Medium-range global ensemble prediction system at 12 km horizontal resolution and its preliminary validation

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Abstract
Forecasts of high-impact weather systems require sufficiently high resolution of state-of-the-art numerical models in order to resolve the small-scale features. At the National Centre for Medium Range Weather Forecasting (NCMRWF) in India, a global ensemble prediction system (EPS—called the NEPS) has been implemented operationally at 12 km horizontal grid size. The NEPS configuration is based on the UK Met Office Global and Regional Ensemble Prediction System (MOGREPS). Initial condition perturbations are generated by the ensemble transform Kalman filter (ETKF) method. Model uncertainties are taken care of by stochastic kinetic energy backscatter (SKEB) and random parameters (RP) schemes. Forecast perturbations obtained from 6 hr short forecasts of 22 ensemble members are updated by the ETKF four times a day (0000, 0600, 1200 and 1800 UTC). Perturbations of surface parameters such as sea-surface temperature, soil moisture content and soil temperature are also included in the new NEPS. The NEPS aims to provide 10 day probabilistic long forecasts using 23 ensemble members (22 perturbed plus one control). The long forecast provided at 0000 UTC is the combination of 11 members from the 0000 UTC cycle and lagged 11 members from the 1200 UTC cycle. The new NEPS shows improvements in terms of forecast agreement among the members in comparison with the previously operational NEPS that was running at 33 km horizontal grid size with 44 perturbed members. The ratio between the root mean square error of the ensemble mean and ensemble spread as a function of lead time has improved in both the Northern and Southern Hemispheres in the new NEPS.

KEYWORDS
ensembles, high-performance computing, high-resolution EPS, medium-range probability forecast, operational weather forecasting, Unified Model (UM)

INTRODUCTION

The forecast of the future state of the atmosphere using a single deterministic model is unlikely to match the true state exactly because of uncertainties in specifying the initial state and in the representation of atmospheric processes in the model. Ensemble prediction systems (EPSs) are numerical weather prediction systems in which
several scenarios from the same model with slightly different initial conditions are used to estimate uncertainty in a weather forecast as well as the most likely outcome. One of the main goals of an EPS is to provide the probabilistic forecast of details of extreme weather events, which requires its resolution to be sufficiently high to resolve small-scale features of these events. Ensemble-based probabilistic forecasts have been a part of the operational forecasting suite in many numerical weather prediction centres around the world such as the European Centre for Medium-Range Weather Forecasts (ECMWF; Palmer, 2018), National Centers for Environmental Prediction (NCEP; Zhou et al., 2017), UK Met Office (UKMO; Bowler et al., 2008, Tennant and Beare, 2014), Canadian Meteorological Centre (CMC; Gagnon et al., 2014), Japan Meteorological Agency (JMA, 2013), and Germany's National Meteorological Service, the Deutscher Wetterdienst (DWD) global EPS with the ICO-sahedral Nonhydrostatic (ICON) model (Zängl et al., 2015). Currently, some of the leading NWP centres have their global EPS at a horizontal grid size in the range of 18–20 km (namely, the ECMWF: about 18 km, and the UKMO: about 20 km).

An increase in horizontal resolution and ensemble size are always desirable (Buizza et al., 1998). It is important to determine how well a probability distribution of a variable can be estimated. These are beneficial in various verification measures and range of applications at different spatial and temporal scales. However, resolution and ensemble size are proportional to the computational cost. By generating a range of possible outcomes, the EPS products can be used objectively for a range of applications. Hunt and Turner (2017) show that increasing model resolution improves forecasts of monsoon depression in the case of the India summer monsoon. However, an increase in resolution enhances the forecasting capability of the intensity of weather events, and these forecasts need to be verified against high-resolution observation data. Better representation of intensity forecast is important in the case of extreme weather events. The EPS products are used by disaster relief agencies, wind and solar energy sectors. Also, application models can be embedded into the products obtained from forecast models. The NCMRWF EPS (NEPS) has been upgraded to a 12 km horizontal grid size with 22 members in the newly acquired “Mihir” high-performance computing system (HPCS). The previous version of the NEPS with a horizontal grid size of 33 km and 44 members was running in “Bhaskara” HPCS. Details related to the earlier operational NEPS and related forecast products are given in Sarkar et al. (2016). The recent version has been implemented operationally and providing products regularly from June 1, 2018. The new NEPS is expected to be more skilful, especially in generating a more accurate and area-specific forecast of extreme weather events such as rains, heat and cold waves, fog, intra-seasonal oscillation, track and the intensity of the cyclonic storms due to its very high horizontal resolution. However, predicting the short-term/small-scale features such as thunderstorms events will remain challenging as a 12 km grid size cannot resolve deep convection. The products from the long forecasts (10 day) outputs are generated according to the need of the user community and ensemble forecast verification techniques. Location-specific forecasts in the form of ensemble Meteogram are now issued for the 660 districts of India as well as for some major cities of neighbouring Bay of Bengal Initiative for Multi-Sectoral Technical and Economic Cooperation (BIMSTEC) countries. The NCMRWF is also contributing to the ECMWF “TIGGE” (Thorpex Interactive Grand Global Ensemble) project from August 2017.

The HPC system resources available with Ministry of Earth Sciences (MoES) was augmented to 6.8 petaflop (PF) in January 2018 and the same has been installed at two of its constituent units, namely, the Indian Institute of Tropical Meteorology (IITM), Pune, housing a 4.0 PF HPCS (Pratyush), and the NCMRWF, Noida a 2.8 PF HPCS (Mihir). Implementation of 12 km grid size global EPS has become possible owing to these HPCS procurements. An attempt has been made in the present paper to provide details regarding implementation of the new NEPS at 12 km grid size based on the latest available version of Unified Model (UM) along with some preliminary verification. The paper is structured as follows. Section 2 discusses the details regarding the NEPS and computing infrastructure. Methods of generating initial condition and model perturbations are discussed in Section 3. The method of generating perturbations in the cold-started model initial condition is described in Section 4. Methods used to compare the performance of the new NEPS with respect to the previous operational version of NEPS are discussed in Section 5. Finally, conclusions are summarized in Section 6.

2 | METHODOLOGY

2.1 | Brief description of the NEPS

The NEPS was upgraded from a 33 km (N400L70) to a 12 km (N1024L70) horizontal grid size. Its configuration is based on the UKMO UM (Wood et al., 2014). It uses non-hydrostatic dynamics with 3D semi-Lagrangian advection and semi-implicit time stepping. It is a grid point model and has the ability to run with a rotated pole and variable horizontal grid (optional). It features an
TABLE 1  Salient features of the new global ensemble prediction system (EPS—called the NEPS)

| Model details | Initial condition and perturbations |
|---------------|------------------------------------|
| Model: Unified model; version 10.8 | Initial condition: Analysis from global deterministic hybrid 4DVar atmospheric data assimilation (DA) system |
| Domain: Global | DA resolution: N320 L70 (about 40 km) with N144 L70 hessian-based preconditioning |
| Resolution: 12 km, 70 levels (model top at about 80 km) | DA method: Hybrid incremental 4D-Var information on “errors of the day” is provided by the NEPS forecast at every data assimilation cycle |
| Grid points: 2048 × 1536 | DA cycles: four analyses per day at 0000, 0600, 1200 and 1800 UTC. Observations within ± 3 hr from the cycle time is assimilated in the respective DA cycle |
| Time step: 5 min | Model physics perturbations: Stochastic kinetic energy backscatter (SKEB) and random parameters (RP) schemes |
| Parameterizations: based on Walters et al. (2017) | Initial condition perturbations: Ensemble transform Kalman filter (ETKF) method |
| Long forecast length: 10.5 days (based on 0000 and 1200 UTC initial conditions) | Surface perturbations: Sea-surface temperature (SST) perturbations, deep soil temperature and soil moisture perturbations |
| Short forecast length: 9 hr (based on 0000, 0600, 1200 and 1800 UTC initial conditions) |

optional mass flux convective parameterization scheme (Gregory and Rowntree, 1990) with convective momentum transport, non-local mixing and entrainment for the boundary layer (Lock et al., 2000), mixed-phase cloud microphysics (Wilson and Ballard, 1999) and surface exchange (Essery et al., 2003). It uses horizontal Arakawa-C grid staggering and a vertical Charney-Phillips grid structure. The model features 70 vertical levels ranging from the ground to the model lid at about 80 km above the surface. The new NEPS is based on UM version 10.8, which is a part of the latest Parallel Suite (PS40). In this upgraded NEPS, more observations and surface perturbations such as sea-surface temperature (SST), deep soil temperature and soil moisture content (SMC) are used. A total of 23 ensemble members (22 perturbed forecasts plus one control forecast) constitute this ensemble system. The 22 analysis perturbations of horizontal wind speed components (u and v), potential temperature (θ), specific humidity (q) and exner pressure (π) are generated by the ensemble transfer Kalman filter (ETKF) method from the forecast perturbations of previous cycles four times a day (0000, 0600, 1200 and 1800 UTC) at all 70 model vertical levels. Perturbations have also been added for deep soil temperature, SMC on four model soil levels and SST. These analysis perturbations are added to the analysis obtained from the flow dependent, hybrid four-dimensional variational data assimilation system (hybrid-4DVar; Clayton et al., 2013) as a part of PS40 suite. Forecast up to 10.5 days from the new NEPS is routinely generated based on 0000 and 1200 UTC initial conditions, which include a control forecast starting from hybrid-4DVar analysis and 22 (11 from 1200 UTC of the previous day plus 11 from 0000 UTC of current day) ensemble members starting from perturbed initial conditions. Details of the configuration of the latest NEPS is given in Table 1.

All the members of the NEPS complete short forecast runs of 9 hr daily in all the assimilation cycles at 0000, 0600, 1200 and 1800 UTC. The control and 22 perturbed members use the analysis obtained from the operational deterministic DA system and initial condition perturbations generated from the ETKF. In the ETKF system, each ensemble member is equally likely/skilful apart from the control which is not perturbed. The outputs from all the perturbed NEPS short forecasts are used in operational Hybrid-4DVar DA system to make the background error covariance flow dependent. Short forecast outputs are also used by the next cycle of ETKF to generate analysis perturbations. These output files contain the forecast fields; horizontal wind components, potential temperature, exner pressure and specific humidity.

The model configuration and input requirements in the long forecast are the same as those in short forecast, except that the model is integrated for 10.5 days. Long forecast runs start daily with initial conditions of 0000 and 1200 UTC. Owing to computational constraints, the new NEPS long forecast uses only 11 perturbed ensemble members out of the available 22. The authors are considering the first 11 members (Group 1; 1–11) for long forecast starting from 0000 UTC and the second 11 members (Group 2; 12–22) for long forecast from 1200 UTC. Probabilistic long forecast at “T” hour are issued on the basis of “T” hour forecast of Group 1 and “T + 12” hr (started from 1200 UTC of previous day) forecast of Group 2 members. Finally, long forecasts of perturbed members from both the cycles and one control member from 0000 UTC
run are combined to form the 23 ensemble members long forecast, which are used for generating post-processed products. The deterministic model that is running at the same resolution is used as the control member of the NEPS.

2.2 | Computational infrastructure

The NEPS is running operationally in the Mihir HPCS at the NCMRWF. The Mihir HPCS is a Cray-XC40 with 2,320 compute nodes running with a peak performance of 2.8 PF and total system memory of 290 TB. The number of nodes used by the NEPS and the wall clock time taken by each component are given in Table 2. The new NEPS uses 550 computer nodes for about 5.5 hr for generating 10.5 days forecasts at 0000 and 1200 UTC, respectively.

3 | GENERATION OF PERTURBATIONS

3.1 | The ETKF and model physics

The inputs to the EPS forecast runs (both short forecast of 9 hr and long forecast of 10.5 days) are provided by the Hybrid 4DVar DA system and the perturbations generated by the ETKF approach (Bowler et al., 2009). The control forecast does not need any input perturbation from the ETKF. The magnitude and statistical error structure of the uncertainties associated with the analysis data are provided by the ETKF system. It generates ensemble perturbations by using information about the observation errors and the background perturbation structure obtained from an ensemble member. In the NEPS configuration, the ETKF cycles are running every 6 hr for all the 22 members. It updates the forecast perturbation matrix by multiplying it with a transformation matrix to generate analysis perturbations for wind components, potential temperature, specific humidity and exner pressure at all 70 model levels. The ETKF uses the background 6 hr forecasts of the previous cycle from each member to determine ensemble spread. Here the ensemble-spread is the square root of the mean squared difference between the ensemble mean and the individual members. It compares this spread with the root mean square error of the ensemble mean with respect to the observation and then computes a region-specific inflation factor which is multiplied with a raw transformation matrix to improve ensemble spread. The analysis perturbations are added to the analysis data using the incremental analysis update (IAU) scheme within the UM.

The NEPS uses two stochastic physics schemes to represent the effects of structural and subgrid-scale model uncertainties that consist of random parameters (RPs) (Lin and Neelin, 2000; Bright and Mullen, 2002) and stochastic kinetic energy backscatter (SKEB) schemes (Tennant et al., 2011). The RP scheme incorporates uncertainties in the empirical parameters of the physical parameterization schemes. It also simulates the non-deterministic processes not explicitly accounted by different parameterizations. In the real atmosphere, energy is up- and downscaled through physical processes. It is very difficult to quantify accurately and model adequately these up- and down-scaled energy flows. Some components of these energy cascades, especially the upscale energy flow from the processes such as convection, are not included in a numerical weather prediction model. This results in a loss of kinetic energy from the model environment. A semi-Lagrangian advection scheme used in the UM involves interpolation of the prognostic field to the departure point and it acts to smooth field and removes energy. Also, the use of horizontal diffusion terms to smooth model fields leads to excessive energy dissipation. The SKEB scheme is implemented in the UM

| EPS tasks                                | Wall clock time (min) | Compute nodes |                   |
|------------------------------------------|-----------------------|---------------|-----------------|
| TrimObstore                              | 3                     | 1             |                 |
| Observation processing system (OPS)      | 10                    | 2 (for each of the 23 members) |         |
| Ensemble transform Kalman filter (ETKF)  | 7                     | 1             |                 |
| Sea-surface temperature (SST) perturbations | 1                    | 1             |                 |
| Soil moisture content (SMC) perturbations | 6                    | 1             |                 |
| Long forecast (11 + 1 members) for 10.5 days | 330/member             | 50 (for each member) |     |
| Short forecast (22 + 1 members) for 9 hr | 15/member              | 45 (for each member) |   |
to inject the loss in kinetic energy back into the model. A justification in using the backscatter scheme to incorporate energy in a numerical weather prediction model is given in Shutts (2005).

### 3.2 Sea-surface temperature (SST), soil moisture content (SMC) and soil temperature (TSOIL) perturbations

These steps are the additional components in the new NEPS as compared with the previous NEPS. Ensemble prediction near the surface is generally under-dispersive, which results in overconfident forecasts of near-surface variables. One of the major reasons for underestimated ensemble spread near the surface is not accounting errors associated with the observations (Setra et al., 2004). A more practical reason behind the underestimation of near-surface dispersion is that the identical lower boundary initial conditions are used for all the ensemble members.

As a part of ocean–atmosphere interaction, generally the SST has a strong impact on the forecast due to the large energy fluxes from the ocean into the atmosphere (Frankignoul, 1985). Atmospheric circulations are also sensitive to soil moisture (Dixon et al., 2013). The SST and SMC perturbations in the UKMO Global and Regional Ensemble Prediction System (MOGREPS) were added to represent better the uncertainties in the initial conditions at the surface. Operational SST and sea-ice analysis (OSTIA) data (Donlon et al., 2011; Roberts-Jones et al., 2012) from the UKMO are used to generate statistics of daily mean SST state. Tennant and Beare (2014) explained the methods of adding the SST and SMC perturbations in the MOGREPS. As the model is atmospheric only, the effect of uncertainties in the SST can be included by specifying different SST lower boundary conditions for each ensemble member. The paper used 5 year (2006–2010) monthly means of delta SST (0.5°x°0.5°) from the UKMO and regridded at N1024 to obtain the climatological values. This scheme is employed to focus on areas where the SST fluctuations are strong (2–3°C) and applies only smaller perturbation to the warm tropical SSTs (< 0.5°C).

Another scheme that is added in the new NEPS is the perturbation of the SMC and TSOIL. The UKMO started the soil moisture assimilation with a simple nudging scheme that made use of screen-level analysis of temperature and humidity and later included surface soil wetness from the Advanced Scatterometer (ASCAT) on the Meteorological Operational (MetOp) satellite (Dharssii et al., 2011). As explained by Tennant and Beare (2014), short forecasts of 6 hr (previous cycle) from each ensemble member are used to extract the soil fields at each soil level in the model. It is a simpler way to develop perturbations that allows soil fields to evolve independently. Soil perturbations for each member are calculated by subtracting the naturally evolved SMC and TSOIL from the ensemble mean. After that, some special checks for these differences (first-guess perturbations) are performed before applying those to the current model start file. These special checks (based on wilting, critical and saturation points) limit soil moisture perturbations to physically sensible bounds. Also, removal of the SMC and TSOIL perturbations are performed at points under snow and land ice fields. These checks are also to make sure that the soil perturbations sum up to zero in order to avoid systematic drift in the forecast. Separate sensitivity experiments are also planned to be carried out to analyse the impact of adding the SST, SMC and TSOIL perturbations on near-surface spread in the NEPS.

### 4 Cold Start of the NEPS

As a global EPS with 12 km horizontal grid size was being implemented for the first time in the world, the ETKF perturbations were not available at this resolution from other centres (such as the UKMO, Bureau of Meteorology Australia, Korea Meteorological Administration). Therefore, the NEPS members were cold-started from the same initial condition. At the first short forecast cycle, all the 22 ensemble members are made to run from the same initial condition (which is the analysis of the deterministic model), but with perturbed model physics. The model physics is perturbed by the SKEB and RP schemes. Owing to the perturbation in model physics, this run produces 22 different model outputs and, hence, 22 forecast perturbations. In the next cycle, the ETKF applies the transformation matrix on these 22 forecast perturbations and multiplies with an inflation factor to generate 22 analysis perturbations. These analysis perturbations are added to the deterministic analysis by the IAU method to generate 22 initial conditions for the next cycle. The cold start of the short forecast runs was carried out in April 2018 and short forecasts from the NEPS have been continuously running after that.

As a part of sensitivity experiments, the authors performed some spin-up experiments to check the number of ETKF cycles required to obtain a realistic spread among the ensemble members if the NEPS is cold-started. Those experiments were done using the old NEPS at a horizontal grid size of 17 km (for 11 and 22 members). The operational old NEPS at 33 km grid size runs were used as a reference for comparing the ensemble spread. The results of these experiments indicated that after 15–16 ETKF cycles, the 17 km NEPS (N768)
ensemble spread becomes nearly equal to the operational 33 km old NEPS (N400) ensemble spread (Figure 1). The ensemble spread is calculated using the analysis perturbations obtained from each ETKF cycle. The change in the global average of spreads at a specific humidity with time at the near surface level (20 m) and at a mid-Troposphere level (5,600 m) geometric height are shown in Figures 1a and b, respectively.

5.1 Spread-skill relationship

Comparing ensemble spread with root mean square (RMS) error is a general method of evaluating the EPS (Toth et al., 2003; Palmer et al., 2006; Johnson and Bowler, 2009). Root mean square error of the ensemble mean (RMSE) and ensemble spread (SPREAD) as a function of lead time are calculated for a two week period (June 10–23, 2018) for both the current and previous EPS (i.e. 12 and 33 km). Area averaged geopotential height at 500 hPa (Figure 2) and mean sea level pressure (MSLP) (Figure 3) over both the Northern and Southern Hemispheres are selected to verify the forecasts. Deterministic 12 km analysis in the new NEPS (12 km) and the deterministic 33 km analysis in the old NEPS (33 km) are used to verify data sets to calculate the RMSS. The RMSE is a measure of the difference between the ensemble's mean of the forecast and the analysis, whereas SPREAD measures the deviation of ensemble members from the ensemble mean. If all the uncertainties associated with the initial conditions and model errors are perfectly represented by the EPS, then the RMSE and SPREAD will be equal (Palmer et al., 2006). It means verifying the analysis is statistically indistinguishable from the ensemble members in a perfect EPS (Toth et al., 2003). However, it is also possible if the ensemble has no sharpness, meaning that the temporal variance of the ensemble mean is much smaller than the ensemble mean of the temporal variance of the single realizations (Polkova et al., 2019). The present authors calculated the ratio between the temporal variance of the ensemble mean and time mean of variance between ensemble members (data not shown). It is found that the temporal variance of the ensemble mean is comparatively larger in all the days forecast of both the NEPS. Compared with the old NEPS, the new NEPS has performed better.

In Figures 2 and 3, the SPREAD is closer to the RMSE in the new NEPS compared with the previously operational NEPS in both hemispheres, particularly at a shorter forecast lead time. The results are similar for both 500 hPa geopotential height (Figure 2) and MSLP (Figure 3), except the fact that the RMSE–SPREAD relationship in the new NEPS for the MSLP does not deteriorate at a longer lead time. Major improvements are noticed over the Southern Hemisphere, as indicated in Figures 2c and d and Figures 3c and d. The old NEPS shows over-dispersion at a shorter lead time, except for the MSLP over the Northern Hemisphere (NH) and the RMSE–SPREAD relationship improves at a longer lead time.
FIGURE 2  Root mean square error of the ensemble mean (RMSE) and ensemble spread (SPREAD) of the (a) old global ensemble prediction system (EPS—called the NEPS); (b) new NEPS over the Northern Hemisphere (NH); (c) old NEPS; and (d) new NEPS over the Southern Hemisphere (SH) as a function of forecast lead time for 500 hPa geopotential height.

FIGURE 3  As for Figure 2, but for mean sea level pressure.
Heavy rainfall was reported over many areas along the west coast region of India on June 10, 2018. Figure 4 shows the difference between the predicted 24 hr accumulated rainfall and the gridded satellite-gauge-merged rainfall product. The rainfall forecasts are based on the initial conditions at 0000 UTC on June 5, 2018. The data were regridded to 33 km resolution before calculating the difference. The present paper has presented the difference between the control forecast (unperturbed member) and the observation because the ensemble mean is by construction and may not be comparable with the single reality case, as it is always much smoother. The locations of maximum rainfall predicted by both the systems on the west coast are slightly shifted towards the east compared with the observations. A positive difference (control forecast – observation) over the Arabian Sea is much larger in the case of the old version of the model as compared with the new. Also, in the case of the new NEPS, the spatial spread of rainfall near the west coast over the sea is less (data not shown) and it agrees well with observations. It indicates that the new NEPS is better at predicting heavy rainfall. The authors also analysed one more rainfall event that affected a large area over central India and the west coast on June 29, 2018. The difference in Day 3 forecasts for rainfall from both the NEPS versions and the observations are shown in Figure 5. Here, a reduced positive difference is noticed over a broad area over central India and also over the Bay of Bengal. However, over some pockets of the west coast, northwestern India and eastern India,
a higher intensity of rainfall is predicted by the new NEPS.

5.3 Probability of rainfall exceedance

Probabilistic quantitative precipitation forecasts for Day 3 valid for June 29, 2018, from the old and the new NEPS are shown in Figure 6. The probability of rainfall exceeding the thresholds of 15.6 and 65.5 mm-day\(^{-1}\) are predicted by both systems. The striking difference can be noticed in these high-threshold categories of rainfall. In the new NEPS, the probability of having rainfall of > 15.6 mm-day\(^{-1}\) in the Rajasthan and Madhya Pradesh regions is > 75% in many districts. Whereas in the old NEPS, the probability lies between 25% and 50% over most districts. The probability between 50% and 75% is noticed only over a few districts. According to the new NEPS forecast, the probability of getting rainfall of > 65.5 mm-day\(^{-1}\) over some districts in southern Rajasthan lies in the range of 25–50%, but the old NEPS does not predict > 25% probability of getting rainfall > 65.5 mm (Figure 6b). Also, over the west coast, the probability of getting > 65.5 mm-day\(^{-1}\) rainfall is higher in the new NEPS.

Figure 7 shows the histograms of 24 hr accumulated rainfall predicted by each ensemble member at its Day 3 forecasts over two districts: Ratnagiri at 16.98°N, 73.3°E and Banswara at 23.54°N, 74.4°E. The histograms are arranged in order of increasing rainfall predicted by the ensemble members. Figures 7a and b show that larger fraction of ensemble members of the new EPS predicts rainfall amount close to the observed value (61 mm) or more. The same is true in the case of rainfall prediction for Banswara (Figures 7c and d). Here, the observed rainfall is > 100 mm and about 50% of

**FIGURE 6** Day 3 forecast of rainfall (mm-day\(^{-1}\)) probability > 15.6 mm (a, c) and 65.5 mm (b, d) valid for June 29, 2018, simulated by the old global ensemble prediction system (EPS—called the NEPS) (upper) and the new NEPS (lower)
members of the new EPS predict close to or > 50 mm rain, while only a few (about 15%) members of the old NEPS predict rainfall close to or > 50 mm.

### 6 | SUMMARY

Improvement in forecast accuracy of high-impact weather events is a main priority for operational weather forecasting centres. It is well understood that weather forecasts are generally not perfect from a deterministic model and hence require ensemble prediction techniques to quantify uncertainties in the forecast. Ideally, an ensemble prediction system (EPS) should represent uncertainties in initial conditions as well as those uncertainties that should evolve during the forecast. The National Centre for Medium Range Weather Forecasting’s (NCMRF) new EPS (called the NEPS) is based on the UK Met Office’s (UKMO) Unified Model (UM) version 10.8 weather forecast suite called Parallel Suite (PS40). The initial condition perturbations are generated by the ensemble transform Kalman filter (ETKF) method. The model uncertainties are taken care by the stochastic kinetic energy backscatter (SKEB) and random parameters (RPs) schemes. In the new NEPS, surface perturbations (namely, sea-surface temperature (SST), soil moisture content (SMC) and soil temperature) are additional features as compared with the old NEPS. The control forecast run starts with analysis data of the deterministic forecasting system and 22 ensemble members start from different perturbed initial conditions. The forecast perturbations are obtained from 6 hr short forecasts of 22 members, which are updated by the ETKF four times a day (0000, 0600, 1200 and 1800 UTC). Long forecast products are based on 22 members. Those are the combination of 11 perturbed members forecast from the initial condition of 0000 UTC of the current day and 11 lagged perturbed members from 1200 UTC of the previous day.

The new NEPS with a smaller ensemble size and higher resolution shows better root mean square error (RMSE)–ensemble spread (SPREAD) relationship for geopotential height at 500 hPa and MSLP over both Northern and Southern Hemispheres at shorter forecast lead time. Juhui et al. (2012) also found that a higher resolution EPS is more advantageous at a shorter range, while at a longer range, larger ensemble size is more beneficial. An ensemble size of 20–30 is found to be most effective for the National Centers for Environmental Prediction (NCEP) Global Ensemble Forecasting System. Kay et al. (2013) noticed only a slight improvement in forecast skill at a longer forecast lead time by doubling (from 24 to 48) the ensemble size of the UKMO’s Global and Regional Ensemble Prediction System (MOGREPS). Mullen and Buizza (2002) concluded that the coarser resolution EPS of large ensemble size shows a better ability to predict rare precipitation events and can provide more valuable probabilistic forecasts to the users and decision-makers. The old NEPS with coarser grid size and a larger ensemble size also shows improvement in the RMSE–SPREAD relationship at a longer lead time as compared with shorter lead time. Verification with the data over a
very short period may not lead to a conclusive result, but the preliminary validation process indicates that the smaller ensemble size at a higher resolution is useful in the probabilistic forecasting of extreme events at shorter range. The EPS of larger size may show better skill at a longer lead time over a broader range of applications.

Two heavy rainfall events during the Indian summer monsoon season have been considered to compare the probabilistic precipitation forecasts from the old and new NEPS. In both cases, the new NEPS provides higher probabilities of heavy precipitation. Further detailed evaluation of these two modelling systems is required to quantify the improvement in forecast skill.

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