Inter-Comparison of Two Regional Climate Models (RegCM and WRF) in Downscaling CFSv2 For the Seasonal Prediction of Indian Summer Monsoon

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Abstract

The efficacy of two latest versions of regional climate models (RegCM and WRF) for simulating the Indian summer monsoon (JJAS) is tested in this study. The CFSv2 hindcast outputs are downscaled over the Indian monsoon domain for 11 contrasting monsoon seasons using the regional models. The April start ensembles of the CFSv2 are averaged to generate the initial and lateral boundary conditions for driving the WRF and RegCM. The regional models perform better in simulating the Indian summer monsoon features better than the parent CFSv2 model. The rainfall pattern as well as the intensities are improved with the dynamical downscaling and the errors in the rainfall are minimized over the GCM hindcast. On comparing the two regional models, the RegCM overestimates the rainfall during the excess and normal monsoon seasons. The RCMs improve the skill of rainfall prediction as compared to the GCM and WRF shows better skill in particular. One peculiar finding of this study is that the daily rainfall biases averaged over all the years of simulation shows that the two RCMs show similar biases with RegCM showing stronger biases occasionally. It may be implied that the errors from GCM in the form of the ICBC might be influencing the simulation in the RCMs. The upper air and surface parameters analysis shows that the WRF performs better in representing the semi-permanent features of the Indian summer monsoon which may be helping in improving the rainfall over the RegCM. The wind pattern as well as the relative humidity along the vertical column of the atmosphere are captured better in the WRF model. Diagnostics of CAPE & vertically integrated moisture transport supports the finding of the rainfall being simulated better in the WRF model.

1. Introduction

The Indian summer monsoon spanning over the months of June through September is one of the most significant global weather phenomenon influencing about 1/7th of the entire world's population and the economy associated with it. The significance of the monsoon and its prospects for early prediction has been addressed in numerous studies over the past few decades. The rainfall received during the summer monsoon period is about 80% of the annual rainfall for which the agricultural activities are largely dependent on the net rainfall during this period (Parthasarathy et al., 1994). India is an agrarian economy with more than 49% of the population directly or indirectly employed in the agricultural sector and the agricultural sector adds up to 8% of the net GDP of India (Gadgil and Gadgil, 2006). Besides agriculture, hydro power, manning, industrial activities are largely dependent on the monsoon rainfall. With such large scale dependency, the early prediction of the nature of the monsoons for a particular season is of large demand.

Focusing on the seasonal prediction of the Indian summer monsoon, operational forecasting agencies are dependent on the forecasts from the general circulation models (GCMs) and to some extent on regression or statistical models (Palmer et al., 2004; Saha et al., 2006, 2014; Pillai et al., 2018; Mohanty et al., 2019b). GCMs predict the future atmosphere by dynamically solving the mathematical equations over time and space where as statistical models use the methods of relating the past climate with the forecast outputs of GCMs. GCMs are the most important tools to generate monthly and seasonal forecasts in current time. However, they lack in reproducing the rainfall pattern due to many constraints (Wang et al., 2009; Kar et al., 2012; Cash et al., 2019; Mohanty et al., 2021; Chevuturi et al., 2021). The GCMs are run at coarse model resolution because of the computational constraints for which they lack in the proper representation of the land surface as well as the sub-grid scale processes. Apart from these, the systematic biases arising in the GCMs due to the internal dynamics of the model have been a source of constant errors and removal of the systematic biases along with improvement in the internal dynamics has been a broad area of research in the present time (Pokhrel et al. 2012; Saha et al. 2013; Chattopadhyay et al. 2015; Pradhan et al. 2015; Singh et al. 2019). Several studies have been carried out to test the prediction skill of the GCMs for the seasonal prediction of Indian summer monsoon and it was found that the models have poor skill with temporal correlation with the observations (Palmer et al. 2004; Alessandri et al. 2011; Lee et al. 2011; Kim et al. 2012; Ramu et al. 2020; Mohanty et al., 2021). Skillful prediction of the monsoon using a global model has been a matter of concern and there have been case studies on the failure of the GCMs in simulating the summer monsoon (Gadgil et al., 2005). Kar et al. (2012) used 8-member ensemble of NCMRWF global spectral model forecast and found that the model skill is satisfactory on a short range and medium range but the performance of the model was poor on a seasonal scale.

The potential limit on seasonal predictability of rainfall over the Indian monsoon region is lower than that for the rest of the tropics (Goswami 1998). The rainfall is largely influenced by El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) (Rasmusson and Carpenter 1983; Webster and Yang 1992; Saji et al. 1999; Ashok et al. 2001; Rao et al. 2010). Despite considerable progress in predicting dynamical features of ISM variability, models still struggle to simulate the mean and interannual variability of monsoon rainfall (Chevuturi et al. 2021). To improve the skill of prediction and reduce the errors caused by atmospheric chaos and internal dynamics, the ensemble prediction approach is being used for operational forecast (Kumar and Horeling 1995; Acharaya et al., 2012). Despite the fact that Wang et al. (2008) asserted that the multi-model ensemble prediction skill is noticeably better than the average skill of the individual models, the forecast skill of monsoon precipitation over land during the summer remained inadequate.

An alternative approach to minimize the errors and improve the seasonal forecasts can be by the process of downscaling the GCMs using a RCM. RCMs have the advantage of better representation of the terrain, higher resolution for dynamic computations, improved representation of the sub-grid scale processes. Systematic biases in GCMs arising due to topography, model physics, can be addressed and reduced by the process of dynamical downscaling. For the purpose of Indian summer monsoon, the usage of dynamical downscaling has been studied by researchers as an alternate tool to the existing methods of statistical methods and dynamical methods using GCMs. The studies can be dated back to late 1990s. Indian summer monsoon, being a complex process, lacked the representation of mesoscale influences associated with topography, vegetation characteristics, coastline etc. (Vernekar 1995; Christensen et al. 2007; Kripalani et al. 2007). Attempts to simulate the Indian summer monsoon using a RCM has been made in many studies and the RCMs were able to capture the mean seasonal features (Bhaskaran et al. 1996; Jacob and Podzun 1997; Ji and Vernekar 1997; Bhaskaran and Mitchell 1998; Ratnam and Cox

2006; Dash et al. 2006; Dobler and Ahrens 2010; Saeed et al. 2011). Dynamical downscaling using a RCM for the purpose of seasonal prediction has been used as a method for fine tuning the output from GCMs. The availability of the RCMs has opened up an avenue for more accurate climate prediction if recent decades (Giorgi et al., 2001; Christensen et al., 2007). But all the RCMs do not have potential skill to simulate the complex climatic features such as the Indian summer monsoon (Piani et al., 2009). Piani et al (2009) showed that the improvement in forecasts can be done by statistical bias correction methods as well.

But the major hindrance was in the form of simulation of the rainfall where most of the RCMs failed to perform. Like as the GCMs, RCMs too use parametrization equations to parametrize the sub-grid scale processes occurring within the grid box. Parameterizations are carried out for cumulus convection, radiation, land surface physics, cloud physics etc. Sensitivity studies have been carried out in large numbers to select the best parametrization scheme for a particular region of interest (Dash et al., 2015; Bhatla et al., 2016; Maity et al., 2017; Maurya et al., 2017; Mohanty et al., 2019a). Selection of an in appropriate convective parametrization scheme can be a major source of error and influence the skill of a RCM (Pal et al., 2007). Maurya et al., (2018) stated that the domain size and horizontal resolution play an important role in simulating the monsoon. They made a point that the horizontal resolution can be reduced up to a particular point and beyond that the model skill deteriorates further. Thus, even while downscaling RCMs can be downscaled to a particular grid resolution, beyond which there is no fruitful result.

The RegCM and WRF models have been used quite frequently to study the monsoon processes on a seasonal scale as well as test the efficacies of both the models using GCM output on hindcast modes. The prediction of monsoon can be marginally improved by using the method of dynamical downscaling using regional models (Attada et al., 2014; Bhatla et al., 2016; Viswanadhapalli et al., 2017; Prathipati et al., 2021). In this study, two RCMs having a good predictive skill of the Indian summer monsoon rainfall have been used to downscale the high resolution CFSv2 output. An attempt has been made to study the RCM’s efficacy for simulating the rainfall as well as mean features of the Indian summer monsoon.

2. Data And Methodology

The latest Regional Climate Model version 4.7 (herein referred as RegCM4), initially designed by National Center for Atmospheric Research (NCAR) and maintained by the Abdus Salam International Centre for Theoretical Physics (ICTP) is used as one of the RCM in this study (Giorgi et al., 2012). Since the inception of RegCM by the pioneering works of Diskinson et al (1989) and Giorgi and Bates (1989), the RegCM has been widely used for the purpose of dynamical downscaling for climate projection under different scenarios. But the model has been used efficiently for seasonal to sub-seasonal prediction lately (Maurya et al., 2018, 2021). The other model used for downscaling is the Weather Research and Forecasting model version 4, (WRF4) which is a mesoscale model designed to serve both operational and research purposes (Skamarock et al., 2008). The WRF model is one of the most widely acclaimed meso scale model for forecasting mesoscale weather events but recent studies have concluded that the model can be used for seasonal prediction and possess good predictability (Viswanadhapalli et al., 2017; Prathipati et al., 2021). Table 1 shows the brief description of the model domain and configuration of different parametrization schemes used in both the regional models.

RegCM and WRF have been initialized from 1st of May through 1st of October, for the purpose of simulating the Indian summer monsoon (JJAS). The 1st month of the simulation is truncated from the analysis and is considered as spin up time of the RCMs. The initial and lateral boundary conditions have been derived from the high resolution CFSv2 data at T382 spectral resolution (~38 km). The ensembles from the month of April initialized at 5th, 10th, 15th, 20th and 25th of April at 00UTC are averaged and the ensemble mean in used as the initial and boundary conditions. The verification strategies are mainly focused on the rainfall which is primarily verified by the 'eyeball' method along with a few statistical scores. The rainfall simulated by the RegCM and WRF are verified with the IMD gridded daily rainfall data set at 0.25^0x0.25^0 (Pai et al., 2014) whereas the upper air parameters are verified with the ERA5 data sets at 0.25^0x0.25^0 (Hersbach et al., 2019) spatial resolutions. The model is simulated for 11 contrasting monsoon seasons, of which 5 are normal (1989, 1992, 2003, 2005, 2008), 3 are excess (1988, 1990, 1994) and 3 are deficit (1987, 2002, 2004) monsoon seasons. Verification of the models are carried out by evaluating the mean as well as composite performance of the models for excess, normal and deficit monsoon seasons. Both the models are simulated at 15km horizontal resolution.

3. Results And Discussions

The results presented in this chapter are analyzed in two sections namely (a) Efficacy of the RCMs in simulating the rainfall and (b) Surface and upper air meteorological parameters.

a) Simulation of rainfall:

The composites of the mean seasonal rainfall (JJAS) for the deficit, normal and excess monsoon seasons as observed in IMD data set and as simulated by the CFSv2, WRF and RegCM is shown in Figure1. From the rainfall as observed in contrasting monsoon seasons, it can be clearly witnessed that the rainfall is quite discreet. The rainfall is scanty over most of India, especially the central India region during the composite deficit seasons whereas it is quite in excess over the particular region in the excess monsoon seasons. But quite interestingly, the rainfall over the north-east India during the deficit monsoon seasons as compared to the excess and normal seasons is in excess. Very less amount of rainfall (<100mm) rainfall is received over north-western India during the deficit season. About 600-1400mm/800-1600mm/800-2000mm rainfall is received by the monsoon core region during the deficit/normal/excess monsoon seasons respectively (Figure1a,e,i). The highest amount of rainfall can be witnessed over the Western Ghats and north-east India (1600-3000mm). Comparing the rainfall pattern with the CFSv2, the rainfall simulated by the GCM is quite scanty for all the seasons (Figure 1b,f,j). The rainfall over the monsoon core region is simulated in varying amounts for all the composite seasons. Though the rainfall pattern is quite in unison with the observation, the intensities of rainfall are underestimated in CFSv2. Heavy rainfall regions of Western Ghats and north-east India are captured by the GCM. Besides, the rainfall simulated over the north-western India is much less for all the seasons (<100mm). With the downscaling experiments, the rainfall pattern and intensities is improved significantly than the parent GCM. The rainfall is simulated better by both the RCMs than the CFSv2 and the heavy and scanty rainfall regions of India are captured. The rainfall over the monsoon core region is reproduced by both the RCMs which is a boon for the downscaling method. In addition to it the rainfall over Western Ghats, north-east India and north-west India is improved significantly as compared to the GCM. However, the seasonality of rainfall as simulated for the composite deficit, normal and excess monsoon seasons is not quite well captured by the RegCM model. The RegCM model fails to reproduce the rainfall during excess seasons and tends to simulate copious amounts of rainfall over the peninsular India. Large wet biases over most of the central India are simulated by RegCM as well. On the other hand, the rainfall seasonality is well captured by the WRF model and the rainfall is discretized during the contrasting monsoon seasons. The rainfall over the Western Ghats is overestimated by the WRF. Over some regions of the Western Ghats, the rainfall crosses beyond 3000mm with the WRF model. Overall, the WRF model tends to reproduce the rainfall pattern and intensities closer to the observations and reduces the regions with large biases in the CFSv2 model.

The rainfall probability density function on a normal distribution curve and the Taylor diagram depicting the correlation coefficients, normalizes standard deviation and RMSE are shown in Figure 2. The daily rainfall distribution over the mean rainfall spread over the 11 years used in this study shows that the rainfall is quite well distributed in the downscaling experiments as compared to the GCM. The rainfall is widely distributed from 2mm/day to 11mm/day (all India average) in the IMD data set. This shows the large scale variation of summer monsoon rainfall over India. The distribution of rainfall is not captured by the CFSv2 and has a short distribution ranging from 3mm/day to 8.4 mm/day. The rainfall is mostly concentrated on the 6mm/day level in the CFSv2. The same is quite well distributed in the RegCM and WRF and the normal distribution curves are quite similar to the IMD. The Taylor diagram shown in Figure2 (lower panel) clearly shows the improvement in rainfall prediction skill with the RCMs. The correlation coefficients and the RMSE are improved with the RegCM and WRF over the CFSv2. Along with it, the relative bias is improved with downscaling. CFSv2 has a dry bias of 10-15% as compared to 5% in the RCMs. The RMSE are improved to 0.78,0.85 from 1.02 in the CFSv2. The correlation coefficients are 0.31, 0.55 and 0.47 with CFSv2, WRF and RegCM respectively (Figure 3).

The equitable threat scores (ETS) and critical success index (CSI) are calculated as mentioned in Maurya et al. (2019) and are shown in Figure4. The daily rainfall is divided into 4 categories (<1mm, 1-3mm, 3-5mm and >5mm). It can be clearly seen that the RCMs improve the skill of the model for the above mentioned rainfall categories. The ETS in CFSv2 is higher than WRF and RegCM for all the categories. The WRF has better skill than CFSv2 and RegCM for all the categories of rainfall except the 3-5mm category. The critical success index also compliments the findings from the ETS where the RCMs perform better over the GCM. Sparing the 1-3mm category, the success index is higher with the RCMs and the index is higher for WRF especially.

b) Simulation of upper air and surface parameters:

The winds at 850 hpa are one of the most important semi-permanent features of the Indian summer monsoon and has major consequences in the rainfall received over India for a particular season. The lower tropospheric winds after overturning near the Somali coast bring moisture laden winds from the Arabian sea to the land surface. They are an important component of the monsoon Hadley cell for which weaker or stronger lower tropospheric winds can lead to extremes in rainfall. The differences in the intensities of wind over Arabian sea can be witnessed in the composite years of the ERA data set (Figure 5a, e, i). Maximum intensities of 850hpa winds are observed in the normal and excess monsoon seasons as compared to deficit seasons. The 850hpa winds form a peculiar pattern that helps in the transport of moisture from the Arabian sea as well as the Bay of Bengal.

The winds over the Bay of Bengal turn towards the land surface that help in the transport of moisture to the eastern part of India. The pattern of wind can be witnessed in the GCM and RCMs. But the intensities vary within the models. CFSv2 tends to simulate very weak winds during the extreme years, but performs quite closely to that of the reanalysis data. The inability of the CFSv2 in simulating the mean winds during extreme years may be a reason for the dry bias in rainfall. The winds which have a speed of about 18-25m/s over the Arabian sea is simulated by only 10-16m/s. On the other hand, the RCMs do a better job in correcting the wind biases in the GCM. The intensities and pattern of wind is improved with the WRF and RegCM and the seasonality of the winds during the composite seasons can be witnessed. However, the RegCM possess similar characteristics to that of the CFSv2 and tends to simulate weaker winds during the extreme seasons. The WRF model simulates the wind closer to the reanalysis but represents an anomalous cyclonic circulation over the upper Arabian sea. This pattern is witnessed for all the composite years as well as in the mean wind pattern over the 11 seasons (Figure 6c). On an average over the 11 monsoon seasons used in this study, the wind pattern as well as intensities are improved with the downscaling experiments. Over the western part of the domain the wind ranges between 18-25m/s in the ERA data set as compared to 12-20m/s in the CFSv2, 16-25m/s in the WRF and 12-25m/s in the RegCM model.

The mean winds and the composite winds at 200hpa level as observed in the ERA dataset and as simulated by CFSv2, WRF and RegCM are shown in Figure 6 and 7. 200hpa winds are an important factor like as the 850hpa winds as they compose of one of the semi-permanent features of the summer monsoon. The tropical easterly jet (TEJ) is an important part of the monsoon Hadley cell and is present at 200hpa levels. The upper level winds are not quite closer to the ERA data set in the dynamical models. The overturning of the winds is shifted downwards over to the Gangetic plains as compared to the Tibetan plateau in the observations. The TEJ is a large scale phenomena and entire of its components cannot be visualized in the domain of our study. However, the upper tropospheric winds are simulated better with the CFSv2 and RegCM as compared to the WRF. Large anti-cyclonic circulations can be observed over the Gangetic plains in all the dynamical models. This circulation pattern is prominent over the Tibetan plateau and a small portion of it can be witnessed in the ERA data set (Figure 6a & 7a,e,i). The intensities of mean winds are not quite different with the composite monsoon seasons in the observations but small discrepancies can be seen with the CFSv2 and RegCM for the composite excess and deficit monsoon seasons. The WRF on the other hand tends to simulate similar wind pattern and intensities for all the composite monsoon seasons.

The mean 2 meter temperatures and the mean sea level pressure isobars for the composite monsoon seasons and the mean of the study period are presented in Figures 8 and 9. High temperatures over the north-western India and Pakistan region are a significant semi-permanent feature of the summer monsoon. The high temperatures over the Thar desert result in the formation of heat lows that drive the moisture laden winds from the ocean to the main land region by the formation of monsoon trough ranging from the head Bay of Bengal to the north-western India. Another significant feature is the high pressure belts over Tibetan plateau and Mascarene region. This feature is witnessed in the ERA data set where the temperatures are higher over the north western India than most of India and the mean sea level pressure is higher over the Tibetan plateau and at the lower boundary of the domain. The pressure reaches as high as 1020hpa over the Tibetan plateau and decreases southwards which increases over the oceans. At the equator, the pressure reaches about 1010hpa. This feature of the varying sea level pressures creates the monsoon pressure gradient which in turn drives the monsoon circulation. Weaker/stronger pressures can lead to extreme monsoon seasons. The sea level pressure along the equator is around 1010hpa for the deficit seasons as compared to 1008hpa for the normal and excess monsoon seasons.

The temperature at 2 meters doesn't change significantly over the contrasting monsoon seasons. It is more over constant throughout the monsoon season in the observed data set. On comparing the simulation of temperature with the ERA5 data set, it can be clearly seen that the CFSv2 possess a significant warm bias over most of the India (Figures 8b, f, j & 9b). Previous studies have also pointed out the presence of warm bias over northern India that largely impacts the simulation of rainfall over the monsoon core region (Roxy et al., 2015). Due to the warm temperatures over the Indo-Gangetic plains, the mean sea level pressure is overestimated. The pressure over Indian land region is overestimated but over the Tibetan region and Mascarene regions the pressure is underestimated. The pressure which reaches about 1020hpa over the Tibetan plateau is underestimated in the CFSv2 model which represents 1010hpa over the particular region. This inability of the model to represent the sea level pressure might be a reason for the biases in rainfall. On visualizing the RCMs, they do a better job by removing the biases in temperature as well as the pressure over the entire domain. The warm biases in CFSv2 are removed by the WRF as well as RegCM. The pattern of temperature is also quite similar to that of the ERA dataset. Higher temperatures (>30^0C) are represented in the WRF and RegCM over the north western India. But, the RegCM in particular simulates the temperature better than the WRF model. At the same time, the WRF reproduces the mean sea level pressure over the Tibetan plateau quite well as compared to CFSv2 and RegCM. The RegCM fails to reproduce high pressure belts over the Tibetan plateau. The pressure ranges between 1000-1010hpa over the Tibetan plateau in the RegCM whereas the WRF simulates the pressure around 1016-1020hpa which is closer to the ERA data set. The isobars of mean sea level pressure are quite similar to that of the ERA in the RCMs. Thus, it can be clearly inferred that the RCMs improve the simulation of the significant parameters temperature and pressure over the GCM. The differences in temperature for the composite monsoon seasons can be clearly witnessed in the RegCM where warm biases are simulated for the deficit monsoon seasons (Figure9d). Contrastingly, WRF possess a cold bias over most of India during the deficit monsoon season (Figure9c). The average temperatures over the entire period of study shows that the CFSv2 possess a large warm bias spatially whereas the WRF shows a cold bias over most of India. The RegCM also possess cold bias but in very less quantities. This distinctive feature in the dynamical models may be a reason for the variation in rainfall simulation by the models.

The relative humidity along the vertical column of the atmosphere is one of the most significant parameter that controls the simulation of rainfall in a dynamical model. The relative humidity is used in almost all of the parametrization equations involving convection, cloud microphysics etc. The relative humidity can be represented better when the simulation moisture and temperature is carried out realistically. Figure10 shows the spatial pattern of the relative humidity averaged over the vertical from the surface to 100hpa levels and over all the monsoon seasons used in this study. The vertical profiles of the relative humidity and the temperature biases from the surface to 100hpa levels over some of the significant regions are shown in Figure11. The relative humidity profiles are computed over the monsoon core region on Indian main land region (10^0N-25^0N, 73^0E -85^0E), over the Arabian sea (13^0N -17^0N, 64^0E -68^0E) and over Bay of Bengal (11^0N -15^0N, 85^0E -89^0E).

In the reanalysis ERA dataset, it can be seen that the relative humidity is maximum along the column of the atmosphere. This type of pattern is not seen over the Arabian sea as much of the moisture is advected in the lower troposphere due to the Somali jet stream at 850hpa level. The Western Ghats act as a barrier to the winds due to the orography of this region. Due to this reason, the relative humidity is observed to be maximum over the Western Ghats as compared to Arabian sea. Over the Indian main land region, maximum relative humidity is observed along the coast of Odisha and Andhra Pradesh which gradually decreases north west wards and is minimum over the Thar desert. Non-availability of moisture along with higher temperatures over the north western India is the major cause for very low relative humidity over this region. On comparing the same with the dynamical models, all the models fail to simulate the relative humidity over maximum regions of India. The relative humidity is simulated in much lesser quantities over the land region. The CFSv2 captures the pattern over the Western Ghats better followed by WRF. The RegCM fails to simulate the relative humidity closer to observations over most of the Indian land region. The vertical profiles of relative humidity show that the dynamical models fail to simulate the relative humidity in the upper tropospheric levels but are quite better in the lower tropospheric levels. Above 500hpa levels, all the models simulate very less amounts of relative humidity. Over the Arabian sea, the relative humidity profile decreases from the 900hpa levels and forms a minimum at 500hpa (40%) which then rises along the vertical column. This peculiarity can be attributed to the lower tropospheric jet stream at 850hpa level. Most of the moisture is advected east wards. The same feature is not quite captured by the dynamical models. The mid troposphere minima are not witnessed in the vertical profiles of the models. This may be because the relative humidity is computed as a function of temperature and specific humidity and the horizontal transport of moisture is not quite well simulated by the dynamical models. Over the Bay of Bengal, the relative humidity profile is steady and ranges between 75-90%. All the models behave quite equally in simulating the relative humidity along the column of the atmosphere. The WRF model is closer to the observations over CFSv2 and RegCM over the Indian main land region and Bay of Bengal. The relative humidity ranges between 60-90%, 40-95% and 75-90% over the Indian land region, Arabian sea and Bay of Bengal respectively in the ERA data set. The same is found to be in the range of 50-80%, 65-90%, 65-80% in the CFSv2, 50-80%, 70-90%, 65-85% in the WRF and 45-80%, 55-90%, 50-90% in the CFSv2 respectively. The temperature biases along the column of the atmosphere are reduced with the RCMs as compared to the GCM in the lower troposphere to the level of 400hpa. In the upper troposphere, the temperature biases are warmer by 3-5^{0}C.

Figure 12 shows the mean convective available potential energy (CAPE) and the vertically integrated moisture flux (VIMF) computed as per the equations discussed in section 2. The CAPE and VIMF are averaged over all the seasons used in this study after integrating the parameters along the specified vertical levels. The CAPE is one of the important parameter in determining the stability of the atmosphere. Moist convection during the summer monsoon is a complex process that determines the thermodynamic state of the atmosphere. CAPE determines the potential regions for deep convection. From the ERA data set, it can be seen that the eastern India has large potential for mesoscale convection which is one of the primary reasons for the convective activities over this region. The pattern of CAPE is captured by the CFSv2 and WRF, but is completely overestimated by the RegCM. The RegCM largely overestimates the CAPE over the land as well as over Arabian sea. This may be the reason for the heavy rainfall during the excess and normal monsoon seasons. Over the Arabian sea the CAPE lies between 1200-1600 J/kg which is quite the same in CFSv2 and WRF but is above 2500 J/kg in the RegCM. Over the main land region, the CAPE is 2000-2600 J/kg in the ERA which is about 2000-2400/2000-2600/2400-2800 J/kg in the CFSv2/WRF/RegCM respectively. The VIMF can present an idea on the moisture sources in the atmosphere as well as in the dynamical models. Major sources of moisture can be seen over the oceans where the flux values lie between 100-160 kg/m^2/s (Figure12). The pattern of the VIMF is not captured in the CFSv2 but is improved with the RCMs. The WRF produces the VIMF quite closer to the observations but the RegCM fails to capture the same over the Bay of Bengal. The WRF has the best predictability of the VIMF over the entire domain of study. Lack of representation of the moisture in the RegCM may be reason for the biases in rainfall.

4. Summary And Conclusions:

This study is aimed at testing the efficacy of two efficient limited area models, RegCM and WRF in fine tuning the seasonal scale forecasts from CFSv2 model. The RegCM has been widely acclaimed as a skillful tool for predicting the climate projections under different scenarios whereas the WRF is one of the most widely used mesoscale model to forecast short scale weather as well extreme events. The usage of both the models outside their regimes have been made in this study. Keeping in view the importance of a skillful forecast for the summer monsoon, the analysis of the rainfall and downscaled outputs have been compared for the JJAS period with the observations as well as the parent GCM over 11 monsoon seasons.

The RCMs do a fairly good job in improving the rainfall as well significant meteorological parameters as compared to the observations as well as the parent GCM, CFSv2. The regional models used in this study do possess the potential to reduce the errors and systematic biases in CFSv2. The forecast of rainfall is improved with the method of dynamical downscaling. The impact of simulating the dynamical model at higher resolution with better representation of the terrain along with the physical parameterization schemes help in improving the representation of the fundamental parameters in the model which ultimately improves the simulation of rainfall. CFSv2 being a comparatively finer GCM with spectral resolution of T382, possess certain lacunae that hampers the simulation of the monsoon. Downscaling corrects the problem of grid spacing in the model to some extent.

CFSv2 lack in the representation of the rainfall pattern as well as intensities over the Indian main land region. Though the seasonality of the monsoon rainfall is captured by the CFSv2, persistence of large scale dry bias over the central and north western India tends to underestimate the mean rainfall for JJAS (Chapter 3). Similar findings are observed with the composite monsoon seasons with CFSv2. Though the contrast between excess and deficit monsoon seasons can be identified in the CFSv2, relative bias in the model is too high to be considered for deterministic forecast. Downscaling experimenters do a fairly good job in representing the monsoon rainfall pattern as well as intensity. Also, the contrast between the rainfall observed over deficit and excess monsoon seasons can be observed with the downscaling experiments. However, the skills of the two RCMs differ quite significantly over the contrasting monsoon seasons. The WRF has similar rainfall pattern over central India but the rainfall is shifted southwards in the excess monsoon season especially. The RegCM performs quite well for the deficit monsoon season but overestimates the rainfall for normal and excess monsoon seasons. The biases in the daily rainfall shows that both the RegCM and WRF have similar rainfall biases but the RegCM has large wet bias in the initial days of the simulation whereas there are days of large dry biases during the course of the simulation. This pattern of similar biases may be arising due to the biases in the initial and boundary conditions of the CFSv2. Since the pattern of the biases are similar in both the models, it may be arising because of the errors in the input. This signifies that the choice of initial and boundary conditions along with the choice of a GCM for dynamical downscaling is extremely important for generating a skillful forecast. The rainfall distribution and the error minimization are improved with the downscaling experiments which is a positive sign for the RegCM and WRF. The RCMs possess the potential for improving the GCM forecasts and minimizing the errors. Though the RCMs improve the forecast as compared to the GCM, the skills of both the RCMs differ. Statistical analysis as well as mean rainfall over the composite monsoon seasons support the eye ball findings that the WRF does a better job than RegCM in simulating the mean seasonal rainfall over the extreme as well as normal monsoon seasons.

Analysis of surface and upper air parameters show that the rainfall closely follows the wind, relative humidity, moisture flux etc. The CFSv2 as well as the RCMs show the discrepancies in the mean simulated meteorological parameters over the contrasting monsoon seasons. The lower level tropical jet streams are an important component of the summer monsoon and the differences in the intensities for contrasting monsoon seasons can be clearly witnessed in the GCM as well as the RCMs. The RegCM shows stronger wind biases which may be a reason for the weaker Hadley circulation, ultimately generating biases in rainfall. Significant biases within the RCMs can be observed with the relative humidity over the entire column of the atmosphere. The relative humidity is an important parameter for the rainfall as well as conservation of moisture in a dynamical model. The dynamical models underestimate the relative humidity over the land region as well as the Bay of Bengal which may be affecting the rainfall simulation over these regions. The vertical moisture transport as well as the CAPE is underestimated in the CFSv2 whereas it is overestimated in the RegCM model over the Deccan plateau especially. The overestimation of the CAPE over the southern peninsula might the reason for excessive rainfall during the normal and excess monsoon seasons. On evaluating the two RCMs, the WRF consistently performs better than the RegCM. The seasonal rainfall as well as the intra seasonal variability is well captured in the WRF over RegCM. The low level and high level winds along with the fundamental parameters temperature, pressure, relative humidity are simulated better in the WRF which helps in overcoming the RegCM as far as the skill of rainfall prediction is considered.

Declarations

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The first author carried out the experimental design, data analysis and framing of the manuscript. The second author provided his assistance in guiding through the research work and provided useful comments and suggestions to improve the quality of the manuscript.

Availability of data and material:

Data will be made available on appropriate request.

Code availability:

Not applicable

Ethics approval:

Not applicable

Consent to participate:

Not applicable

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Tables

Table.1 Configuration of the RegCM4 and WRF4 used in this study:

	RegCM	WRF
Model domain	5°S-40°N; 55°E-110°E	5°S-40°N; 55°E-110°E
Initial Condition (CFSv2)	26 April 00UTC	26 April 00UTC
Simulation period	1^{st} May to 1^{st} October (Each Year)	1^{st} May to 1^{st} October (Each Year)
No. of vertical levels	18 σ levels	35 σ levels
Horizontal Resolution	15 km	15 km
Central longitude and latitude	79°E and 21°N	79°E and 21°N
Dynamical core	Hydrostatic	Hydrostatic
Map-projection	Rotated Mercator (ROTMER)	Rotated Mercator
Cumulus convection scheme	Land: Grell scheme Ocean: MIT-Emanuel scheme (Sinha et al., 2018)	Kain-Fritsch (new Eta) scheme (Prathipati,et al., 2021)
Radiation Scheme	Modified CCM3	RRTM
Boundary layer scheme	Holtslag PBL	YSU scheme
Microphysics scheme	Explicit moisture (Mohanty et al., 2019)	WRF Single-Moment (WSM) 5-class (Prathipati,et al., 2021)
Land Surface Physics	CLM4.5 (Maurya et al., 2017)	Noah land surface model

Figures

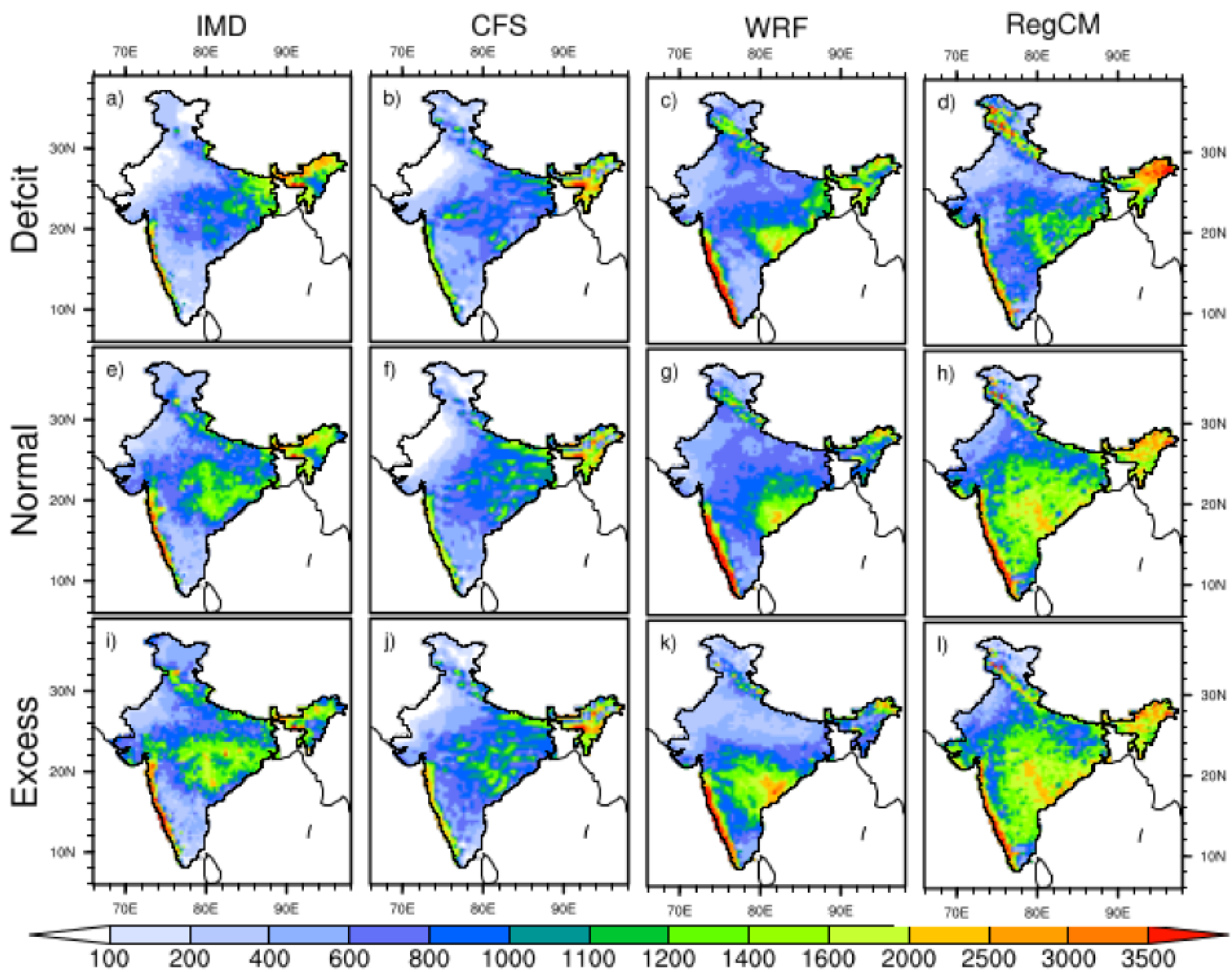

Figure 1

Mean seasonal (JJAS) rainfall (in mm) of the composite deficit monsoon seasons a) as observed in IMD and as simulated by b) CFSv2 c) WRF d) RegCM. Panels (e)-(h) and (i)-(l) are same as (a)-(d) but for normal and excess monsoon seasons respectively.

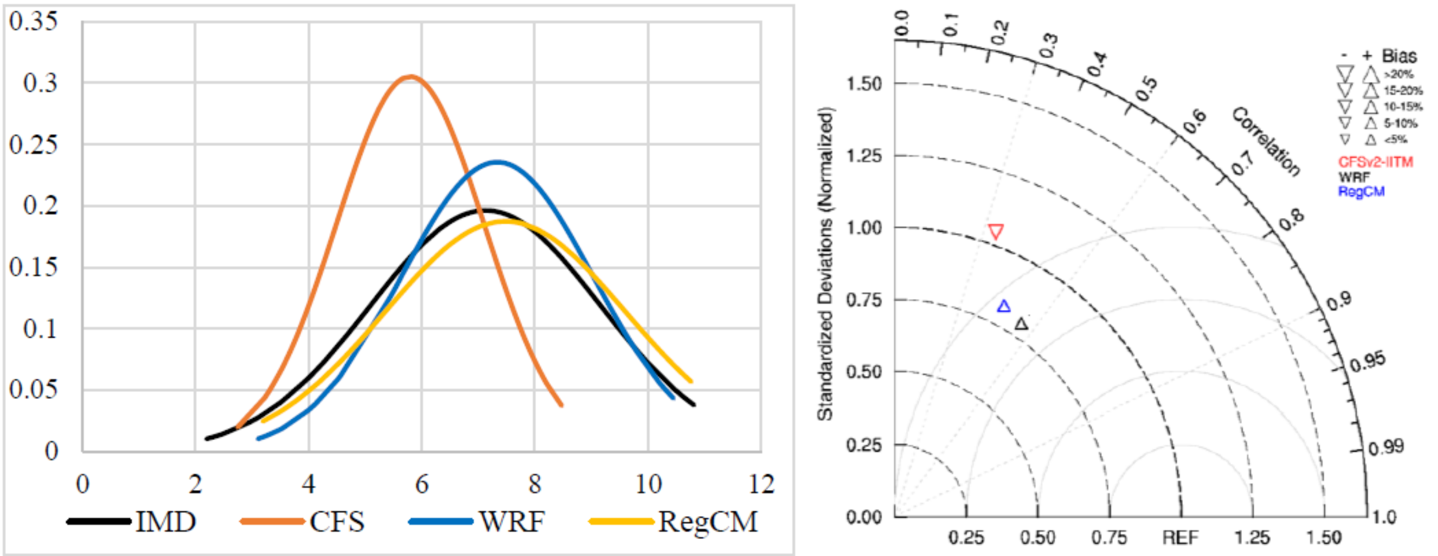

Figure 2

Probability density functions of the daily climatological rainfall (JJAS) as observed in IMD and as simulated by CFSv2, WRF and RegCM (left panel). Taylor diagram representing the correlation coefficients, normalized standard deviation and RMSE of the daily rainfall as simulated by CFSv2, WRF and RegCM with respect to IMD rainfall (right panel).

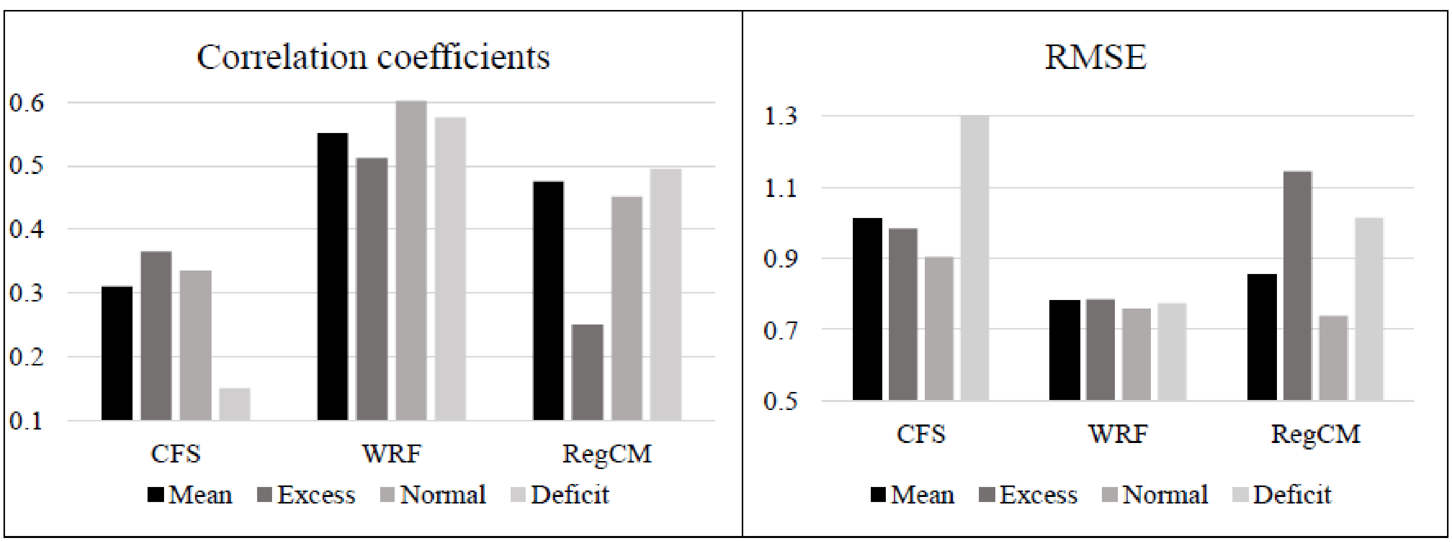

Figure 3

Correlation coefficients and mean RMSE of the daily rainfall for the total, and composite excess, normal and deficit monsoon seasons as simulated by CFSv2, WRF and RegCM with respect to IMD rainfall.

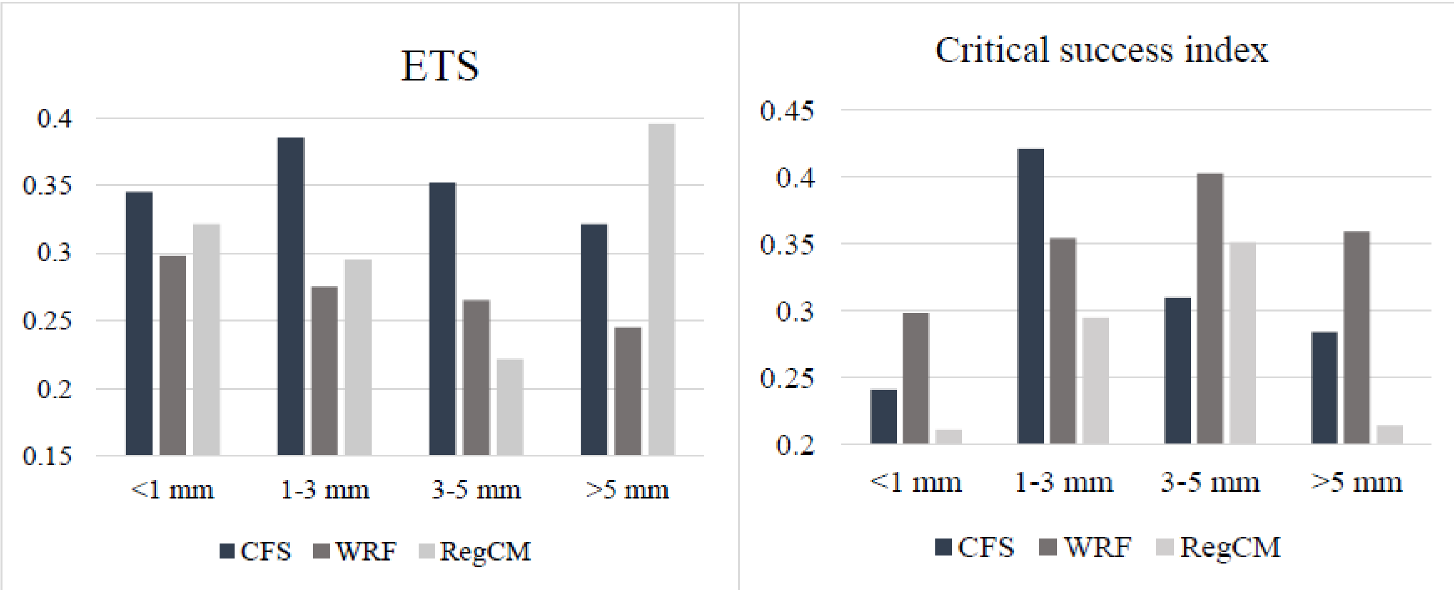

Figure 4

Equitable threat scores (ETS) and critical success index of the daily rainfall divided into 4 bins as simulated by CFSv2, WRF and RegCM with respect to IMD rainfall.

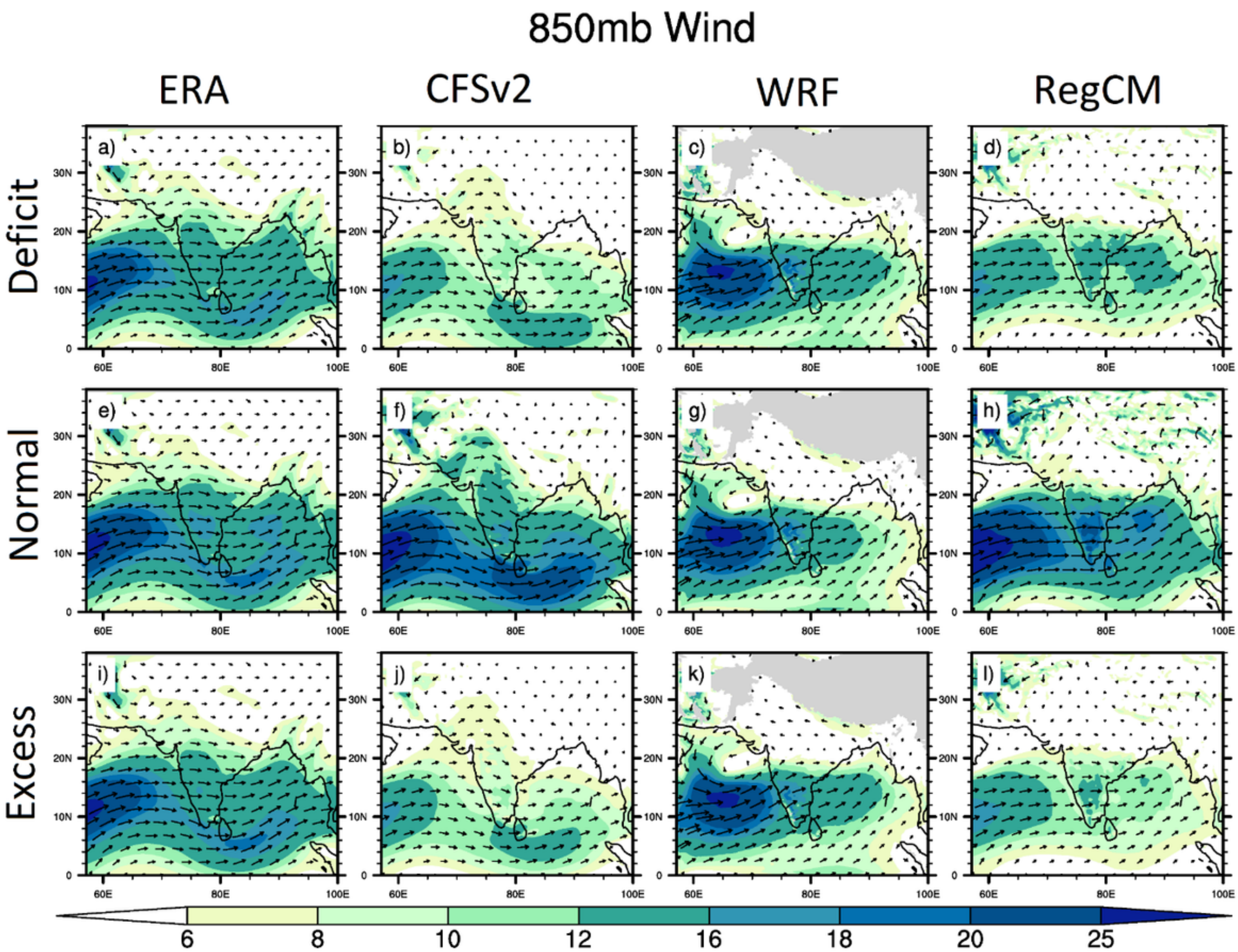

Figure 5

Mean seasonal (JJAS) wind (in m/s) at 850hpa pressure level for the composite deficit monsoon seasons a) as observed in IMD and as simulated by b) CFSv2 c) WRF d) RegCM. Panels (e)-(h) and (i)-(l) are same as (a)-(d) but for normal and excess monsoon seasons respectively.

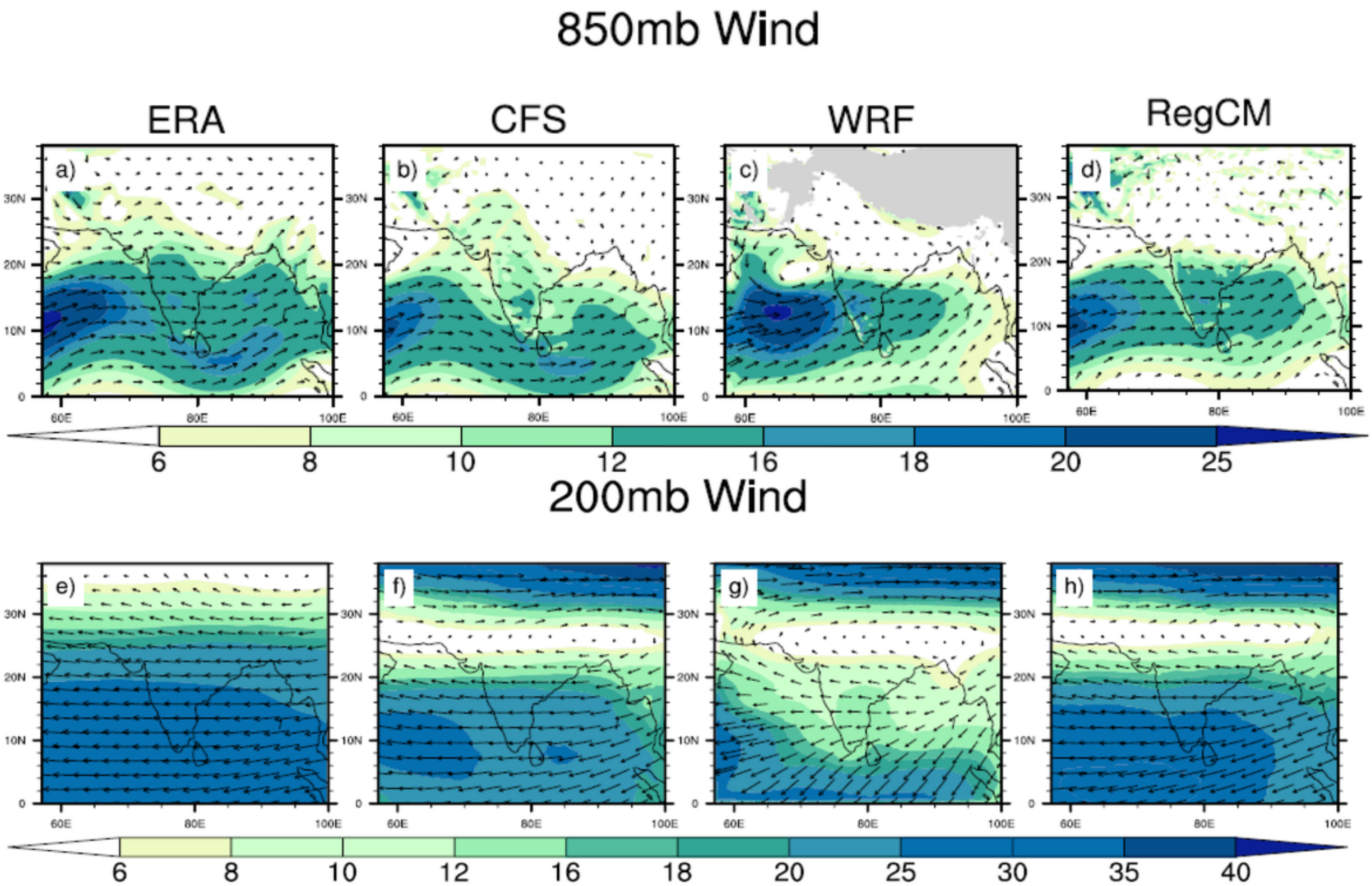

Figure 6

Mean seasonal (JJAS) wind at 850hpa pressure level averaged over the 11 monsoon seasons a) as observed in IMD and as simulated by b) CFSv2 c)WRF d)RegCM used in this study. Panels (e)-(h) are same (a)-(d) but for 200hpa winds respectively.

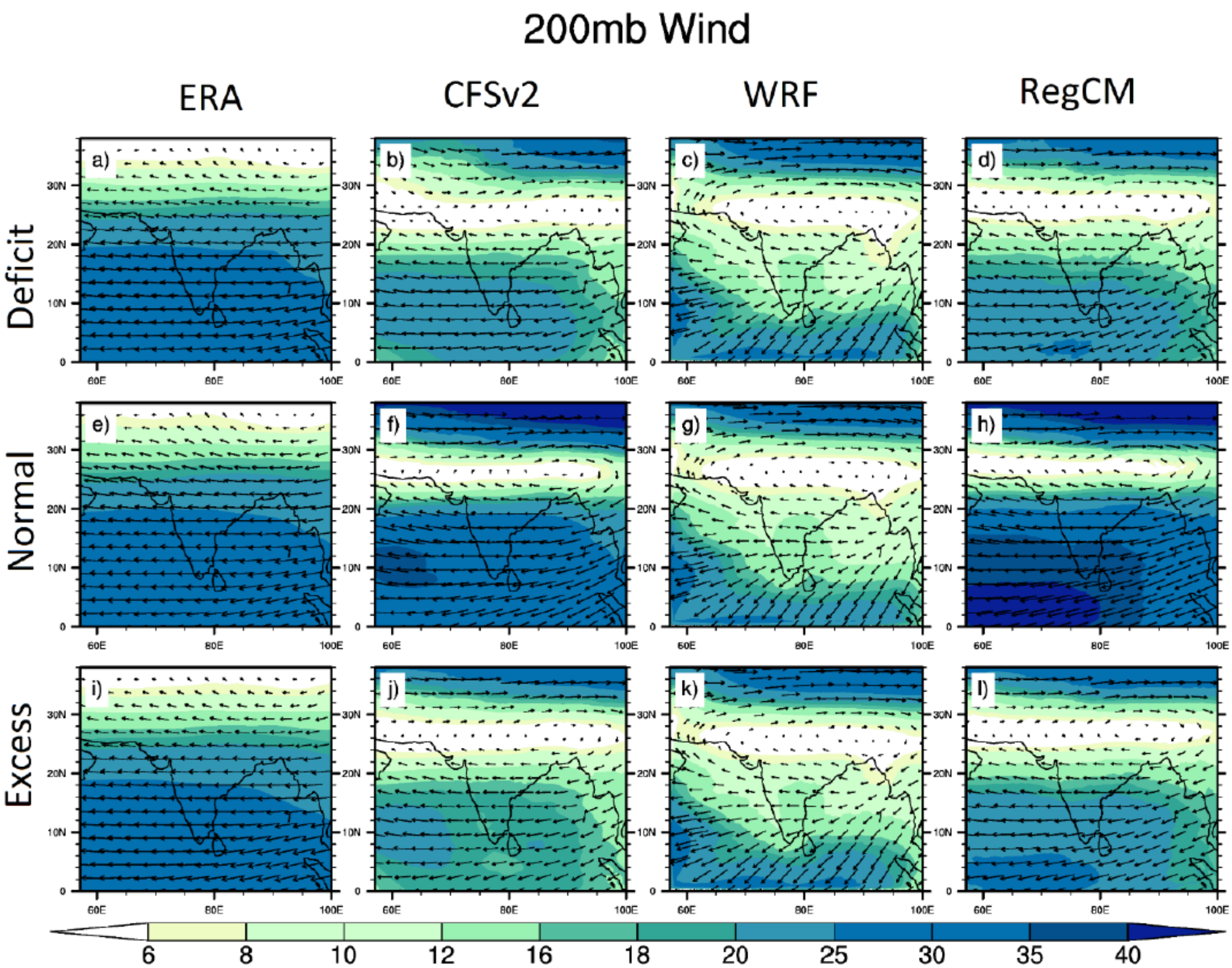

Figure 7

Mean seasonal (JJAS) wind at 200hpa pressure level for the composite deficit monsoon seasons a) as observed in IMD and as simulated by b) CFSv2 c) WRF d)RegCM. Panels (e)-(h) and (i)-(l) are same as (a)-(d) but for normal and excess monsoon seasons respectively.

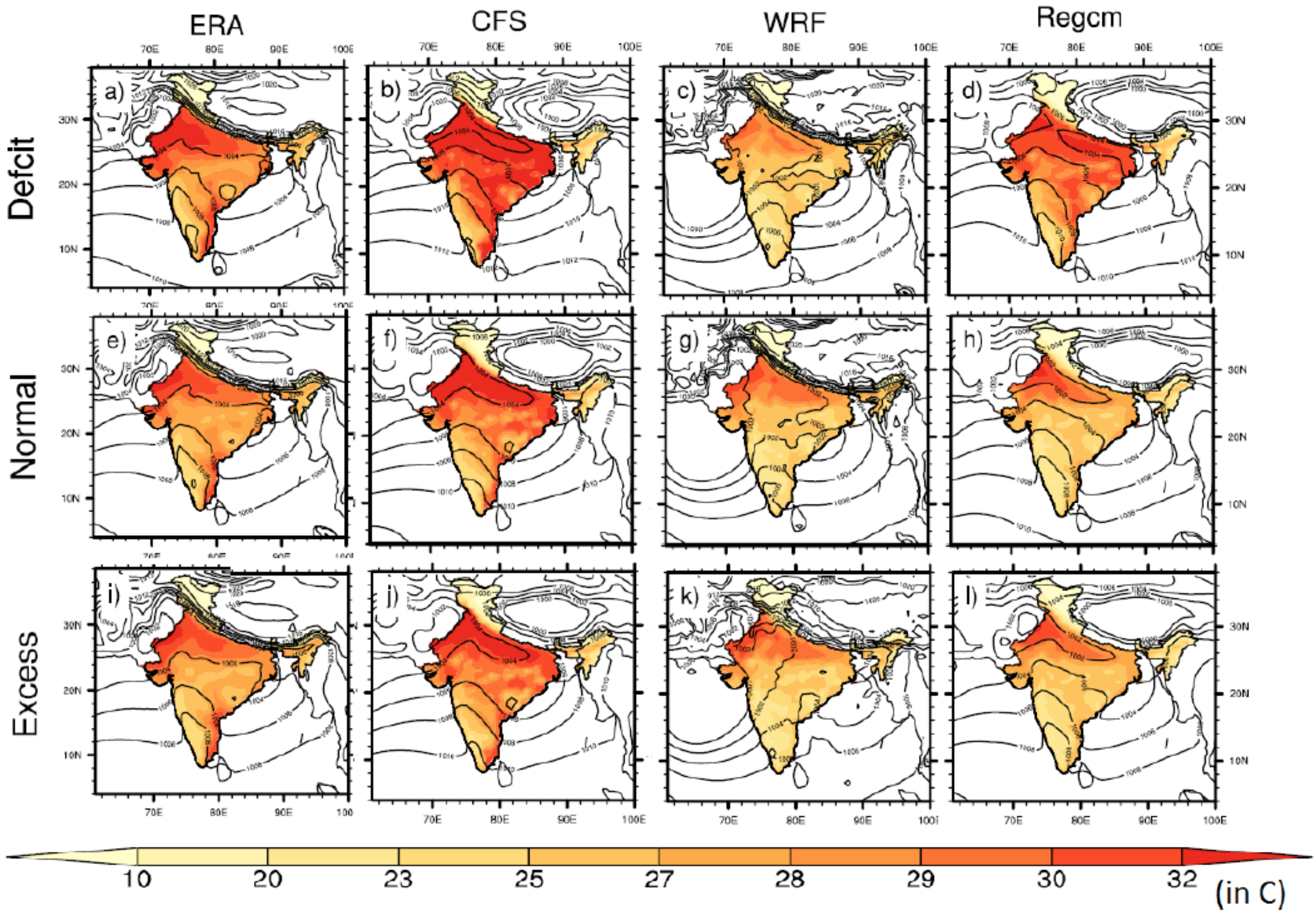

Figure 8

Mean seasonal (JJAS) temperature at 2 meters above surface level (filled contours) and isobars of mean sea level pressure (contour lines) for the composite deficit monsoon seasons a) as observed in IMD and as simulated by b) CFSv2 c) WRF d) RegCM. Panels (e)-(h) and (i)-(l) are same as (a)-(d) but for normal and excess monsoon seasons respectively.

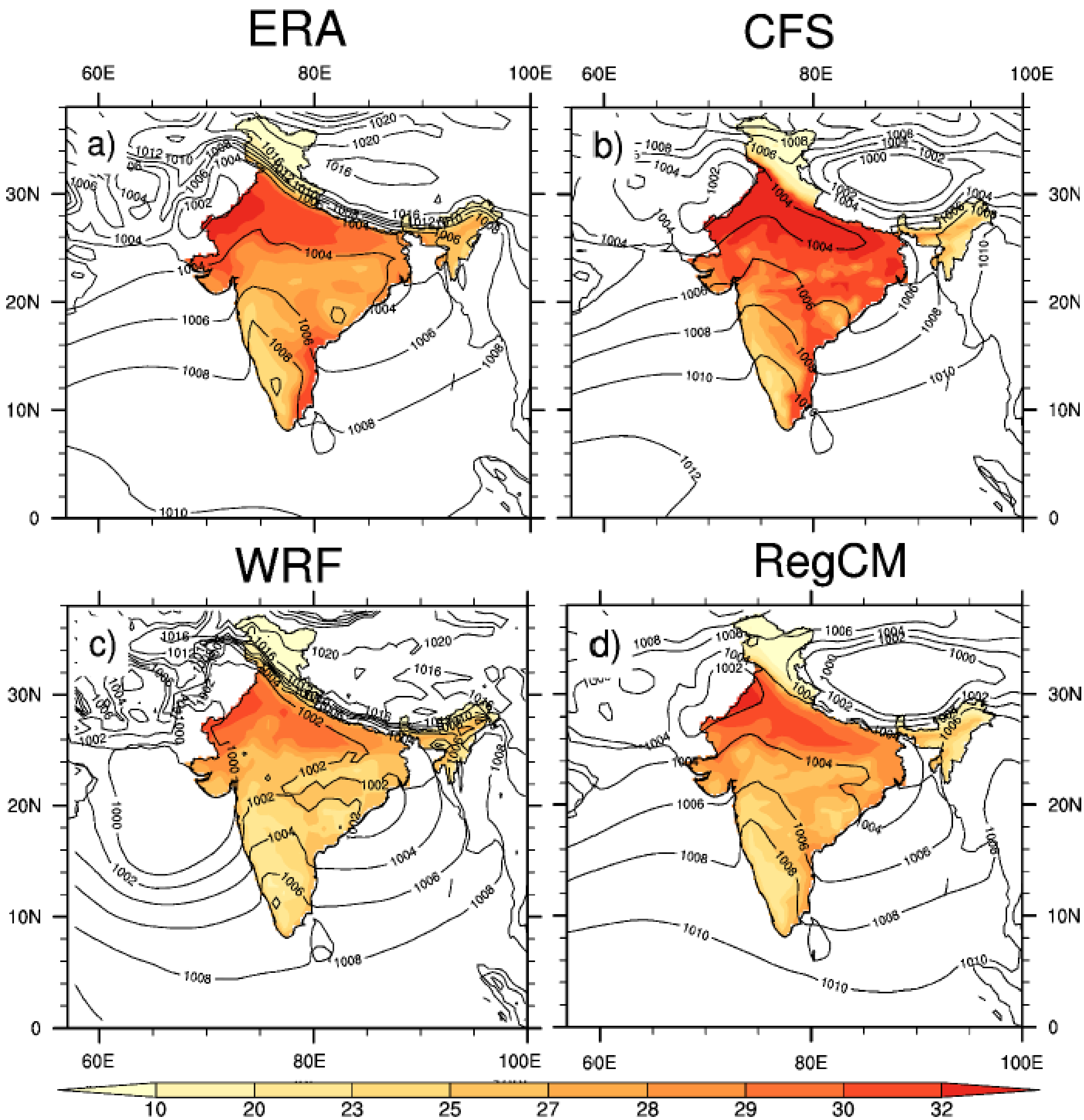

Figure 9

Mean seasonal (JJAS) 2 meter temperature and mean sea level pressure isobars averaged over the 11 monsoon seasons a) as observed in IMD and as simulated by b) CFSv2 c) WRF d) RegCM used in this study.

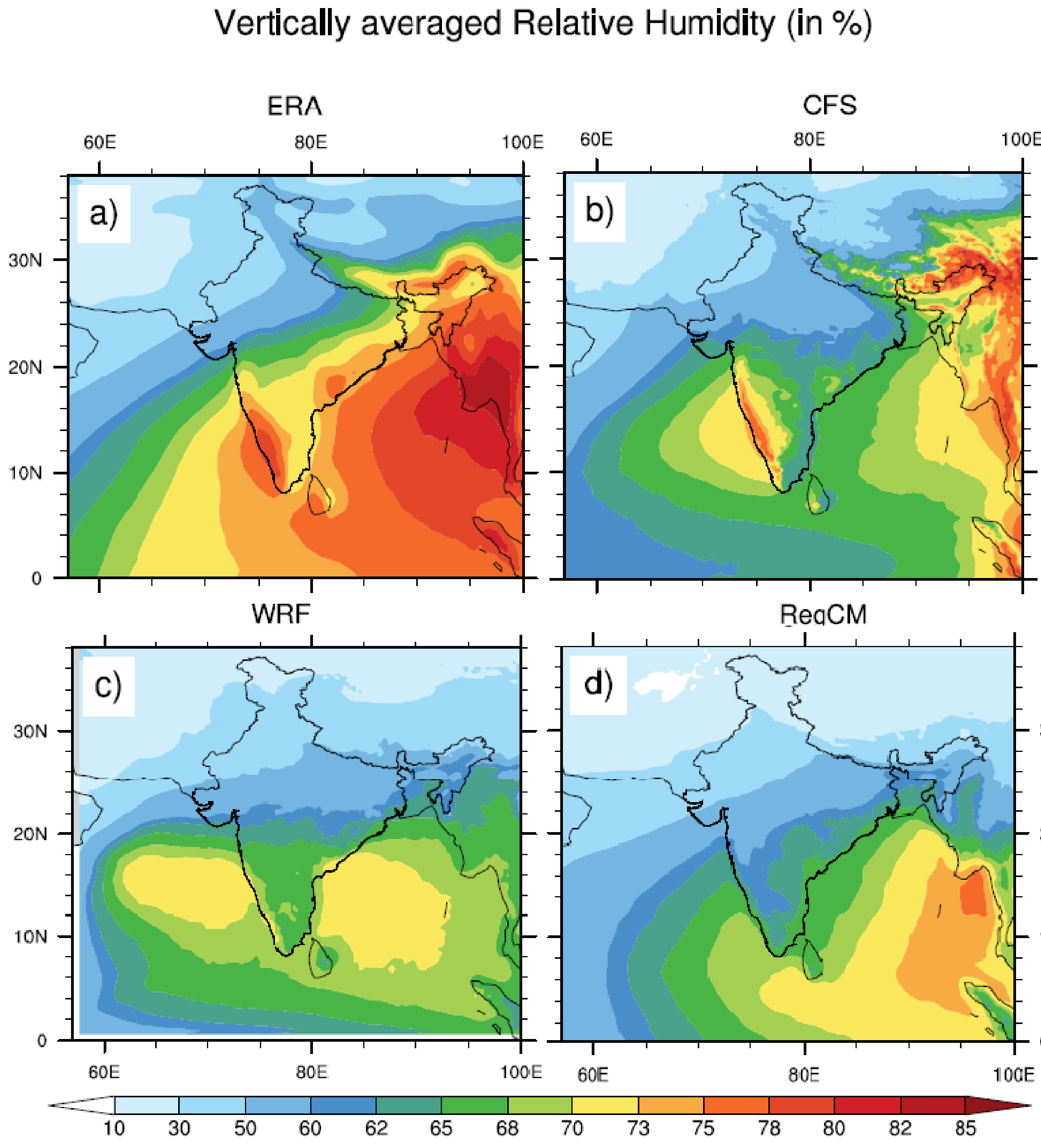

Figure 10

Mean seasonal (JJAS) relative humidity averaged over the entire vertical column of the atmosphere and over the 11 monsoon seasons a) as observed in IMD and as simulated by b) CFSv2 c) WRF d) RegCM used in this study.

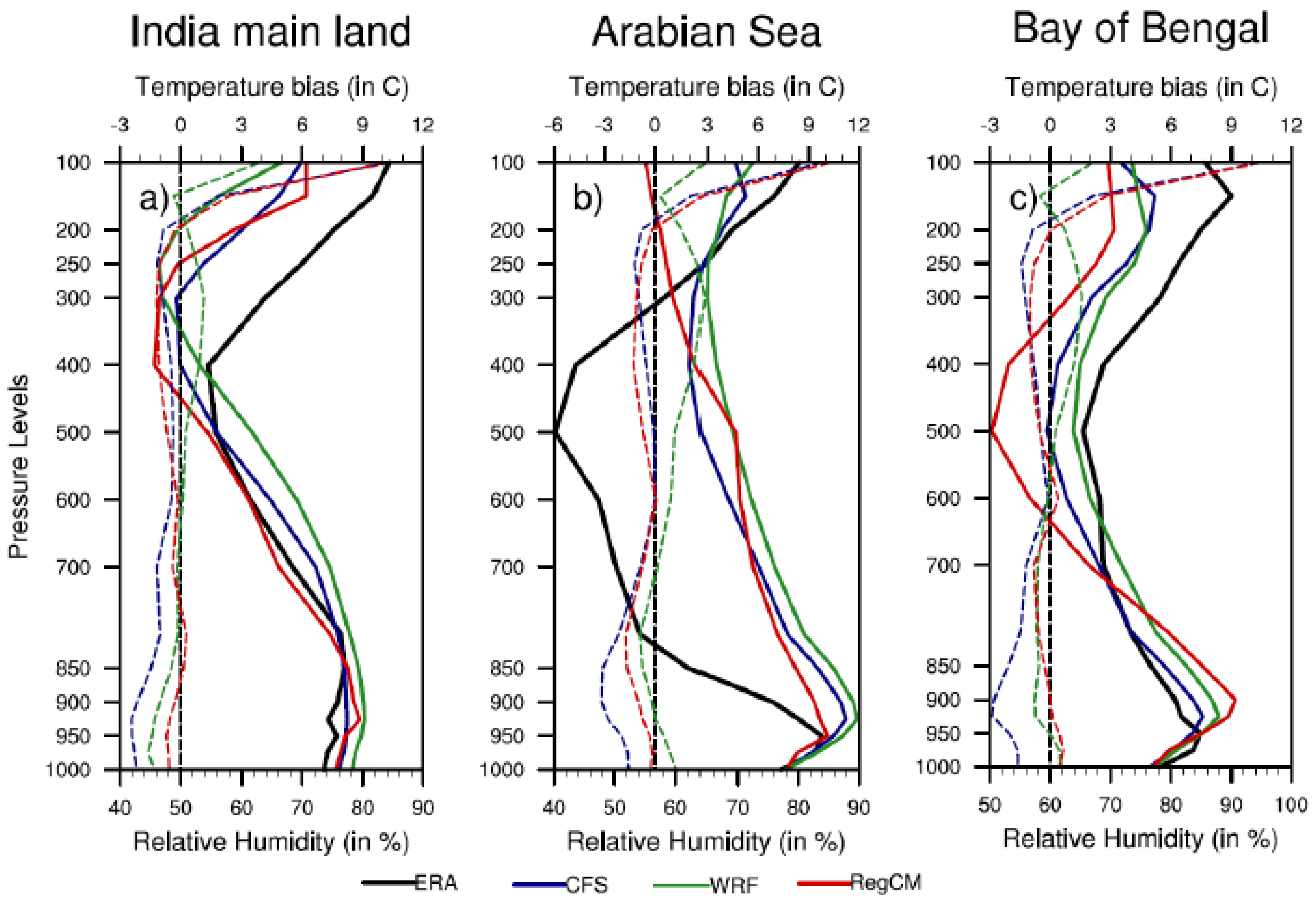

Figure 11

Vertical profiles of the relative humidity (in %) and temperature bias (in C) averaged over the 11 years used in this study over the monsoon core region over a) India (100N-250N, 730E -850E), b) Arabian sea (130N -170N, 640E -680E) and c) Bay of Bengal (110N -150N, 850E -890E). Solid lines represent the relative humidity profile whereas dashed lines represent the temperature biases along the column of the atmosphere.

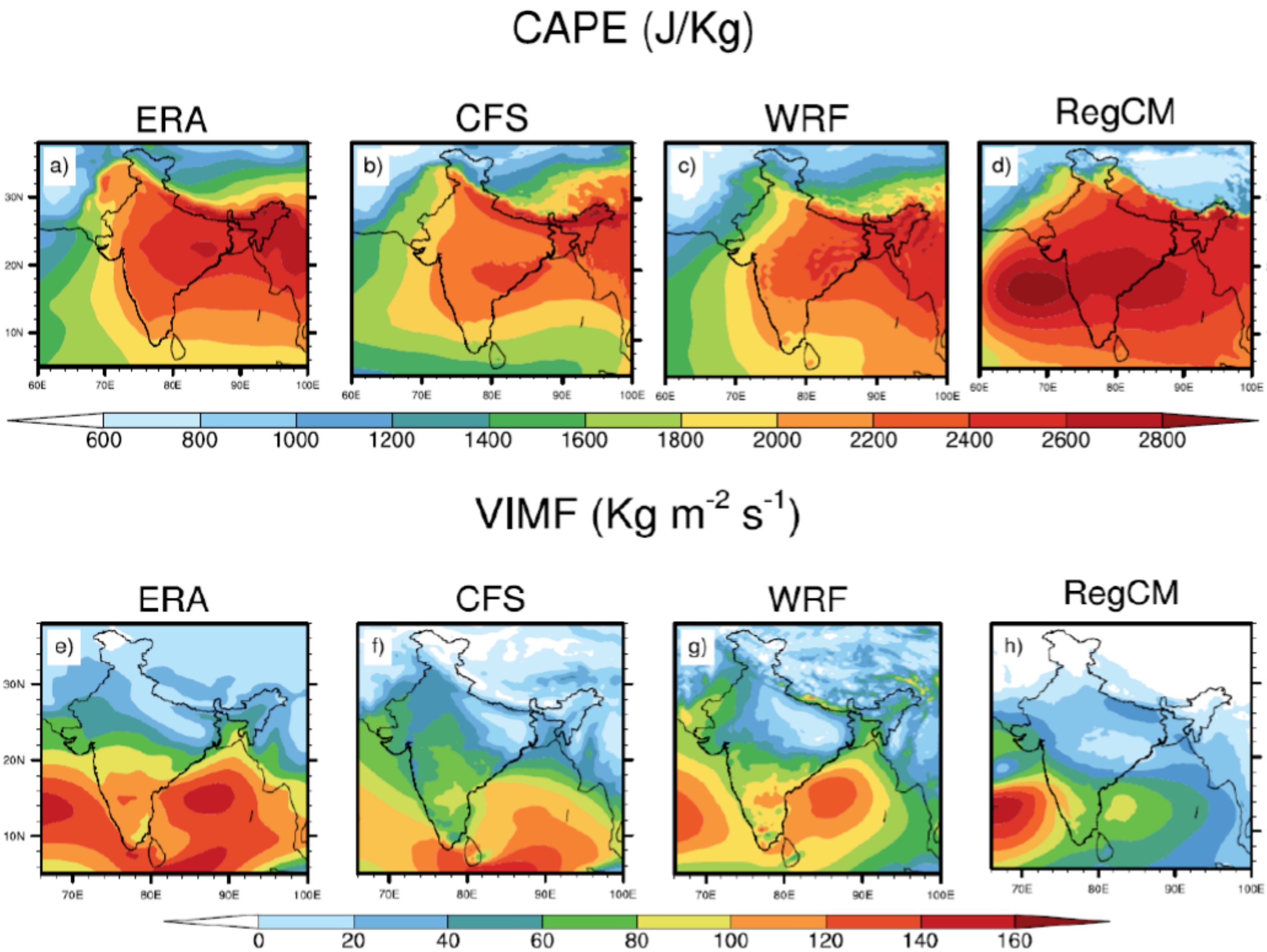

Figure 12

Mean seasonal (JJAS) CAPE calculated from the surface to 300hpa level and averaged over the 11 monsoon seasons a) as observed in IMD and as simulated by b) CFSv2 c) WRF d) RegCM used in this study. Panels (e-h) are same as (a-d) but for vertically integrated moisture flux.