Simulations of Vertical Wind Profile and Water Vapour Mixing Ratio during Indian Summer Monsoon Season over Arabian Sea

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ABSTRACT

The purpose of this study is to examine the monthly variations in circulation fields and moisture content at different atmospheric levels (850, 500 and 200hPa) over the Arabian Sea (AS) during summer monsoon season. A regional climate model (RegCM3) was used for this purpose and two experiments like (a) Control (unperturbed SST) and sensitivity (perturbed SST by +0.50C) runs were conducted to examine the implications on monthly composite Vertical Zonal Wind Shear (VZWS) and Water Vapour Mixing Ratio (WVMR) during Indian Summer Monsoon Season. Monthly wind profile over AS (50-150N, 500-800E) has been studied. Monthly vertical distributions of the moisture content in terms of WVMR up to 200hPa during summer monsoon season were also calculated over entire AS centered at 62.50E-67.50E longitude and over Indian region centered at 75^0E-80^0E longitude. The analysis shows that the wind shears between the atmospheric levels 850-500 hPa and 500-200 hPa were increased in the warm SST run. The peak of the wind shear was obviously attained in July. The water vapour was found of high value mostly at all atmospheric levels in July and August in the case of increased SST of AS. In the experiments centered over AS (Indian region), maximum enhancement of moisture was noticed between 50N-150N (100N-150N) latitudes respectively. The model performance in perturbed SST state was found appreciable in the months of July and August (representative months of Indian monsoon season). Simulated average zonal winds between 850hPa and 500hPa in June (September) were sharply increased (decreased) in the SST run. In the study of Indian Monsoon Index (IMI) as an indicator of the strength of monsoon circulation, higher IMI was noted in the warm SST run as compared to the Control (CTL) run.

Keywords: *Wind profile, Indian monsoon index, Water vapour mixing ratio and Sea surface temperature.*

1. Introduction

Over the past few decades rainfall variability has emerged as a dominant environmental theme in the international community because of its importance to any country and its inhabitants. The study of Indian summer monsoon variability is one of the important socially relevant scientific themes that receive lots of attention (Webster et al. 1998) and about 60 to 90% of the mean annual rainfall is received over the various meteorological subdivisions of India during the four month monsoon period (Ramesh Kumar and P. Schlussel, 1998). Arabian Sea (AS) is the entry region of the Indian summer monsoon and the cross equatorial flow and Somali Jet along with the moisture flux contribute significantly to the strength of the monsoon current. The continued variations in SSTs and the uncertainties in different climate models generate uncertainties in the Indian monsoon characteristics and its strength. Trends of variability of SST are complex and zigzag pattern is noticed over AS, but evidence exists for its continuous increasing trends particularly 1995 onwards (Figure 1). The effect of increasing/decreasing SST may result in changes in the precipitation and atmospheric moisture due to changes in atmospheric circulation. In India, there are no clear long-term trends in the monsoonal rainfall (Krishna Kumar et al. 1999). Washington et al. (1977) used cold SST with different internal parameterizations in their numerical model and concluded that the SST anomalies have not influenced the monsoon rainfall over India much due to its local effects. Ramesh Kumar et al. (1986) in their study showed that the zonal anomaly of SST off the coast of Somalia and the central Indian Ocean are highly correlated with the monsoon rainfall over the western and central parts of India. The pre-monsoon anomalies of SST in the western and southern AS have a predictive value for the monsoon rainfall (Rao and Goswami, 1988).

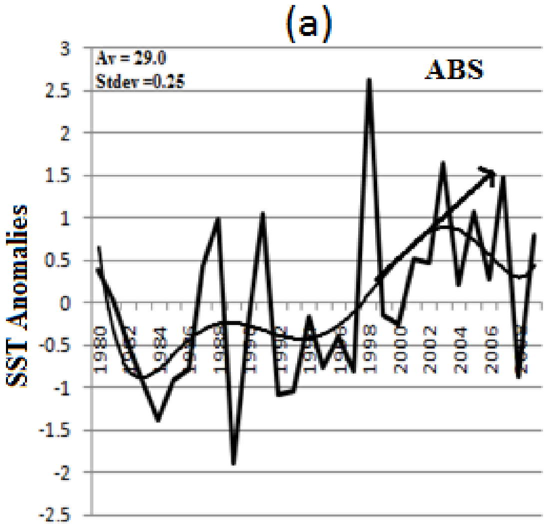

Figure 1: Pattern of annual SST changes in the period of study 1980-2009.

Shukla and Mishra (1977) and Ramesh Kumar and Sastry (1990) also looked into the role of SST in AS over the Indian Summer Monsoon Rainfall (ISMR). Most of these studies presumed that higher values of SST lead to higher rates of evaporation which in turn can contribute to excess monsoon rainfall. Choudhary et al. (2015) also found in their study the increase of rainfall over northern Indian Ocean (AS and BOB) including the Indian coastal regions (west and east coast) in the case of increased SST over Arabian Sea.

Moisture budget reaching AS from Southern Hemisphere is vital and Pisharoty (1965) concluded evaporation from the AS as the main contributor for the ISMR. Saha and Bavadekar (1973) also observed the importance of the moisture flux from the southern hemisphere to the monsoon rainfall. Many other scientists like Hastenarath and Lamb (1980), Cadet and Reverdin (1981 a&b), Cadet and Greco (1987) and Sadhuram and Ramesh Kumar (1988) in their study stressed the importance of inter hemispheric moisture transport. Recently Puranik et al. (2014) have shown with high resolution data that the maximum transport occurs across the equatorial region between 42–60^{o}E and below 650hPa level. Therefore, the variation in monsoon circulations and moisture flux can be considered as measuring tools to examine climate variability over Indian subcontinent in the context of SST variability. Vertical WVMR and wind variability are examined from the outputs of the RegCM3 model. This study does not represent an evaluation of model performance nor provide insights into the deficiencies of the model because performance of RegcM3 has been already tested in several studies (Dash et al. 2006; Singh and Oh 2010). The analysis is limited to study the variability of monthly wind profile and vertical WVMR during summer monsoon season over Arabian Sea and Indian region. The forced perturbation in SST provides an opportunity to compare responses of the warming of AS on the regional climate variations in terms of vertical WVMR and wind profile.

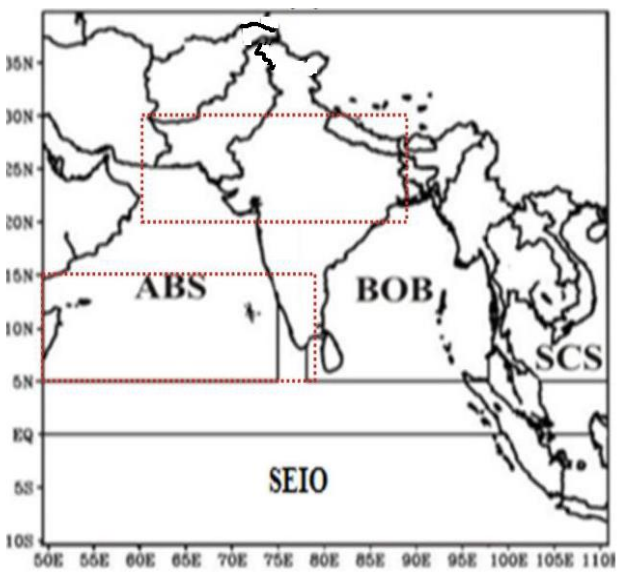

Figure 2: preferred domains (red dotted line) for the calculation of Indian monsoon index.

2. Methodological Frameworks

In the present study, a warm SST experiment over AS has been conducted by increasing temperature 0.5^0C which is more relevant and nearer to the mean changes in SST of AS (Figure 1). For the study of the Indian monsoon circulation anomalies and the determination of severity of weather phenomenon, VZWS is calculated by subtracting the mean zonal low level wind at 850hPa (U_1) from a mid level mean zonal wind at 500hPa (U_2) or a mean zonal upper level wind at 200hPa (U_3); that is

VZWS = U_1-U_2= U_{850} (5^0N-15^0N, 50^0E-80^0E) – U_{500} (5^0N-15^0N, 50^0E-80^0E)

or U1-U_3= U_{850} (5^0N-15^0N, 50^0E-80^0E) – U_{200} (5^0N-15^0N, 50^0E-80^0E).

To analyze the variability of the Indian summer monsoon, we have defined Indian Monsoon Index (IMI) as the meridional difference of the 850hPa zonal wind (U_{850}) between domains 20^0N-30^0N, 60^0E-90^0E over the Indian region and 5^0N-15^0N, 50^0E-80^0Eover the Arabian Sea i.e. IMI = U_{850} (5^0N-15^0N, 50^0E-80^0E) – U_{850} (20^0N-30^0N, 60^0E-90^0E). The areas in parentheses and red dotted line in Figure 2 denote the regions over which the mean zonal winds are averaged.

Details of the RegCM3 model were already described by Singh and Oh (2007) and Choudhary et al. (2015). A warm SST experiment is conducted for 5 years from 2005 to 2009over the oceanic region (5^0N-25^0N, 48^0E-75^0E) in the model domain. The control runs are integrated from April 1 to October 1 for 20 years (1990-2009). Details of all experiments are described by Choudhary et al. (2015).

3. Result and Discussion

3.1 Simulated wind profile and monsoon index in unperturbed SST condition

In the process of analyzing the vertical profile of wind speed in the layers of the atmosphere, the simulated VZWS in the composite 20 yrs. control run during monsoon season (JJAS) were found 4.4 m/s and 7.3 m/s between 850-500 hPa and 850-200 hPa levels respectively over 25^0N-15^0N, 50^0E- 80^0E (Figure 3a&b). Figures show that VZWS line between 850-500 hPa is nearly constant because of westerly winds at these two pressure levels with feeble variations while zig-zag path of VZWS line between 850-200 hPa is due to more variable winds in opposite directions (westerly at 850hPa and easterly at 200hPa). Vertical profile of zonal winds (m/s) averaged over this Arabian Sea sector during July and August is calculated for three different rain years (Figure 4a&b). The black line indicates condition in a normal year (2005), the red line indicates 2009 El Nino conditions and the blue line indicates conditions during the active 2008 season. The enhanced vertical directional shear during 2008 coincided with developing La Nina conditions and resulted from a combination of stronger than normal lower level westerlies and enhanced upper level easterlies throughout the depth of the atmosphere.

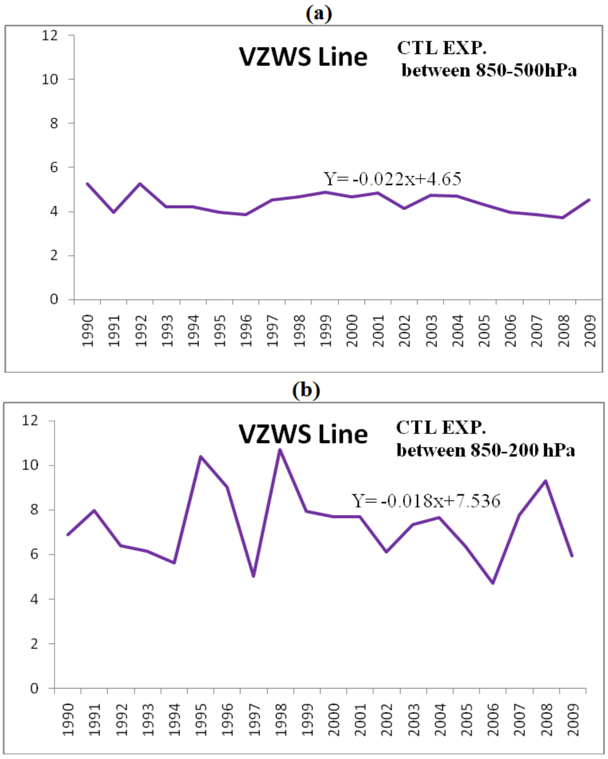

Figure 3: averaged VZWS of four months (JJAS) during the period of study 1990-2009 between pressure levels of 850-500 hPa and 850-200 hPa.

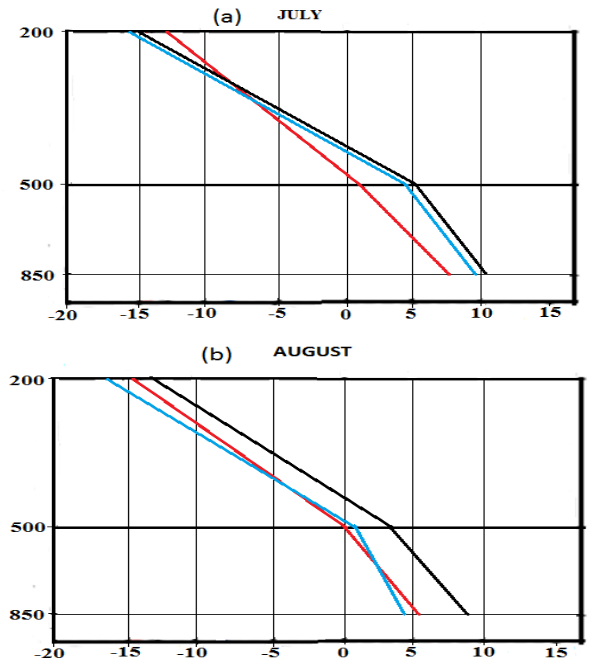

Figure 4: Vertical profile of zonal wind during (a) July and (b) August, for three different rain years (black line representing normal, blue line active and red line deficient rain).

In contrast, the low vertical shear during 2009 resulted from relatively weak lower level westerly and upper level easterly winds.

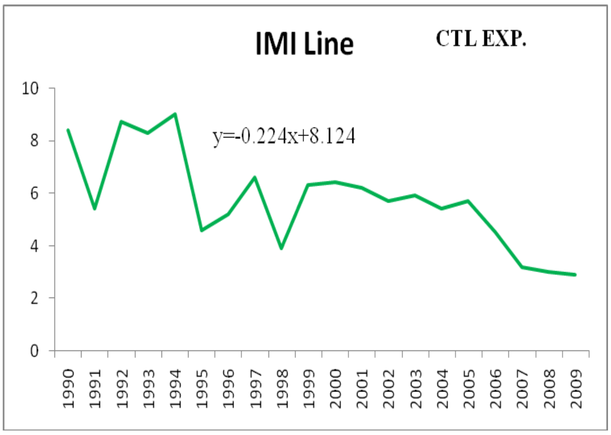

Figure 5: averaged IMI of four months (JJAS) during the period of study 1990-2009.

Zonal winds over AS in the domain of examine is obviously higher than that of zonal winds over northern Indian land mass of our domain of consideration. The simulated composite value of IMI in 20-yr CTL run is found to be 5.8 m/s during four months of the season (Figure 5). IMIs are varying steeply showing decreasing trend in recent years (trend value per season is -0.22 m/s). Weaker IMIs shows weaker shear vorticity of the Indian monsoon trough and associated southwesterly monsoon. The lower simulation of IMI and VZWS is understandable with the fact that the model underestimates the rainfall over Indian landmass due to simulation of weaker synoptic systems such as monsoon trough and depression.

3.2 Simulated vertical WVMR in no SST change

In the control experiment for the calculation of vertical WVMR centered at 65^0E longitude, the towers showing the water vapour reached maximum height in July while minimum in September (Figure 6). The latitudinal extension of higher moisture content is also seen maximum in July and August and reached up to 33^0E having 9 gm moisture content per 1kg of dry air. The thicker atmospheric moisture is available in the ABS as expected. Figure 7 shows the composite mean monthly vertical WVMR in the experiment centered at 77.5^0E longitude. Again the increased moisture in the atmosphere over Indian region is found in the month of July. The simulated vertical WVMR over PI (9^0N to 20^0N) is 0.012 while it is 0.015 over central India (20^0N to 30^0N).

3.3 Simulated wind profile and monsoon index in SST change

In this section, we used here the VZWS to measure the Indian monsoon circulation anomalies in the warm SST experiment. VZWS in the SST run is higher than that of the control run as observed in the composite analysis (Table 1). The zonal winds at both levels (U_{850} and U_{500}) are increased. When the monthly mean composite VZWS are computed for June to September, it is higher throughout in the warm SST run (Figure 8a). The peak of the wind shear is obviously attained in July, but it increased highest (≈1.0 m/s) in August. Moreover, enhanced vertical wind shear in the warm SST run reduced the easterly winds at 200hPa by 0.5 m/s in comparison to the CTL run due to frictional drag. Figure 8(b&c) shows the vertical profile of zonal winds (m/s) averaged over the Arabian Sea sector (5^0-15^0N, 50^0-80^0E) during July and August. The black line indicates observed condition, the red line indicates warm SST experiment condition and the blue line indicates Control experiment condition of the wind fields at three different levels (850hPa, 500hPa and 200hPa). The depth of the atmosphere having westerly winds increased in the warm SST experiment in comparison to the CTL experiment and observed winds. The easterly winds at 200hPa are marginally influenced by the warm SST experiments of the model. The analysis of the monthly composite VZWS shows the enhanced wind shear in the warm SST run between the levels of 850-500 hPa and 500-200 hPa. The observed VZWS is higher throughout the depth of the atmosphere.

The higher (lower) IMIs are indicator of higher (lower) rainfall over the Indian region of maximum precipitation. In the composite analysis of IMI, higher IMI is found in warm SST run in comparison to the CTL run (Table 2). Table 2 shows the difference of IMIs between warm SST run and CTL run is ≈ 2 m/s for the summer monsoon season. This verifies the finding of Wang et al. (2001). In the composite monthly analysis of IMI, the peak is observed in July (Figure 8d). The

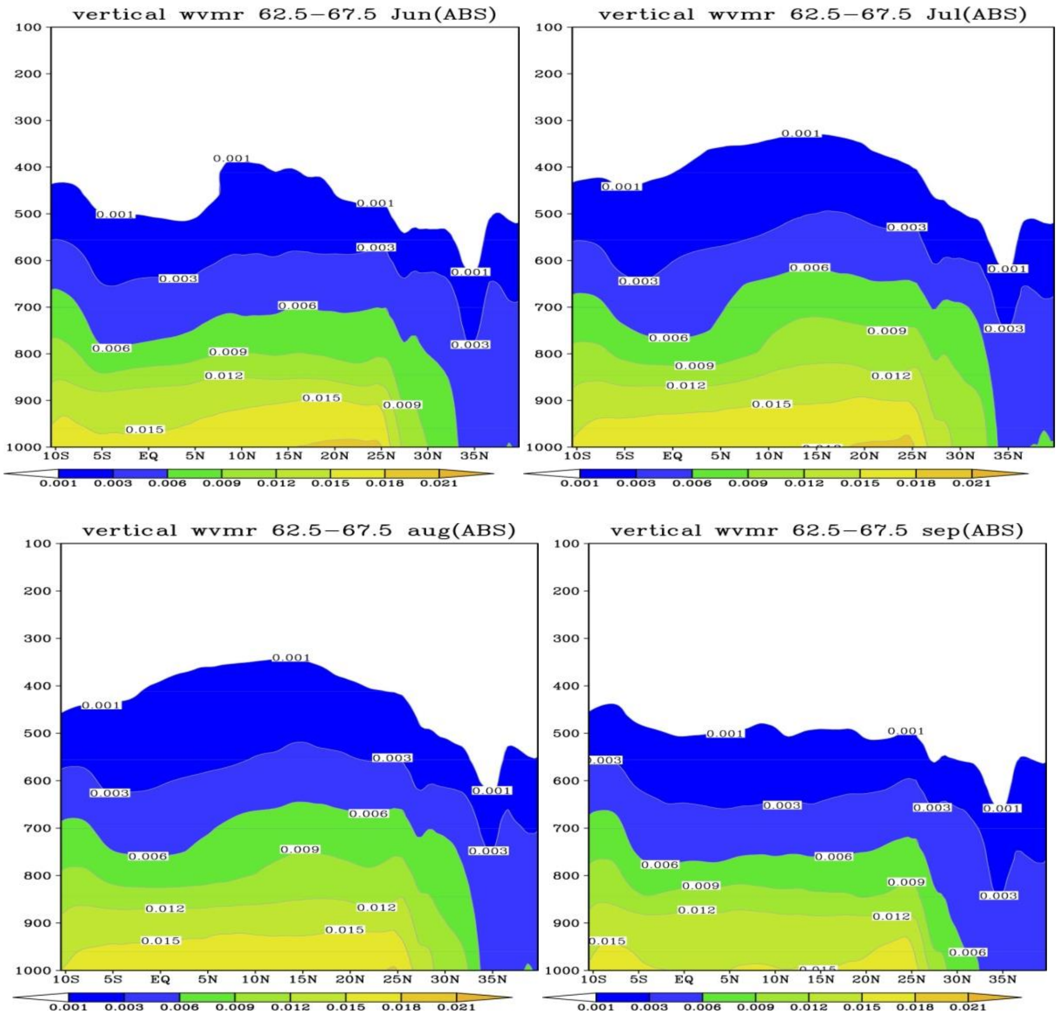

Figure 6: Monthly simulated WVMR in CTL experiment centered at 65^{0}E longitude.

Table 1. Vertical Zonal Wind Shear (VZWS) during summer monsoon season.

Composite result	**Zonal wind (U_{850}) (m/s)**	**Zonal wind (U_{500}) (m/s)**	**U_{850}-U_{500} (m/s)**
CTL Run	+6.15	+2.07	+4.08
SST Run	+7.23	+2.80	+4.43
SST-CTL	+1.08	+0.73	+0.35

highest difference in IMI is found in August (≈3.0 m/s). The composite value of IMI in CTL run during July is 7.5 m/s whereas it is 10 m/s in warm SST run. This is the verification of enhanced ISMR in the warm SST experiment and these facts add confidence to this regional dynamic monsoon index defined here in terms of its representing the regional monsoon variability.

Figure 9 and Table 3 show the average zonal winds between 850hPa and 500hPa atmospheric levels in July-August (JA) and JJAS months in the SST experiment are increased by 22.4% and 21.4% respectively in comparison to the CTL experiment. This increasing tendency is also maintained throughout the different monsoon months. This shows the enhancement of cross equatorial flow during summer monsoon season at the case of warm Arabian Sea. The decrease of zonal winds (by 15%) during the monsoon season (JJAS) is observed in SST experiment in comparison to the observed winds. It clearly shows that the model performance in the months of June and September

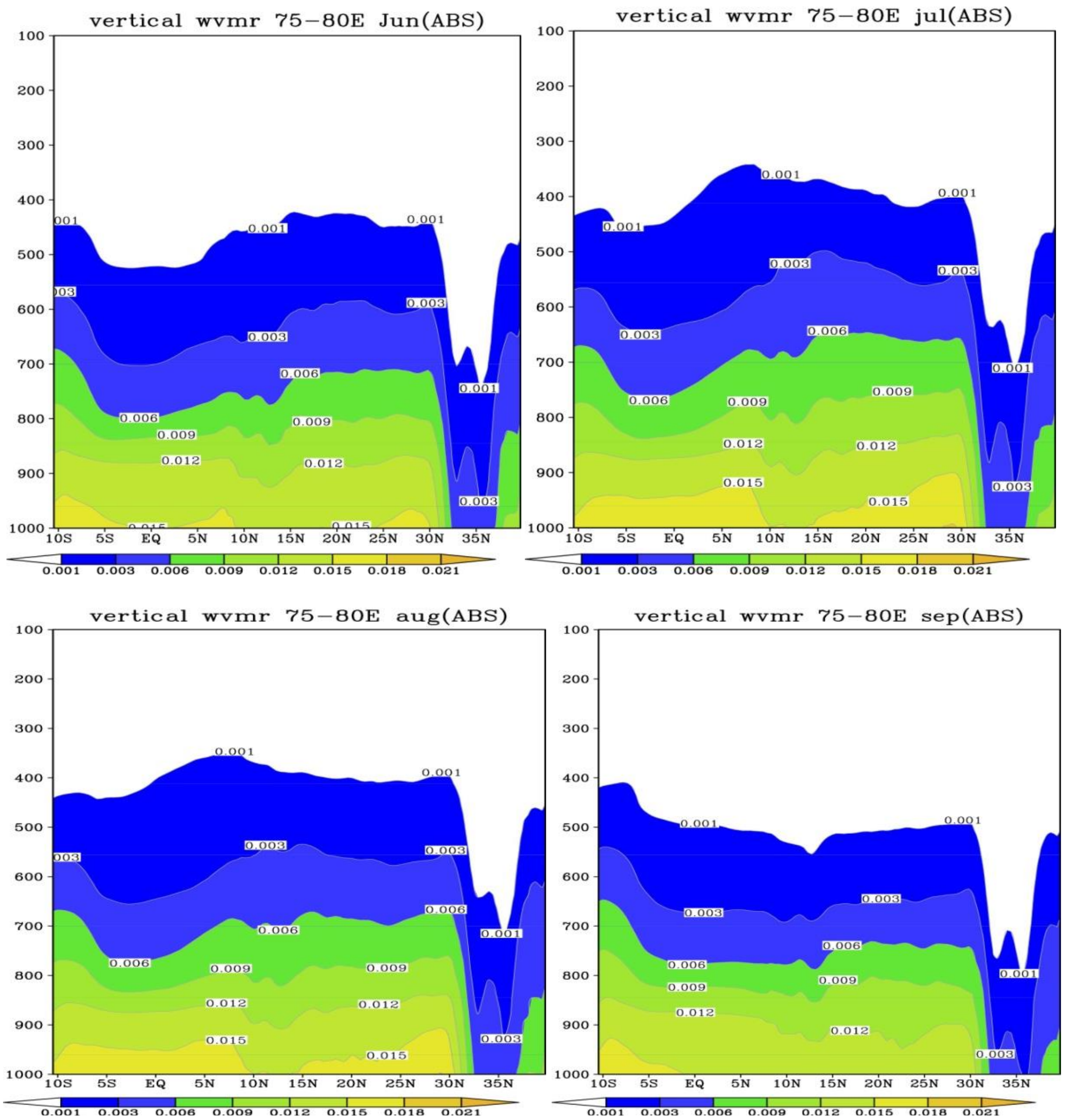

Figure 7: Same as in Figure 6 except for centered at 77.5^{0}E longitude.

(during onset and withdrawal phase of monsoon) was poor. Zonal winds in June and September were decreased by 1.8 m/s and 2.9 m/s respectively in the SST run. Remarkably, average wind between 850hPa and 500 hPa shows sharp increasing and decreasing trends during June and September respectively in both SST and CTL experiments in comparison to the observed winds (Figure 9).

3.4 Simulated vertical WVMR in SST change

Figure 10 shows the monthly variations of vertical WVMR over ABS in the sensitivity experiments centered at 65^{0}E longitude. The water vapour is high at all atmospheric levels during July and August. In the case of increased SST of AS, the arrival of moisture along with cross equatorial flow after onset of monsoon has increased over AS by

Table 2. Composite values of IMI in different months and during JJAS season.

Months	SST Run	CTL Run	SST-CTL
June	3.65	2.73	0.92
July	9.99	7.53	2.46
August	7.50	4.58	2.92
September	0.96	0.61	0.35
JJAS	5.52	3.86	1.66

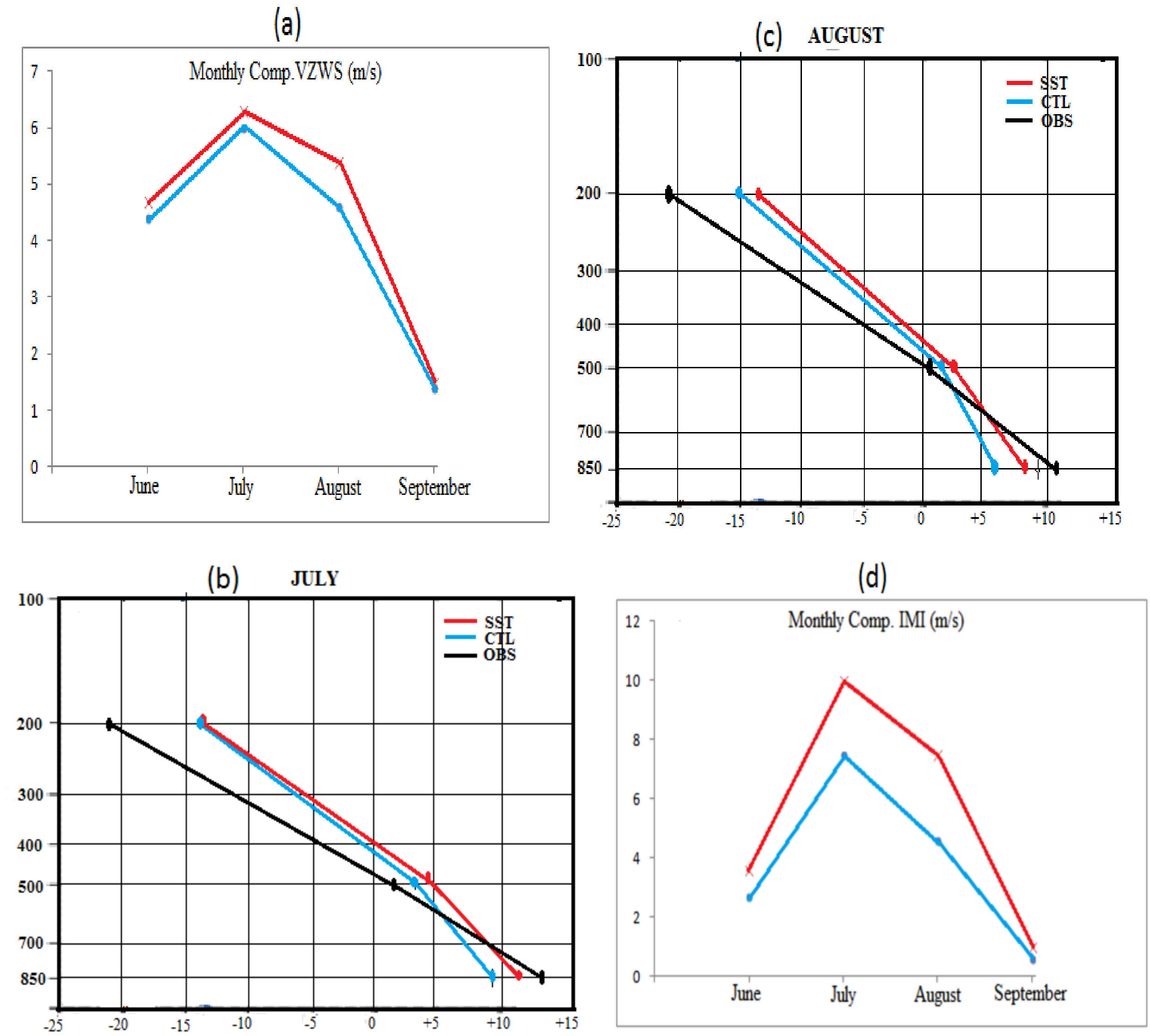

Figure 8: Monthly composite VZWS over Arabian Sea (a) sensitivity experiment (red line) and control experiment (blue line), (b) same as in (a) except for July with an additional observed VZWS (black line), (c) same as in (b) except for August and (d) same as in (a) except for composite IMI.

15% to 20% in the latitudes between 5^0N to 20^0N (Figure 10b). It is remarkable to see that the zone of maximum moisture is shifted towards equator in July and August.

Figures 11 shows the difference in WVMR in terms of percentage of moisture in (SST-CTL) condition over Indian region in the experiment conducted at centered 77.5^0E longitude. Patterns of monthly change of water vapour are well simulated by the model in both regions over Indian regions and ABS. Model shows negative moisture percentage around the seas in the month of June between 5^0N to 10^0S whereas the zone of maximum moisture (20%) has larger extension in the month of July up to 20^0N latitude and it comes down to 15^0N in the month of August (Figure 11d&f). Remarkably, the vertical WVMR comes down from 0.015 to 0.012 in July and August between 10^0N-15^0N and there is a break up of maximum WVMR at mean sea level pressure. Maximum water vapour is found at

Table 3. Zonal wind Percentage Increase/ Decrease of Zonal Wind.

	SST Vs CTL	SST Vs OBS
U_{JA}	+22.4	+7.6
U_{JJAS}	+21.4	-15.0

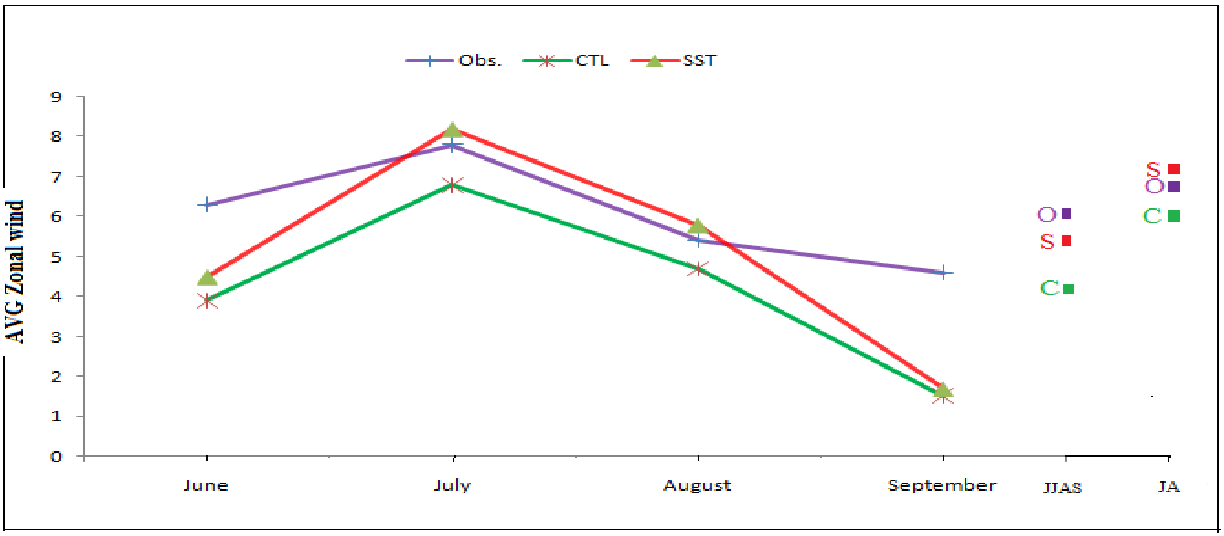

Figure 9: Patterns of monthly average zonal winds in observed, CTL and SST cases.

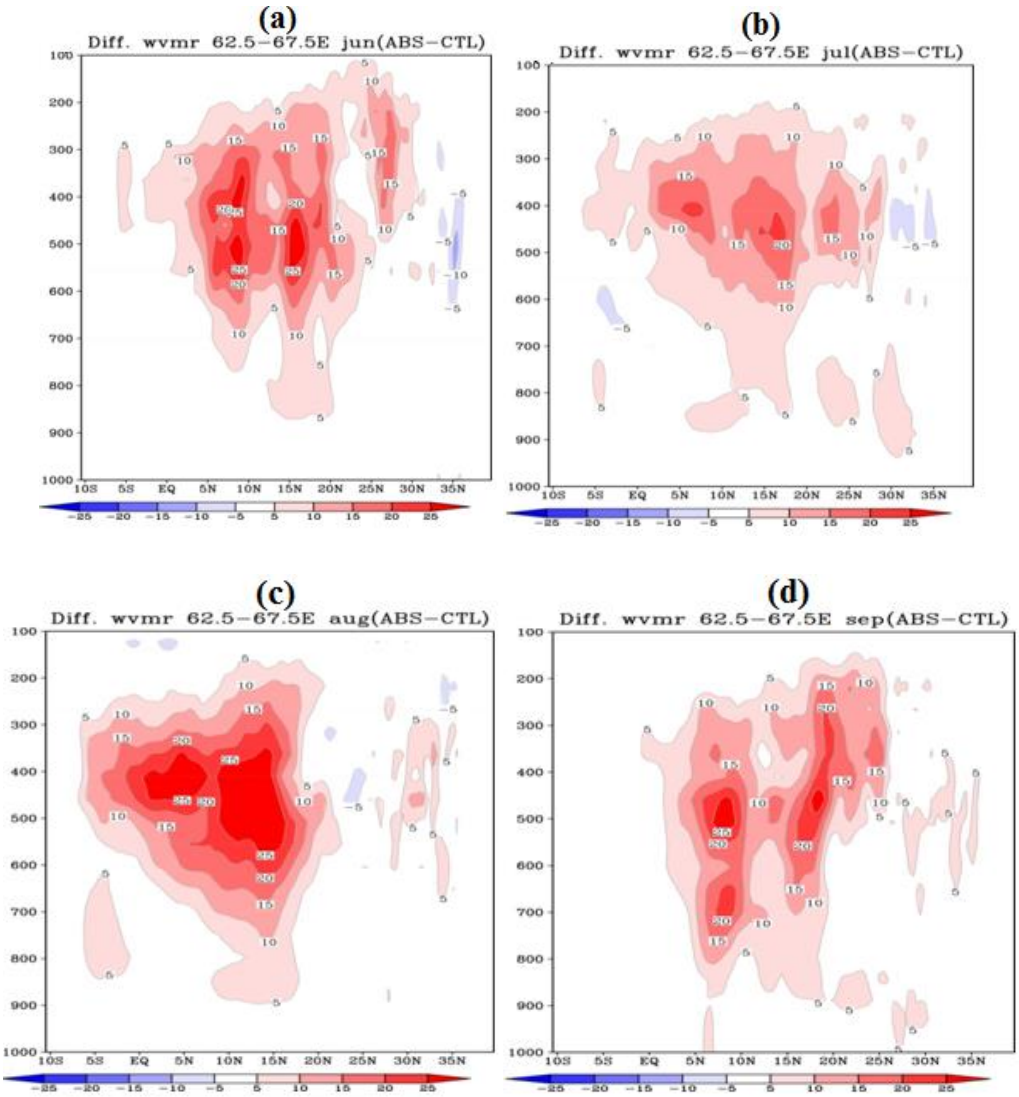

Figure 10: Monthly simulated difference (SST- CTL) WVMR centered at 65^{0}E longitude.

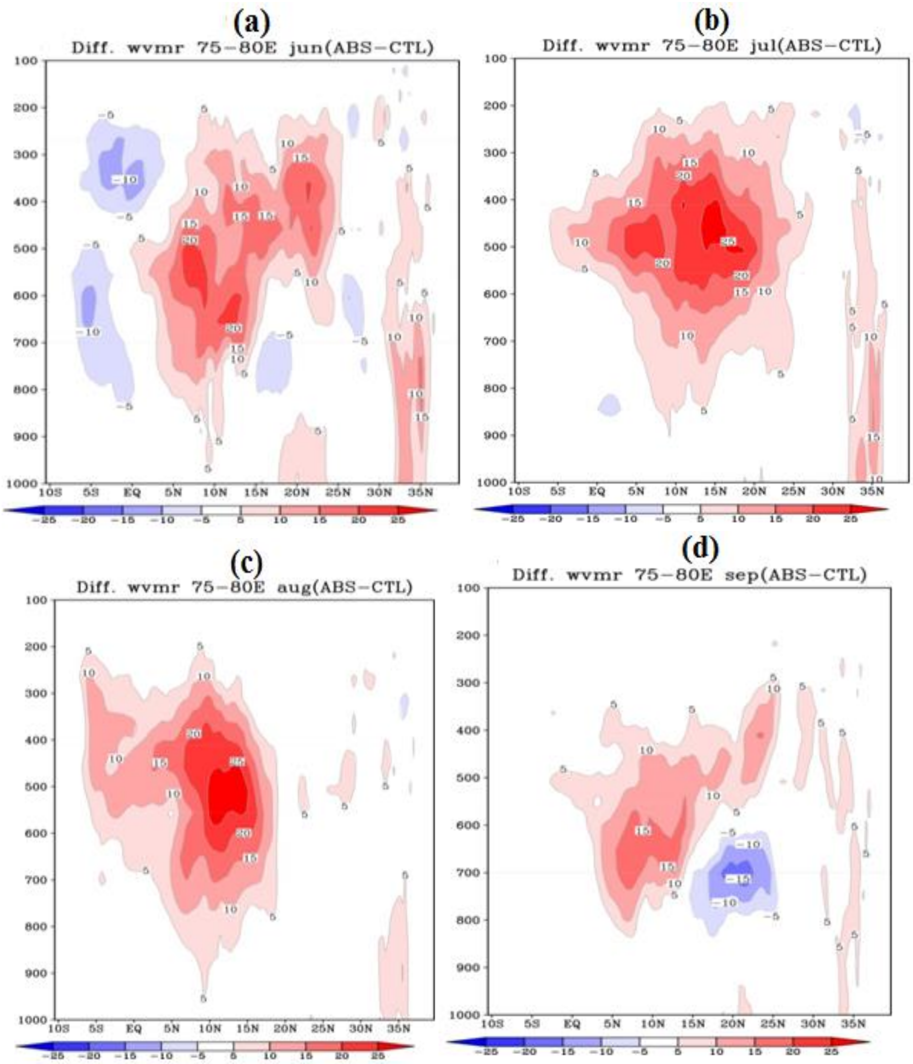

Figure 11: Same as in Figure 10 except for centered at 77.5^{0}E longitude.

around 500hPa in the months of June and July, but intensity was highest in August between the atmospheric levels of 400-600 hPa. It was also found that the intensity of water vapour in July was higher over Indian region in comparison to the AS region. It is understandable with the fact that the summer monsoon enveloped over entire India in the month of July. The study of WVMR over Arabian Sea and Indian region in the sensitivity experiments clearly shows that the water vapour at all higher atmospheric levels are increased significantly (up to 20%) and this enhancement is observed in the latitudes between 5^{0}N to 20^{0}N in both cases. In the experiments centered over the ABS (Indian region), we find maximum enhancement of moisture between 5^{0}N-15^{0}N (10^{0}N-15^{0}N) latitudes. Moreover, figure shows any enhancement of water vapour in the atmosphere lying in between the latitudes 20^{0}N to 30^{0}N in both experiments. Thus the model performance in simulating the patterns of monthly change of moisture content over the Indian region and ABS is reliable.

4. Conclusions

We examined the monthly wind profile and vertical water vapour mixing ratio during the summer monsoon season over Arabian Sea and India using a RegCM3 model. In this study, some important conclusions are follows

1. The Vertical Zonal Wind Shear for the wind profile between 850hPa and 500hPa (U_{850}-U_{500}) averaged over the Arabian Sea in the domain 5^{0}N-15^{0}N, 50^{0}E- 80^{0}E in the warm SST run is higher

than that of the control run throughout the summer season. The higher zonal winds at both levels (U_{850} and U_{500}) are found in the warm SST run.

2. The depth of the atmosphere having westerly winds increased in the warm SST experiment in comparison to the CTL experiment during JJAS months which is favourable to Indian monsoon.

3. The average zonal winds between 850hPa and 500hPa atmospheric levels throughout the monsoon season in the SST experiment were increased in comparison to the CTL experiment. But decrease of zonal winds (by 15%) during the monsoon season (JJAS) is found in the SST experiment in comparison to the observed winds.

4. In the composite monthly analysis of IMI, higher IMI is found in warm SST run in comparison to the CTL run. The higher (lower) IMIs are indicator of higher (lower) rainfall over the Indian region of maximum precipitation.

5. In the case of warm ABS, a good amount of moisture along with monsoon circulation reached around western coast with south peninsular and central India (5^0N to 25^0N) at almost every atmospheric level. This might be due to the early onset of monsoon in the case of warm AS. Maximum moisture content is observed in July and August.

6. The RegCM3 model simulates realistic Indian summer monsoon circulation anomalies and hence moisture contents along with monsoon current throughout the experiments. Performance of the model in simulating the Indian monsoon circulation variability is consistent.

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