Performance of cumulus parameterization schemes in the simulation of Indian Summer Monsoon using RegCM4

S. MAITY[1]*, M. MANDAL[1], S. NAYAK[2] and R. BHATLA[3]

[1] *Centre for Oceans, Rivers, Atmosphere and Land Sciences (CORAL), Indian Institute of Technology, Kharagpur, Kharagpur-721302, India*
[2] *National Research Institute for Earth Science and Disaster Resilience, Department of Integrated Research on Disaster Risk Reduction, Division Tennodai, Tsukuba-shi Ibaraki, 305-0006, Japan*
[3] *Department of Geophysics, Banaras Hindu University, Varanasi - 221 005, Uttar Pradesh, India*
*Corresponding author; email: suman.buie@gmail.com

RESUMEN

El monzón de verano de la India (MVI) se origina a partir de una convección de gran escala, por lo que su simulación debe basarse en la representación adecuada de la convección de cumulus en el modelo. En este estudio se analiza el desempeño de diversos esquemas de parametrización en simulaciones del MVI. El modelo climático regional RegCM4 se acopla con el modelo de suelo CLM 3.5 con una resolución de 30 km para simular el MVI en el periodo comprendido entre el 1 de mayo y el 30 de septiembre en tres años consecutivos: 2007, 2008 y 2009. Se llevaron a cabo cinco experimentos numéricos con cinco esquemas de convección (Kuo, Grell, MIT, GO_ML [MIT sobre tierra y Grell sobre el océano] y GL_MO [Grell sobre tierra y MIT sobre el océano]) para cada uno de los años mencionados. Algunas características importantes del MVI simulado con el modelo, a saber la corriente en chorro del oeste de niveles bajos, la corriente en chorro del este de niveles altos, los sistemas de baja presión superficial y los de alta presión sobre la meseta tibetana, etc., se analizan y comparan con datos de reanálisis del National Center for Environmental Prediction (NCEP). Se encontró que el modelo con el esquema de convección MIT simula mejor los sistemas de baja presión superficial asociados con alta temperatura en el noroeste de la India y Paquistán durante los tres años, en tanto que el esquema GL_MO simula mejor la distribución espacial y exactitud de la temperatura. El modelo con el esquema de convección MIT reproduce adecuadamente la corriente en chorro del oeste de niveles bajos con fuerza algo menor que el reanálisis del NCEP. Todos los esquemas simularon aceptablemente la ubicación y fuerza de la corriente en chorro tropical del este, con cierta incertidumbre en cuanto a la fuerza, y mayor exactitud con el esquema MIT. La comparación entre la precipitación simulada y las bases de datos de la Unidad de Investigación del Clima con resolución de 0.5º (CRU TS3.22) indica que la precipitación media estacional y mensual se simula mejor con los esquemas de convección MIT y GO_ML. Sin embargo, todos los esquemas de convección del modelo subestiman de manera significativa estas mismas variables sobre el centro y el oeste de la India. Un flujo mayor de calor sensible y un flujo menor de calor latente afectan de manera significativa la simulación de temperatura superficial y precipitación con todos los esquemas. El análisis estadístico indica que los esquemas GL_MO y GO_ML del modelo reproducen de manera adecuada la temperatura superficial y la cantidad de precipitación, pero el esquema MIT simula mejor la circulación. Aunque este último implica una desviación ligeramente mayor a la de los dos esquemas combinados, se observó que la distribución espacial y otras características sinópticas de la temperatura superficial y la precipitación durante el MVI fueron bien simuladas por el esquema MIT. En conclusión, tomando en cuenta el desempeño de todos los esquemas, el modelo RegCM4 con el esquema MIT de convección de cumulus ofrece una mejor simulación de las características estacionales y mensuales del MVI.

ABSTRACT

The Indian Summer Monsoon (ISM) is driven by organized large-scale convection; hence, its simulation is expected to depend on an appropriate representation of cumulus convection in the model. In the present study, the performance of different cumulus parameterization schemes is examined towards simulations of the ISM. The Regional Climate Model (RegCM4) is coupled with the Community Land Model (CLM 3.5) at 30 km resolution for the period May 1-September 30 for seasonal simulation of the ISM in three consecutive years, 2007, 2008, and 2009. Five numerical experiments with five convection schemes (Kuo, Grell, MIT, GO_ML [Grell over ocean and MIT over land], GL_MO [Grell over land and MIT over ocean]) are conducted for each of these three years. Some important features of the ISM simulated by the model, viz. low level westerly jet, upper level easterly jet, heat low, Tibetan high, etc., are analyzed and compared with that of the National Center for Environmental Prediction (NCEP) reanalysis. We found that the heat low over northwest India and Pakistan in all the three years is better simulated by the model with the MIT convection scheme compared to other convection schemes, whereas spatial distribution and accuracy of surface temperature is better simulated using GL_MO rather than MIT. The low level westerly jet is well captured by the model with MIT with slightly weaker strength compared to the National Center for Environmental Prediction (NCEP) reanalysis. The location and strength of the tropical easterly jet is well predicted in each simulation with some uncertainty in strength, and are better simulated with MIT. The comparison of the model simulated rainfall with $0.5° × 0.5°$ datasets from the Climate Research Unit (CRU TS3.22) indicates that seasonal and monthly average rainfall are well simulated with MIT and GO_ML; however, the same over central and western India is significantly underestimated by the model with all the convection schemes. Comparatively, higher sensible heat flux and lower latent heat flux are noticed in the model simulation with all schemes. This change of fluxes affects surface temperature and rainfall simulation significantly. The statistical analysis indicates that surface temperature and rainfall are well reproduced by the model with GL_MO and GO_ML, but circulation is better simulated with MIT only. It is observed that although the bias in the model with MIT is slightly higher than that of the two mixed schemes, the spatial distribution and other synoptic features of surface temperature and rainfall during ISM are well simulated. Thus, considering overall performances, the RegCM4 with MIT the cumulus convection scheme provides better simulation of seasonal and monthly features of the monsoon.

Keywords: Indian summer monsoon, seasonal simulation, cumulus convection.

1. Introduction

The Indian Summer Monsoon (ISM), which is characterized by seasonal reversal of trade winds from northeast to southwest due to differential heating of the Indian landmass and neighboring oceans, is a major component of the tropical circulation. It contributes to more than 70% of the annual rainfall over India (Parthasarathy et al., 1994). Due to its large impact on Indian economy, the ISM has been an important topic of research for more than a century now. Numerous studies have been conducted to understand the mechanism and physical processes (i.e., large scale circulation processes) of the ISM (Shukla and Paolino, 1983; Shukla and Fennessy, 1994; Bhaskaran et al., 1996; Goswami et al., 1998; Webster et al., 1998; Lal et al., 2000; Zhou and Li, 2002; Mohanty et al., 2002, 2005; Kang et al., 2002; Rao et al., 2004; Singh et al., 2007; Raju et al., 2010; Zou and Zhou, 2013, 2014; Zhu, 2015; Almazroui et al., 2016). However, convection plays an important role in the development and maintenance of the ISM

through the release of latent heat and vertical transport of heat, moisture and momentum (Ghosh et al., 1978; Kain, 1993; Zhu, 2015). A number of schemes have been developed over the years to parameterize the cumulus convection in large-scale numerical models, but none of the studies show a universal conceptual framework to parameterize convection. Thus, it is important to undertake a sensitivity study to have a suitable choice of convection scheme for a particular region.

A comparative study of different Kuo type of cumulus convection schemes (CCS) (Kuo, 1965, 1974) during different epochs (pre-onset, onset and break) of the Asian Summer Monsoon was conducted by Das et al. (1988), who inferred that the Kuo-Anthes scheme (Anthes, 1977) performs better in simulating heating, moistening and precipitation rate in a moderate convective regime. A similar kind of study was conducted by Alapaty et al. (1994) using the Naval Research Laboratory/North Carolina State University (NRL/NCSU) nested grid regional model

with Kuo and Betts-Miller schemes (Betts, 1993) during an active monsoon period; they reported that different regional monsoon features are better simulated with the Kuo scheme. Das et al. (2001) performed a sensitivity study of ISM to CCS using the global spectral model of the National Centre of Medium Range Weather Forecasting (NCMWRF), India, considering three CCS, viz. the simplified Arakawa-Schubert scheme (SAS), the relaxed Arakawa-Schubert scheme (RAS), and the Kuo scheme. They concluded that SAS performed better in simulating the regional features of ISM. Das et al. (2002) carried out another sensitivity study using the above CCS to observe the skill of medium range forecast over the Indian region which corroborates their previous findings.

Dash et al. (2006) investigated the sensitivity of ISM on cumulus convection for a four-yr. period (1993-1996) using RegCM3 and concluded that the Grell scheme (Grell, 1993; Grell et al., 1994) performed better. Martínez et al. (2006) observed that the Grell scheme with Arakawa-Schubert closure is better in simulating summer precipitation in the Caribbean region using RegCM3. Venkata and Cox (2006) inferred that the Kain-Fritsch scheme (Kain, 1993) performed better than the Grell scheme in simulating monsoon depression using a mesoscale model (MM5). In a recent study, Sinha et al. (2013) showed that the MIT scheme (Emanuel, 1991) is a better choice for the simulation of ISM. These studies clearly indicate that the monsoon features are highly sensitive to the choice of CCS. Although, a number of studies on the ISM have been conducted using regional models, but mostly with the Biosphere-Atmosphere Transfer Scheme (BATS) (Dickinson et al., 1993). No study has been conducted so far using RegCM4 in combination with other land surface schemes present in the model (e.g, the Community Land Model [CLM] v. 3.5) for the seasonal simulation of ISM.

In this study an attempt is made to test the sensitivity of the ISM simulation to some of the CCS that have not been considered in earlier studies. The following section contains three subsections in which the model is described, numerical experiments are conducted and datasets are used. Results and discussions are presented in Section 3, followed by a conclusion in Section 4.

2. Model description, experimental design and datasets used

2.1 Model description

The regional climate model (RegCM4, version 4.1.1), which is developed by the Abdus Salam International Center for Theoretical Physics (ICTP, Italy), is an evolution of RegCM3 with inclusion of some improved physical parameterization schemes. Its dynamical core is, as its previous version (Pal et al., 2007) a hydrostatic, primitive equation model which has a terrain-following sigma coordinate in the vertical. RegCM4 consists of multiple state-of-the-art physics options. Radiative transfer calculations follow the radiative transfer scheme of the global model CCM3 (Kiehl et al., 1996). Along with the planetary boundary layer (PBL) scheme proposed by Holtslag et al. (1990) and used in RegCM3, a new PBL scheme developed by the University of Washington (Bretherton et al., 2004) is implemented in RegCM4. The model also includes parameterization schemes for ocean fluxes, interactive aerosol schemes and interactive lake models.

In RegCM3, land surface processes were described using BATS (Dickinson et al., 1993). In addition, CLM3.5 (Tawfik and Steiner, 2011), developed by the National Center for Atmospheric Research (NCAR) is coupled with RegCM4 to improve the representation of land surface processes. CLM has the best capability to represent various land surface process like snow and soil layers, land surface heterogeneity, land cover types and vegetation fraction (Steiner et al., 2005). A detailed description of CLM3.5 implemented in RegCM4 is presented in Steiner et al. (2009) and Collins et al. (2006).

In the RegCM4 modeling framework, precipitation is classified broadly into two categories, viz. non-convective scale (grid-scale) and convective (sub-grid scale). The former, also known as large/resolved scale precipitation is derived using the sub-grid explicit moisture scheme (SUBEX; Pal et al., 2000) while the later (sub-grid scale) is explained using different CCS mentioned below. The SUBEX scheme accounts for the sub-grid variability in clouds by linking the average relative humidity of a grid cell to the cloud fraction and cloud water, whereas the precipitation produced by a CCS illustrates the effects of sub-grid scale convective clouds.

There are three major CCS available in RegCM4, viz. MIT (Emanuel, 1991), Grell (Grell, 1993; Grell

et al., 1994), Kuo (Anthes, 1977). A Major improvement in RegCM4 is the option of choosing different CCS over land and ocean (mixed scheme), instead of using a single CCS over the whole model domain. The reason is the limited performance of CCS over land and ocean (Giorgi et al., 2012); therefore, in addition to the three main CCS, the model has two mixed convection schemes: Grell over land and MIT over ocean (GL_MO) and Grell over ocean and MIT over land (GO_ML).

In the Kuo scheme (Anthes, 1977), the convection is activated when the moisture convergence of a column exceeds a threshold value and vertical sounding is convectively unstable. A fraction of the moisture convergence moistens the column and the remaining forms precipitation. It is explicitly mentioned that the moisture convergence of an atmospheric column is computed considering the advective tendency of water vapor only. The latent heat due to condensation is distributed between the cloud top and bottom by a function that allocates the maximum heating to the upper portion of the cloud layer (Giorgi et al., 2011).

The second CCS option is the Grell scheme (Grell, 1993; Grell et al., 1994), which assumes that the convective cloud stabilizes the environment as fast as the non-convective cloud destabilizes it. It is a mass flux convection scheme that considers the cloud as a two steady-state circulation having an updraft and a penetrative downdraft. The updraft and downdraft are initiated at the level where the moist static energy is maximum and minimum, respectively. It works when a lifted air parcel in the updraft attains moist convection level. The mixing of cloudy and environmental air is possible except at the top and bottom of the circulation. The mass flux is assumed to be constant and no entrainment/detrainment is allowed through the cloud edges. The scheme is employed with a closure approximation such as the Arakawa and Schubert (Arakawa and Schubert, 1974; Grell et al., 1994) closure or the Fritsch and Chappell closure (Fritsch and Chappell, 1980).

The third CCS option is the MIT scheme (Emanuel, 1991; Emanuel and Zivkovic-Rothman, 1999), where it is assumed that the cloud mixing is highly episodic and inhomogeneous and convection is triggered when the level of neutral buoyancy is greater than the cloud base level. A part of the condensed moisture forms precipitation and the remaining part forms cloud between these two levels. The fraction of the total cloud base mass flux that mixes with the environment at each level is proportional to the change rate of undiluted buoyancy with altitude. A more detailed description of RegCM4 is available in Giorgi et al. (2012).

2.2 Experimental design

The configuration of the model used in the present study is given in Table I. The model domain ranges from 30-120º E, 15º S-45º N with 30-km horizontal

Table I. Model overview for this study.

Contents	Description
Model dynamics	Hydrostatic
Model domain	30-120º E ; 15-45º N
Horizontal resolution	30 km
Vertical level	23 (terrain-following sigma level)
Map projection	Lambert conformal
Central latitude and longitude	16º N, 75º E
Lateral boundary condition scheme	Relaxation, exponential
Model integration time step	30 s
Cumulus convection scheme	MIT, KUO, GRELL, GO_ML, GL_MO
Land surface scheme	Community Land Model (CLM3.5; Oleson et al., 2008)
Closure scheme	Arakawa and Schubert (1974)
PBL scheme	Holtslag scheme (Holtslag et al., 1990)
Ocean flux scheme	Zeng's scheme (Zeng et al., 1998)
Radiative transfer scheme	CCM3 (Kiehl et al., 1996; Giorgi et al., 2011)
Explicit moisture scheme	SUBEX (Pal et al., 2000)

resolution and 23 vertical levels (Fig. 1). The initial and lateral boundary conditions are provided by global reanalysis datasets. Similar to the other regional model, RegCM4 is employed with a buffer zone of 12 grid points inside the lateral boundary (Wang et al., 2003; Giorgi et al., 2011). Different prognostic variables of the model, such as wind components, temperature, water vapor, etc., are nudged to the reanalysis data with an exponential nudging technique. The polygon inside the model domain (Fig. 1) represents the buffer zone selected for this study.
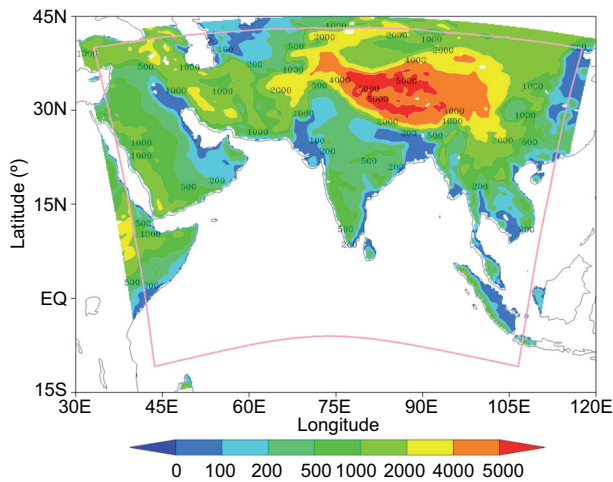

Fig. 1. Model domain and topography of the study region (in meters) along with buffer zone of the model.

The model is integrated from 00:00 UTC on May 1 to 18:00 UTC on September 30 for seasonal simulations of the ISM in 2007, 2008, and 2009. First, one month (May) is considered as the model spin-up period based on previous studies (e.g., Dash et al., 2006; Tchotchou and Kamga, 2010; Sinha et al., 2013; Zou et al., 2014; Tiwari et al., 2015); then, the simulation for the period June-September is considered for the analysis. Although spin-ups of regional models vary in the range of 10 days to one month (Wang et. al, 2003; Martínez et al., 2006; Zhong et al., 2006; Kang et al., 2014) and even longer for climate scale simulation, one month is sufficient for a seasonal scale (five months) simulation to achieve dynamical equilibrium of the model internal physics and lateral boundary conditions, as mentioned in the earlier literature. It is reported in an earlier study by Anthes et al. (1989) that regional models reach the

equilibrium stage around 2-3 days. Five numerical experiments with five CCS (MIT, KUO, GRELL, GO_ML and GL_MO) for each of the three years (2007, 2008, 2009) are conducted in this study. The Indian Meteorological Department (IMD) provides a detailed report regarding different features of the monsoon, including the indian summer monsoon rainfall (ISMR) for the years 2007-2009 at http://www.imdpune.gov.in/Clim_Pred_LRF_New/Reports/Monsoon_Report/. As reported by the IMD, 2007 was an above-normal year with 105% of all India rainfall (long period average), 2008 was a normal year with 98% of all India rainfall, and 2009 was a deficit monsoon year with 77% of all India rainfall. The long period average rainfall is the average of the ISM precipitation for 1951-2000; it provides an opportunity to investigate the performance of RegCM4 in these three contrasting monsoon years.

2.3 Datasets used

The meteorological parameters for the initial and boundary conditions of the model were derived from the NCEP/NCAR reanalysis (Kalnay et al., 1996) at $2.5º \times 2.5º$ resolution. The geophysical parameters, viz. topography and land use, are obtained from United States Geological Survey (USGS) global data at 10 min resolution. Sea surface temperature (SST) for the model initial condition is taken from NOAA optimum interpolation (OI) global data at $1º \times 1º$ resolution. Additional datasets including land cover, soil texture and color, leaf area index, etc., required for CLM, are obtained from http://clima-dods.ictp.it/data/regcm4/CLM/. Surface temperature and rainfall simulated by the model were validated with high resolution ($0.5º \times 0.5º$) Climate Research Unit time series (CRU TS 3.22) datasets (Harris et al., 2014; Trenberth et al., 2014). Wind fields and different fluxes from the model simulation are compared with NCEP/NCAR datasets.

3. Results and discussion

The model-simulated results with different convection schemes are analyzed and presented to evaluate their performance in simulating important features of the monsoon and seasonal and monthly scale precipitation over India and its five homogeneous regions. At first, surface temperature is analyzed in reference to heat low, land-ocean temperature

gradient and its spatial variation over the region in the monsoon season (section 3.1). Next, the monsoon circulation features in the three consecutive monsoon years are discussed in section 3.2. Rainfall distribution over India and its homogeneous regions is discussed in the subsequent section. The homogeneous regions considered for this study, viz. northwest India (NWI), west central India (WCI), central northeast India (CNEI), south peninsular India (SPI) and northeast India (NEI), are based on rainfall characteristics (Parthasarathy et al., 1994) (see Fig. 3). The model's ability to capture surface temperature and rainfall is also evaluated by means of different statistics such as spatial correlation, standard deviation and root mean square error (RMSE) using the Taylor diagram (Taylor, 2001), which provides pictorial representation of these features in a single diagram and is successfully used in numerous studies (Ali et al., 2015; Almazroui et al., 2016).

3.1 Surface temperature

Figure 2 presents June-September (JJAS) averaged temperature (ºC) for the years 2007-2009 from model simulations using the MIT, GRELL, KUO, GO_ML and GL_MO schemes and the CRU dataset. It clearly indicates that the model using MIT, GO_ML and GL_MO (KUO and GRELL), produces higher (lower) surface temperatures in all of three years compared to the CRU dataset over the whole domain, except peninsular India. Heat low over northwest India and Pakistan is reasonably well simulated using MIT, GO_ML and GL_MO. It is also observed that heat low is elongated to eastern India in the simulation with the MIT scheme. Temperature at the center of the heat low is overestimated in all of the three CCS (it varies in the range of 33-35 ºC in the CRU observation, which is more than 35 ºC in the model simulation). The region of heat low has larger spatial extent in the model simulation using the MIT scheme. Although higher surface temperature is noticed in the three schemes, MIT shows slightly higher (2-3 ºC) temperature. The strength of the heat low as well as the temperature over Indian landmass is not well simulated using GRELL and KUO.

The bias (observation-model) in the model simulated JJAS averaged surface temperature is analyzed in all of these years. For brevity, a figure is not presented as a part of the manuscript. A warm bias is observed

in the model simulation with MIT and two mixed schemes, viz. GO_ML and GL_MO over most part of the Indian landmass. Although the pattern of the bias is similar in all of these three schemes, the magnitude is higher in MIT. This result is consistent with many previous studies (Zou et al., 2014; Tiwary et al., 2015).

The temperature bias varying in the range of 1-5 ºC (even more in some regions) is observed over large areas in different parts of India (NWI, north India, Gangetic West Bengal and central India) using MIT except in peninsular India, where a slight cold bias (0.5-1 ºC) is observed. The temperature bias over the 4 regions using GO_ML and GL_MO (the mixed schemes) is found to be 0-3 and 0-2 ºC, respectively. A significant cold bias (more than 3 ºC) is observed in the simulation with KUO and GRELL. As a whole, the model using GL_MO reproduces the surface temperature better compared to MIT and GO_ML in each of the three years.

Biases in the model simulated surface temperature over different homogeneous regions (Fig. 3) of India using all the schemes (Table II) are analyzed to examine the model performance over different parts of India. It is clearly specified that the model shows a positive bias in the simulation with MIT in all the homogeneous regions except peninsular India in each of the three years. A significant negative bias is observed with KUO and GRELL over all of the homogeneous regions, with exception of 2008, when GRELL shows a slight warm bias over WCI. Although the signature of the positive/negative bias in the model simulated surface temperature over different regions varies form year to year, the detected magnitude of the bias is lower in GO_ML and GL_MO. No particular scheme has a better performance in all the regions. The model shows a better skill with GO_ML, GL_MO and MIT over NWI, CNEI SPI and NEI, respectively, irrespective of the years. Better performance is observed with GL_MO, GRELL and GO_ML in 2007, 2008 and 2009, respectively over WCI. Considering all the regions, the model performance is relatively better in the simulations with two mixed schemes, and specifically with GL_MO.

The Taylor diagram depicted in Figure 4 represents spatial correlation, standard deviation and RMSE between modeled and observed temperature (CRU). The design of the diagram considers the
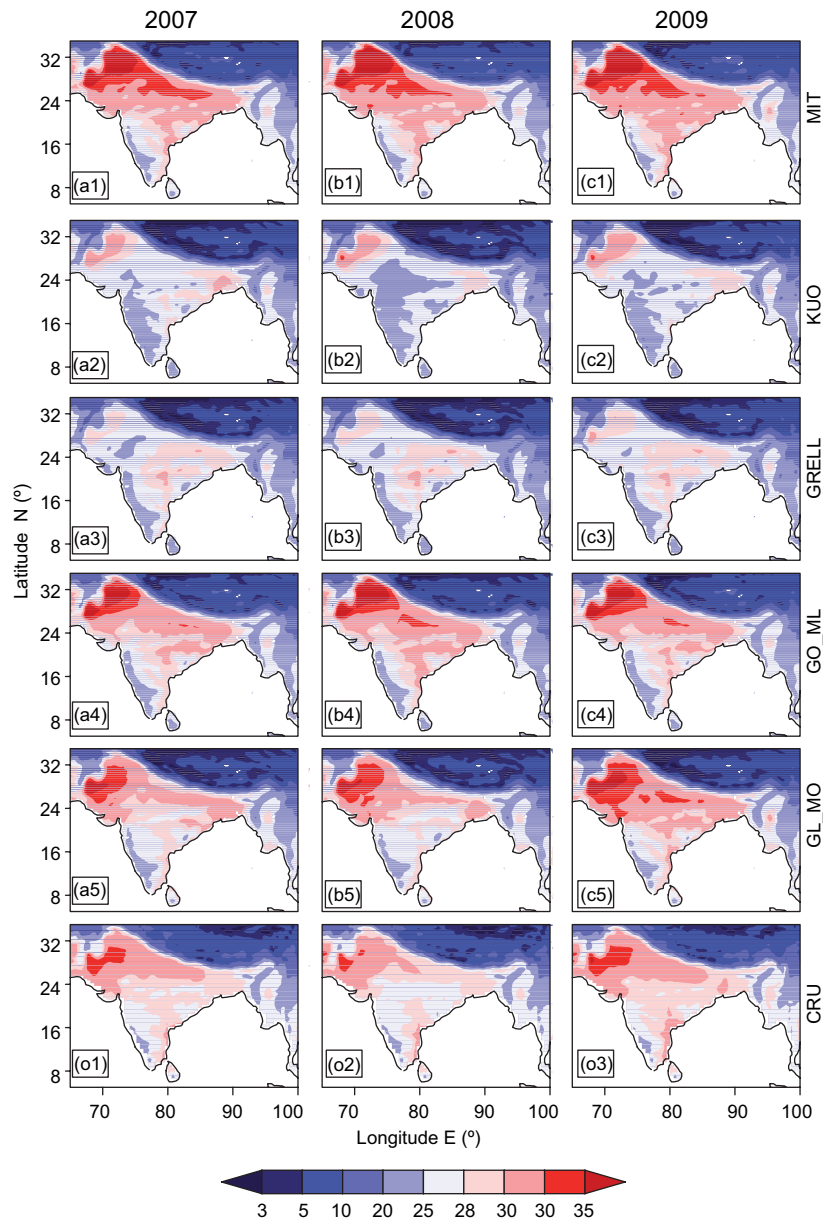
Fig. 2. JJAS averaged surface temperature (at 2 meter) for the year 2007, 2008, 2009 as obtained from model simulations and CRU dataset.

average of seasonal (JJAS) surface temperature for three years. It shows that the model performs reasonably well with all the CCS. The highest correlation (~0.97) and lowest RMSE (~2.1 ºC) are obtained using GL_MO, while the modeled standard deviation is almost equal to the observed one using KUO and GRELL. The other three schemes show a slightly higher standard deviation (7.5 ºC), which infers that spatial distribution and accuracy are better simulated

by the model with GL_MO followed by MIT and GO_ML, with slightly higher variations than the CRU observation.

Seasonally averaged (JJAS) sensible heat flux (SHF) simulated by the model using different convection schemes along-with NCEP/NCAR datasets is presented in Figure 5. A higher SHF is noticed in the model simulation with MIT and the two mixed schemes specifically over central and northwest
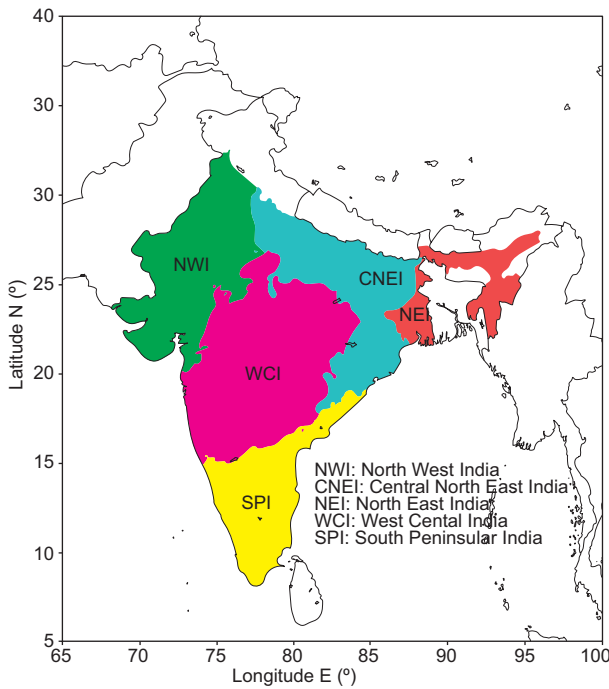
Fig. 3. Five homogeneous regions (Partahsarathi et al., 1994) over which performance of the convection schemes are evaluated.

India. The highest SHF is noticed using MIT, which may lead to model simulation of higher surface temperature with those schemes. A lower magnitude of SHF over Indian landmass is observed in the simulation with KUO, indicating lower surface temperature with that scheme. This result is consistent with an earlier study by Nayak et al. (2017). Analyzing seasonally averaged fractional cloud cover (figure not shown), it is observed that the model produces lower values using MIT compared with the other schemes. This indicates that a larger amount of solar radiation reaches the land surface and increases the SHF, which results in higher surface temperature in the model simulation with MIT.

The model-simulated monthly mean surface temperature for JJAS (figure not shown) in 2009 (a draught year) shows a weaker heat low located over a smaller area. This is in agreement with the IMD monsoon report for that year. Dynamics of the monsoon circulation mostly depend upon the land ocean temperature gradient over the Indian subcontinent during the monsoon period. To analyze this aspect, four grid boxes (based on Mohanty et al., 2002) are introduced as shown in Figure 6, Box1

Table II. Scheme-wise bias of surface temperature during 2007-2009 over different homogeneous regions.

	NWI	WCI	CNEI	SPI	NEI
2007					
MIT	−1.87	−1.45	−2.48	0.42	−1.11
KUO	4.12	2.43	2.31	2.86	1.34
GRELL	5.12	0.64	1.82	2.02	2.01
GO_ML	0.03	−0.57	−1.44	1.16	0.02
GL_MO	−0.47	0.34	−0.27	0.99	−0.38
2008					
MIT	−3.01	−2.40	−2.90	0.27	−0.69
KUO	3.97	3.10	2.33	2.88	1.78
GRELL	3.93	−0.01	1.11	2.25	2.44
GO_ML	−1.28	−1.66	−2.36	0.98	−0.02
GL_MO	−1.78	−0.18	−0.13	1.27	0.31
2009					
MIT	−1.62	−1.64	−1.93	0.11	−0.76
KUO	4.30	3.55	2.96	3.48	1.76
GRELL	4.64	1.13	2.21	2.47	2.65
GO_ML	0.05	0.14	−1.05	1.64	0.46
GL_MO	−1.39	−0.80	−1.14	0.92	−0.18

NWI: Northwest India; WCI: west central India; CNEI: central northeast India; SPI: south peninsular India; NEI: northeast India.
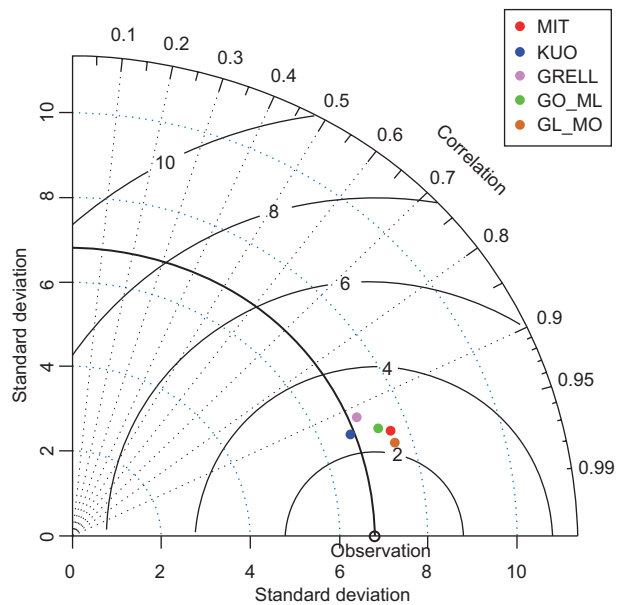

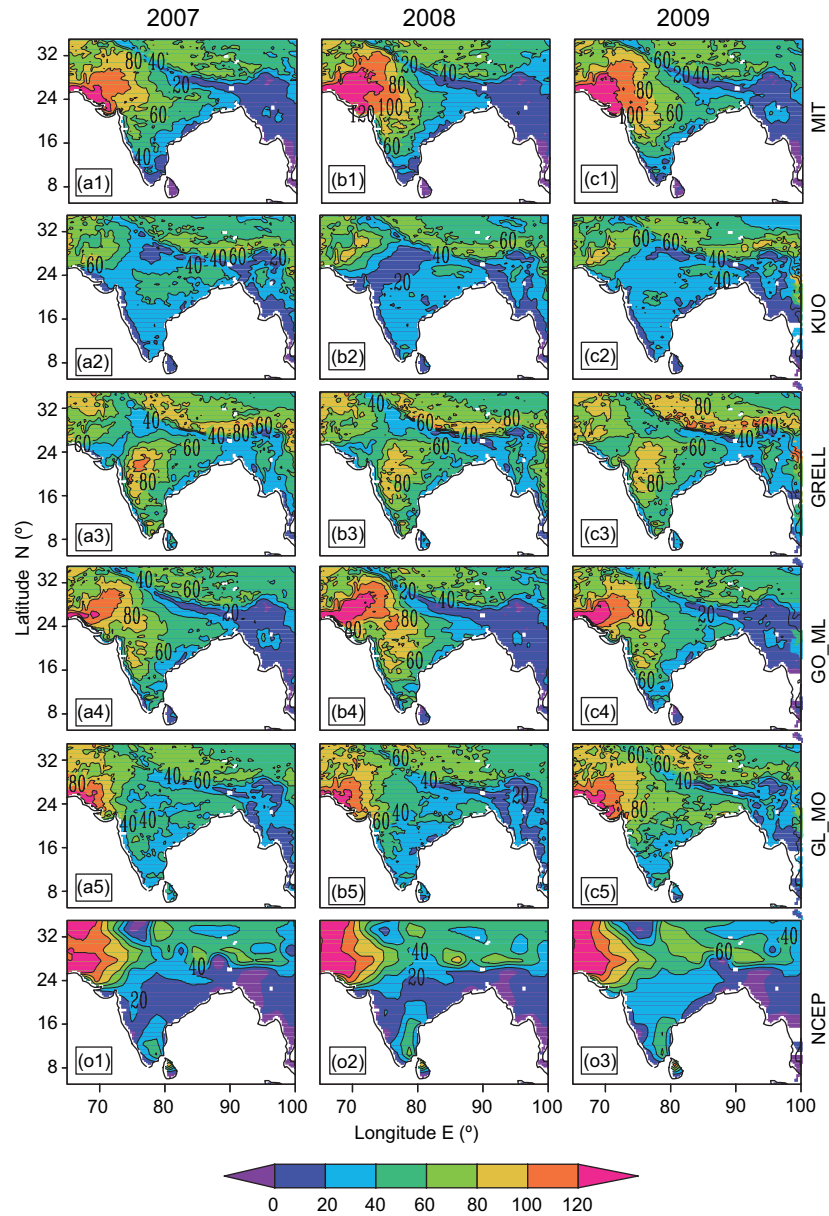Fig. 4: Taylor Diagram of JJAS surface temperature averaged for three years.

Fig. 5. JJAS averaged sensible heat flux (W/m²) for the year 2007, 2008, 2009
as obtained from model simulations and NCEP reanalysis dataset.

over NWI (70-75º E, 28-32º N), where the heat low dominates during monsoon season; Box2 over central India (72.5-82.5º E, 17.5-27.5º N); Box3 over the Arabian Sea (60-70º E, 10-20º N) near the east of Somalia coast, and Box4 over the Bay of Bengal (85-95º E, 10-20º N). The differences in the area averaged surface temperatures between these boxes in the month of May are computed and compared with NCEP/NCAR data due to non-availability of

CRU temperature data over the oceanic region. The temperature differences between Box1 and Box3 in 2007 (a normal monsoon year) and 2009 (a deficit monsoon year) are 5.19 and 5.11º C, respectively, in the simulation using MIT, whereas in the NCEP/ NCAR reanalysis datasets they are 3.27 and 3.28º C, respectively. This implies that the model is able to reproduce the temperature gradient for the two contrasting years better than NCEP datasets. The
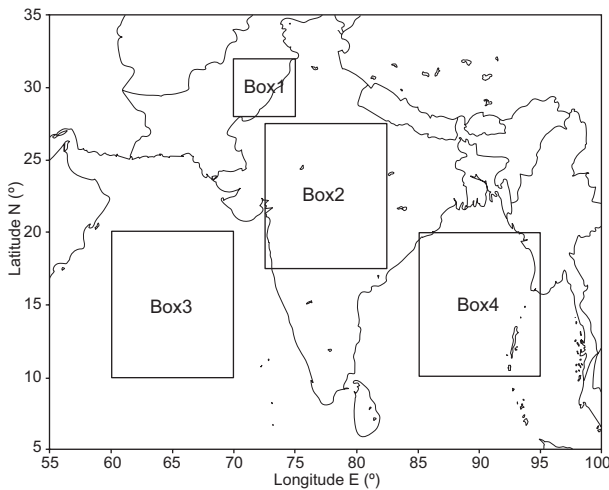
Fig. 6. Four grid boxes considered in calculating land ocean temperature gradient.

temperature difference between Box2 and Box4 in the simulation using MIT and NCEP data are 2.18º C, 5.2º C, respectively in 2007, and 4.44º C, 5.5º C, respectively in 2009, which clearly indicates that the temperature gradient between central India and the Bay of Bengal shows inverse relationship with that between NWI and the Arabian Sea in contrasting monsoon years.

3.2 Monsoon circulation
3.2.1 Low level winds (850 hPa)
Figure 7 presents the seasonal (JJAS) winds at 850 hPa computed from model simulations and NCEP/ NCAR reanalysis for the years 2007-2009. The three columns of Figure 7 represent the simulation in three different years while the six rows correspond to five CCS and the reanalysis datasets. The model is able to simulate low-level circulation features such as the Somali jet stream, strong westerly winds over the Arabian Sea, the cross equatorial flow, the westerly flow over Indian landmass, etc., in all of the years with all of the schemes. It is also worth to mention that the performance of RegCM4 in simulating low-level circulation is comparatively better with MIT than with other schemes. Although the model underestimates the strength of the winds over both land and ocean in every CCS, it is lower in MIT followed by GO_ML and GL_MO. KUO and GRELL produce significantly weaker (5-8 m s^{-1}) winds over the entire model domain.

In the year 2007, the strength of the Somali jet and cross equatorial flow are found to be 16 and 10 m s^{-1}, respectively, in the simulations with MIT, while the same are found to be 18 and 10 m s^{-1} in the NCEP reanalysis data and in the range of 8-12 m s^{-1} in all other schemes. The westerly flow over the Arabian Sea and southern peninsular India simulated by the model is weaker except with MIT. The flow over the Bay of Bengal is also reasonably well simulated by the model with MIT (maximum strength is ~10 m s^{-1}). Moreover, the area over which strong wind is simulated by the model agrees well with the reanalysis though the spatial extent differs.

The model exhibits similar performance in 2008 and 2009. However, the monthly average winds (figure not shown) for August and September 2009 show that the low-level wind is significantly weaker compared to that in 2007 in the simulation with MIT. The difference between model-simulated seasonal winds in 2007 and 2009 (figure not shown) shows that the strength of the Somali jet in 2009 is 2-3 m s^{-1} weaker than in 2007 in the simulation with MIT, GL_MO, and GO_ML. Another interesting fact to be mentioned here is that unlike the reanalysis datasets, RegCM4 with MIT could simulate stronger westerly winds over the Bay of Bengal in 2009 than in 2007 and 2008, which is consistent with the findings of Raju et al. (2010) and Mohanty et al. (2005). This indicates that the model with the above mentioned schemes could be able to simulate the differences in wind magnitudes during contrasting monsoon years. With GRELL and KUO, the model does not simulate this contrasting feature.

It is important to note that low-level winds in the RegCM4 simulation with all CCS is weaker compared to reanalysis data. In particular, the region of the south easterly flow before crossing the Equator shows smaller spatial coverage in the model simulation than in NCEP/NCAR data. This weaker wind flow favors a weaker Somali jet in the simulation, which may lead to less supply of moisture to the Indian landmass. Underestimation of low-level winds in the RegCM simulation is also observed and discussed in Sinha et al., 2013. In addition, a close inspection reveals that the circulation over central India shows an anti-cyclonic structure, which may hamper the moisture pulling mechanism from the neighboring ocean and lead to suppress the convective activity.