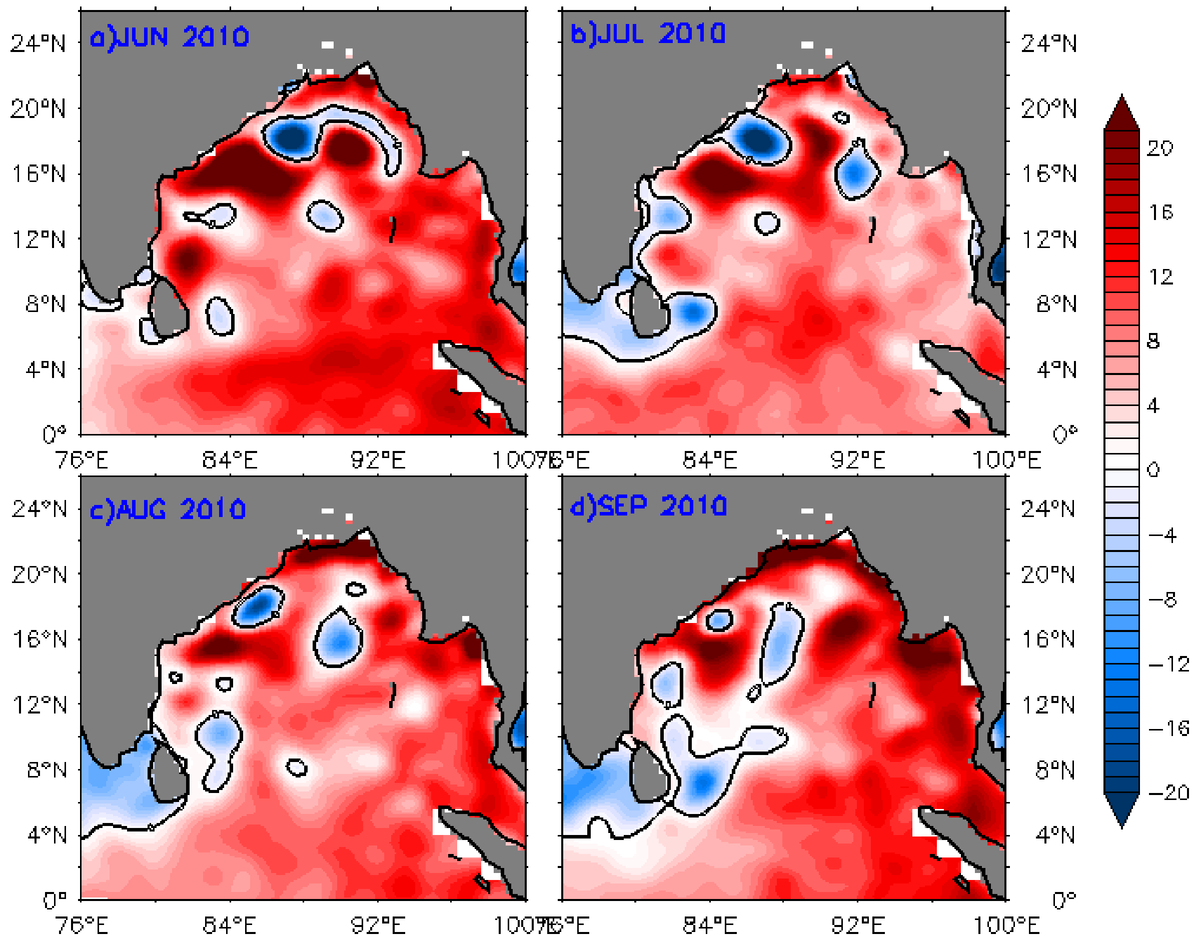

Figure 4: SSHA(cm) during 2010 (a)June (b)July (c) August (d) September

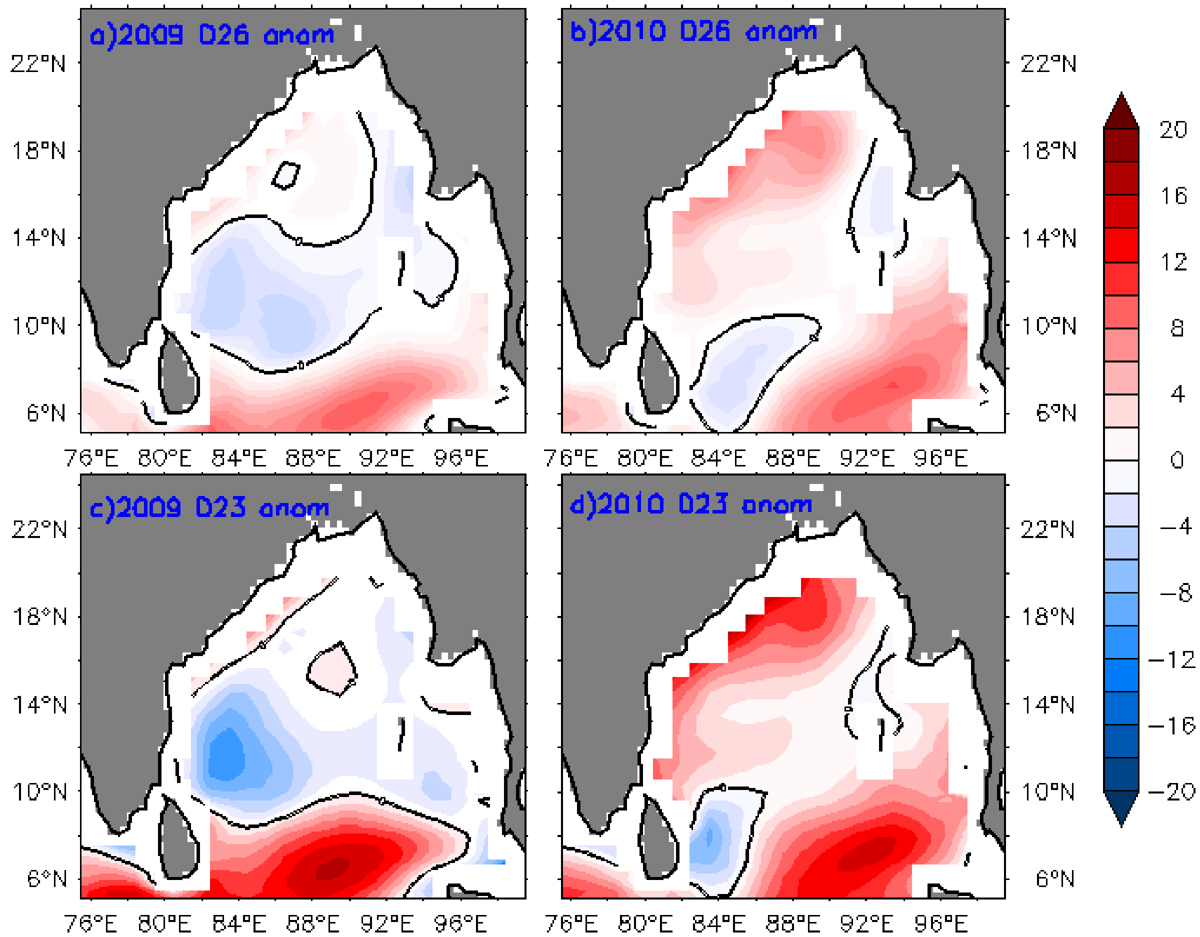

Figure 5: JJAS anomalies of D26(m) for (a) 2009 and (b) 2010 and D23(m)for (c) 2009 (d)2010

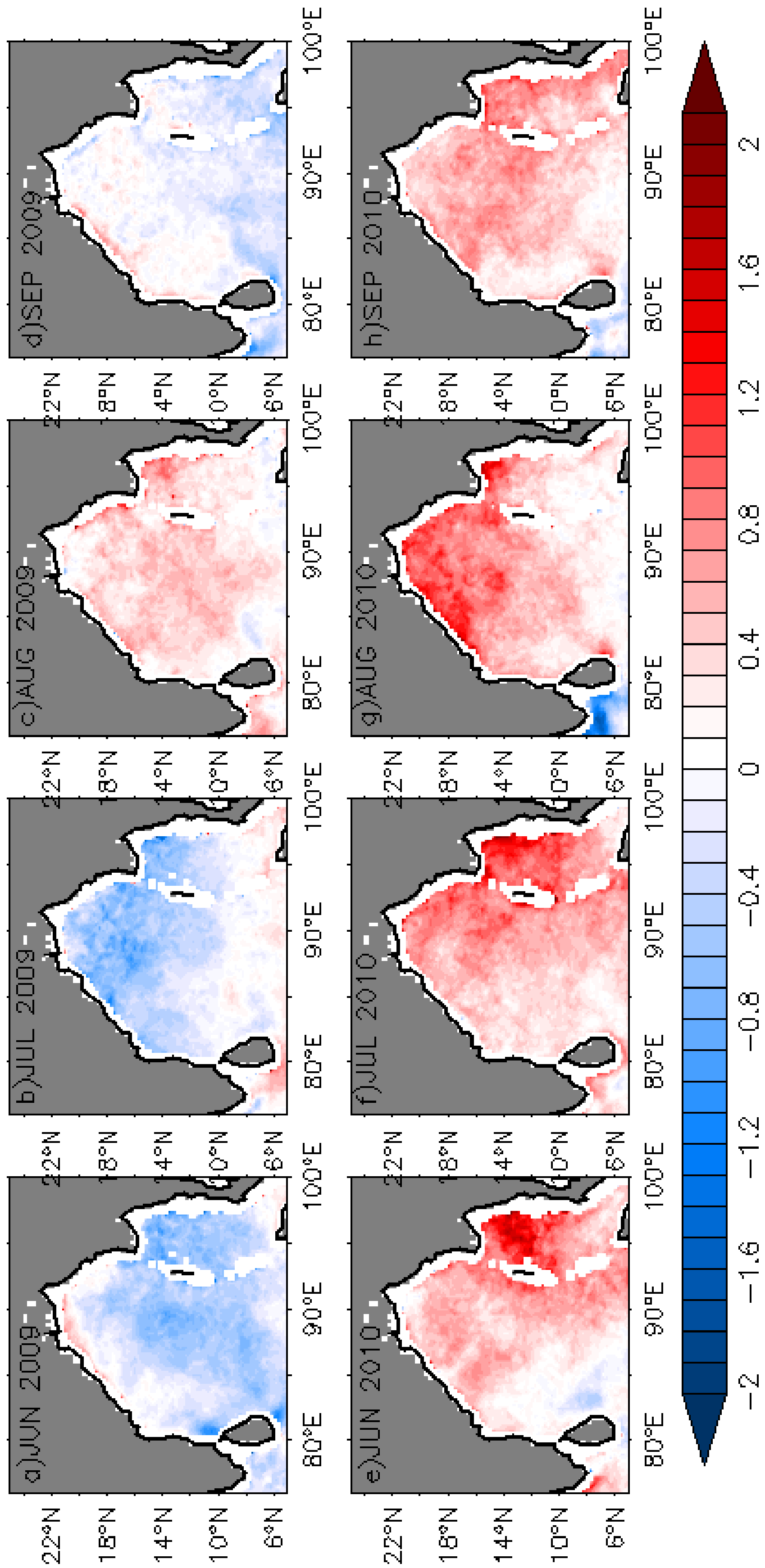

Figure 6: SST anom in ^{0}C during 2009 (a)June (b)July (c) August (d) September and 2010(e) June (f)July (g) August (h) September

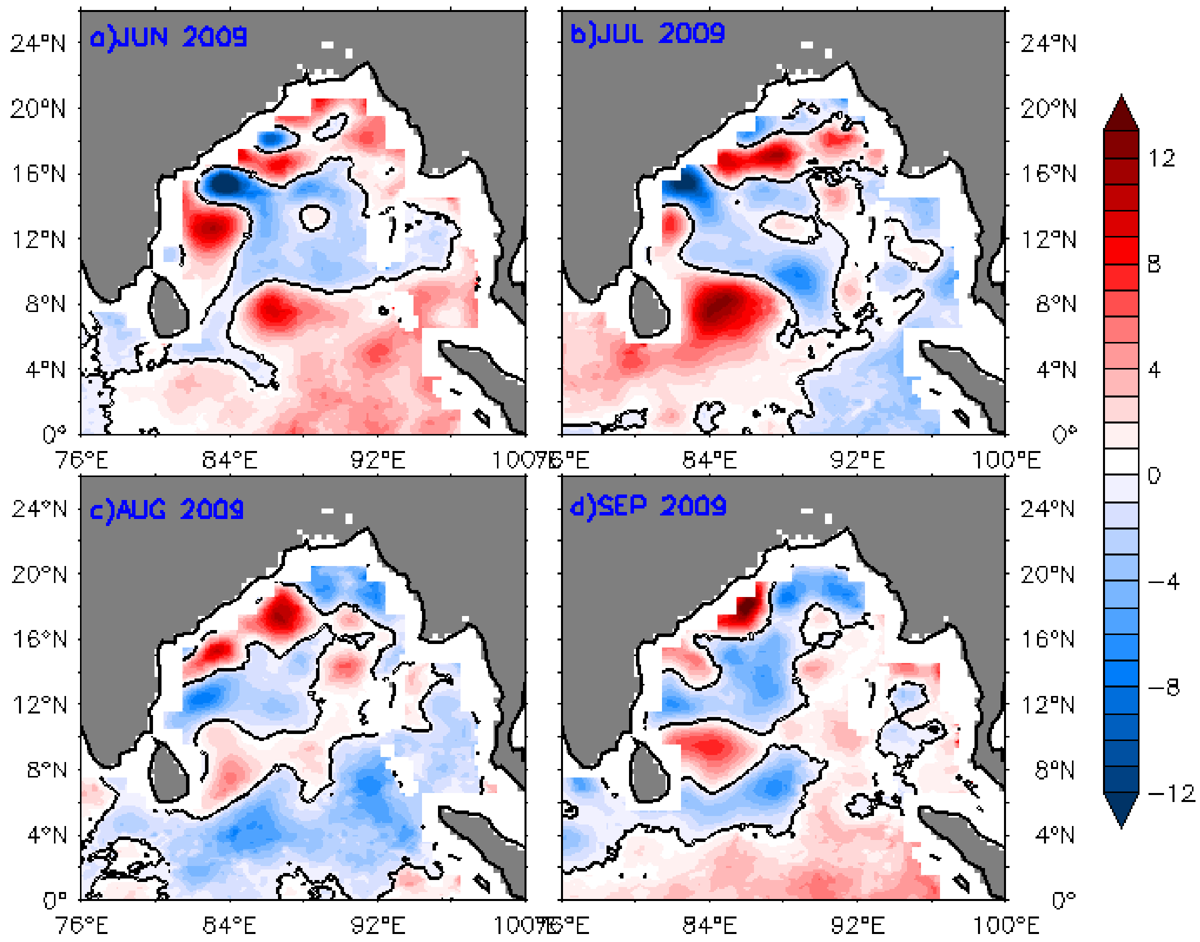

Figure7. UOHC anomaly(X10^8 in J/m^2) during 2009 (a)June (b)July (c)August (d)September

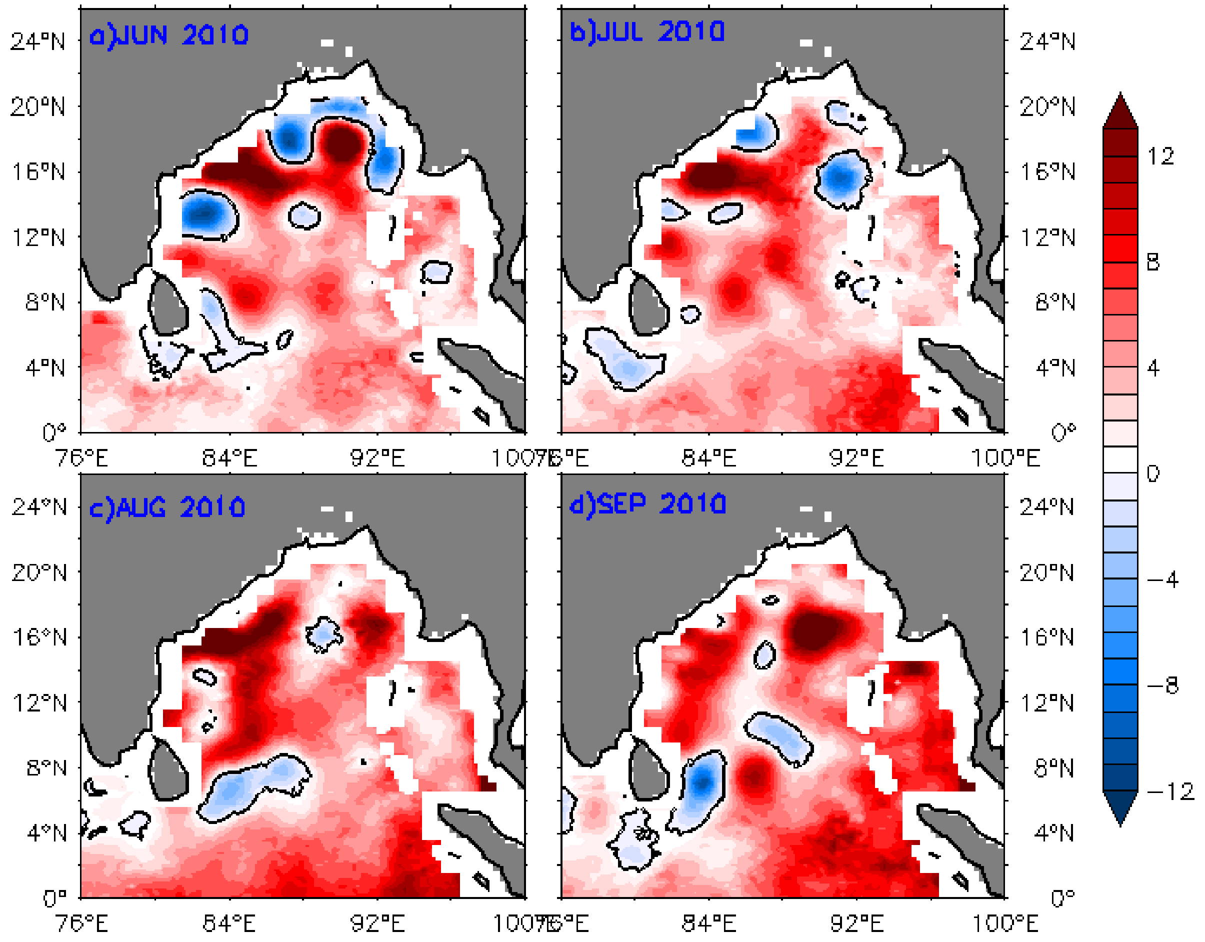

Figure8. UOHC anomaly(X10^8 in J/m^2) during 2010 (a)June (b)July (c)August (d)September

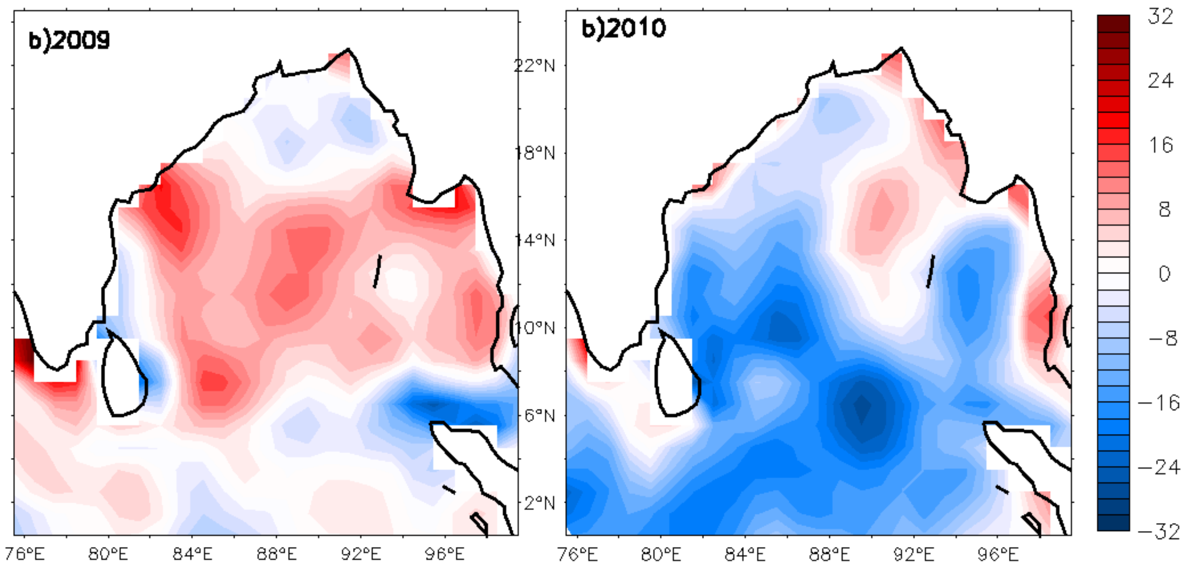

Figure 9. Net heat flux during (positive into ocean and negative out of ocean)JJAS (a) 2009 and (b)2010

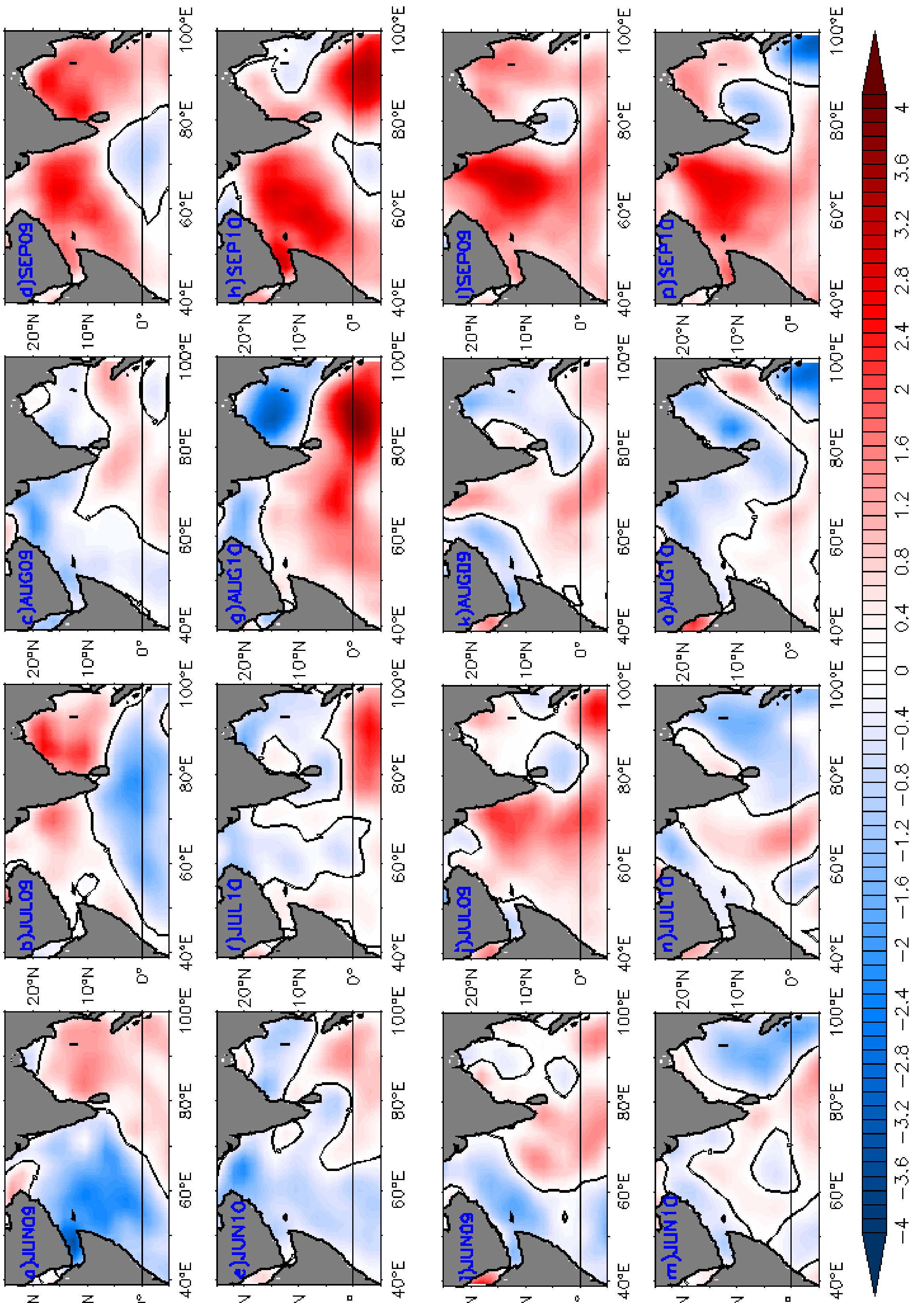

Figure10. Zonal wind anom (m/s) during 2009 (a)June (b)July (c)August (d)September and 2010 (e)June (f)July (g)August (h)September and Meridional wind anom (m/s) during 2009 (i)June (j)July (k)August (l)September and 2010 (m)June (n)July (o)August (p)September

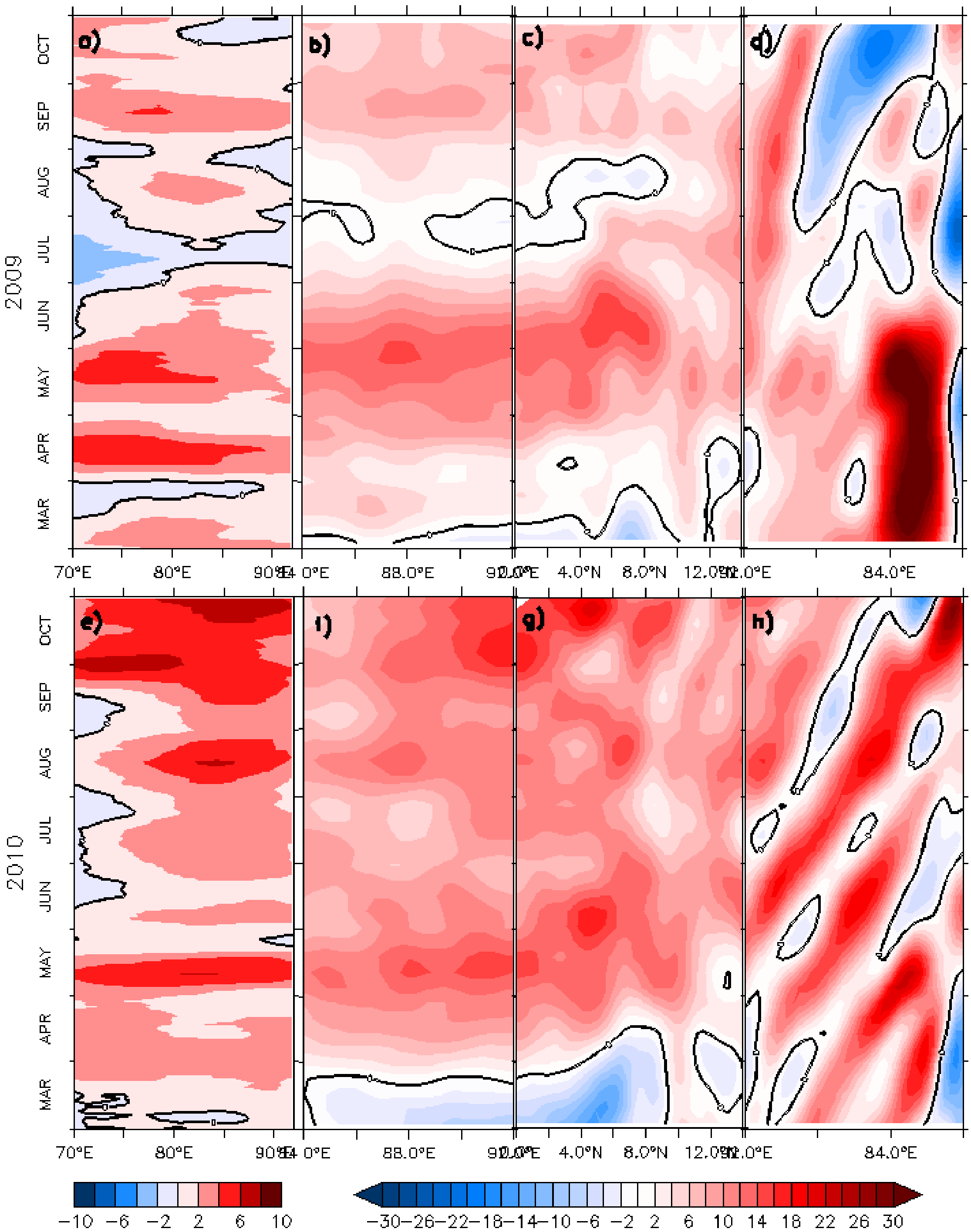

Figure 11.(a) Equatorial zonal winds from 70E to 92E(b) equatorial SSHA from 80E to 92E (c) SSHA along 92E from equator to 14N (d) SSHA along 14N from 92E to 80E during March to October 2009

Figure 11(e)(f) (g) and (h): same as figure 11(a) (b) (c) and(d) respectively but for march to October 2010

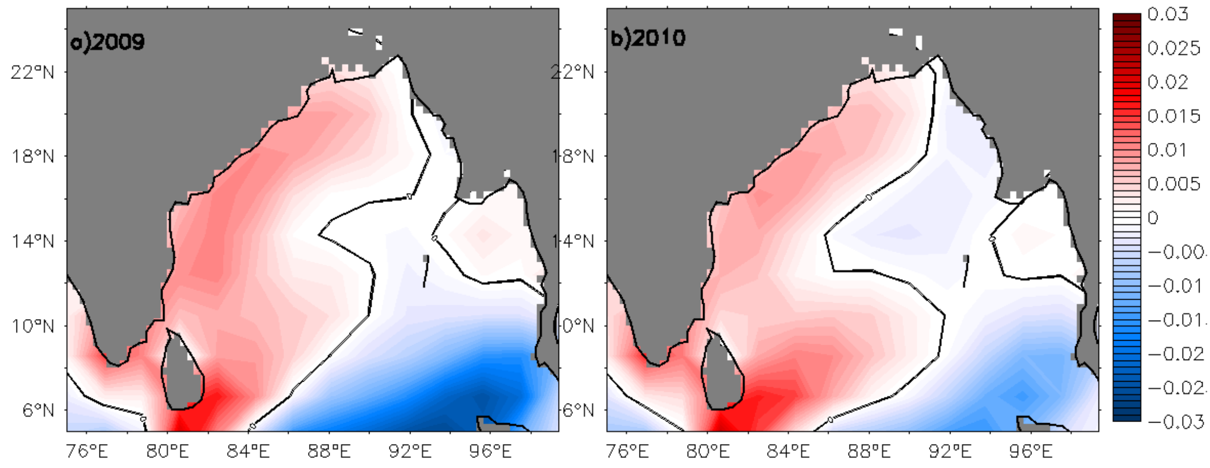

Figure12: JJAS average of curl τ / f (a) 2009 (b) 2010

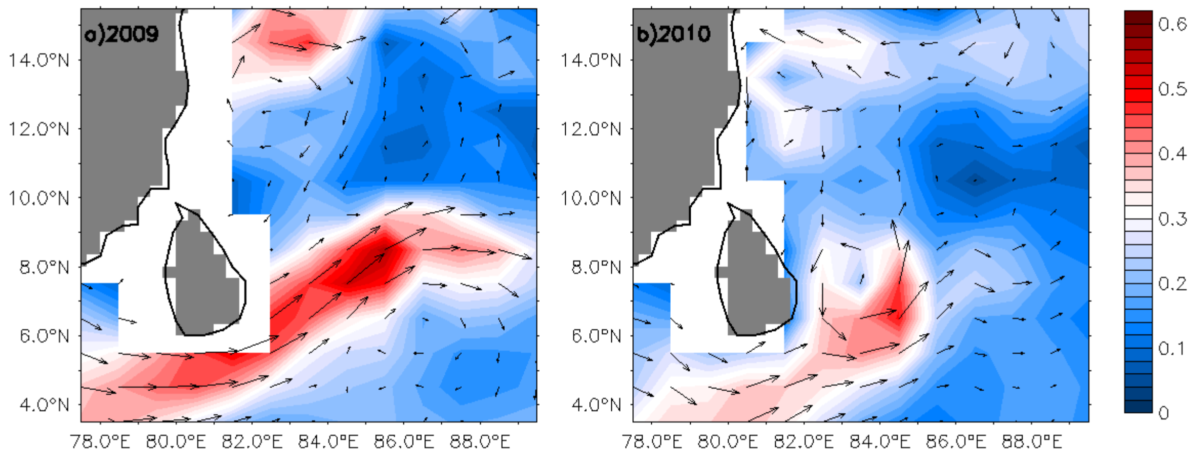

Figure13: OSCAR current speed (colour) overlaid with vectors of June to August average for (a) 2009 and (b) 2010