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TECHNICAL REPORT

Implementation of NCMRWF Regional Ensemble Prediction System (NEPS-R)

S. Kiran Prasad, A. Sarkar, A. Mamgain and E.N. Rajagopal

September 2019

National Centre for Medium Range Weather Forecasting
Ministry of Earth Sciences, Government of India
A-50, Sector-62, NOIDA-201 309, INDIA

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Abstract

Ensemble based prediction systems over the years have proved their worthiness in providing better forecast guidance. These systems, in the past two decades, have evolved from global scale to regional scale. The efforts to tackle the uncertainty at kilometre scale have led to the ensemble approach applied at convective scale resolution. The NCMRWF Regional Ensemble Prediction System (NEPS-R) is based on the regional version of Met Office Global and Regional Ensemble Prediction System (MOGREPS) with 12 members (1 control + 11 perturbed). This regional ensemble prediction system having ~4 km horizontal resolution and 80 vertical levels up to a height of 38.5 km is implemented in “Mihir HPCS”. The NEPS-R runs with initial and boundary conditions generated from the NCMRWF Global Ensemble Prediction System (NEPS-G). The model uncertainties are taken care of by Random Parameters (RP) scheme. An operationally feasible configuration has been arrived at after carrying out various sensitivity experiments involving driving model resolution, boundary condition frequency and different science configurations. The NEPS-R is aimed at providing 3-day probabilistic forecasts using 12 members. Results of a few severe weather systems are presented in this report. NEPS-R has performed better than its global counterpart (NEPS-G) in predicting these severe weather phenomena.

1. Introduction

Numerical weather prediction (NWP) has steadily moved towards ensemble based prediction systems in the last two decades or so largely due to the success of these systems in providing better guidance in forecasting. It is seen that an estimate of future probability density of a variable may provide more information to forecasters than a lone deterministic forecast initialized from the best obtainable estimate of initial state (Leutbecher and Palmer, 2007). The ensemble approaches of numerical weather prediction have become as an effective way to handle the forecast errors in a strictly deterministic NWP. It is a well-known fact that the initial conditions of a deterministic numerical weather prediction model can be estimated only within a certain accuracy. There will be significant forecast errors due to the amplification of some of the initial errors. Adding to this, the representation of the dynamics and physics of the atmosphere by numerical algorithms introduces further uncertainties, for instance truncation errors and uncertainty of parameters describing sub-grid scale processes. Although the idea of ensemble forecasting was brought forth in the 1960s by Lorentz (1965) and Epstein (1969), the implementation of ensemble forecasting was accomplished by Leith (1974) using random perturbations in the initial condition. The operational prediction using ensemble based approach started in the 1990s at European Centre for Medium-range Weather Forecasting (ECMWF) [Palmer et al., 1993; Molteni et al., 1996] and National Centers for Environmental Prediction (NCEP) [Toth and Kalnay, 1993]. These systems essentially are intended to mainly focus on the uncertainties due to synoptic-scale baroclinic instability for a forecast lead time of 3-10 days. But, the uncertainty on shorter time and length scales is still significant and a need to address this issue is also significant as this leads to large uncertainty in finer weather details at a local scale. This has made to shift focus towards developing Ensemble Prediction Systems (EPS) to tackle the uncertainties on a short-range.

Over the years the short range ensemble prediction systems have been developed based on a single and multiple models with different types of approaches for generating perturbed initial conditions and have been run at many operational facilities around the world. NCEP's SREF is one such multi-model short range ensemble prediction system using two limited area models with boundary conditions taken from the NCEP's medium range global ensemble (Traction et al., 1998; Stensrud et al., 1999). Another of multi model EPS, namely, SREPS, has been developed by the Spanish Met service, INM. This system runs with five different regional models, each run with four different analyses and lateral boundary conditions (LBCs) from different NWP centres around the world (Garcia-Moya et al., 2007). The single model based ensemble system developed by Meteo-France is known as PEACE which is based on the ARPEGE model with a resolution of 20 km over France. There were 11 ensemble members with perturbations computed using singular vectors (SV) and without using any model uncertainty schemes. The Norwegian Meteorological Institute's EPS, LAMEPS (Frogner et al., 2006) is set over Scandinavia with LBCs and IC perturbations from ECMWF-EPS with SV perturbations. The primary drawback of the multi model EPS is that the ensemble members are systematically different from each other. So, different ensemble members are expected to have different skills, hindering the extraction of probabilities from the ensemble and also that they tend to cluster by model (Alhamed et al., 2002), so that the forecast ensemble probability distribution function (PDF) may be dictated more by the distribution of models or schemes than by the synoptically-dependent forecast uncertainty. These issues are avoided in the single model based ensemble prediction systems.

Convection permitting forecasts are strongly sensitive to uncertainties in initial conditions, boundary conditions and physical processes because convective processes are highly non-linear and have short-life times. So, there is a far greater requirement of an ensemble approach to account for uncertainty at kilometre scale than at coarser resolutions. Keeping this in mind, many operational forecasting centres have moved from short range EPS to convective scale EPS in order to handle the uncertainty in forecasts at a local scale. The phenomenal increase in computing power also has boosted the efforts in developing convective scale ensemble systems around the globe. Today convective scale ensemble systems are in operation at Met Office, UK (UKMO), Meteo-France, German Weather Service (DWD) and also at many other centres. Meteo-France convective scale ensemble is based on 2.5 km AROME model, nested in the ARPEGE EPS, which runs operationally with 12 members twice a day (Boutteir et al., 2012; Nuissier et al., 2012). The German Weather Service (DWD) implemented a 2.8 km ensemble (COSMO-DE-EPS), which is nested within a regional-scale ensemble and has 20 members running 8 times a day for 21 hours (Bouallegue et al., 2013). The UKMO runs a convective scale ensemble, Met Office Global and Regional ensemble Prediction System-UK (MOGREPS-UK) at a resolution of 2.2 km nested inside their Global - EPS (MOGREPS-G). MOGREPS was developed by UKMO in order to address the very basic requirements of tackling uncertainty at shorter time scales. A very high resolution model was required to address this issue but the resolution of global EPS was not high due to limited computational resources. So a high resolution regional EPS became necessary. Again, an appropriate method of generating initial condition perturbation is required to be adopted which becomes effective from the initial time itself. The uncertainties arising from approximations in model formulation should also be addressed appropriately. MOGREPS has taken care of these three key requirements (Bowler et al., 2008). In MOGREPS the IC perturbations are generated using Ensemble Transform Kalman filter (ETKF) (Bishop et al., 2001), in which the perturbations determined for each cycle are a linear combination of the forecast perturbations from the previous cycle. The model error within a single model environment is handled by the use of stochastic perturbations to the model, mainly to parameterized model physics. This is implemented through Random Parameters (RP) scheme which takes care of uncertainty caused by the choice of tunable parameters in physical parameterization schemes and uncertainty due to sub-grid scale (not fully resolved) processes.

2. Methodology

2.1 Brief Description of NEPS-R

The NEPS-R implemented is same as the original MOGREPS Regional based on UM Version 10.6 developed at UKMO. This regional ensemble prediction system has a horizontal grid spacing of 0.04^0 (~4 km) and has an irregularly spaced but smoothly varying hybrid-height levels with a lid at 38.5 km. Further, these levels are terrain-following near the surface, but relax towards the horizontal in the free atmosphere. Model variables use Charney-Phillips staggering in the vertical. Primary field advection uses a semi-implicit semi-Lagrangian scheme which allows a longer time-step to be used. Parameterized physical processes include long- and short-wave radiation, a nine-tile (broad-leaf trees, needle-leaf trees, C3 (temperate) grass, C4 (tropical) grass, shrubs, urban, inland water, bare soil and ice) surface exchange scheme (Best et al., 2011), mixed phase cloud microphysics, a boundary-layer turbulence scheme and a random parameters stochastic physics scheme (Macabe et al., 2016, Bowler et al., 2008).

The RP scheme works by assuming that there is some uncertainty in the default values of a subset of parameters in the model physics schemes. For each parameter, a maximum and minimum value is specified, defining a range of values over which the parameter can sensibly be expected to vary. Each parameter is initialized randomly within its specified range and is then updated stochastically over the course of the forecast. The updating is performed using a firstorder auto-regression process so that each parameter essentially takes a random walk through its parameter space as the forecast updates. The parameter values are the same for all points in the domain. The list of tunable parameters in boundary layer and microphysics parameterization schemes, used in the RP scheme are given in Table 1. More details of this scheme can be found in Macabe et al., 2016.

The model domain of NEPS-R has 1200 × 1200 grid points in east-west and north-south directions spanning over a domain 62^0 E -106^0 E and 6^0 S - 41^0 N, with Arakawa C staggering and is set on a rotated latitude-longitude projection. NEPS-R currently comprises 12 ensemble members (1 Control + 11 perturbed members) and runs up to 75 hours.

Table1: List of Tunable Parameters in Random Parameters (RP) Scheme

Parameter	Value		
	default	**Minimum**	**maximum**
M_CI Ice fall speed multiplication factor	1.0	0.6	1.4
X1R_RP Rain particle size distribution intercept coefficient	0.22	0.07	0.52
NDROP_SURF_RP Surface droplet number concentration	7.5 x 10^7	2 x 10^7	10 x 10^7
EC_AUTO_RP Auto conversion of cloud water to rain in microphysics	0.55	0.01	0.6
G0_RP Flux profile parameter in boundary layer scheme	10	5	20
LAM_META_RP Mixing length control coefficient	1.0	0.2	3.0
PAR_MEZCLA Neutral mixing length(m)	0.15	Varies with LAM_META	
LAM_MIN_RP Minimum mixing length for RP(m)	40	Varies with LAM_META	
RICRIT_RP Critical Richardson number	1.0	Varies with G0_RP	
A_ENT_1_RP Entrainment parameter A1 for RP	0.23	0.1	0.4
G1_RP Cloud top diffusion control parameter	0.85	1.5	0.5
CHARNOCK Charnock parameter	-	0.010	0.026
RHCRIT Maximum critical relative humidity at reference level 3	0.89	0.87	0.92

The initial conditions for control and perturbed ensemble members are obtained from the high resolution (12 km) NEPS-G which is operational since June 2018. The unperturbed initial conditions or analyses fields of NEPS-G are provided by Hybrid 4D-VAR data assimilation system. The initial condition perturbations of NEPS-G are generated by ETKF method (Mamgain et. al., 2019). The perturbations of sea surface temperature, deep soil temperature and soil moisture are included in NEPS-G. These analysis perturbations are added to the analysis fields by Incremental Analysis Update (IAU) method (Clayton, 2011) to generate 11 sets of perturbed initial conditions for NEPS-G. These initial conditions (both perturbed and unperturbed) from NEPS-G are reconfigured to prepare the initial conditions for NEPS-R. The boundary conditions for NEPS-R are also provided by NEPS-G. So NEPS-R essentially runs with initial and boundary conditions from a global ensemble. This method of providing the initial and boundary conditions to a regional EPS from a global EPS is due to non-availability of an EPS based hybrid regional DA operational at NCMRWF. The flow chart of processes involved in NEPS-R is shown in Figure 1.

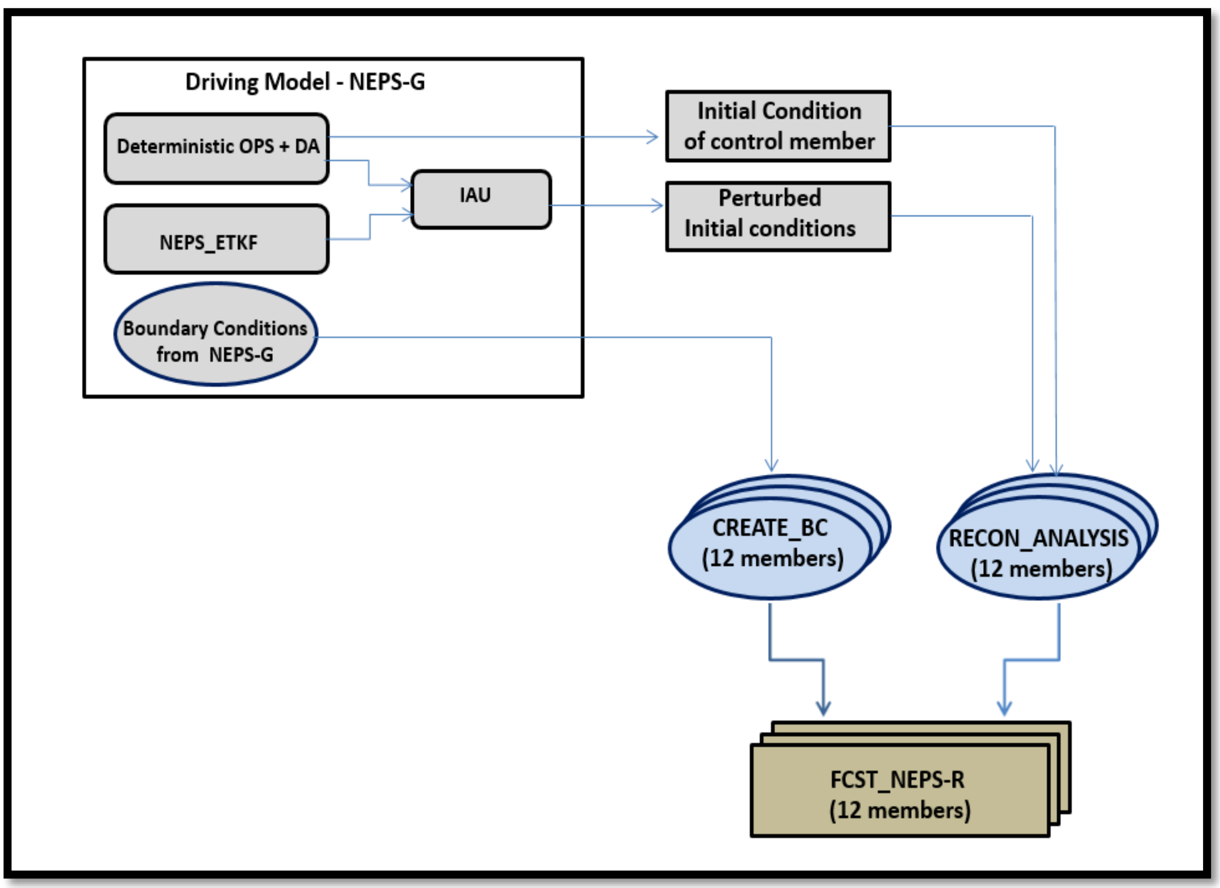

Figure 1: Flow chart of processes involved in NEPS-R.

2.2 Driving Model

NEPS-G is running operationally at NCMRWF at 12 km resolution, so the initial and boundary conditions for the control and 11 perturbed members are obtained from NEPS-G for the operational run.

The NEPS-G is based on Unified Model version 10.8 (UM10.8), which is a part of 'Operational Parallel Suite', PS40, developed at Met Office, UK. It operates with a total of 23 ensembles members (1 control + 22 perturbed forecasts). The Ensemble Transform Kalman Filter (ETKF) system generates the 22 analysis perturbations of horizontal wind speed components (u and v), potential temperature (θ), specific humidity (q) and exner pressure (π) at all 70 model levels. In addition to these, perturbations for deep soil temperature, soil moisture content on four model soil levels and sea surface temperature are also included. These analysis perturbations are added to the reconfigured analysis obtained from the flow dependent, hybrid four-dimensional variational data assimilation system (hybrid-4DVar; Clayton et al., 2013). The control member runs directly with the analysis produced by the Hybrid 4DVar DA system.

The ETKF generates ensemble perturbations using information of observation errors and the background perturbation structure. It updates the forecast perturbation matrix by multiplying it with a transformation matrix to generate analysis perturbation for wind components, potential temperature, specific humidity and exner pressure at all the model levels. Further, the spread of the ensemble members is determined using forecasts of previous cycle and this spread is compared to the root mean square error of ensemble mean with respect to the observation. Then a region specific inflation factor is computed and multiplied with raw transformation matrix to improve ensemble spread. The analysis perturbations are added to the analysis data using the Incremental Analysis Update (IAU) scheme (Clayton, 2013) within the UM. More details of NEPS-G and its components can be found in Sarkar et al., 2016 and Mamgain et al., 2018.

2.3 NEPS-R Components

The NEPS-G generates 3-hourly boundary conditions for the control and 11 ensemble members for 72 hours as output. The initial and boundary conditions generated by NEPS-G are used by NEPS-R employing the 3 components, namely, (i) CREATE_BC (creating boundary conditions), (ii) RECON (reconfiguration) and (iii) FCST (forecast). These are described below:

2.3.1 CREATE_BC

This module extracts and reconfigures the boundary conditions supplied by NCUM-G to match the grid dimensions of the NEPS-R both in the horizontal and vertical directions using the grid information provided by the namelist 'input.nl'. The horizontal interpolation is carried out on Arakawa C grid using bilinear interpolation and the vertical interpolation is implemented using linear interpolation. CREATE_BC generates 16-point boundary data in the E-W as well as N-S directions comprising of 7-point halo at the edge of the domain followed by 9-point rim. The 9-point rim, which is considered as a part of the LAM domain, enables the field data to blend smoothly with the lateral boundary condition (LBC) data by employing blending weights of 1.0, 1.0, 1.0, 1.0, 1.0, 0.75, 0.5, 0.25, 0.0 (for 9-points) starting from the outer edge. At the start of the run, the values of a field in the rim points are obtained by linear interpolation between the LBC values and those in the start dump.

Inputs to CREATE_BC:

Input to "CREATE_BC" is the 3-hourly boundary condition files generated by NEPS-G. The horizontal resolution of the input data is 12 km.

Output of CREATE_BC

The output of "CREATE_BC" is the extracted and reconfigured boundary condition file. The horizontal resolution of this output data is about 4 km.

2.3.2 RECON (Reconfiguration)

The reconfiguration module interpolates the global analysis fields to the regional model grids and generates a reconfigured initial dump. The reconfiguration process takes initial global analysis file produced by the Hybrid 4DVar DA system as input and generates a suitable initial dump for the control run at a resolution of approximately 4 km. It also reconfigures the perturbed initial analysis and prepares the initial dump at approximately 4 km for the perturbed ensemble members to run.

Inputs to RECON: The inputs to "RECON" are:

i) Initial analysis file produced by the Hybrid 4DVar DA system.

ii) Perturbed initial analysis files generated by NEPS-G.

Output of RECON

The output of “RECON” is the reconfigured initial dump at approximately 4 km for control and perturbed ensemble members.

2.3.3 FCST (Forecast)

The forecasts of the control member and perturbed members of NEPS-R run with inputs from CREATE_BC and RECON. The forecast starts at 00 UTC with an integration time of 75 hours for all the 12 members.

Main inputs for FCST: The main inputs for “FCST” are:

i) Reconfigured initial dump at approximately 4 km resolution for control and perturbed ensemble members.
ii) Reconfigured boundary condition file at a horizontal resolution of approximately 4 km.

Outputs of FCST: The outputs of “FCST” are:

i) Forecast file (PP0) containing forecast fields of u, v, w, geopotential height, MSLP, RH, T and surface pressure at 18 vertical levels at 24 hour interval.
ii) Forecast file (PP2) containing daily maximum and minimum temperatures at 2 m above surface and 24 hourly accumulated rainfall.
iii) Forecast file (PF) containing mean sea level pressure (MSLP), specific humidity (q), relative humidity (RH) and temperature (T) at 2 m, horizontal wind components (u and v) at 10 m and accumulated rainfall at a frequency of 1 hour.

2.4 Computational Requirements

NEPS-R is implemented in Mihir HPCS at NCMRWF. Mihir HPCS is a Cray-XC40 Liquid Cooled System with 2320 nodes running with peak performance of 2.8 PF and a total system memory of 290 TB. Each node is configured with 2 Intel Xeon Broadwell processors adding to 36 cores and 128 GB memory per node. The number of nodes and the wall clock time taken by each component are given in Table 2.

Table 2: Node usage and wall clock time of different components of NEPS-R

NEPS-R Components	Forecast Length (hour)	Nodes per member	Total no. of processors	Cycles (UTC)	Wall clock time (minute)
Create_BC	75	1	8	00	8
RECON	-	2	64	00	3
Forecast	75	86	1536	00	88

2.5 Rose Suite/Cylc scheduler

Rose suite and Cylc scheduler are python based and are used for managing the execution of NEPS-R jobs. “Rose” is a framework for managing and running “suites” (suite is a collection of scientific application softwares for a common purpose). “Rose” contains all the features required for configuration management of “suites” and their components. “Cylc” is the “suite” engine or work flow engine (tools for managing the workflows required by the Rose) that drives task submission and monitoring. Cylc has all the key features required for both operational and research job scheduling - including run, rerun, kill, poll, hold individual task or a family of tasks. NCMRWF uses “Rosie” database for Rose Suite management. Both Rose and Cylc are Open Source projects, managed under GitHub.

3. Sensitivity Experiments for Model Customization

Various sensitivity experiments have been performed to arrive at an operationally feasible setup and a customized configuration to produce better forecasts by saving computational time and resources. The sensitivity experiments were undertaken for different resolutions of initial and boundary conditions, different frequencies of boundary conditions and different science configurations suitable for tropical environment.

The sensitivity experiments were performed with initial conditions (IC) and boundary conditions (BC) from 12-km and 20-km NEPS-G. NEPS-R performed only slightly better using IC and BC from 12-km NEPS-G (Figure 2). The spatial pattern of rainfall is nearly same in both the experiments throughout India with an exception of rainfall over central India, where the area of over predicted rainfall (16-32 cm) was reduced slightly in the experiment using IC & BC from 12-km NEPS-G compared to the experiment using IC & BC from 20-km NEPS-G. It may be noted that the initial conditions for the 20-km NEPS-G was interpolated from the 12-km Hybrid 4DVAR analysis.

Further, there was no noticeable difference in the forecasts using 1-hourly and 3-hourly boundary conditions apart from rainfall over south Madhya Pradesh and adjoining Maharastra where the over predicted rainfall of 16-32 cm is marginally larger in the experiment with 3-hourly boundary conditions compared to the experiment with 1-hourly boundary conditions (Figure 3). Hence, to reduce computational time and resources, 3-hourly boundary conditions have been preferred over 1-hourly conditions.

Sensitivity experiments were also performed using 2 science configurations, namely Singv4.1 and Proto-RA1T. The main difference between the two science configurations is in the radiation driver where Singv4.1 uses Global Atmosphere 3 configuration (GA3) and Proto-RA1T uses Global Atmosphere 7 configuration (GA7). The corresponding spectral files of GA3 and GA7 differ in various aspects like changes to spectral bands, solar spectrum (including Rayleigh coefficients) and gaseous absorption for shortwave radiation. They also differ for gaseous absorption and thermal emission for longwave radiation. The spectral file of longwave radiation in GA7 contains new solar spectrum ("lean_12") taken as a mean of the spectral data from 2000-2011 (data from Judith Lean, available at http://solarisheppa.geomar.de/ccmi). Further, newly derived gaseous absorption in spectral files of GA7 for all gases (except CO_2 in band 4) is based on HITRAN 2012 (Rothman et al., 2013) and CAVIAR water vapour continuum. N_2O and CH_4 have been added to the list of minor gases in GA7. The improved representation of CO_2 in the window region in GA7 provides a better forcing response to increases in CO_2. Greenhouse gases included in the spectral file of GA7 are H_2O, CO_2, O_3, N_2 O, CH_4, CFC11, CFC12, CFC113, HCFC22 and HFC134a. Absorption due to Sulphur dioxide (SO_2) and Carbonyl Sulphide (OCS) is also included based on HITRAN 2012. Change with respect to the thermal emission in spectral files of GA7 is for Planck's function in each band which is represented by a quartic fit in the temperature, generated by a least squares fit over the range 160 K to 330 K instead of 150 K to 330 K used in the spectral file of GA3. This slightly improves the fit over the important temperature range for the Earth's atmosphere. It can be seen in Figure 4 that there is no large difference in the precipitation forecast using the two science configurations. Both the configurations over-predicted rainfall (16-32 cm) over a small area in north Kerala.

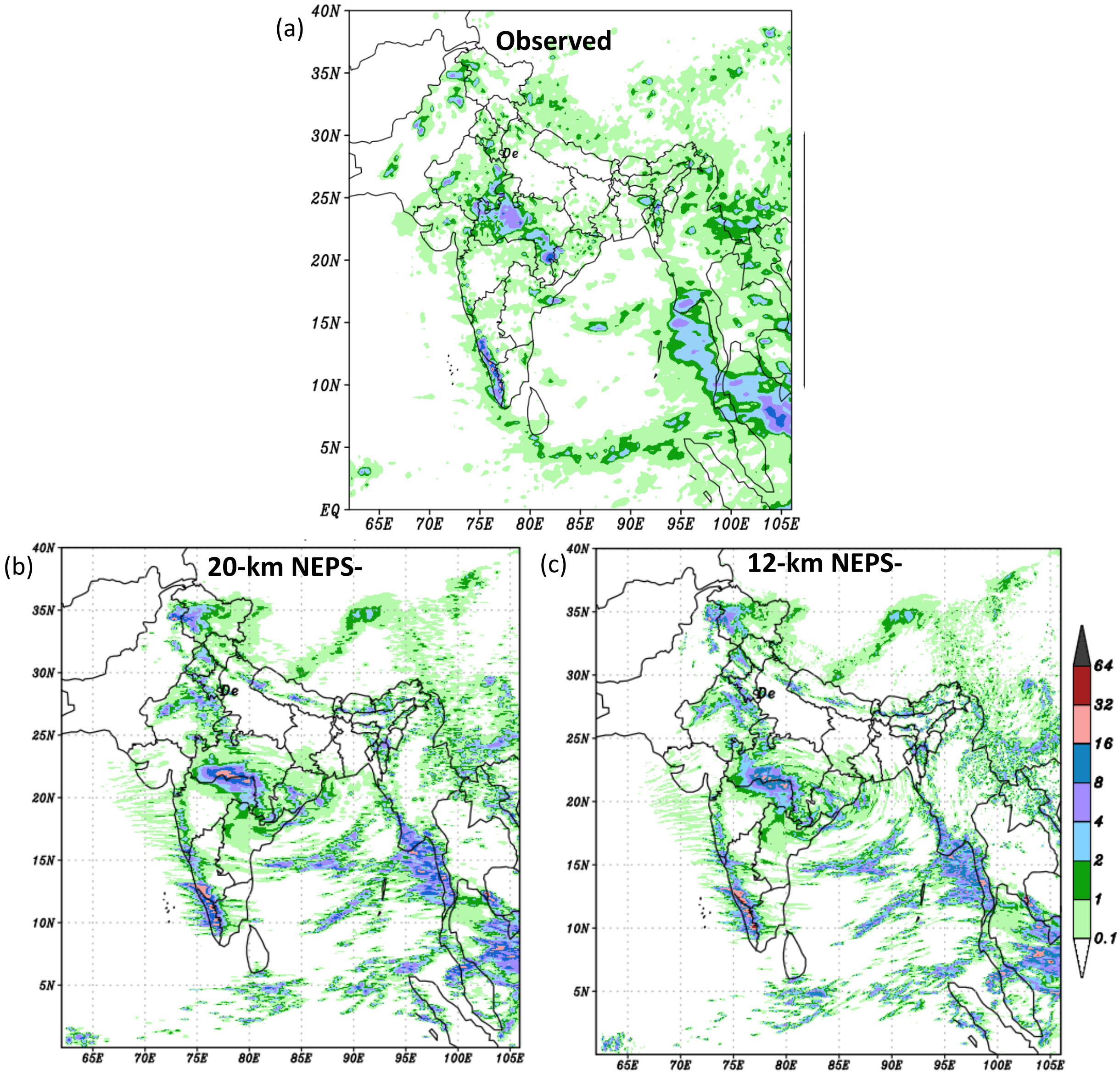

Figure 2: (a) Observed (Merged satellite and gauge) rainfall (cm), NEPS-R Day-1 control rainfall forecast valid for 03 UTC 9 August, 2018 with initial and boundary conditions from (b) 20-km NEPS-G and (c) 12-km NEPS-G

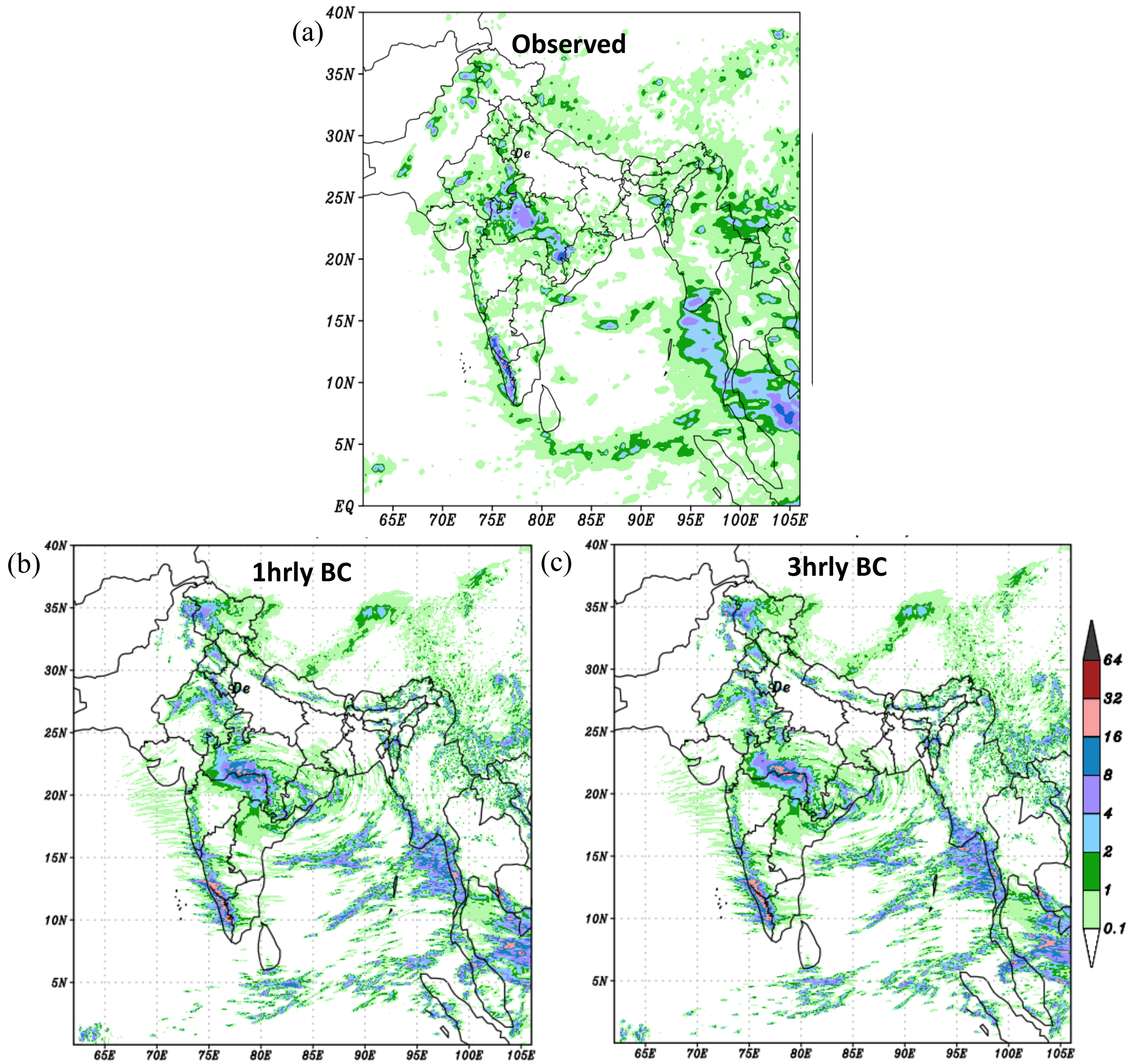

Figure 3: (a) Observed (merged satellite and gauge) rainfall (cm), NEPS-R Day-1 control rainfall forecast valid for 03 UTC 9 August, 2018 (b) with 1hrly and (c) 3hrly boundary conditions from NEPS-G (12-km).

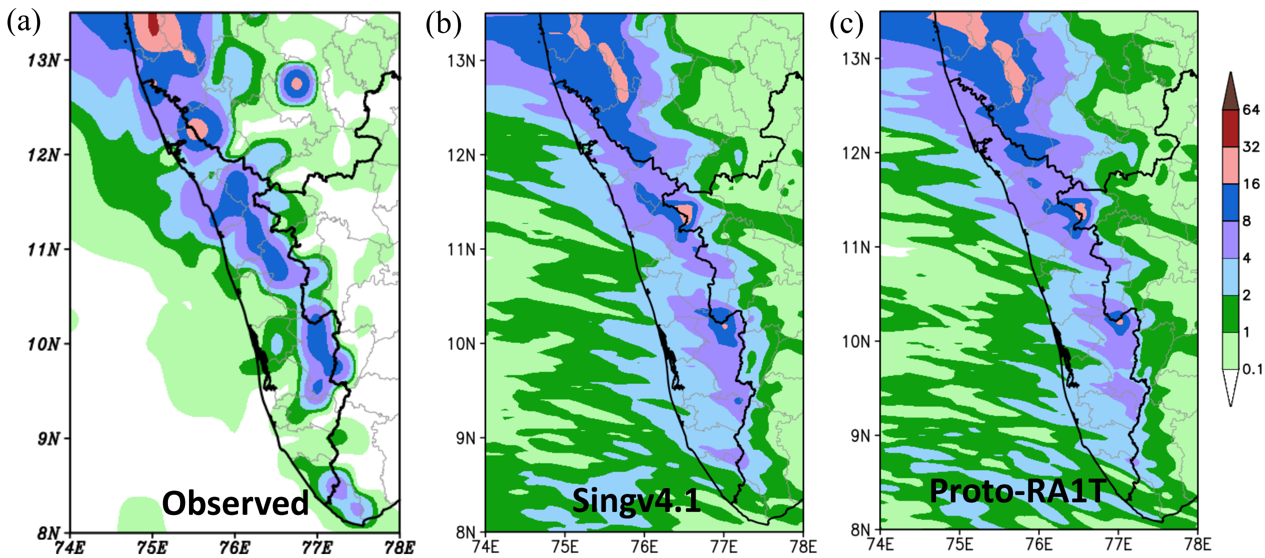

Figure 4: (a) Observed (merged satellite and gauge) rainfall (cm), NEPS-R Day-1 ensemble mean rainfall forecast valid for 03 UTC 15 August, 2018 (b) Singv4.1 and (c) Proto-RA1T.

4. NEPS-R Forecast Products

The operational products generated from NEPS-R are given in Table 3. The spatial plots are prepared for the whole model domain covering 62^0 E -106^0 E and 6^0 S - 41^0 N.

Table 3: Operational NEPS-R products

Products	Variables	Resolution	levels	Frequency (hours)
Geopotential height	Ht	$0.036^0 \times 0.036^0$	925, 850, 700, 500, 200 (hPa)	24
MSLP	MSLP	-do-	Mean sea level	24
EPSgrams	T2m, RH2m, U10m, V10m, MSLP, 1-hourly accumulated precipitation	-do-	2 m, 10m, surface, mean sea level	1
Rainfall-Probability, Stamp Plots	Accumulated Precipitation	-do-	Surface	24
Wind-Forecast	U, V, surface pressure	-do-	925, 850, 700, 500, 200 (hPa)	24

4.1 Ensemble Mean and Spread

The ensemble prediction system provides a measure of uncertainty in the forecast which is not possible to determine with a control forecast alone. The ensemble mean and spread of different variables calculated from the ensemble forecasts is a way to assess the future weather scenarios. The ensemble mean is arithmetic mean of the values of the meteorological variable predicted by all the ensemble members, which gives us the most likely outcome on an average and is normally better than forecast of individual members. This is because it brings out the more predictable elements by smoothing out the relatively unpredictable features on a smaller scale, thus providing good forecast guidance. At the same time the risk of missing the prediction of extreme weather scenarios is always associated with the use of ensemble mean. Further, the ensemble spread illustrates the level of uncertainty associated with the forecast. It is the standard deviation of a model variable, which when large indicates greater uncertainty in the forecast and is generally displayed along with ensemble mean.

Figure 5 (a) shows the Day-3 forecast of ensemble mean value of mean sea level pressure (MSLP) as contours and spread of MSLP as shaded in colour. The ensemble mean and spread of geopotential height at 850 hPa, 500 hPa and 200 hPa levels in Day-3 forecast are illustrated in Figure 5 (b-d). The areas of strong colours indicate larger spread and therefore lower predictability.

Figure 6 shows analysis and forecast of ensemble mean wind vector and spread of wind speed at 500 hPa for Day-1, Day-2 and Day-3 forecasts. The weak and elongated circulation spanning over west and central India in the analysis is reproduced with larger intensity in all the days with centre of the circulation shifting slightly eastward in Day-2 and Day-3. The intensity of the circulation is the largest in Day-3 and it can also be seen that the winds over the entire domain have been reproduced stronger compared to those in the analysis. The typical characteristic of spread is that it increases with the forecast lead time, which is clearly seen in Figure 6 where the spread is confined to a smaller area in Day-1 and has increased spatially in Day-2 and Day-3, forecasts indicating the increase in uncertainty with forecast lead time. Also, it can be noted that the regions with more spread are also the regions of stronger wind, which suggests that the uncertainty in forecast increases over dynamically active regions (Bowler et al., 2008).

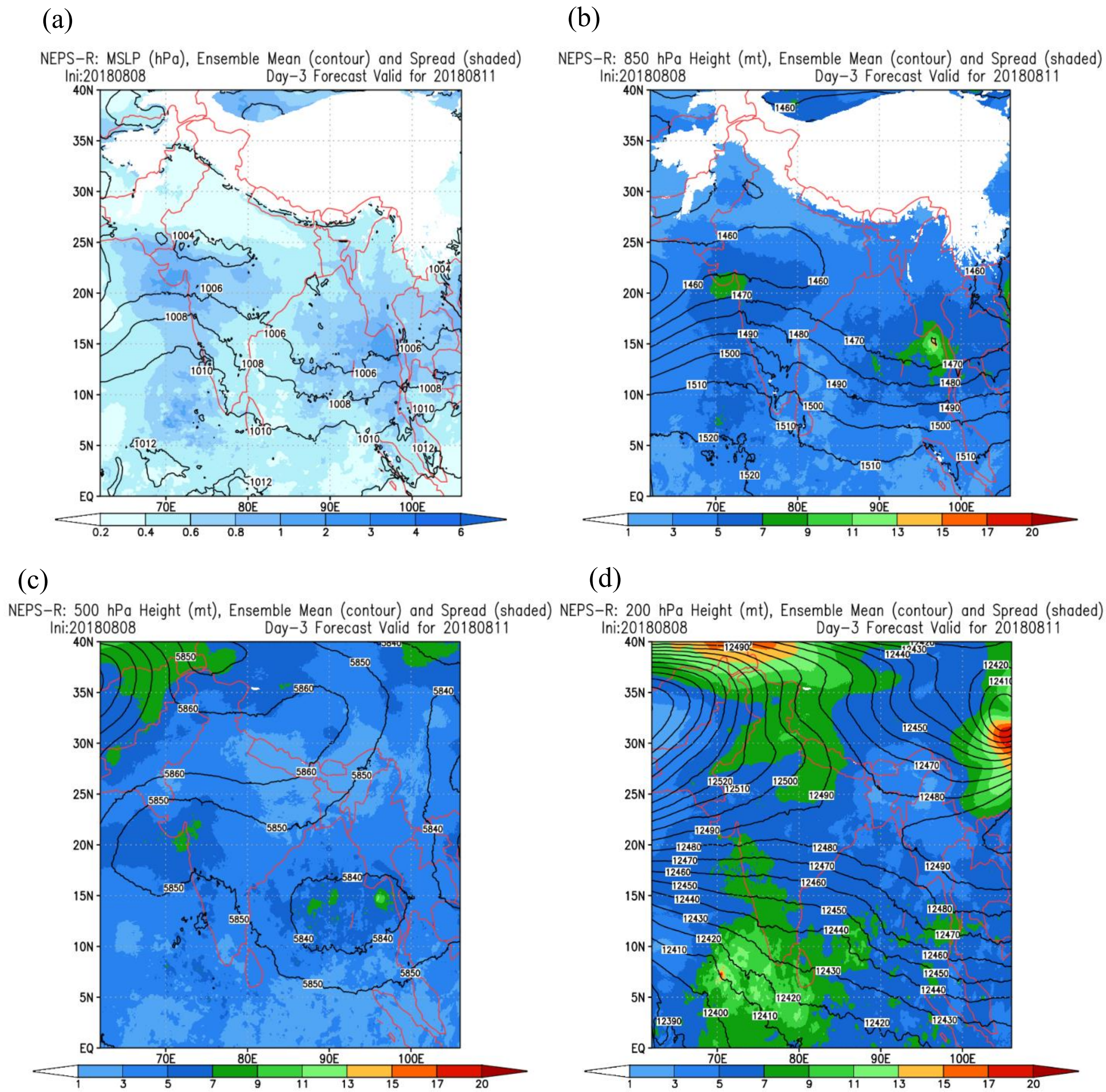

Figure 5: Ensemble mean and spread in Day-3 forecast of (a) MSLP and Geopotential height at (b) 850 hPa (c) 500 hPa (d) 200 hPa valid for 00 UTC 11th August 2018.

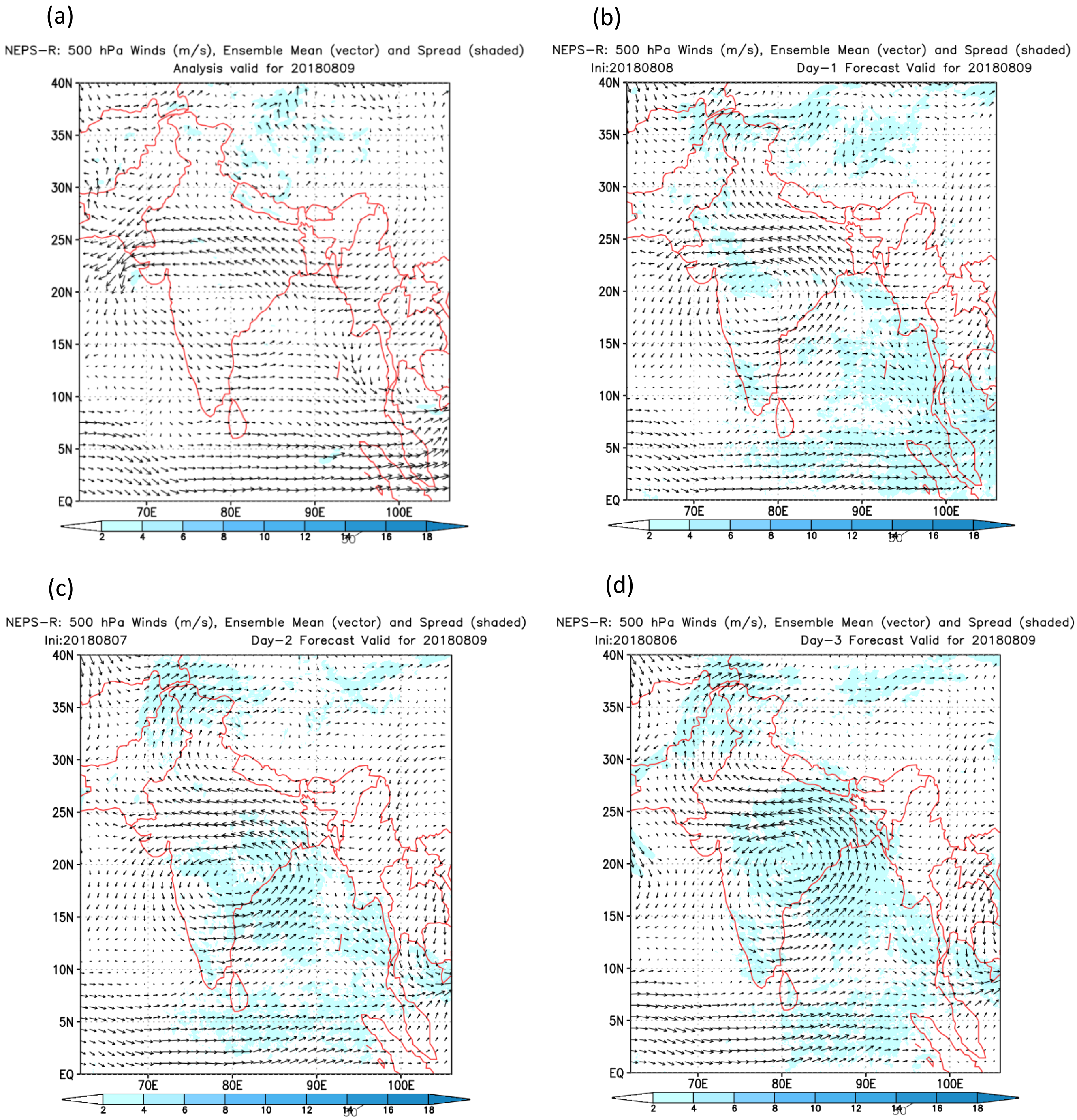

Figure 6: (a) Analysis, (b) Day-1, (c) Day-2 and (c) Day-3 forecasts of ensemble mean (vector) and spread (shaded) of wind at 500 hPa valid for 00 UTC 9 August, 2018.

Figure 7 illustrates the observed (satellite-gauge merged) rainfall and ensemble mean rainfall for Day-1, Day-2 and Day-3 valid on 03 UTC 9 August, 2018. Observed rainfall shows that moderate to heavy rainfall is confined to central India, the west coast and parts of Rajasthan, Punjab, Haryana, Himachal Pradesh, Uttarakhand and Jammu and Kashmir. The heaviest rainfall of an amount of about 40 cm/day occurred over Kerala. The Day-1 forecast of NEPS-R agrees well with the observed rainfall over most parts of India and has done well in predicting heavy rain over Kerala. Further, the rainfall is over-predicted over Central India, parts of Rajasthan, Jammu and Kashmir and Odisha. The rainfall over Bay of Bengal and the Equatorial Indian Ocean is captured well by the model in Day-1 in terms of position and intensity but with large spread. The rainfall in Day-2 forecast shows that the heavy rainfall zone has displaced to East Maharashtra from Madhya Pradesh and the rainfall is over-predicted over Jammu and Kashmir, Odisha, Bay of Bengal and Equatorial Indian Ocean. Rainfall over the west coast has been predicted well on Day-2 with a decrease in the intensity. In Day-3 forecast the heavy rainfall zone has got further displaced southeast from Madhya Pradesh covering east Maharashtra, Telangana and Chhattisgarh. The over-prediction of rainfall over Odisha, Jammu and Kashmir, Bay of Bengal and Equatorial Indian Ocean persists also in Day-3. However, NEPS-R has done well in retaining the heavy rainfall over Kerala in Day-3 with slight displacement in the location of peak rainfall.

4.2 Probabilistic Quantitative Precipitation Forecast

The forecast uncertainty information from ensemble prediction system can be best conveyed in terms of probability of occurrence of an event beyond a threshold. Figure 8 illustrates the probabilities of occurrence of 24-hr accumulated rainfall exceeding threshold values 0.25 cm (light), 1.56 cm (moderate), 6.55 cm (heavy), 11.5 cm (very heavy) and 19.5 cm (extremely heavy) for Day-1, wherein it can be seen that a rainfall amount of 1-8 cm is predicted by the ensemble mean over Jammu and Kashmir, 1-4 cm over Rajasthan and Odisha, 1-16 cm over Central India and 4-64 cm over the west coast. The probability of rainfall exceeding 0.25 cm/day is more than 90% over Jammu and Kashmir, Rajasthan, Central India and the west coast. There is more than 90% probability of rainfall exceeding 1.56 cm/day over some places of Jammu and Kashmir, Rajasthan and the west coast. The probability of rainfall exceeding 6.55 cm/day is more (50-90%) over south Karnataka and central Kerala. There is less than 50%

chance of very heavy rainfall (>11.5cm/day) over central India and 10-90% over south Karnataka and Kerala. Extremely heavy rainfall (>19.5cm/day) is confined to Kerala with a probability of 10-90%.

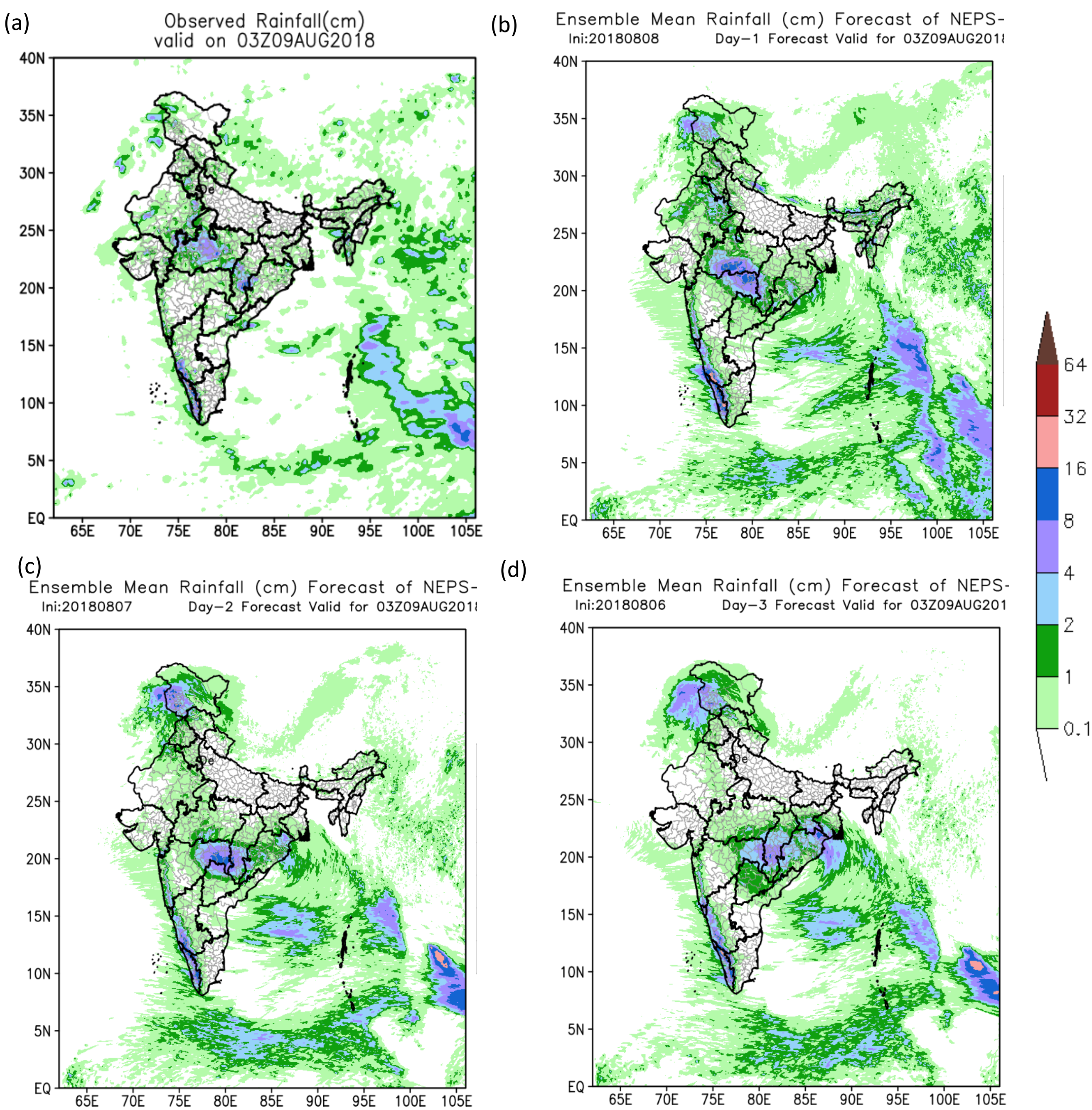

Figure 7: (a) Observed (satellite-gauge merged) rainfall, (b) Day-1, (c) Day-2, (d) Day-3 forecasts of ensemble mean rainfall valid for 03 UTC 9 August, 2018.

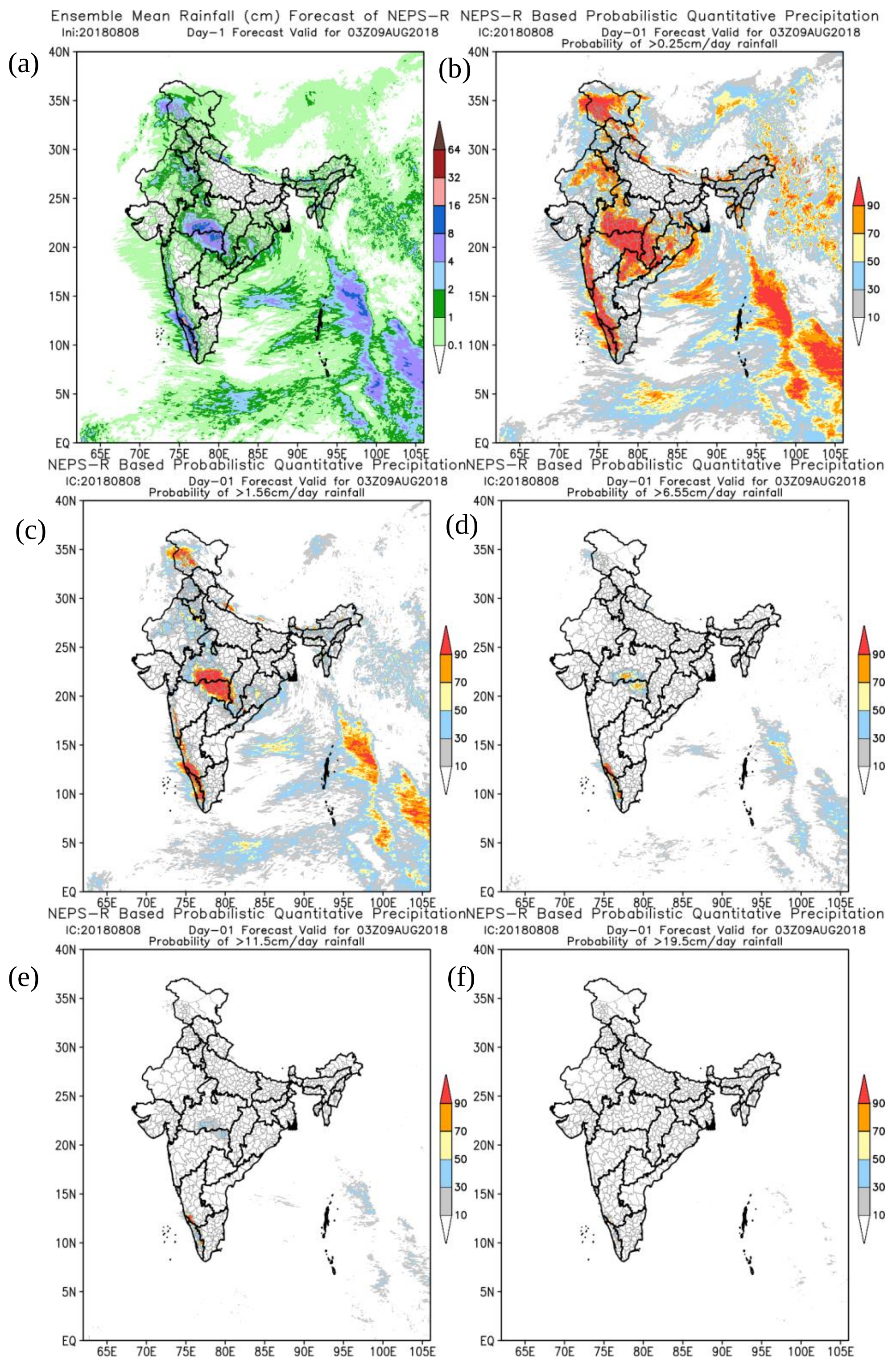

Figure 8: (a) Ensemble mean rainfall (cm) forecast (Day-1) and probabilistic quantitative precipitation forecast of NEPS-R for Day-1, (b) >0.25 cm, (c) >1.56 cm, (d) >6.55 cm, (e) >11.5 cm and (f) >19.5 cm valid for 03 UTC 9 August, 2018.

4.3 Postage Stamp Maps

Postage stamp maps give us the information of the forecast scenario in each individual ensemble member. It is a set of small maps consisting individual forecast of each member, which facilitate the forecasters in assessing the possible risk of extreme events. Figure 9 shows the postage stamp maps of Day-1 rainfall forecast valid for 03 UTC 9 August, 2018. It can be clearly seen that most of the ensemble members could capture the heavy precipitation over Kerala and hence ensemble mean forecast also shows heavy rain concentrated over this region. Rainfall over central India is also captured by most of the members but with slightly larger intensity. Further, there is strong agreement of over predicted rainfall over Jammu and Kashmir in all the member forecasts and as a result the over-prediction is also noted in the ensemble mean (Figure-8(a)).

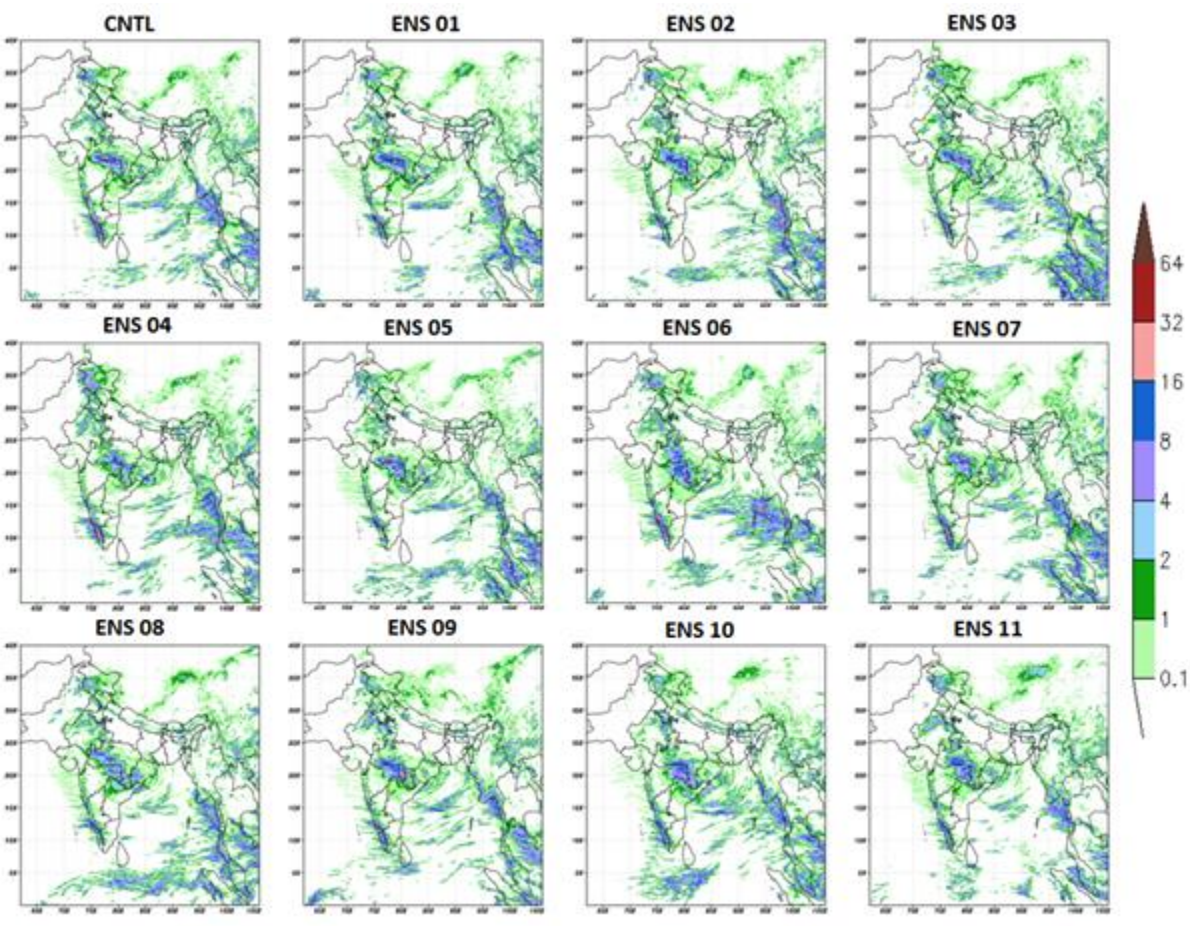

Figure 9: The postage stamp maps of 24 hr accumulated rainfall (cm) for each of the 12 ensemble members for Day-1 forecast valid at 03 UTC 9 August, 2018.

5. Comparison of NEPS-G and NEPS-R Rainfall Forecasts

Increase in model resolution, in general, improves performance of a NWP model as the different atmospheric parameters are resolved much better. Since NEPS-R runs at a convective scale resolution of ~4 km which is almost one-third of the resolution of NEPS-G (12 km), a preliminary evaluation of the forecasts is essential to assess the performance of NEPS-R in comparison to NEPS-G. The precipitation forecasts for two severe weather events have been analysed.

5.1 Heavy Rain Event over Kerala on 15 August, 2018

A heavy rainfall event occurred over Kerala on 15 August, 2018 under the influence of a depression over Coastal Odisha and neighborhood. Heavy rainfall amount between 20 and 35 cm/day were reported at many places. This particular event caused severe floods in Kerala.

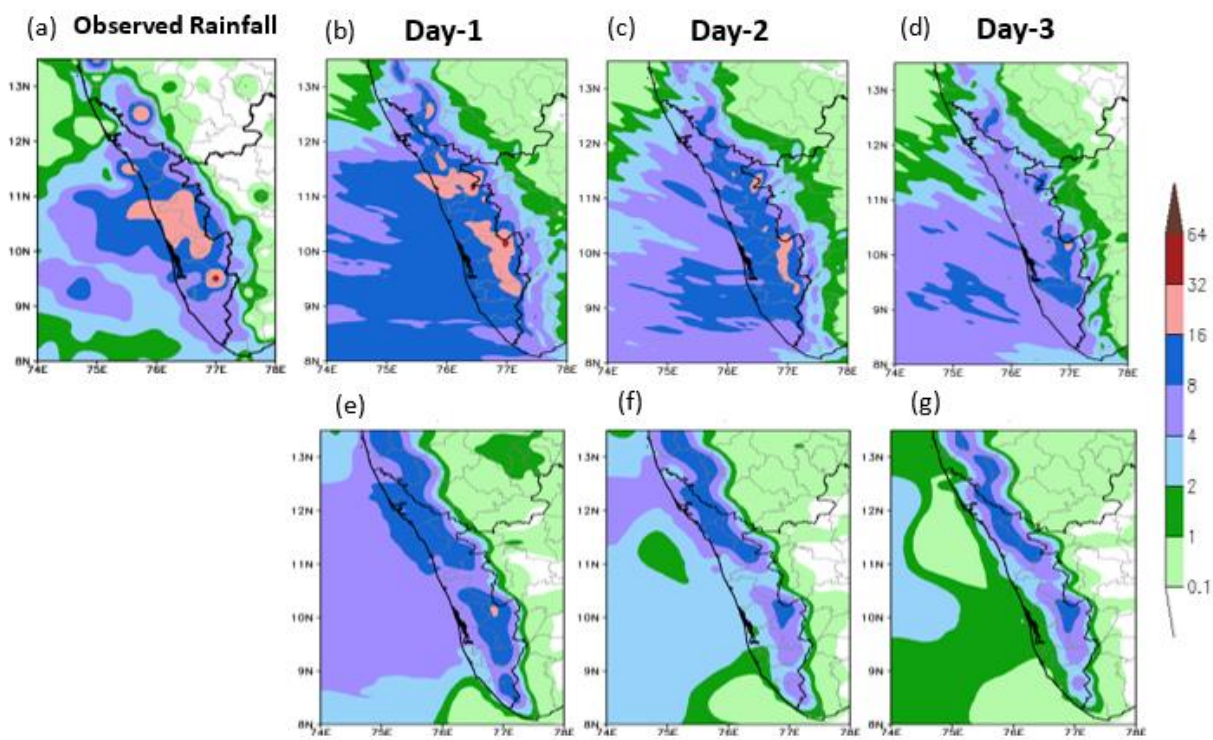

Figure 10 : (a) Observed (merged satellite and gauge) rainfall(cm), ensemble mean rainfall (cm) forecast of NEPS-R for (b) Day-1 (c) Day-2 (d) Day-3 valid for 03 UTC 16 August, 2018. (e-g) are same as (b-d) but for NEPS-G.

To analyse this heavy rain event, Day-1, Day-2 and Day-3 forecasts valid on 03 UTC 16th August 2018 have been considered from both NEPS-G and NEPS-R. Ensemble mean forecast of rainfall accumulated between 03 UTC 15th August and 03 UTC 16th August has been compared with observed accumulated rainfall within the same period. Figure 10 shows the observed rainfall and ensemble mean rainfall forecasts of NEPS-R and NEPS-G for Day-1, Day-2 and Day-3. It can be clearly seen that the observed rainfall is spread over entire Kerala with regions of heavy rainfall in the north (16-32 cm), central (16-32 cm) and south-central (>32 cm) parts of the state. Few of these locations fall on the wind ward side of the highest points in the Western Ghats in Kerala. The rainfall forecasts of NEPS-G and NEPS-R for Day-1 indicate that NEPS-R has performed better in predicting the heavy rainfall areas over central and south-central parts of Kerala with the same intensity (16-32 cm). Further, NEPS-R has over-predicted rainfall over north Kerala and the heavy rainfall zone in over north-coastal Kerala is displaced southwards in the forecast. NEPS-G could predict only 8-16 cm on Day-1 over the north and south-central parts of Kerala.

In Day-2, the heavy precipitation (16-32 cm in NEPS-R and 8-16 cm in NEPS-G) regions have been reduced considerably in both NEPS-G and NEPS-R. In Day-3, NEPS-R could still predict the intensity of 16-32 cm over a small area at south-central Kerala and precipitation of intensity 8-16 cm is confined to the south-central parts and a few small patches in the northern part of Kerala. Heavy precipitation (8-16 cm) area has been reduced further in NEPS-G forecast of Day-3 and is confined to north and south-central parts of Kerala.

The probabilistic quantitative precipitation forecasts for Day-1 (Figure-11) of heavy rain (>6.55 cm/day) indicate higher probability (>75%) in NEPS-R spread over a larger area compared to that of NEPS-G. Moreover, in NEPS-R more than 50% of the members have predicted heavy rain over Kerala, which is consistent with the observed rainfall. On the contrary NEPS-G predicted less probability over the coastal area and central parts of Kerala. NEPS-R has predicted a rainfall probability of >50% over most parts of Kerala for the very heavy (>11.5 cm/day) rainfall compared to isolated patches of probability >50% predicted by NEPS-G over north and south Kerala. NEPS-R could predict extremely heavy rain (>19.5 cm/day) with probability >25% over many places and >75% over some places in the north, central and south-central parts of Kerala. In contrast, NEPS-G could predict extremely heavy rainfall only at few locations with probability less than 25%.

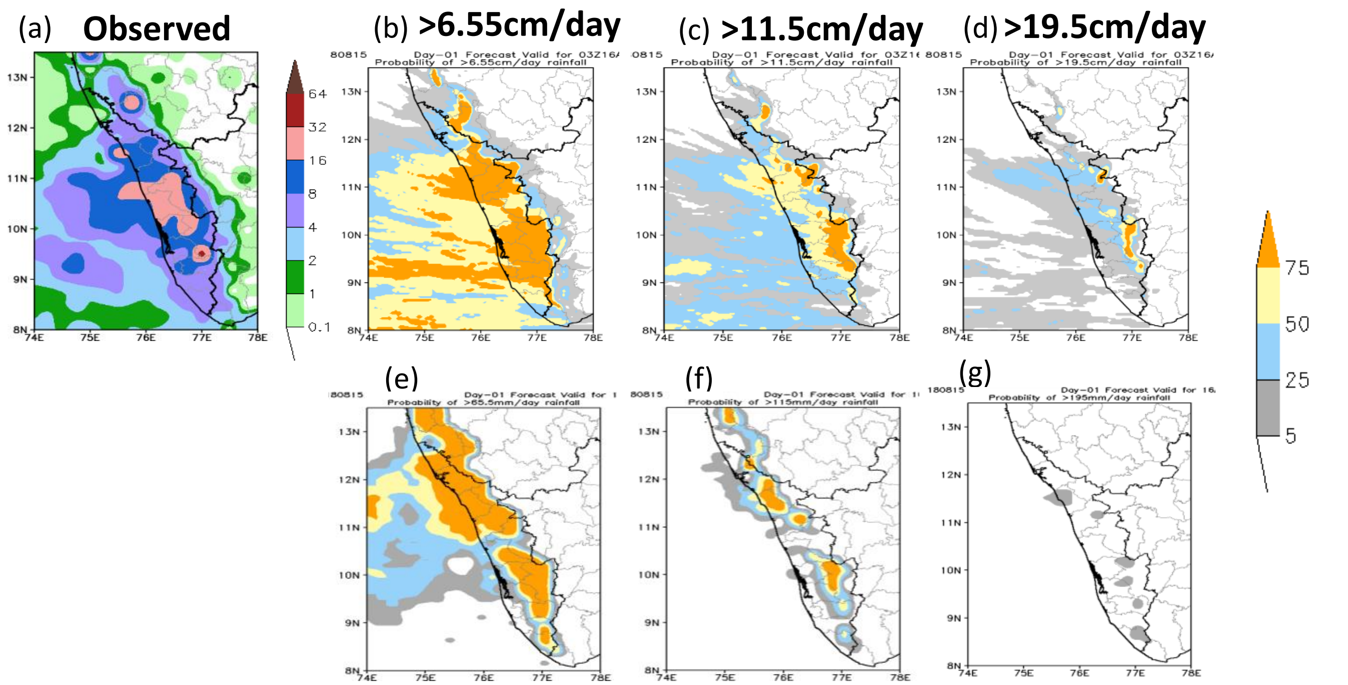

Figure 11: (a) Observed (merged satellite and gauge) precipitation (cm) and Day-1 probabilistic quantitative precipitation forecast of NEPS-R for (b) >6.55 cm (c) >11.5 and (d) >19.5 cm valid for 03 UTC 16 August, 2018. (e-g) are same as (b-d) but for NEPS-G.

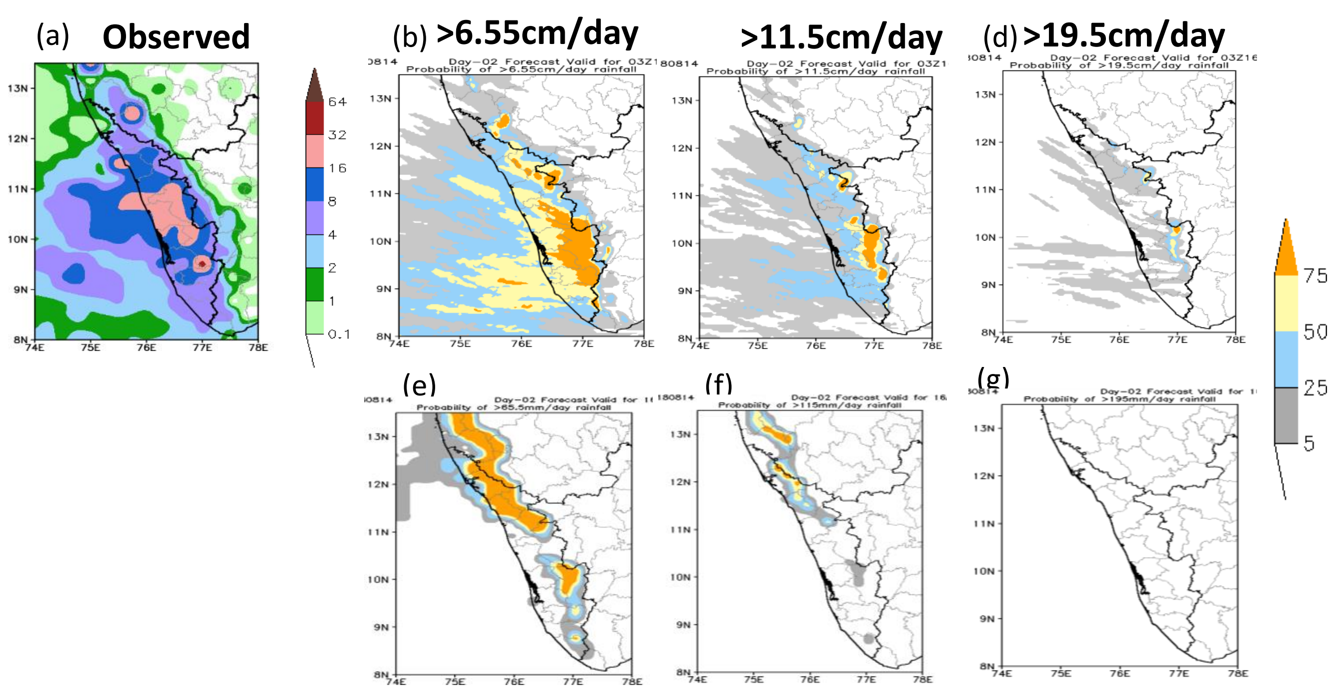

Figure 12: (a) Observed (merged satellite and gauge) rainfall (cm) and Day-2 probabilistic quantitative precipitation forecast of NEPS-R for (b) >6.55 cm (c)>11.5 (d)>19.5 cm valid for 03 UTC 16 August, 2018. (e-g) are same as (b-d) but for NEPS-G.

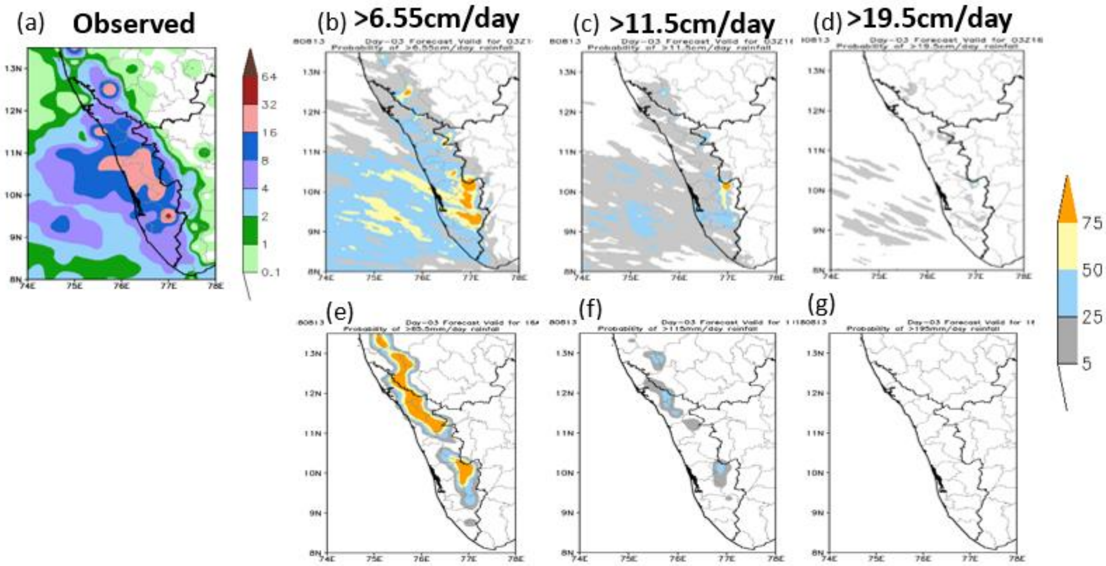

Figure 13: (a) Observed (merged satellite and gauge) rainfall (cm) and Day-3 probabilistic quantitative precipitation forecast of NEPS-R for (b) >6.55 cm (c)>11.5 (d)>19.5 cm valid for 03 UTC 16 August, 2018. (e-g) are same as (b-d) but for NEPS-G.

The probabilistic quantitative precipitation forecasts for Day-2, illustrated in Figure 12 shows that NEPS-R has predicted heavy rainfall (>6.55 cm/day) with probability >50% over most parts of Kerala and also over the adjoining Arabian Sea, whereas NEPS-G prediction of heavy rain is confined to the north and south Kerala. Further, NEPS-G was unable to predict the heavy rain over Arabian Sea. Similar features of prediction can be seen for the very heavy rainfall category (>11.5 cm/day) but the area having rainfall probability >50% and >75% over Kerala and adjoining Arabian Sea is getting reduced compared to Day-1 in NEPS-R. In NEPS-G, the prediction is confined to an elongated patch over north Kerala and two small isolated patches over central and south Kerala.

The probabilistic quantitative precipitation forecasts (Figure-13) for Day-3 shows that NEPS-G forecast has retained the same rainfall pattern as that of Day-2 with minor differences, whereas in NEPS-R the area of probability >75% and 50-75% has decreased over north, central and south-central Kerala and also over the Arabian Sea. Similar to Day-2, NEPS-G was unable to predict heavy rain (>6.55 cm/day) over some parts of Kerala and over the Arabian Sea. Further, for the very heavy rain category (>11.5 cm/day), at least 25% of the members of NEPS-R have predicted rainfall over entire Kerala and also over the Arabian Sea with locations of rainfall probability >75%, 50-75% and 25-50% over south-central and north Kerala. In contrast, NEPS-G could only predict with a probability of 5-25% and 25-50% over a few locations in north and south-central Kerala. The extremely heavy category of rainfall (>19.5 cm/day) was predicted by NEPS-R with probability of 5-25% , 25-50% and 50-75% over isolated regions of north and south-central Kerala and over Arabian Sea. NEPS-G was unable to predict any rainfall in this category.

5.2 Tropical Cyclone Titli

The Very Severe Cyclonic Storm (VSCS) “Titli” developed from a well-marked low pressure area over east central Bay of Bengal on 8th October, 2018 and made landfall over north coastal Andhra Pradesh on 10th October, 2018. The system, after landfall, weakened and re-curved towards northeast direction. The Day-1, Day-2 and Day-3 forecasts starting from 00 UTC 9th October, 2018 have been considered for assessing the performance of NEPS-G and NEPS-R. Figure 14 shows the observed (satellite and gauge merged) and ensemble mean forecast of 24 hour accumulated rainfall on Day-1, Day-2 and Day-3 forecasts valid at 03 UTC 10, 11 & 12 August 2018 for NEPS-G and NEPS-R. It can be seen that both NEPS-G and NEPS-R have done well in capturing the observed rainfall pattern over Bay of Bengal and have over predicted the rainfall of 8-16 cm which was spread over a smaller area in the observation. NEPS-R shows good skill in simulating the maximum rainfall of 16-32 cm over a slightly larger area than NEPS-G, which matches well with the observed rainfall. At the same time the rainfall over land is also well predicted by NEPS-R in terms of location and intensity compared to the forecast of NEPS-G. Further, in Day-2 forecast valid at 03 UTC of 11th October, 2018, it is clearly seen that the rainfall of 8-16 cm was captured well in terms of location by NEPS-R compared to NEPS-G. Higher amount of rainfall of 16-32 cm is predicted well by NEPS-G over a larger area than NEPS-R. The rainfall prediction over land is again better captured by NEPS-R in Day-2 forecast.

In Day-3 forecast valid at 03 UTC 12 October, 2018, the rainfall pattern is better captured by NEPS-G though the location of very heavy rainfall (16-32cm/day) zone has shifted in the forecast. Further, the rainfall amount of 8-16 cm is better captured by NEPS-R, which is displaced northeastwards in NEPS-G, thereby over predicting rainfall over Bengal. Overall, the performance of NEPS-R for TC-Titli is comparatively better over land in Day-1, Day-2 and marginally better in Day-3 forecast.

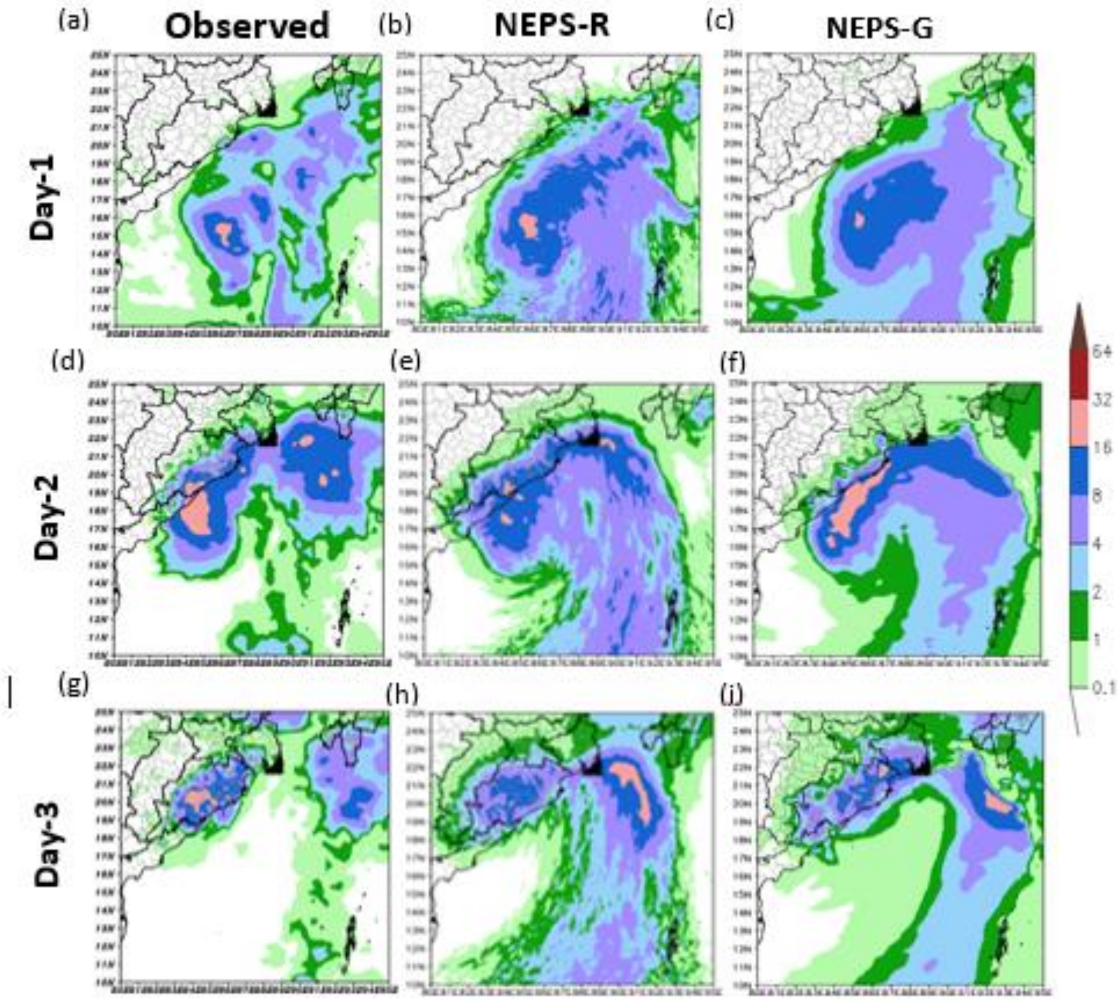

Figure 14: (a) Observed (merged satellite and gauge) rainfall(cm), ensemble mean rainfall (cm) forecast of (b)NEPS-R (c) NEPS-G for Day-1 valid for 03 UTC 10 October, 2018. (d-f) are same as (a-c) but for Day-2 valid for 03 UTC 11 October, 2018. (g-i) are same as (a-c) but for Day-3 valid for 03 UTC 12 October, 2018.

The Day-1, Day-2 and Day-3 probabilistic quantitative precipitation forecasts by NEPS-R and NEPS-G are illustrated in Figures 15, 16 and 17 respectively. Probabilistic quantitative precipitation forecast of Day-1 (Figure 15) for an amount >6.55 cm/day of NEPS-R matches better with the observed rainfall pattern compared to NEPS-G. In NEPS-G the probability of 50-75% is spread over a larger area indicating over prediction of rainfall by more than 50% of the members. Similarly for rainfall >11.5 cm/day, the probability of NEPS-R matches better than NEPS-G over central Bay of Bengal but over-predicts rainfall over south Bay of Bengal. Both NEPS-R and NEPS-G predicted rainfall >19.5 cm/day with 25-50% probability which agrees well with observed rainfall.

Day-2 forecast (Figure 16) shows that NEPS-G does better for the rainfall threshold of >6.55 cm/day, whereas NEPS-R over-predicted rainfall over south central and south Bay of Bengal. Similar pattern is found in rainfall >11.5 cm/day. For rainfall >19.5 cm/day, NEPS-R does well with the highest probability matching well with that of the observed pattern.

Day-3 forecast (Figure 17) indicates that there is a displacement of rainfall location in both NEPS-G and NEPS-R over head Bay of Bengal, with NEPS-R over predicting the rainfall of >6.55cm/day over central and south Bay of Bengal. Over land NEPS-R performs better for this category of rainfall with higher probability of prediction. For rainfall threshold of >11.5 cm/day, NEPS-R does better than NEPS-G over land but NEPS-G out-performs NEPS-R over Head Bay of Bengal by capturing the location of very heavy rainfall better. For the rainfall category of >19.5 cm, NEPS-G predicts higher probability over north-east Odisha and adjoining West Bengal unlike the observed heavy rainfall region which is located more southward. NEPS-R shows a rainfall probability of 5-25% which matches well with that of the observed location of rainfall. Both the models have predicted rainfall over Bay of Bengal at wrong locations. Overall, it can be seen that although NEPS-R has performed better over land most of the time its prediction of rainfall location over Bay of Bengal is not good.

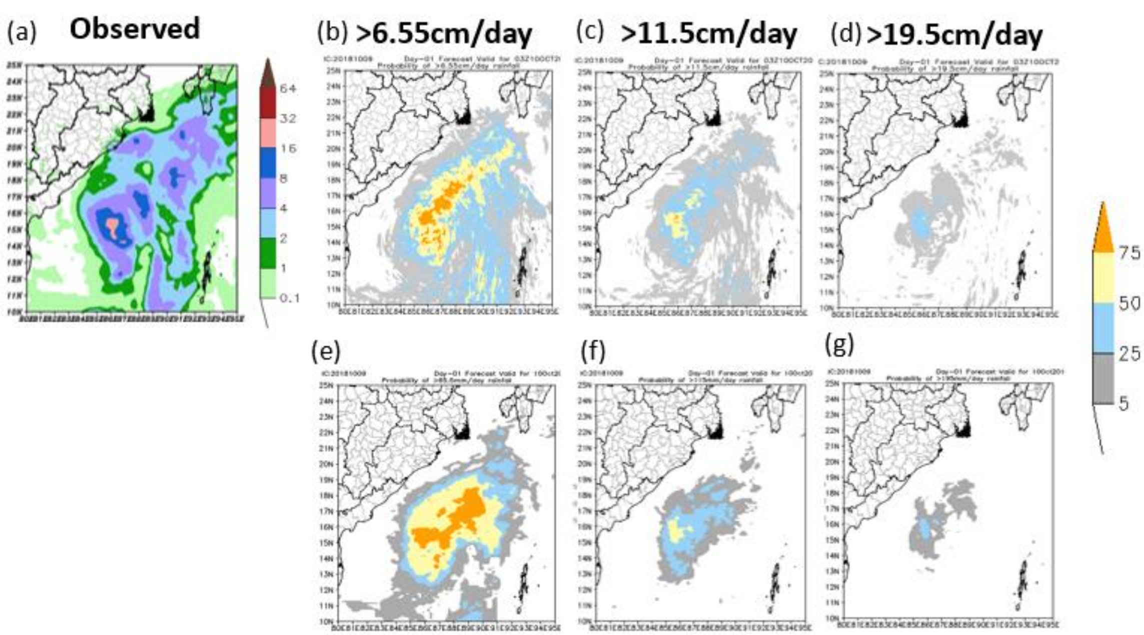

Figure 15: (a) Observed (merged satellite and gauge) rainfall (cm), Probabilistic quantitative precipitation forecast of NEPS-R for TC-Titli for Day-1 (b) >6.55 cm (c)>11.5 cm (d)>19.5 cm valid for 03 UTC 10 October, 2018. (e-g) are same as (b-d) but for NEPS-G.

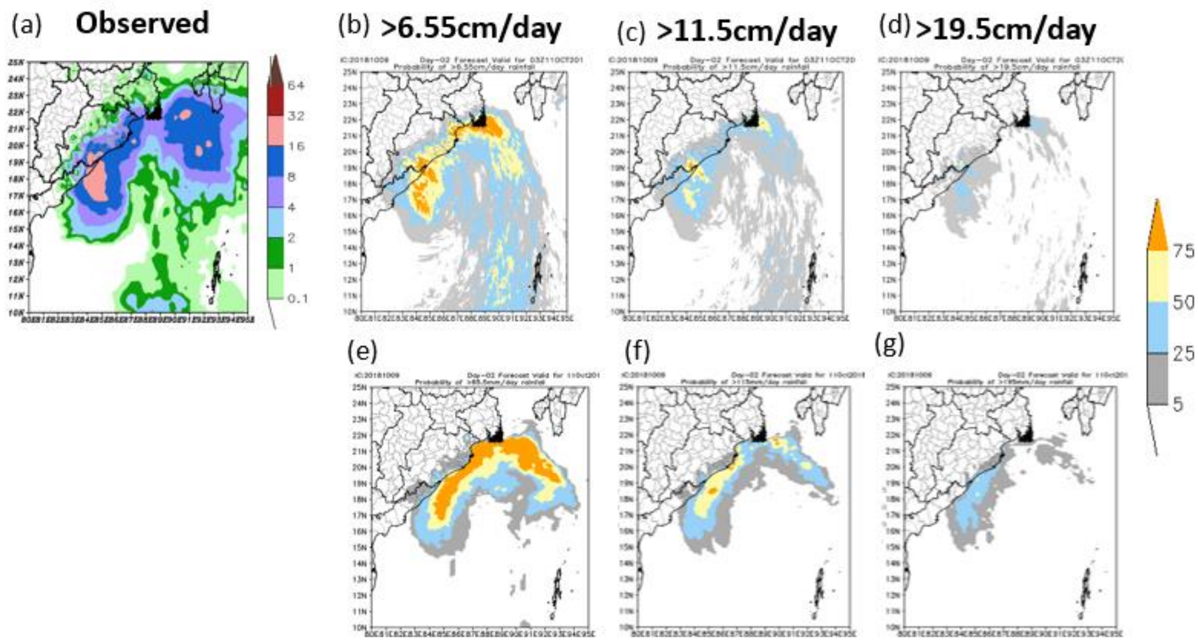

Figure 16: (a) Observed (merged satellite and gauge) rainfall (cm), Probabilistic quantitative precipitation forecast of NEPS-R for TC-Titli for Day-2 (b) >6.55 cm (c)>11.5 cm (d)>19.5cm valid for 03 UTC 11 October, 2018. (e-g) are same as (b-d) but for NEPS-G.

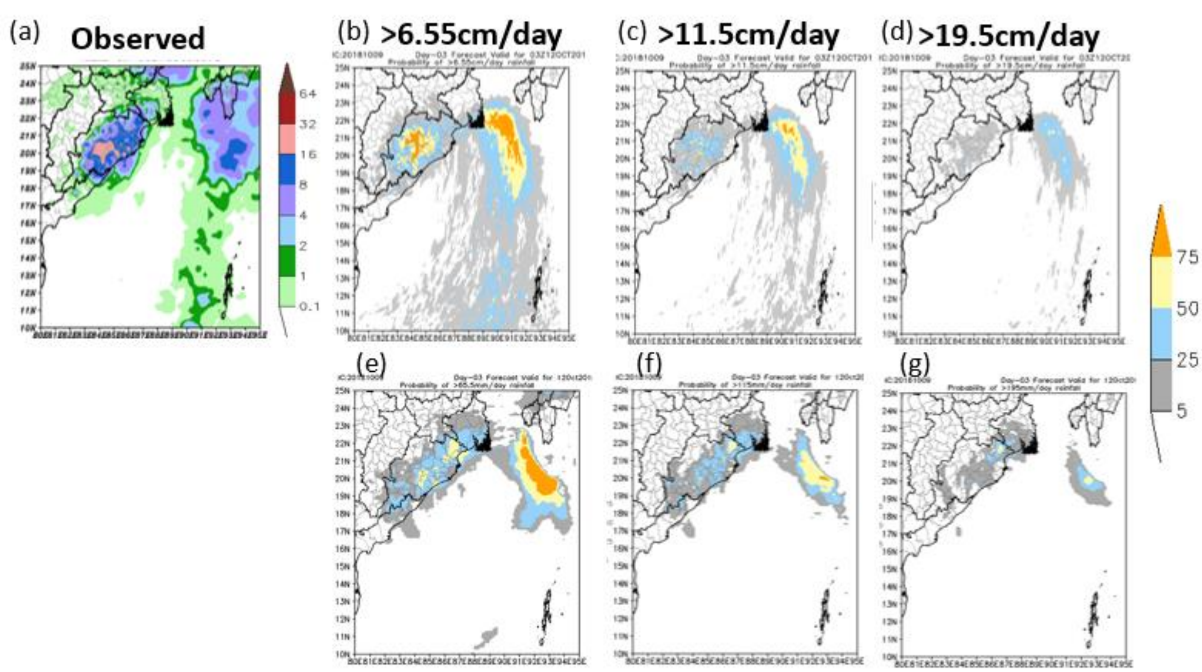

Figure 17: (a) Observed (merged satellite and gauge) rainfall (cm), Probabilistic quantitative precipitation forecast of NEPS-R for TC-Titli for Day-3 (b) >6.55 cm (c)>11.5 cm (d)>19.5 cm valid for 03 UTC 12 October, 2018. (e-g) are same as (b-d) but for NEPS-G.

6. Summary

Ensemble based prediction systems have been successful in providing better forecast guidance and have evolved in the past few decades starting with Global EPS focusing on uncertainties due to synoptic scale baroclinic instability. With rise in computing capacity, short range EPS has been developed and operationally implemented at many meteorological centres around the world to address the significant uncertainty on shorter time and length scales. The convective scale ensemble is very much essential in order to handle the uncertainty in forecasts at a kilometre scale.

Unified Model based convective scale regional ensemble prediction system has been implemented at NCMRWF using MOGREPS. The initial and boundary conditions for the control and 11 perturbed members are obtained from the operational runs of NEPS-G. NEPS-R has its own Random Parameters (RP) scheme to take care of model uncertainties.

Several sensitivity experiments were carried out to arrive at an operationally feasible model setup and configuration to save computational time and resources. Sensitivity experiments were performed with different resolutions of the driving Global EPS (20 km and 12 km), 1-hourly and 3-hourly boundary conditions and different science configurations (Singv4.1 and Proto-RA1T) suitable for the tropical environment. It is seen that NEPS-R performs slightly better with the inputs from 12-km NEPS-G. There is no significant difference in forecast using 1-hourly and 3-hourly boundary conditions, so 3-hourly boundary conditions are used to save computational time and resources. There was no major difference in the forecasts using the two science configurations Proto-RA1T and Singv4.1.

Various forecast products are generated from NEPS-R which include MSLP, geo-potential height, rainfall probability, ensemble stamp and EPSgrams and the same are made available to user community through NCMRWF web page.

Preliminary evaluation of rainfall forecast of NEPS-G and NEPS-R for the Kerala heavy rain event on 15 August, 2019 and tropical cyclone ‘Titli’ indicate that NEPS-R has performed better than NEPS-G. NEPS-R was able to predict the heavy rainfall of 16-32 cm for the Kerala heavy rain event at different lead times, whereas NEPS-G was able to predict a maximum of 8-16 cm at different lead times. The probabilistic quantitative precipitation forecasts of both the models indicate that NEPS-R predicted higher probability of rainfall for different thresholds over comparatively larger area than NEPS-G.

Both the global and regional ensemble prediction systems have performed well in predicting rainfall during TC-Titli. NEPS-R has captured the rainfall intensity better than NEPS-G in Day-1 by predicting higher amount of rainfall over a larger area. Although Day-2 and Day-3 forecasts of NEPS-R over land are better than NEPS-G in terms of location for some categories of rainfall, NEPS-R over predicted rainfall over Bay of Bengal compared to NEPS-G. The probabilistic quantitative precipitation forecasts indicate that NEPS-R performed better for lesser thresholds of rainfall (>6.55 cm/day and >11.5 cm/day) and was at par with NEPS-G for rainfall threshold of >19.5c m/day in Day-1. For Day-2 and Day-3, NEPS-R performed better for higher rainfall threshold over land and is found to be over predicting for lesser rainfall thresholds. Overall, NEPS-R performs better for different extreme weather events and shows its capability in providing better forecast guidance and also stresses the necessity for a convective scale ensemble prediction system for extreme weather forecasting over Indian region.

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