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RESEARCH REPORT

PERFORMANCE OF GLOBAL ENSEMBLE FORECAST SYSTEM (GEFS) DURING MONSOON 2012

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Contents

Abstract

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1. Introduction

The atmosphere is a chaotic system and the forecasts based on a single model (deterministic approach) generally have uncertainty (Buizza et al., 2005). Small errors in the initial conditions grow rapidly, leading to large forecast errors. Early studies (Lorenz, 1969, 1982) suggested that initial errors could grow very fast into different scales no matter how small the initial error is. Furthermore, errors also come from each component of the numerical weather prediction (NWP) system (Zhu, 2005), which include the observation system, data assimilation system and forecast model (dynamical processes, computation, physical parameterization). The two sources of errors (initial errors and model errors) together limit the skill and predictability of a deterministic forecast system.

Ensemble forecasting has emerged as the practical alternative approach to complement a single deterministic forecast with an estimate of the probability density function (PDF) of forecast states. Ensemble forecasts are initialized with a sample of initial states drawn from a PDF of multiple (perturbed) initial conditions to sample initial-value-related forecast uncertainty. Thus an ensemble approach produces a set of randomly-equally-likely (independent) forecasts. The diversity of these forecasts (forecast spread) represents the forecast uncertainty.

The skill of the ensemble forecast shows marked improvement over the deterministic forecast when comparing the ensemble mean with deterministic forecast after a short lead time. Additionally, ensemble forecasts can be used to make *probabilistic* forecasts. Thus ensemble forecasts not only improve the forecast accuracy (by reducing errors in the estimate of first moment of forecast PDF) but also offer a practical way of measuring case dependent variations in forecast uncertainty (by providing an estimate of higher moments of forecast PDF) (Buizza et al., 2005). Ensemble approach has gained substantial ground in NWP since 1990s. With increase in the computational capability, many NWP centers use ensemble approach in their modelling suites (WMO, 2003).

A Global Ensemble Forecasting System (GEFS) at T190L28 resolution (about 70 km in horizontal resolution and 28 levels in the vertical) with 20 members has been implemented at NCMRWF for real time medium range forecasting. The initial perturbations are generated using the Ensemble Transform with Rescaling (ETR) method. The forecasts from each of the 20 members are run up to 10 days. The present implementation is an upgrade to the earlier experimental model based on T80L18 (Iyengar et al., 1996; Zhu et al., 1996; Iyengar et al., 2004 and Kar et al., 2011). This report gives a summary of the performance of GEFS during the monsoon (JJAS) 2012. The report includes a brief introduction to the GEFS system along with some results of intercomparison with the operational deterministic model (T574L64; T574 hereafter) forecasts.

2. Brief Description of GEFS

The GEFS is developed at National Centers for Environmental Prediction (NCEP) and is used for operational forecasting. It is a single-model, global ensemble system consisting of 21 members and is run 4 times daily (00, 06, 12, and 18 UTC). GEFS is initialized by the method of Ensemble Transform with Rescaling (ETR) (Wei et al., 2008) and Stochastic Total Tendency Perturbation (STTP). The ETR makes use of the operational high resolution (T574) deterministic analysis and forecast outputs (Prasad et al., 2011). The GEFS's atmospheric model is a low resolution model of Global Forecast System (GFS). Detailed description of the GFS can be found in Hamill et al. (2011), Prasad et al. (2011) and at (www.emc.ncep.noaa.gov/gmb/moorthi/gam.html). The current horizontal resolution of the atmospheric model of GEFS is T190 (~70 km) and has 28 vertical levels (T190L28). The model is run daily up to 240 hours based on 00 UTC initial conditions. The model outputs are post-processed at 6 hour interval to a 1° x 1° regular latitude-longitude grid.

3. Initialization Method

The perturbed initial conditions for the GEFS runs are generated by the method of Ensemble Transform with Re-scaling (ETR) developed at NCEP (Wei et al., 2008). A brief description of the ETR method is presented below

3.1 ETR Method

In the ETR method the atmospheric model of GEFS is run for 6 hours for the 06, 12, 18, and 00 UTC forecast cycles with a set of 20 perturbations applied to the initial conditions. The following steps are followed for each of the 4 forecast cycles:

1) The 20 perturbed initial conditions are run for 6 forecast hours.
2) The 20 forecasts are compared to the analysis valid at the same time, and differences are determined.
3) The 20 resulting differences are then made statistically independent of each other ("orthogonal"), and then re-scaled to a size representative of the known observational and first guess errors. Below 500-hPa, the re-scaling factor for the initial perturbations is increased linearly to a final value 20% higher at the model surface (schematic of scaling appears below).
4) The cycle repeats every 6-hour, breeding a new 20-member set of independent perturbations as illustrated below.

This process is repeated until the 6-hour analysis minus perturbation area-averaged differences become stable and the perturbed initial conditions are ready for forecast run.

3.2 Operational breeding of perturbations

The graphic below (Figure 1) shows the breeding cycle used at NCMRWF. The horizontal red arrows represent four of the 20 perturbations to the control forecast. At NCMRWF the forecasts are carried out up to day-10 for the 00Z cycle only due to computational constraints.

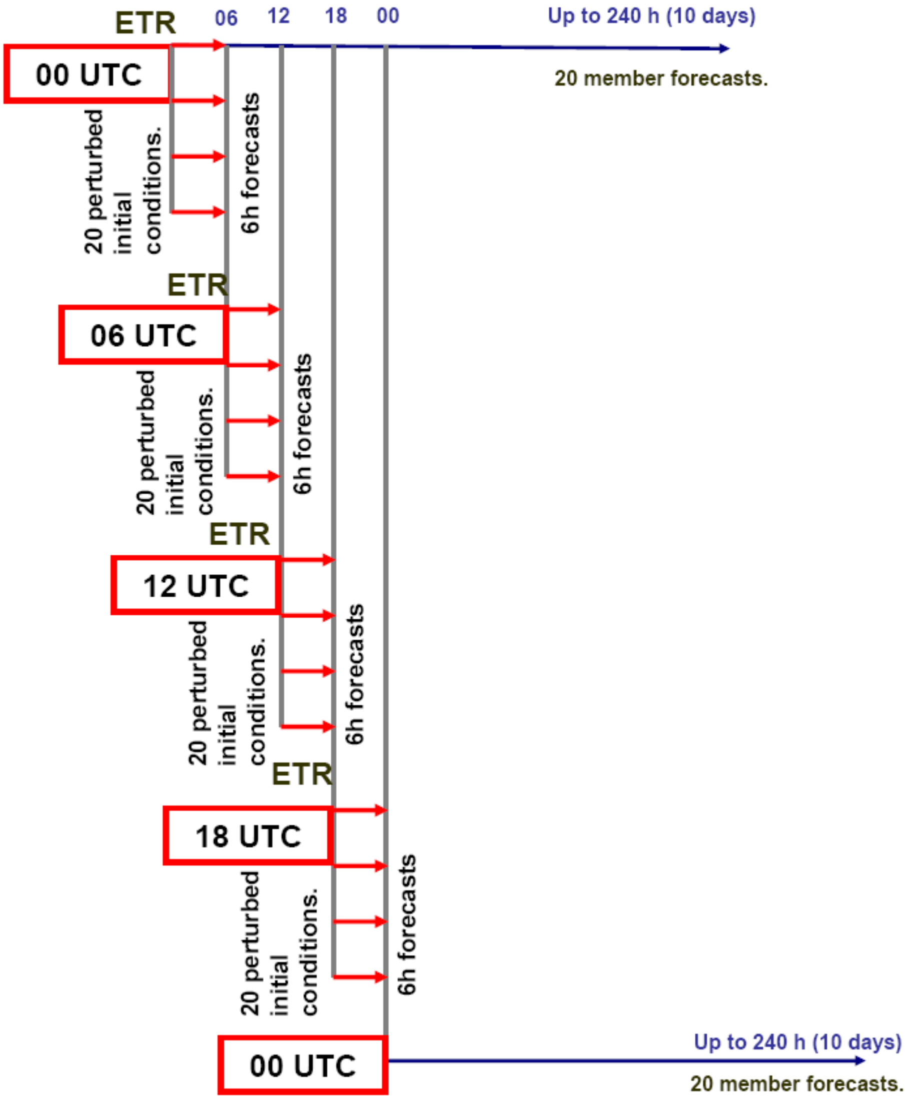

Figure 1: The GEFS initialization and forecast cycles (4 times daily) operational at NCMRWF.

3.3 Stochastic Perturbations

To emulate the effect of uncertainty in NWP models on the forecast variables (temperature, specific humidity, and winds), the Stochastic Total Tendency Perturbation (STTP) scheme is applied. The scheme is applied every six hours, after forecast output is created, as follows:

1) The total time tendency for each forecast variable from all physical and dynamical processes is calculated.
2) The tendency is perturbed by a random factor, and then
3) Re-scaled to be size-appropriate to the region of the globe (e.g. extra-tropics have larger

perturbations than the tropics) and forecast lead time (e.g. longer lead times have larger perturbations than short lead times).

The calculation of the time tendency perturbations is done at the same time across all ensemble members, with the perturbations made statistically independent of each other before being applied to the variables.

4. GEFS Forecast Products

4.1 The Ensemble Mean and Spread

The ensemble spread is a measure of the difference between the members and is represented by the standard deviation (SD) with respect to the ensemble mean (EM). On average, low (*high*) spread indicates high (*low*) forecast accuracy.

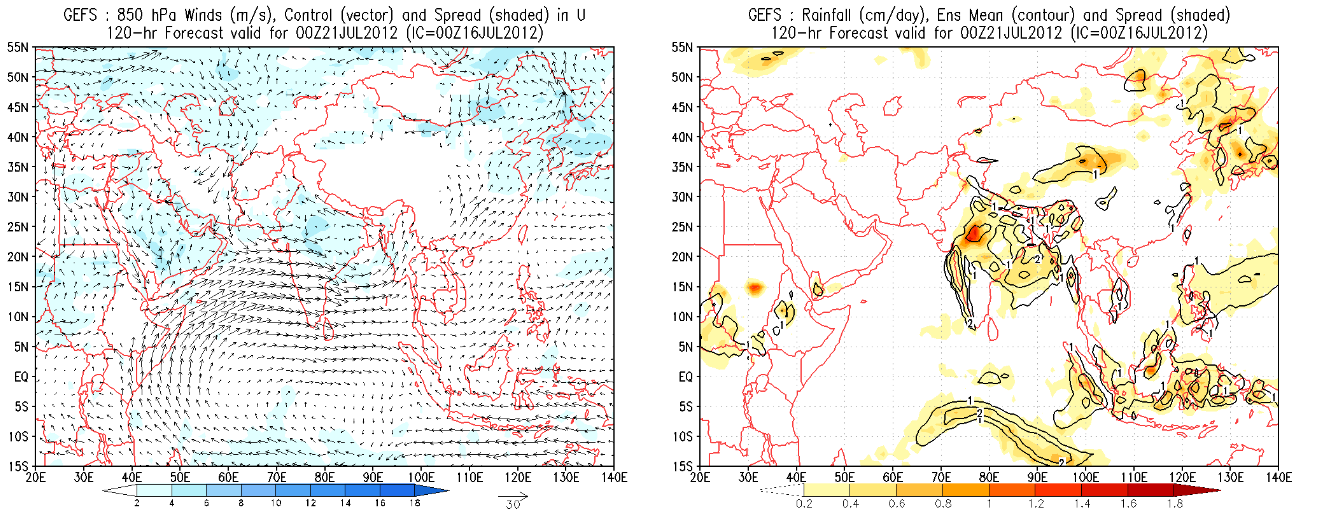

Figure 2: The Ensemble mean and standard deviation (spread) in the day-5 forecast valid for 21st July 2012. Panels show the 850 hPa mean wind vectors and spread in zonal wind (shaded). Similarly right panel shows mean 24-hr rainfall (cm; contour) and the spread.

Figure 2 shows typical example of ensemble mean and spread in the 120 hour forecast of zonal wind at 850 hPa and rainfall. The mean wind is shown by vectors in the left panel and the mean rainfall in the right panel in contours. Spread in the ensemble members is shaded in both panels. Low spread over the region of cross equatorial flow, Arabian Sea and along the west coast of India is striking. However, the spread along the monsoon trough is higher suggesting uncertainty in the predicted flow associated with the monsoon trough and the low pressure systems. Uncertainty in the predicted intensity and position of the low pressure systems results in large uncertainty in the predicted rainfall amounts and distribution which is evident from the right panel. Kar et al. (2011) attribute the high spread in predicted rainfall over regions of high rainfall amounts to the uncertainties in the diabatic processes in the model. The forecast rainfall amounts and the spread shown in the right panel reflect the similar conclusion.

The ensemble spread is flow-dependent and varies for different parameters. It usually increases with the forecast lead time, but there can be cases when the spread is larger at shorter forecast ranges than at longer range. This might happen when the first days are characterized by strong synoptic systems with complex structures but are followed by large-scale “fair weather” high pressure systems.

4.2 Spaghetti Plots

Mean and spread diagrams give information what is most often (but not always) the most likely outcome (the ensemble mean) and the degree of uncertainty in that outcome (the ensemble spread). However, unless the ensemble forecasts are distributed normally about the ensemble mean, the information in the mean and spread diagrams can mislead the forecaster if the forecast distribution clusters around more than one value (so-called multi-modal distributions). Examining all of the ensemble member forecasts together is a good way to get a handle on the ensemble forecast distribution. The forecaster can look at all ensemble members through use of what are known as "spaghetti" diagrams. These are plain view graphics of only one or a few contour values for the variable of interest, which keeps the presentation relatively simple. Spaghetti diagrams are a good complement to ensemble mean and spread diagrams.

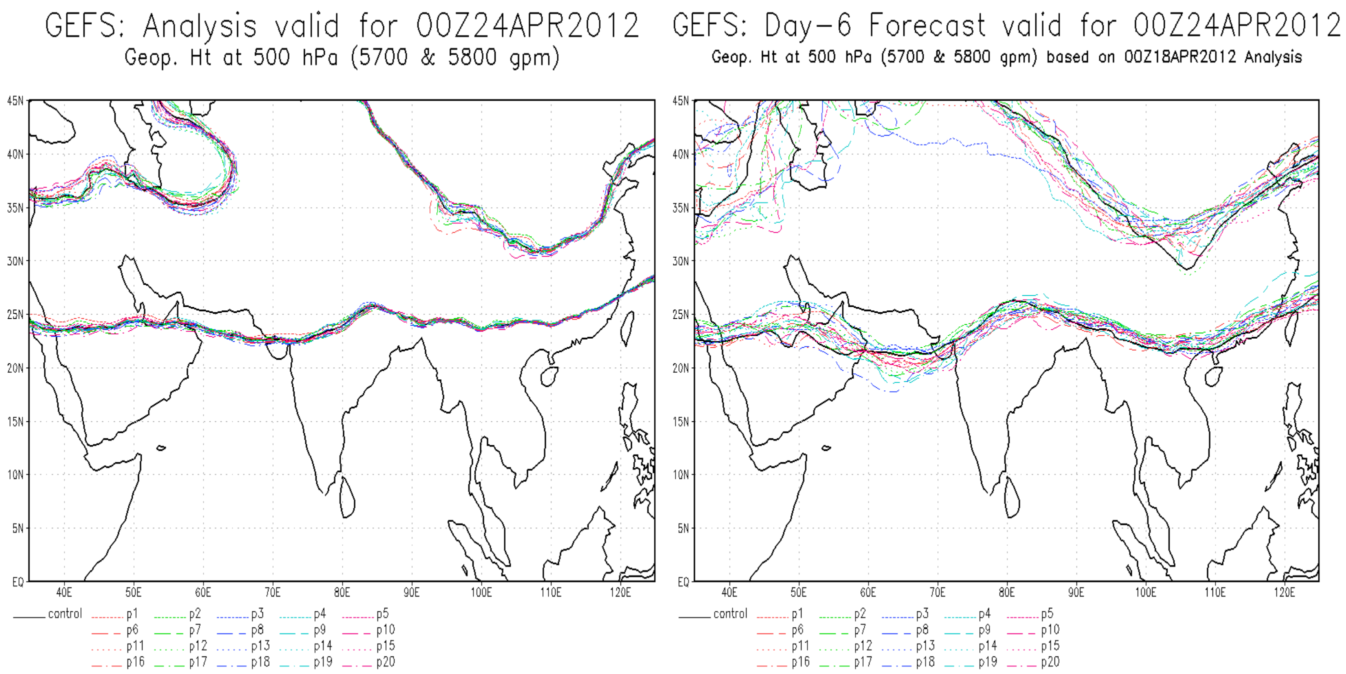

Figure 3: Spaghetti plots showing the 500 hPa geopotential height contours (5700 and 5800 gpm) in the analysis and day-5 forecasts valid for 24th April 2012.

4.3 Probabilistic forecasts of quantitative precipitation

In these charts, the probability of 24-hour precipitation amounts over a 2.5°x2.5° lat-lon grid box exceeding certain threshold values are given. The forecast probability is estimated directly from the 20-member global ensemble. At each grid point the number of ensemble members having a 24-hour precipitation amount within a specified range (e.g. 1-2cm, 2-5cm etc) is counted (M) and the probability is expressed as 100*(M/20).

Figure 4 shows an example of the PQPF plots depicting the forecast rainfall distribution alongside the spatial distribution of rainfall probabilities in the 1-2cm/day, 2-5cm/day and 5-10cm/day categories. The top left panel shows the mean rainfall (from 20 members) in contours and the spread (shaded) in the forecasts.

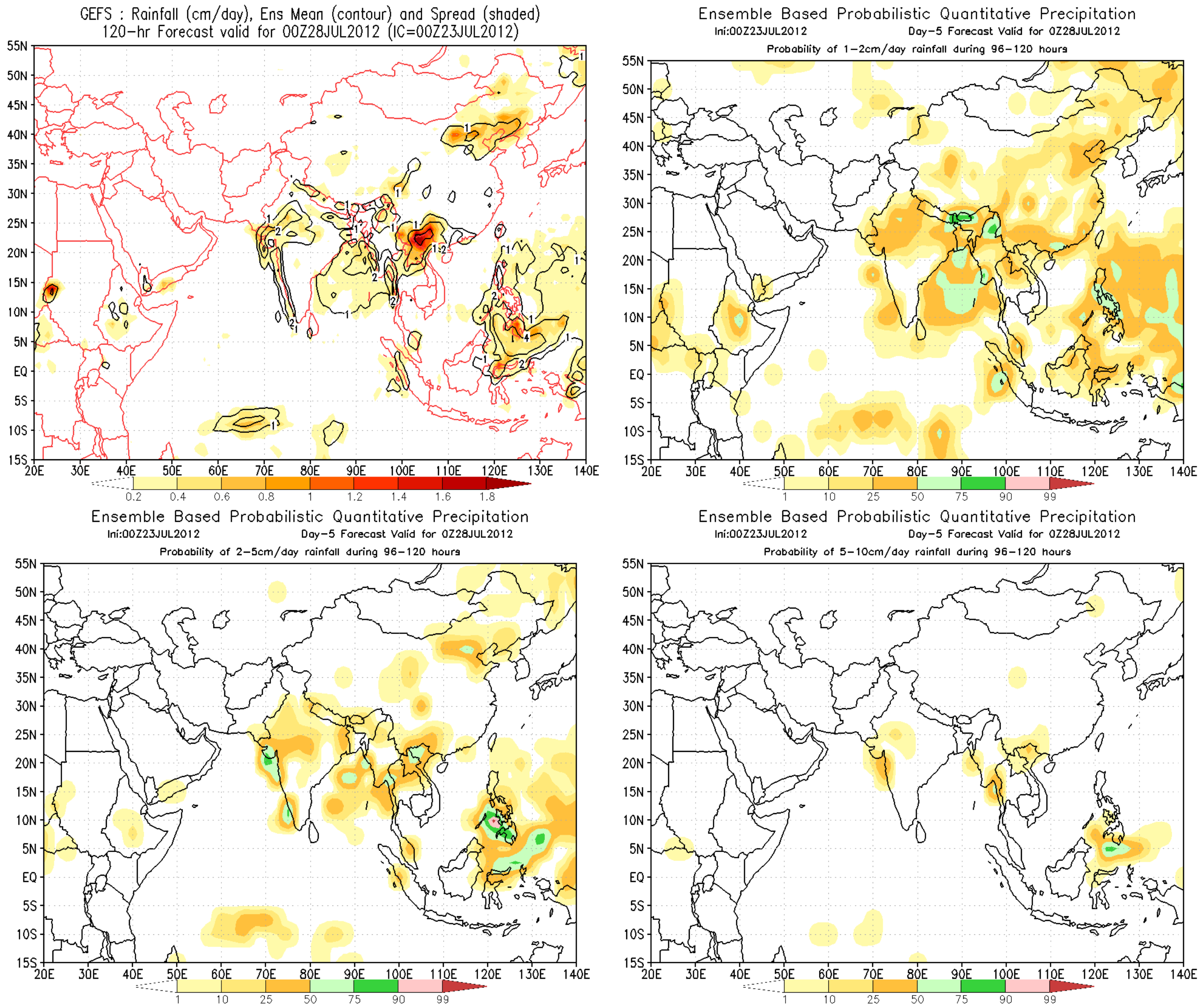

Figure 4: Day-5 forecast of 24-hr rainfall valid for 28th Jul 2012 (top left) over RSMC region. The probability of the rainfall in the 1-2cm/day range (top right), 2-5cm/day range (bottom left) and 5-10 cm/day range (bottom right).

4.4 GEFS Forecast of cyclone Nilam (29th October-1st November 2012)

The ensemble prediction system (under test since March 2012 and operational since June 2012) is tested for ensemble tropical cyclone track forecasts. The cyclone module in the GEFS is based on the automated tracker (Marchok, 2002) and can be used to produce three different kinds of products. (a) Tracks of the cyclone from each of the members of the GEFS, (b) Circle of track uncertainty (based on the ensemble spread) and (c) Strike Probability. This module mainly caters to the Atlantic and Pacific basins. Buckingham et al. (2010) demonstrated the skill of GEFS system in predicting the tracks of the tropical cyclones over western North Pacific and Atlantic Oceans during 2006-2008. The module was suitably modified for the Arabian Sea (AS), Bay of Bengal (BoB) and South Indian Ocean (SI) prior to implementation at NCMRWF. The system was tested extensively for several cases of cyclones over all the basins during July-August 2012 and was implemented at NCMRWF for real time prediction during the current cyclone season (October-December 2012).

The tropical cyclone forecast tracks are derived from post-processed files of GEFS runs at NCMRWF. This cyclone module tracks the vertical weighted average of the max or min of several parameters in the vicinity of a vortex in the input first guess (lat, lon) and forecasts. Briefly, for tropical cyclones, 7 parameters are tracked, including the relative vorticity maximum, geopotential height minimum and wind speed minimum at both 850 and 700 hPa, as well as the minimum in sea level pressure. The geographical locations of these 7 parameters are averaged to provide mean position at each forecast hour. In order to avoid tracking weak, transient disturbances (either real or artifacts of model noise), 2 constraints have been added to the tracking criteria in order for a found disturbance to be reported as being a tracked storm: (1) the storm must live for at least 24 hours within a forecast, and (2) the storm must maintain a closed MSLP contour, using a 2 mb contour interval. The output from the tracker contains forecast positions of the cyclone at 6 hour interval plus the maximum wind near the storm center.

(a) Mean Track and Spread

Based on the tropical cyclone track (automated tropical cyclone track forecast; ATCF) from the various ensemble perturbation members, an ensemble mean track is computed. Additionally spread of the ensemble is also computed. The spread of the ensemble track forecasts is defined as the average distance of the ensemble members to the mean track.

(b) Strike Probability

Strike probability is the chance of a given location (grid point) being within a specified distance (~101 km) of an ensemble mean track point. Strike probability is calculated both individually for each forecast hour and for the total accumulated probability up to 120 hr forecast. For the case of Bay of Bengal cyclone Nilam, Figure 5 shows the GEFS forecasts (top) and T574 track (bottom left panel). The strike probability is shown (left) along with the mean track. Individual member tracks (right) cluster about the mean in the early part of the forecast. Track errors (Figure 6) computed against observations suggest a reduction in the GEFS track errors (by more than 75 km and 150 km in 48 and 72 hour forecasts respectively) compared to T574 and the official IMD forecasts. Thus GEFS demonstrates huge potential for tropical cyclone forecast applications.

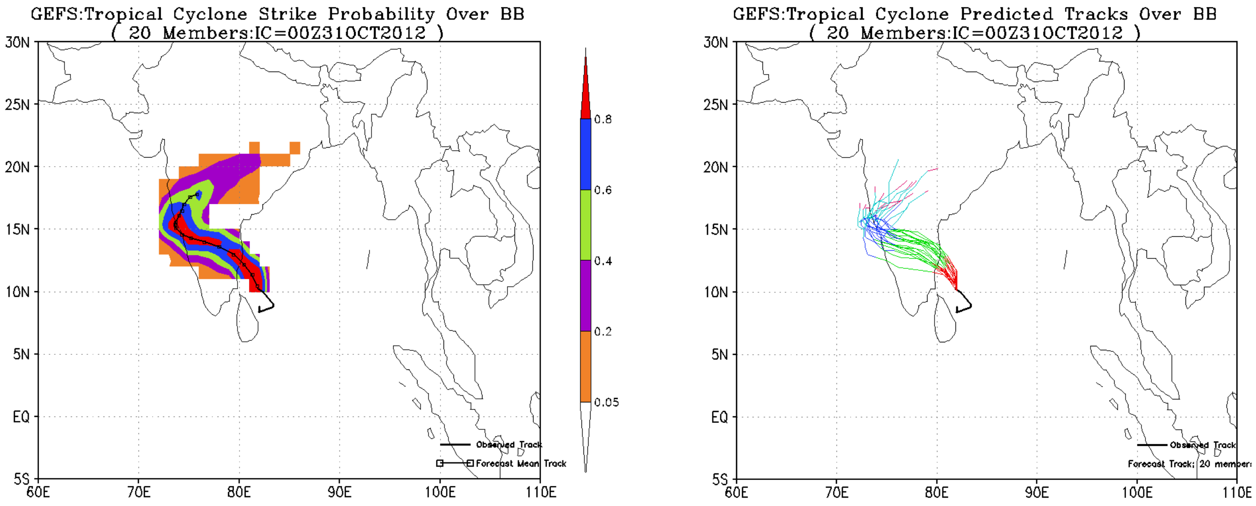

Figure 5: GEFS Forecast (a) Strike probability (b) Tracks of the members of ensemble prediction of Arabian Sea cyclone 'NILAM' on 31st October 2012.

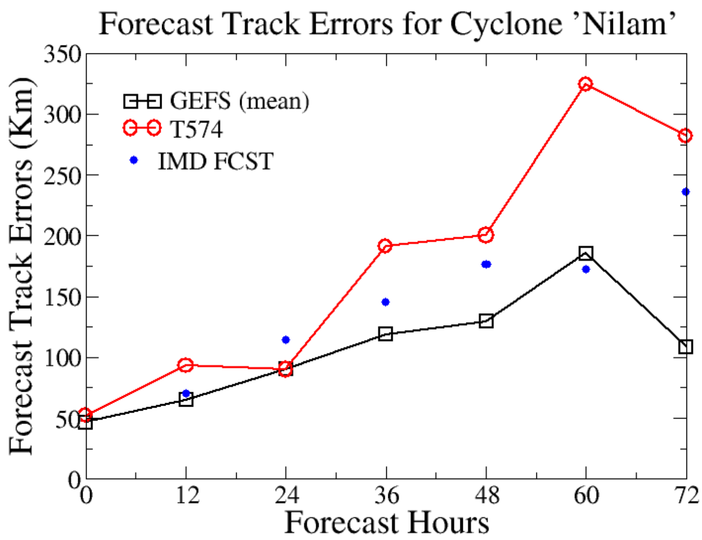

Figure 6: Forecast track error (FTE) in the GEFS and its comparison with FTE in T574 and IMD forecasts for the case of Bay of Bengal cyclone 'NILAM' during 29 - 31 October 2012.

5. GEFS Forecasts during JJAS 2012

The root mean square error (RMSE) and anomaly correlation (AC) are good measures of overall forecast performance. As Buizza et al. (2005) note they are both influenced by systematic errors and random error variance. Here the accuracy of the ensemble system and its performance against the deterministic system are measured using RMSE and AC.

5.1 Root Mean Square Error (RMSE)

The brief assessment presented here is based on NCEP's Verification Statistics Data Base (VSDB) package implemented at NCMRWF. The verification is done at 2.5° grid resolution and several scores are computed. The evaluation is performed for Global (G2), Tropics (TRO; 20°S to 20°N), Northern Hemisphere (NHX; 20°N to 80°N), Southern Hemisphere (SHX; 20°S to 80°S) and Indian region (RSMC; 15°S to 55°N and 20°-140°E). For brevity RMSE for three fields (geopotential height, temperature and vector wind) is presented for two levels (500 and 850 hPa) and for three spatial domains (G2, TRO and RSMC). Figure 7 shows the results of the RMSE for G2. The GEFS shows generally expected improvements over the deterministic forecast in terms of lower RMSE at higher forecast leads times at 500 and 850 hPa for all three fields. The lower part in each panel demonstrates the difference in RMSE (red line) and statistical significance (bars) at all lead times using Monte-Carlo significance test (Hope, 1968). In the short range there is almost no difference in the skill of the two models as indicated by low difference in RMSE. At longer lead times the difference in skill is high and significant. Similarly over TRO region (Figure 8) GEFS has lower (*higher*) RMSE for long (*short*) forecast lead times compared to RMSE in T574 forecasts. This is further evident in Figure 9 for verification done over Indian region. Thus, over the TRO and Indian region, GEFS shows lower skill than the T574 in day-1 and day-2 and higher skill at longer lead times. Similar results have been reported earlier (Zhu, 2005; Zhu and Toth, 2008) which is attributed to model resolution and initial errors.

5.2 Anomaly Correlation (AC)

The anomaly correlation for three fields (geopotential height, temperature and vector wind) is presented for two levels (500 and 850 hPa) and for three spatial domains (Figures 10-12). The AC for 850 hPa geopotential height was not available and is replaced by the AC computation results for 700 hPa. AC averaged over the globe (Figure 10) shows higher skill in GEFS at all lead times for all three fields at both levels. Averaged over the tropical region (Figure 11), AC in geopotential height and temperature at 500 hPa suggest no improvement in GEFS over T574. However, in the lower levels (850 hPa) winds and temperature do show significantly higher AC for GEFS than T574. This is seen only in day-3 or day-4 and beyond. In the short range the GEFS has lower AC. Similar analysis over the RSMC region (Figure 12) shows significantly higher AC for GEFS in all three fields at both levels. Again this is seen only in day-3 or day-4 and beyond. In the short range the GEFS has lower AC.

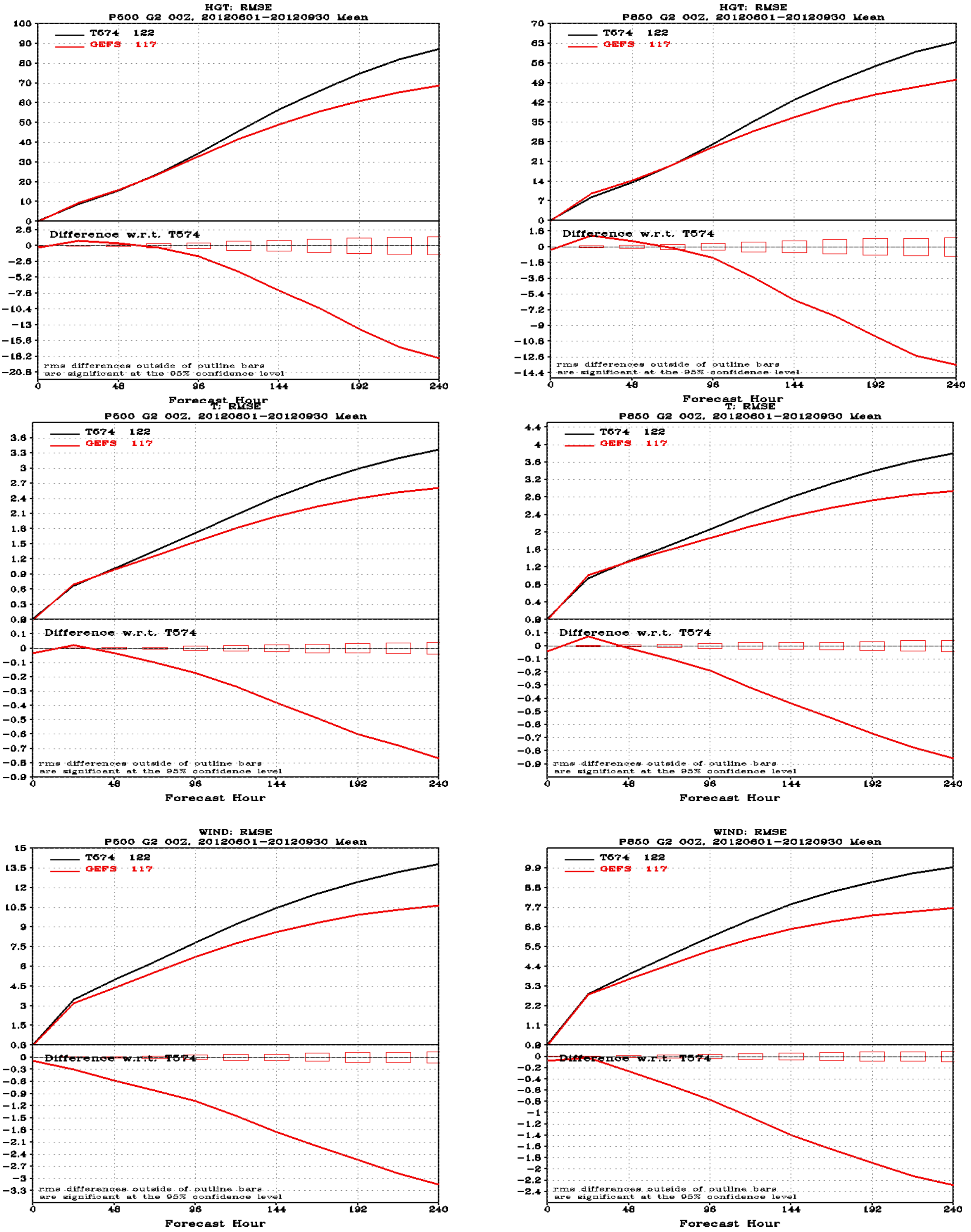

Figure 7: RMSE in the global 500 hPa (left) and 850 hPa (right) geopotential height (top) temperature (middle) and wind (bottom) in the GEFS and T574 forecasts during JJAS 2012.

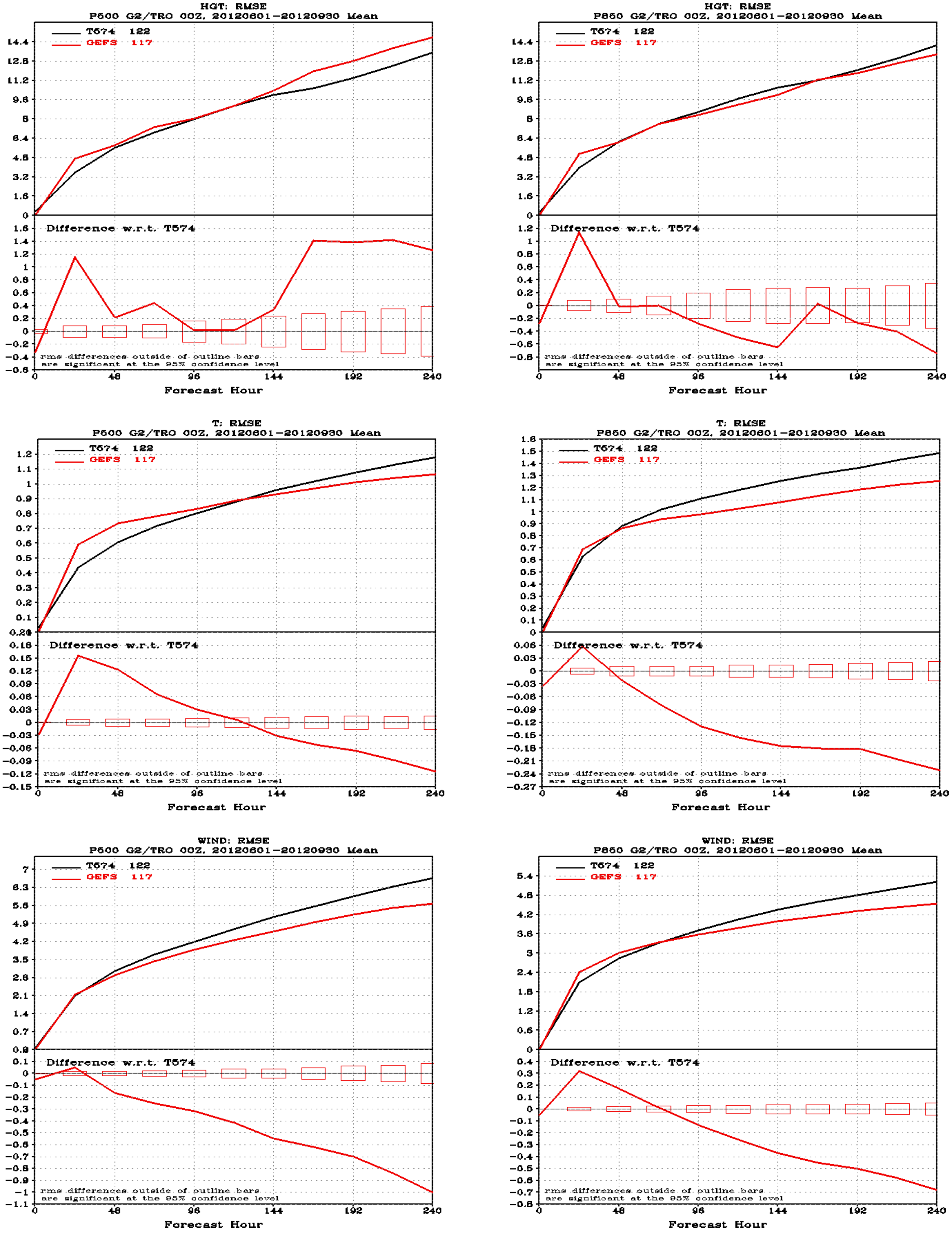

Figure 8: As in Figure 7 for tropical region.

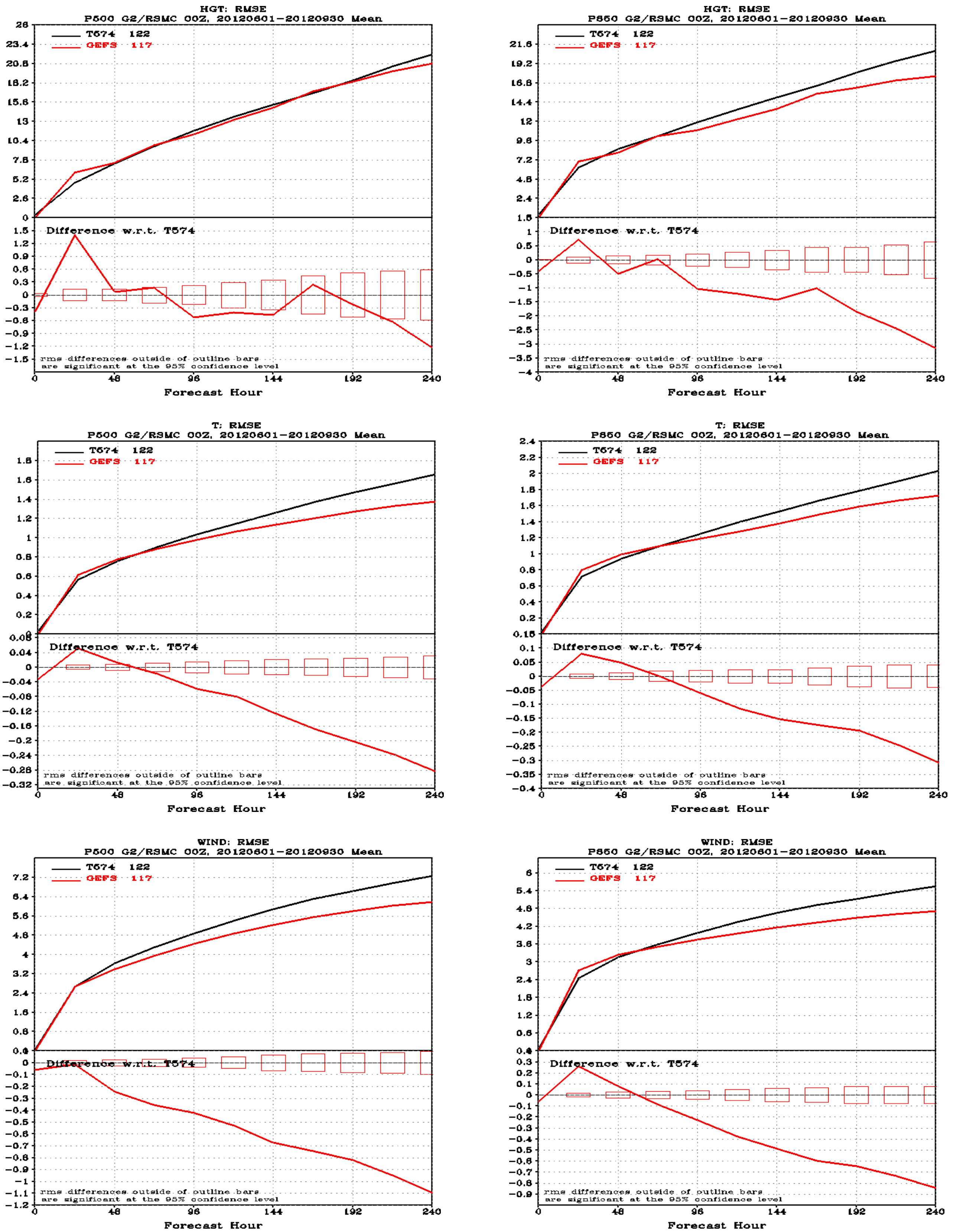

Figure 9: As in Figure 7 for Regional Specialized Meteorological Centre (RSMC) region V (15°S-55°N/20°-140°E)

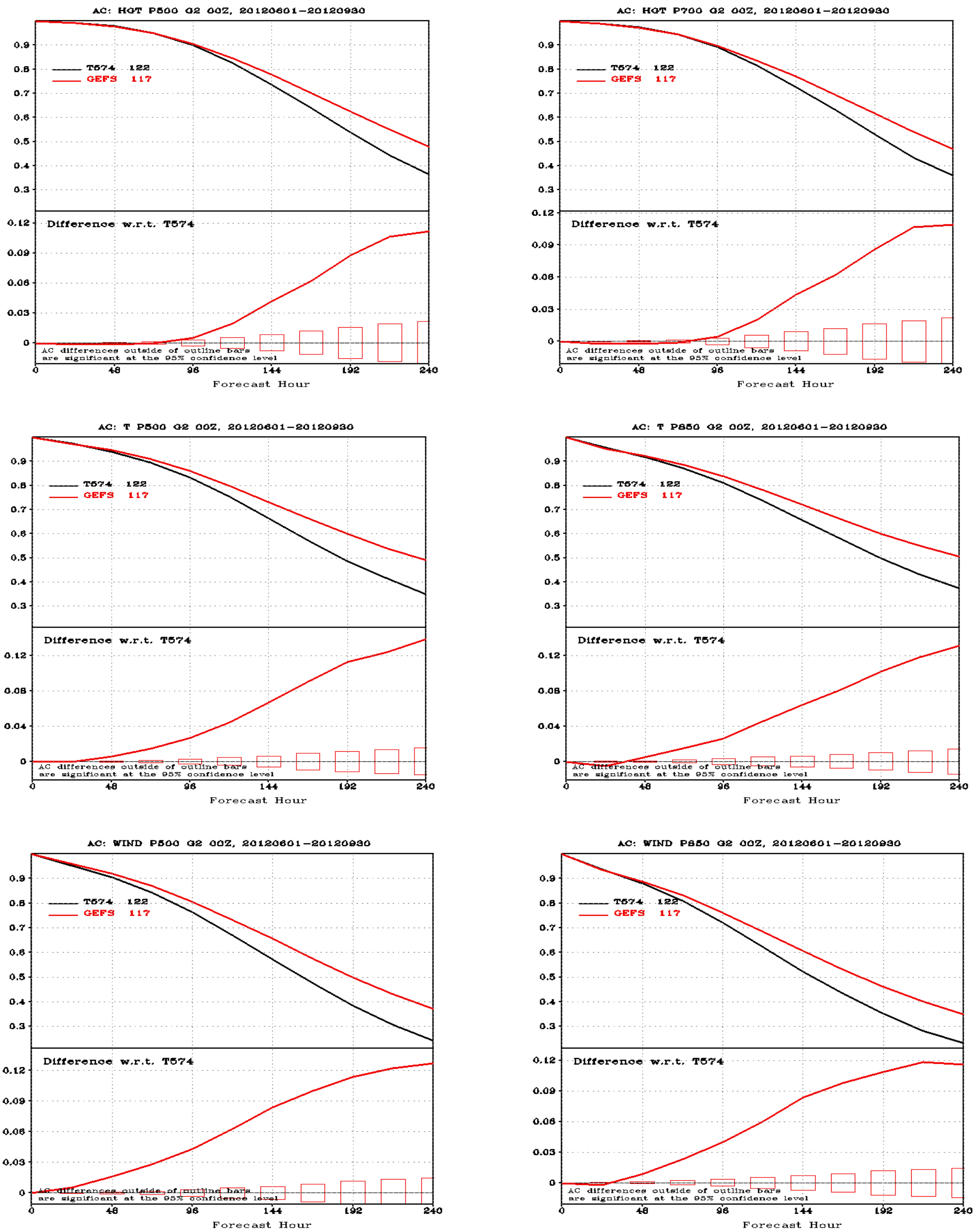

Figure 10: Anomaly correlation in the global 500 hPa (left) and 700 hPa (right) geopotential height (top), 500 hPa (left) and 850 hPa (right) temperature (middle) and wind (bottom) in the GEFS and T574 forecasts during JJAS 2012.

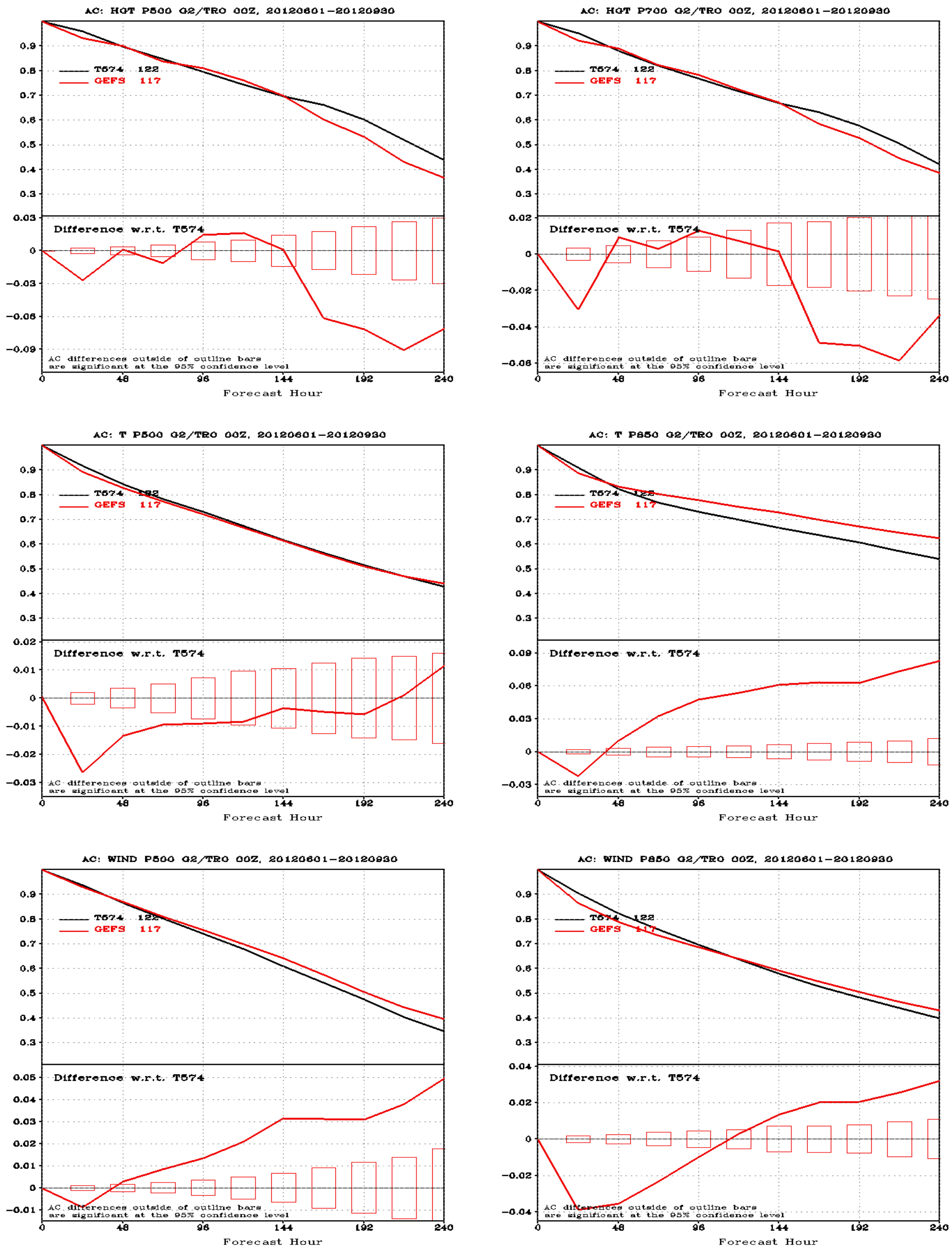

Figure 11: As in Figure 10 for tropical region.

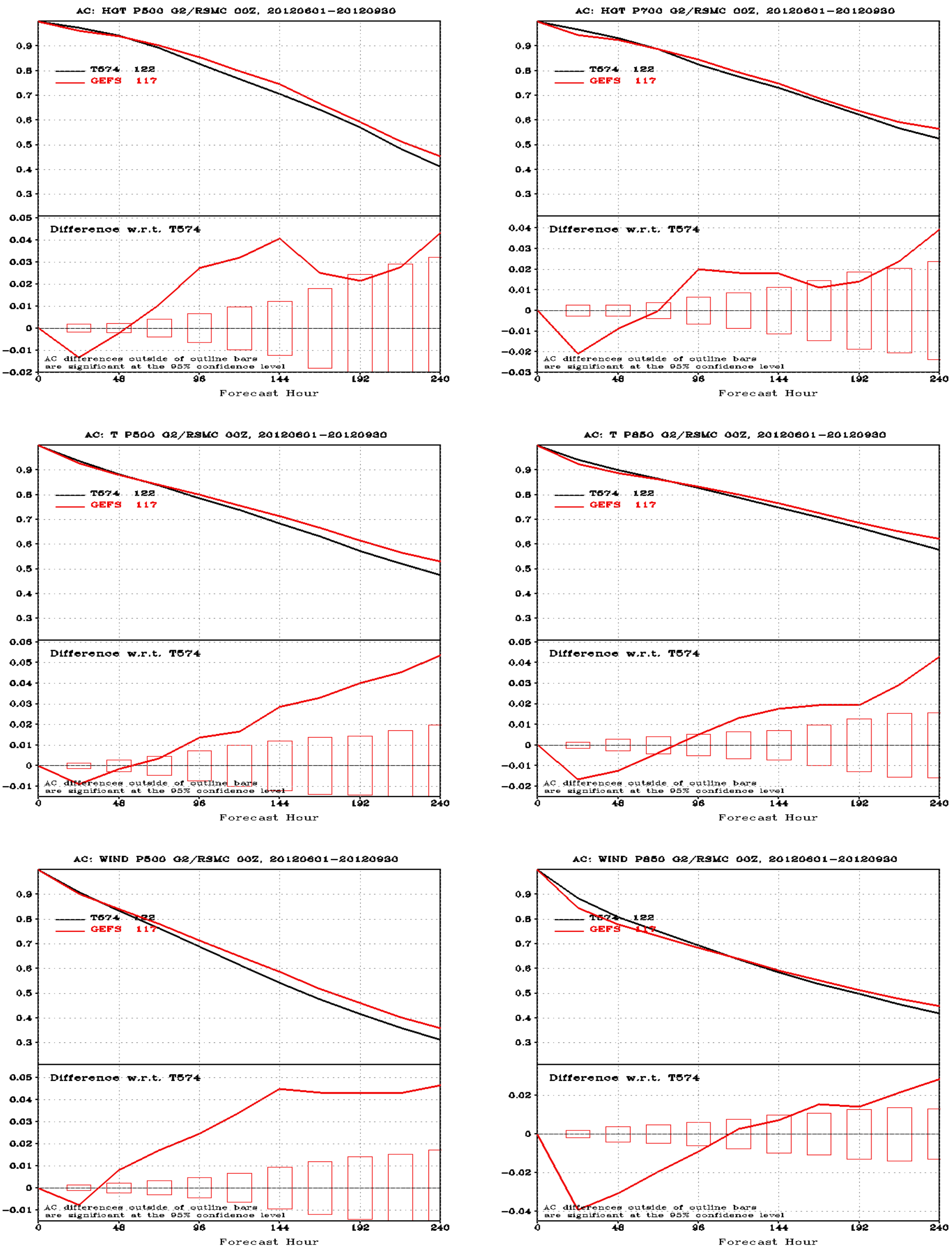

Figure 12: As in Figure 10 for Regional Specialized Meteorological Centre (RSMC) region V (15°S-55°N/20°-140°E)

5.3 Reliability (RMSE and Spread)

The discrepancy between the RMSE of ensemble mean and ensemble spread is a good measure of the statistical reliability of an ensemble forecast system (Buizza et al., 2005). For a reliable ensemble forecast system this discrepancy should be low. Large difference between the two indicates statistical inconsistency. Buizza et al. (2005) demonstrate the match in increasing RMSE of ensemble mean and the ensemble spread in the predicted 500 hPa geopotential height over 20-80°N. Similar analysis is presented here (Figure 13a) for JJAS of 2012. Consistent with Buizza et al. (2005) the growth in RMSE exceeds the growth in the spread. This graphic indicates decreasing reliability with increasing forecast lead time. The ensemble system shows reliability up to day 7 forecast and then the reliability decreases. For the Indian Monsoon region (Figure 13b) the RMSE and spread show a consistent mismatch. The growth in the RMSE and in the spread is low and the difference between the two shows no change with the forecast lead time. This clearly shows statistical consistency over Indian Monsoon region is unchanged with increasing forecast lead time. This is also reflected in the 850 hPa zonal and meridional wind (Figure 13c, d).

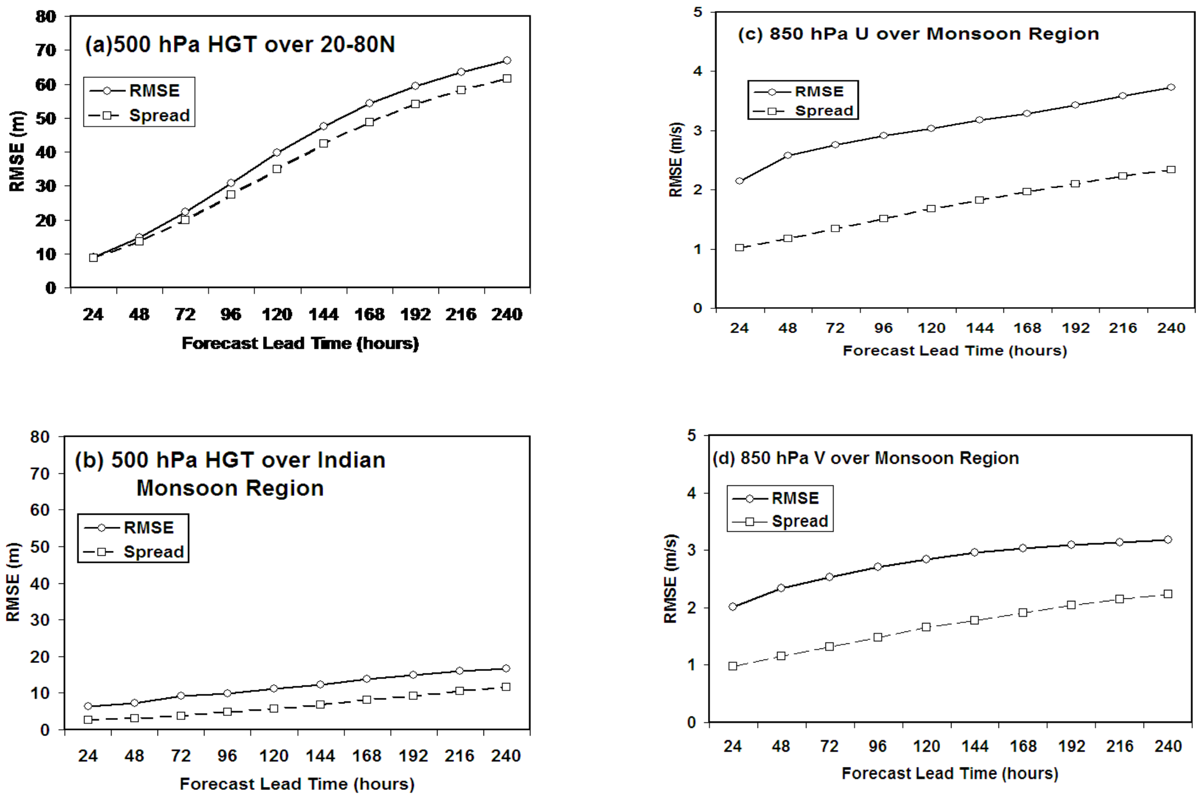

Fig13: JJAS 2012 average RMSE of ensemble mean and spread in the 500 hPa geopotential height over (a) Northern Hemisphere 20-80°N (b) Indian Monsoon region 10°S-40°N and 40-120°E. (c) RMSE and spread in 850 hPa U and (d) 850 hPa V over the Monsoon Region.

5.4 Heavy Rain due to Low Pressure System

During 3rd to 10th September 2012 a low pressure area formed over west central and adjoining northwest Bay of Bengal off north Andhra Pradesh – south Orissa coasts. It moved west and northwest inland remained as well marked low pressure area over Orissa and adjoining Chattisgarh on 4th September. It lay as low pressure area over west Madhya Pradesh and neighborhood on 6th September. The system finally dissipated over southeast Pakistan and adjoining southwest Rajasthan. Large parts of Orissa, Chattisgarh, Madhya Pradesh, Gujarat and southern Rajasthan had heavy to very heavy rainfall. Observations (Figure 14 top panels) do indicate rainfall excess of 8cm/day over central India on 5-7th September 2012 and excess of 16 cm/day at isolated location on 6th September 2012.

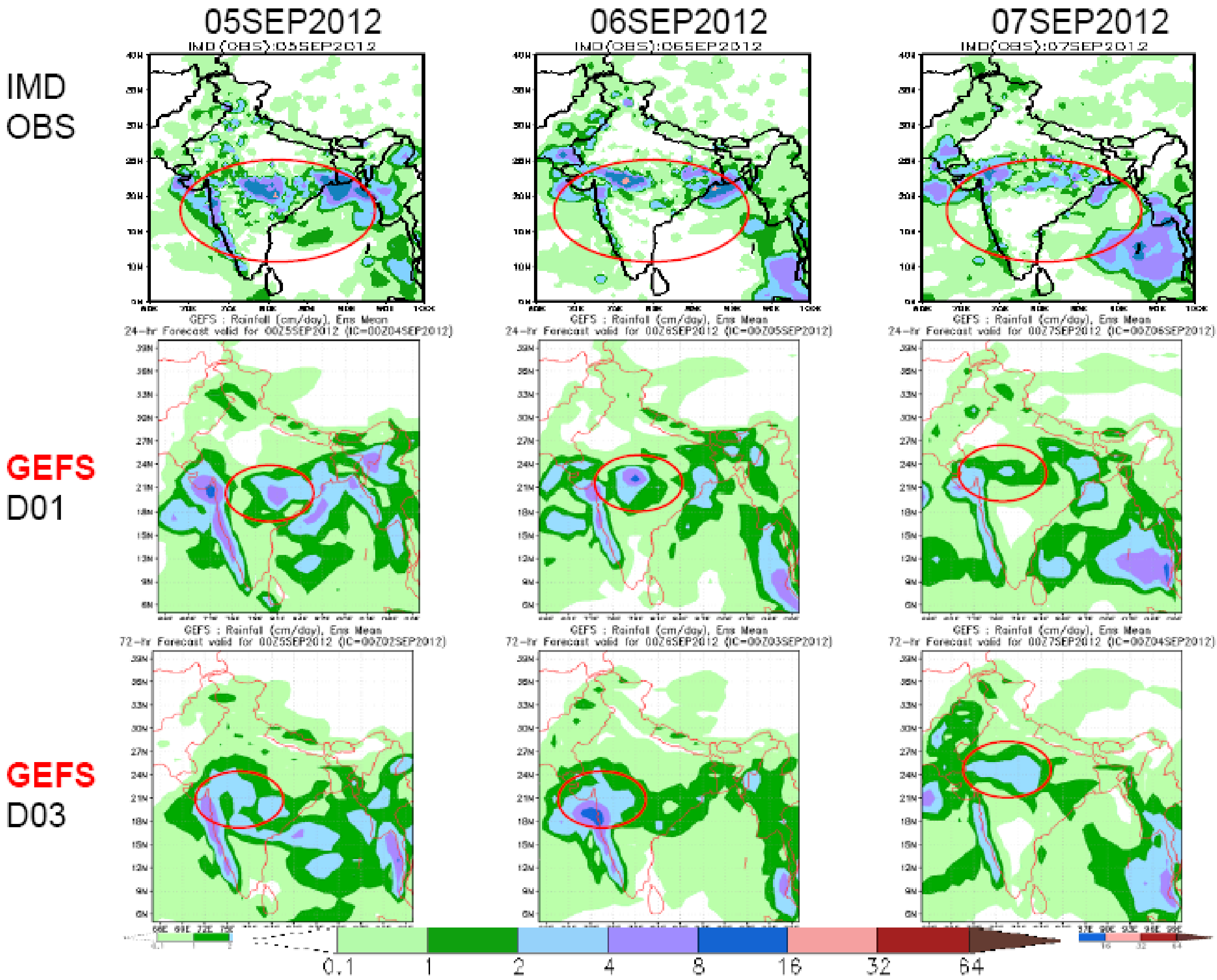

Figure 14: The heavy rainfall associated with the low pressure system during 5-7 September in the observations (top panel) and the GEFS day-1 (middle) and day-3 (bottom) forecasts.

The day-1 forecasts clearly capture the isolated nature of the heavy rainfall event accurately over the affected areas as seen in the observations. Predicted rainfall probabilities are shown in Figure 15 along with the observed and forecast rainfall amounts. Observed rainfall amounts exceed 2cm/day over large region over western India and the Day-5 forecasts show high (>50%) probability of rainfall for 1-2 cm/day and 2-5 cm/day (indicated by circle).

GEFS :Rainfall (cm/Day) Ens Mean (Top left) and Ens Based Probabilistic Quantitative Precip
120 Hr FCST valid for 00Z07SEP (Initial Condition=00Z02SEP2012)

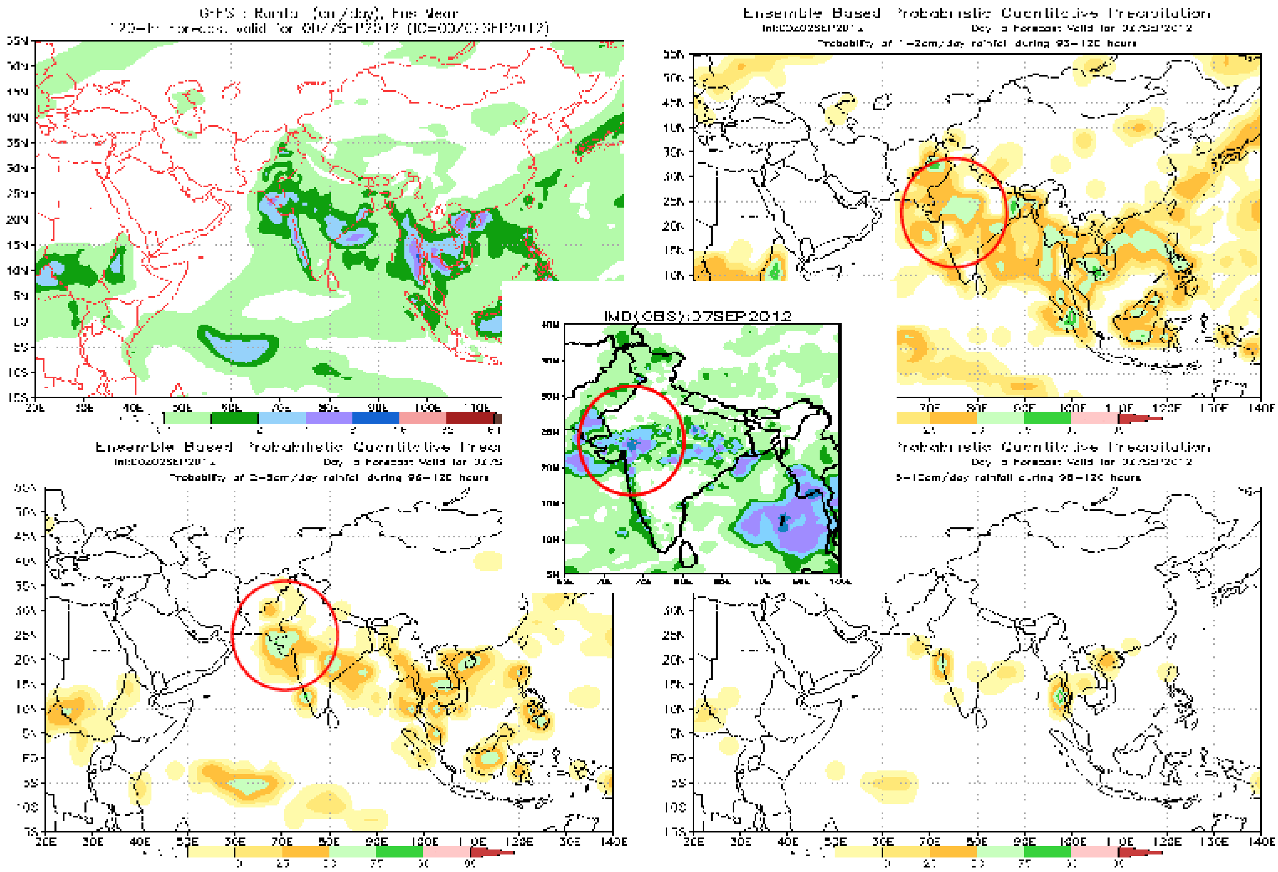

Figure 15: The heavy rainfall associated with the low pressure system on 7 September 2012 in the observations (inset) and the GEFS day-5 forecasts. Panels show prediction of high probability of 1-2 cm over MP and parts of adjoining states (top right) and 2-5cm over Gujarat (bottom left).

6. Summary

The Global Ensemble Forecast System (GEFS) implemented at NCMRWF is an upgrade to the earlier ensemble forecast system based on coarse resolution T80L18 model discussed in Kar et al. (2011). The new system was used for real-time forecasting during the monsoon season (June-September) of 2012. Besides improved forecasts, the GEFS system also provided probabilistic outlook on rainfall quantities. The results can be summarized as follows:

- The RMSE and AC averaged over the globe suggest that GEFS has comparable skill with the T574 in the short range and significantly higher skill at longer lead times. Over tropics and the RSMC region, GEFS has lower skill than the T574 in short range and higher skill at longer lead times.
- Besides the forecast of the rainfall amounts, the probabilities of the rainfall in the 1-2 cm, 2-5 cm and 5-10 cm range is provided by the GEFS model. PQPF gives the forecaster confidence he/she can attach to a forecast, thus helping the forecaster in making a better forecast. In case of heavy rain events, if the forecasts also show high probability, it would provide additional reliability to forecast which in turn would aid the forecaster to issue a heavy rainfall warning with better confidence.
- For forecasting the tropical cyclones, GEFS provides an ensemble of tracks based on which mean track and strike probabilities can be estimated. As demonstrated in case of cyclone Nilam, GEFS shows significant reduction in the forecast track error compared to the T574.
- With a reduction of track error by 75 km in 48-hour and by over 150 km in the 72-hour forecasts GEFS demonstrates huge potential for tropical cyclone forecast applications.
- The discrepancies between the RMSE of ensemble mean and ensemble spread (-which is a good measure of the statistical reliability) show a consistent mismatch for the Indian Monsoon region. The growth in the RMSE and in the spread is low and the difference between the two shows no change with the forecast lead time. This clearly shows statistical consistency over Indian Monsoon region is unchanged with increasing forecast lead time.

7. Concluding Remarks

Ensemble forecasting has large number of applications in various sectors. Flood forecasting using hydrological models has shifted from deterministic models to ensemble models in recent years. Ensemble predictions are being used to model the propagation of uncertainty through complex, coupled meteorological, hydrological and coastal models, with the goal of better characterizing flood risk. Cloke and Pappenberger (2009) provide a detailed review of the application of the ensemble forecast products in flood forecasting and address some of the key questions and possible value additions to ensemble forecasts for flood forecasting applications. Dance and Zou (2010) discuss the issues important in designing and evaluating ensemble predictions, and make recommendations for the guidance of future research. Short range ensemble forecasts can be useful in forecasting hazardous weather involving convection. Ensemble based storm surge forecasting involves running storm surge prediction model using each of the ensemble member, and thereby estimating the risk of damaging events given the forecast uncertainties which are sampled by the ensemble (Flowerdew et al., 2010). In situations when the ensemble develops rather little spread, it suggests a fairly predictable situation and a high degree of confidence in the forecast. On some occasions when the spread is much larger, it a greater degree of uncertainty in the predicted risk of storm surge.

Ensemble-based data assimilation techniques have shown promise of dramatic improvements over techniques such as 3- or 4-dimensional variational assimilation. Hamill (2004) introduced the method of data assimilation involving ensemble forecasts. Ensemble based assimilation techniques utilize an ensemble of parallel data assimilation and forecast cycles. The background-error covariances are estimated using the forecast ensemble and are used to produce an ensemble of analyses. The dramatic improvements in the forecast skill was attributed to the flow dependent background-error covariances which provide a different adjustment to the observations compared to methods such as 3- dimensional variational assimilation (Whitaker et al., 2008)

More recently hybrid techniques that use both ensemble and variational approaches have been developed (Wang et al., 2008; Demirtas et al., 2009). The premise is that the 4D-Var provides flow-dependent covariances via the linear (perturbation forecast) model. However it is still limited by climatological background error covariance. Although the ensemble approach brings in the flow-dependent perturbations in the data assimilation it is likely to suffer from significant sampling error (Whitaker and Hamill, 2012). Recent studies indicate benefit of ‘hybrid’ approach particularly for forecasting of high impact events. At NCMRWF efforts are already underway to implement the hybrid approach (using ensemble and 3D-Var) in data assimilation in the deterministic global forecast system.

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