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Verification of real-time WRF-ARW forecast in IMD during monsoon 2010

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सार – वर्ष 2011 के समूची मॉनसून ऋतु के लिए मेसोस्केल मॉडल WRF-ARW के निष्पादन का मूल्यांकन किया गया। भारतीय क्षेत्र में अल्पावधि मौसम प्रागुक्ति के लिए भारत मौसम विज्ञान विभाग में प्रत्येक दिन के वास्तविक समय मॉडल पूर्वानुमान तैयार किए गए। प्रेक्षित वर्षा विश्लेषण के लिए वर्षा पूर्वानुमान सत्यापित किए गए जबकि सभी अन्य मौसम वैज्ञानिक प्राचलों के लिए WRFDA समेकन प्रणाली का उपयोग करते हुए सत्यापन विश्लेषण किए गए। वर्षा के सत्यापन के लिए भारत में सात विभिन्न क्षेत्रों में रूढ़िगत सतत स्कोरों और सुनिश्चित कौशल स्कोर आकलित किए गए। अन्य प्राचलों के लिए (उपरी वायु के साथ-साथ सतह) समूची ऋतु में कालिक और स्थानिक लक्षणों के लिए सतत स्कोरों का आकलन किया गया।

स्थानीकृत पैटर्न सहित बड़े पैमाने पर मॉनसून के लक्षणों का अनुरक्षण करने के लिए मॉडल क्षमता को प्रस्तुत करने के लिए वर्षा के अतिरिक्त मौसम वैज्ञानिक प्राचलों की पूर्वानुमान त्रुटियों का विश्लेषण किया गया। इस अध्ययन में मॉनसून के असमान चरणों के दौरान मॉडल पूर्वानुमानों का आकलन करने के लिए समूची ऋतु में त्रुटियों की समय श्रृंखलाओं की युक्तिपूर्ण ढंग से प्रस्तुत किया गया। सुनिश्चित स्कोरों से पता चलता है कि मॉडल पूर्वानुमान सभी सात क्षेत्रों के लिए सामान्य वर्षा वर्ग के लिए विश्वसनीय हैं। किंतु भारतीय समुद्रों के स्थान परिवर्तित मौसम प्रणाली से सम्बद्ध प्रतिदिन 35.5 मि.मी. से ऊपर होने वाली वर्षा के क्षेत्रों में प्रागुक्ति नहीं की जा सकती है क्योंकि मॉडल उन्हें पूर्वानुमान से अलग कर देता है। समूचे मॉनसून ऋतु के सत्यापन से पता चला है कि मॉडल में पश्चिमी घाटों में कम स्तर के मॉनसून प्रवाह वाले पारस्परिक प्रभाव के क्षेत्रों के लिए पर्वतों पर होने वाली वर्षा की प्रागुक्ति करने की क्षमता है। मॉडल क्षमता को सामान्यत: एकल मॉनसून ऋतु के लिए तैयार किया जाता है और आगे सुधार के लिए त्रुटियों के अभिलक्षणों पर विचार-विमर्श किया गया जिसका मॉडल के वास्तविक समय उपयोग के दौरान पता नहीं चलता है।

ABSTRACT. Performance of the mesoscale model WRF-ARW has been evaluated for whole monsoon season of 2011. The real-time model forecasts are generated day to day in India meteorological Department for short-range weather prediction over the Indian region. Verification of rainfall forecasts has been carried out against observed rainfall analysis whereas for all other meteorological parameters verification analysis which was generated using WRFDA assimilation system. Traditional continuous scores and categorical skill scores are computed over seven different zones in India in the verification of rainfall. For other parameters (upper-air as well as surface), continuous scores are evaluated with temporal and spatial features during whole season.

The forecast errors of meteorological parameters other than rainfall are analyzed to portray the model efficiency in maintaining monsoon features in large scale along with localized pattern. In the study, time series of errors throughout the season also has been maneuvered to evaluate model forecasts during diverse phases of monsoon. Categorical scores suggest the model forecasts are reliable up to moderate rainfall category for all seven zones. But, rainfall areas with rainfall above 35.5 mm per day associated with migrated weather system from Indian seas could not be predicted as the model displaces them in the forecast. The verification for a whole monsoon season has shown that the model has capability to predict orographic rainfall for the interactive areas with low level monsoon flow over Western Ghats. The model efficiency are in general brought out for a single monsoon season and errors characteristics are discussed for further improvement which could not perceived during real-time use of the model.

Key words – WRF-ARW model, WRFDA assimilation system, Verification and categorical skill scores.

1. Introduction

Indian summer monsoon season is the most suitable to verify model performance, as the rain bearing systems embedded in large scale monsoon flow portray varieties in nature and cover scales of events. Many studies on rainfall verification over Indian peninsular region and its sub-regions during monsoon season have been carried out considering seasonal and monthly time-scale. Verification of two different global models over Indian region are investigated using generalized and categorical skill scores (Basu, 2005) and which shows that only a satisfactory performance can be achieved upon averaging the scores over the grid boxes (greater than 60 km) and forecast quality degrades as rainfall intensity increases. Verifying the operational forecasts of a simple hydrostatic regional model categorically Roy Bhowmik *et al*. (2006) demonstrated that the model with coarse resolution produced comparable performance (up to moderate intensity ~ 2 - 5 mm of rain) with other operational models over Indian region and role of model horizontal resolutions. A study by Roy Bhowmik and Durai (2009) investigated the performance of different models and respective improvement after using multi-model ensemble technique for the district-wise rainfall forecasts over Indian region during monsoon season. Mandal *et al*. (2007) framed their study of model verification mainly on spatial distribution to show that two global models preformed differently over different geographical regions. Categorical scores also could not bring reasonable picture for regions with higher values of observed rainfall. Verification Studies on the verification of model performance over Indian region during monsoon revealed that in quantitative term mesoscale models produced collectively an inadequate representation of monsoon rainfall and flow features (Das *et al*., 2008). Ashrit and Saji (2010) also brought out the fact that specific single mesoscale model could not capture various weather characteristics during whole monsoon season. Although, they showed the superiority of WRF model over others in general sense. There are numerous model verification studies using different mesoscale models over geographical locations which do not experience monsoon circulation. Miao *et al*. (2008) evaluated and compared the performance of the MM5 model (previous generation of WRF) with four different planetary boundary layer (PBL) and three land surface model (LSM) parameterization schemes using GÖTE2001 CAMPAIGN data. Based on this study, Miao *et al*. (2009) also evaluated the sensitivity of MM5-simulated sea breeze characteristics to different PBL and LSM parameterization schemes. Borge *et al*. (2008) carried out a details sensitivity study to find out appropriate configuration of WRF model for air quality application over Iberian Peninsula. In their study, the variations of errors for meteorological surface variables compared with measurements from observational network have been found out and optimal setup of WRF model has been defined. In a recent study by Durai *et al*. (2010), thorough investigation on the performance of an operational global model in India Meteorological Department (IMD) illustrated the fact that the quality and horizontal resolution of observation plays a critical role in forecast verification. In the same study, authors illustrated the rapid degradation of model performance above a rainfall threshold of 10 mm/day and model is incapable of predicting location and peak values of rainfall.

In all above mentioned studies, the standard scores could not provide any information about the error characteristics and evolution in different temporal and spatial scales. Even, different categorical skill scores have variant properties with changing amount (dimension) and therefore a single or collective number of scores can not solve the problem of verification (Hogan *et al*., 2010).

In this study, customized approach has been adopted following the recommendation of WWRP/WGNE (World Weather Research Programme/Working Group of Numerical Experimentation; WMO, 2008) for rainfall verification. The scope of the study has been the operational monitoring of forecast quality over time along with the better understanding of the forecast errors which would help model improvement. There are various diagnostic methods of deterministic forecast verification alternative to point-wise verification of categorical or continuous variables with different verification scores. The continuous verification scores (*e.g*., standard root mean square error statistics) are very restrictive as the rainfall amount is not normally distributed and sensitive to large errors. They provide very less information about the nature of the forecast error. Applying three such different verification techniques for wind components (*e.g*., anomaly correlation, object-based verification and variance anomalies), Daran and Davis (2005) illustrated the benefit of high-resolution over coarse grid structure of the model in terms of temporal error variance and realistic nature of error growth. Newly modified neighborhood verification approach (*e.g*., fuzzy; Ebert, 2008, fractions skill scores; Roberts and Lean, 2008) are a bit superior to old type of the same class (*e.g*., root mean square error, mean error, correlation coefficient, skill scores and etc.; Theis *et al*., 2005) but give credit only to the close forecasts. A class of diagnostic methods, which includes scale separation method for precipitation forecasts defines the intensity and scale of the errors (Casati *et al*., 2004). In another class, object oriented verification methods *e.g*., Contiguous Rain Area (CRA) method (Ebert and McBride 2000), Method for Object-based Diagnostic Evaluation (MODE) by Davis *et al*. (2006) and Structure-Amplitude-Location (SAL) method (Wernli *et al*., 2008) are feature based model evaluation and address the skill of forecasts for episodic and localized phenomena. Most of them are applicable for rainfall verification at high resolution.

Within the scope of three levels process (WMO, 2002), the gridpoint by gridpoint verification is mostly utilized for more extensive verification. Different methods

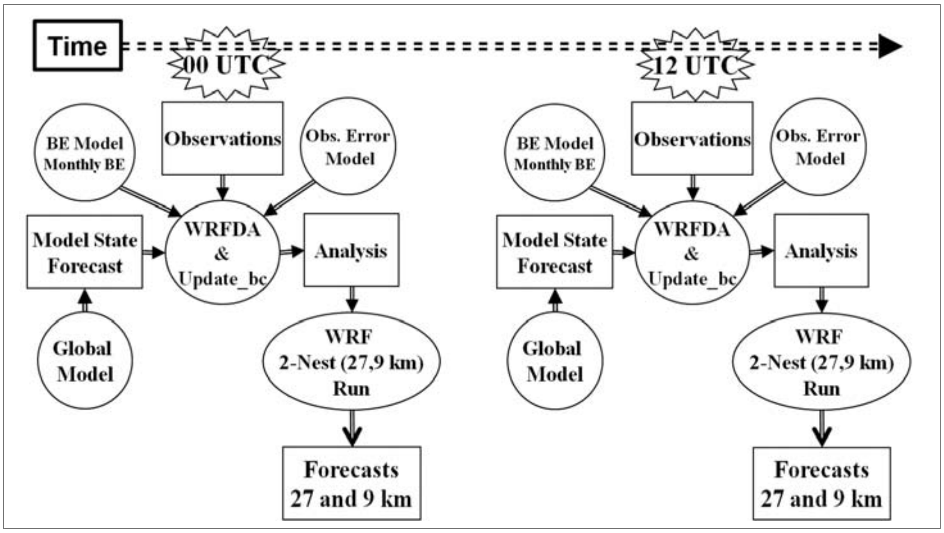


Fig. 1. The schematic diagram of the operational procedure of WRFDA-WRF-ARW system in IMD

already exists which match suitably the resolutions (temporal and spatial) of model forecasts and observations and usually gain information about the scale dependency and growth characteristic of errors. But concrete inference can be approached after pursuing rigorous and repetitive experiments on the same forecasting system for whole season. In this paper, heuristic approach has been adopted for quantitative description of model performance using standard neighborhood technique. This signifies qualitatively operational monitoring and performance evaluation.

The operational WRF model with its mesoscale analysis system is operational in IMD throughout the year 2010. The model is capable of forecasting monsoon weather events with its non-hydrostatic and full physics configuration. In a previous study, a comparison between three different cumulus parameterization schemes (*i.e.*, Betts-Miller-Janjic´-BMJ, Grell-Devenyi-GD, and Kain-Fritsch-KF) has been carried out using WRF model as a regional climate model (Mukhopadhyay *et al*., 2010) and the BMJ have been found to produce reasonable simulated results over Indian region. In another study, Taraphder *et al*. (2010) studied the predictability of active and break phases of monsoon by WRF model with full physics. The study by Yu *et al*., 2011 over south-east Asia has assessed the performance of WRF model with similar three schemes and indicted that the GD scheme performed better than others. The regional climate modeling over West African monsoon region by Flaounas *et al*. (2011) has investigated the sensitivity of WRF model to convection and boundary layer parameterization schemes. Their study indicated that the specific combination of KF and Mellor-Yamada-Janjic (MYJ) planetary boundary layer scheme produce better temporal variability of rainfall. The study by Ardie *et al.* (2012) over Malaysia for a few heavy rainfall episodes have shown that the performances of different schemes are very much case dependent. Wapler *et al*. (2008 and 2010) brought out the fact that MYJ planetary boundary layer scheme produced better simulation for tropical cloud systems. Therefore, the present study is not testifying the specific combination of physical parameterization schemes in the model but has been chosen for operational forecasting purpose before going into rigorous experiments.

We only carried out the forecast verification of operational version of WRF model during JJAS (June, July, August and September) of monsoon 2010. The performance evaluation is based on the availability of rainfall and verification analyses during the period.

2. Methodology

2.1. *Model and evaluation data*

ARW (Advanced Research WRF) version of WRF model, developed by National Center for Atmospheric Research (NCAR), USA, is widely used in IMD for day-to-day forecasting over Indian region. The whole mesoscale modeling system in IMD is also consisting of assimilation component WRF Data Assimilation (WRFDA). This is a unified variational data assimilation system built within the software framework of the WRF-ARW model, used for application in both research and operational environments (WRF ARW Version 3.1.1 Modeling System Users's Guide 2011). WRFDA system based on variational data assimilation technique, increments the first guess state of the atmosphere using observations through the iterative minimization of a prescribed cost (or penalty) function. The cost function represents the cumulative differences between the analysis and observations/first guess which weighted/penalized according to their perceived error statistics. Although, WRFDA unified system can be configured with WRF-ARW forecasting model to act as a four dimensional variational assimilation system, in IMD, the system is operating with limited three dimensional variational mode (not with FGAT - First Guess at Appropriate Time).

The processed observational data from different sources are assimilated in mesoscale analysis system WRFDA to improve the first guess attained from the global analysis generated from operational global data assimilation system (GDAS). The "cold-start" mode of assimilation at each specified time is presently adopted for WRFDA system to yield mesoscale analysis after modifying first guess and schematic diagram of the procedure is shown in Fig. 1. The WRFDA background error covariance for a month is estimated through the National Meteorological Center (NMC) method (Parrish and Derber, 1992) which utilized WRF model forecasts generated during the specified month of previous year. Data assimilation is done only in mother domain with 27 km horizontal resolution and 38 vertical eta levels. Using mesoscale analysis as its initial condition, twice daily at 0000 and 1200 UTC, WRF-ARW model has been integrated for 75 hours with a nested configuration (27 km mother and 9 km child domains are shown in Fig. 2). The boundary condition from global forecasts generated by GFS (Global Forecasting System) in IMD has been suitably updated to get a consistency with mesoscale analysis. The operational physics configuration of the model has not been selected on the basis of rigorous sensitivity studies with physical parameterization schemes. The RRTM long-wave and Goddard short-wave radiations physics schemes, Mellor-Yamada-Janjic planetary boundary layer scheme, WRF single moment 5-class cloud microphysics and Grell 3 dimensional ensemble cumulus physics scheme have been selected for operational run. The model configuration included Eta and Noah Land Surface Model for surface physics.

The observational data from GTS and other local data (Automatic Weather Station and Pilot observations) after decoding and quality control has been preprocessed to create PREPBUFR files (in NCEP-BUFR format) which is used as an input to WRFDA system. Observations are accumulated within ±3 hour time-window from a specific hour to generate corresponding PREPBUFR file. In the assimilation

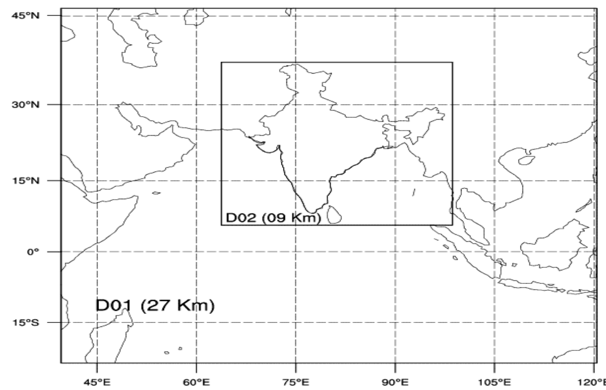


Fig. 2. Domain setup of WRFDA-WRF modeling system at IMD

system, available observations (except satellite radiances as those are already assimilated in GDAS) over a domain (20° S to 45° N; 40° E to 115° E; covering region of Delhi RSMC - Regional Specialized Meteorological Center) are ingested to create improved mesoscale analysis.

The post-processing programs WPP (WRF Post Processor) and NCL (NCAR Command Language) have been utilized for the processing of model forecasts so that it can utilized by the MET (Model Evaluation Tools; 2011) developed by NCAR.

The verification analyses for different meteorological parameters except rainfall at model resolution (27 km) have been generated through WRFDA system. Grid-point rainfall analyses are generated in IMD at 0.5° spatial resolution using all station observations during monsoon season (Rajeevan and Bhate, 2009). The resolution of rainfall forecasts from model are matched up with observed rainfall analyses (0.5°) using bilinear interpolation. We only considered the series of forecasts based on 0000 UTC initial conditions every day and verified the rainfall forecasts within the duration of observation, *i.e.*, from 0300 UTC of a day to next day 0300 UTC.

2.2. *Verification experiment*

The grid-point verification experiments are framed according to the nature of available verification analyses generated operationally everyday in IMD. Only forecasts of 27 km domain have been utilized as the scope was limited due to unavailability of verification analyses (rainfall analyses) at 9 km resolution. Day 3 forecasts have also been discarded to keep smooth and reasonable limit of the discussion in this paper.

The GRID_STAT utility inside MET (v3.0) has been used to compute forecast errors for zonal and meridional

TABLE 1

Seven geographical regions considered for rainfall verification

Zone name	Geographical region of India	Abbreviated name
Zone 1	Kerala	KRL
Zone 2	West Coast	WC
Zone 3	Southern Peninsula	SP
Zone 4	Central India	CTR
Zone 5	East India	EI
Zone 6	North-East India	NE
Zone 7	North-West India	NW

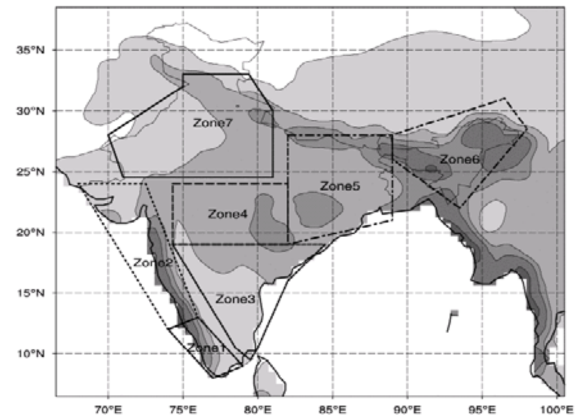


Fig. 3. Locations of seven geographical regions for rainfall verification along with GPCC climate normal rainfall in mm/day

winds, temperature, geopotential height and relative humidity (U, V, T, Z and RH) at various selected pressure levels up to 48 hours. Errors in the forecasts are also generated for a few more surface variables *e.g.*, U and V wind at 10 m height and temperature at 2m height above ground. Although, the verification of rainfall and other variables have been worked out separately, same GRID_STAT processing program is utilized in both cases.

Verification of rainfall has been accomplished individually considering seven different zones along with whole Indian region during monsoon season (June, July, August and September - JJAS) 2010. The masking over the specified zones has been employed to compute skill scores separately. The seven zones are specified by their serial number and their respective geographical areas are described in Table 1. The geographical locations of all seven zones have been represented in Fig. 3. The GPCC climate normal precipitation (Meyer-Christoffer *et al.*, 2011) has also been shown in Fig. 3 to portray the spatial distribution of seasonal rainfall over the region. Different zones are approximately specified on the basis of characteristic influences of weather events and resulting rainfall distribution over the geographic regions during monsoon season. Although they do not exactly match with IMD definition of these regions, still it is mentioned in Table 1.

Zone 1 and zone 2 are situated at the west coast of India and experiences low level jet (LLJ) of monsoon flow during active phase scenario. But, the rainfall maximum always lies over any of these two zones in general. Sometimes, two spate maxima occurred over both zones in case of LLJ branching. Spatial distribution over zone 3 east of zone 1 and 2 has comparatively lower amount of rain due to rain-shadow effect of Western Ghats. Low pressure systems from Bay of Bengal (BOB) not often migrate over the zone. During active monsoon, after genesis over BOB, low pressure systems move towards inland over zone 4 and zone 5 depending on the orientation and position of monsoon trough (MT). Whenever MT lies over its normal or south of its normal position then zone 4 mostly receives higher rainfall distribution. On the other hand, MT lying over north of its normal position with its eastern end locked to the center of the low pressure system from BOB, produces rain belt over zone 5. During the season, a few land depressions also form over zone 5. Rainfall climatology shows that zone 6 covering north-east India and adjoin Bangladesh experiences highest rainfall compared to other regions. Rainfall characteristics and associated weather events are also very much different from other zones. Complex orographic feature is also particular to the region. Zone 7 represents an area over north-west India covering least rainfall belt over Rajasthan to heavy precipitation belt at foot hills of Himalayas. But, the influencing weather events are similar in nature. Migrated low-pressure systems reaching to this zone mostly remain as tropospheric cyclonic circulation and sometime interact with upper level westerly over the region. In a few occasion, mid-tropospheric cyclones situating south of the zone also cause significant rainfall.

The categorical verification scores for rainfall have been tried to evaluate model performance. The different rainfall categories are defined on the basis of the classification used in India Meteorological Department (described in Table 2). In this study, last two categories above heavy rain class are not considered for the verification purpose. In this document, the verification has been completed for a limited number standard skill scores for whole India and other seven indicative zones. Critical success index (CSI) commonly known as threat score has been considered to show the efficiency of the forecasts "yes" events against observed "yes" events whereas Gilbert Skill Score (GSS) *i.e.*, equitable threat score has been considered to adjust the correct forecasts by random chance. Hanssen and Kuipers discriminant (HK) are

TABLE 2

Classification of rainfall based on intensity

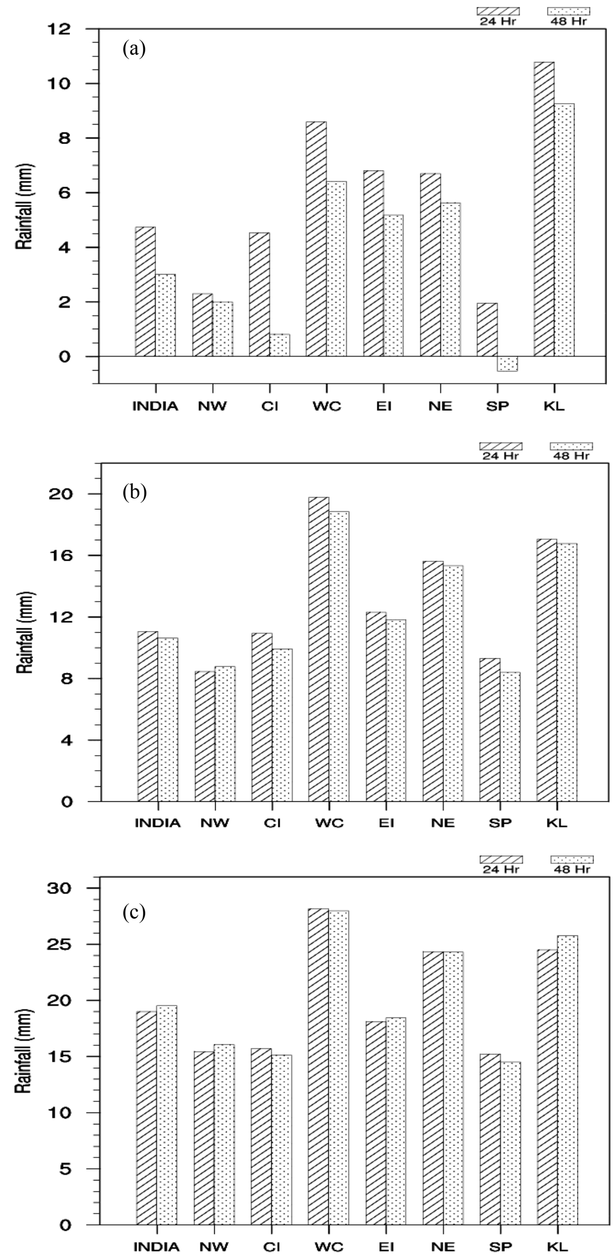
Descriptive term used	Rainfall amount (mm)
No Rain	0.0
Very light Rain	0.1- 2.4
Light Rain	2.5 – 7.5
Moderate Rain	7.6 – 35.5
Rather Heavy	35.6 – 64.4
Heavy Rain	64.5 – 124.4
Very Heavy Rain	124.5 – 244.4
Extremely Heavy Rain	≥ 244.5
Exceptionally Heavy Rain	When the amount is a value near about the highest recorded rainfall at or near the station for the month or season. However, this term will be used only when the actual rainfall amount exceeds 120 mm.

considered to evaluate model forecasts separately for "yes" and "no" events as well as for the events which occurred frequently. Heidke skill score (HSS) is a generalized score to specify the utility of the model forecasts relative to climatology or persistent forecasts. The definition of these skill scores are omitted in the discussion for their obviousness.

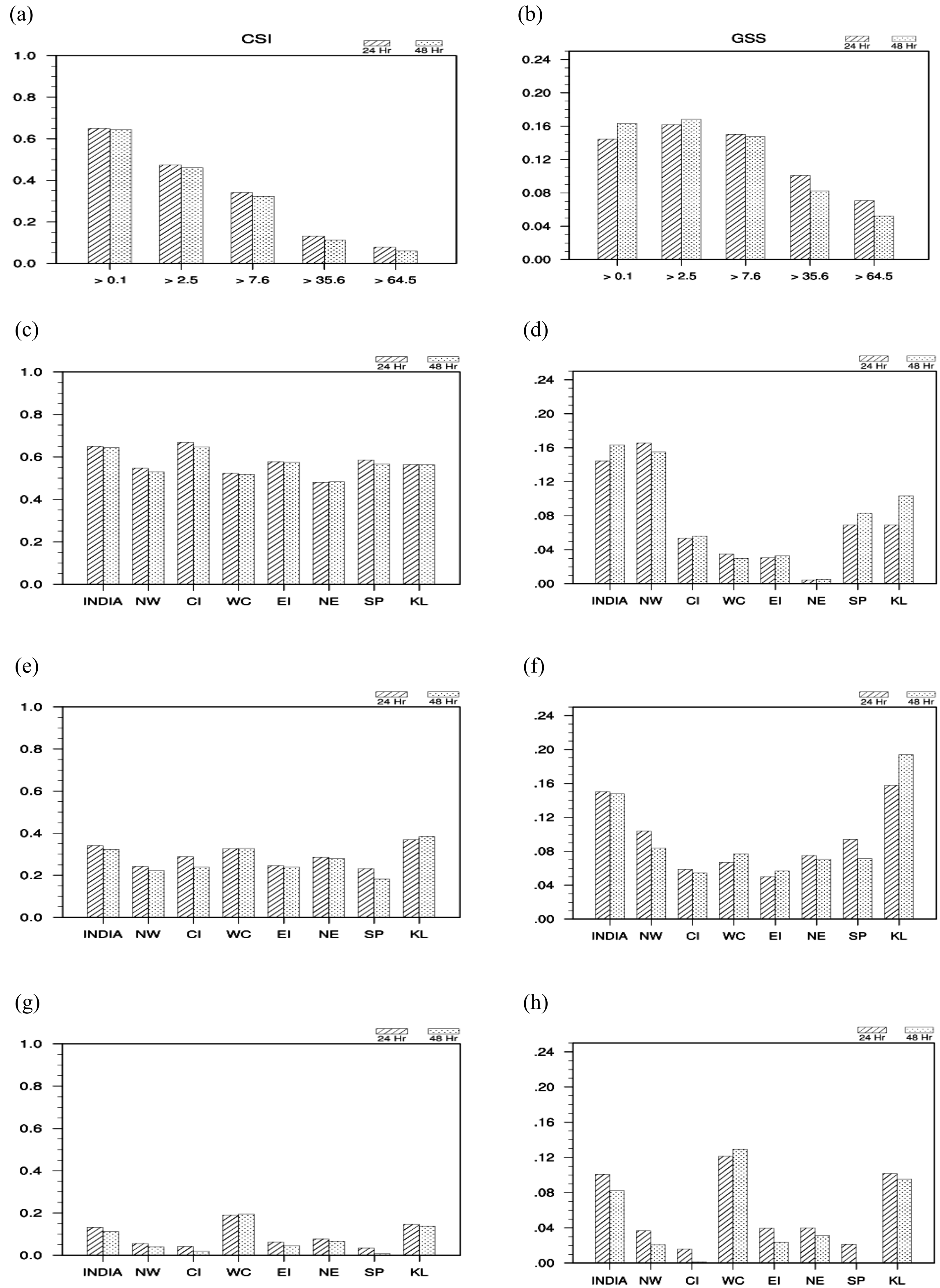
3. Results and discussion

3.1. *Verification of rainfall*

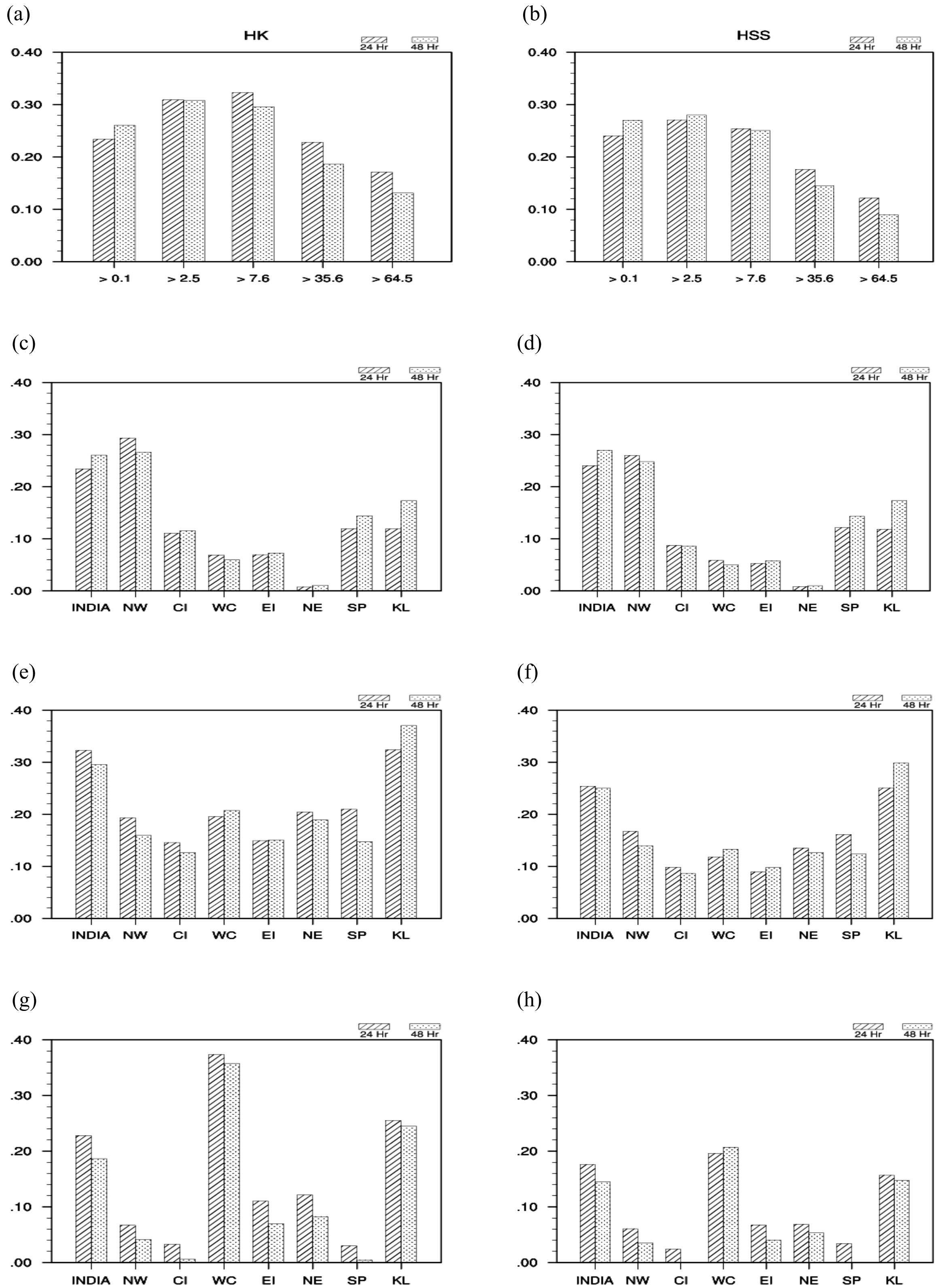
Forecast rainfall has been compared with rainfall analyses for full India and for seven different regions; and Mean root mean square error (RMSE), mean error (ME), mean absolute error (MAE) has been computed and summarized for day 1 (24 hour), day 2 (48 hour) forecasts. In 24 hour forecasts, mean errors are positive for full Indian Region and all other seven regions and therefore rainfall has been overestimated by the model forecasts [Fig. 4(a)]. The overestimation of rainfall over WC, KL, NE and EI region are higher than the errors over other regions (Fig. 4). This brings out the fact that the model has a tendency of overestimation over the regions where rainfall amount is higher during whole monsoon season. The overestimation is reduced significantly in 48 hour forecasts. Over SP region (rain shadow region), mean error is very less and changes its sign fro 24 hour to 48 hour forecasts. In Figs. 4(b&c), MAE and RMSE in rainfall forecast respectively represent the higher values for WC, KL and NE region. If the contribution of mean error (overestimation) is considered in RMSE, the error in rainfall forecast is more random than systematic over all regions. Although, the order of errors (MAE and RMSE) is not showing any prominent change from 24 to 48 hour forecasts, still errors in 24 hour forecasts are more systematic than 48 hour forecasts. Higher values of MAE and RMSE are again found over the regions of higher rainfall (WC, KL and NE). Over these regions, the shifting of heavy rainfall area might cause "double penalty" in error computation. The performance of the model over other regions is comparable in terms of MAE and RMSE taking into account whole monsoon season.



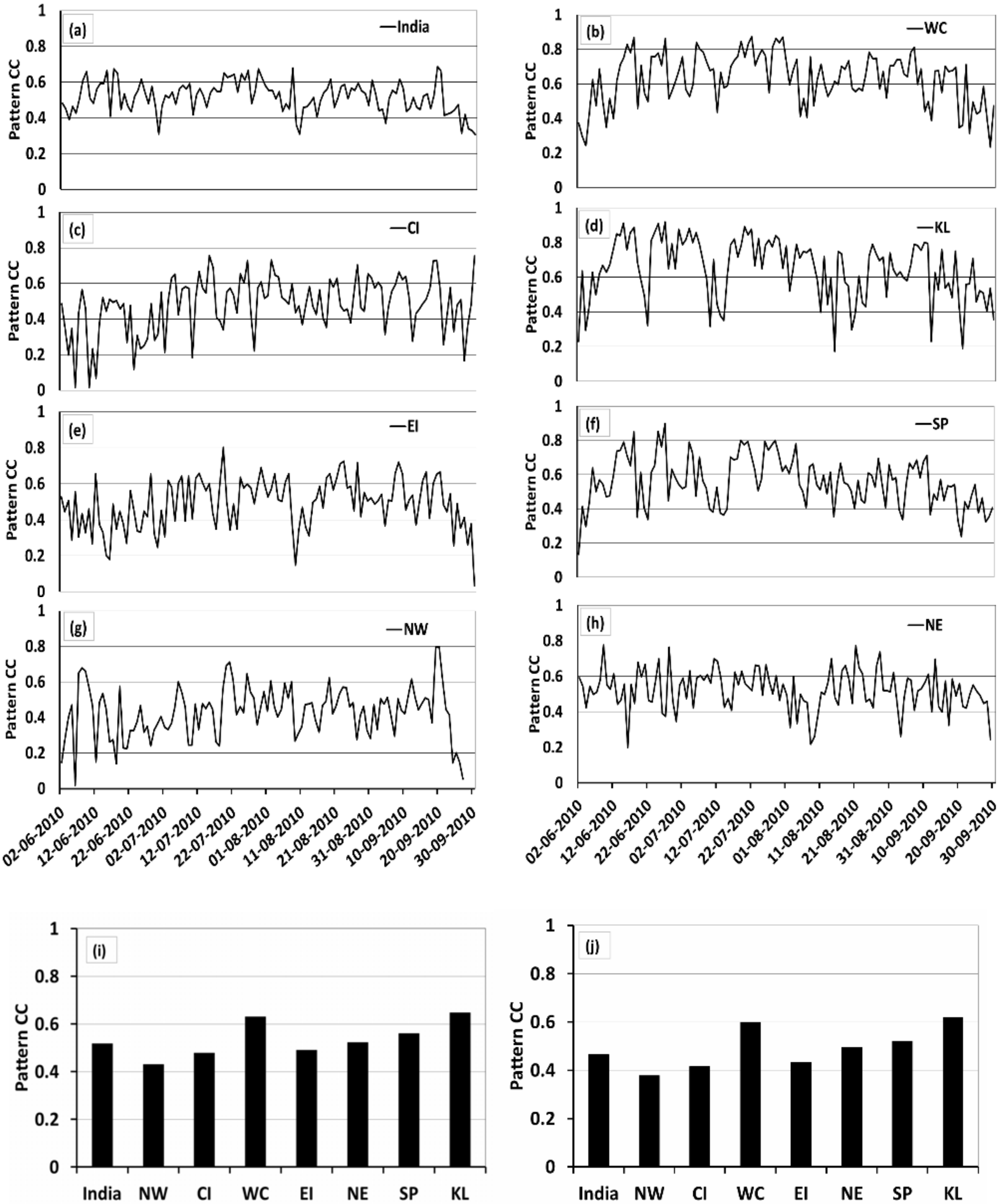
Figs. 4(a-c). (a) Mean error, (b) mean absolute error and (c) root mean square error of rainfall for eight different regions for 24 and 48 hours forecasts averaged over whole monsoon season of 2010



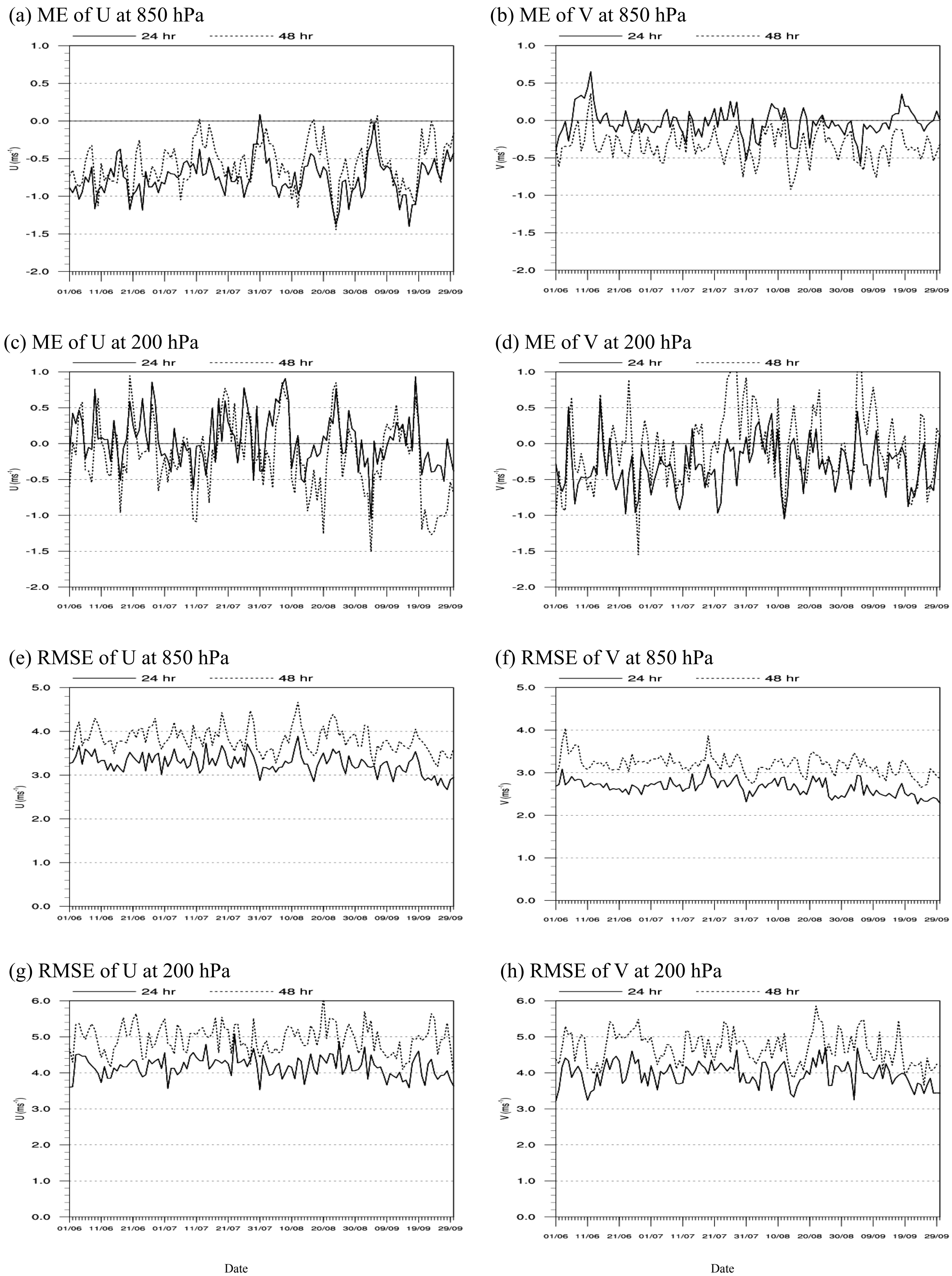
Figs. 5(a-h). CSI and GSS (a) and (b) over whole Indian domain for five different rainfall category respectively. (c), (e) and (g) for CSI and (d), (f) and (h) for GSS over eight different zones for rainfall threshold 0.1, 7.6 and 35.5 mm respectively



Figs. 6(a-h). HK discriminant and HSS (a) and (b) over whole Indian domain for five different rainfall category respectively. (c), (e) and (g) for HK and (d), (f) and (h) for HSS over eight different zones for rainfall threshold 0.1, 7.6 and 35.5 mm respectively



Figs. 7 (a-j). Pattern correlations between observed rainfall and WRF forecasts for different regions. Pattern correlation for 24 hour forecasts over (a) full domain, (b) west coast, (c) central India, (d) Kerala, (e) eastern India, (f) southern peninsular India, (g) northwest India and (h) northeast India regions. Comparison of pattern correlation between regions for (i) 24 hour and (j) 48 hour forecasts



Figs. 8 (a-h). Daily variation of errors in wind components. (a) & (b) show MEs at 850 hPa and (c) & (d) MEs at 200 hPa pressure level; (e) & (f) show RMSEs at 850 hPa and (g) & (h) RMSEs at 200 hPa pressure level for U and V respectively

Categorical skill scores for whole India region and seven other sub-zones are plotted in Figs. 5(a-h) and Figs. 6(a-h). CSI and GSS are plotted together in figure 5 considering their more suitability in the presentation whereas two specific scores, *e.g.*, HK and HSS are plotted in Figs. 6(a-h). The CSI for seven threshold values of rainfall masked over whole Indian domain [Fig. 5(a)] depicted well-known characteristics of the score. The CSI score degraded with an increase in rainfall threshold limit. Performance of the model is below per (CSI < 0.2) for rainfall threshold above 35.5 mm. GSS score also suggests similar information [Fig. 5b)]. CSI values for all regions decreases with an increase in rainfall amount [Figs. 5 (c, e&g)] and this tendency does not show any marked variation amongst different zones. Model also does not show any significant deviation in CSI with forecast length (from 24 to 48hr) as it was also seen in previous study by Ashrit and Saji (2010). As usual, model provides best performance in predicting rain and no-rain events (considering threshold of 0.1 mm). Analyzing the scores over eight different geographical regions in Figs. 5 (c-h), it is clear that model perform poorly over a few individual zones (*e.g.*, for NE, CI and EI, the value of CSI < 0.2 and GSS < 0.1). Changes in model performance vary differently over different zones over different rainfall categories. For some regions (NW, CI and SP) with lower value of threshold, the model performance is better than the higher threshold. But for the region with higher seasonal rainfall (KL and WC), model performs better with higher rainfall threshold, although above heavy rainfall category (> 64.5 mm) the model performance dropped below a reasonable limit. Over NE zone the rainfall is poorly predicted in all categories and for southern peninsula over three lower rainfall categories (up to moderate rainfall) performance is uniform. These two scores over whole India region signify that the model perform below an acceptable quality above 7.5 mm of rainfall amount *i.e*., below rather heavy category in strict sense and GSS approaches to zero (no skill value) as rainfall amount increases above 35.5 mm. In a study by Basu (2005) with different global models it has been shown that threat score drops below 0.2 beyond rainfall amount 2 cm. IMD GFS model also show similar behavior (Durai *et al*., 2010). Although the values of the score far below 1.0 associated with correct forecast, the GSS score sometimes portray inadequate picture about the model performance at high resolution and the scores attest to the ability of phase correction and filtering over scales are necessary (Bousquet *et al*., 2006). The HK and HSS scores for different rainfall categories over whole India region have plotted in Figs. 6 (a&b). The HK and HSS both produce higher values near rainfall category (greater than 7.6 mm) whereas in the categories with lower amount of rainfall the scores are comparatively low. This implies the fact that the model forecasts carry more points with lower amount of rainfall and forecast by chance is more likely. Grid-points with heavier rainfall are less in model forecasts and therefore the scores degrade rapidly as seen for other skill. At the same time, chances of random forecasts within medium rainfall category are less likely during the season compared to other categories. Other Figs. 6 (c-h) represent the HK and HSS for rain categories over seven separate zones along with all India scores. The all figures justify a common fact that for least rainfall (rain/no-rain) model forecasts are biased towards overestimation over number of grid points with random false alarms except over NW region where number of heavy rainfall episodes during whole monsoon season are less compared to other zones. Scores for higher rain categories (beyond rather heavy rainfall) drop below acceptable limit except two regions (WC and KL) with higher rainfall occurrence due to topography of Western Ghats and this specific model characteristics have also been brought out in previous study by Ashrit and Saji (2010). The model performs better in medium rainfall category but fails peeking up heavy rains over most of the regions.

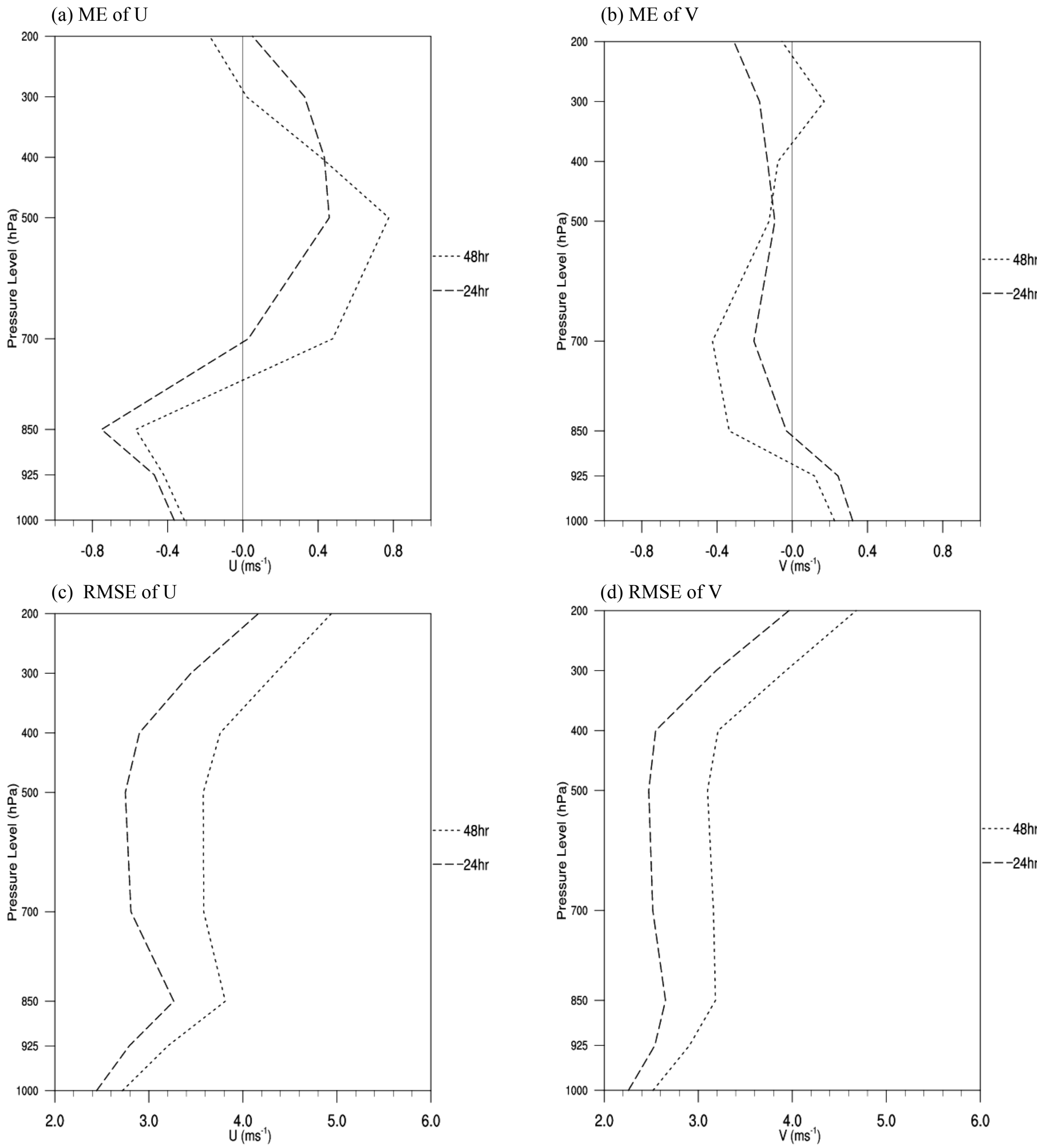
The panels of Figs. 7(a-j) show the daily variation of pattern correlation (SPCORR) over different regions selected in the study during the monsoon season 2010. The time averages of pattern correlation over the regions for two different forecast hours are shown in bottom two panels of Figs. 7(a-j). It has been found that the model has higher pattern correlation of rainfall over the zones with higher rainfall (*e.g*., WC and KL). As expected, different zones have random variation SPCORR compared to whole India. During the season, the zones have several spells with higher/lower values of spatial correlation. But, the different zones show variation in the behavior of time series of SPCORR. The NW zone has lowest values of SPCORR for both day 1 and day 2 forecasts. There is a little decrease in SPCORR from day 1 to day 2 forecasts.

3.2. *Verification of other parameters*

Grid-point to grid-point comparison of other meteorological parameters between analyses and model forecasts has also been done for JJAS 2010. The characteristics of errors for different parameters have been described separately. Upper-air and surface parameters are categorically discussed for convenience although linkages between them are maintained.

3.2.1. *Upper-air wind components (U and V)*

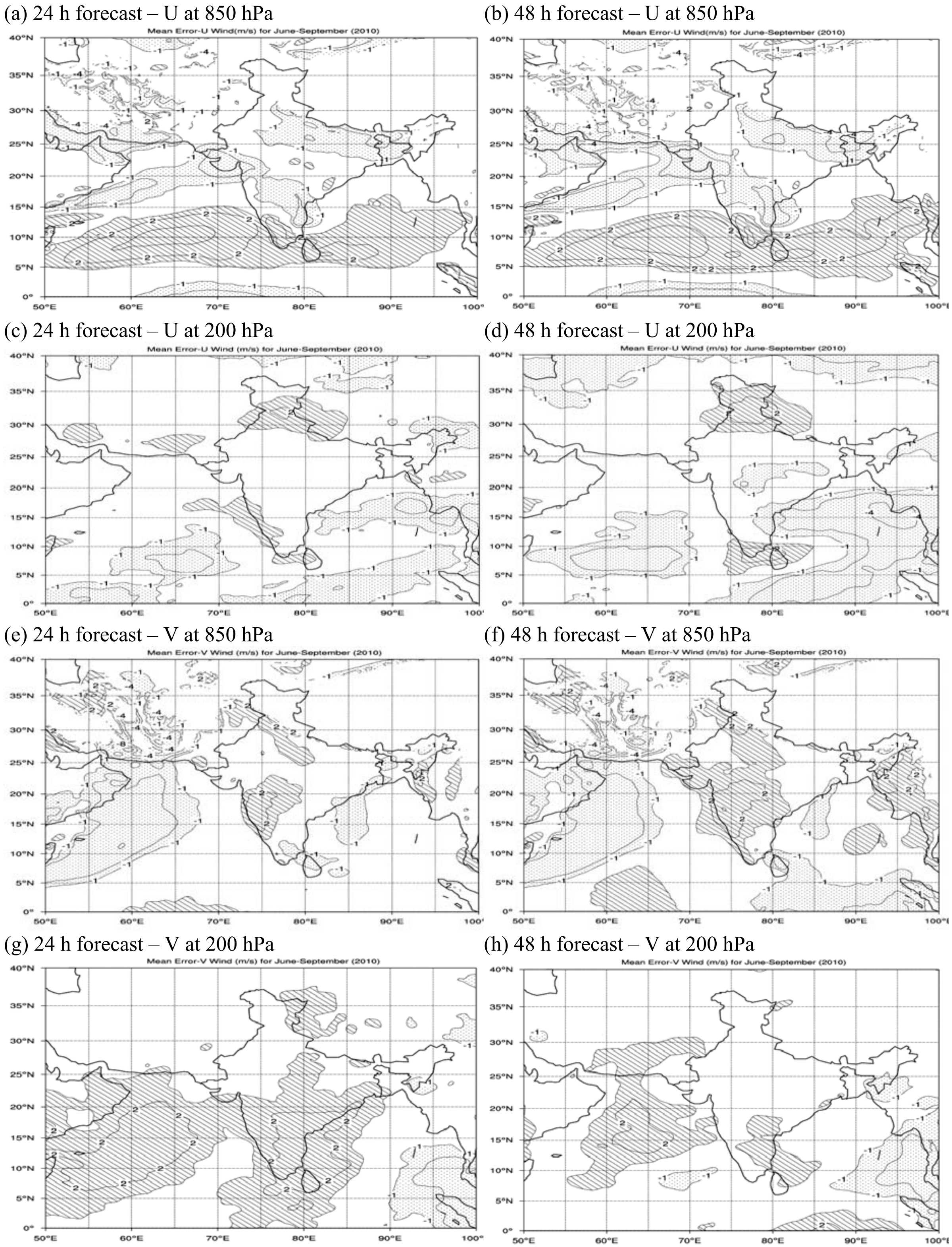
The daily variation of errors for wind components averaged over Indian domain at 850 hPa and 200 hPa pressure levels are shown in Figs. 8(a-h). First two panels 8a and 8b represent mean error for U and V wind at



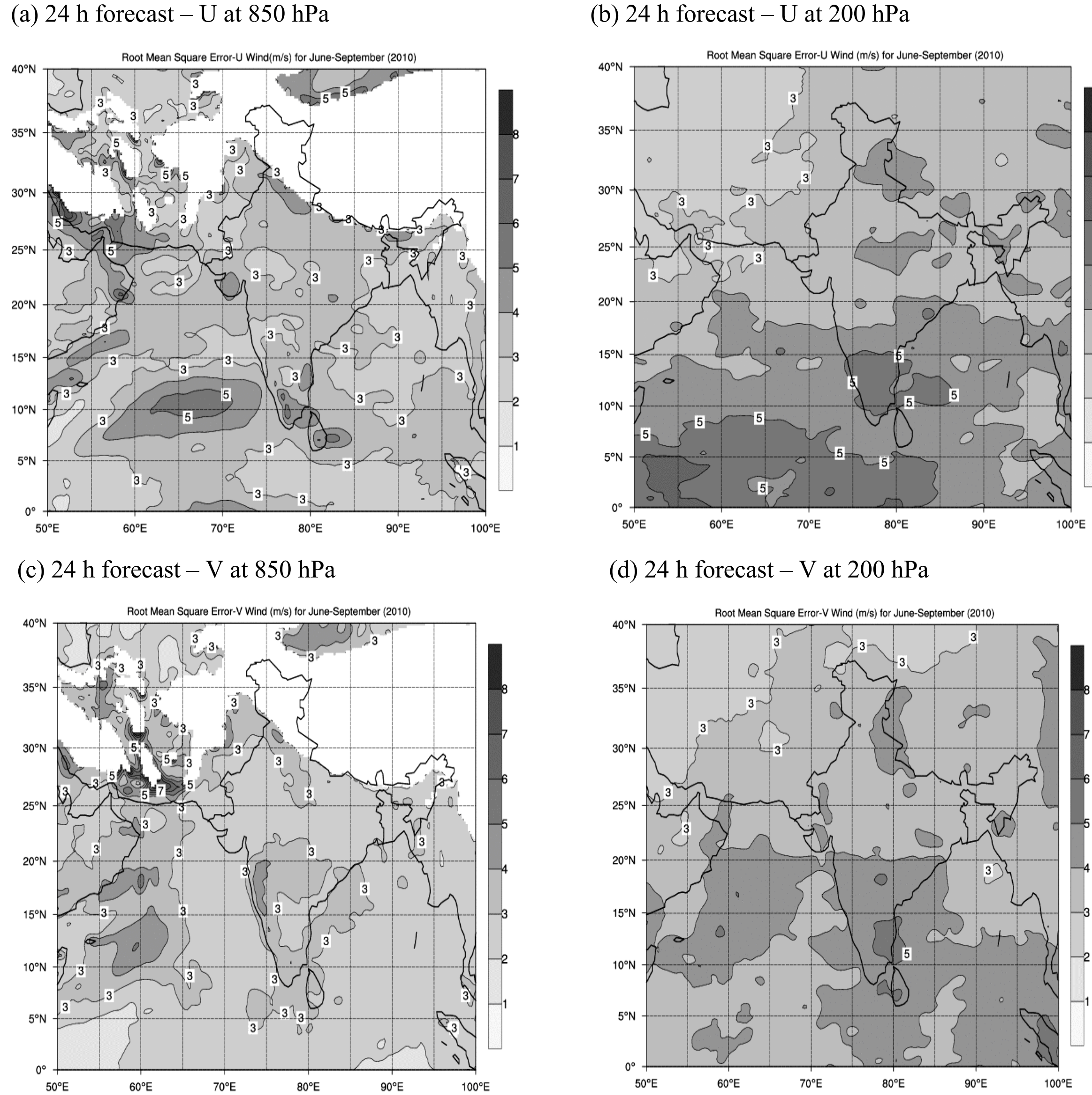
Figs. 9(a-d). Vertical profiles of errors averaged during whole season. MEs are in (a) and (b) for U and V respectively; RMSEs are in (c) and (d) for U and V respectively

850 hPa pressure level respectively. MEs at 200 hPa are plotted in next two Figs. 8 (c&d). During the whole season, the model always underestimated the westerly wind with a value ranging from 0.0 to -1.0 ms^{-1} but the mean error in easterly at 200 hPa does not show any distinct systematic feature with values fluctuating between -1.0 to 1.0 ms^{-1}. It reflects the fact that the strength of the lower level monsoon westerly flow has not been peaked up by the model whereas the strength of upper level easterly flow is invariant in the model. The MEs of V wind do not show any kind of systematic feature (trend or bias) in lower level of the troposphere but a feeble northerly bias developed with forecast length. Mean errors for both wind components at upper level exhibit similar kind of random nature.

The general observation from Figs. 8 (e-h) is that both in the upper and lower atmosphere, root mean square errors (RMSEs) of U wind are within moderate range of 5 ms^{-1} in both forecast hours. Although, in general errors increased with the length of forecast at each levels. Day-to-day fluctuations of RMSEs in U wind show the



Figs. 10(a-h). Spatial distribution of seasonal ME (area with +ve error hatched and area with –ve error dotted) for wind components in 24 hour and 48 hour forecasts. (a), (b), and (c), (d) for U at 850 and 200 hPa respectively; (e), (f), and (g), (h) for V at 850 and 200 hPa respectively



Figs. 11(a-d). Spatial distribution of seasonal RMSE for wind components in 24 hour forecasts. (a) and (b) for U, (c) and (d) for V at 850 and 200 hPa respectively

differences between forecast hours but the errors at 200 hPa are larger than 850 hPa level. Higher value of RMSE of U wind in upper level relates to the higher magnitude of the wind compared to the lower level. RMSEs in V winds are shown in Figs. 8 (f&h). RMSEs are higher in upper level compared to lower level during whole monsoon season which is similar to U wind. The RMSE graph for 24 hour forecast is well separated from error graphs for 48 hour forecast with much lower values of errors. The RMSEs of U and V wind represent a slight decreasing trend at 850 hPa (lower level) with time from start of the season towards the end whereas such kind of trend is not clearly observed at 200 hPa. The order of RMSEs and mean errors for both wind components represent a fact that the contribution of mean errors to RMSEs are very less and errors in model wind forecasts are not systematic rather mostly random in nature.

In Figs. 9(a-d), vertical profiles of errors in wind have been plotted after time averaging the errors during whole season. The RMSE profiles of both U and V wind [Figs. 9 (c&d)] depict that the errors in the middle level of the atmosphere is comparatively smaller than other levels and do not vary with levels. On both sides of the error plateau of middle atmosphere, the RMSE of wind components have their peaks towards surface and upper atmospheric levels as well. The profiles of errors show that the RMSE is one order higher than mean errors [Figs. 9 (a&b)]. Therefore, the forecast errors in predicting monsoon flow in lower (low level jet) and upper levels (tropical easterly jet) which are also comparatively stronger than the middle atmospheric flow are random rather than systematic. The mean errors of wind components depict clearly that the model, throughout the season systematic error in U wind is larger than V wind. Growth of RMSE in both wind components with forecast duration is uniform.

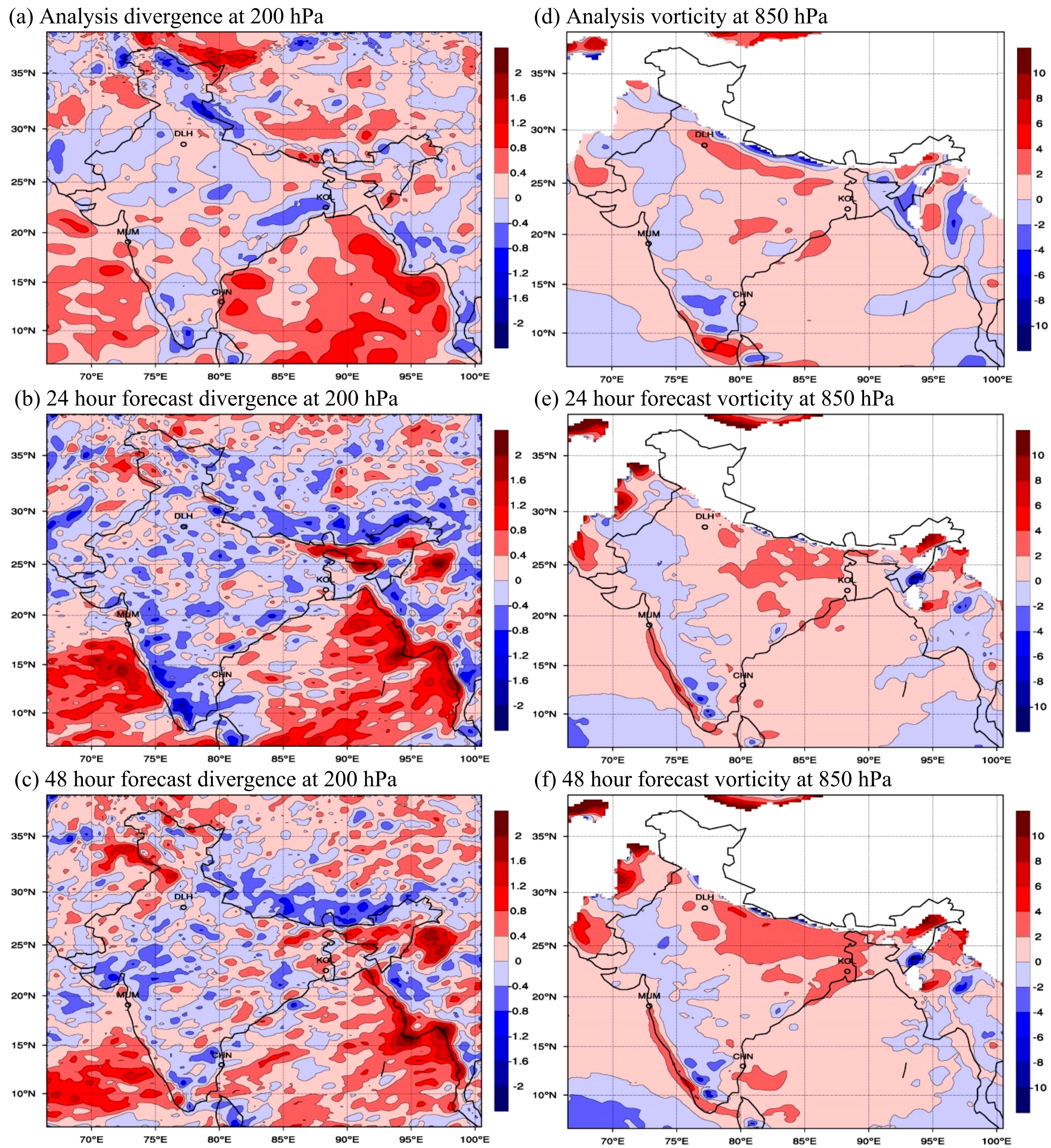
Times series and profile errors averaged over domain only shows the general nature without their spatial features. Figs. 10(a-h) shows the spatial distribution of mean errors in wind forecast. In Figs. 10 (a&b), low level (850 hPa) U wind has shown a westerly bias over latitude belt between 5° N and 15° N whereas it exhibit systematic easterly bias at north of this zone towards Indian land mass. The mean error features in U wind at 850 hPa are fairly similar in 24 and 48 hour forecasts. In 24 hour forecast, mean error in U wind at 200 hPa has significantly small (~ 1 ms^{-1}) westerly bias over southern peninsular India and north part of north-west India and easterly bias over Indian seas which increases in 48 hour forecast [Figs. 10 (c&d)]. This signifies that the U component of low level south-westerly monsoon flow is overestimated in southern latitudes and underestimated over Indian main land mass. Same way, upper air tropical easterly jet is underestimated over India at its peak but overall overestimation over sea area. The V wind at 850 hPa in Fig. 10(e) shows a significant southerly bias over central and north-west India whereas the zone of strong southerly wind component is systematically underestimated around head bay. The monsoon flow in the lower levels crossing over Bay of Bengal in the model forecast has a tendency to get southerly bias over Arakan coast and Myanmar rather than heading towards NE India region. This error feature is getting pronounced with forecast duration from 24 to 48 hour. V wind over north parts of Arabian Sea and its western side in the lower levels is persistently weakening southerly component (northward push) over the region in model forecasts. Figs. 10 (g&h) are representing the mean error of V wind at 200 hPa pressure level. They show that the upper air return flow of monsoon towards equator is systematically weak and have southerly bias and contrary to other figures the error is reduced with forecast length. Although, systematic errors of wind components from WRF forecasts portrayed reverse picture in the previous study by Das *et al*. (2008).

Therefore, the reason behind the underestimated rainfall forecasts with higher threshold over central India (CI) and north-east India (NE) is due to the fact that the monsoon flow over India getting its turn towards eastern India and NE is weaker (systematic easterly bias) in the model forecasts. In model forecasts monsoon flow is getting its U component more oriented towards South China Sea crossing Bay of Bengal rather turning towards Indian region.

In Figs. 11(a-d), spatial feature of RMSE of 24 hour forecast is only plotted for convenience although the nature of error has not been changed abruptly in 48 hour forecast but overall increase in errors over whole domain has been observed. In this discussion, we ignore the spurious errors near the periphery of mountainous region of Middle East Asia. In Fig. 11(a), RMSE of U wind over south central Arabian Sea and southern tip of Indian peninsula shows its maxima and error is uniform over rest of the area (~ 3 ms^{-1}). As seen in Fig. 11(b), upper level U has larger errors near equatorial belt of monsoon return flow although we have not seen any systematic mean errors over the same region in Figs. 10 (c&d). Therefore, day to day variation of the upper level winds has not been predicted by the model where the errors have generated arbitrarily. RMSE of V wind at 850 and 200 hPa levels are plotted in Figs. 11 (c&d) respectively. The errors are comparatively lower than U wind but reflects nearly similar spatial feature. Higher RMSEs in wind components over southern peninsular region of India have major contribution from systematic errors but near equator the errors are random. The rainfall over west coast and southern peninsula is greatly influenced by the interaction of low level monsoon flow over Western Ghats. The orographic rainfall in WC and KL region is predicted in a better way for higher rainfall threshold which may be due to the overestimated U wind produced more frequently than other region which mainly experience higher rainfall due to synoptic scale weather system. Better performance of the model over rain shadow region of SP up to moderate rainfall category is due to the fact that the model prescribed monsoon flow over the area after crossing mountain barrier is also featured in the mean error of wind components at 850 hPa level.

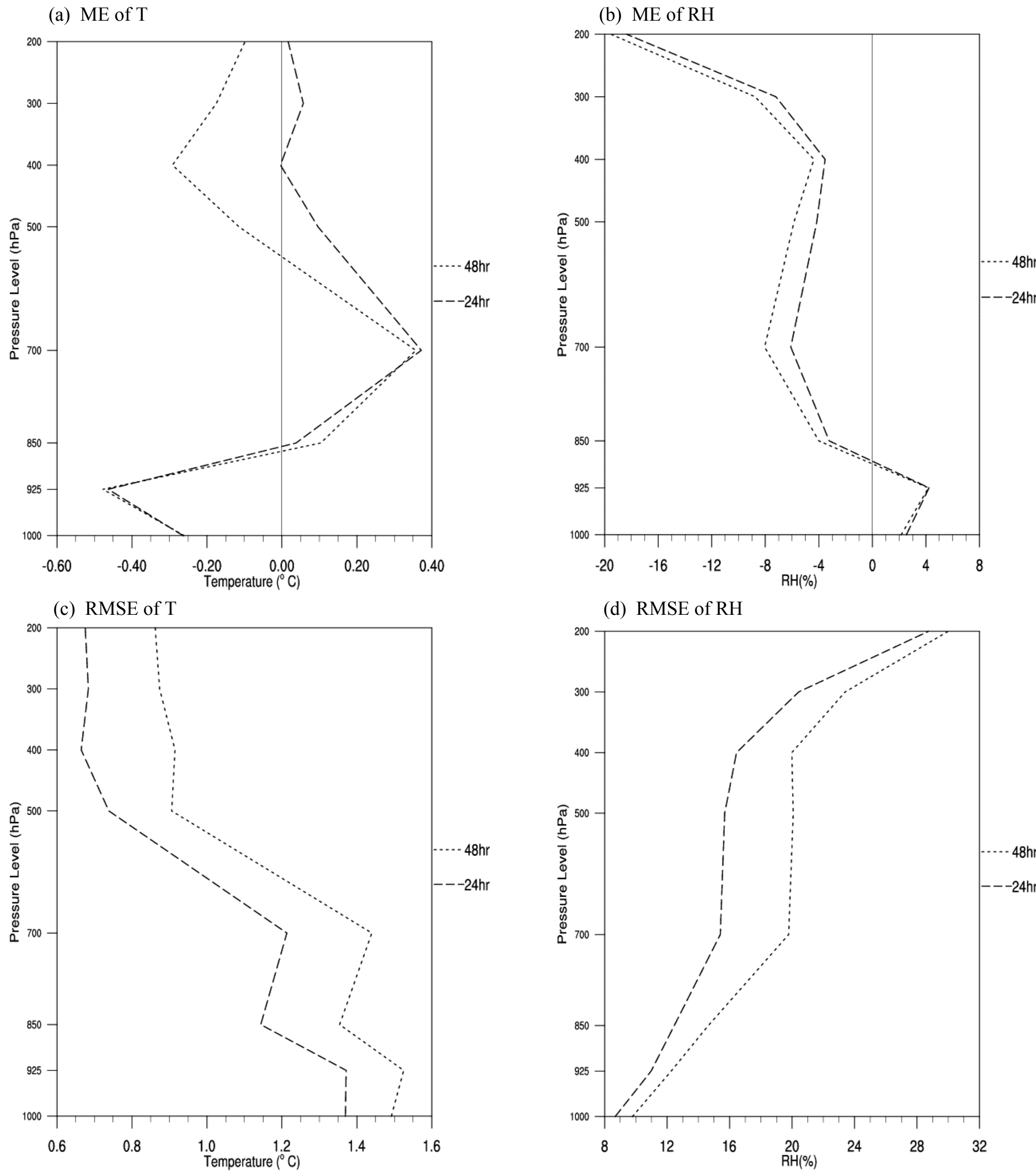
3.2.2. *Divergence and vorticity*

The left three panels of Figs. 12(a-f) shows the seasonal mean divergence at 200 hPa level for analysis and forecasts whereas right panels represent vorticity at 850 hPa level. The top panels show the corresponding mean spatial distribution of verification analysis generated using WRFDA assimilation system. The below them forecast divergence and vorticity have been plotted. The comparison between Fig. 12(b) (24 hour forecast) and [Fig. 12(c)] (48 hour forecast) with the analysis [Fig. 12(a)] clarifies that the divergence at 200 hPa has been over-predicted by the model in 24 hour forecast which diminishes in 48 hour. The divergence due to accelerating



Figs. 12(a-f). Mean divergence and vorticity during the monsoon season 2010. (a), (b) and (c) are mean spatial map of divergence at 200 hPa from model analysis, 24 hour forecast and 48 hours forecast respectively. (d), (e) and (f) are mean spatial map of vorticity at 850 hPa from model analysis, 24 hour forecast and 48 hours forecast respectively

easterlies over western part of Bay of Bengal cannot be captured by the model forecast. In turn over western Ghat region the advent of convergence in 24 hour forecast does not match with analysis. The vorticity, in Figs. 12 (d-f) depict a scenario where the model forecast is biased to generate cyclonic vorticity near MT or north of MT near foothills region. The vorticity generation over western Ghat cannot be seen in the analysis mean. This also shows model produce monsoon activity skewed towards north-east part of MT region.



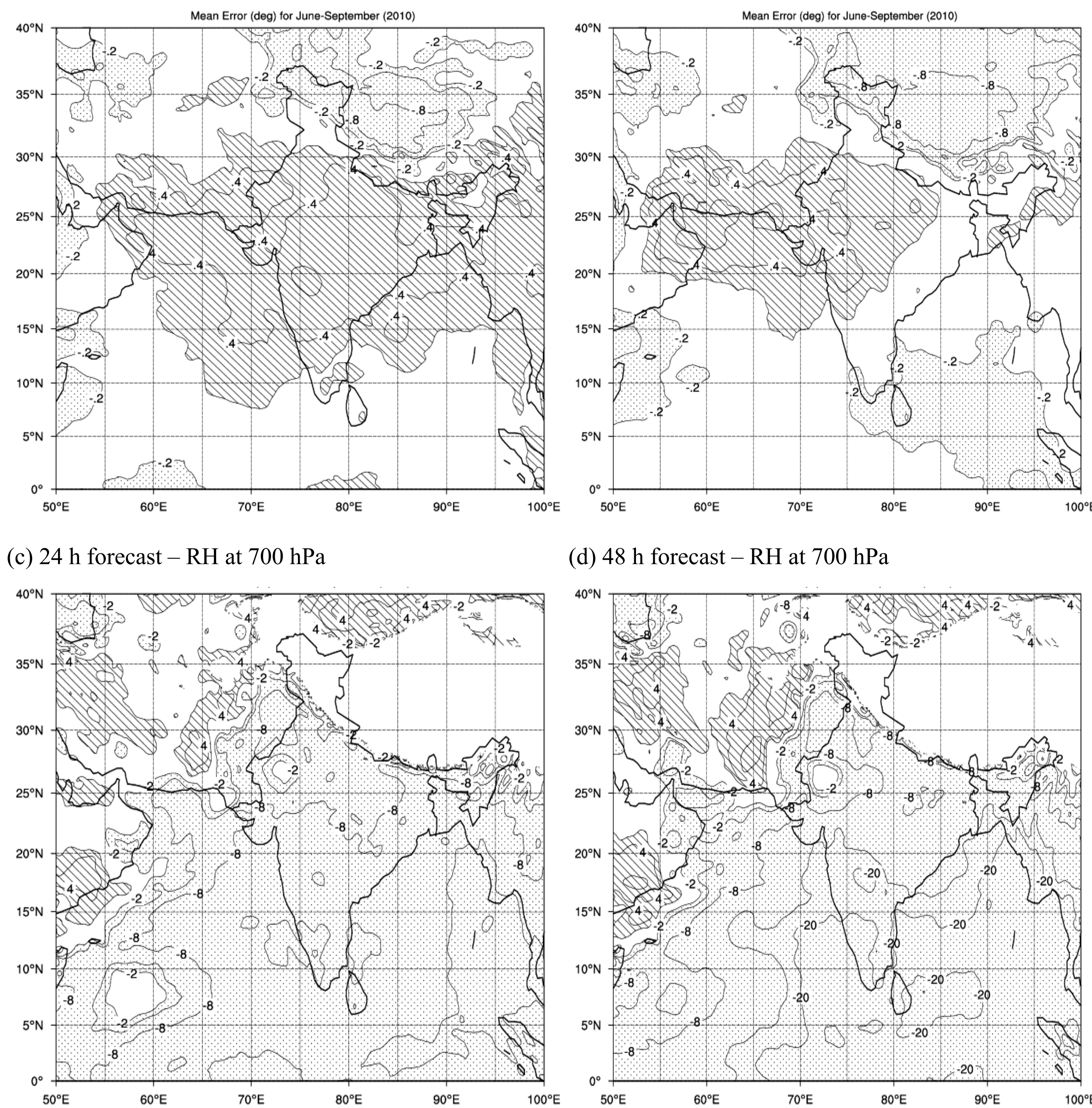
Figs. 13(a-d). Veritcal profiles of errors averaged during whole season. MEs are in (a) for T and (b) for RH respectively; RMSEs are in (c) for T and (d) for RH respectively

3.2.3. *Upper-air temperature (T)*

Similar to the wind components, the forecast errors are computed against verification analysis with same resolution and not with point observation and therefore the error values show consistent nature. Error profiles of T and relative humidity are plotted in the same Figs. 13(a-d). The ME of T is relatively small compared to RMSE. In lower levels, the mean error of T is negative (cooling by 0.4 °C) and changes its sign and become positive in the middle level below 500 hPa level [Fig. 13(a)]. The mid-level warming (~ 0.4 °C) during monsoon is more dominant in model forecasts than analyses. In upper levels, the T does not show any significant systematic bias in 24 hour forecasts but a feeble cooling bias developed in 48 hour forecasts. Fig. 13(c) shows the RMSE is larger in lower levels compared to higher levels and error increases from 24 to 48 hour forecasts. The vertical profile RMSE

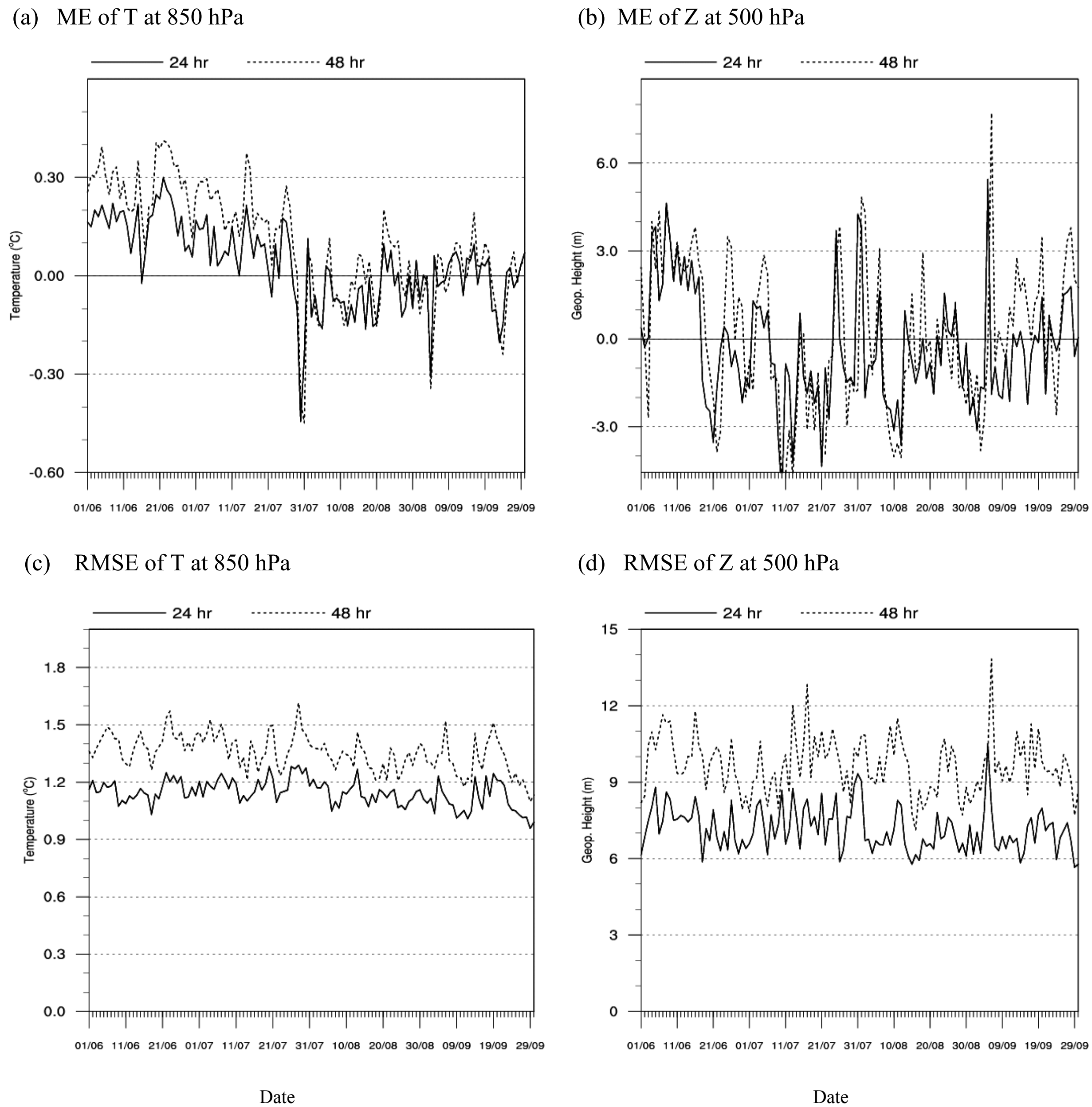
(a) 24 h forecast – T at 500 hPa (b) 48 h forecast – T at 500 hPa

(c) 24 h forecast – RH at 700 hPa (d) 48 h forecast – RH at 700 hPa



Figs. 14(a-d). Spatial distribution of seasonal ME (area with +ve error hatched and area with –ve error dotted). (a) and (b) for T at 500 hPa, (c) and (d) for RH at 700 hPa in 24 hour and 48 hour forecasts respectively

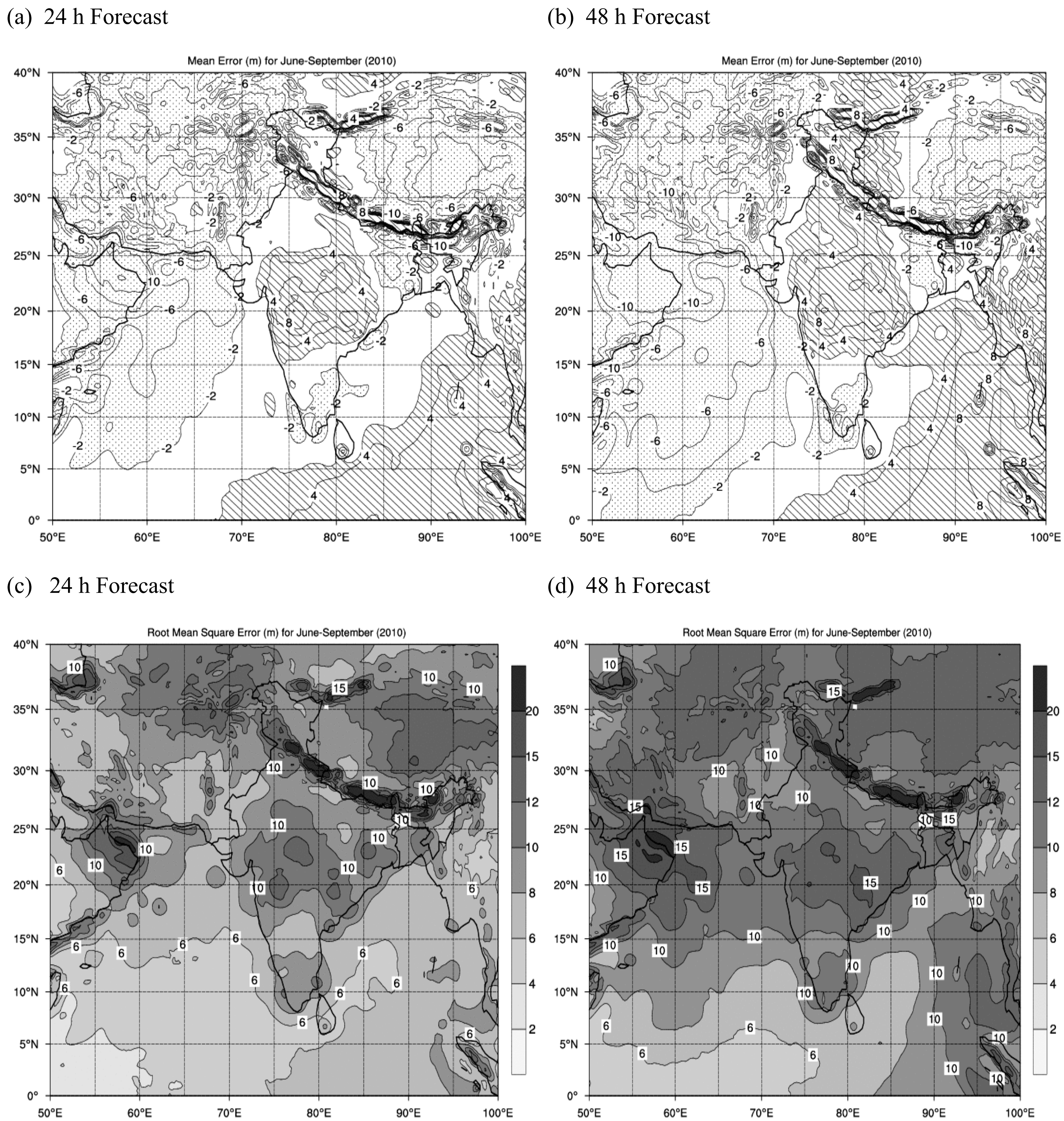
of T shows values less than a degree centigrade except near surface. The similar kind error profile has also been found in a study over Asian monsoon region by Kumar *et al*. (2012). The spatial error distribution of T has been plotted at 500 hPa level in Figs. 14 (a&b) to verify the mid-level larger feature of monsoon. Reversal of mid-tropospheric meridional temperature gradient during monsoon season is underestimated in the model forecasts in general as the negative ME (~ -8 °C) is found over Tibetan plateau and positive ME (~ +4 °C) around central India. The inception of negative ME over Bay of Bengal and adjoining north Indian Ocean in 48 hour forecasts indicate that the monsoon feature near 500 hPa level over India is gradually diminishing with forecast length.



Figs. 15(a-d). Time series of errors averaged over model domain during whole monsoon season 2010. MEs are in (a) for T at 850 hPa and (b) and for Z at 500 hPa respectively; RMSEs are in (c) for T at 850 hPa and (d) for Z at 500 hPa respectively

Therefore, the key characteristics of monsoon air-mass over continent are not well predicted considering the season as a whole.

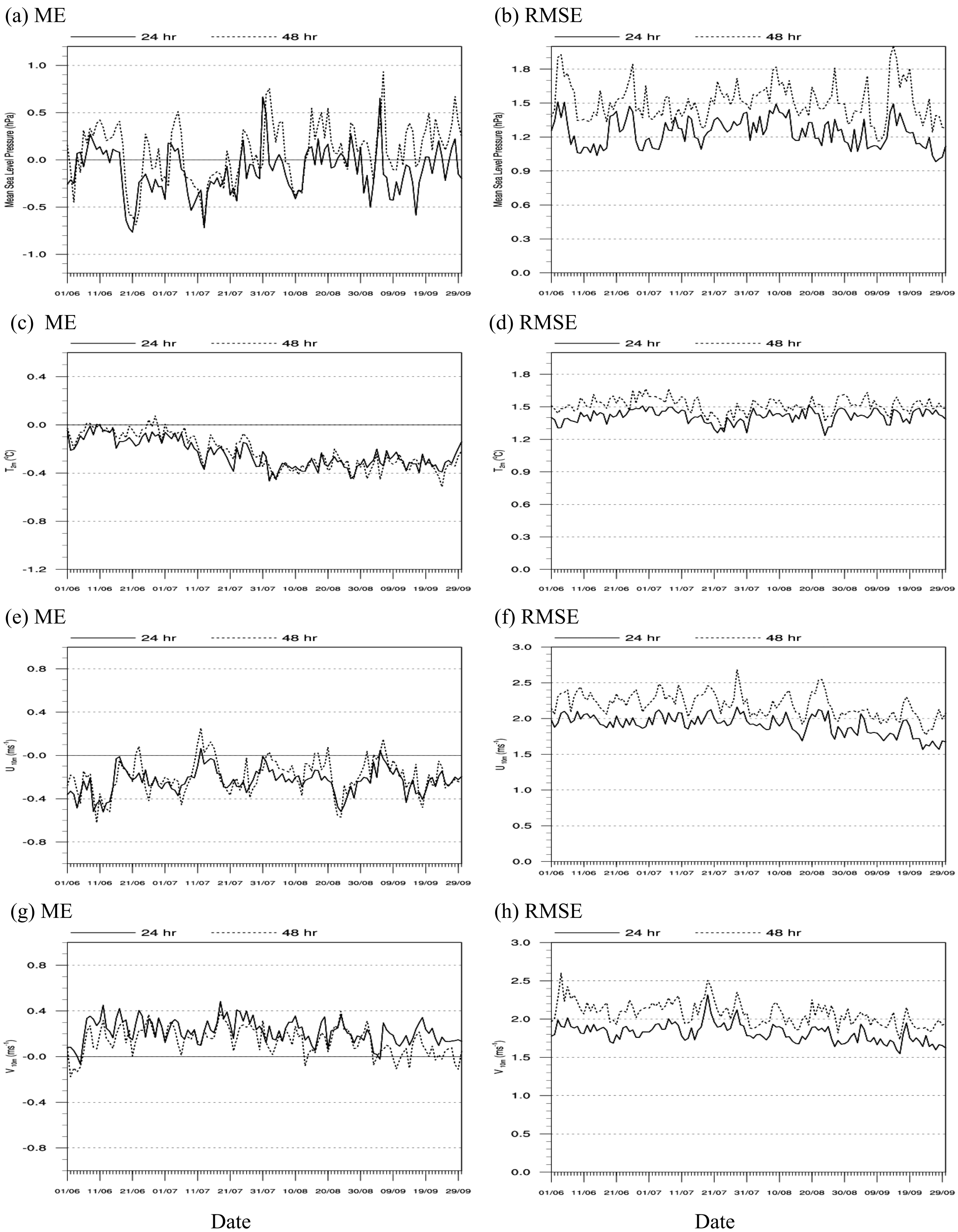
Day-to-day change in RMSE of temperature at 850 hPa [Fig. 15(a)] is frequent and sharp and nature of variation does not show any significant trend-like feature but a positive ME of temperature in starting two months of the season decreases gradually and in last two months fluctuates near zero value. Higher values of temperature in June and July over sub-continent are slightly over-estimated by the model and as the monsoon rainfall caused the overall decrease in temperature (cooling) over the region, the heating bias of the model vanishes. The error lines for different forecast hours do not show much difference amongst each other but ME and RMSE increases with the duration of model forecast.



Figs. 16(a-d). Spatial distribution of seasonal Errors for Z at 500 hPa. (a) and (b) for ME (area with +ve error hatched and area with –ve error dotted) and (c) and (d) for RMSE in 24 and 48 hour forecasts respectively

3.2.4. *Relative humidity (RH)*

Vertical profile of ME and RMSE in specific humidity are shown in Figs. 13 (b&d) respectively. Near surface below 850 hPa the model overestimated moisture built up but a rather dry atmospheric condition prevails in over-laying levels. During monsoon season moisture built up takes place extending up to 700 hPa level, but the mean error characteristics of relative humidity clarifies that the moist zone near surface is shallow in the forecasts compared to analysis. Above 400 hPa level, the sudden increase in errors corresponds to the lower value of moisture and higher error representation in relative humidity terms. Figs. 14 (c&d) bring out the spatial feature of moisture distribution error in model prediction. The model under predict the moisture content at 700 hPa levels with its negative value of mean error throughout the season over entire region except north-west part of the



Figs. 17(a-h). Time series of ME and RMSE averaged over model domain during whole monsoon season 2010 - (a) and (b) for MSLP; (c) and (d) for T at 2 m height from ground; (e) and (f) for U at 10 m above ground and (g) and (h) for V at 10 m above ground respectively model domain reaching outside the fetch of monsoon. The dry bias is evident in all forecast hours and increased with forecast duration. RMSE values in Figs. 15(a-d) separate out forecasts hours according to their magnitude. Comparatively higher values of temperature do not support the higher amount of moisture holding capacity of these layers and probably the moisture lift up from the surface is not sufficient in the model forecasts. On the other hand, the mid-tropospheric temperature distribution depends on the warming due latent heat release by monsoon clouds in turn depends on moisture availability at these levels.

3.2.5. *Geopotential height (Z)*

Temporal variations of errors in geopotential height at 500 hPa are shown in Figs. 15 (b&d) and spatial variation in Figs. 16 (a-d) which is demonstrating the model performance in middle level of the troposphere during monsoon. Excessive jumpiness and inconsistent mean error pattern of the daily error fluctuation signify that the model representation of middle levels of the troposphere during the season is randomly erroneous and evolution-migration of weather systems mainly controls the error in the model forecast. Although the mean error of Z at 500 hPa increases meekly with forecast length, the RMSE increases significantly from 24 to 48 hours forecasts.

Although daily mean error in Z averaged over whole domain throughout the season is very less (value less than ± 3 m), the spatial feature shows that Z has a significant systematic pattern of ME over Indian monsoon region. But in 48 and 72 hour forecast, the model generates a significantly large mean error in Z. Weakening of low in Z with positive mean error over Bay of Bengal and central India, which is migration zone of monsoon low pressure system respectively is very much important error feature of model forecasts. Arabian Sea and adjoining continental areas are covered by negative ME of Z. Therefore, the model prescribed system in the middle level of the troposphere is erroneous by their location and movement. This caused the shifting of the prominent rainfall zones. This is reason the rainfall forecasts of the model is penalized doubly while computing continuous scores at grid points. The rainfall verification also shows that the zones (CI, EI and NE) experiencing higher rainfall due to migration of transient synoptic weather systems have poor scores compared to other zones. The RMSE pattern remains similar in each forecast hour with a consistent increase in the value. The systematic contribution of ME in RMSE is noteworthy but the randomness in geopotential structure in the model forecasts compared to analysis cannot be ignored.

3.8. *Surface parameters*

Mean error and root mean square error have been computed for four surface variables *e.g.*, mean sea level pressure (MSLP), air temperature at 2 m height (T2m) and wind components (U and V wind U10m and V10m respectively) at 10 m height from surface. Domain averaged error fluctuations for MSLP on day to day basis are plotted in Figs. 17 (a&b). The fluctuation of ME is very much random between -1.0 and 1.0 hPa. Mean error of MSLP in 48 hours forecast is higher than 24 hours forecast. As the MSLP has been diagnosed from other variables, errors in MSLP may be caused by other forecast variables too (Miao *et al*., 2008). In general the model has a tendency of filling up of low with time and intensification of high in the region during whole monsoon season. The RMSE varies within a range from 1 to 2 hPa but forecasts hours are separated by their values increasing with forecast duration. The variation of ME (±0.5 hPa) is very much lower than that of RMSE which in turn shows up the randomness in model errors which gradually increases with forecast hour. Still, gradual decent and ascent of ME lines reveal the episodic nature of errors which relates to the life-span of different monsoon system.

Consistently negative mean error of air temperature at 2 m height is visible in Fig. 17(c) during the whole season and this cooling tendency has an increasing trend with days in a random way. But, the RMSE values of the same in Fig. 17(d) are not showing any kind of trend with time. No major difference is notable amongst forecast hours in their time series of mean error whereas RMSE value increases considerably from 24 to 48 hour.

Error features of wind components at 10 m height portray random characteristics in their daily fluctuations. Graphical lines of mean error for different forecast hours are interweaved against each other and show on the whole analogous features. U wind component carries an easterly bias varying and V wind has a southerly bias which is more or less consistent throughout the season. Although RMSEs of wind components for all forecast hours are distinctly separated by their magnitude, both of them represent decreasing trend with time as the season progressed.

4. Summary

The performance of WRF model during whole monsoon season has been investigated as a part of operational monitoring. The skill scores for rainfall and standard errors for other variables have been examined. All skill scores suggest that rainfall forecasts over Indian region as a whole is satisfactory but individual zone-wise performance differs from one rain category to other. For high rainfall amount performance degradation is an established feature and also has been noticed in this study. The spatial variation of model performance to predict rainfall is familiar and this study only investigated the categorical scores specific seven zones. The model configuration used in real-time forecast in the season is found to be better suited for the zones receiving lower rainfall below rather heavy rainfall categories. Rainy-day forecast can be a reasonable option for all different zones of India as all categorical scores show higher values except north-east India (GSS approaches zero). HK and HSS shows that for moderate rainfall category the model is more reliable and randomness and chance forecast is less compared to other higher rainfall categories. But, accurate rainfall intensity prediction over a specific zone is still not within the capable limit of the model as the categorical skill scores drops below acceptable limit.

Wind errors suggested that the model represented comparatively weaker low level south-westerly wind flow and weaker upper level north-easterly wind as well over Indian main land. In general, monsoon flow in model forecasts could not attained its usual turning over Bay of Bengal rather flowing towards east over South China Sea as the ME of U wind (more than 2 ms^{-1}) has its extended belt over the region.

In mid-levels as ME of T shows nearly 6 °C temperature gradient reversal which is contrary to the thermo-dynamical characteristics of monsoon. A significant dry bias, ME of relative humidity reaching from -8 to -20 % in the layers near 700 hPa also suggests, the moist layer of monsoon systems is shallow in the model. The rainfall performance over CI, EI and NW region for higher rainfall category (greater than 35.5 mm) suggested that the rain bearing synoptic scale weather systems could be not predicted well with their transient behavior. This fact is also clearly brought out in the mean error features of Z at 500 hPa. Although, the order and nature of the errors do not show any unusual behavior, randomness of the errors for surface parameters restricts the use of any systematic error correction algorithm to improve the forecasts for real-time use. But there is a scope to correct the forecast values of 2m air temperature removing the systematic bias.

Verification of forecasts using eye-ball estimation does show the usability of model predicted rainfall over the region but with specific consideration of displacement, intensity and structural correction. Other methods suitable for high resolution forecast verification are necessary to identify specific weakness and limitation of the model. Scale separation and object-oriented validation is necessary for the development of a suitable modeling system to forecast Indian summer monsoon processes. Improvement of the modeling system and synchronous validation studies have to be repeated for several monsoon seasons taking into consideration the inherent diverse nature of scale interaction.

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