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TECHNICAL REPORT

**Generation of Probabilistic Forecast Products from
NCMRWF Ensemble Prediction System (NEPS)**

**Paromita Chakraborty, Anumeha Dube, Harvir Singh,
Arulalan T., S. Kiran Prasad, Ashu Mangain, Aditi,
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and E. N. Rajagopal**

April 2019

**National Centre for Medium Range Weather Forecasting
Ministry of Earth Sciences, Government of India
A-50, Sector-62, NOIDA-201309, INDIA**

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Abstract

The NCMRWF global Ensemble Prediction System (NEPS) was upgraded to 12 km resolution and made operational from 1st June 2018 for generation of 10 day forecasts at 00 and 12 UTC. The initial condition perturbations are generated by Ensemble Transform Kalman Filter (ETKF) method. The forecast perturbations obtained from 6 hour short forecasts of 22 ensemble members are updated by ETKF four times a day at 00, 06, 12 and 18 UTC. The model uncertainties are estimated by the Stochastic Kinetic Energy Backscatter (SKEB) and Random Parameters (RP) schemes. Surface parameters like sea surface temperature, soil moisture content and soil temperature are also perturbed in the initial condition to remove the deficiency of lack of ensemble spread near the surface. 10-day probabilistic forecasts are issued daily using 23 ensemble members (1 control + 22 perturbed). The operational deterministic forecast running from 00 UTC is used as control forecast. One set of 11 perturbed members run from 00 UTC of current day and another set of 11 perturbed members run from 12 UTC of previous day to form 22 perturbed ensemble members. This report outlines various ensemble forecast products generated using high resolution 12 km NEPS. It highlights the probabilistic predictions for extreme weather phenomena of different scales. The aim of this report is to help forecasters interpret and make optimal use of the probabilistic medium-range ensemble forecast products from NCMRWF.

1. Introduction

The ensemble prediction system offers the most consistent method of identifying the predictable scale and dampening forecast jumpiness, estimating the overall confidence and drawing attention to possible alternative developments, in particular those which involve extreme or hazardous weather events. A high spatial resolution enables a better representation of topography and its effect on the large-scale flow. It also produces a more accurate description of horizontal and vertical structures, which facilitates the assimilation of observations. Increasing the resolution not only benefits the analyses and forecasts of the small-scale systems associated with severe weather but also those of large-scale systems. For medium-range or extreme weather events particularly, instead of over-interpreting a single high-resolution deterministic forecast, it is better to combine the probabilistic forecasts as well for risk assessments. Now, with the advent of expanding computing resources, the global ensemble prediction systems (EPS) can be run at resolutions comparable to that of the deterministic models. High resolution EPS can resolve the small scale features of the extreme events along with providing uncertainty information in predicting these events way ahead in time. For example, location-specific forecasts and strike probability can be essentially useful in such cases.

The horizontal resolution of NCMRWF global Ensemble Prediction System (NEPS) was recently upgraded to 12 km. Previous version of NEPS i.e. N400 had a horizontal resolution of 33 km and ensemble size of 45 (44 perturbed + 1 control) members. The forecast products generated from the previous version of NEPS operational in Bhaskara HPCS are detailed in Sarkar et al., 2016). NEPS N1024 (Mamgain et al., 2018) has a horizontal resolution of 12 km and the updated version was made operational on 1stJune, 2018. The upgraded NCUM (Kumar et al., 2018) analysis is used as the initial condition for the control model forecast. The perturbations are generated by Ensemble Transform Kalman Filter (ETKF) method (Bishop et al., 2001), which are added to the global deterministic analysis to create 22 perturbed initial conditions. These are used for generating ensemble member forecasts. One control and 11 perturbed ensemble members run from initial condition of 00 UTC of current day and another 11 perturbed members run from 12 UTC of previous day to give 23 members (11+11+1 control) ensemble forecasts up to 10 days lead time. To make the best use of the products, the timely generation of these high resolution forecasts is necessary and the same became feasible after the commissioning of state-of-the art Mihir HPCS recently. Forecast products are generated from the

12 km NEPS regularly from 1st June 2018. City-wise and district-wise probabilistic forecasts are currently issued all over India. Forecast products are also being developed for block level as well to meet future demands. The choice of few products largely depends on user demands and necessities of particular meteorological services. The performance of the high resolution NEPS forecasts of heavy precipitation events associated with western disturbances and monsoon lows, heat and cold waves, cyclonic storms, fog and intra-seasonal oscillation have been presented in this report. The 12 km NEPS forecast products can be used as guidance to forecasters and also to provide direct input to help end-users such as regional and national authorities, to make the optimal decision for preventive/recovery action. The use and interpretation of NCMRWF probabilistic products for different applications will be discussed in the following sections.

2. Methodology

12 km NEPS long forecasts are generated daily for 10.5 days from 00 and 12 UTC initial conditions. The deterministic global model, which also has the same horizontal resolution (12 km) is used as the control member of NEPS. Long forecasts of perturbed members from both 00 and 12 UTC cycles and one control member from 00 UTC run are combined to form the 23 ensemble member long forecast. The post-processing products from the combined long forecast are generated using UMRider (Arulalan et al., 2019).

NEPS forecast products are generated in grib2 format using UMRider at 6 hourly intervals. All fields are bi-linearly interpolated to a 0.125° lat/lon grid. Few forecast products are also being generated at 1-hourly interval. Each post-processed file contains 252 hours ensemble forecasts of 11 members from 00 UTC 00 UTC of current day merged with 11 members from 12 UTC of previous day. The data are extracted using wgrib2 utilities and processed for computation of ensemble statistics using Climate Data Operators (CDO) (Schulzweida et al., 2006). The files in wgrib2 format are directly read in Grid Analysis and Display System (GrADS), for computation and plotting the ensemble statistics of some of the specific parameters. Various software packages, Viz., python, R and GrADS are used for graphical visualization of the products. The NEPS operational forecast products are generated as per national as well as international user needs.

3. Some advantages of probabilistic forecasts over deterministic forecasts

The weather forecasts will be much more beneficial for public, decision makers and end users if it contains the uncertainty information in addition to the issued forecasts. It is advisable for forecasters to make use of uncertainty since it is better to present an uncertain weather forecast than that with misleading certainty.

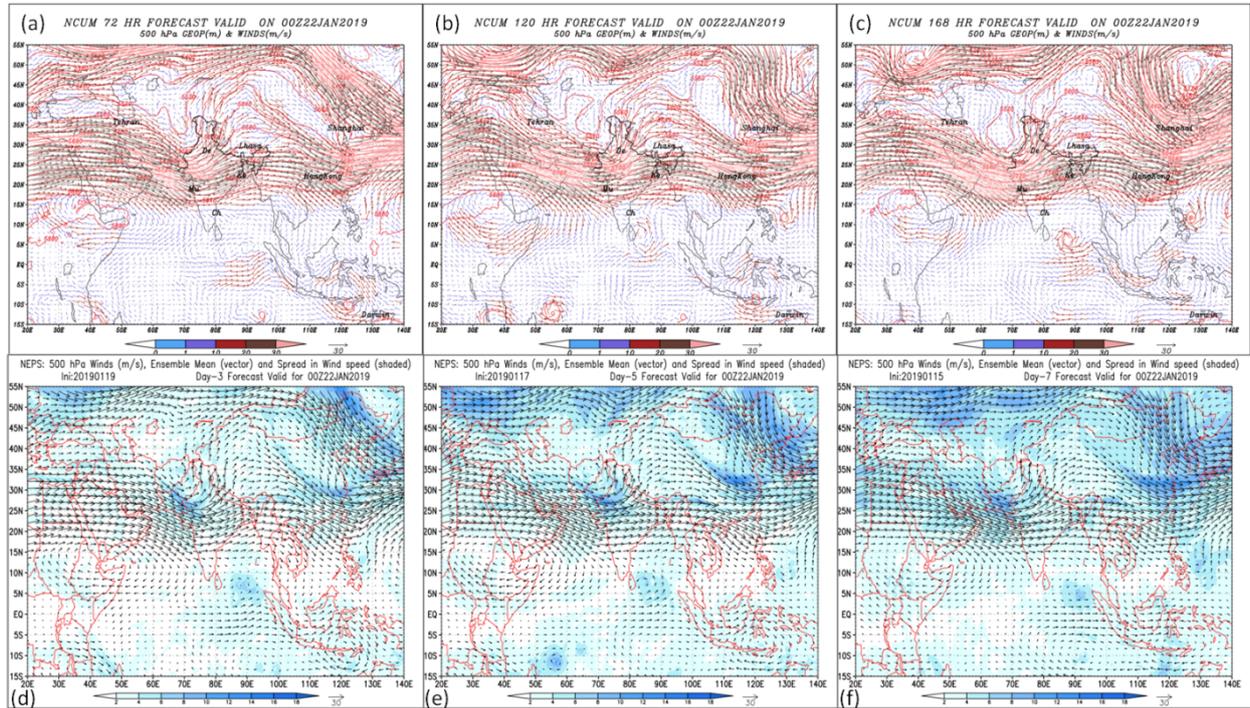


Figure 1: Deterministic (a) day-3, (b) day-5 and (c) day-7 forecasts of wind (vectors) and geopotential height at 500 hPa from NCUM; (d) Day-3, (e) day-5 and (f) day-7 forecasts of ensemble mean (vectors) and spread (shaded) in wind at 500 hPa from NEPS, all valid at 00 UTC of 22 January 2019.

The deterministic and probabilistic wind forecasts are compared in Figure 1 to show the consistency from one forecast to the next. The difference between consecutive forecasts or jumpiness is dampened in ensemble forecasts, which are more consistent due to less jumpiness between consecutive forecasts from different ICs. These clustering help forecasters judge how far into the future the ensemble mean can carry informative value for large synoptic patterns. There is a tendency of jumpiness to increase in the deterministic forecasts but decreases in the ensemble mean with increasing forecast range (Zsótér et al., 2009).

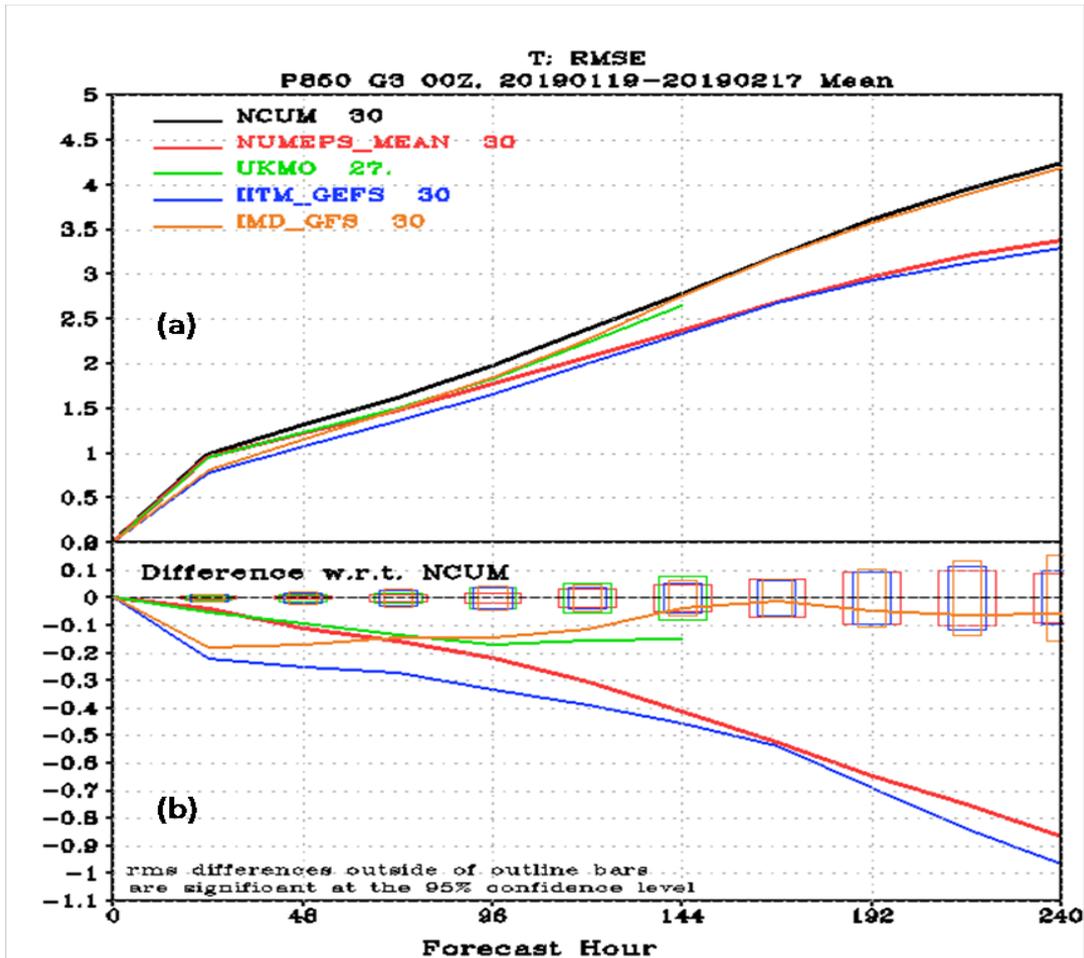


Figure 2: (a) RMS error of NCUM, NEPS mean, UKMO, IITM GEFS and IMD GFS for global domain (b) Difference in RMSE of the models with respect to NCUM.

In short range (till day-2), there is less difference in RMSE values between ensemble and deterministic forecasts. With increasing forecast range, this difference is considerable and ensemble forecasts are more skilful than the deterministic forecasts in medium range (Figure 2).

4. NEPS Operational Forecast Products

The NEPS forecast products generated for RSMC region (covering 15°S to 55° N and 60° E to 140°E) made available in NCMRWF website under ‘Monsoon Region’ (http://www.ncmrwf.gov.in/product_main_mihir.php) are detailed in sections 4.1 and 4.2.1.

4.1 Ensemble Mean and Spread

The ensemble mean is a simple mean of the parameter values of all ensemble members. It is generated to assess, on average, the most likely outcome. It displays a higher degree of day-to-day consistency. The ensemble mean is normally better than the control forecast or any

individual ensemble member forecast as it smooths out smaller-scale, relatively unpredictable features and simply presents the more predictable elements of the forecast. In order to avoid over-interpretation of the ensemble mean, in particular underestimating the risk of extreme weather events, it is preferably presented together with a measure of the ensemble spread or event probabilities.

Ensemble Spread is calculated as the standard deviation of a model output variable. It gives a priori estimation of the accuracy of the ensemble mean: the larger the spread, the larger the expected error in ensemble mean, on average. It is often plotted on charts overlaid with the ensemble mean. The spread refers to the uncertainty of the values of mean sea-level pressure, geopotential height, wind or temperature, and not necessarily to the flow patterns.

4.1.2 Ensemble mean and spread in MSLP

Ensemble mean and spread in MSLP plots are routinely generated for NEPS analysis and Day-1 to Day-10 forecasts based on 00 UTC. Analysis (Figure 3a) depicts two TCs: Very Severe Cyclonic Storm (VSCS) “Titli” (08-13 October 2018) making landfall over Odisha coast which developed over east-central Bay of Bengal (BoB) and VSCS “Luban” (06-15 October) which is persisting over Arabian Sea (AS) near Oman coast. NEPS predicted the landfall location of TC Titli at its VSCS stage near South Odisha and adjoining north Andhra Pradesh coast, 5-days in advance (Figure 3b). The magnitudes of isobars as well as their gradients towards the centre are slightly overestimated in the ensemble mean forecast than those in the analysis for TC Titli, with 2-4 hPa spread (blue shade) between MSLP contours. The centre of TC Luban developed at Arabian Sea is predicted near Oman coast (Yemen) with 6-8 hPa spread in the location of MSLP contours.

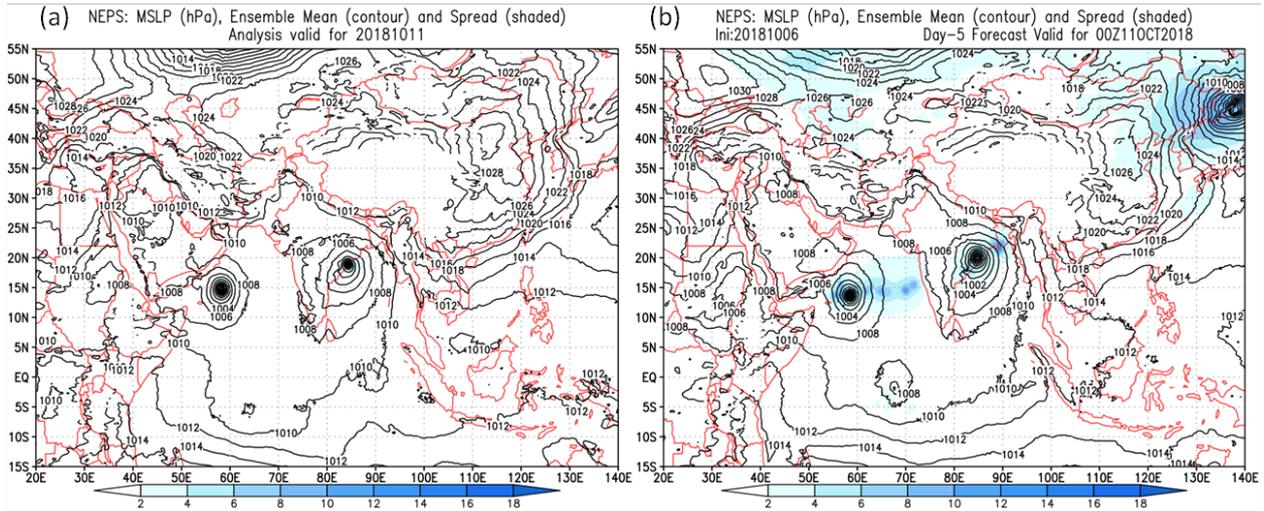


Figure 3: Ensemble mean and spread in (a) Analysis and (b) Day-5 forecast of MSLP valid for 00 UTC 11th October 2018

4.1.2 Ensemble mean and spread in Wind and Geopotential Height at pressure levels

Ensemble mean and spread in wind and geopotential height are calculated at different pressure levels (925, 850, 700, 500 and 200 hPa) and routinely generated for NEPS analysis and Day-1 to Day-10 forecasts based on 00 UTC. The spatial distribution of uncertainty in the ensemble mean forecasts aids in understanding the tendency of genesis, development and propagation of various synoptic and mesoscale features.

The ensemble mean wind at 850 hPa (Figure 4a) shows strong cyclonic circulation associated with CS Luban over AS with a spread of 10-12 m/s, 5-days in advance. A well defined vortex of CS Titli over BoB is predicted by the ensemble mean winds with lesser spread of 4-8 m/s. The instability driving the systems both extend upto 500 hPa in day-5 forecast of ensemble mean geopotential height (Figure 4b). There is a spread of 20-40 m in the forecast of the ensemble mean contours of geopotential height for the system persisting at BoB and that up to 80 m for the AS system. The ensemble spread tends to show a strong geographical dependence. For spreads in MSLP (Figure 3b) and geopotential (Figure 4b), it takes low values at low latitudes and high values at mid-latitudes, where the variability is higher.

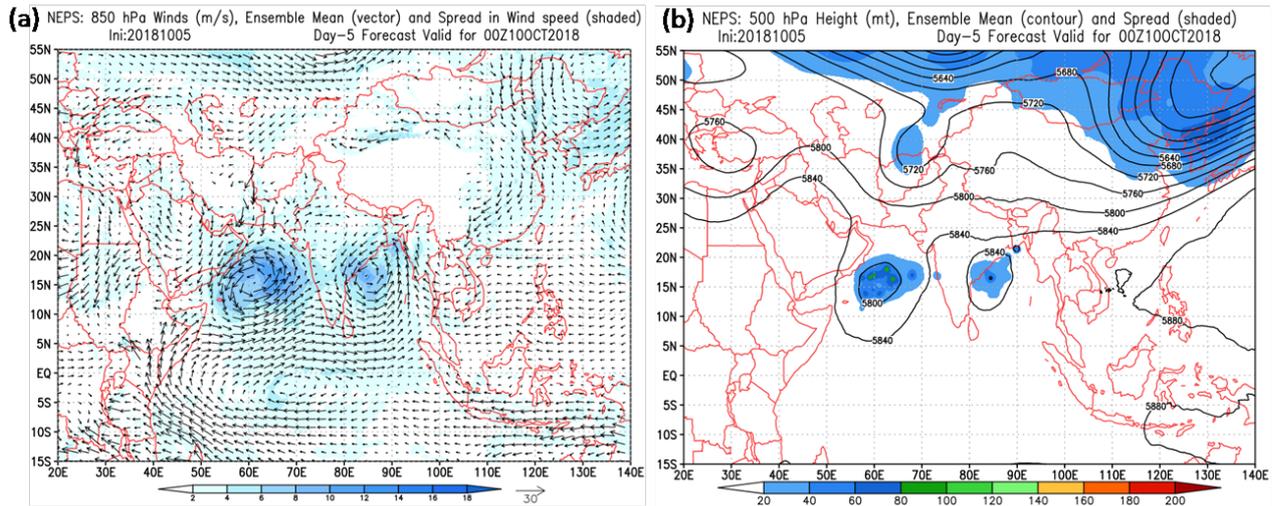


Figure 4: Day-5 forecast of (a) Ensemble mean (vector) and spread (shaded) in Winds at 850 hPa and (b) Ensemble mean (contour) and spread (shaded) in Geopotential height at 500 hPa valid at 00 UTC 10th October 2018.

4.2 Probability of exceedance

Probability of occurrence of an event can be quantified in terms of exceedance of a threshold. It is the most consistent way to convey forecast uncertainty information. The event threshold often corresponds to the point at which the user has to take some action to mitigate for the potential damage due to a significant weather event.

4.2.1 Probability of exceedance of precipitation for RSMC region

Probabilities of occurrence of 24-hr accumulated rainfall exceeding threshold values 2.5 (light), 15.6 (moderate), 65.5 (heavy), 115 (very heavy) and 195 (extremely heavy) mm/day as per criteria prescribed by IMD, are calculated for daily (Day-1 to Day-10) forecasts from six hourly NEPS outputs.

Ensemble mean (Figure 5a) predicted moderate (2-4 cm) with a few patches of heavy (4-8 cm) rainfall over coastal north Andhra Pradesh, Odisha, West Bengal, Bangladesh and Myanmar on 11th October 2018. Light (1-2 cm) rainfall is predicted over north J&K region and Kerala. The probability of rainfall exceeding 2.5 mm/day (Figure 5b) is more than 75% over north J&K region, Kerala and east coast of India. It is most likely (70% probability) that coastal Myanmar and adjoining places get rainfall exceeding 15.6 mm/day (Figure 5c). There is fair chance (25-50%) that east coast of India and Myanmar receives rainfall beyond 65.5 mm/day (Figure 5c, 5d).

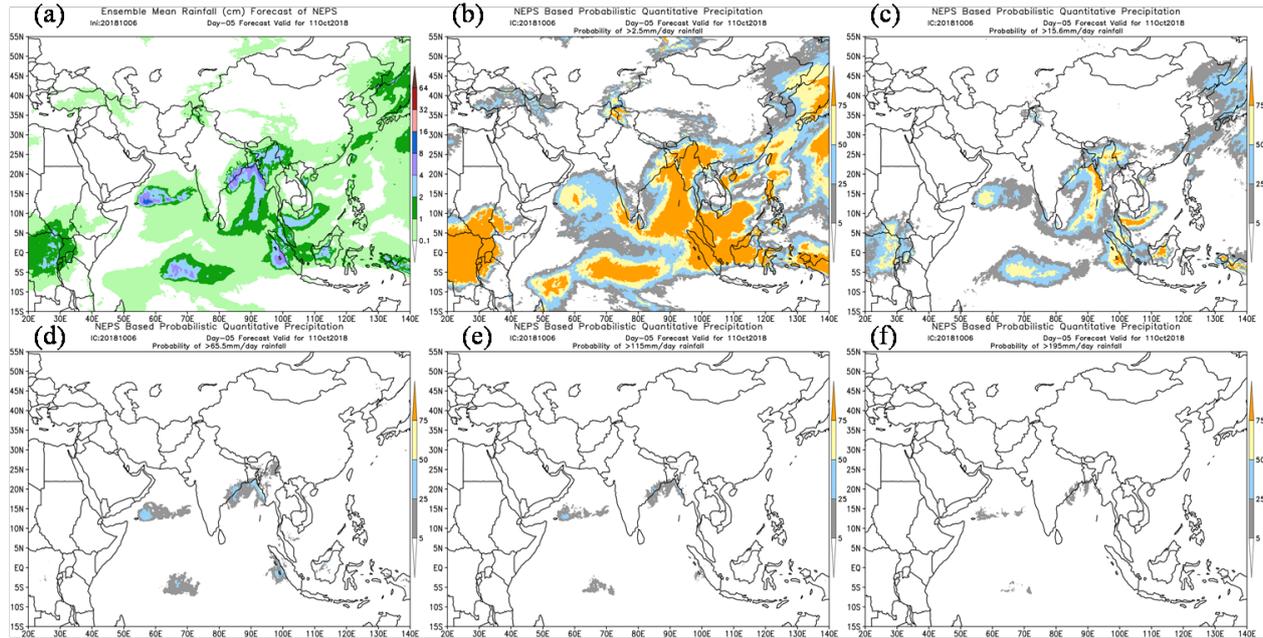


Figure 5: Day-5 forecast of (a) Ensemble mean precipitation and Probabilistic quantitative precipitation forecast exceeding (b) 2.5, (c) 15.6, (d) 65.5, (e) 115, (f) 195 mm/day valid for 11th October 2018

4.2.2 Probability of exceedance versus probabilistic forecasts in ranges:

Probability expressed in terms of exceedance is often preferred over that within certain ranges of thresholds since it considers the cumulative probability whereas the probability within certain range does not consider the values above the upper limit of the range. This is further illustrated below.

Stations reporting >35 cm rainfall are mentioned in Table 1. There is an increase in the area of probability 50-75% of rainfall >1.56 cm/day (Figure 6) compared to the probability of rainfall range of (2-6) cm/day (Figure 7) over Gujarat & adjoining Pakistan in day 5 forecast due to higher amount (>6 cm) of predicted rainfall. However probability over the west coast remains same.

Table 1: Rainfall amounts (cm) at stations reporting >35 cm rainfall

Stations Reporting >35 cm Rainfall	Rainfall Amount (cm)
Mount Abu (24.6N, 72.7E)	73
Mount Abu (T) (24.6N, 72.5E)	77
Reodar (24.6N, 72.5E)	40
Shirohi (24.7N, 72.8E)	38

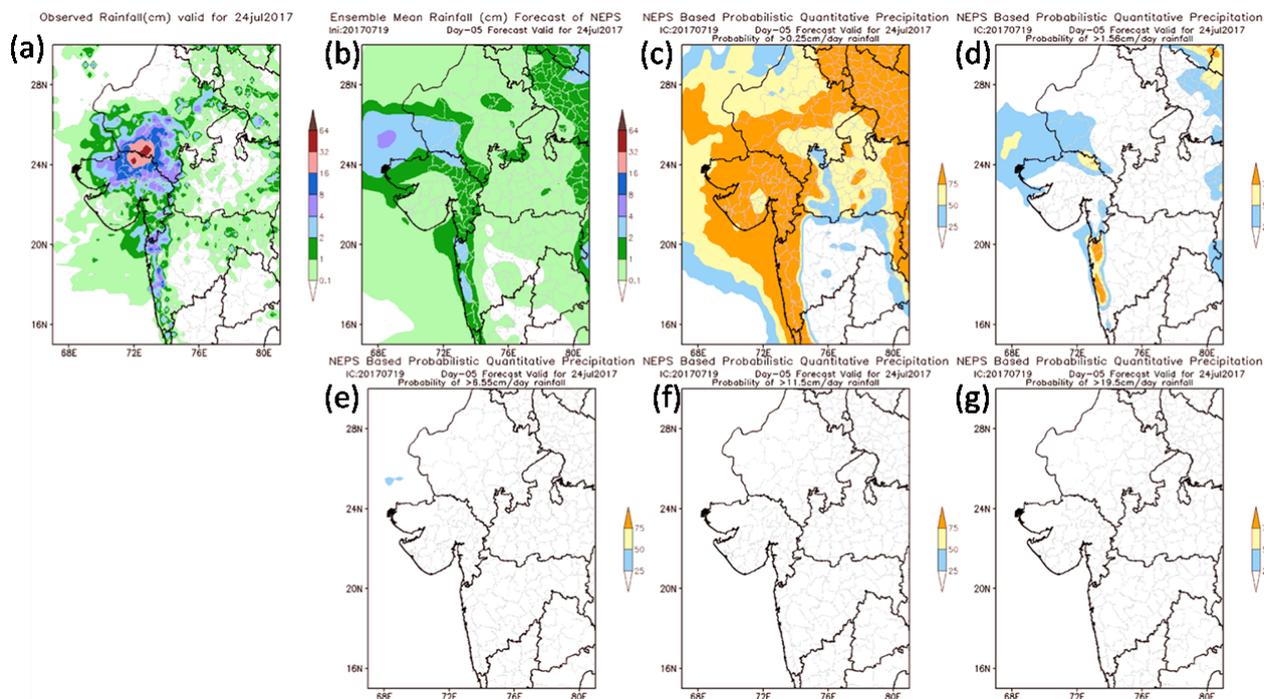


Figure 6: (a) Observed rainfall on 24th July 2017; (b) Ensemble mean rainfall (cm) forecast, Probabilistic quantitative precipitation forecast exceeding (c) 0.25, (d) 1.56, (e) 6.55, (f) 11.5 and (g) 19.5 cm/day based on NEPS valid for 24th July 2017.

Comparison of probability of rainfall exceedance (Figure 6) and probability of rainfall ranges (Figure 7) over West India (including Gujarat and adjoining Rajasthan) show that the exceedance plots either show higher probability (Table 2) or a larger area of same probability compared to the corresponding rainfall range plots. The probability of rainfall remains unchanged in rainfall exceedance plots and rainfall range plots over the west coast in Maharashtra except for day 1 forecast in two cases. The areas where predicted rainfall is more than the corresponding range appear with zero probability due to the rainfall range restriction in plotting. So, in order to avoid such ambiguities, probability of rainfall exceedance may be a better product than the probability of rainfall ranges. Hence, the probabilistic quantitative precipitation forecast (PQPF) plot for RSMC region is updated from probability of rainfall ranges to probability of exceedance since 3rd October 2018.

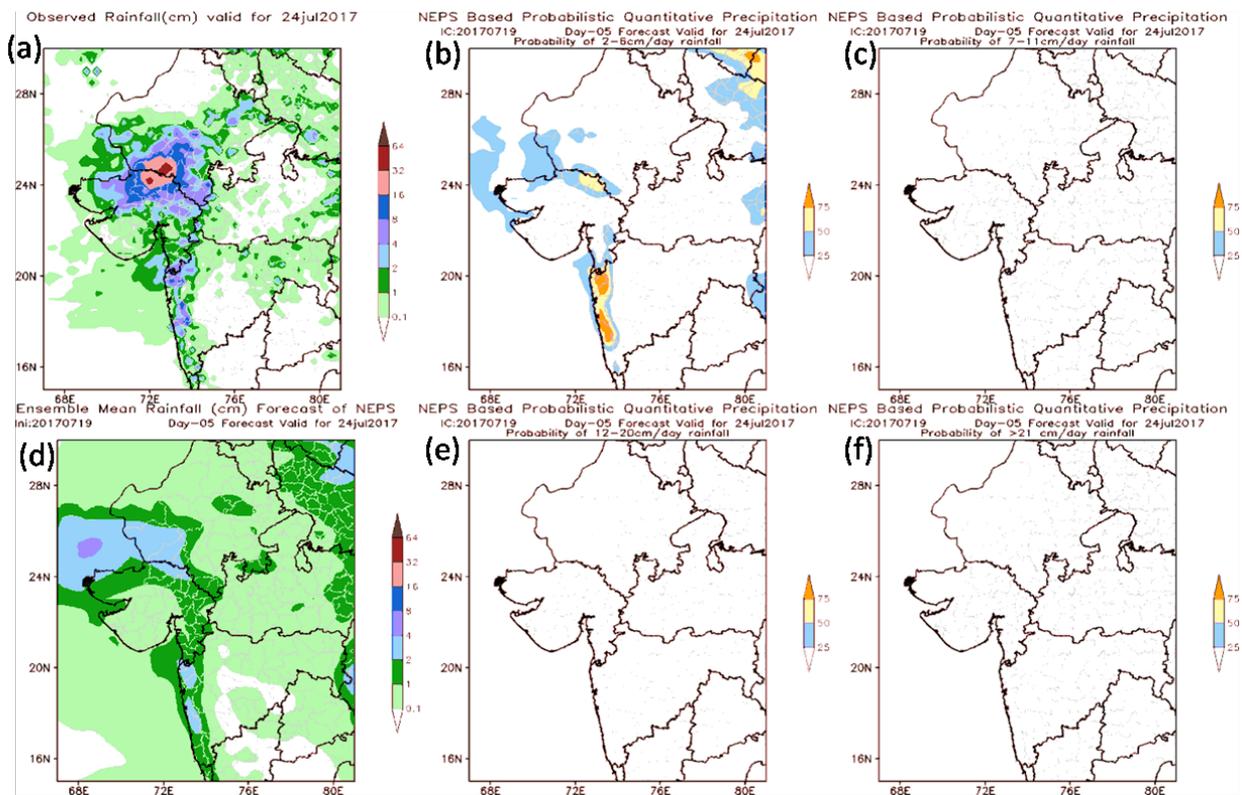


Figure 7: (a) Observed rainfall on 24th July 2017; Day-5 forecast of (d) Ensemble mean rainfall (cm), Probabilistic quantitative precipitation within (b) 2-6, (c) 7-11, (e) 12-20 (f) >21 cm/day based on NEPS valid for 24th July 2017.

Table 2: Maximum predicted probability, p (%) for different rainfall threshold values

Maximum predicted probability, p (%)					
2-6 cm	>1.56 cm	7-11 cm	>6.55 cm	12-20 cm	>11.5 cm
p>75 at west coast 50<p<75 over Gujarat, Rajasthan	p>75 at west coast 50<p<75 over Gujarat, Rajasthan	p<25	p<25	p<25	p<25

4.2.3 Probability of rainfall exceedance charts for Indian region

Daily predicted ensemble mean rainfall and probabilities of occurrence of rainfall exceeding 2.5, 15.6, 65.5 and 115 mm/day are issued for Indian region with state and district boundaries, available under ‘Indian Region’ (http://www.ncmrwf.gov.in/product_main_ind_mihir.php). These forecasts are particularly

generated for use by the India Meteorological Department (IMD) as well as Snow and Avalanche Study Establishment (SASE).

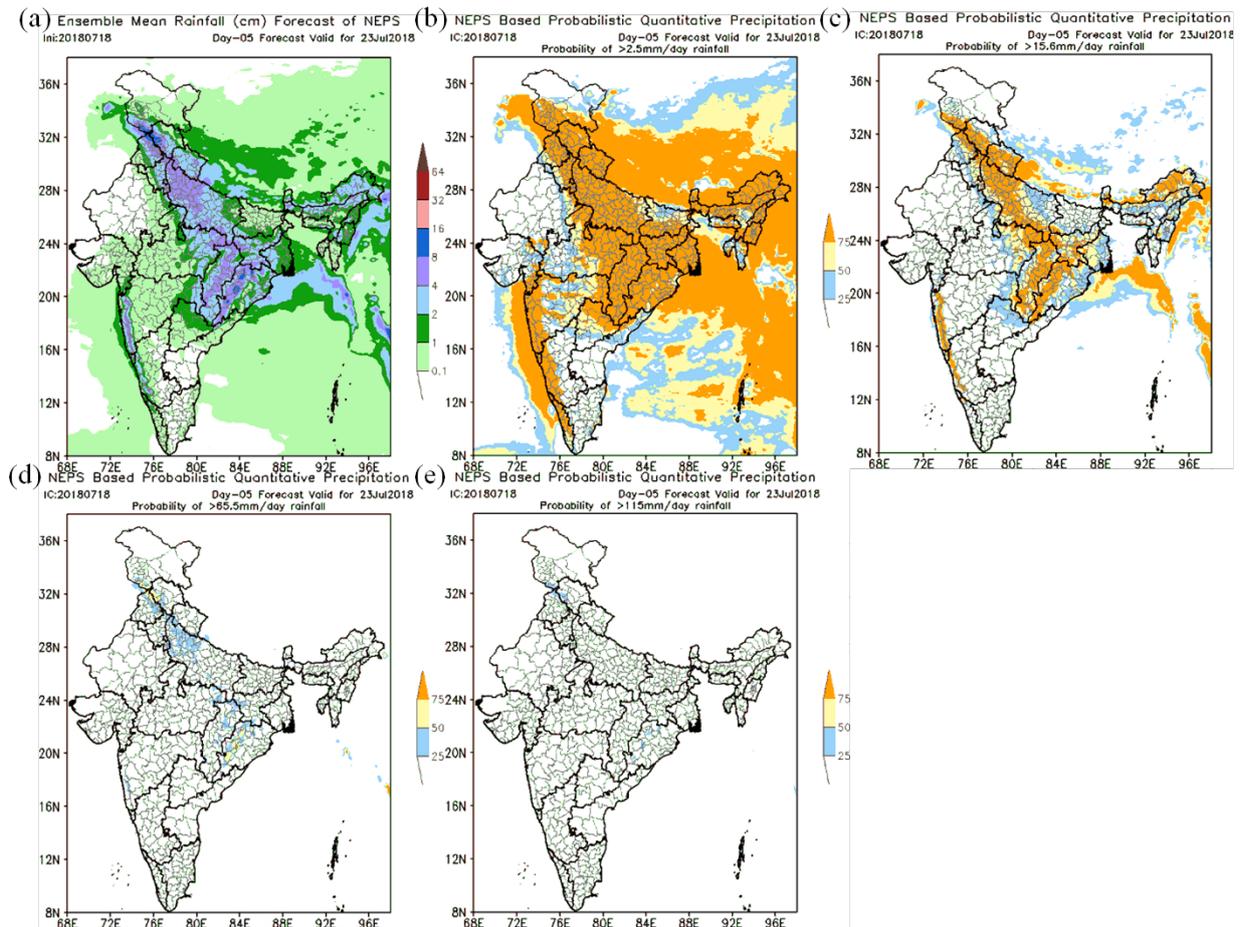


Figure 8: Day-5 forecast of (a) Ensemble mean rainfall (cm), Probabilistic quantitative precipitation exceeding (b) 2.5, (c) 15.6, (d) 65.5 and (e) 115 mm/day based on NEPS valid for 23rd July 2018.

Very heavy rainfall (8-16 cm) was predicted over Jammu and Kashmir, Himachal Pradesh and Odisha by ensemble mean (Figure 8a) on 23rd July 2018. Heavy rainfall of 4-8 cm was predicted over North Gangetic plains extending from Jammu and Kashmir to Odisha and coastal areas of Western Ghats. There is more than 75% probability of rainfall exceeding 2.5 mm/day (Figure 8b) and 15.6 mm/day (Figure 8c) in these areas.

4.2.4 Probability of temperature exceedance charts for Indian region

Probabilities of maximum and minimum temperatures exceeding few threshold values are calculated for daily (Day-1 to Day-10) from the 6 hourly forecast outputs. In summer, temperature probabilities greater than 40, 43 and 46°C for maximum temperature and 23, 26 and

29°C for minimum temperature are used. In winter, threshold values used are less than 15, 20 and 25°C for maximum temperature and 5, 10 and 15°C for minimum temperature.

Temperature observed by IMD on 30th December ranges between 2-4°C over the northern plains, associated with a passing/prevaling cold wave in Figure 9a. Most of northern J&K region, Sikkim and North-east India shows ensemble mean minimum temperature below -4°C. The cold tongue extends in north central Gangetic plains up to MP and Chhattisgarh with minimum temperature ranging between 2-4°C. There is 95% probability of the minimum temperature below 5°C (Figure 9d) in these regions. The probability of minimum temperature below 15°C (Figure 9b) and 10°C (Figure 9c) is more than 95% over north, north-west and central India and a few places over north-east India.

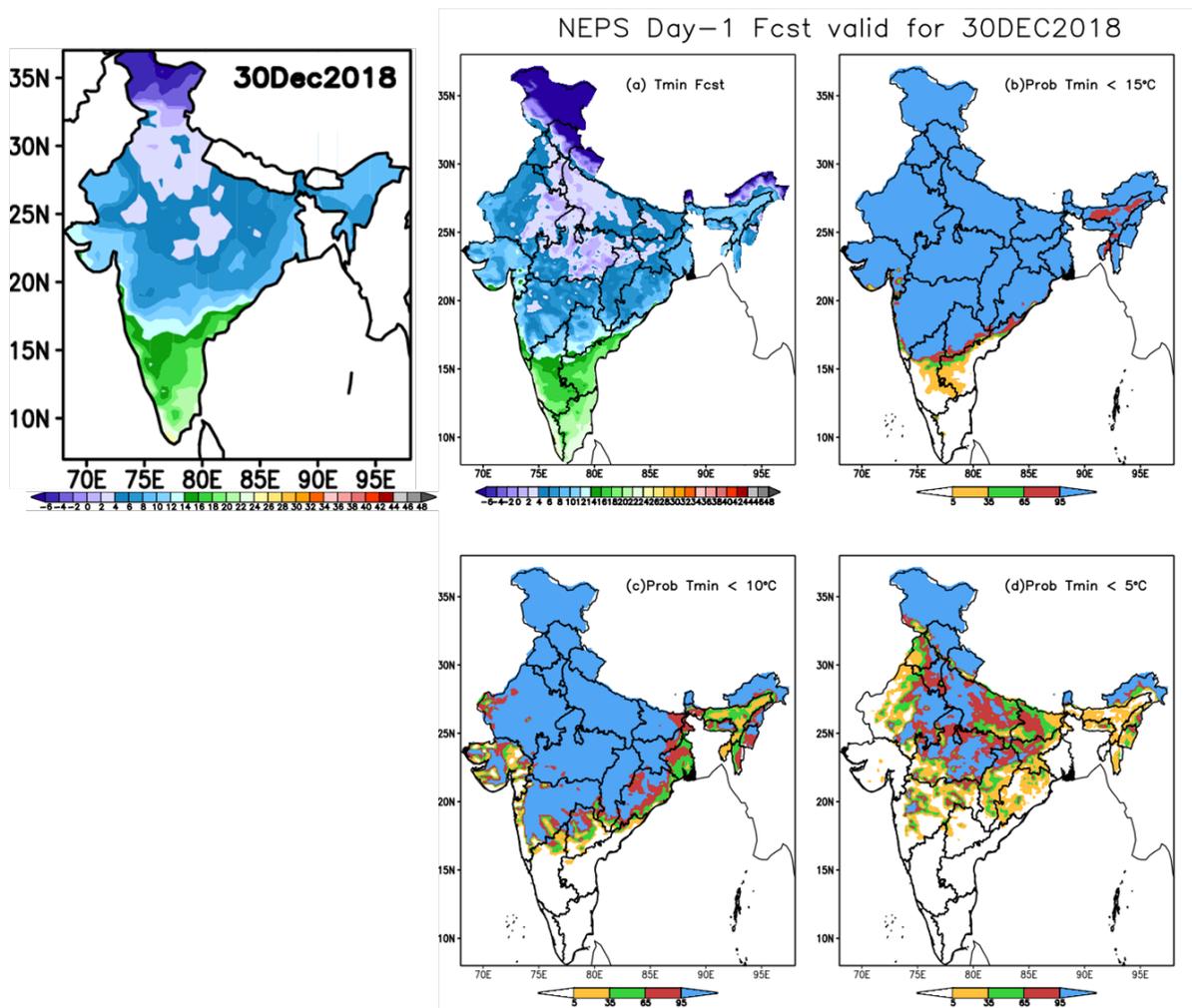


Figure 9: Observed temperature on 30th Dec 2018, Day-3 forecast of (a) Ensemble mean minimum temperature, Probability of Minimum Temperature below (b) 15°C; (c) 10°C and (d) 5°C on 30th Dec 2018 based on NEPS.

4.2.4 Probabilistic Visibility/Fog forecast

The probabilistic forecast of visibility is available at an interval of one hour. The product is used to generate spatial plots of Day-1 forecast of ensemble mean of visibility over Indian region. In addition, the spatial plots of probabilistic forecast of visibility are generated for three thresholds of visibility viz. 1000 m, 500 m and 200 m. Fog is considered to occur when visibility drops below 1 km.

Figure 10 depicts the ensemble mean visibility predicted between 200-800 m over north-west and central parts of the country. There is high probability (65%-95%) of having visibility less than 1000 m over large parts of north-west and central India (Figure 10b). The probability of visibility less than 500 m (Figure 10c) and 200 m (Figure 10d) is also high but for smaller regions.

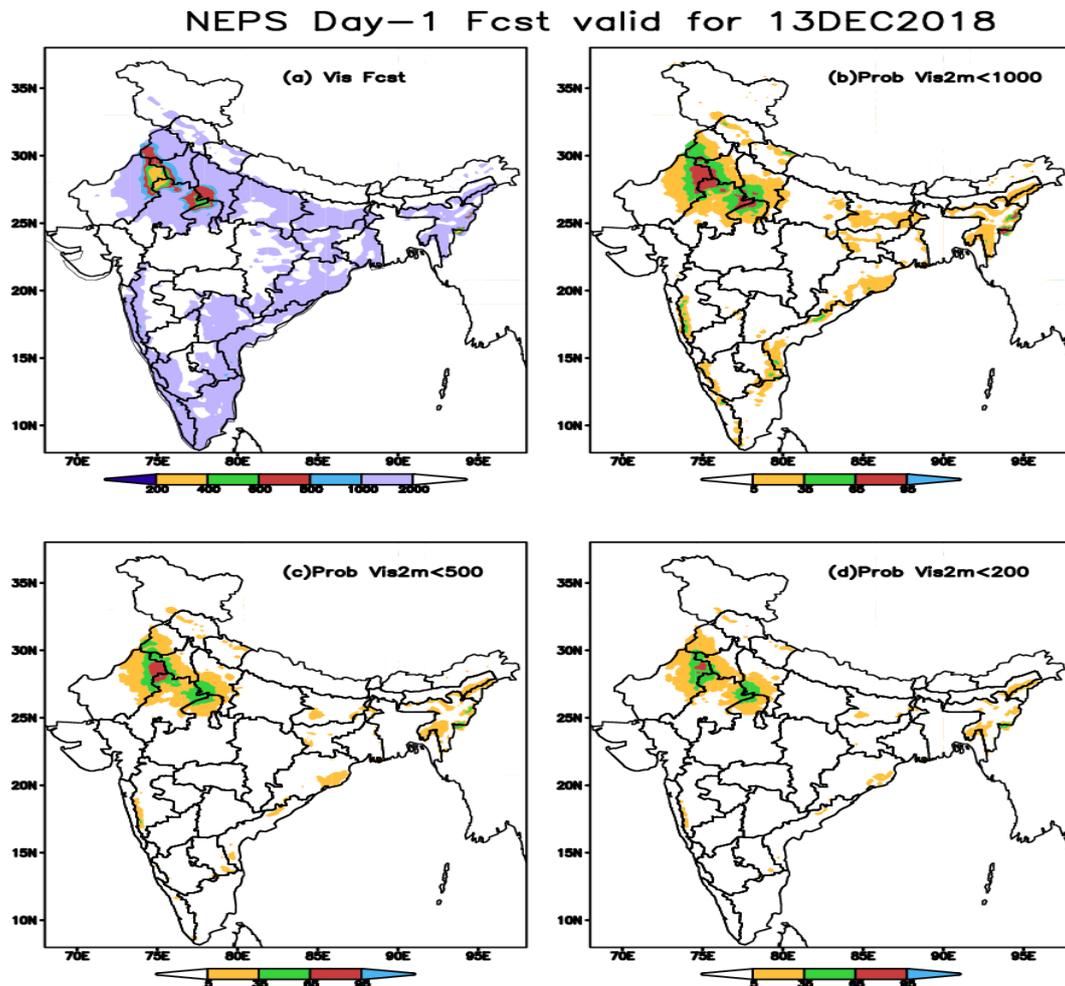


Figure 10: (a) Ensemble mean visibility forecast (b) Day-1 Probabilistic forecast of visibility <1000 m, (c) same as b but for <500 m and (d) same as b but for <200m, all valid on 13th December, 2018.

4.3 EPSGRAMS

Ensemble meteogram or EPSgram is a prognostic presentation of location specific forecasts from the ensemble prediction system. It contains 240 hours forecast statistics at every 6 hr interval. The parameters included are temperature at 1.5 m, relative humidity at 1.5 m, wind speed at 10 m, rainfall and mean sea level pressure. Full range of distribution of the values of these surface meteorological parameters predicted by the ensemble members are displayed through box and whisker plots. The boxes show a range of 25-75% percentile values and whiskers show the range between minimum and maximum values. The red line joins median values. Model output variables are extracted from the forecast at six hourly intervals to summarize forecasts at one location. These are currently generated for 660 districts in the country and made available on NCMRWF website <http://www.ncmrwf.gov.in/india-map.php>. Epsgrams for 34 major cities of India are also available at http://www.ncmrwf.gov.in/product_main_mihir.php under '12 km ENSEMBLE output' section as well as for some major cities of neighboring BIMSTEC (Bay of Bengal Initiative for Multi-Sectoral Technical and Economic Cooperation) countries http://www.ncmrwf.gov.in/product_main_reg_mihir_BIMSTEC.php under "12 km ENSEMBLE Outputs" Tab. Epsgram for 'Maitri' station of Antarctica was started on request from National Center for Polar and Ocean Research (NCPOR), Goa.

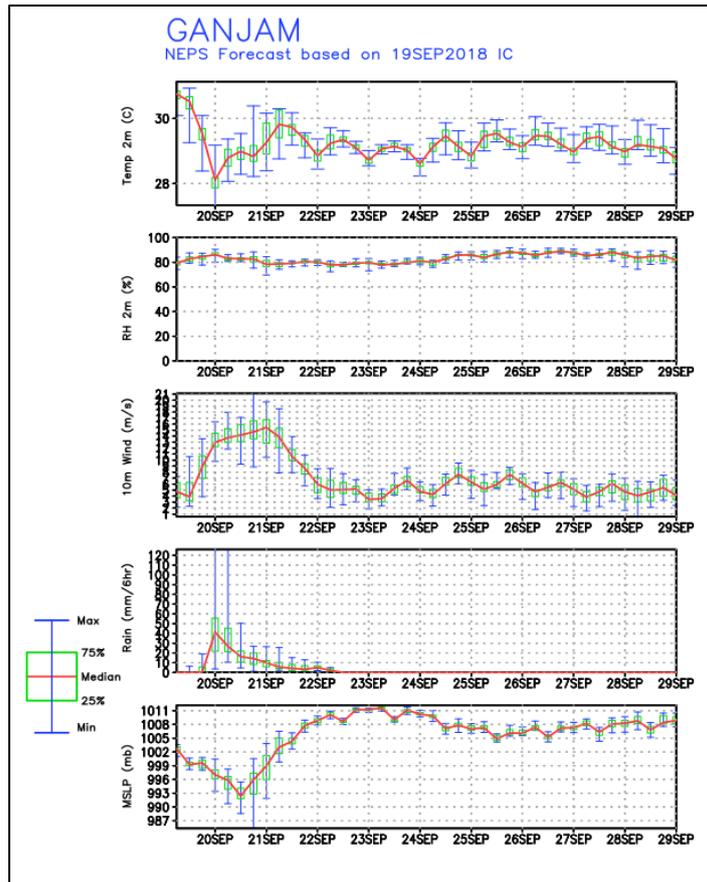


Figure 11: EPSGRAM for Ganjam based on 19th September 2018 initial conditions, depicting Temperature ($^{\circ}\text{C}$) & Relative humidity at 2m (%), 10m wind (m/s), rainfall (mm/6hr) and MSLP (hPa) for next 10 days.

Cyclonic storm Daye which formed over east-central BoB crossed south Odisha and north Andhra Pradesh coast close to Gopalpur (Odisha) as a cyclonic storm with a wind speed of 16-20 m/s gusting to 22 m/s during 1900-2000 UTC of 20th September. The instability associated with the system is depicted by the surface parameters in the EPSgram for Ganjam district based on initial conditions of 00 UTC 19th September 2018 shown in Figure 11. The median dips down by 2°C for temperature at 2m within 24 hours along with a precipitation peak of 40 mm/6 hour on 20th September. The surface wind intensifies to 16 m/s with a drop of 8 hPa in MSLP on 18 UTC of the same day. This is followed by gradual stability in the surface parameters which becomes normal over the following days.

4.4 Postage Stamp Maps

A set of small maps showing the scenarios in each individual ensemble member forecast helps the forecaster to assess the possible risks of extreme events. Postage stamp maps are intended to explain the spread in the solutions (forecast) in synoptic terms, in particular the reasons for extreme weather. Day-1 to Day-10 forecast of postage stamp maps are routinely prepared from the 6-hourly outputs containing CNTL and ensemble forecast information of merged 22 members all valid for the same time.

4.4.1 Stamp Maps of Winds at 850 hPa

Figure 12 shows the distribution of wind streamlines associated with two cyclonic circulations persisting at BoB (CS Titli) and that at AS (Luban). 21 out of 22 members have captured the wind intensity of CS Luban between 30-40 m/s in day-5 forecast valid at 00 UTC 10th October, 2018. This agrees well with IMD observed best track intensity of this system which is 33 m/s at 00 UTC 10th Oct 2018. The wind speed around vortex of CS Titli is between 20-30 m/s for most of the members. 7th Ensemble member predicted the wind speed beyond 40 m/s for TC Titli. IMD observed wind intensity is 28 m/s for SCS Titli.

4.4.2 Stamp Maps of Rainfall

Figure 13 depicts the postage stamp maps of Day-7 NEPS forecast of 24 hour accumulated rainfall on 11th Oct 2018 associated with the cyclonic circulations seen in figure 12. This chart shows the very heavy to extremely heavy rainfall amount of 32-64 cm/day for TC Luban captured by 14 out of 22 members. The heavy to very heavy precipitation between 8-16 cm/day is predicted at Bay of Bengal for TC Titli by 16 out of 22 members, 7 days before.

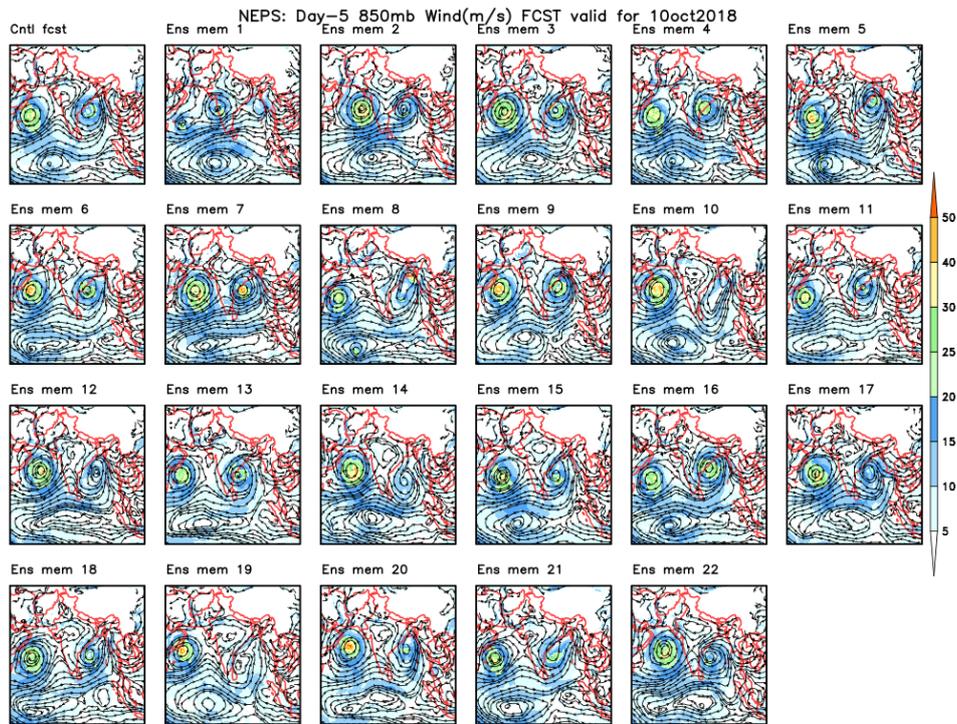


Figure 12: Postage stamp maps of Day-5 forecasts of winds (m/s) at 850 hPa for CNTL and each of 22 ensemble members valid for 00 UTC 10th October 2018.

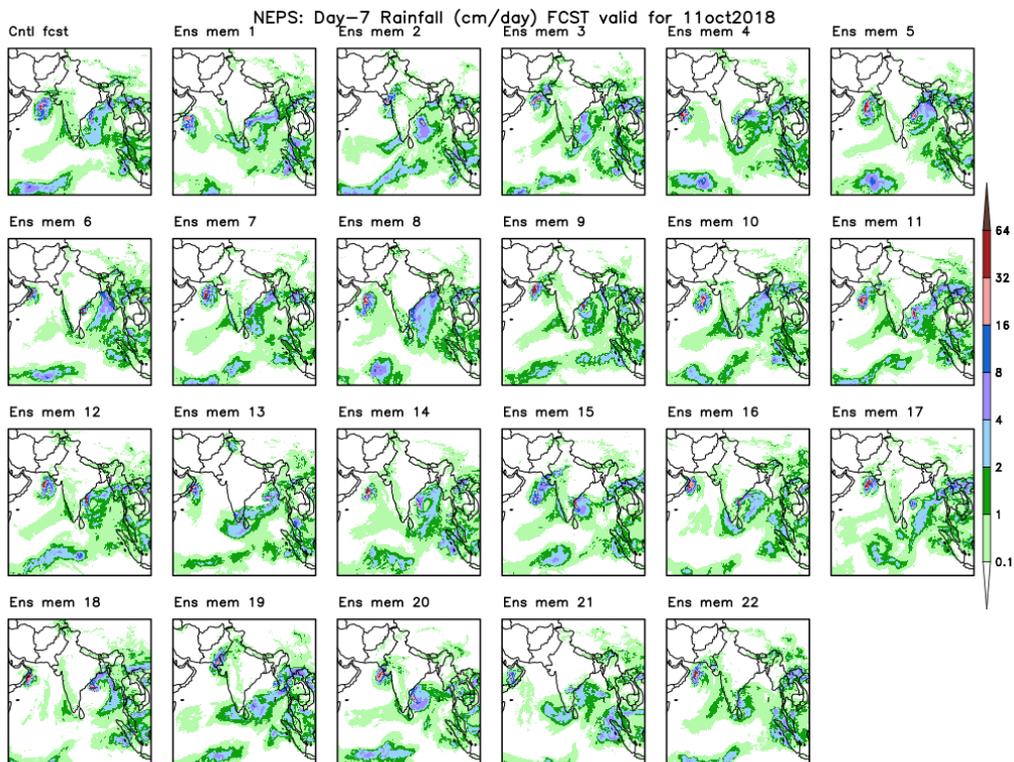


Figure 13: Postage stamp maps of 24 hr. accumulated Day-7 rainfall (cm/day) forecasts for CNTL and each of 22 ensemble members valid for 00 UTC 11th October 2018

4.5 Departures

Departure gives a measure of the extent to which ensembles over- or under-forecast the risks of anomalous or extreme weather events with respect to climatology. It also shows if the forecasts have the ability to span the full climatological range. Daily rainfall departures are calculated with respect to model climatology since model has generally underestimated the extreme values in past as compared to observed values. Therefore, the signature of the extremes can be captured better if departure in forecast is considered with respect to model mean values. Also, observations at resolution comparable to the model resolution are unavailable and downscaling or interpolation may lead to shift in location of extreme values. Since NEPS data is available since only recently (October 2015 onwards), the climatological reference is obtained as 2007-2015 mean values from MOGREPS (Met Office Global and regional ensemble prediction system) data available in TIGGE portal. Areas where rainfall probabilities are more than 90th and 99th percentiles are also provided in these figures.

4.5.1 Rainfall departure

Rainfall in excess of 4cm is predicted over normal at South J&K, Himachal Pradesh, Punjab, west UP and west interior Odisha on 23rd July, 2018. Model has predicted little excess (1-2 cm) over normal for Jharkhand, Chhattisgarh and coastal Maharashtra. Predicted rainfall is 3-4 cm below normal in Bangladesh and North Bengal and that by 1-2 cm in Bihar, east UP and east Rajasthan. The contours in Figure 14d and 14e represent the 90th and 99th percentile rainfall of MOGREPS climatology and the shaded areas depicts the excess in predicted rainfall over climatology. Extreme rainfall of 2.5-3 cm in excess over climatological 99th percentile over parts of South J&K, Himachal Pradesh and Punjab is predicted on this day. It is over 2.5 cm in excess over 90th percentile over Chhattisgarh and west interior Odisha.

NEPS Day-5 FCST Valid for 23Jul2018: Rainfall (cm/day)

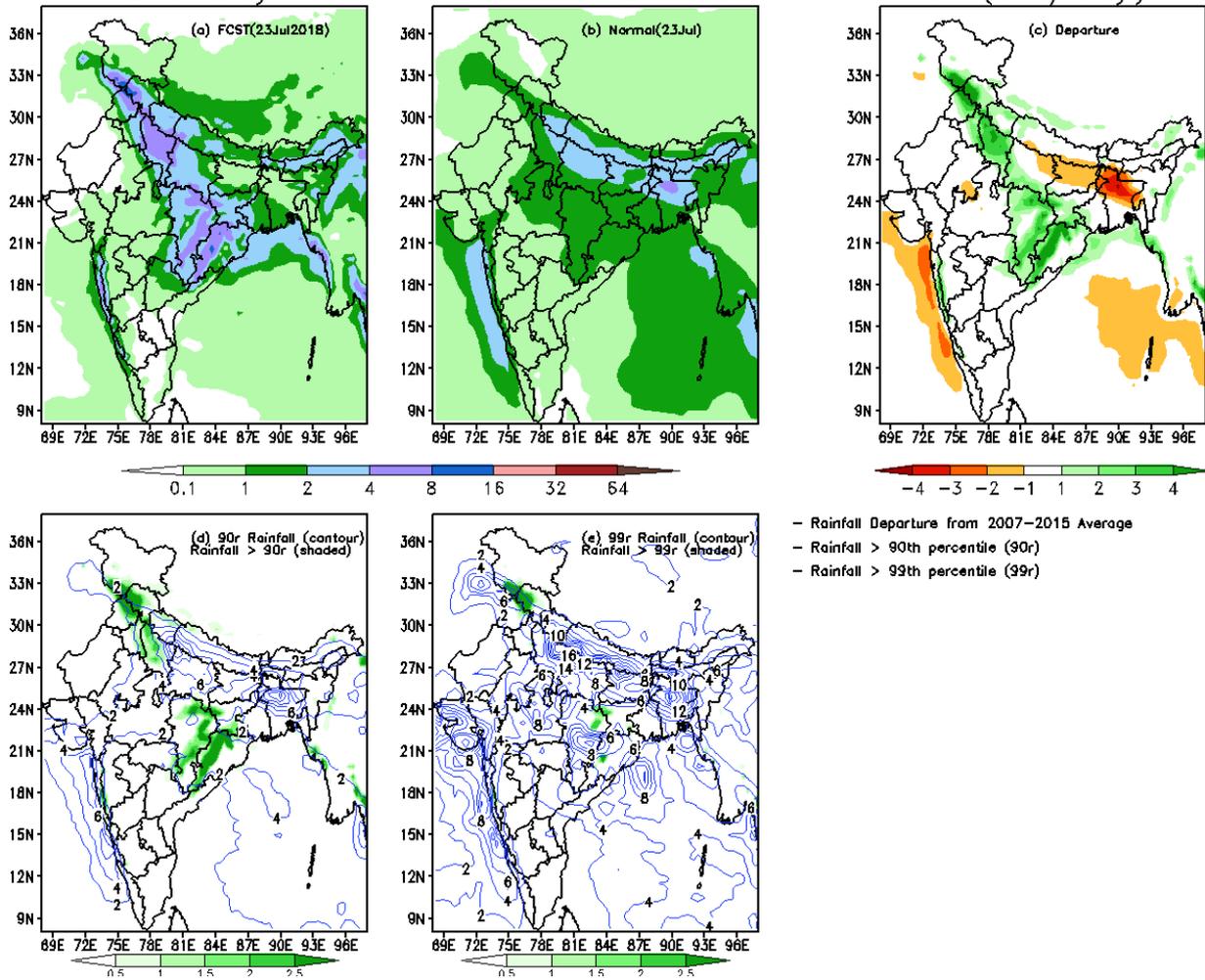


Figure 14: (a) Day-5 forecast of ensemble mean precipitation (b) Normal (2007-2015 average) precipitation (c) Departure (d) Precipitation > 90th percentile (e) Precipitation > 99th percentile based on NEPS

4.5.2 Temperature departure

Daily maximum surface temperature (Tmax) and minimum surface temperature (Tmin) departures are calculated with respect to 2007-2013 mean values from MOGREPS data. Areas with probabilities of extreme cold (Tmin < 10th percentile) and extreme warm (Tmax > 90th percentile) temperatures are marked in shades of blue and red respectively.

NEPS Day-7 FCST Valid for 30Dec2018: Tmin (°C)

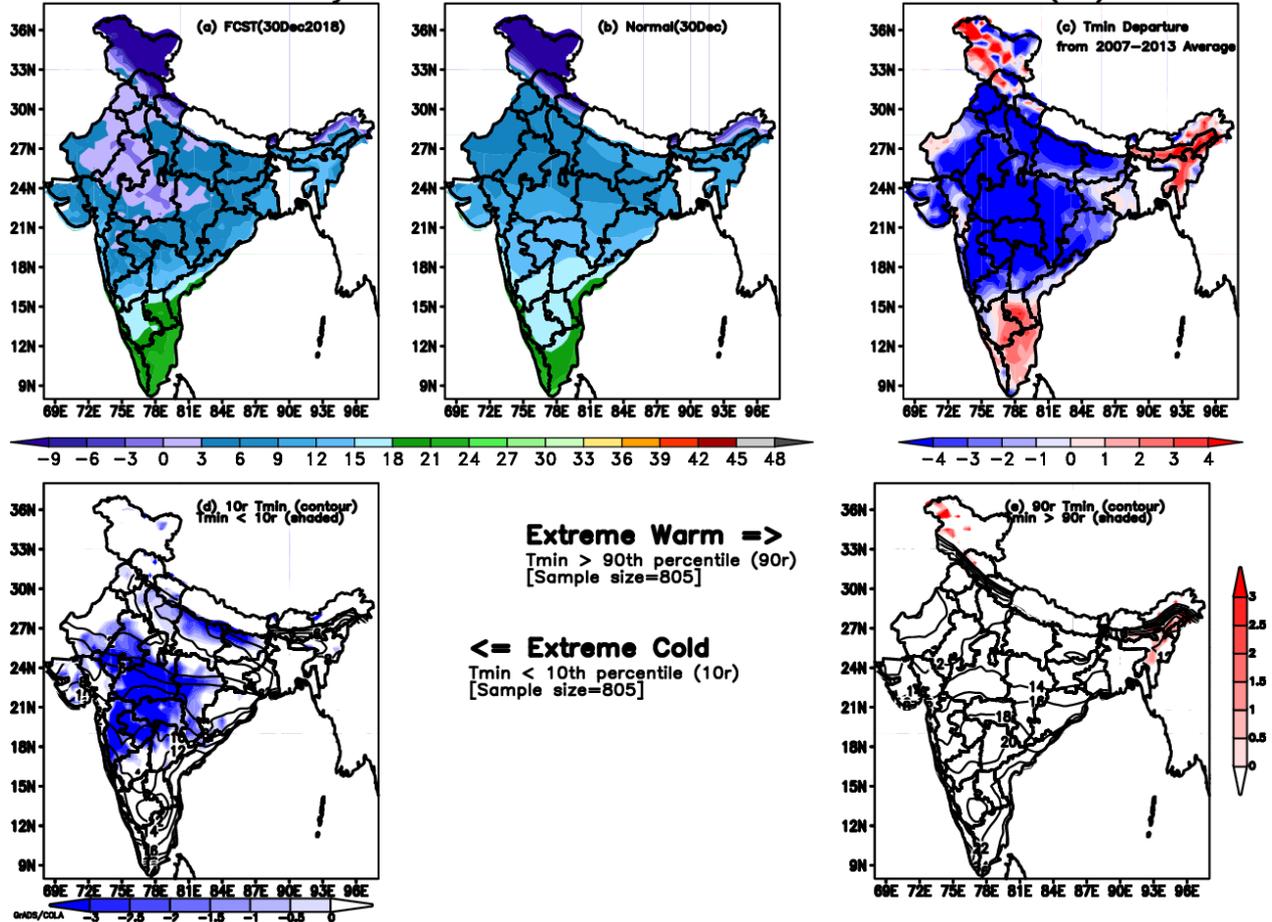


Figure 15: (a) Day-7 forecast of ensemble mean minimum temperature (Tmin) (b) Normal (2007-2013 average) Tmin (c) Tmin Departure (d) Tmin < 10th percentile (e) Tmin > 90th percentile based on NEPS.

Ensemble mean Tmin (Figure 15a) predicted for 30th December, 2018 is below -4°C for northern J&K region, Sikkim and North-east India. This is same as or more than normal (Figure 15b) for these regions and are depicted (red) in the Tmin departure (Figure 15c). However, the association of Tmin ranging between 0-3°C over north central India with a cold wave passing across these zones is clearly understood from the departure of -4°C in Figure 7c. This is also shown by the extreme cold scenario of these regions in Figure 7d as well.

4.6 NEPS TC tracking and TC ensemble forecast products

4.6.1 NEPS post processing for TC tracking

The NEPS global ensemble forecast outputs are post-processed to produce tropical cyclone forecast products. Currently, the NEPS output for TC tracking (pe file) is reinitialised

after 120 forecast hours. The first file generated pe_000 contains first 5days forecast information and another file named pe_144 contains next 5days (day-5 to day-10) forecast information. The NEPS outputs in “field file format” are to be converted first into “pp format” for each ensemble member. In order to use the MOGREPS Tropical Cyclone tracking and plotting code, input data are to be provided in the same format as it expects. The MOGREPS-G system expects one input file in pp format for each of 44 or 22 ensemble members with the following naming convention:
MOGmem\$mem_YYYYMMDDHH.pp

Each of these files currently contains 5 fields at each time step + 2 additional fields. There are currently 25 time steps (T+0 to T+144 at 6 hourly intervals) in each file. Each time step has 5 fields (U&V at 10m, U&V at 850hPa, MSLP) plus there are 2 additional fields: Skin Temperature at T+0 and Orography.

4.6.2 MOTCTracker program

The MOTCTracker (Met Office Tropical Cyclone Tracker) code is designed to produce TC forecast advisories for developed as well as those developing storms during the forecast. The program examines the model fields and detects tropical cyclones which either already exist or are predicted to develop in the forecast. These tropical cyclones are tracked in the model fields and the tracks are output in a variety of formats for different applications. The thresholds for all parameters are put in namelist for easy adjustment. A search is made within an adjustable radius (nominally set to 2°) for the grid point with the highest value of relative vorticity at 850 hPa. Once this point has been located a further search is initiated, starting from the grid point of maximum 850 hPa relative vorticity, for the nearest grid point with a local minimum MSLP within an adjustable radius nominally set to 2°.

4.6.2 TC ensemble products plotting

The data from each ensemble member is first put through the MOTCTracker in order to produce forecast tracks for named storms and those predicted to form during the forecast. The forecast tracks are then combined together from each member into one file and plotted using Python to produce the following products:

- Animation of TC activity (both named and forming storms) for each TC basin
- Composite plot of TC activity for each basin

4.6.2 TC Strike probability charts

Strike probability is defined as the proportion of members that predict that the tropical cyclone will pass within a 120 km radius of a given location at any time during the next five days. The time dimension is integrated over the forecast range.

Figure 16 shows strike probability for two CS Titli on BoB and CS Luban on AS, with the CNTL track positions shown in green, based on 12 UTC 8th October 2018. This chart allows for a quick assessment of high-risk areas, regardless of the exact timing. A 80% probability at a specific location means that, within a circular area of 120 km radius, 80% of members have a tropical cyclone centre during the coming five days.

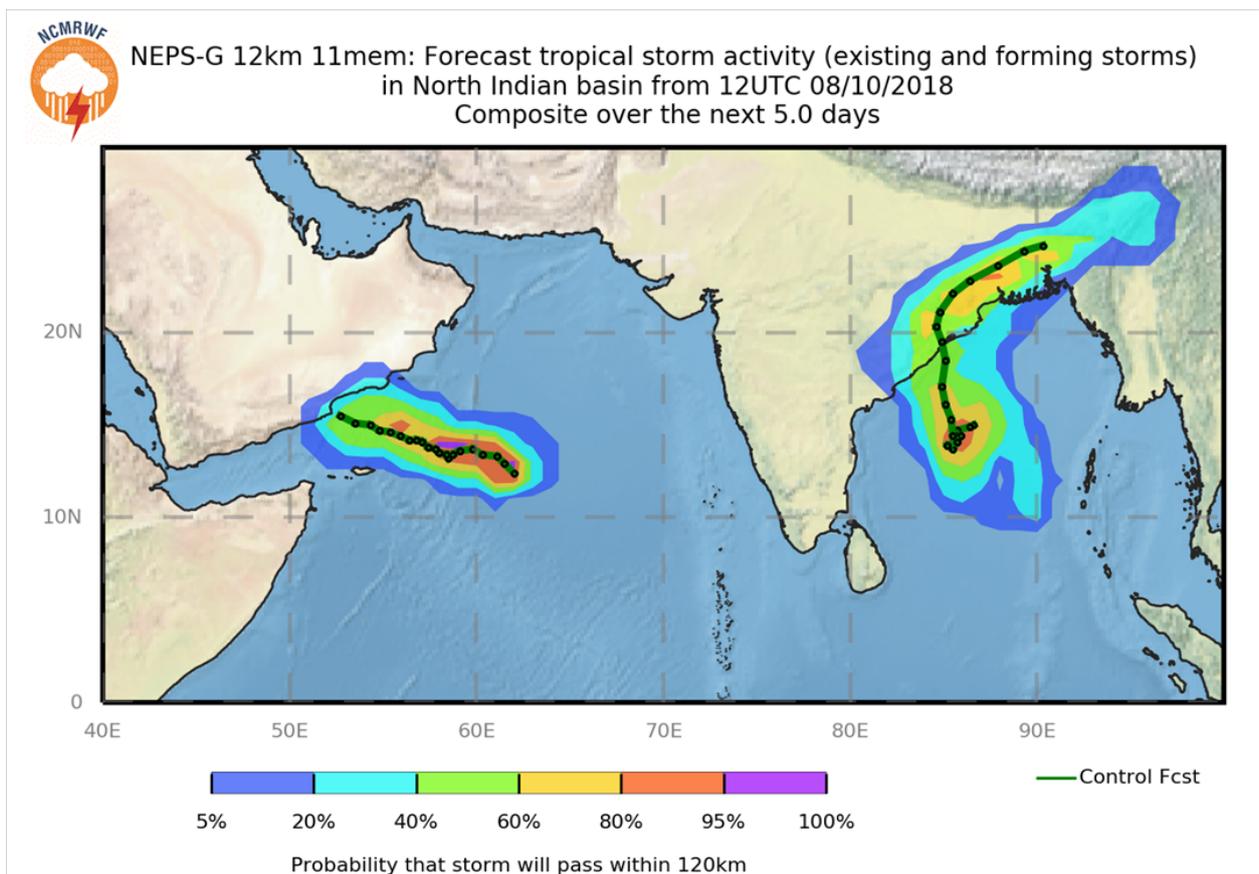


Figure 16: 12-km NEPS Strike probability of 11 members composited over next 5days over NI basin based on 12 UTC 8th October 2018.

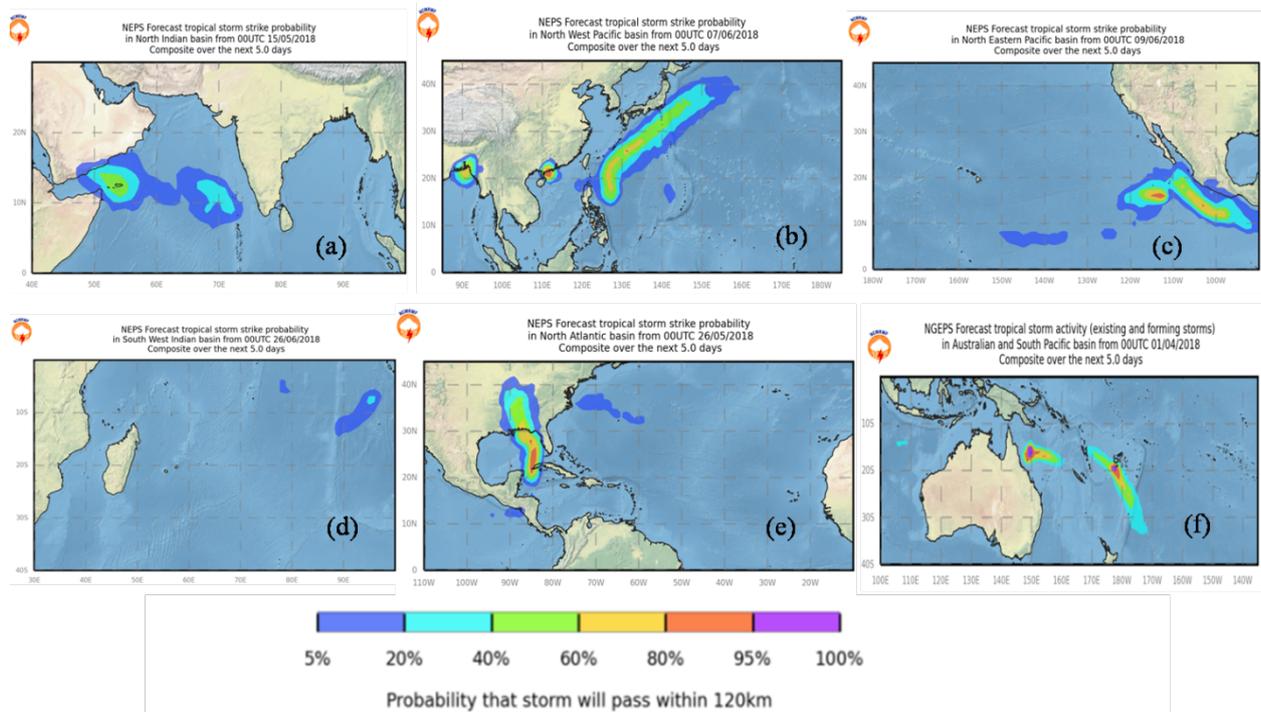


Figure 17: TC activity for all the six basins: (a) NI, (b) NWP, (c) NEP, (d) SWI, (e) NAT and (f) AUS composite over next 5 days.

The Tropical cyclone strike probability charts are made available operationally for six different ocean basins (Figure 17) namely: North Indian (NI), South-west Indian (SWI), North-east Pacific (NEP), North-west Pacific (NWP), North Atlantic (NAT) and Australian (AUS) basin since 11th April 2017. It is uploaded on the ftp site ftp://ftp.ncmrwf.gov.in/pub/outgoing/TC_FDP/neps_tc_00UTC regularly for NI basin. Earlier it was generated from 33-km NEPS tracker with 44 ensemble members at 00UTC. Since 17th September 2018 it is generated using 12-km NEPS outputs with 11 ensemble members from 00 UTC and 12 UTC.

4.6.3 TC activity animation

The animation of TC activity at each lead time and animation for the six basins are also generated based on NEPS. TC activity animation for NI basin is made available in ftp site: ftp://ftp.ncmrwf.gov.in/pub/outgoing/TC_FDP/neps_tc_00UTC/

4.7 MJO monitoring

Real-time MJO Monitoring (RMM), Forecast and Verification are being carried out at NCMRWF since 1st September 2018. Panel (a) of Figure 18 shows the real-time MJO

monitoring for the past 90 days based on observations (NCEP AVHRR OLR) and model analysis (NCUM WINDS) from 7th September to 5th December 2018. The monitoring shows weak MJO in Phase-8 (Western Hemisphere and Africa) beginning from September. It gains strength while being in phase 1 and 2 in October and then weakens in phase 3 and beyond. It is most active in November as it propagates through Indian Ocean (phase 2 and 3) and Maritime continent (phase 4). The MJO index activity is in phase 1 and 2 while reaching Indian Ocean by 5th December. The panel (a) also shows the real-time MJO forecast using NCUM deterministic model as control forecast and 22 members ensemble forecasts up to 10 days lead time (11 perturbed ensemble members run from initial condition of 00 UTC of current day and 11 perturbed members run from 12 UTC of previous day). The 22 member ensemble mean is also plotted based on initial condition of 00 UTC 6th December 2018. The deterministic as well as ensemble members predict active phase (2, 3 and 4) of MJO in Indian Ocean between 6th and 15th December 2018.

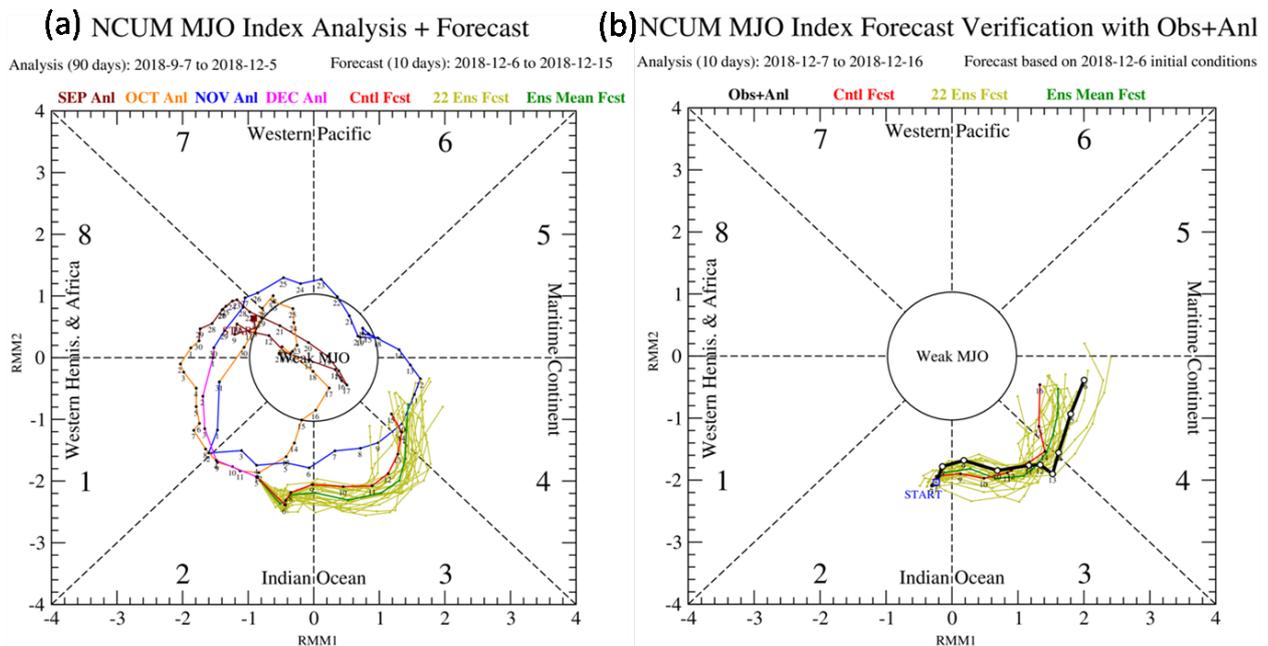


Figure 18: (a) NCUM MJO Index Analysis and Forecast (b) NCUM MJO Index Forecast Verification with Obs+Anl based on IC of 6th December 2018.

For the verification of MJO predictions, past 11 days initial conditions and 10 days forecasts can be considered. Real time verification is based on AVHRR OLR, and NCUM analysis winds. Panel (b) of Figure 18 shows the forecast verification. NCMRWF is the first operational centre to carry out the near real-time verification of MJO forecast at medium range timescale. This real-time MJO monitoring, forecast and verification is operational at NCMRWF

from 1st September 2018 onwards. The MJO forecasts match with observation (OLR) + analysis (winds) during active phases, but forecasts fail to match with observation + analysis during weak phase. The ensemble mean matches better with observation (OLR) + analysis (winds) as compared to CNTL (NCUM deterministic) in terms of both phase and amplitude of MJO.

5. EPS Products for Global Forecast projects and end users:

5.1 TIGGE products

NCMRWF has been contributing NEPS forecast products to ‘The International Grand Global Ensemble’ (TIGGE) project since 1st August 2017. THORPEX is an international research programme established in 2003 by the World Meteorological Organization to accelerate improvements in the utility and accuracy of weather forecasts up to two weeks ahead (WMO, 2005b). Earlier, 6-hourly 33-km NEPS output fields used to be interpolated to 0.35^o x 0.45^o grid resolution in grib2 file packing format and transferred to the TIGGE archive via the ECMWF Meteorological Archival and Retrieval System (MARS) archive system. 10 days forecast datasets (containing variables at surface and different pressure levels) from 45 members (1 control + 44 perturbed) based on 00 UTC initial conditions were provided to the TIGGE portal as Version-1 till 30th June 2018. After the recent up-gradation to 12-km NEPS, 10 days forecast outputs (0.12^o x 0.18^o grid resolution) are provided to the TIGGE project for 12 members (1 control + 11 perturbed) at both 00 and 12 UTC respectively from 1st July 2018. At present, NCMRWF is providing EPS forecast products to TIGGE at the highest horizontal resolution among all the international centres.

5.2 SWFDP

NCMRWF is one of the global centres along with IMD and INCOIS which provides NWP guidance to the Severe Weather Forecasting Demonstration Project (SWFDP). This project aims to deliver improved forecasts and warnings of severe weather to save lives, livelihoods and property to the participating nations. The Severe Weather Forecasting Demonstration Project-Bay of Bengal (SWFDP-BoB) includes Bangladesh, India, Maldives, Myanmar, Sri Lanka and Thailand as participants with the domain lying between 10^oS - 45^oN and 45^oE – 110^oE as the area of responsibility. NEPS forecast products including probability of 10 m wind exceeding 17 and 34 knots, rainfall and EPSgrams for stations of the participating nations are made available to the SWFDP web portal: <http://www.ncmrwf.gov.in/HomePage/index.php>

5.2.1 Probability of exceedance in Winds at 10 m

Six-hourly probabilistic forecasts for 10 m wind speed exceeding 17 and 34 knots based on NEPS are prepared up to 120 hours and are made available at SWFDP site. Additionally, the ensemble mean forecast of the 10m wind based on 22 members is also presented in these charts at every 6 hours interval (A sample plot is given in Figure 19).

The low pressure near equatorial Indian Ocean is captured in ensemble mean plot for the day-5 forecast based on 19th January 2019, with a speed of 15-20 knots. 65% of members are seen to be forecasting 10 m winds exceeding 17 knots on 24th January 2019. Very few members are forecasting 10 m winds greater than 34 knots and hence the probability for this threshold lies in the range 5-35%.

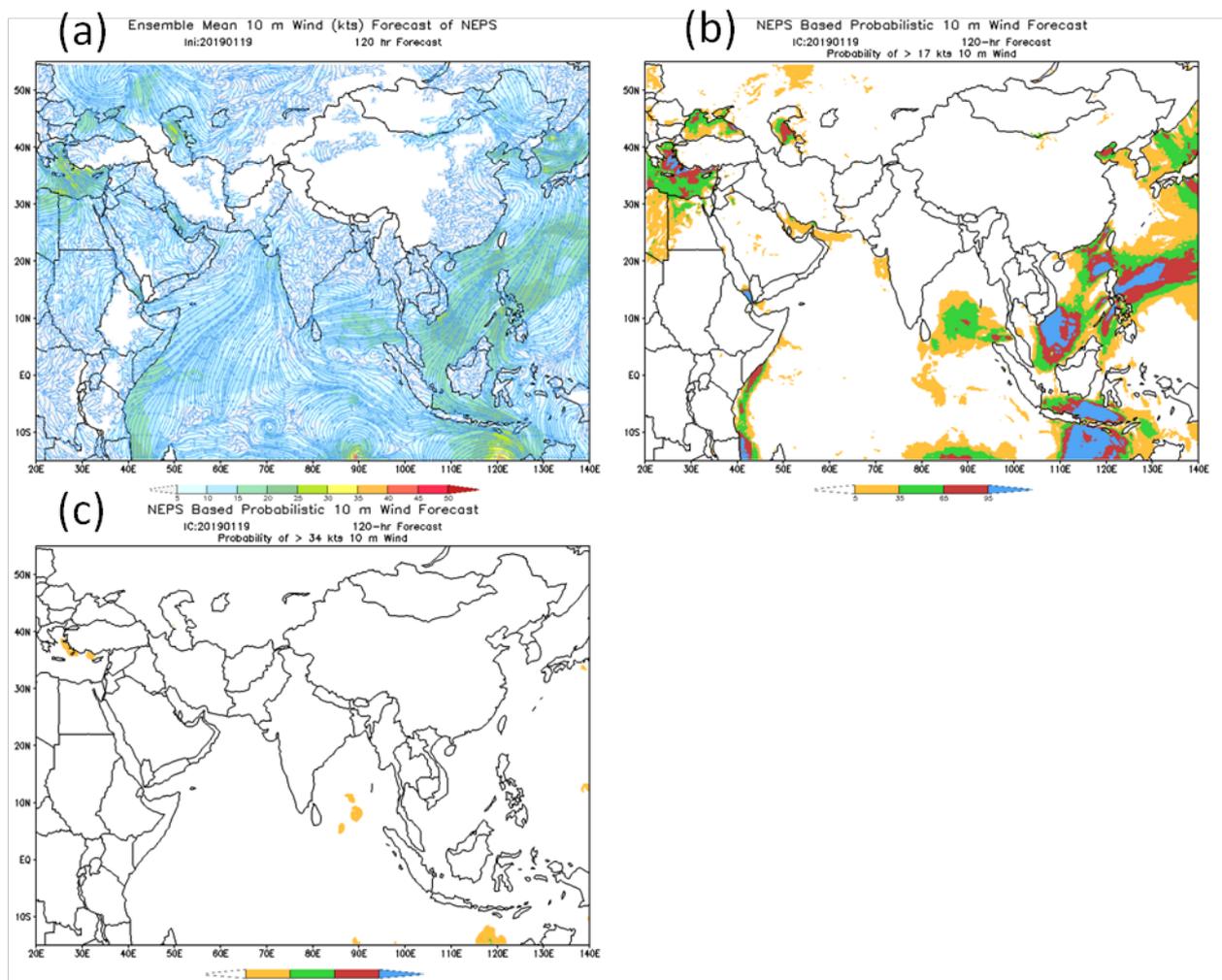


Figure 19: (a) Ensemble mean 10m wind (knots) forecast; Probabilistic 10 m wind forecast exceeding (b) 17 knots and (c) 34 knots, based on NEPS.

5.2.2 Probability of exceedance in Rainfall

Probabilistic quantitative precipitation forecasts based on NEPS are issued daily up to 120 hours for SWFDP. Ensemble mean rainfall accumulated over a time interval of 24 hours is generated based on 22 members. Probabilities are calculated from the proportion of members exceeding 5 cm and 10 cm threshold of precipitation accumulated over 24 hours.

Figure 20a shows the predicted 24-hrly accumulated ensemble mean rainfall of 6-8 cm (heavy) and beyond in Northern India and adjoining regions of Himalayan ranges. This includes rainfall associated with thunderstorms that occurred on 7th February 2019 in these regions. There were higher probabilities of rainfall exceeding 5 cm/day (Figure 20b). It was less likely that rainfall amounts would be received beyond 10cm (Figure 20c) in this event.

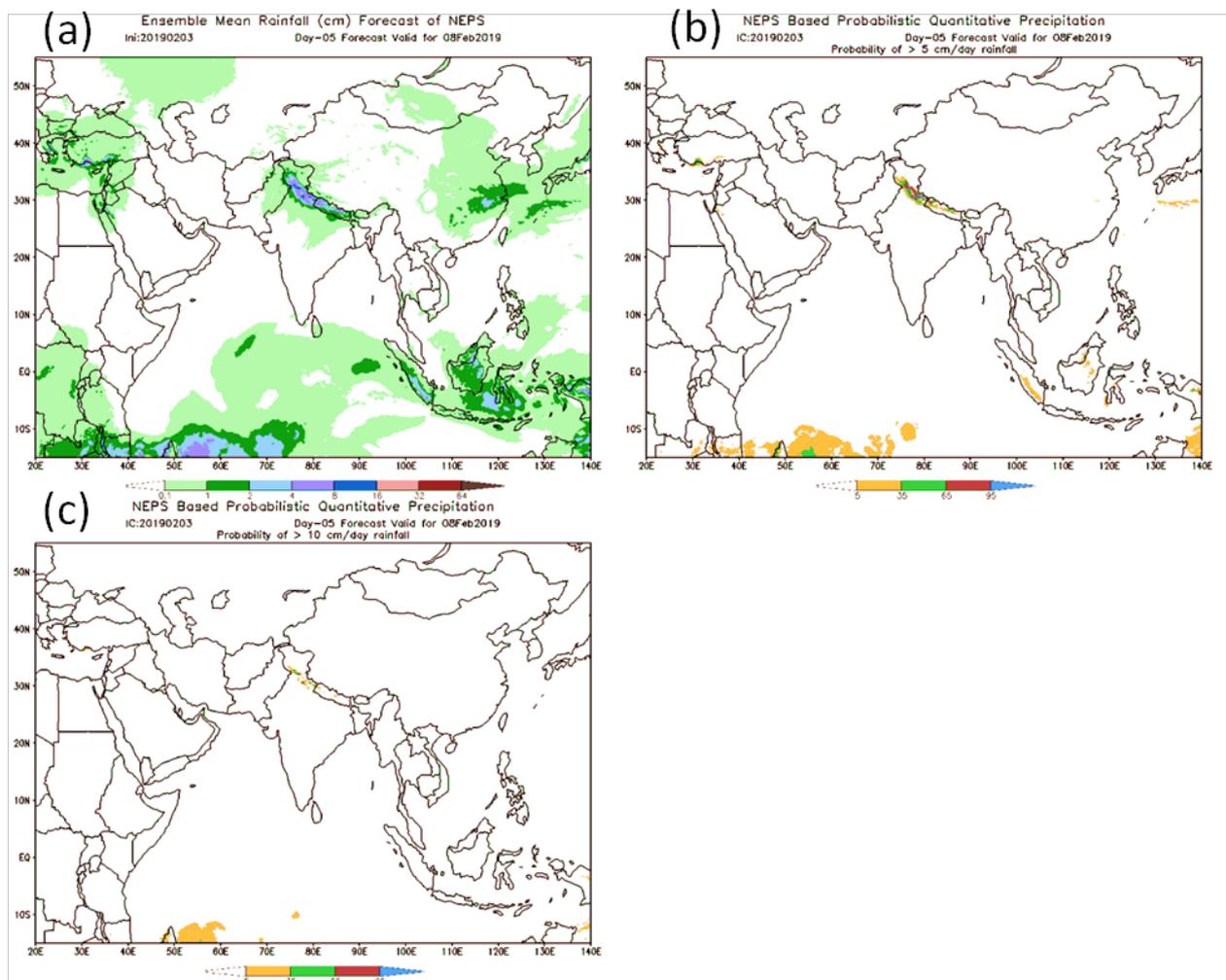


Figure 20: (a) Ensemble mean rainfall (cm) forecast; Probabilistic quantitative precipitation forecast exceeding (b) 5 cm/day and (c) 10 cm/day, based on NEPS.

5.3 EPS products for BIMSTEC Countries

EPSgrams are generated and made available for BIMSTEC countries under the tab: http://www.ncmrwf.gov.in/product_main_reg_mihir_BIMSTEC.php. Figure 21 shows EPSgram of next 10 days for Colombo based on initial condition of 00 UTC 19 September 2018.

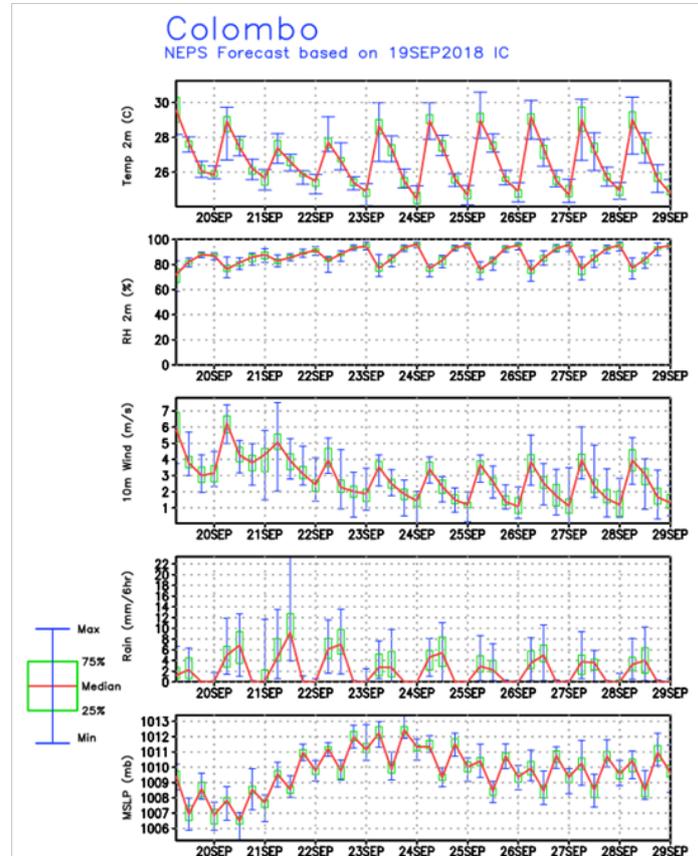


Figure 21: EPSGRAM for Colombo based on 19th September 2018 initial conditions, depicting Temperature ($^{\circ}\text{C}$) & Relative humidity at 2m (%), 10 m wind (m/s), rainfall (mm/6hr) and MSLP (hPa) for next 10 days.

5.4. Data products for end users in India

NCMRWF prepares data products for end users which are packed in grib2 file packing format and shared on demand on ftp server (ftp.ncmrwf.gov.in).

5.4.1 Ensemble Rainfall Data for Chennai Flood Warning System (C-FLOWS)

Following the unprecedented floods in Chennai in 2015 which displaced over 1.8 million people, the Principal Scientific Advisor to Government of India, National Centre for Coastal Research (NCCR), NCMRWF, IMD, IIT, Chennai and various other IITs got together to build a flood warning system designed to be used in Chennai. Chennai Flood Warning System (C-FLOWS) is a six-module ensemble that can predict flooding due to heavy rainfall, sea-level rise

and increase in water levels of three rivers near the city: the Cooum, the Adyar and the Kosasthalaiyar river. NEPS rainfall products are used to predict locations at risk of flooding as well as the depth of flooding, for the C-FLOWS from 6-hourly grib2 files of NEPS outputs up to 240 hours for domain (7.92°N-38.04°N, 67.86°E- 98.1°E).

5.4.2 Bhakra and Beas management Board (BBMB) and Krishna-Bhima Basin Study Division (KBBSD):

The ensemble model based Probabilistic Quantitative Precipitation Forecast (PQPF) products are made available operationally for two regions for Hydrological applications. 24-hourly ensemble mean rainfall and PQPF charts for ranges 2-6, 7-11, 12-20 cm/day rainfall up to 240 hours are prepared for Bhakra and Beas management Board (BBMB) for domain (28°N-35°N, 73°E-84°E). Figure 22 shows the day-5 ensemble mean forecast and PQPF for these rainfall ranges over BBMB based on initial condition of 00 UTC, 4th June 2018.

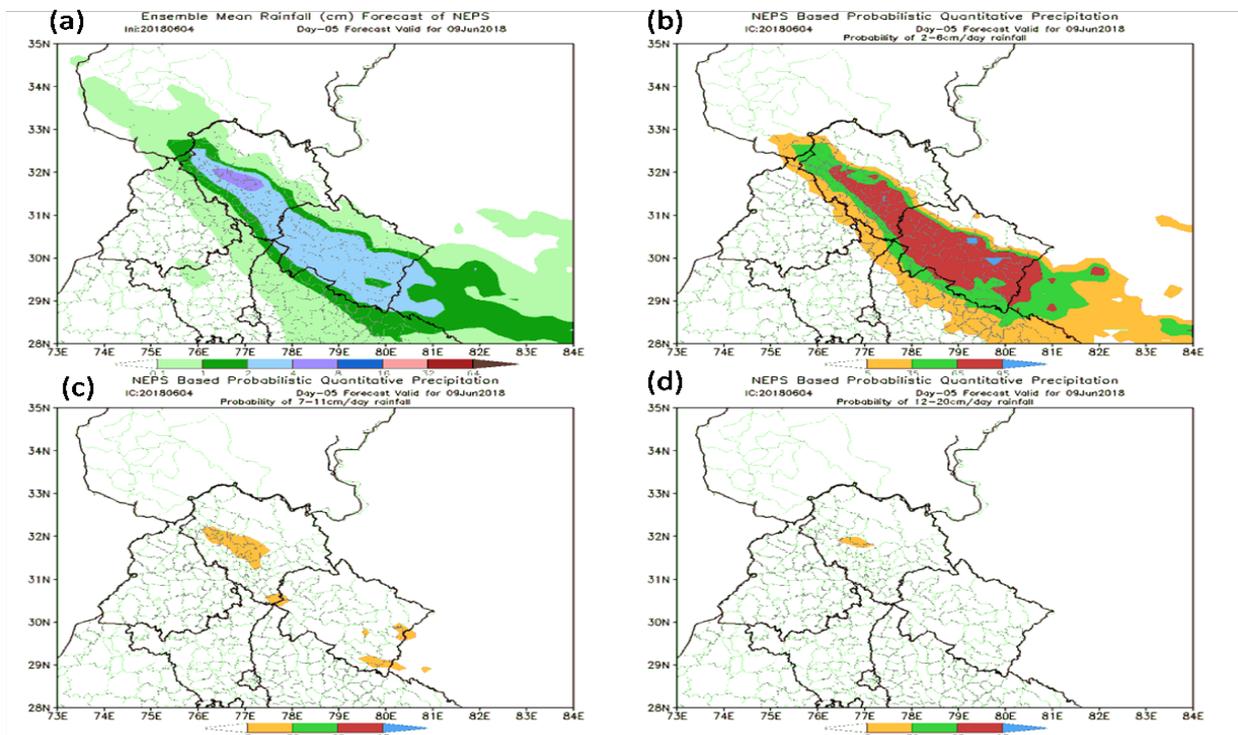


Figure 22: Day-5 forecast of (a) ensemble mean rainfall (b) probability of 2-6, (c) 7-11, (d) 12-20 cm/day rainfall based on NEPS for BBMB basin

24-hourly ensemble mean rainfall and PQPF charts for ranges 2-6, 7-11, 12-20 cm/day rainfall up to 240 hours for Krishna-Bhima Basin Study Division (KBBSD) over the domain (15°N-20°N, 72°E-81°E) Day 5 ensemble mean forecast and the PQPF for these rainfall ranges based on initial condition of 00 UTC, 4th June 2018 are shown in Figure 23.

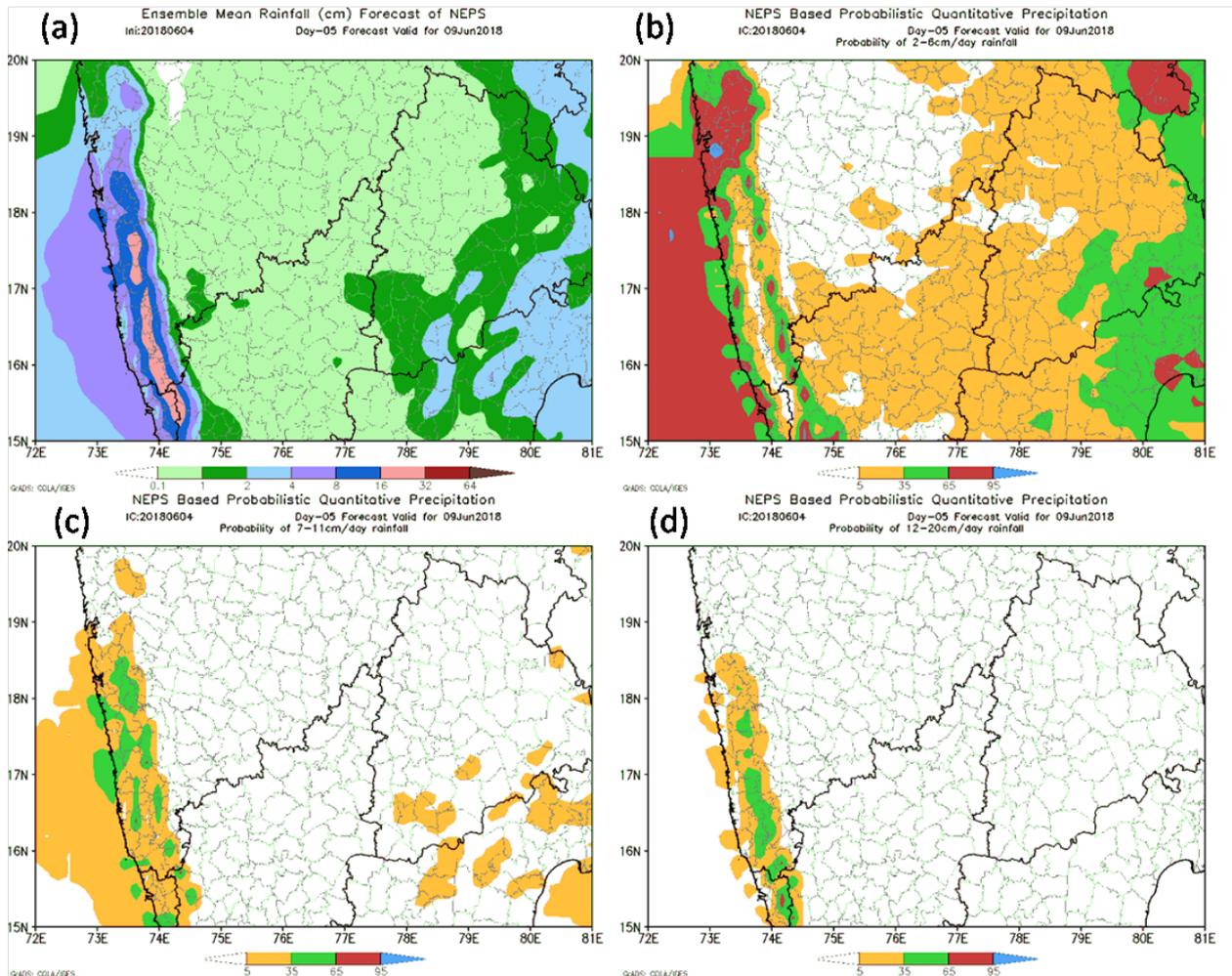


Figure 23: Day-5 forecast of (a) ensemble mean rainfall (b) probability of 2-6, (c) 7-11, (d) 12-20 cm/day rainfall based on NEPS for KBBSD basin

6. Ongoing Development of new products for future implementation

Few more products discussed in this section are being developed and may be generated routinely as per future demands and needs of end-users.

6.1 Spaghetti diagram

Spaghetti diagrams display the spatial distribution of single value isolines for a field of interest from all the ensemble members to highlight probability distributions for a variable on a region. The distance between members gives a notion of uncertainty. Also, it gives an idea of the probability distribution for the forecast for the contours displayed. 15 cm precipitation is plotted for ease of readability in Figure 24, for all 23 members including control, each member forecast in different colours. While the contours for individual members are initially very tightly packed,

they spread out more and more with increasing forecast lead time, reflecting the flow-dependent increase in forecast uncertainty.

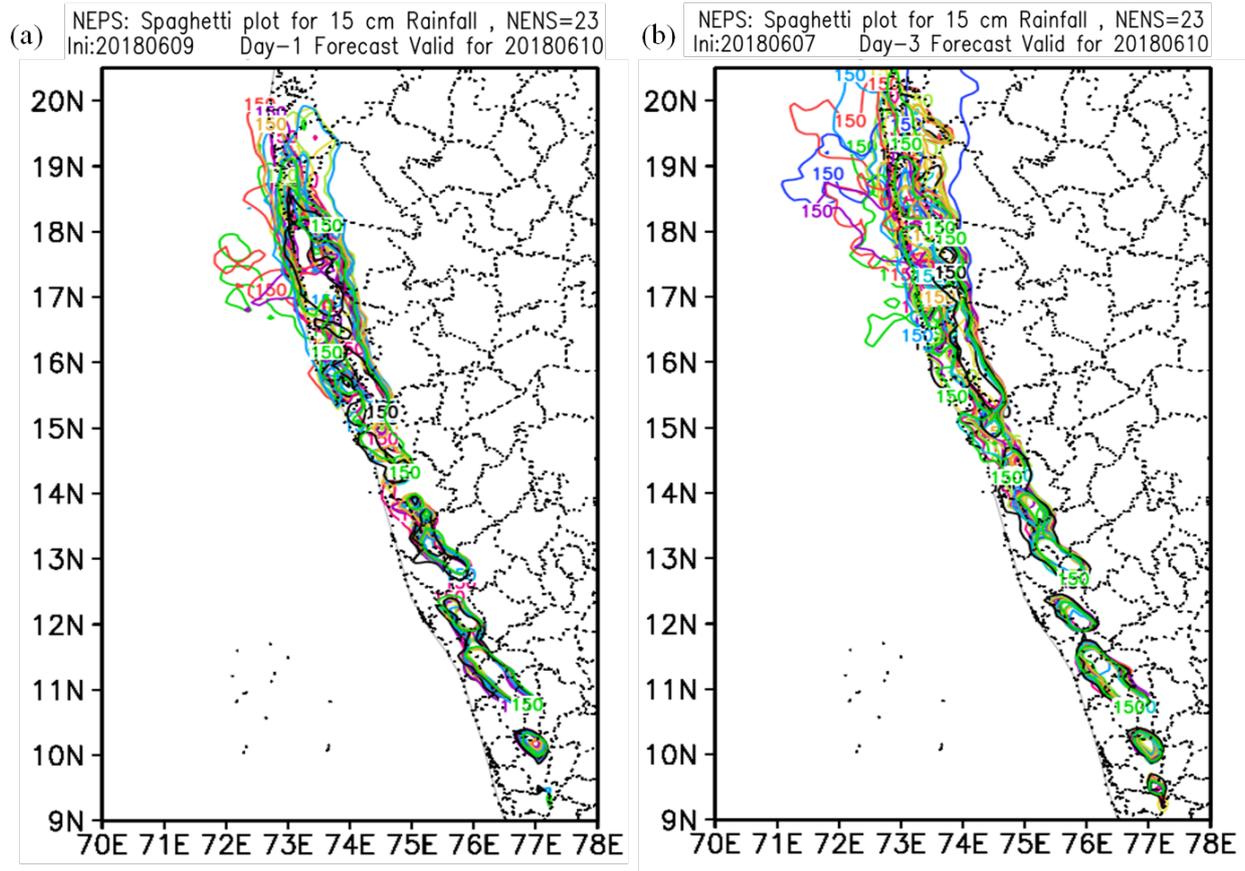


Figure 24: (a) Day-1 forecast of Spaghetti of 15cm/day precipitation, (b) Day-3 forecast of Spaghetti of 15 cm/day precipitation, both valid for 10th June 2018 at Western Ghats.

6.2 Plumes

Plume diagram shows time evolution of a forecast variable for each ensemble member. It depicts ensemble forecasts at a point, or more properly, over a grid box. Figure 25 illustrates the T_{min} forecast for all the 22 members in green, CNTL (NCUM) in blue and the ensemble mean in red over next 10 days. The spread generally increases with the model integration time, but the amount of spread may change with different initial conditions, depending on the atmospheric flow. In contrast to EPSgrams, plumes can display bi-modal characteristics.

DELHI : Tmin FCST based on IC:00Z05Feb2019

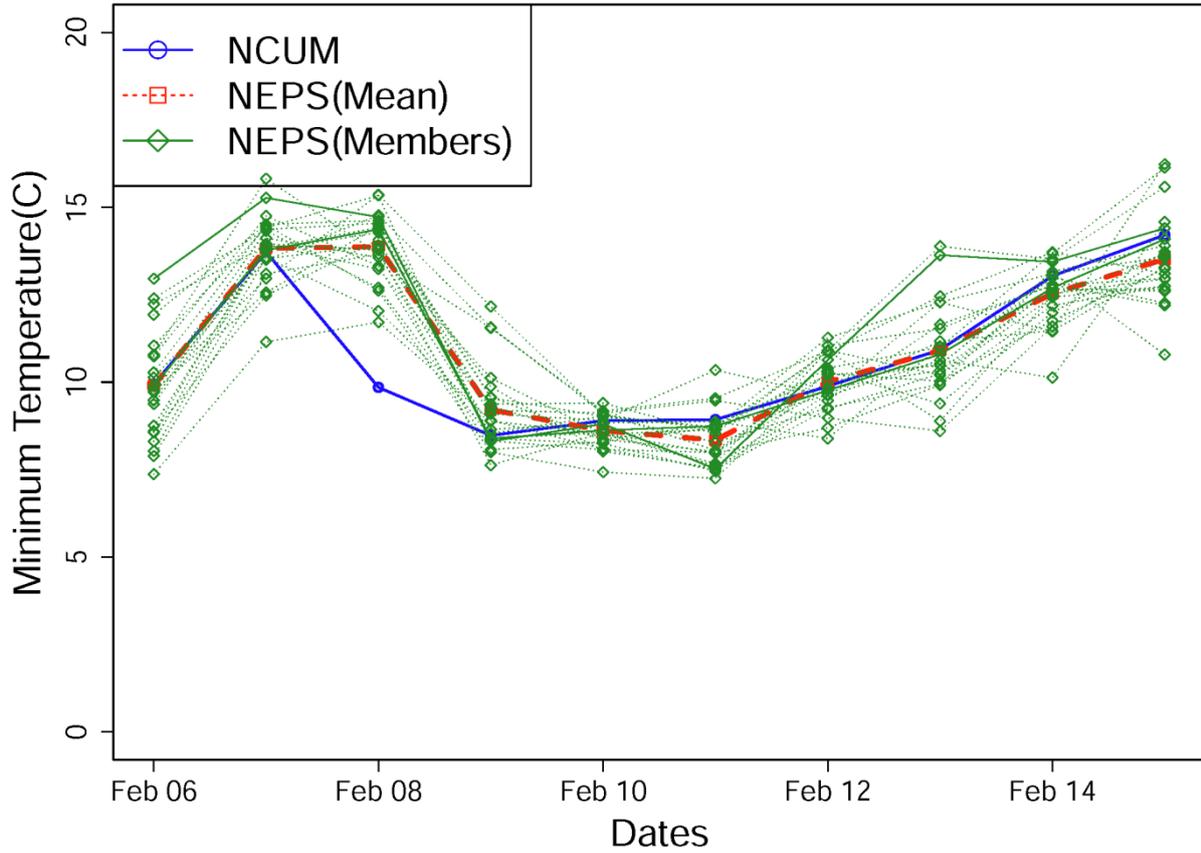
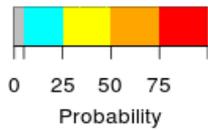


Figure 25: Tmin plume for 22 members of NEPS and CNTL (NCUM) over Delhi based on 00 UTC 5th February 2019.

6.3 Composite PQPF

NEPS precipitation data is extracted for a district based on IMD shape files and probabilities are quantified over CNTL + 22 ensemble members over all the grid points within the district boundary. It is composited for day-1 to day-10 for each district. This plot gives the temporal variability of PQPF for different spatial distributions at district level.



NEPS PQPF: (IC=20180814) Kannur

100	100	90	64	25	DAY01
100	100	76	30	0	DAY02
96	77	36	6	0	DAY03
100	75	13	2	0	DAY04
100	60	1	0	0	DAY05
100	45	0	0	0	DAY06
92	25	0	0	0	DAY07
100	33	0	0	0	DAY08
99	29	0	0	0	DAY09
92	10	0	0	0	DAY10
>2.5mm	>15.6mm	>65.5mm	>115mm	>195mm	

Figure 26: NEPS PQPF exceeding 2.5, 15.6, 65.5, 115 and 195 mm for next 10 days at Kannur district based on 14th August 2018.

Heavy rainfall exceeding 65.5 mm/day is predicted with 90% probability and on 15th August at Kannur in Figure 26. It is most likely (>75%) that this district will receive rainfall exceeding 65.5 mm/day on 16th August and that exceeding 15.6 mm/day on 17th August. There is a fair chance of light rain exceeding 15.6 mm on day-4 and day-5. The probability of rainfall exceeding 2.5 mm/day is always >90% over next 10 days for this district.

6.4 Ensemble Skew-T plot

Delhi and National Capital region (NCR) experienced heavy rainfall accompanied with hailstorms on 07th February 2019. Figure 27 shows the instability developed at 00 UTC of 07th February 2019 as depicted in the thermodynamic vertical profile at New Delhi based on 12 km NEPS. Dry adiabats (grey lines), temperature lines (blue), mixing ratio lines (purple), moist adiabats (green), and wind barbs with direction at vertical levels are coloured according to wind speed.

The hodograph displays absolute and storm-relative helicity, with trace (green) and storm motion vector (red arrow). The thick Temp (yellow), dew-point temp (light blue) and parcel (red) sounding correspond to ensemble mean. The long dashed lines represent ensemble maximum and minimum values. The dotted lines represent the 75th and 25th percentile values. The thermodynamic parameters inside the box on right correspond to ensemble mean values.

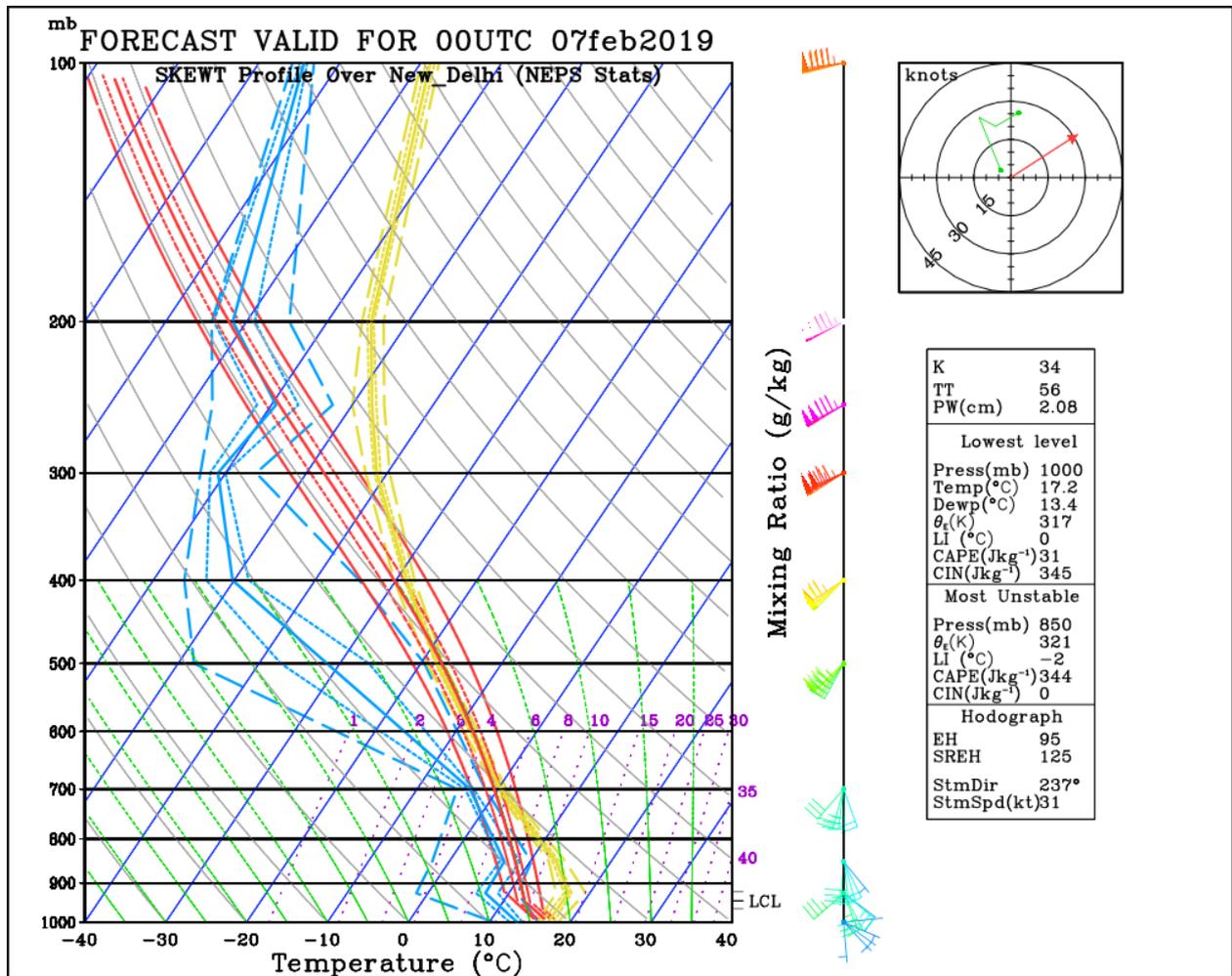


Figure 27: 12-km NEPS Skew-T profile over New Delhi on 7 February 2019.

Acknowledgments

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References

- Arulalan. T, Jayakumar A., Sreevathsa M.N.R., Chakraborty P., Kumar, Sumit., Johny, C.J., Kumar, Sushant., Ashrit, R., Mali, P., Dube, A., Aditi, Mamgain, A., Sarkar, A., Mohandas, S., Indira Rani, S., George, J. P., and Rajagopal E. N. (2019): Application of UMRider for NCUM Forecast Products, *NMRF/TR/04/2019*
- Bishop, C. H., Etherton, B. J., & Majumdar, S. J. (2001). Adaptive sampling with the ensemble transform Kalman filter. Part I: Theoretical aspects. *Mon. Wea. Rev.*, 129(3), 420-436.
- Kumar, Sumit, A. Jayakumar, M. T. Bushair, Buddhi Prakash J., Gibies George, Abhishek Lodh, S. Indira Rani, Saji Mohandas, John P. George and E. N. Rajagopal (2018): Implementation of New High Resolution NCUM Analysis-Forecast System in Mihir HPCS, *NMRF/TR/01/2018*, 17 pp.
- Mamgain, Ashu, Abhijit Sarkar, Anumeha Dube, Arulalan T., Paromita Chakraborty, John. P. George and E.N. Rajagopal (2018): Implementation of Very High Resolution (12 km) Global Ensemble Prediction System at NCMRWF and its Initial Validation, *NMRF/TR/02/2018*, 21 pp.
- Sarkar A., Chakraborty P., John P. George., E.N. Rajagopal (2016): Implementation of Unified Model based Ensemble Prediction System at NCMRWF (NEPS), *NMRF/TR/02/2016*, 26 pp.
- Schulzweida, U., Kornblueh, L., & Quast, R. (2006). CDO user's guide. *Climate data operators, Version, 1(6)*.
- WMO, 2005b: Report of the 1st workshop on the THORPEX Interactive Grand Global Ensemble (TIGGE). Reading, UK, 1-3 March 2005. *WMO/TD-No. 1273, WWRP/THORPEX No. 5*, 39 pp.
- Zsoter, E., R. Buizza & R. Richardson, 2009: 'Jumpiness' of the ECMWF and UK Met Office EPS control and ensemble-mean forecasts. *Mon. Wea. Rev.*, 137, 3823-3836.