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Diurnal-scale signatures of monsoon precipitation over India

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The pattern of diurnal-cycle signatures of precipitation varies with season and region. This study focuses on spatio-temporal variations in numerical model based forecasts of the rainfall amount and its intensity over Indian region during the monsoon season 2013 and some specific days of monsoon season 2017. Spatial patterns of 3-hourly rainfall during the season, as seen in day-1, day-3 and day-5 predictions of two numerical weather prediction models viz NGFS and NCUM have been examined here. Temporal changes in the frequency distribution of hourly rainfall amounts have been studied. It is noted that NGFS model predicts more rain than NCUM model during all the hours of the day. Maximum rainfall over the land and oceanic region has been predicted during the late afternoon and early morning hours, respectively.

Keyword: Southwest monsoon, NGFS, NCUM, Indian land mass, Active, Break, Rain fraction, Convection and precipitation

1 Introduction

The diurnal cycle of rainfall and convective activity is a basic characteristic of the climate over the tropics. The diurnal variation is one of the important characteristics of precipitation over a region, and is often related to physical processes or atmospheric dynamics over the area[1]. On the meso-scale domain there are local land and sea breezes, mountain/ valley circulations, and surface heterogeneities that influence precipitation patterns over the monsoon regions of the world.

Generally, information on rainfall climatology is available for time scales such as monthly, seasonal or annual rainfall, which is derived from daily rainfall amounts recorded at individual regions/stations[2]. It is also important to know the climate features of rainfall on shorter time scales such as daily, hourly and even minute-wise, for the water management systems[3], agricultural operations and soil erosion studies, etc. Another important aspect is the distribution of rainfall during a heavy rain spell of 24 h duration. Water balance on land surface is highly sensitive to the time distribution of rainfall. It is essential to provide information of the rainfall distribution on a 'rainy day' along with the estimation of extreme rainfall event, such as Probable Maximum Precipitation at a place, for designing the spillway capacity of the reservoir/dam, etc. of a river basin.

The main objectives of this study are to examine: (a) spatial and temporal variations in the seasonal rainfall over India, (b) lemporal changes in the diurnal cycle of rainfall and (c) average time distribution of rainfall during active periods of monsoon, etc.

During the northern hemispheric summer, southwesterly winds bring moisture from the Indian Ocean and results heavy rains across India during June to September. During the northern summer, the atmosphere over India is highly unstable due to the large amount of moisture present in the lower troposphere, and only a small perturbation is often enough for formation of clouds and result in precipitation[4]. On average, India receives rainfall with a range of 70 to 110 cm in a year out of which summer monsoon contributes nearly 75-80 % to the annual rainfall in many parts of the country[5].

In June the inter-tropical convergence zone (ITCZ) marches northward after crossing the southernmost tip of peninsular India and establishes itself about 5° south of the Himalaya for next two months. In September the ITCZ starts its annual migration southward and precipitation ceases over the central part of India by the end of this month. In addition to ITCZ there are other rain-producing mechanisms like monsoon low, off-shore vortex, mid-tropospheric cyclone that trigger precipitation in different parts of the country. A salient feature of monsoon rainfall is the movement of depression/storms originating over Bay of Bengal or Arabian Sea.

1.1 NWP models

During monsoon 2013, National Centre for Medium Range Weather Forecasting (NCMRWF)

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employed the following two global models namely (a) a high resolution spectral (T574L64) Global Forecast System (NGFS) for generating ten day forecasts from the initial conditions of 00Z every day. In this study NGFS, or T574 are used invariably in the text and figures the above two notations meant the same model. Here after the NGFS resolution can be marked as T574 (in the figures). This forecast model has a resolution of approximately 22 km in horizontal and has 64 levels in the vertical. The resolution is not uniform everywhere near to equator it is 22 Km (app). When we move away from equator towards higher latitudes it will reduce. The associated 3-D VAR data assimilation system namely, grid-point statistical interpolation (GSI) is used to initialize the global model. This model has the capabilities to assimilate various conventional as well as satellite observations including radiances from different polar orbiting and geostationary satellites. (b) a high resolution grid point model called NCMRWF unified model (NCUM). The details of the NCUM are given below: Observation Processing System (OPS), four dimensional variational data assimilation system (4D-VAR) and integration are the main components in this global forecast suite. The OPS prepares quality controlled observations for 4D-VAR in the desired format. 4D-VAR system produces the analysis, which is the best estimate of the atmospheric state, used as the initial condition for the NCUM forecast. The NCUM resolution is 25 Km (app) during the year 2013; whereas during 2017 it is 17 Km (app). This detailed information may be obtained from www.ncmrwf.gov.in

1.2 Earlier studies

The diurnal variation in the rainfall patterns has been a subject of research, but the scarcity of observational data sets with high temporal and spatial resolution has led to some conclusions which may not be generalized to a reasonable extent.

Several previous studies have identified the modulating role of orography as a major factor in the convectional process affecting the diurnal patterns of the rainfall in the tropics[6-9]. Many studies available on hourly rainfall data over the tropical region, describes diurnal variation during summer monsoon season or a particular season in India[6,7,10-12] with the space-based observation.

Over India the diurnal variation of precipitation has been studied by many authors[4,13-15] using data from a few rain gauge stations according to their availability.

There have been numerous studies on the diurnal cycles of convection over Asia[16-18]. Over land, many areas exhibit an afternoon maximum of convection, as expected from daytime heating; however, certain regions such as the base of the Himalayas and mountain basins have a late night, early morning maximum[19].

Over the open ocean, an early morning maximum of precipitation has been observed, which has been attributed to horizontal gradients in radiative cooling between cloud systems and their environment, daytime stabilizatation of the upper troposphere by short-wave heating, and/or the life cycle effects of meso-scale convective systems[20,21]. While an early morning maximum has been found over some ocean areas around Asia, the diurnal cycle there is rather complex.

Convective propagation tied to the diurnal cycle is also present over land in monsoon regions. Wang *et al.*[9], documented a diurnal cycle of convection over the eastern Tibetan Plateau, peaking in the late afternoon or early evening then propagating eastward.

The distribution of rainfall or breakup of extreme rainfall amounts on the daily time scale into shorter time intervals requires analysis of hourly rainfall records. Many studies on the time distribution analysis of rainfall, in the Indian context, are connected with certain hydraulic projects or for certain river basins[1,2,22,23]

At NCMRWF for the first time we have examined some characteristic features of short durations (1 h and 3 h) rainfall in India along with the temporal changes in their characteristics during the monsoon 2013 and seasonal mean of 2017. Accordingly, the main objectives of this study are to examine: (a) spatial patterns of 3-hourly rainfall during the season as seen in day-1, day-3 and day-5 predictions. The odd days are chosen just as sample from the 10 days model integration data (b) spatial and temporal variations in the number of rainy hours contributing to seasonal rainfall over India (c) temporal changes in the frequency distribution of 3 hourly rainfall amounts (d) temporal changes in the diurnal cycle of rainfall (e) contribution of daytime and nighttime rainfall to the total monsoon rainfall and (f) area average rainfall during all the hours of the day over different regions of India.

1.3 Data description and methodology

The precipitation information used in this work is obtained from both space-based precipitation observation and precipitation obtained from NCMRWF model forecasts. The observational data are primarily from three-hourly rainfall remotely sensed by satellites.

The Tropical Rainfall Measuring Mission (TRMM) satellites with the Precipitation Radar (PR) and the Microwave Imager (TMI), estimation of precipitation became possible.

The 3-hourly Tropical Rainfall Measuring Mission (TRMM) product 3B42 version 7.0[17] was used for the period 01 June-30 September 2013 and 2017. The 3-hourly averaged values are centered at the middle of each 3 hour period; for instance, the rain rate corresponding to 00Z represents the average value between 22:30 IST and 01:30 IST. The spatial resolution of this data set is 0.25°X 0.25°, and the domain of coverage is 50°S~50°N, 0°~360°E. This product is an optimal combination of various high quality microwave estimates to adjust infrared estimates from high-frequency geostationary observations (see http://trmm.gsfc.nasa.gov). The data set thus manages to avoid the risk of aliasing longer time scale variability onto the diurnal cycle and hence provides an opportunity to study the diurnal-scale variability of rainfall.

In addition to 3B42, the other TRMM products like 3G68, 3B41 are also available. However, the primary advantage of the former product is its greater spatial coverage at any given point in time. Also, since rainfall retrieval using passive microwave sensors could introduce phase and amplitude errors. Some time the under estimation of west coast rainfall is one of the major limitations of TRMM rainfall.

A large difference in the observed and model-predicted diurnal variations in precipitation will indicate a deficiency in the models to capture some of the physical processes producing precipitation. In addition to total precipitation the convective precipitation, the Total Perceptible Water Content (PWAT) obtained from model are also examined for this monsoon period.

Understanding the diurnal cycle of convection in coastal region is important because so much precipitation occurs over there and global models[21] do not properly represent the diurnal cycle of convection.

In global atmospheric prediction models only the vapor phase of water is carried as a prognostic variable, and precipitation is computed as a by-product of the conservation of the water vapor principle. Precipitation is produced by saturation, due to convergence of moisture and resultant upward motion. Parameterization schemes for a large scale condensation in a layer clouds, and for convection of both shallow and deep types, are used to take care of the saturation of water vapor in all of the parameterization process fraction of the water vapor condensing in the cloud is allowed to fall out of the cloud base; part of this is allowed to evaporate as it falls through unsaturated layers below the cloud base, and the rest reaches ground as precipitation. The parameterization schemes for the computation of precipitation and some other characteristics of the NCMRWF models are well documented in the research reports (www.ncmrwf.gov.in).

For the present study, the time duration (24 h) of one calendar day is divided into eight equal temporal scale intervals. The day time (05:30 IST ~ 17:30 IST) period is divided into four temporal scale namely 00-03Z, 03-06Z, 06-09Z and 09-12Z. Similarly the night time period (17:30 IST ~ 05:30 IST) divided into four temporal scale 12-15Z, 15-18Z, 18-21Z and 21- 00Z respectively.

2 Results and Discussion

In this paper the results and discussions are written into four parts. The first part deals with the diurnal variation of rainfall during the season June to September (JJAS) in the spatio-temporal scales. The second part deals with the diurnal variation of the Total Precipitable Water Content (TPWC) during the season JJAS. The third part deals with the diurnal variation of rainfall during the active and weak phases of the monsoon in the spatio-temporal scales. The last part deals with the area average rainfall distribution in the hourly temporal scale.

2.1 Diurnal variation during the season

Figure 1 shows three hourly accumulated seasonal mean of (a) rainfall plots obtained from TRMM-3B42 estimation/observation (b) precipitation obtained from day-1 forecast of NGFS model (c) precipitation obtained from day-1 forecast of NCUM respectively.

In general the TRMM observations show the strongest diurnal variability over the topographical rich Himalayan regions. Over the central India, rainfall appears to be peak during 06-12Z. In ocean, the most striking observations over the Bay of Bengal are the presence of multiple modes of diurnal variation in rainfall. Several other studies also reported similar behavior[13,20,24]. Bay of Bengal receives most of its rainfall during 00-09Z. Extremely

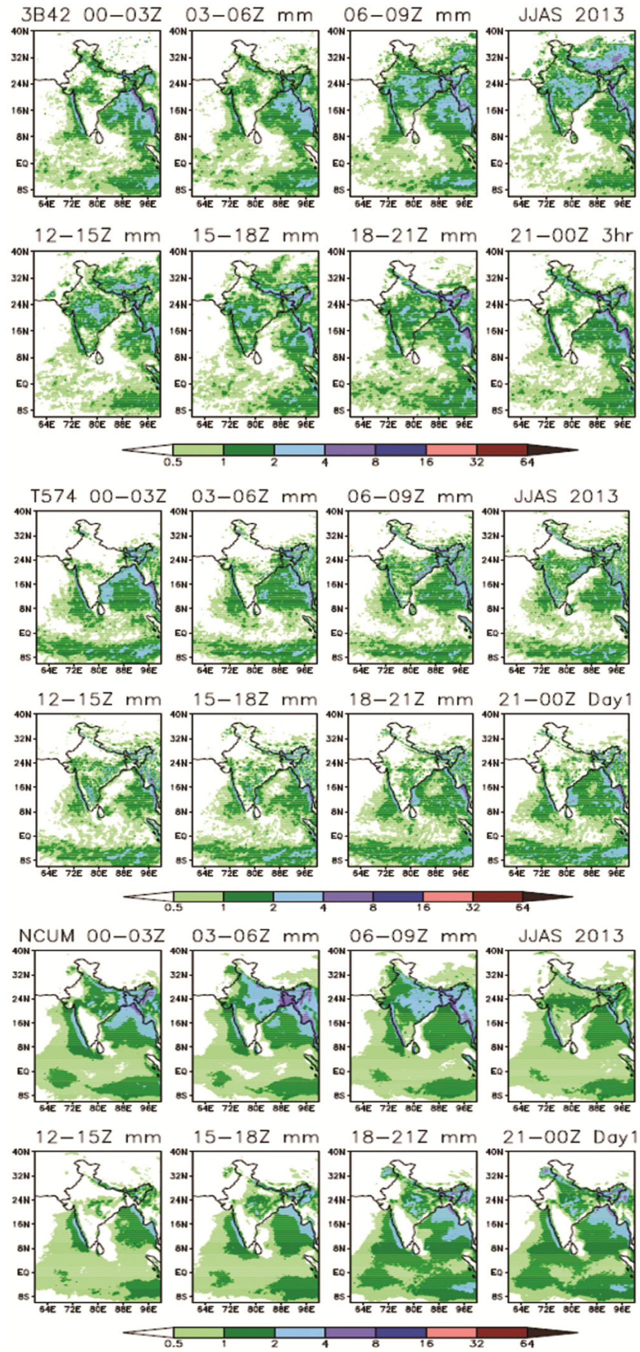

Fig. 1 − The rainfall for JJAS corresponding eight octets as seen in day-1 fcst.

minimum or no-rainfall event occurred over southern part of Tamil Nadu, Kerala and parts of Karnataka during the period 21-06Z.

During 06-09Z, it is noted that the NGFS model under predicts the rainfall; whereas the NCUM model is predicting the rainfall almost the same amount as observed from TRMM over Indian land mass region. During the early morning 00-03Z, the NGFS is under predicting, but at the same time the NCUM is over predicting the rainfall amount by 1~2 mm over Bay of Bengal. In the evening time 12-15Z the west and central India region receives rainfall at the rate of 1-2 mm; the NGFS is able to predict the same amount as observed by TRMM, but the NCUM predicts extremely less rainfall during same evening period. In the equatorial region the satellite observed rainfall is seen only in the south East Indian oceanic region. The NGFS model predicts almost the same amount of rainfall throughout the day over that region; whereas the NCUM model predicts this oceanic rain from midnight to dawn. The maximum intensity of the rain is seen in NCUM during morning hours over central and north east region of India; whereas the NGFS model does not predict any rainfall at that time. The foothills of Himalayan region is getting significant amount of rain during early forenoon. During day time the head Bay is active in NGFS and NCUM model which is observed in TRMM observation also.

Figure 2 shows three hourly accumulated seasonal mean rainfall plots obtained from day-3 forecast of NGFS, day-3 forecast of NCUM and day-1 forecasts of NCUM respectively. Over equatorial Indian Ocean, NGFS model is consistently raining almost the same amount of rainfall during day and night time; which indicates that NGFS is having less diurnal variability of rainfall over this region. The NCUM model predicts considerable amount of diurnal variability over this oceanic equatorial region in the day-3 forecast plots.

Over land, the NCUM model shows maximum intensity of rainfall during morning hours 03-06Z over central, east and north east region of India; whereas the NGFS does not predict the desire intensity in the day-3 forecasts. During night time the Bay of Bengal region start getting more rainfall from the midnight to early morning time ie 21-03Z. Almost the same salient features are seen during the monsoon 2017 also. The results are almost same for the year 2013 and 2017.

Figure 3 shows three hourly accumulated seasonal mean rainfall plots obtained from day-5 forecast of NGFS and NCUM, respectively. Over the equatorial Indian Ocean, the NGFS is predicting considerably less amount of rainfall when compared to day-1 and day-3 plots; whereas the NCUM model is maintaining location and time of rainfall within this region. Over land region the NCUM model predicts rainfall of the order of 3-5 mm in the central, east and adjoining oceanic region during forenoon hours

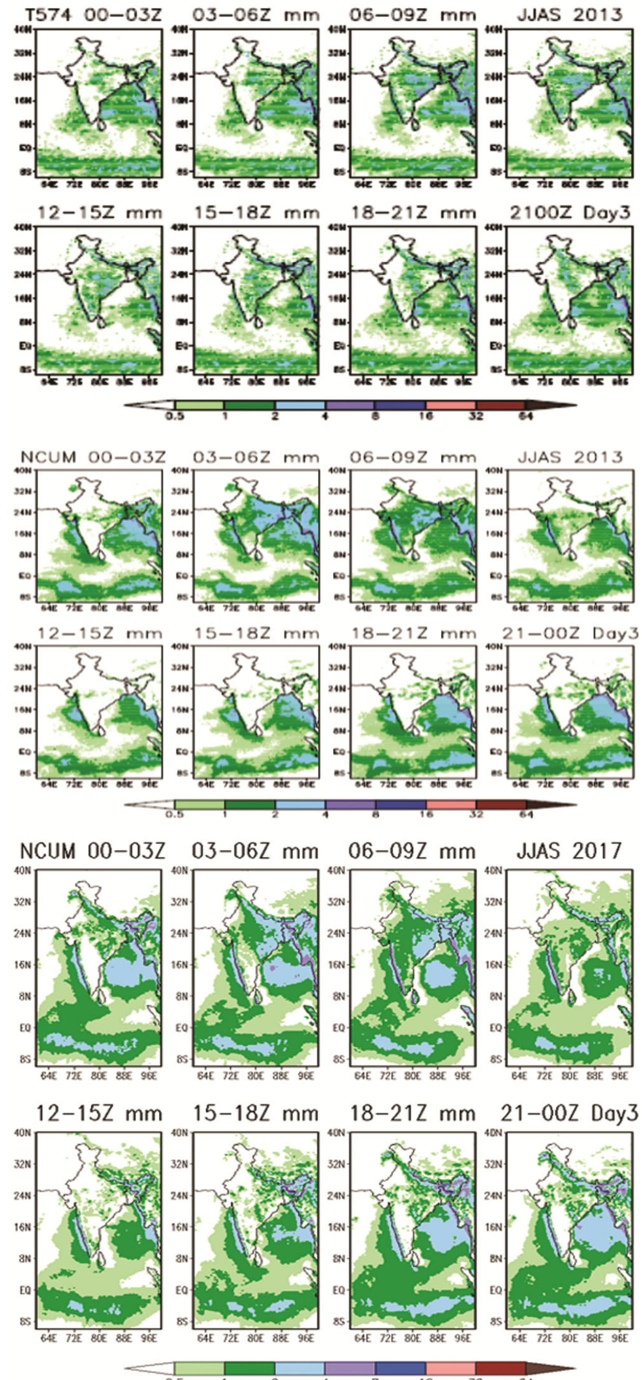

Fig. 2 − The rainfall for JJAS corresponding eight octets as seen in day-3 fcst.

03-06Z; whereas the NGFS model is not able to predict the same.

The diurnal cycle has its maximum amplitude over a small area in the east head bay of Bengal.

The NGFS moisture analysis (the corresponding figure not shown here) show the moisture variable in

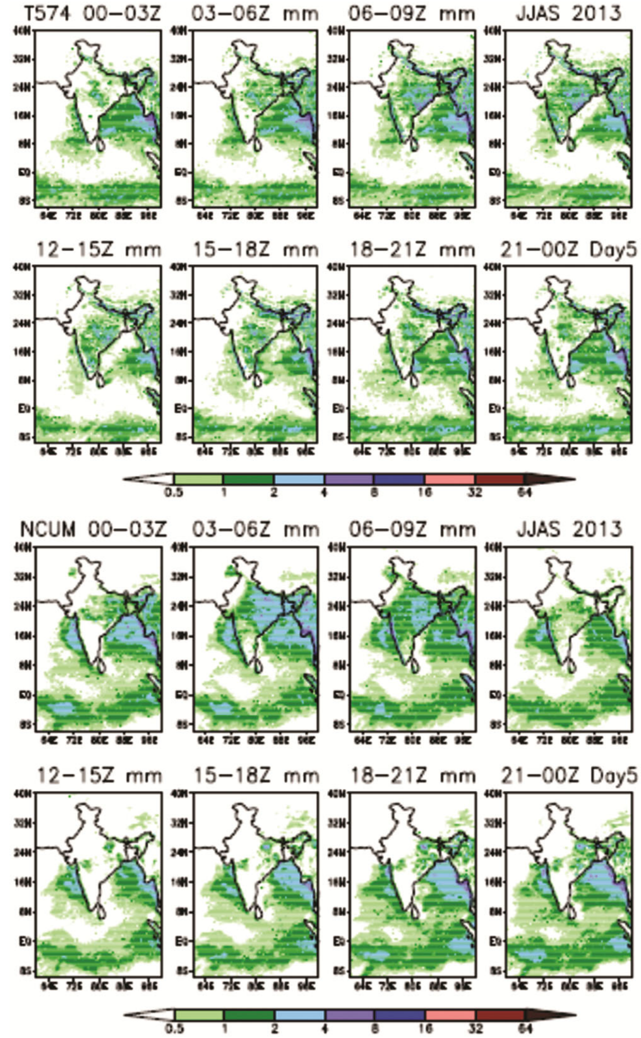

Fig. 3 − The rainfall for JJAS corresponding eight octets as seen in day-5 fcst.

terms of TPWC is seen of the order of 60-80 mm in the coastal region of east India and adjoining head Bay of Bengal throughout the day and night time. There is no significant diurnal variability of TPWC noticed during this season. The maximum amount of TPWC of the order of 70-80 mm is predicted over Sunder ban delta region during day time; gradually it is reducing after 12Z. There is no correlation found between diurnal variability of TPWC and the diurnal variability of rainfall in this study. Here it is learnt that a significant amount of TPWC variation (at the wide range of 35~90 mm) is seen over Indian longitudes during the northern summer. The above result is different from these model predictions.

2.2 Diurnal variation during active and weak phase

During 2013 the active phases[25,26] of the monsoon are realized during the following period: (a) 5-16 June

(b) 26-31 July (c) 15-20 August (d) 23-30 September. One of the above periods 5-16 June 2013 is discussed in this part. These active periods are chosen according to the usual criteria of continuous rainfall for more than three consecutive days over the core monsoon region. During June the rainfall activity over the country as a whole was above normal. Most of the subdivisions of India received excess/normal rainfall in June. The monsoon covered the entire country on 16th June, nearly a month ahead of the normal scheduled date. During this onset phase India has witnessed considerable amount of rainfall (wet spell) during 5-16 June 2013.

Figure 4 shows three hourly accumulated rainfalls for the above period (a) rainfall plots obtained from TRMM-3B42 estimation/observation (b) precipitation obtained from day-3 forecast of NGFS/T574 (c) precipitation obtained from day-3 forecast of NCUM model respectively.

The TRMM observation shows that the central and eastern part of India has more rainfall activity during 06-12Z time. The Western Ghats of India is also received considerable amount of rainfall throughout the day. Over the northern hemispheric equatorial belt, rainfall amount is same during both day time as well as night time. In the foothills of Himalayas frequent rainfall activity is estimated during later part of the day time.

With the NGFS/T574 plots, the diurnal variability over Arabian Sea is seen between early morning and late evening; whereas the NCUM plots have very less or no variability over the west coast of India and the adjoining Arabian Sea region. The central, eastern, north eastern part of the country received more rain during 03-09Z as seen by NCUM. But these features are not reflected in the NGFS/T574 plots when compared TRMM observation.

None of the model is having significant amount of rainfall activity over foothills of Himalayan region during 12-18Z time zone as seen in TRMM estimates. When compare with the other space-based observations it is noted that probably the TRMM satellite may be over estimating the rainfall during 09-12Z time zone.

Figure 5 shows three hourly accumulated seasonal mean for (a) rainfall plots obtained from TRMM-3B42 estimation/observation (b) precipitation obtained from day-3 forecast of NGFS/T574 (c) precipitation obtained from day-3 forecast of NCUM model, respectively.

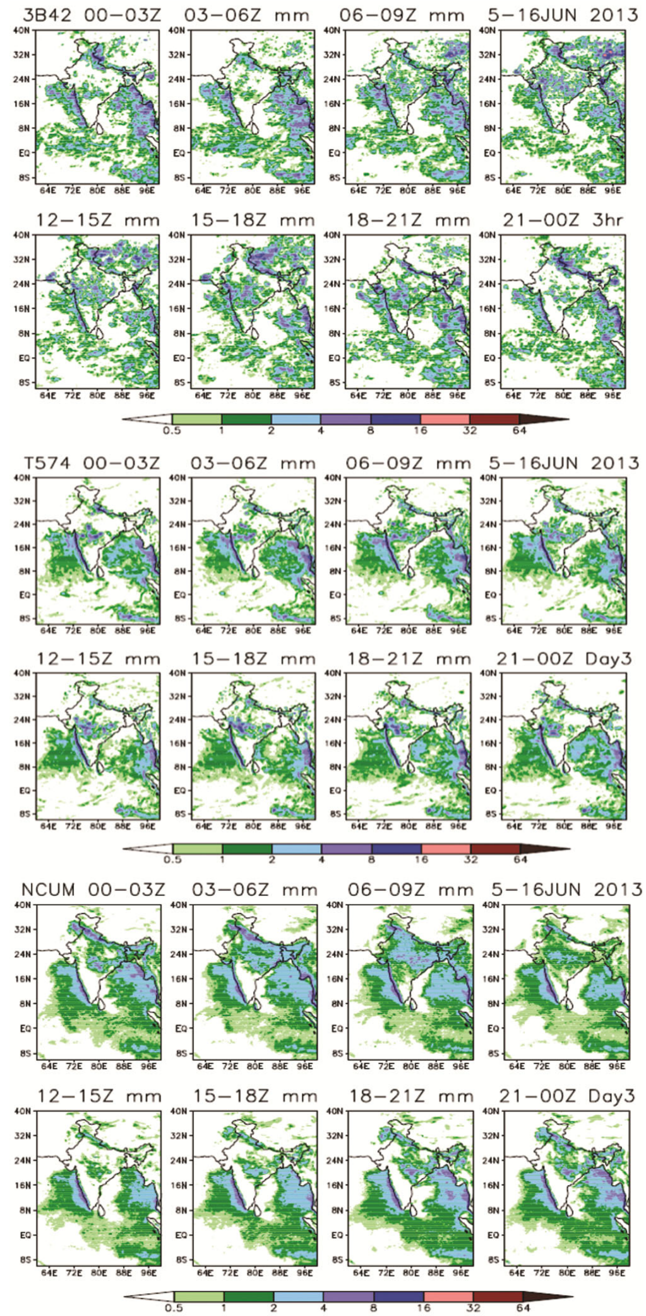

Fig. 4 – The rainfall for 5-16 Jun corresponding eight octets as seen in day-3 fcst.

There were more than 2 weak phases noticed during this monsoon season. July is the representative month for the summer season even then a weak/less amount of rainfall phase has been occurred during July. Another the weak phase is seen during 21 Aug-4 Sep 2013.

In general the observations show that the strongest diurnal variability is noticed over the eastern part of

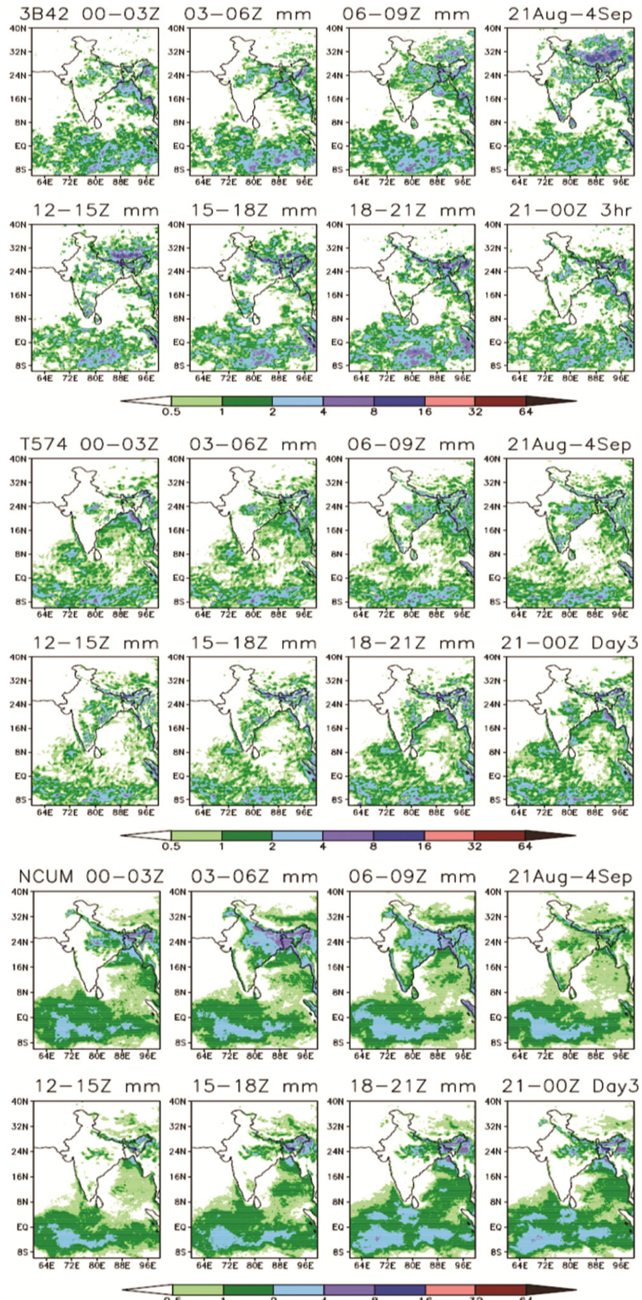

Fig. 5 − The rainfall for 21 Aug-4 Sep corresponding eight octets as seen in day-3 fcst.

the Himalayan mountains and the adjoining neighboring countries, Nepal, Tibet, China and Bhutan during 09-15Z. The central Indian regions west Uttar-Pradesh, east Uttar-Pradesh, east Madhya-Pradesh, Bihar and Uttarkhand receives the peak amount of rainfall during 06-09Z. The equatorial Indian oceanic regions have least diurnal variability. The peak rainfall amounts are noticed during 00-09Z time zone.

The coastal region of west Bengal is receiving consistently same rainfall amplitude during 00-09Z. In the peninsular India least amount or no rainfall events occurred during 00-06Z; whereas little amount of rainfall is seen during 12-18Z. The general conclusion during the weak phase is that the equatorial region and adjoining southern hemisphere rains almost all times of the day in the TRMM observations, NGFS and NCUM models. Here it is noteworthy to write that the day-3 forecasts of NCUM model are showing the maximum amount precipitation at the order of 2-4 mm over this region. As per the observation the northern part of central India gets peak amount of rainfall during 00-06Z. In the NCUM model then gradually it is reducing up to 9Z time; whereas the NGFS model shows this feature but the amplitude is very less.

With reference to the mountain peak precipitation which occurred during 09-12Z is not reflected in the NGFS/T574 and NCUM models. Of course no rainfall over southern peninsular region during 00-09Z can be validated with NGFS model. This may be due to snow. The distinct feature of Tamil Nadu, Kerala rainfall during 06-09Z in the NCUM model is not realized in the observation. During this weak phase the rainfall occur over coastal region of northern Bay of Bengal during 00-09Z in observation and NGFS model predictions whereas the NCUM captured this rainfall three hours ahead (i.e. 18-06Z time zone).

In order to study the diurnal variation during active and weak phase, the difference in rainfall amounts between these phases (wet period minus dry period) are chosen as follows. We have chosen 5-16 June for wet period and 21 August ~ 4 September for dry period during this monsoon. The difference plots obtained between observation and the day-3 prediction of NGFS model, day-3 prediction of NCUM model are shown in Fig. 6. In the observation the findings are listed as: Most of the positive values are seen over the land region during 06-21Z. The west coast consistently has positive value at the order of 2 to 4 mm during day time. Specifically the peak positive values are noted over the west coast and Gujarat coast during 06-09Z. A small pocket of positive rainfall is noticed over the Uttar Pradesh and Himachal Pradesh region during 00-06Z. Negative amount of rainfall is predominately seen over Pakistan and adjoining region but with very less amounts. The equatorial Indian coastal region is seen

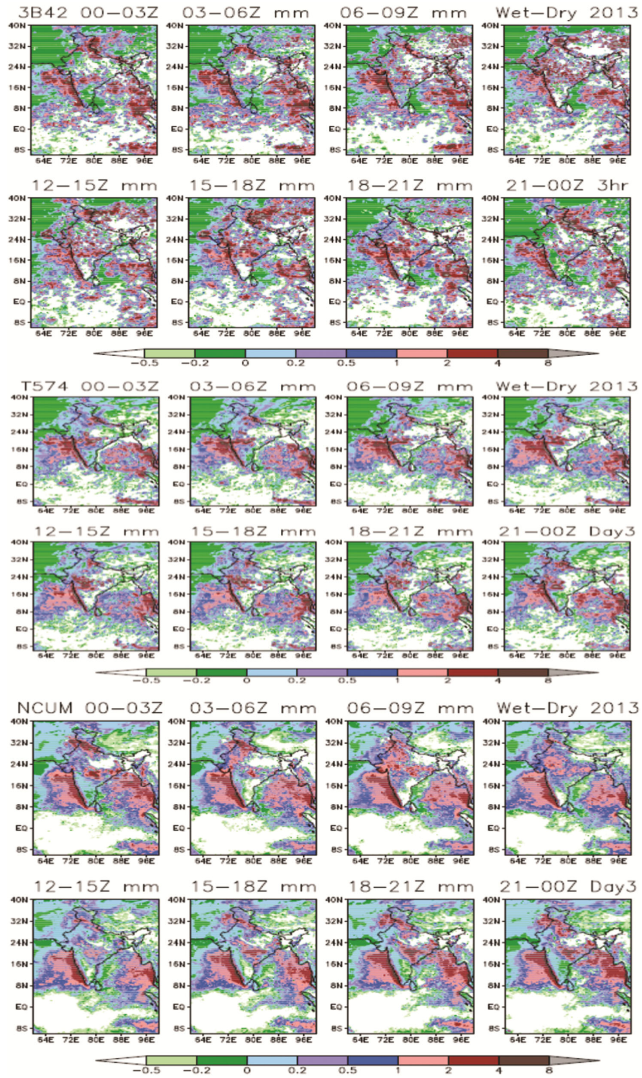

Fig. 6 − The difference in rainfall for the wet and dry period as seen in day-3 fcst.

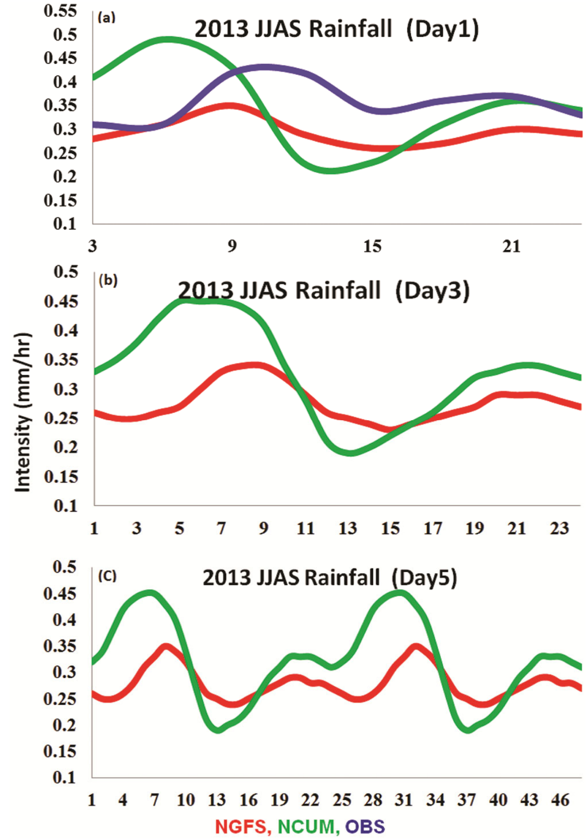

Fig. 7 − Diurnal cycle of rainfall intensity over land of India during all the phases of monsoon.

with negative rainfall from the early morning hours to late evening.

The rainfall difference obtained from day-3 forecasts of NGFS model results indicate that the Kerala coast; Maharashtra, Gujarat and adjoining Arabian Sea region receive rainfall 2-4 mm more in the active phase during 00-12Z. The central India, Himalayan region shows less rainfall value as compared to observation. The Bay of Bengal is more active in the wet period during 21-00Z, because of this the costal part of Myanmar is covered with positive amount of rainfall more than 2 mm. Most of the equatorial ocean is seen with negative amount of rainfall during this wet minus dry period. The rainfall difference obtained from day-3 of NCUM model shows that the Kerala coast, Maharashtra Gujarat and adjoining Arabian Sea receive rainfall more during day and night time. These NCUM model predicted rainfall plots are clearly bring out the negative amount of rainfall in the oceanic region within the 8°N to 8°S region. It implies that during dry phase the NCUM model predicts rainfall almost during all the hours of the day. During 09-12 Z the central, foot hills of Himalaya, Nepal regions receives extremely less values when compared with the observations. From Fig. 6 it is found that the NCUM rainfall octets do not have the small amount of positive and negative pockets in this diurnal cycle; whereas the NGFS is able to have these rainfalls when compare with the observations.

2.3 The area averaged hourly mean rainfall

The hourly intensity of the seasonal mean rainfall over the Indian region for day-1, day-3 and day-5 are shown in Fig. 7 (a and c). Figure 7 (a) shows the hourly mean rainfall at the order of 0.3 mm/hr during the 24 hrs period in the NGFS plots. For the NCUM the intensity value at the order of 0.3 ~ 0.4 mm/hr during 09-15Z are seen, then it maintain its value as 0.35 mm/hr. The TRMM-3B42 shows rain intensity

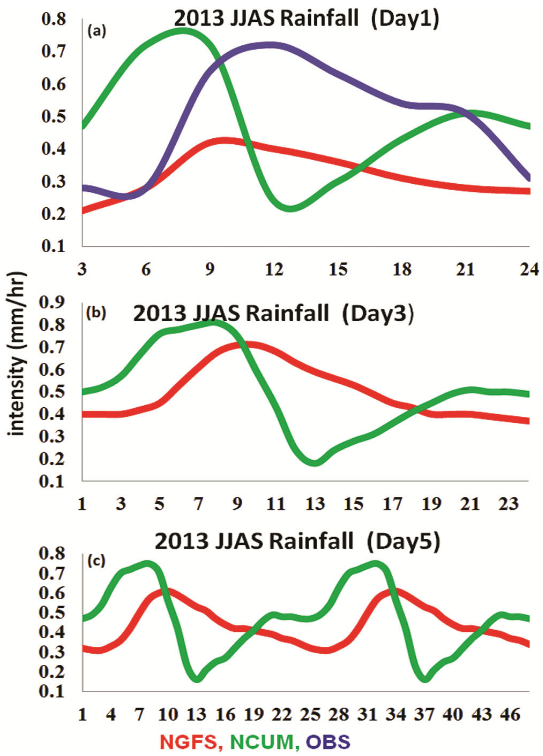

Fig. 8 − Diurnal cycle of rainfall intensity over Central India during all the phases of monsoon.

value more than 0.3 mm/hr during all the hours of the day. In the forenoon hours NCUM model over estimates the rainfall than NGFS and TRMM estimates. During the time slot 10 ~ 20Z the NCUM model under predicts the rainfall by more than 0.1 mm/hr. After 20Z it goes up and attains its maximum value, the same order of rainfall also seen in the observation plots. Figure 7 (b and c) are clearly showing the bi-modal values around 04Z and 18Z time. Thus it is noted that the diurnal variability is more in NCUM than NGFS over land and oceanic region. These exercises are repeated with the day-1, day-3 and day-5 for both the models. The corresponding figures are not shown here.

Figure 8 (a and c) corresponds to the aerial average amount of hourly rainfall over the Central India (CI). From these figures it is noted that the NCUM model predicts (>1mm) rain than the NGFS model. Figure 9 (a and c) corresponds to the hourly average rainfall over Equatorial Ocean (EO) estimated from TRMM multi-satellites, day-3 predictions of NGFS rainfall and day-3 predictions of NCUM rainfall. From this day-3 figure it is noted that the average amount of rainfall vary from 0.28 to 0.38 mm/hr only. The graph attains its peak value during 20-23Z and minimum value at 10-13Z. During all the hours of the day NGFS model is predicting more rain than NCUM model.

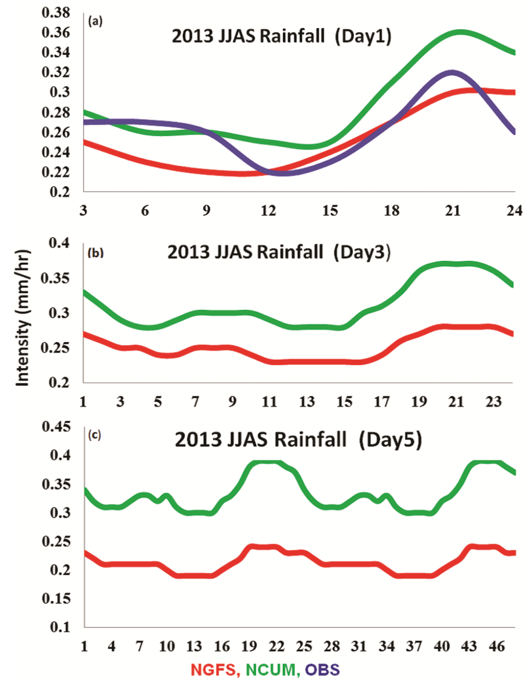

Fig. 9 − Diurnal cycle of rainfall intensity over Equatorial Ocean during all the phases of monsoon.

3 Conclusions

The main conclusion includes investigation of the diurnal cycle phase and amplitude of rainfall predicted by the models with the TRMM rainfall estimates. Since much of tropical precipitation is due to convective systems, the hour of occurrence of the maximum precipitation is expected to be the same as the hour of maximum occurrence of convection but may not coincide with the hour of maximum frequency of precipitation as the latter may be due to frequent low-intensity rain from non-convective clouds.

The characteristics of the convective systems producing the rain along the Himalayas are distinct from those of the precipitating systems of the costal and oceanic regions.

The models those are in operation at NCMRWF grossly reproduce the estimated diurnal variation in precipitation in the day and night time. The NGFS model has less diurnal variability than NCUM model.

It is recommended that ultimately high-resolution models with highly responsive synoptic, meso-scale, convective and micro-physical repetitive will be necessary to model the precipitation process in this complex region.

These conclusions recorded above are based on only two years of data and needs to be revalidated with more years of space-based and ground-based observations over India and adjoining regions.

Proper representation of the interactions among the various elements of the atmosphere-land-Ocean-Cryosphere systems is crucial for achieving these correct amplitude and phases of this forced diurnal cycle.

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