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Multi-ensemble regional simulation of Indian monsoon during contrasting rainfall years: role of convective schemes and nested domain

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Abstract Regional simulations of the seasonal Indian summer monsoon rainfall (ISMR) require an understanding of the model sensitivities to physics and resolution, and its effect on the model uncertainties. It is also important to quantify the added value in the simulated sub-regional precipitation characteristics by a regional climate model (RCM), when compared to coarse resolution rainfall products. This study presents regional model simulations of ISMR at seasonal scale using the Weather Research and Forecasting (WRF) model with the synoptic scale forcing from ERA-interim reanalysis, for three contrasting monsoon seasons, 1994 (excess), 2002 (deficit) and 2010 (normal). Impact of four cumulus schemes, viz., Kain–Fritsch (KF), Betts–Janjić–Miller, Grell 3D and modified Kain–Fritsch (KFm), and two micro physical parameterization schemes, viz., WRF Single Moment Class 5 scheme and Lin et al. scheme (LIN), with eight different possible combinations are analyzed. The impact of spectral nudging on model sensitivity is also studied. In WRF simulations using spectral nudging, improvement in model rainfall appears to be consistent in regions with topographic variability such as Central Northeast and Konkan Western Ghat sub-regions. However the results are also dependent on choice of cumulus scheme used, with KF and KFm providing relatively good performance and the eight member ensemble mean showing better results for these sub-regions. There is no consistent improvement noted in Northeast and Peninsular Indian monsoon regions. Results indicate that the regional simulations using nested domains can provide some improvements on ISMR simulations. Spectral nudging is found to improve upon the model simulations in terms of reducing the intra ensemble spread and hence the uncertainty in the model simulated precipitation. The results provide important insights regarding the need for further improvements in the regional climate simulations of ISMR for various sub-regions and contribute to the understanding of the added value in seasonal simulations by RCMs.

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1 Introduction

The dynamics and moist processes that occur during the Indian summer monsoon (ISM) are influenced by complex land–atmosphere–convection interactions, which make simulations, predictions and projections of monsoon challenging (Goswami 2005; Niyogi et al. 2010; Pathak et al. 2014). Realistic monsoon prediction for hydrological applications is necessary for planning and management of water resources in India. Efforts are underway to improve predictions using dynamical models that may have the ability to capture the interactions that occur during the monsoon (Chowdhary et al. 2014; Saha et al. 2014). Regional climate models (RCMs) are useful tools that can be used to further our understanding of these processes and might be useful for

seasonal monsoon predictions (Castro et al. 2012; Liu et al. 2016; Siegmund et al. 2015).

Recent literature has raised the question on the added value in the simulations of precipitation by RCMs to justify the high computational costs (Castro et al. 2007; Lo et al. 2008; Di Luca et al. 2012; Racherla et al. 2012; Xue et al. 2014; Singh et al. 2016). In the context of these studies principally over Americas, Europe, and African regions, the overall conclusions suggests that RCMs do not unequivocally add value to the global model outputs and the value addition seems to be contingent upon a number of factors like the variable, region, season, time scale and metrics of analysis. On the other hand, a group of studies identify the added value across multiple regional models in regions characterized by complex topography (Prömmel et al. 2010), or land ocean contrasts (Feser et al. 2011; Di Luca et al. 2013; De Haan et al. 2015). However, for India, the number of such analysis is limited. Recently, Singh et al. (2016) evaluated nine coordinated regional downscaling experiment (CORDEX) RCM outputs for Indian monsoon and did not find consistent improvements with respect to host global model outputs. This poses an interesting and important question regarding the future strategies need for dynamical downscaling and regional climate simulations over the Indian monsoon region.

Lucas-Picher et al. (2011) examined the ability of four RCMs to represent the Indian monsoon and found biases in temperature, mean sea level pressure and winds over the sea. The authors hypothesize that the missing processes and lack of representation of feedback in RCMs are the major causes for the bias. Representation of physical processes through parameterizations has been found to be a major source of model uncertainty for regional water budgets (Fersch and Kunstmann 2014). The dynamical models have been found to be especially sensitive to the representation of convection in the tropics (Rajendran et al. 2013; Zittis et al. 2014; Raju et al. 2015). The existence of multiple parameterization options for these physical processes in RCMs has led to identification of optimum parameterization combinations for different regions in the world. Even at seasonal scale different schemes are found to be realistic for different regions of the North American monsoon region (Xu and Small 2002; Liang et al. 2004), African monsoon region (Ratna et al. 2014; Flaounas et al. 2011), East Asian monsoon region (Choi et al. 2015) and Indian monsoon region (Mukhopadhyay et al. 2010; Srinivas et al. 2013). Whether the quest for the best parameterization combination is the meaningful approach is also under contention with some studies advocating the use of multi-physics and multi-model ensembles for added value (Kim et al. 2014; Klein et al. 2015; De Haan et al. 2015).

Indian monsoon simulations have been found to be highly sensitive to regional model domain size, especially with respect to the simulated hydrological cycle. Bhaskaran et al. (2012) found that the seasonal mean hydrological cycle and day-to-day precipitation variations over a smaller sub-region within the model domain are highly sensitive to domain size. This sensitivity contributes to the uncertainty in the simulated sub-regional precipitation over the Indian monsoon region. They concluded that the use of a single optimum RCM domain may not work for all sub-regions within the regional model domain for hydrological applications. They suggest that the use of large-scale nudging techniques that ensures consistency between forcing and regional models might be useful in this context. Spectral nudging for longer time scale simulations, introduced by von Storch et al. (2000), provides better conformity to the large scale and reduced distortion of large scale flows on interaction with RCM boundaries in regional model simulations. There is consensus on improved regional simulations of large scale patterns using spectral nudging in various studies from different parts of the globe (Miguez-Macho et al. 2004; Castro et al. 2005; Rockel et al. 2008; Perez et al. 2014). Modest improvements in finer scale surface variables, such as, precipitation at a seasonal scale are reported in some studies (Kanamitsu et al. 2010; Miguez-Macho et al. 2005). Bullock et al. (2014) found improvements in finer resolution simulations of precipitation over Central and Eastern United States only when some form of nudging is applied. For Indian monsoon, Paul et al. (2016) found improvements in climatology of regional simulations with the use of spectral nudging in WRF model.

Thus, evaluation of added value by a regional model, at seasonal scale, in conjunction with model uncertainties due to parameterizations, resolution and nudging techniques are necessary before application for seasonal prediction. A good regional prediction model for seasonal simulations should perform well under different interannual conditions such as surplus rainfall season, deficit rainfall season. The evaluation of RCMs using different parameterization combinations, understanding uncertainty and quantification of added value during different types of monsoon years are yet to be performed, and is undertaken in this study. The aim is to study the sensitivity of WRF simulated seasonal monsoon rainfall to cumulus and microphysics schemes for various sub-regions of the country for surplus, deficit and normal monsoon years. The effect of spectral nudging and finer resolutions on simulated sub-regional monsoon precipitation is also studied. Evaluation of RCM sensitivity to convective parameterizations for Indian monsoon in literature has focused on realistic simulations of monsoon climatology (Mukhopadhyay et al. 2010; Srinivas et al. 2013). The novelty of this work lies in evaluating RCM performance with respect to the large scale forcing data for contrasting monsoon years, with a view of application for seasonal prediction. The work helps to identify combination

of parameterizations that are able to capture the inter-annual variability in monsoon rainfall for different sub-regions and also to evaluate the performance of eight member multi physics ensemble for monsoon simulations.

2 Model configuration and data details

The Weather Research and Forecasting model (WRF) version 3.7 (Skamarock et al. 2008) is used for seasonal scale simulations of Indian monsoon. Experiments are undertaken for three contrasting monsoon years, 1994, an excess monsoon year, 2002, a deficit year and 2010, a normal rainfall year. For each year, the simulation is performed from May to October over a regional model domain covering the entire sub-continent (64.5°E–108°E, 8°S–43°N) at a horizontal resolution of 36 km with 30 vertical levels. Simulations using similar number of vertical levels have been found to show reasonable results for seasonal scale WRF simulations over the Indian and African monsoon regions by Mukopadhyay et al. (2010) (31 levels), Srinivas et al. (2013) (28 levels), Flanous et al. (2011) (28 levels), Ratna et al. (2014) (28 levels). Pohl et al. (2011) conducted sensitivity experiments over the east African monsoon region for a monsoon season (1999) using 28 and 35 model vertical levels and did not observe significant added value on increasing the number of vertical levels. However, a few researchers have used larger number of vertical levels for monsoon simulations over the African and North American monsoon regions, viz., Fersch and Kunstmann (2014) (40 levels), Racherla et al. (2012) (45 levels). To understand the impact of higher vertical resolution on simulated seasonal rainfall over the Indian monsoon region, we have performed some additional simulations using 42 vertical levels, spaced closer together in the planetary boundary layer.

The domain of 36 km spatial resolution is shown in Fig. 1a. The model is provided lateral boundary and initial conditions using the European Centre for Medium Range Weather Forecast (ECMWF) ERA Interim reanalysis data at 0.75° resolution (Dee et al. 2011). For regions where the model does not show a consistent improvement across all the three different years, additional experiments were conducted to study the value of utilizing nested domain simulations at a finer resolution of 12 km (shown in Fig. 1b–d). To study the sensitivity to convection and cloud physics, we perform simulations using the eight possible combinations of four cumulus and two microphysics parameterizations for all the 3 years. To analyze the effect of spectral nudging, the simulations are further conducted with and without spectral nudging. In both sets of simulations (with and without spectral nudging), we use lateral boundary nudging through a buffer zone of five grid points. In the simulations with spectral nudging, in addition to the lateral

boundary conditions, the large scale variability (~1500 km or higher) of the regional model simulated temperature and winds above the planetary boundary layer are nudged towards that of the forcing data. Spectral nudging is applied so as to not hamper the boundary surface forcing, as was performed by Miguez-Macho et al. (2004) and Paul et al. (2016). Thus for the different monsoon regimes, a total of 96 numerical experiments are conducted, 48 each at 36 km (48 experiments for 3 years × 8 combinations × 2 nudging) and 12 km resolutions (48 experiments for 3 years × 4 combinations × 4 regions).

The cumulus schemes tested in this study are those typically used in the WRF model simulations over the Indian monsoon region. These schemes include, Kain–Fritsch (KF), Betts–Janjić–Miller (BMJ), Grell 3D (G3) and the modified Kain–Fritsch (KFm). The KF scheme is a dynamic mass flux scheme that uses a plume model to calculate the mass transfer in updrafts and downdrafts from one vertical model level to the next. The KF scheme uses a convective adjustment time scale, τ, as the time over which the convective available potential energy (CAPE) is reduced to stabilize the atmosphere. The scheme calculates τ based on the mean horizontal tropospheric wind speed and grid resolution, with an upper limit of 1 h and lower limit of 0.5 h (Kain and Fritsch 1993; Kain 2004). BMJ scheme is a static scheme that is based on the final atmospheric state after convection occurs, and adjusts the model field towards a base state based on the background convection neutral atmospheric state (Betts and Miller 1986). The scheme uses a relaxation time τ, that is dependent upon cloud efficiency, for the adjustment. The cloud efficiency is defined based on the mean cloud temperature and entropy change. In this scheme τ varies from 4285s (minimum cloud efficiency) to 3000s (maximum cloud efficiency) (Janjić 1994). Both these schemes have been widely used for longer time scale simulations in the tropics. Grell 3D is an improved version of the Grell–Devenyi ensemble scheme, designed to work for relatively finer resolutions as well. The ensemble convective parameterization scheme uses a variety of closure assumptions and parameters to model the mean model convective tendency (Grell and Devenyi 2002). The modified KF scheme is a new addition in WRFv3.7 and introduces scale dependency to the original Kain–Fritsch parameterization (Zheng et al. 2016) and has not been tested for the ISM region. KFm scheme uses a grid resolution dependent dynamic formulation for the adjustment timescale τ. A scaling parameter, β, is introduced into the timescale formulation of the KF scheme. For a 25 km grid β value becomes 1, while for a 1 km grid it would be four times larger (Zheng et al. 2016). However, the modification of cloud radiation feedback possible with this scheme is not considered in this study as its baseline performance over the ISM region is still being established (Yue Zheng, Personal Communication, 2016).
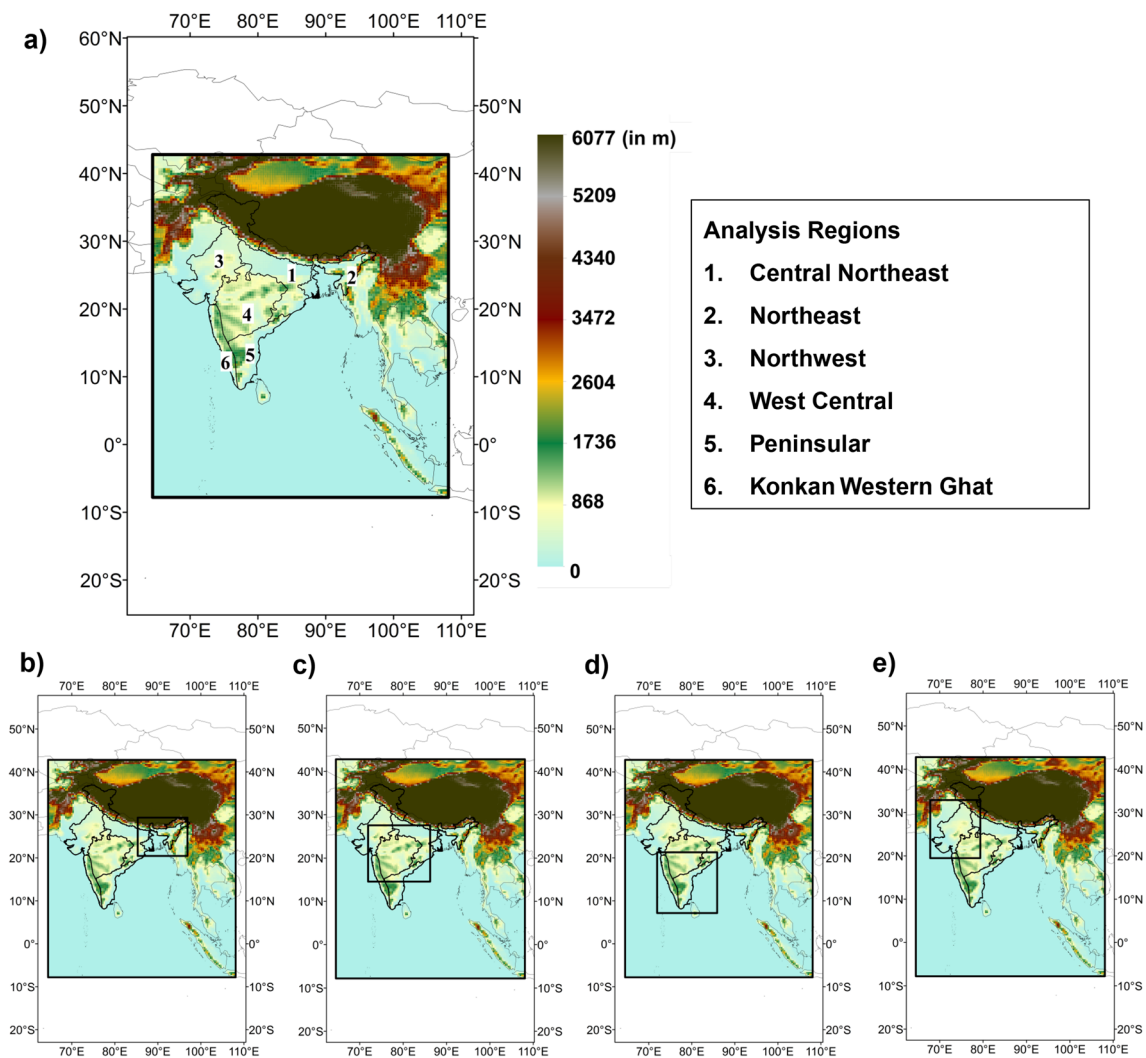
Fig. 1 **a** WRF single domain at 36 km resolution used for seasonal scale monsoon simulations and the sub-regions used for analysis. The *shading* shows terrain elevation in meters, **b–e** WRF nested domain configurations used for finer resolution simulations showing domains 1 (36 km) and 2 (12 km) with the nested domains centered over Northeast, West Central, Peninsular and Northwest sub-regions, respectively

The microphysics schemes, considered here, are WRF Single Moment Class 5 scheme (WSM5) and Lin et al. (1983) scheme (LIN). Both microphysics parameterizations are single moment schemes that predict the particle mixing ratios of hydrometeors. The experimental setup used in this study does not consider simulations with double moment microphysics schemes because in the preliminary runs, microphysics schemes had a relatively lower influence on the simulated monsoon rainfall at seasonal scale. In particular the double moment Thompson microphysics scheme did not show markedly different results from the single moment schemes used. The fixed parameterizations used for all simulations are Yonsei University Scheme (YSU) Planetary Boundary Layer, Community Land Model 4 (CLM4) land surface, Rapid Radiative Transfer Model (RRTM, Mlawer

et al. 1997) for longwave and Dudhia (Dudhia 1989) short-wave radiation schemes. We use CLM4 to represent land surface as the model has been found to provide a reasonable representation of land processes during the summer monsoon in coupled land–atmosphere simulations of the Indian monsoon (Paul et al. 2016; Halder et al. 2016). The fixed parameterization schemes selected, especially the planetary boundary layer schemes used (Klein et al. 2015; Qian et al. 2016), may also have an impact on the results. Due to computational constraints, we limit this study to documenting the impact of change in cumulus microphysics schemes, spectral nudging and model resolution on the monsoon rainfall.

Simulated sub-regional monsoon rainfall is evaluated against observations and this is further compared with the

same from the reanalysis data over the homogeneous meteorological regions as identified by the India Meteorological Department (IMD). IMD gridded rainfall data at 0.25° resolution is used as the observed rainfall data for the analyses. In addition to the IMD climate regions, the Konkan Western Ghat belt is treated as a separate region due to its complex topography and different monsoon rainfall features from the rest of peninsular India. This sub-region is also of interest as a preliminary review of number of prior studies over the ISM domain suggests there is a larger uncertainty in simulating the rainfall over the Konkan Western Ghat region particularly when using the WRF model. The sub-regions, used for the analysis of monsoon rainfall, are shown in Fig. 1a. The errors in seasonal totals and the differences in the spatial and temporal variability of regional monsoon rainfall are the metrics used for evaluation. The evaluation of sub-regional seasonal rainfall patterns is sufficient to assess model applicability for seasonal monsoon prediction, as it considers the spatio-temporal variability of rainfall.

3 Results and discussions

First the comparison of regional model simulated synoptic scale monsoon circulations with that of the large scale forcing data are presented. This is followed by discussion of the "added value" in the WRF simulated sub-regional monsoon rainfall, which is the major focus of this analysis. The WRF simulated precipitation is compared with observations and also with precipitation from the forcing reanalysis, to quantify the added value in regional simulations. The regional modeling is considered to have "added value" if the errors in simulated sub-regional precipitation characteristics are consistently (across the 3 years) lower than the errors in the same from forcing reanalysis data. The spread of the eight member physics ensemble is used to quantify the uncertainty in model simulations.

3.1 Large scale circulation

Model simulated 2 m air temperature (T2m) and mean sea level pressure (MSLP) are compared against the large scale features of the forcing model in Fig. 2. The simulated seasonal mean large scale features are more sensitive to the use of spectral nudging than the change of model physics. The fields in Fig. 2 have been averaged over the eight different cumulus-microphysics parameterization combinations to portray the effect of spectral nudging. The comparison shows that WRF simulations without nudging show positive deviations in T2m and negative deviations in MSLP, especially over Northern India. The ensemble mean shows a 3 year mean bias of +1.15 K (RMSE = 2.05 K) in T2m and −2.81 hpa (RMSE = 3.12 hpa) in MSLP over a box over

the North Indian subcontinent (20°–30°N, 65°–90°E). This strengthening of monsoon trough seen in WRF simulations without the use of spectral nudging is also associated with a stronger monsoon flow. Supplementary Figure S1 shows the comparison of vertically integrated moisture transport from WRF simulations with that from the forcing data. The deviations of T2m and MSLP over the Indian monsoon region seen in the simulations in this study are broadly representative of previous studies using other regional climate models as well (Saeed et al. 2009; Lucas-Picher et al. 2011). The use of spectral nudging helps to reduce this bias in large scale circulation for all combination of parameterizations tested. The ensemble means of simulations using spectral nudging exhibit a 3 year mean bias of +0.09 K (RMSE = 1.46 K) in T2m and +0.20 hpa (RMSE = 0.71 hpa) over the North Indian subcontinent (20°–30°N, 65°–90°E). The comparison of upper level circulation features is beyond the scope of this study because spectral nudging is employed to maintain consistency in large scale variability of winds and tropospheric temperature above the planetary boundary layer. Indeed the improvements within the boundary layer do influence the regional and mesoscale feedbacks and the nudging technique appears to be effective in reducing deviations of surface level large scale patterns as well.

3.2 Precipitation

Before analyzing the sub-regional rainfall characteristics to identify the added value by the regional model, the spatial pattern of errors in simulated rainfall over India is examined. Figure 3 compares the errors in seasonal (JJAS) total rainfall from WRF simulations with the same from the forcing reanalysis. The errors are computed with respect to the IMD gridded data. The seasonally averaged WRF simulations remain almost the same across all the microphysics schemes and they are only sensitive to the selection to cumulus scheme. Therefore, only the cases for different cumulus scheme with the average across microphysics schemes are presented.

The spectrally nudged WRF simulations generally show lower errors than the simulations without nudging. Further, the nudged simulations show a spatial consistency of errors across the cumulus schemes. For example, all the nudged simulations for wet year 1994 exhibit a dry bias in seasonal rainfall over West Central India, but of varying magnitudes. The underestimation of year 1994 monsoon rainfall in West Central India exists in forcing data ERA as well (shown in Fig. 3a1), which the WRF simulations with nudging do not completely eliminate. The simulations without the use of nudging show a variable pattern of errors, with areas of high positive and negative errors. The improvements in simulated rainfall achieved through the use of spectral nudging are more clearly visible during years 2002 (deficit) and 2010
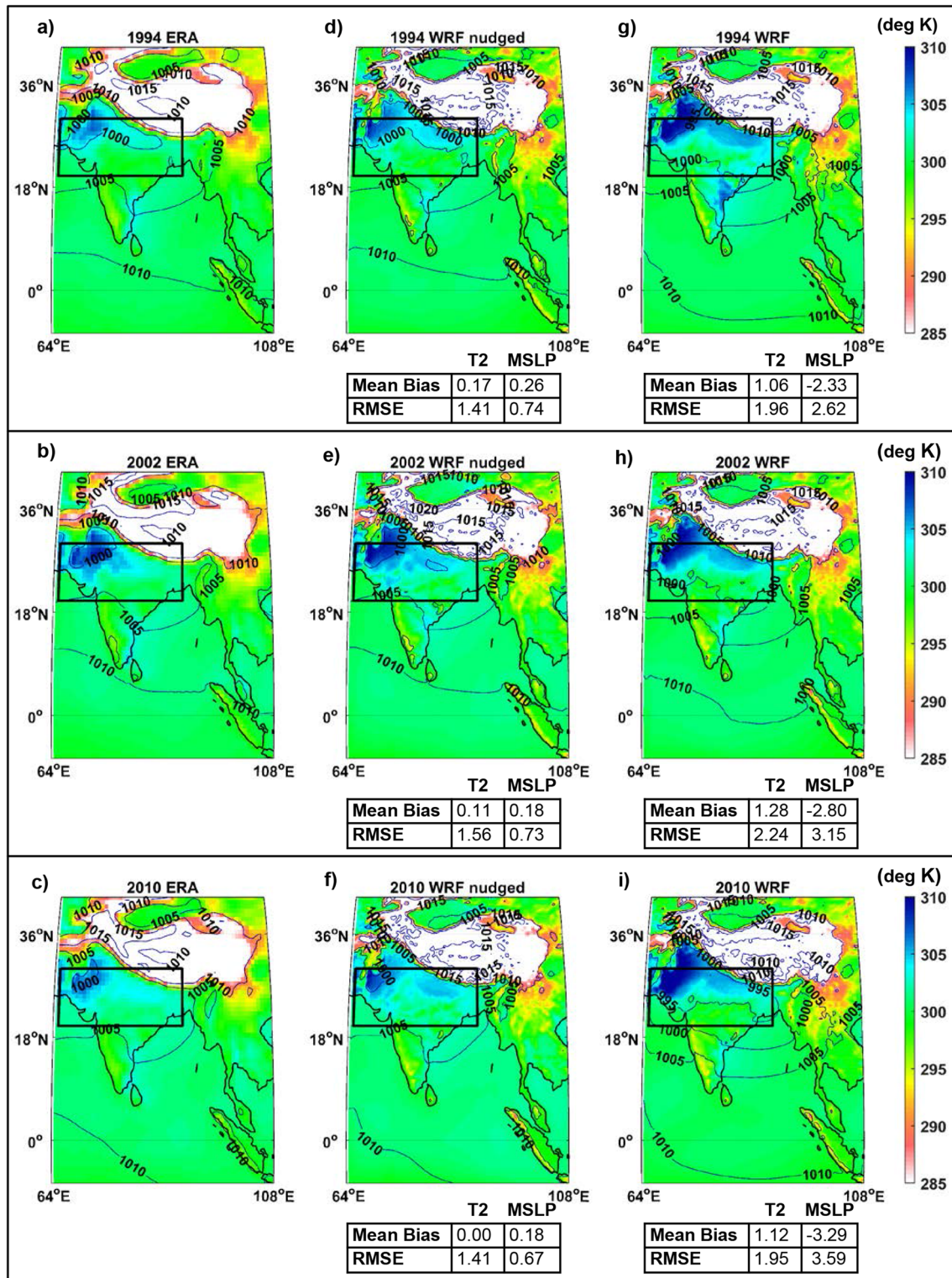
Fig. 2 Comparison of the large scale patterns of 2 m air temperature, T2m in K (*shading*) and mean sea level pressure, MSLP in hpa (*contours*) from forcing reanalysis and regional model simulations, **a–c** ERA T2m and MSLP for 1994, 2002 and 2010, **d–f** WRF nudged 8 member physics ensemble mean T2m and MSLP for 1994, 2002 and 2010, **g–i** WRF 8 member physics ensemble mean T2m and MSLP for 1994, 2002 and 2010. The mean bias and root mean square error (RMSE) of simulated T2 (in K) and PMSL (in hpa) over a *box* over Northern India (20–30N, 65–90E) are shown in the figure. WRF without overestimates T2 (average mean bias 1.15 K) and underestimates MSLP (average mean bias −2.80 hpa); spectral nudging reduces the bias for all 3 years

(normal). For these 2 years, the nudged simulations show lower errors all over the Indian landmass compared to their non-nudging counterparts. Looking at the general behavior of specific schemes, we find that the G3 scheme largely over-estimates precipitation over areas of orographic precipitation like the west coast (Konkan Western Ghat region) and Himalayan foot hills. The larger errors in simulations using G3 scheme may be partially improved using higher vertical resolution. A few additional simulations have been performed using 42 vertical levels spaced closer together in the PBL, for the 3 years and four convective parameterizations (12 simulations for 3 years×4 parameterizations). For simulations using KF, KFm and BMJ schemes, the increase in vertical resolution does not show significant added value for mean seasonal rainfall. However, simulations using the G3 scheme, especially over Konkan Western Ghat and Northeast regions, show reduction of errors compared to simulations using 30 vertical levels (Supplementary Figure S4). KF, BMJ and KFm schemes show more reasonable patterns of errors, that is, similar to errors in the forcing data ERA. The rainfall from ERA shows larger errors over regions of higher monsoon rainfall—the west coast, central India and Northeast India, for all the 3 years, 1994, 2002 and 2010. In the following section, the performance of WRF simulations using individual schemes and multi-physics ensemble on a sub-regional scale is evaluated.

3.2.1 Region averaged rainfall errors from simulations at 36 km resolution

Figure 4 shows the errors in average regional monsoon rainfall from the WRF simulations at 36 km spatial resolution. The errors are computed with respect to observed IMD rainfall data and compared to the errors of the same in the forcing reanalysis. In Fig. 4, the errors in mean monsoon rainfall are grouped by simulations using specific schemes and nudging techniques. For each cumulus scheme (KF, BMJ, G3, KFm) there are four data points, two from simulations using spectral nudging and two from simulations without nudging. For each microphysics scheme (WSM5, LIN) there are eight data points, four from simulations using nudging and four from simulations without nudging. The number of data points may appear fewer in some cases due to overlap of circles representing very close data points. From Fig. 4, in all sub-regions, a larger spread of rainfall errors are seen across cumulus than microphysics schemes. Thus the simulated sub regional monsoon rainfall is more sensitive to cumulus than microphysics schemes. Table 1 shows the changes in sub-regional precipitation (in mm/season) arising from change of cumulus and microphysics schemes for the 3 years. In case of microphysics, the changes are calculated as the difference of average precipitation from WRF simulations using WSM5 and LIN schemes. For cumulus schemes

the changes presented are the average difference in simulated precipitation of all six combinations of cumulus scheme pairs. The uncertainty in sub-regional seasonal rainfall associated with the change of microphysics scheme is low, typically accounting for 2–8% of mean seasonal rainfall for all years and sub-regions. The uncertainty in sub-regional rainfall due to change of cumulus scheme are much higher (range of 12–165%) and shows large variation across sub-regions and years. Table 1 also includes the uncertainty in the simulated rainfall values as percentages of the observed seasonal rainfall, to highlight the magnitude of the parameterization induced spread relative to the seasonal rainfall.

We compared the convective/total seasonal (JJAS) rainfall ratios during 2002 and 2010 summer monsoon with TRMM 3A25 data and found that the simulations using spectral nudging generally overestimates this ratio by 15–20%. The simulations without nudging are closer to observed proportions (Supplementary Table S1). However, the spread of sub-regional rainfall associated with change of microphysics scheme remains similar for both sets of simulations (Table 1).

In general, it is found that the use of spectral nudging reduces the intra-ensemble spread of model simulated seasonal rainfall; however, the Peninsular India stands out as an exception. The reduction in model spread is due to the elimination of deviations of regional model simulated large scale circulation, leading to better consensus among simulations. Unconstrained model simulations using different physics show intra-ensemble differences in large scale circulation patterns (not shown) which are largely eliminated using nudging. This contributes to reduction of model spread. Hence, the use of nudging constrains the ability of model physics to generate variability in temperature and winds above the planetary boundary layer on a large scale (>1500 km in this study), while allowing for variability and hence differences on smaller scales. It is found that over most of the sub-regions, this has translated to a reduction of spread in model simulated rainfall as well.

The added value in simulated sub-regional precipitation by the regional model is evaluated next. In the Central Northeast sub-region improvements are noted in model simulated seasonal precipitation compared to forcing data ERA (Fig. 4d–f). WRF simulations using the KF scheme and the eight member physics ensemble mean show consistently (for the 3 years) lower errors in simulated monsoon rainfall compared to ERA. Precipitation from ERA shows larger errors over this region and fails to capture inter annual variability of observed monsoon rainfall. ERA underestimates the wet year seasonal rainfall, and overestimates the dry and normal year seasonal totals. The WRF ensemble mean and individual simulations using the KF parameterization scheme capture the wet year better and improves upon the simulated inter annual variability for these 3 years (Fig. 4d–f). The
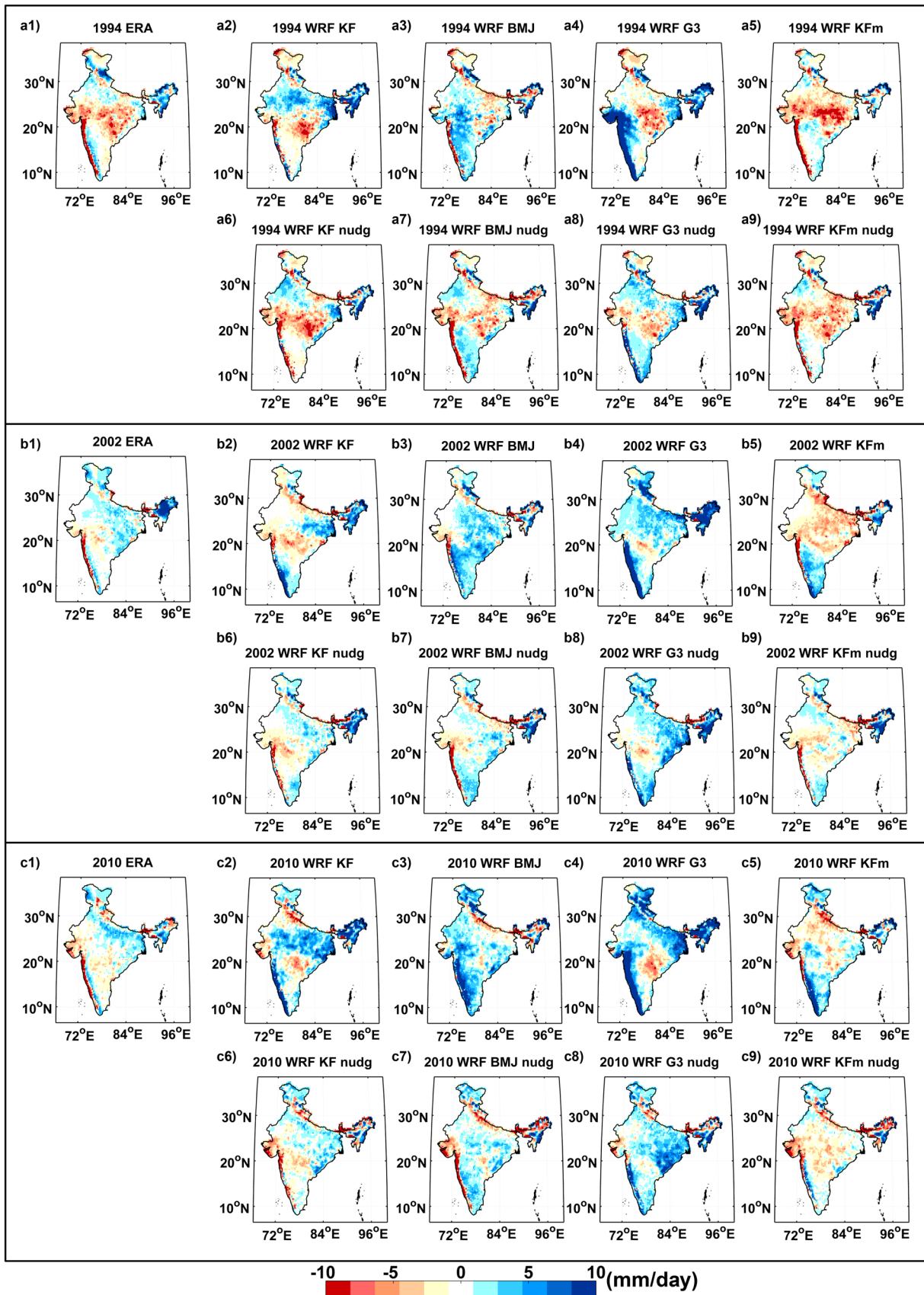
◄**Fig. 3** Errors in seasonal (JJAS) total rainfall with respect to IMD gridded data from ERA and WRF simulations, for years 1994, 2002 and 2010 in mm/day. The WRF simulated rainfall is averaged across microphysics schemes and presented separately for each cumulus scheme (KF, BMJ, G3, KFm) **a1–c1** ERA-IMD JJAS rainfall, 1994, 2002, 2010, **a2–a5** WRF-IMD JJAS rainfall 1994, **a6–a9** WRF nudged-IMD JJAS rainfall 1994, **b2–b5** WRF-IMD JJAS rainfall 2002, **b6–b9** WRF nudged-IMD JJAS rainfall 2002, **c2–c5** WRF-IMD JJAS rainfall 2010, **c6–c9** WRF nudged-IMD JJAS rainfall 2010

nudged WRF simulations show similarity in the order of cumulus schemes with respect to simulated seasonal rainfall magnitude across the 3 years. The order of cumulus schemes for mean seasonal rainfall in descending order for this region is G3 > KF > BMJ > KFm. The Central Northeast sub-region includes the Ganga basin which is known to be a region of strong land–atmosphere coupling (Koster et al. 2004; Pathak et al. 2014). It is speculated that the value addition seen in Central Northeast sub-region is due to better representation of land atmospheric interaction in the regional model (Zheng et al. 2015).

WRF simulations in the Northeast region does not show consistent added value over the forcing data (Fig. 4g–i). The performance of the ensemble as a whole mirrors the pattern of errors in the ERA rainfall, where simulations for years 1994 and 2002 show an overestimation and year 2010 is near zero error. The individual simulations and the physics ensemble mean do not consistently add value over the large scale forcing data. The order of cumulus schemes for seasonal mean rainfall in descending order for this region is G3 > KF > BMJ or KFm. Previous studies have noted that the rainfall over northeast part of India shows an out of phase active-break relationship with the rainfall over central and western India (Dhar and Nandhargi 2000; Goswami et al. 2010). Most of the extreme rainfall events in this region are found to occur with the monsoon system. Goswami et al. (2010) found the monsoon extreme rainfall events in this region to be the result of complex multiscale interactions of the circulation with the local topography. Similarly Medina et al. (2010) show that even under regions of complex topography, the land surface representation and feedbacks could also be an important modulator. Present results also lead to the conclusion that the use of a very high resolution model may be required to capture the observed interactions. This could be the reason for the lack of value addition for this sub-region, seen in the simulations. Here it can be stated that better resolved topography gradients (as is the case in WRF vs ERA) are not sufficient to guarantee added value in regional simulations. This finding is also consistent with Srinivas et al. (2015). They report a lack of value addition in onset phase monsoon rainfall over this sub-region.

From Fig. 4j–l, it is seen that over the Northwest India, the general pattern of seasonal rainfall from the nudged WRF multi-physics ensemble mirror the forcing data. Simulations

for years 1994 and 2010 underestimate the seasonal rainfall while that for year 2002 is having around zero error. In terms of consistent improvements in seasonal rainfall, there was no evidence for added value in WRF simulations with respect to forcing reanalysis in this region. The cumulus schemes in a descending order of mean seasonal rainfall simulated in this region is similar to Central Northeast and Northeast regions, i.e., G3 > KF > BMJ or KFm.

The forcing reanalysis data exhibits large negative error (2.9 mm/day on average or 354 mm over the entire season) over the West Central region in the excess monsoon year 1994 (Fig. 4p–r). WRF simulations using specific schemes (BMJ, G3) are able to improve upon this error with around 50% reduction in underestimation. But these simulations fail to show consistent improvements across all the 3 years tested. The ensemble mean precipitation adds value to seasonal totals of 1994 and 2010 as shown in Fig. 4p–r. For the year 2002, ERA interim rainfall is very close to observed (Model—Obs error of −0.2%) and it might be unreasonable to expect added improvements through regional modeling. The WRF ensemble mean exhibits a Model—Obs error of −8% in seasonal total over this region during 2002. Thus the nudged WRF simulations fail to show consistent improvements over the forcing reanalysis in this region. The hierarchy of cumulus schemes for seasonal mean rainfall in a descending order over the West Central region is different from the northern regions, and it is G3 or BMJ > KF or KFm. The changes of the above mentioned order across regions probably attribute to the geographical features such as homogeneity, orography etc. of the region.

WRF simulations over the Peninsular region overestimate monsoon rainfall for all the 3 years (some individual seasonal simulations show exceptions), and the overestimation is visible in ensemble means as well (Fig. 4m–o). Individual simulations using KF and KFm cumulus schemes show lower errors in seasonal totals during the years 1994 and 2010. The observed sub-regional rainfall during the deficit monsoon year 2002 is very low (233 mm), and ERA and WRF simulations show large overestimation for this particular year. The observations show near zero monsoon rainfall in many grid points across this region, which the model fails to capture. Thus our analysis does not show added value through consistent improvements in regional simulations over this region. The hierarchy of cumulus schemes for mean sub-regional monsoon rainfall in a descending order over Peninsular region is similar to that of West Central region with G3 or BMJ > KF or KFm.

In the Konkan Western Ghat sub-region, simulations using the KFm scheme and physics ensemble mean with spectral nudging are found to consistently improve upon the errors in ERA rainfall (Fig. 4s–u). ERA underestimates the rainfall over Konkan region for all the 3 years tested; the underestimation is reduced in WRF simulations. The order
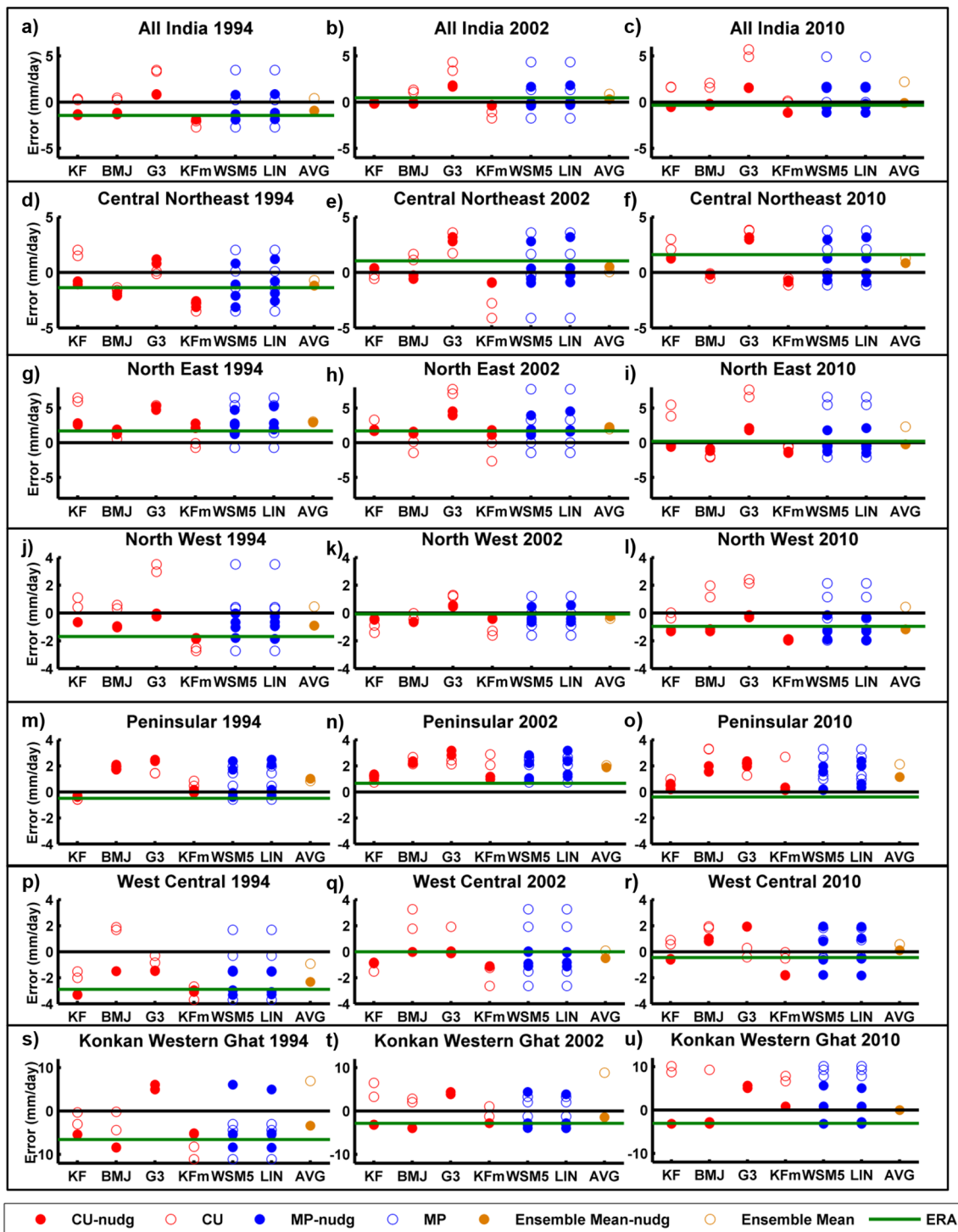
Fig. 4 Comparison of errors in seasonal (JJAS) total rainfall from ERA forcing data (*green line*) and 36 km regional model simulations (*circles*) for 1994, 2002 and 2010. The simulations using different schemes and spectral nudging as well as the physics ensemble mean are represented separately for each sub-region. **a–c** All India, **d–f** Central Northeast, **g–i** Northeast, **j–l** Northwest, **m–o** Peninsular, **p–r** West central, **s–u** Konkan Western Ghat. For each cumulus scheme (KF, BMJ, G3, KFm) there are four data points, two from simulations using spectral nudging (*filled red circles*) and two from simulations without nudging (*open red circles*). For each microphysics scheme

(WSM5, LIN) there are eight data points, four from simulations using nudging (*filled blue circles*) and four from simulations without nudging. The number of data points may appear fewer in some cases due to *overlap of circles* representing very close data points. Subplots **s–u** do not show the without nudging simulations using G3 scheme as these errors are much higher that the y-axis scale. Consistent reduction of errors in RCM simulated rainfall over forcing reanalysis is visible in Central Northeast (KF and Ensemble mean) and Konkan Western Ghat (KFm and Ensemble mean) sub-regions, for simulations with spectral nudging

Table 1 The differences in WRF simulated sub-regional rainfall associated with change of cumulus and microphysics parameterizations for years 1994, 2002 and 2010 in mm/season

	1994		2002		2010	
	Nudged	w/o nudging	Nudged	w/o nudging	Nudged	w/o nudging
All India						
Cumulus	167 (18%)	352 (37%)	129 (19%)	349 (50%)	168 (19%)	324 (36%)
Microphysics	12 (1%)	25 (3%)	14 (2%)	12 (2%)	11 (1%)	41 (5%)
Central Northeast						
Cumulus	257 (24%)	328 (31%)	255 (31%)	409 (50%)	265 (34%)	342 (43%)
Microphysics	44 (4%)	8 (1%)	25 (3%)	43 (5%)	4 (0%)	34 (4%)
Northeast						
Cumulus	213 (18%)	492 (43%)	176 (12%)	597 (39%)	215 (15%)	664 (46%)
Microphysics	23 (2%)	24 (2%)	43 (3%)	101 (7%)	20 (1%)	21 (1%)
Northwest						
Cumulus	110 (16%)	364 (51%)	72 (28%)	184 (71%)	104 (16%)	293 (44%)
Microphysics	5 (1%)	19 (3%)	5 (2%)	17 (6%)	4 (1%)	48 (7%)
Peninsular						
Cumulus	206 (65%)	164 (52%)	139 (60%)	93 (40%)	145 (26%)	175 (31%)
Microphysics	26 (8%)	5 (2%)	30 (13%)	15 (6%)	46 (8%)	16 (3%)
West Central						
Cumulus	144 (13%)	328 (30%)	85 (12%)	314 (44%)	258 (28%)	149 (16%)
Microphysics	3 (0%)	6 (1%)	1 (0%)	44 (6%)	7 (1%)	30 (3%)
Konkan Western Ghat						
Cumulus	852 (43%)	3114 (157%)	498 (41%)	1766 (147%)	596 (37%)	2655 (165%)
Microphysics	30 (2%)	365 (18%)	15 (1%)	90 (7%)	7 (0%)	130 (8%)

The values are represented as percentages of observed seasonal rainfall in brackets

of cumulus schemes in a descending order of simulated mean precipitation over Konkan region is G3 > KFm > KF or BMJ.

This sub-regional analysis reveals that regional model adds some value in two out of the six sub-regions over India, viz., the Central Northeast and Konkan Western Ghat. For the other sub-regions, we do not find added value in monsoon precipitation from the 36 km resolution model simulations. Over the Northeast and Northwest regions, the precipitation from the ensemble of WRF simulations, mirror the precipitation from ERA and IMD data. Over the West Central region the ensemble simulations are not able to match the very low error in precipitation from ERA in year 2002. Peninsular region is the only zone where the regional model simulations fail to improve upon large errors in the forcing reanalysis, particularly for dry year 2002.

We use Fig. 5 and Table 1 to understand the ensemble spread of simulated regional precipitation from the 36 km WRF simulations. The seasonal evolution of sub-regional rainfall cycle is presented in Fig. 5. A smoothened seasonal cycle using 15-day mean sub-regional rainfall, averaged over the eight member ensemble is shown, the shading represents the ensemble spread in sub regional rainfall. We use the 15-day mean to present the variations in the monsoon

seasonal cycle simulated by specific schemes, the daily temporal variability of rainfall is evaluated in Sect. 3.2.4. Temporal window smaller than 15 days may also be considered, however the same may not be sufficient to remove the high frequency variability to represent the smoothened pattern of precipitation. In line with the seasonal total rainfall, the change of microphysics scheme adds very little variability to the seasonal cycle (not shown).

From Fig. 5 it is noted that the use of spectral nudging results in reduction of intra-ensemble spread throughout the season, over all regions except Peninsular India. We find the effect of spectral nudging on regional precipitation in Peninsular India to be different from that in the other sub-regions; the nudged and without nudging simulations show comparable ensemble spreads in seasonal rainfall over this region. Over the sub regions Central Northeast, Northeast, Northwest and Konkan Western Ghat, the use of nudging achieves around two to threefold reduction of intra ensemble spread (Table 1). Over the West Central region, the use of spectral nudging shows reduction of ensemble spread in years 1994 and 2002. Nudged simulations of 2010 monsoon show more ensemble spread in terms of seasonal total (Table 1) but, the seasonal cycle however is more consistent with observations in the nudged simulations.
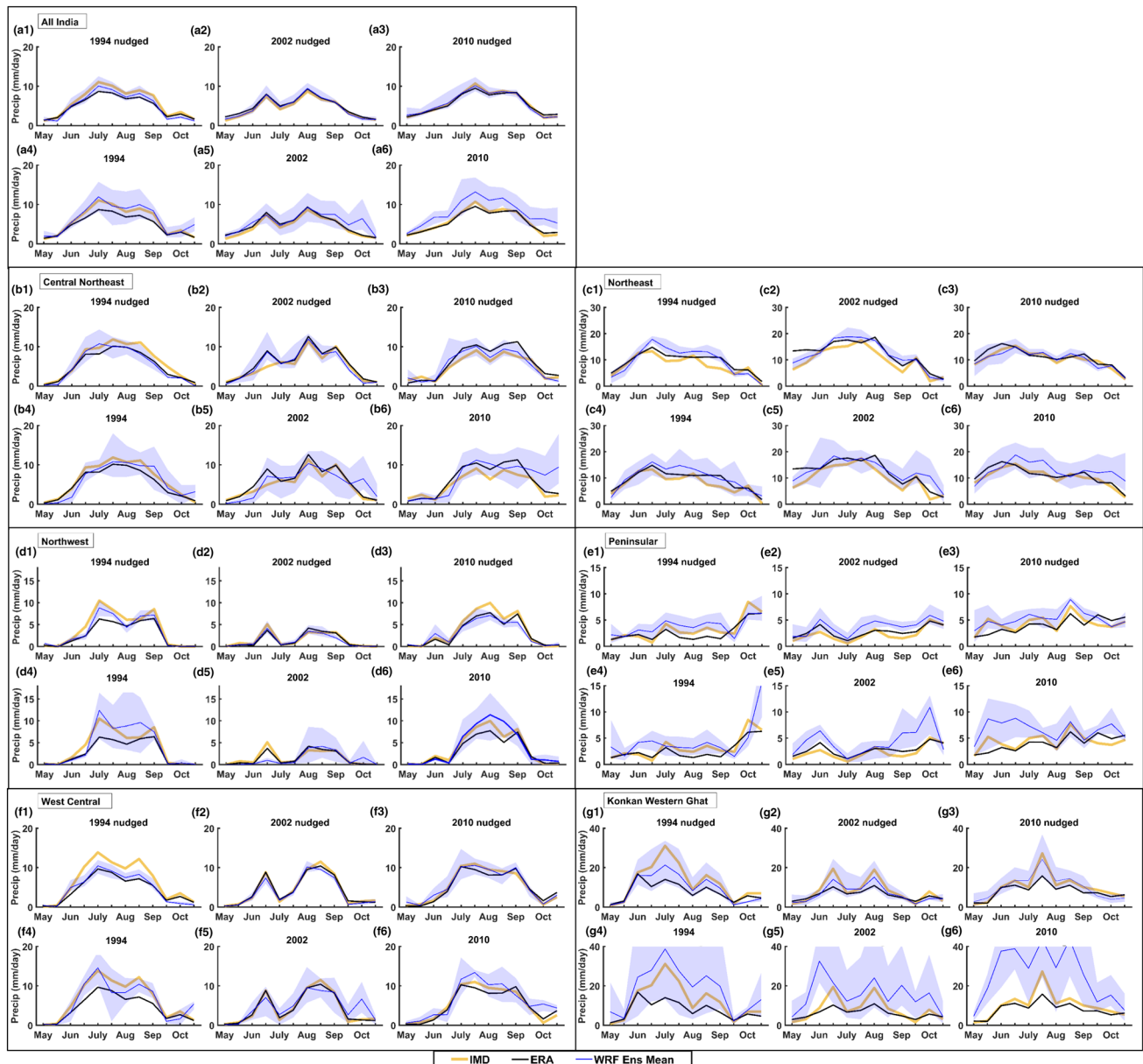
Fig. 5 Comparison of the seasonal cycle of region averaged rainfall (15 day mean) from forcing data ERA (*black*) and WRF eight member ensemble mean (*blue*) with IMD gridded observations (*yellow*) for each sub-region. The *shading* represents the ensemble spread. The plots are presented separately for simulations with and without spec-

tral nudging for years 1994, 2002 and 2010. **a1**–**a6** All India, **b1**–**b6** Central Northeast, **c1**–**c6** Northeast, **d1**–**d6** Northwest, **e1**–**e6** Peninsular, **f1**–**f6** West Central, **g1**–**g6** Konkan Western Ghat. Reduction of uncertainty in model simulated rainfall is visible in all sub-regions throughout the monsoon season for spectrally nudged runs

To understand if a further improvement in resolution helps to improve the simulations, nested domain for subregional simulations at a spatial resolution of 12 km are analyzed in Sect. 3.2.2.

3.2.2 Region averaged rainfall errors from simulations at 12 km resolution

The finer resolution simulations are performed at a spatial resolution of 12 km for nested domains over Northwest,

West Central, Peninsular and Northeast sub-regions. The domains used for these simulations are shown in Fig. 1b–e. The 12 km nested simulations have been performed for the four cumulus schemes for all the 3 years. The computational cost and the relatively low impact of microphysics schemes seen in the coarser resolution simulations discussed in previous section are two main reasons for focusing only on the cumulus schemes.

Figure 6 shows the errors in seasonal rainfall from the 12 km nested WRF simulations for Northwest, West

Central, Peninsular and Northeast sub-regions. The errors in finer and coarser resolution simulations are compared using the same physics and dynamical configuration. Results indicate that simulations using specific parameterization schemes show consistent improvements in simulated seasonal rainfall in Northwest (Fig. 6d–f) and West Central (Fig. 6a–c) sub-regions, at this finer resolution. In the 12 km resolution simulations, the BMJ scheme perform well for the Northwest and KF scheme for the West Central sub-regions. In both the sub-regions, improvements are seen as reduction of errors in simulated monsoon rainfall. In Northwest and West Central regions,

the four member ensemble mean of the finer resolution simulations do not consistently add value over the forcing reanalysis data. For two of the sub-regions, Peninsular and Northeast, we do not find any combination of schemes tested or the ensemble mean to perform consistently better than the reanalysis. Thus the increase of model resolution has not resulted in improved regional rainfall in these sub-regions. The quality of the observed data in the Northeast region poses a challenge due to lack of good number of rain gauges in the area. This could also play a role in the lack of value addition in the Northeast region that emerges from this analysis.

Fig. 6 Comparison of errors in seasonal (JJAS) total rainfall from ERA forcing data (*green line*) and 12 km regional model simulations for 1994, 2002 and 2010. The simulations using different cumulus schemes at 12 km (*black asterisks*) and 36 km (*red circles*) are represented separately for each sub-region. **a–c** West Central, **d–f** Northwest, **g–i** Peninsular, **j–l** Northeast. The 12 km simulations show consistent improvement in seasonal rainfall errors in Northwest (BMJ) and West Central (KF) sub-regions
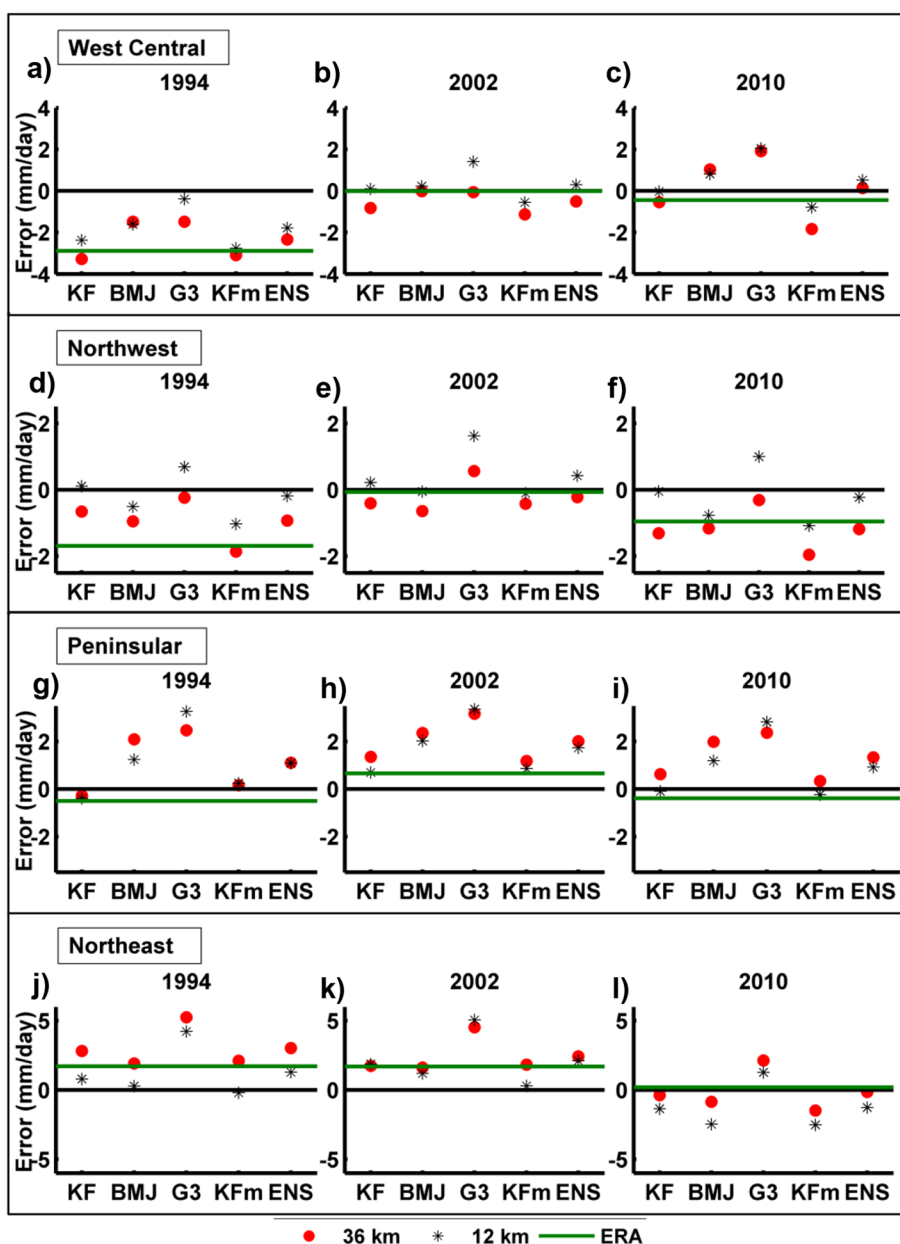
3.2.3 Spatial variability

The probability distribution functions (PDFs) of seasonal rainfall are plotted to evaluate the spatial variability of simulated rainfall. However, it should be noted that the observed data is at 0.25° resolution, while the simulation is at 36 km resolution. They cannot be compared directly, and hence the evaluation provides only a qualitative idea of the model skill in terms of simulating spatial variability. While re-gridding is one possible approach, it accumulates the error that is inherent in the methodology and therefore not considered in this study. The observed spatial variability in each sub-region is represented by PDFs of seasonal rainfall using all grid points that fall within the region. They are compared to the same as obtained from simulated/reanalysis precipitation

of WRF and ERA. The comparison of the observed PDFs of spatial variability with PDFs of WRF simulations and ERA is shown in Fig. 7. The PDFs of the eight member ensemble mean with shading to indicate ensemble spread, are presented for each sub-region and year.

The choice of cumulus schemes cause variability in spatial distribution of regional precipitation for all six sub-regions. The use of spectral nudging does not show reduction of intra-ensemble spread in case of spatial variability of regional precipitation, as observed for the regional seasonal total rainfall. The PDFs of WRF simulated rainfall are visually compared against the same from ERA and observed data to identify parameterizations that show consistent improvements (i.e. similarity to observed rainfall PDFs) with respect to ERA.
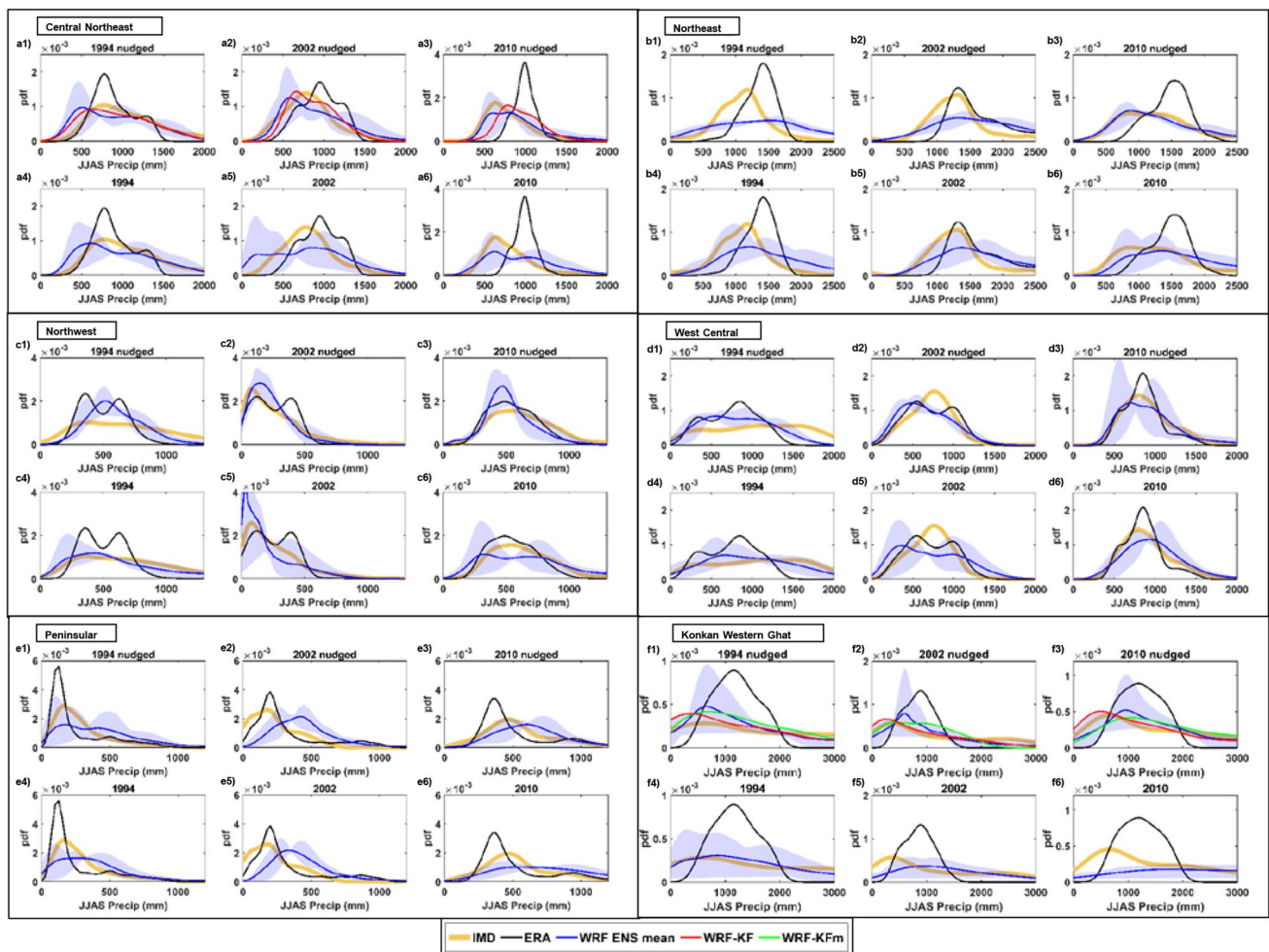

Fig. 7 Comparison of the PDFs of spatial variability of seasonal (JJAS) total rainfall from forcing data ERA (*black*) and WRF eight member ensemble mean (*blue*) with IMD gridded observations (*yellow*) for each sub-region. The *plots* are presented separately for simulations with and without spectral nudging for years 1994, 2002 and 2010 for sub-regions. **a1–a6** Central Northeast, **b1–b6** Northeast, **c1–c6** Northwest, **d1–d6** West Central, **e1–e6** Peninsular, **f1–f6**) Konkan

Western Ghat. Simulations using KF scheme for Central Northeast and KFm scheme for Konkan Western Ghat sub-regions are included in **a1–a3** and **f1–f3**, respectively. WRF with nudging shows consistent improvements in spatial variability in Central northeast (KF and ENS mean) and Konkan Western Ghat (KFm and ENS mean) sub-regions

We find that in two of the sub-regions, Central Northeast and Konkan Western Ghat, some individual seasonal WRF simulations and the ensemble mean capture the observed PDF of spatial variability better than ERA. In Central Northeast region, nudged simulations using KF and the ensemble mean capture the observed PDF better than ERA as shown in subplots a1–a3 of Fig. 7. In Konkan region, the nudged simulations using KF, KFm and the ensemble mean improve upon the spatial variability of ERA rainfall as shown in subplots f1–f3 of Fig. 7. Results suggest that the use of KF scheme as well as the physics ensemble mean in Central Northeast region, and KFm or KF scheme as well as the eight member ensemble mean in Konkan Western Ghat region, adds value to regional spatial variability in additional to seasonal totals.

For the sub-regions, West Central, Northwest, Northeast and Peninsular India we also compare the spatial variability from the 12 km nested simulations with reanalysis and observations to understand the impact of resolution. The 12 km nested simulations for these sub-regions are not found to result in added improvements over the coarser resolution simulations in terms of spatial variability. Supplementary Figure S2 provides comparison of spatial variability PDFs of the nested domain 12 km simulations and 36 km single domain simulations.

3.2.4 Temporal variability

To evaluate the model simulated temporal variability, PDFs representing variability of spatially averaged rainfall over a region across days in a season are developed. The daily rainfall variability from WRF simulations is compared with the same from original forcing data and gridded observations. Figure 8 shows the PDFs of daily temporal variability of regional rainfall for each sub-region and year. As is the case with spatial variability, PDFs are presented for the eight member ensemble mean with shading to indicate ensemble spread. Simulations with and without spectral nudging are presented separately.

The daily temporal variability of precipitation from ERA is close to observations for all regions and the 3 years. In the case of WRF simulations, the PDFs representing temporal rainfall variability for the nudged simulations are closer to those from observations and forcing reanalysis. Spectral nudging brings the temporal variability of simulated precipitation closer to the reanalysis and observed, and also reduces the intra ensemble spread of the PDFs. The reduction of intra ensemble spread in temporal variability is observed in simulations using spectral nudging over all sub-regions except Peninsular India. In Peninsular India, the use of spectral nudging has not resulted in reduction of intra ensemble differences in temporal variability. Figure 8e1–e6 show

comparable intra ensemble spread of temporal variability for nudged and without nudging simulations, in this sub-region.

For the sub-regions, West Central, Northwest, Northeast and Peninsular India, the temporal variability of simulated rainfall from the 12 km resolution simulations are compared with those from the coarser resolution simulations and observations. Similar to spatial variability, the temporal rainfall variability from the 12 km resolution nested simulations do not show marked improvement over the coarser 36 km resolution simulations (also summarized in Supplementary Figure S3).

To summarize the results in terms of model improvements and uncertainty for all the sub-regions, Figs. 9 and 10 are presented. The discussion on sub-regional rainfall errors in Sects. 3.2.1. and 3.2.2. is summarized in Fig. 9. Figure 9 compares the average error in seasonal rainfall from the different WRF simulations with respect to the error in rainfall from ERA. The whiskers indicate the minimum–maximum ranges of seasonal rainfall errors from simulations with different physics (cumulus–microphysics parameterizations). The consistent improvement in regional model ensemble mean for Central Northeast and Konkan Western Ghat sub-regions can be noted from Fig. 9. Figure 10 presents the time series of daily rainfall from the WRF simulations using the suggested schemes for the four sub-regions, viz., Central Northeast, Konkan Western Ghat, Northwest and West Central. The selected simulations in the Central Northeast (using KF scheme) and Konkan Western Ghat (using KFm scheme) sub-regions is found to improve upon the peaks in daily rainfall, with respect to the forcing reanalysis data. Regional rainfall over Central Northeast region from ERA shows a 3 year mean underestimation of peak daily rainfall by 9.8 mm/day (RMSE = 10.4 mm/day), the underestimation is reduced to 6.5 mm/day (RMSE = 7.8 mm/day) in the WRF-KF simulations. Over the Konkan Western Ghat region, the 3 year mean underestimation of peak rainfall from ERA amounts to 31.8 mm/day (RMSE = 31.9 mm/day), it is reduced to 17.1 mm/day (RMSE = 18.6 mm/day) in the WRF-KFm simulation.

4 Summary and conclusion

In this study we evaluate the performance of WRF model for seasonal scale simulations of Indian monsoon, with focus on the added value by regional model for sub-regional monsoon precipitation during contrasting monsoon years. The use of an eight-member cumulus–microphysics ensemble, spectral nudging techniques and finer resolutions provides information on the impact of these configuration changes on the model skill and uncertainty for sub-regional precipitation. We find consistent added value in simulated seasonal
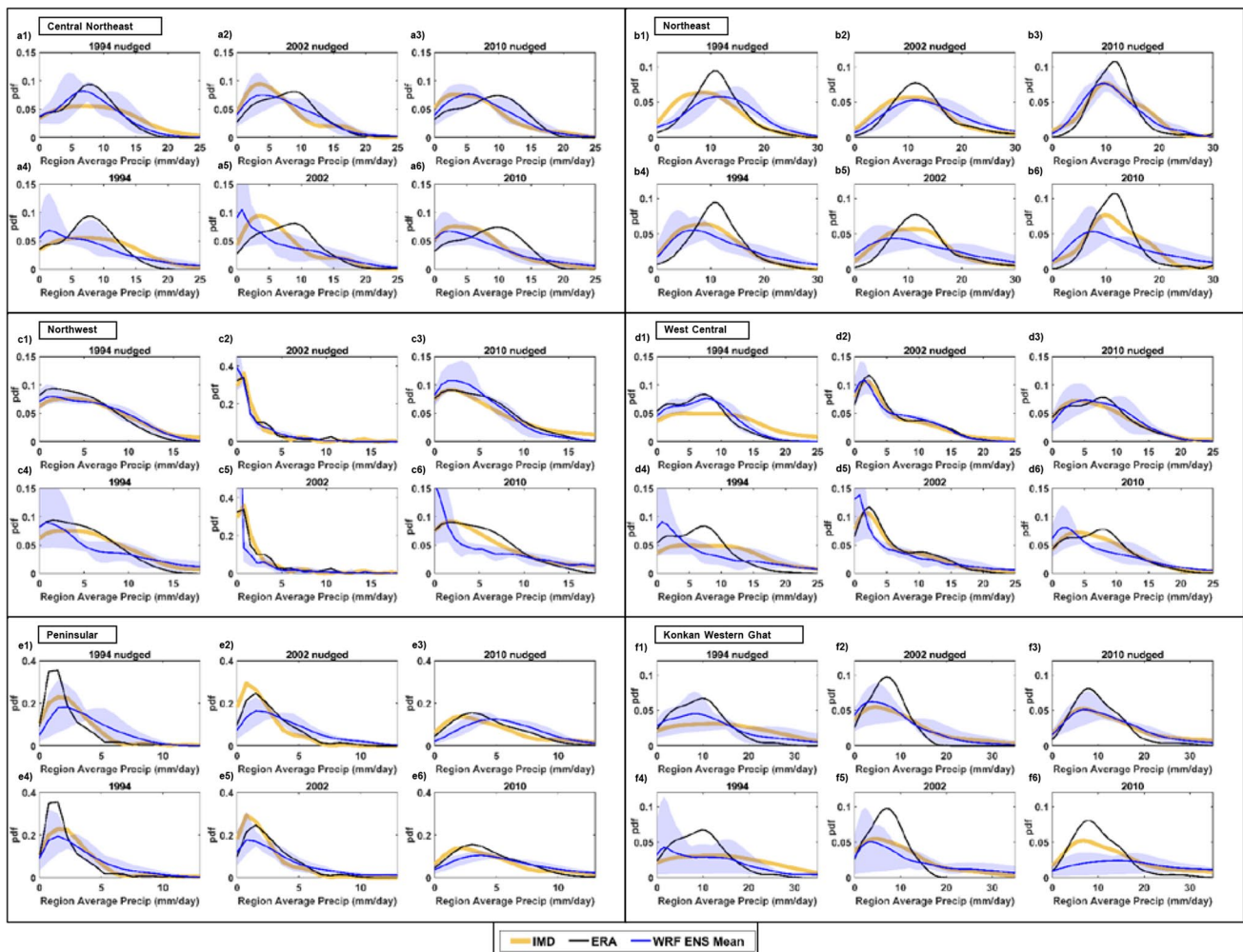
Fig. 8 Comparison of the PDFs of temporal variability of region averaged daily rainfall from forcing data ERA (*black*) and WRF eight member ensemble mean (*blue*) with IMD gridded observations (*yellow*) for each sub-region. The *shading* represents the ensemble spread. The *plots* are presented separately for simulations with and without spectral nudging for years 1994, 2002 and 2010 for sub-regions. **a1–a6** Central Northeast, **b1–b6** Northeast, **c1–c6** Northwest, **d1–d6** West Central, **e1–e6** Peninsular, **f1–f6** Konkan Western Ghat. Use of spectral nudging brings the daily temporal variability of model simulated rainfall closer to reanalysis and observed

rainfall over Central Northeast and Konkan Western Ghat sub-regions through this analysis. At finer resolutions, we are also see added value over the West Central and Northwest sub-regions. To the best of our knowledge, such an evaluation has not been done for the Indian monsoon region before and is necessary for application of the regional model for seasonal prediction of monsoon rainfall. The key findings from the study are the following.

- Model simulated rainfall is more sensitive to cumulus parameterization schemes than microphysics parameterization schemes for seasonal scale Indian monsoon simulations and for all sub-regions.
- The use of spectral nudging reduces the biases in regional model simulated large scale circulation over the Indian monsoon region. This result is consistent with the con-

clusions from earlier studies in other parts of the globe (Miguez-Macho et al. 2004; Castro et al. 2005; Perez et al. 2014). At a sub-regional scale, nudging reduces uncertainty in simulated precipitation both in terms of seasonal total rainfall and seasonal precipitation cycle. The reduction of uncertainty comes from reduced intra ensemble spread of RCM simulations. Results indicate that up to three-fold reduction of ensemble spread in most regions is possible through the use of spectral nudging. Through the use of spectral nudging improvement in the daily temporal variability of simulated precipitation is also found. The reduction of uncertainty in model simulated precipitation through the use of spectral nudging is visible in all sub-regions except Peninsular India.

- Results indicate, consistent added value in WRF simulated monsoon rainfall in the coarser resolution simula-

Fig. 9 Comparison of rainfall error (in mm/day) from the different WRF simulations with that from ERA forcing data, the *whiskers* show the maximum–minimum range of errors. **a** 1994 (excess year), **b** 2002 (deficit year), **c** 2010 (normal year), **d** mean of 3 years
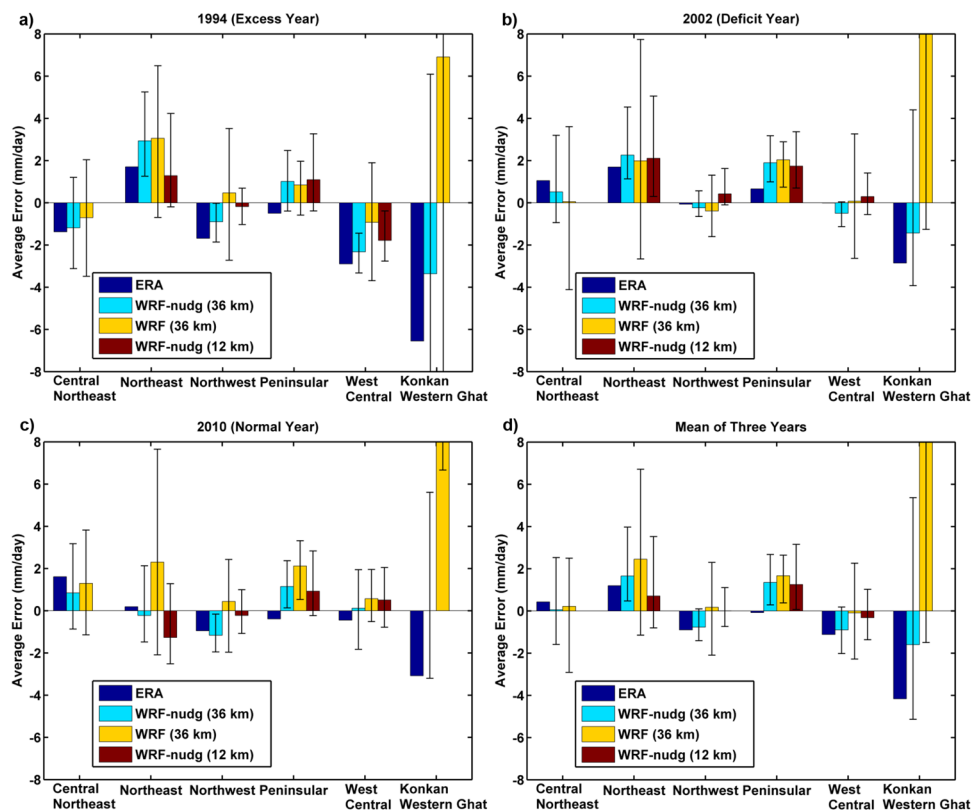
tions for two out of the six sub-regions analyzed, viz., Central Northeast and Konkan Western Ghat. Based on the simulations, the use of KF scheme for Central Northeast and KFm scheme for Konkan Western Ghat region is suggested for seasonal scale monsoon simulations at similar resolutions. The eight member multi physics ensemble mean also shows consistent improvements over forcing reanalysis for these two sub-regions, adding to the robustness of the result. Improvements are visible in spatial variability of rainfall in addition to regional seasonal total rainfall. The value addition in Konkan Western Ghat sub-region is most likely due to a better representation of topography in the RCM. This builds on the conclusions from previous studies in different regions of complex topography (Prömmel et al. 2010; Heikkilä et al. 2011; Di Luca et al. 2013). The value addition noted in Central Northeast sub-region is speculated to be due to better representation of land atmospheric interaction in the regional model and needs to be investigated in the future.

- The finer resolution nested simulations reveal added value in regions North West and West Central in terms of region averaged seasonal total rainfall. This added value is however not noted in the spatial variability of rainfall within the region. For seasonal simulations, to obtain information on regional monsoon rainfall, the results

suggest the use of BMJ scheme for Northwest and KF for West Central regions.

- The results do not identify optimum parameterization scheme combinations to provide added value for the Peninsular and Northeast sub-regions. The model simulations are not able to capture the observed multiscale interactions of topography and monsoon flow in the Northeast region. For the Peninsular region it is found that the model overestimates the seasonal rainfall during all the 3 years. Srinivas et al. (2015) has reported a lack of value addition in onset phase monsoon rainfall in areas falling over these two sub-regions. The study also notes the overestimation of monsoon onset phase rainfall over the semi-arid rain shadow region of southeast India, which is in line with our findings.

In this study the simulations have been performed for three contrasting monsoon years, due to computational constraints. The selection of these years could have an impact on the results. But since our evaluation has focused on consistent (across years) added value in regional precipitation, we feel that the use of three contrasting years is sufficient to yield robust results. The difference in spatial resolution of the model simulations and observed rainfall data deters us from direct comparison of the spatial variability of sub-regional precipitation. Thus the analysis provides only a qualitative idea of the model skill in simulating sub-regional
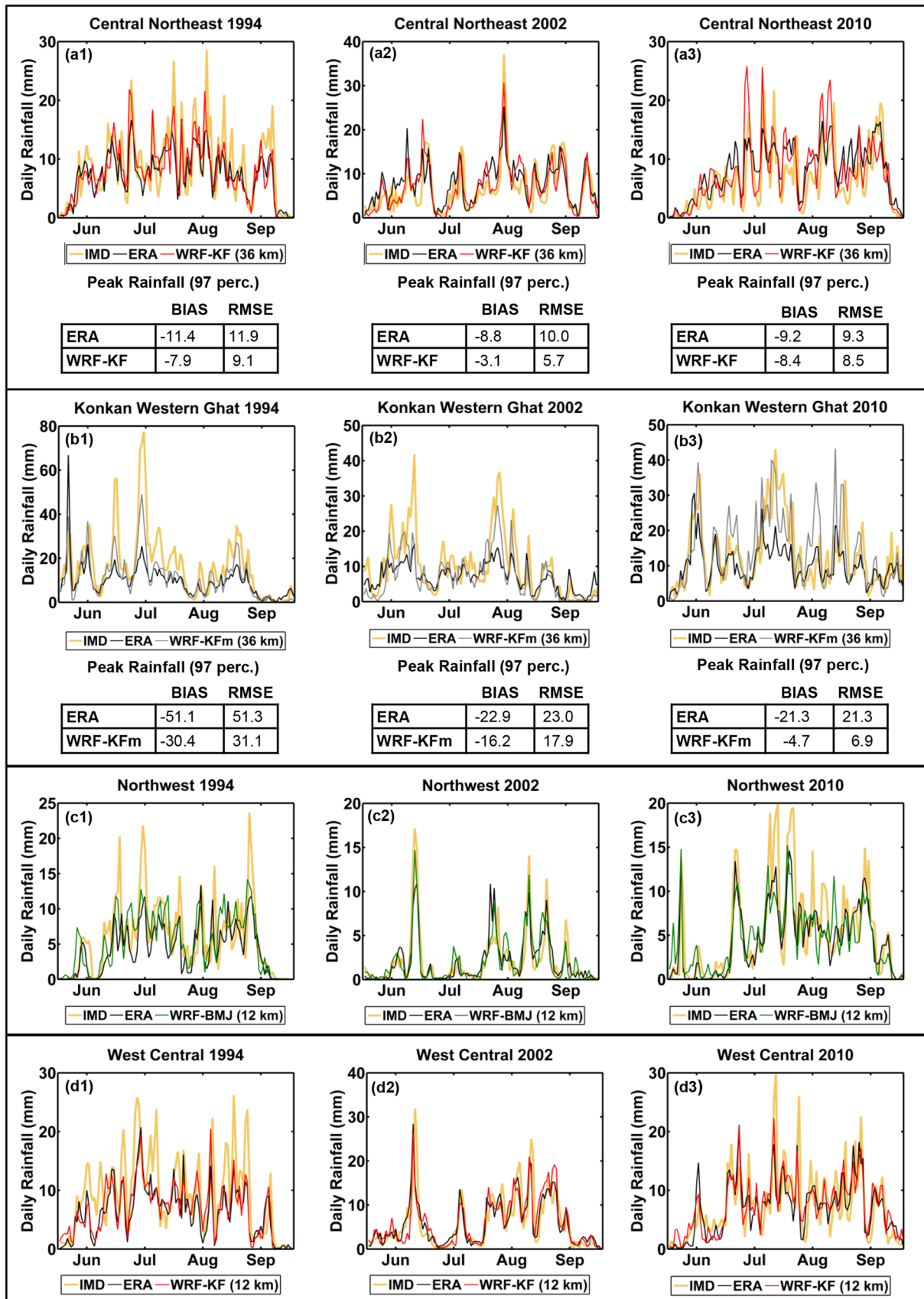
Central Northeast 1994 (a1)

Peak Rainfall (97 perc.)

	BIAS	RMSE
ERA	-11.4	11.9
WRF-KF	-7.9	9.1

Central Northeast 2002 (a2)

Peak Rainfall (97 perc.)

	BIAS	RMSE
ERA	-8.8	10.0
WRF-KF	-3.1	5.7

Central Northeast 2010 (a3)

Peak Rainfall (97 perc.)

	BIAS	RMSE
ERA	-9.2	9.3
WRF-KF	-8.4	8.5

Konkan Western Ghat 1994 (b1)

Peak Rainfall (97 perc.)

	BIAS	RMSE
ERA	-51.1	51.3
WRF-KFm	-30.4	31.1

Konkan Western Ghat 2002 (b2)

Peak Rainfall (97 perc.)

	BIAS	RMSE
ERA	-22.9	23.0
WRF-KFm	-16.2	17.9

Konkan Western Ghat 2010 (b3)

Peak Rainfall (97 perc.)

	BIAS	RMSE
ERA	-21.3	21.3
WRF-KFm	-4.7	6.9

Northwest 1994 (c1)

Northwest 2002 (c2)

Northwest 2010 (c3)

West Central 1994 (d1)

West Central 2002 (d2)

West Central 2010 (d3)

◀ **Fig. 10** Comparison of daily rainfall time series of WRF simulations using the suggested cumulus schemes with the same from ERA and IMD for 1994, 2002 and 2010. **a1–a3** Central Northeast, **b1–b3** Konkan Western Ghat, **c1–c3** Northwest, **d1–d3** West Central. Comparison of ERA and WRF mean bias and root mean square error (RMSE) in peak rainfall above 97 percentiles (in mm/day) are shown in **a1–a3** and **b1–b3**

spatial variability. We have tested combinations of four cumulus and two microphysics schemes in this study. Simulations using more number of cumulus schemes would be useful for additional information on the uncertainty ranges of modelled sub-regional precipitation. We have used "perfect" boundary reanalysis data to understand the regional model added value in sub-regional precipitation. Use of forecasts or projections as boundary conditions would bring in the biases of the source model into the picture, and would need evaluation before direct application of our results.

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