NMRF/VR/MAY/2021

सत्यमेव जयते

VERIFICATION REPORT

NCUM Global Model Verification: Winter (DJF) 2020-21

K. Niranjan Kumar , S. Karunasagar, Mohana S. Thota, Harvir Singh, Sushant Kumar, Anumeha Dube and Raghavendra Ashrit

May 2021

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

Data Control Sheet

1	Name of the Institute	National Center for Medium range weather Forecasting
2	Document Number	NMRF/VR/MAY/2021
3	Date of Publication	May 2021
4	Title of the document	NCUM Global Model Monthly Verification: Post-monsoon 2020
5	Type of the document	Verification Report
6	Number of pages, figures and Tables	38 pages, 35 figures, 2 Tables
7	Authors	K. Niranjan Kumar , S. Karunasagar, Mohana S. Thota, Harvir Singh, Sushant Kumar, Anumeha Dube and Raghavendra Ashrit
8	Originating Unit	National Centre for Medium Range Weather Forecasting (NCMRWF), A-50, Sector-62, NOIDA201 309, India
9	Abstract	This report documents performance of the NCMRWF model forecasts during winter season (DJF) 2020. The verification results are presented to address (a) forecasters and (b) model developers. The information on biases in the forecast winds, temperature humidity, rainfall, etc., are crucial for the forecasters to interpret the model guidance for forecasting..
10	References	
11	Security classification	Unrestricted
12	Distribution	General

Table of Contents

S.No		P.No.
1	**Introduction**	4
2	**Unified Modelling System & Observed Data**	4
	2.1 Model Description	4
	2.2 Observed Data	5
3	**NCUM-G Analysis Mean and Anomalies during DJF 2020**	5
	3.1. winds at 850, 700, 500 and 200 hPa levels	5
	3.2. Temperature at 850, 700, 500 and 200 hPa levels	7
	3.3 RH at 850 and 700 hPa levels	9
4	**Systematic Errors in NCUM-G Forecasts**	10
	4.1 Winds at 850, 700, 500, and 200 hPa levels	10
	4.2Temperatures& Relative Humidity	13
	4.3 surface (10m) winds	17
	4.4 Temperature at 2m	17
	4.5Total precipitable water (PWAT)	18
5	**Rainfall Forecast Verification**	20
	5.1 Mean and Mean Error	21
	5.2 Categorical Verification of Rainfall forecasts	21
	5.3 Categorical verification of TminForecasts	21
6	**Significant Weather during DJF 2020-21**	23
	6.1 CS' Burevi' 30Nov-05Dec2020	23
	6.1.1 Forecast Tracks and Strike Probability	23
	6.1.2Forecast Track Errors	23
	6.1.3 Intensity Forecast (Min SLP and Max Wind)	27
	6.1.4 Verification of Strike Probability	28
	6.1.5CRA Verification of Rainfall forecasts	29
	6.2Cold Wave & Western Disturbance	30
	6.2.1 Verification of Tmin & Western disturbance 31Dec 2020 and 29 jan 2021	30
	6.2.2 Observed and forecast daily Tmin time series 22-23Dec 2020 and 22-23Jan2021	30
7	**Summary and Conclusions**	36
8	**References**	38

1. Introduction

This report documents performance of the NCMRWF model forecasts during winter season (DJF) 2020-21. Forecast verification is carried out against the model analysis and observations. The results are summarized for the season as a whole to understand the average biases and forecast performances. The report is oriented towards both (a) forecasters and (b) model developers. Section 3 to 5 of the report discusses the systematic biases in forecast large scale upper fields, namely, wind, temperature humidity, and rainfall, etc., which are expected to be useful for the forecasters to interpret the model forecasts. Section 2 describes the NCUM-G model description and data assimilation system at NCMRWF. Observational data sets used in this study are also briefly discussed. Section 6 touches upon verification for significant weather events of DJF 2020-21. This includes, verification for Bay of Bengal CS 'Burevi' during 30Nov-5Dec2020 which made landfall over Tamil Nadu coast on 5th Dec 2020.

2. NCMRWF Unified Modelling System& Observed Data

2.1 Model Description

The NCMRWF Unified model (NCUM) was implemented in 2012 with a grid resolution of 25km (NCUM-G:V1) which was upgraded to 17km (NCUM-G:V3) in 2015, 12km (NCUM-G:V5) in 2018.The present version (NCUM-G:V6) of NCUM-G has a horizontal grid resolution of ~12 km with 70 levels in the vertical reaching 80 km height. It uses "ENDGame" dynamical core, which provides improved accuracy of the solution of primitive model equations and reduced damping. This helps in producing finer details in the simulations of synoptic features such as cyclones, fronts, troughs, and jet stream winds. ENDGame also increases variability in the tropics, which leads to an improved representation of tropical cyclones and other tropical phenomena (Walters et al., 2017). An advanced data assimilation method of Hybrid 4-Dimensional Variational (4D-Var) is used for the creation of NCUM global analysis. The advantage of the Hybrid 4D-Var is that it uses a blended background error, a blend of "climatological" background error, and day-to-day varying flow dependent background error (derived from the 22–member ensemble forecasts). The hybrid approach is scientifically attractive because it elegantly combines the benefits of ensemble data assimilation (flow-dependent co-variances) with the known benefits of 4D-Var within a single data assimilation system (Barker, 2011). A brief description of the NCUM Hybrid 4D-Var system is given in Kumar et al. (2020 & 2018).

2.2 Observed Data

The seasonal mean analysis and anomalies are studied using the ERA-5 Hershbach et al., (2020) climatology (1979-2018). The high resolution (12km) NCUM-G analysis data is interpolated to ERA-5 grid resolution (0.25

x0.25). For verification of the forecasts, the NCUM-G model analysis is used. All systematic errors are computed at a native grid resolution of (12km).

Detailed quantitative rainfall forecast verification is based on the IMD-NCMRWF daily high resolution (0.25°) rainfall analysis (Mitra et al. 2009, 2013). The rainfall analysis objectively analyses India Meteorological Department (IMD) daily rain gauge observations onto a 0.25° grid using a successive corrections technique with the GPM Satellite rainfall providing the first guess estimates. The model forecasts are gridded to the 0.25° observed rainfall grids over Indian land regions for 92 days from 1st December 2020 to 28th February 2021. As noted by Mitra et al. (2009), the merged analysis at 0.25° is appropriate for capturing the large-scale rain features associated with the monsoon. The merging of the IMD gauge data into GPM estimates not only corrects the mean biases in the satellite estimates but also improves the large-scale spatial patterns in the satellite field, which is affected by temporal sampling errors (Mitra et al. 2009). Verification of daily Temperature forecasts (Tmin) is carried out against the IMDs daily observed gridded (0.5 x 0.5) Tmax and Tmin data (Srivastava et al 2009).

3. NCUM-G Analysis Mean and Anomalies during DJF 2020-21

3.1 winds at 850, 700, 500 and 200 hPa level:

The NCUM-G mean analysis fields and anomalies relative to climatology are assessed in this section during DJF 2020-21. The discussion is presented for Winds, Temperature, and Relative Humidity for four standard levels of 850, 700, 500, and 200 hPa levels. The anomalies are computed against the ERA5 climatology (1979-2018). The mean winds and anomalies at 850 and 700hPa levels from NCUM-G analysis are shown in Figure 1a-d. At 850 hPa and 700hPa, the NCUM-G model seasonal mean analysis represents northeasterly to easterly winds with increasing altitude having strength ranging from 4 to 8 m/s in addition presence of anticyclone over central India. The westerly wind strength is increasing with altitude having magnitudes which is about 8m/s -12 m/s at 700hPa. This windflow brings in moisture from the Arabian Sea during winter which provides suitable moisture incursion for increased precipitation in association withWestern Disturbances (WDs). In contrast to the westerlies in north, easterlies prevailin south India subsequently creating an anticyclonic circulation clearly visible in the central India in the NCUM-G model analysis. The anomalous conditions for the DJF 2020-21 winter period are estimated by removing the climatological ERA5 reanalysis from the NCUM-G seasonal meanwinds. The mean anomalous winds at 850hPa and 700hPa are shown in Figure 1c-d. The anomalies indicate contrasting features in north and south with weaker and stronger winds in NCUM-G analysis with respect to ERA5 reanalysis, respectively over the Indian subcontinent. On the other hand, over the equatorial Indian Ocean, specifically in southern latitudes, the winds are extremely higher with magnitudes of about 5-

10m/s in NCUM-G analysis. Overall, in the north India where the rainfall is higher in winter period, the magnitude of winds is relatively lower compared to ERA5 reanalysis due to persistent anomalous easterlies.

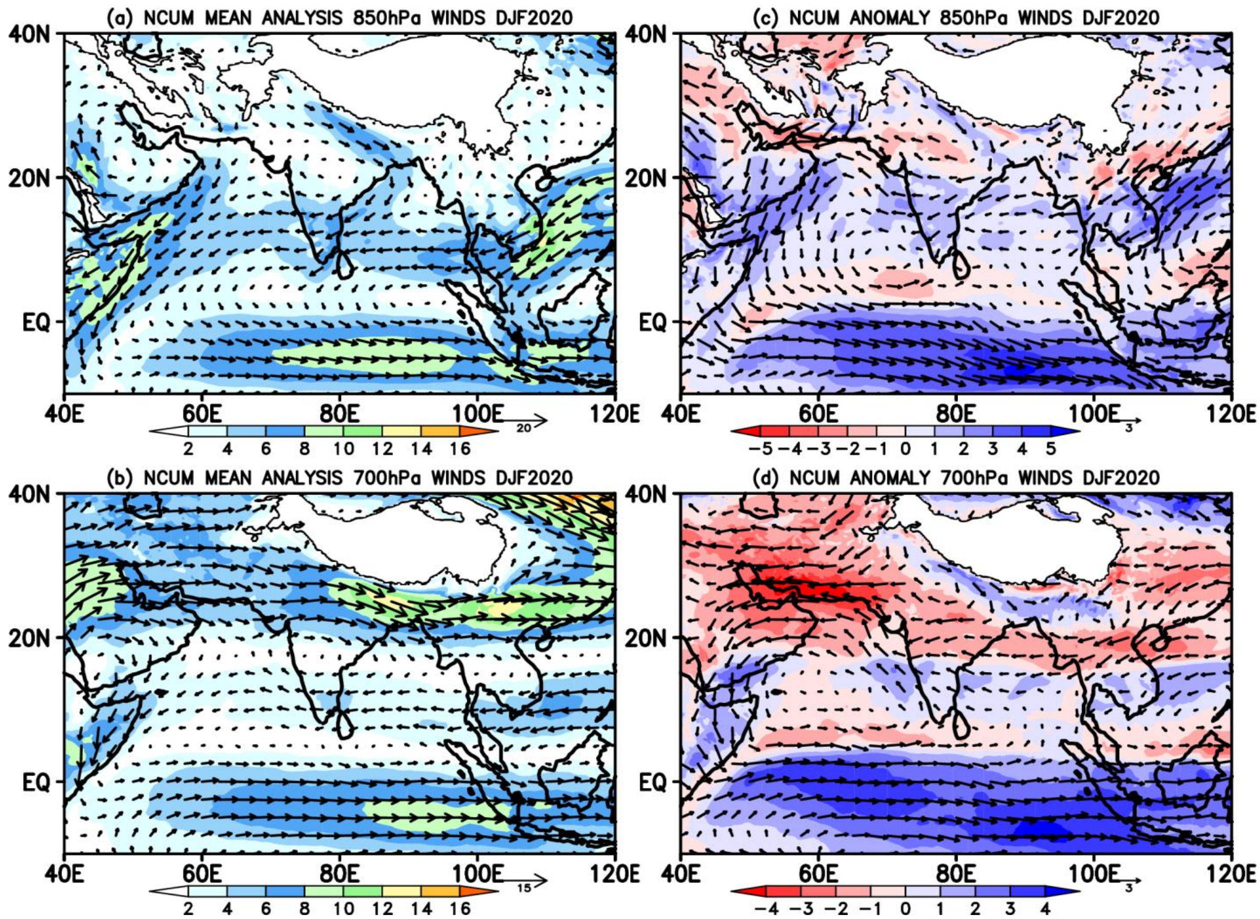


Figure 1. Mean winds at (a) 850 hPa and (b) 700 hPa in the NCUM Analysis during DJF 2020. Right panels show the anomaly circulation at (c) 850 hPa and (d) 700 hPa.

The mean winds from NCUM-G model analysis at 500hPa and 200hPa, representative of mid- and upper troposphere is shown in Figure 2a and 2b. As increasing the altitudes, the mean winds in the north Indian region getting more strengthened from ~16m/s at 500hPa to more than 40m/s in the upper troposphere. Hence, the NCUM-G model analysis could represent the upper-level subtropicalwesterly jet (STWJ) at 200 hPa. This is one ofthe important winter seasonal wind features whichbrings in enormous amount of precipitation in association with WDs as it provides necessary divergence for the intensification of the WDs. At the same time weak easterlies prevails in the south Indian region. The associated anomalous winds in the model analysis are shown in Figures 2c and 2d with respect to ERA5 reanalysis. In the mid- and upper troposphere, the winds are relatively lower compared to climatology in the north Indian while stronger in south Indian region. The anomalous easterliesare clearly discernible prevailing from the west Pacific to middle eastern region in the north India in the upper troposphere. In the equatorial regions, the upper tropospheric winds are quite strongwith magnitudes of more than 6m/s in winter 2020-21.

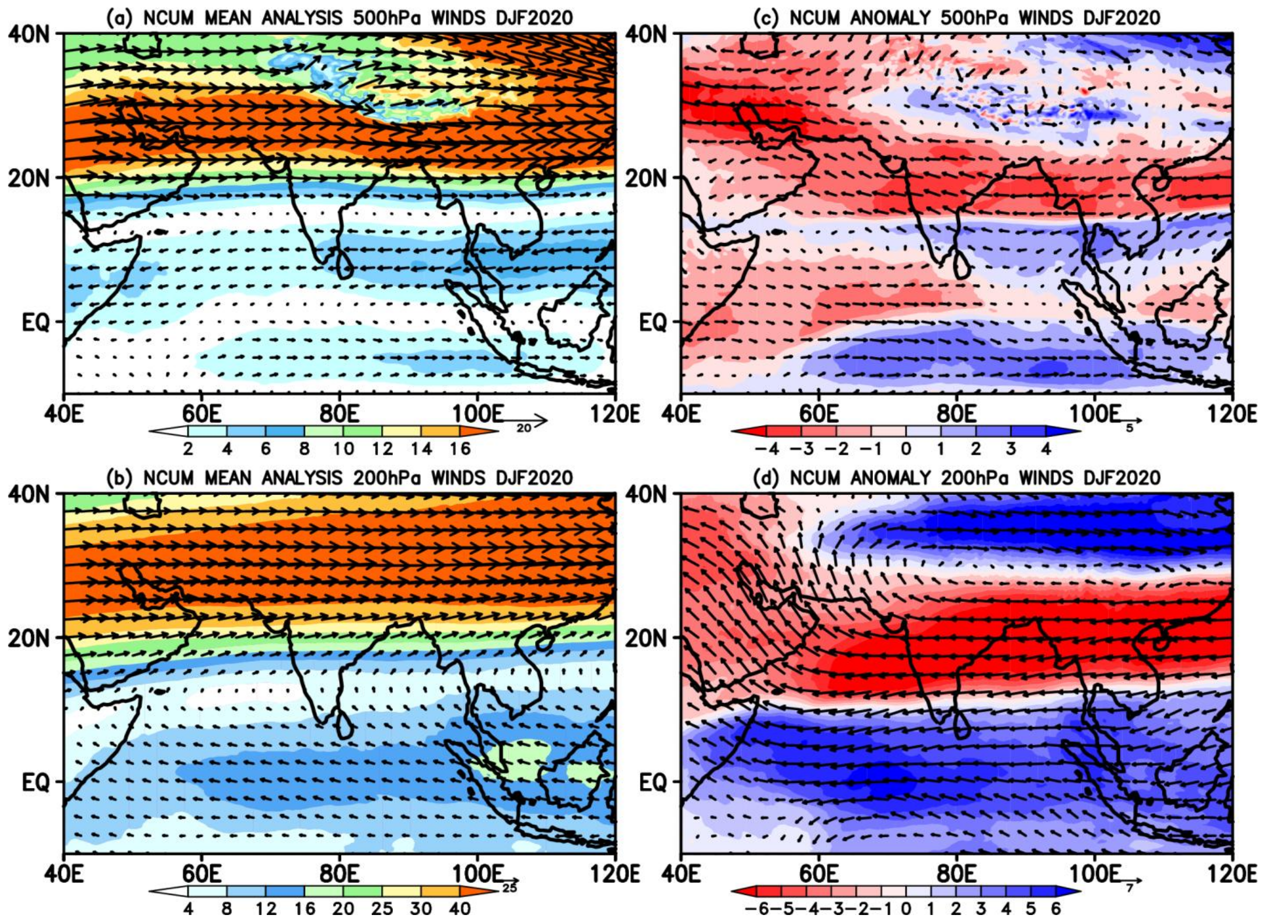


Figure 2. Mean winds at (a) 500 hPa and (b) 200 hPa in the NCUM Analysis during DJF 2020. Right panels show the anomaly circulation at (c) 500 hPa and (d) 200 hPa.

3.2 Temperature at 850, 700, 500 and 200 hPa:

The spatial distribution of seasonal mean temperature distribution in shown in Figure 3. Usually, the cold weatherseason sets in by mid-November in northernIndia. December and January are the coldestmonths in the northern plain. The mean daily temperature remains below 21°C over most parts of northern India (Figure 3a). The Peninsular region of India, however,does not have any well-defined cold weatherseason but the temperature usually rises as we move from north to south. The anomalous temperatures in the lower troposphere (850hPa and 700hPa, Figure 3c and 3d) indicates the winter 2020-21 is warmer than the climatology with magnitudes between 1-2K in north India. The warmer temperatures stretch from northwest to southeast India covering the Indo-Gangetic plains. With increasing pressure levels, the mean temperature distribution at 500hPa and 200hPa drastically decreases (Figure 4a and 4b). At 200hPa, the temperatures are nearly uniform throughout the country. Nevertheless, the temperature anomalies in the north India still indicate the warmer than the climatology.

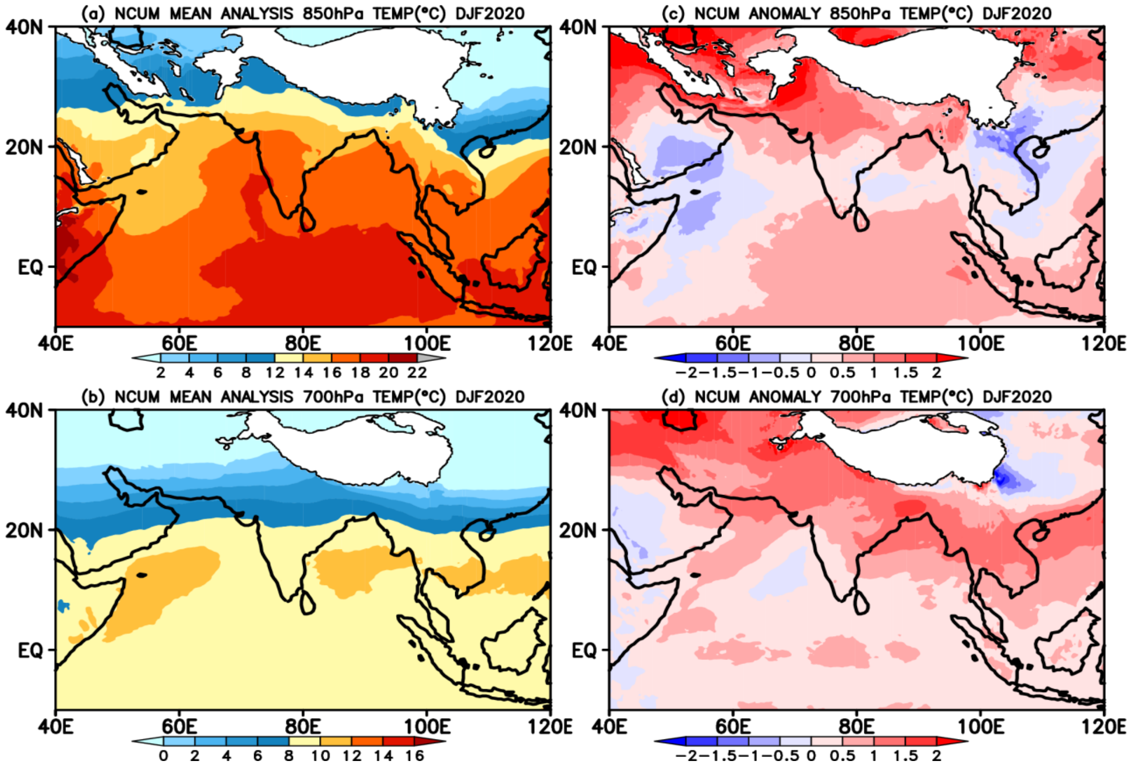


Figure 3. Mean Temperature at (a) 850 hPa and (b) 700 hPa in the NCUM Analysis during DJF 2020. Right panels show the Temperature anomaly at (c) 850 hPa and (d) 700 hPa.

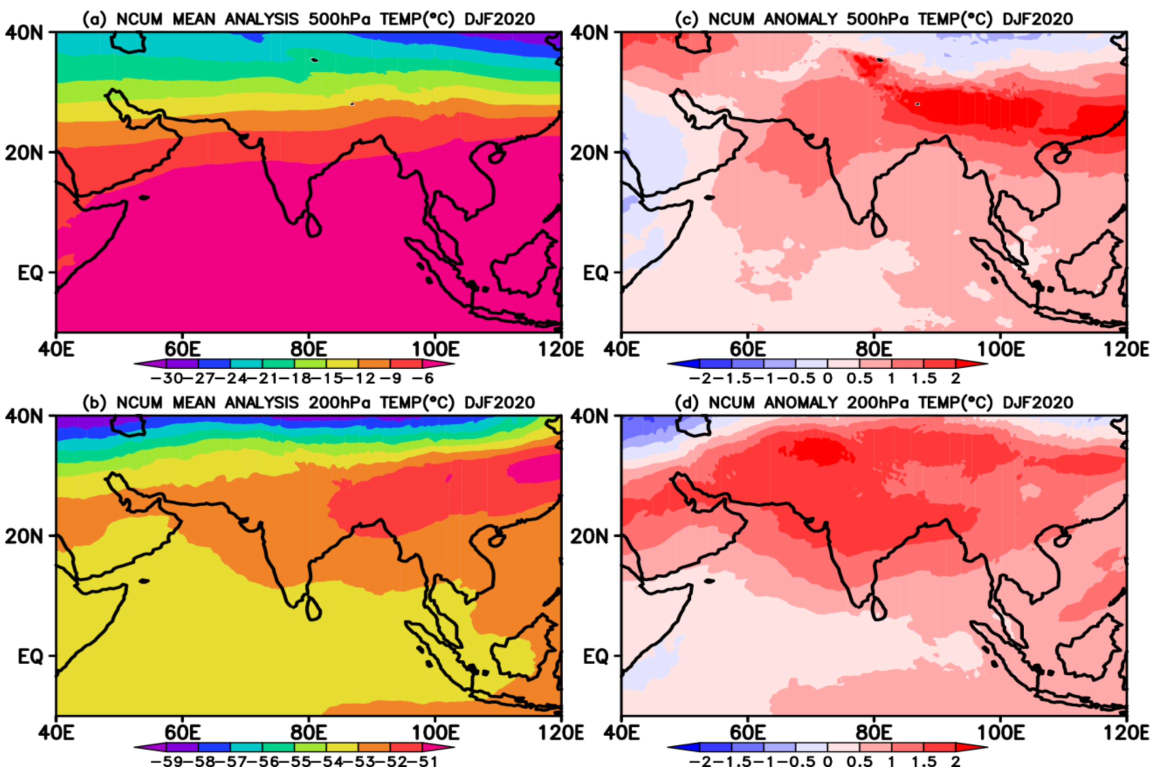


Figure 4. Mean Temperature at (a) 500 hPa and (b) 200 hPa in the NCUM Analysis during DJF 2020. Right panels show the Temperature anomaly at (c) 500 hPa and (d) 200 hPa

3.3 Relative Humidity (RH) at 850 and 700 hPa:

The distribution of humidity is an important field along with winds and temperature for controlling the rainfall. Hence, we further shown the spatial distribution of seasonal mean RH over from NCUM-G model analysis in Figure 5a (850hPa) and 5b(700hPa). Much of the northern part of India is quite dry due to cold dry air blowing from north in the winter from north. While the RH is higher in the south Indian region relative to north India. However, when we investigate the anomalies the DJF2020-21 indicates the higher percentage of RH compared to the climatology in the south India. While the north plains the lower seasonal mean humidity can be noted (Figure 5c and 5d). The Oceanic regions of Bay of Bengal and Arabian seas also shown positive anomalies in the humidity distribution for the winter period. At the same time, negative anomalies are noted in the equatorial regions.

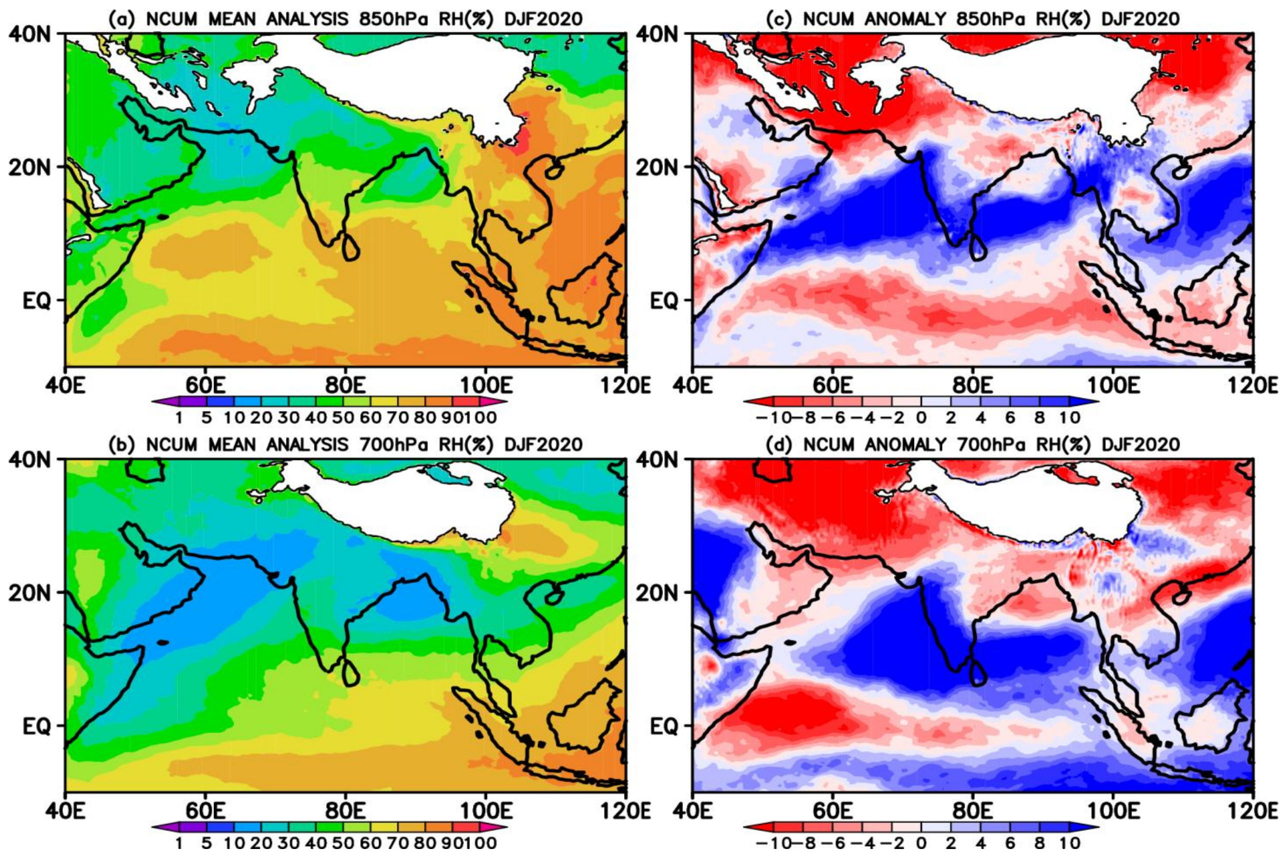


Figure 5. Mean Relative Humidity at (a) 850 hPa and (b) 700 hPa in the NCUM Analysis during DJF 2020. Right panels show the anomaly in Relative Humidity at (c) 850 hPa and (d) 700 hPa.

Further, we also showed in Figure 6, the spatial distribution of RH in the mid troposphere at 500hP level. The RH is almost completely dry in seasonal mean distribution over the Indian Subcontinent. Nevertheless, the occasionally the RH can be increased due to movement of synoptic scale disturbances in the north Indian during winter during which the RH will be increased significantly. On the other hand, in the oceanic regions, specifically in the maritime continent there is significant amount of the available moisture with RH magnitudes of more than 60% can be noticed. The anomalous RH distribution is shown Figure 6(right panel). The south Indian region shows some positive anomalies in RH with respect to climatology, but it may not be a significant as the mean RH itself is extremely low. However, negative RH anomalies can be noticed over the maritime continent where the mean distribution is generally higher.

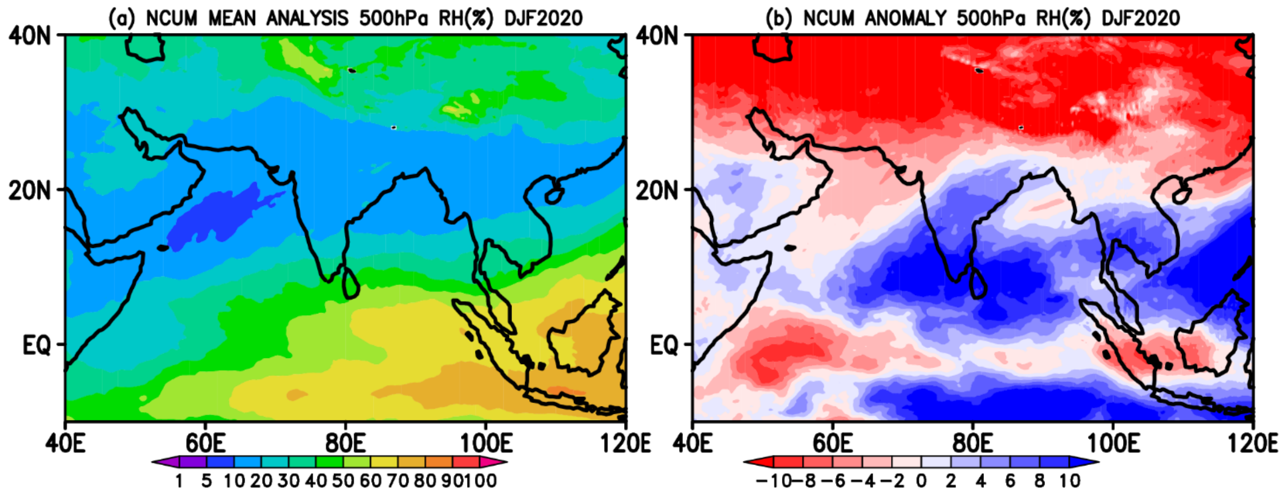


Figure 6: Mean Relative Humidity at (a) 500 hPa and in the NCUM Analysis during DJF 2020. Right panels show the anomaly in Relative Humidity at (c) 500hPa.

4. Systematic Errors in NCUM-G Forecasts:

In this section a brief description about systematic errors in the Day-1, Day-3, and Day-5 forecasts during DJF 2020-21. The forecast errors with respect to model analysis are presented for Winds, Temperature, for 850, 700, 500, and 200 hPa levels and Relative Humidity at 850 and 700 hPa levels (Figure 7-16).

4.1 Winds at 850,700, 500 and 200 hPa levels:

Mean winds at 850hPa level shows presence of low-level anticyclonic circulation over central Indian region with westerlies and easterlies on north and southern planks. Northeasterly winds are prominently seen over Bay of Bengal and AS regions. Maximum northeasterly winds are seen along the coastal regions of Somali and south china seas region. In addition, presence strong westerly winds south of the equator are also noted. Systematic errors in winds from Day-1 forecasts at this level shows an easterly wind bias over south Bay of Bengal. A westerly wind bias over south of the equator around 60E and easterly wind bias around the maritime continent (MC) is also noted. With forecast lead times these errors in low-level winds enhances and this could be due to the enhanced convective activity around the equatorial regions during winter season (Figure 7a-d). Similar systematic errors in winds are also noticed at 700 hPa level over Indian region. Interestingly Day-1 forecast errors are relatively small compared the Day-3 and Day-5 forecasts. In addition, Westerly wind bias is more prominent at 700 hPa level over central India in Day-3 and Day-5 forecasts.

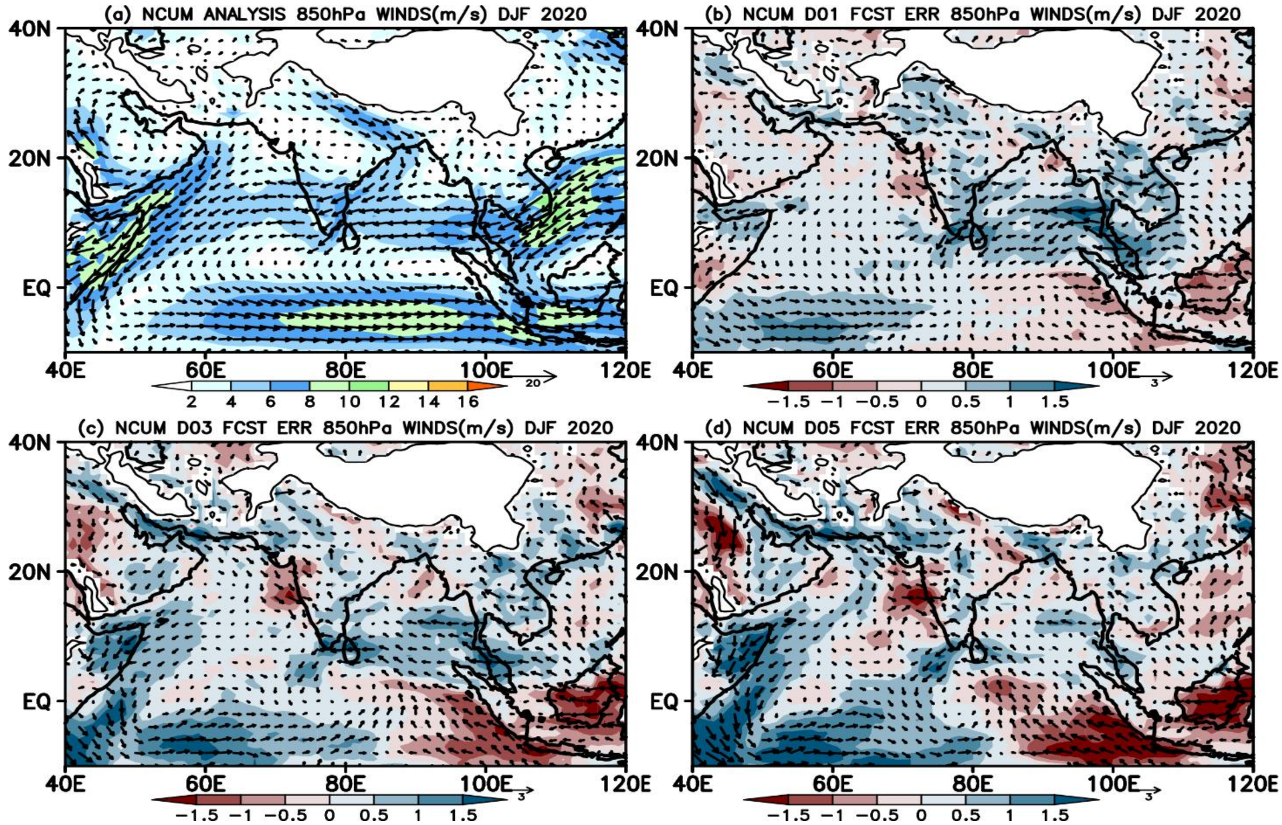


Figure 7. (a) Mean winds at 850 hPa and systematic errors in (b) Day-1 (c) Day-3 and (d) Day-5 forecasts during DJF 2020

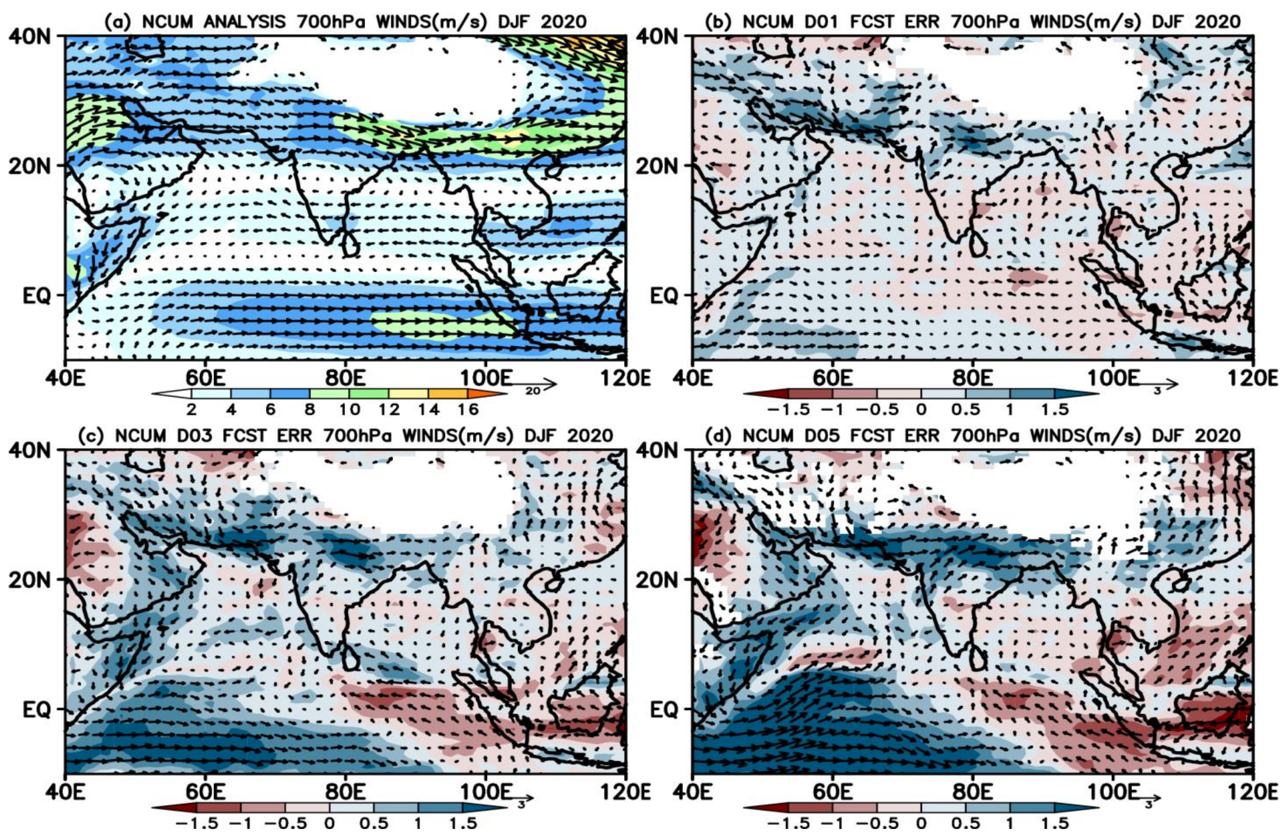


Figure 8. (a) Mean winds at 700 hPa and systematic errors in (b) Day-1 (c) Day-3 and (d) Day-5 forecasts during DJF 2020

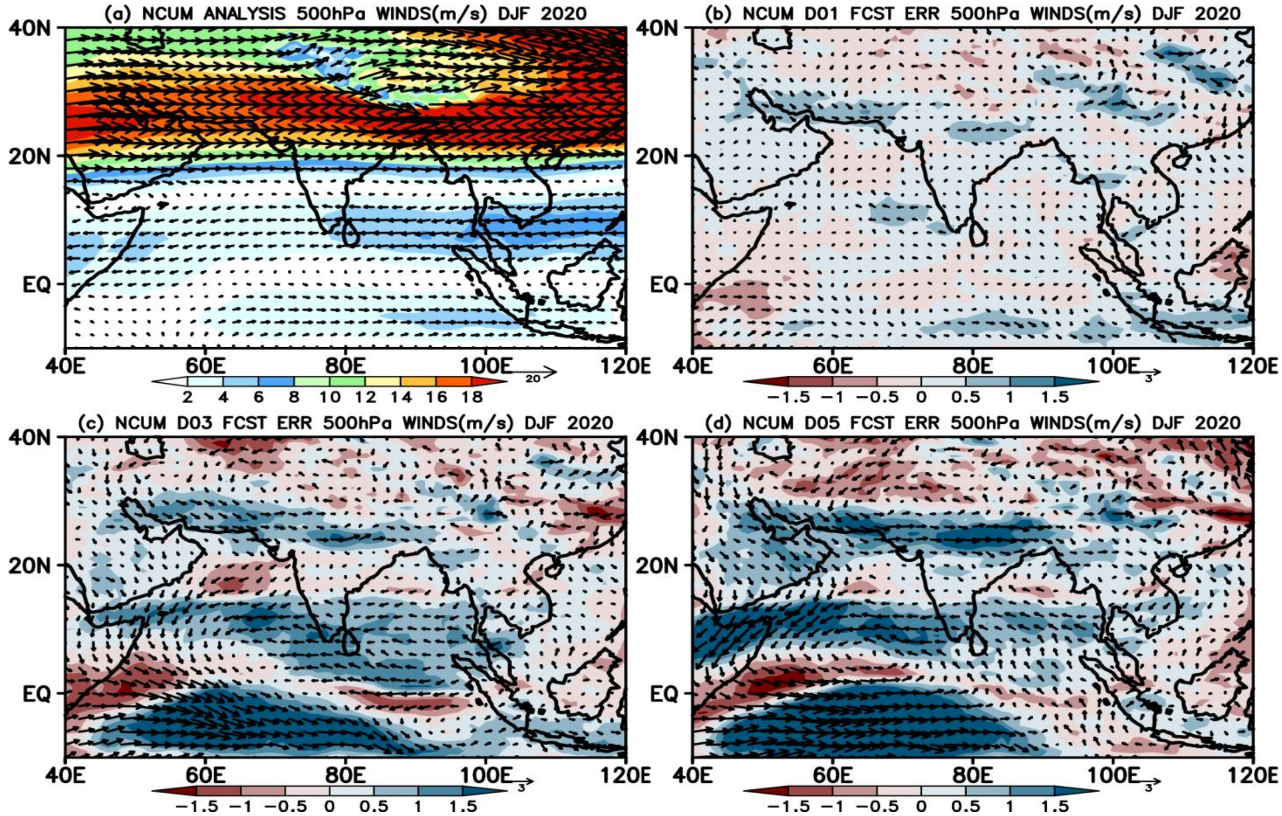


Figure 9. (a) Mean winds at 500 hPa and systematic errors in (b) Day-1 (c) Day-3 and (d) Day-5 forecasts during DJF 2020

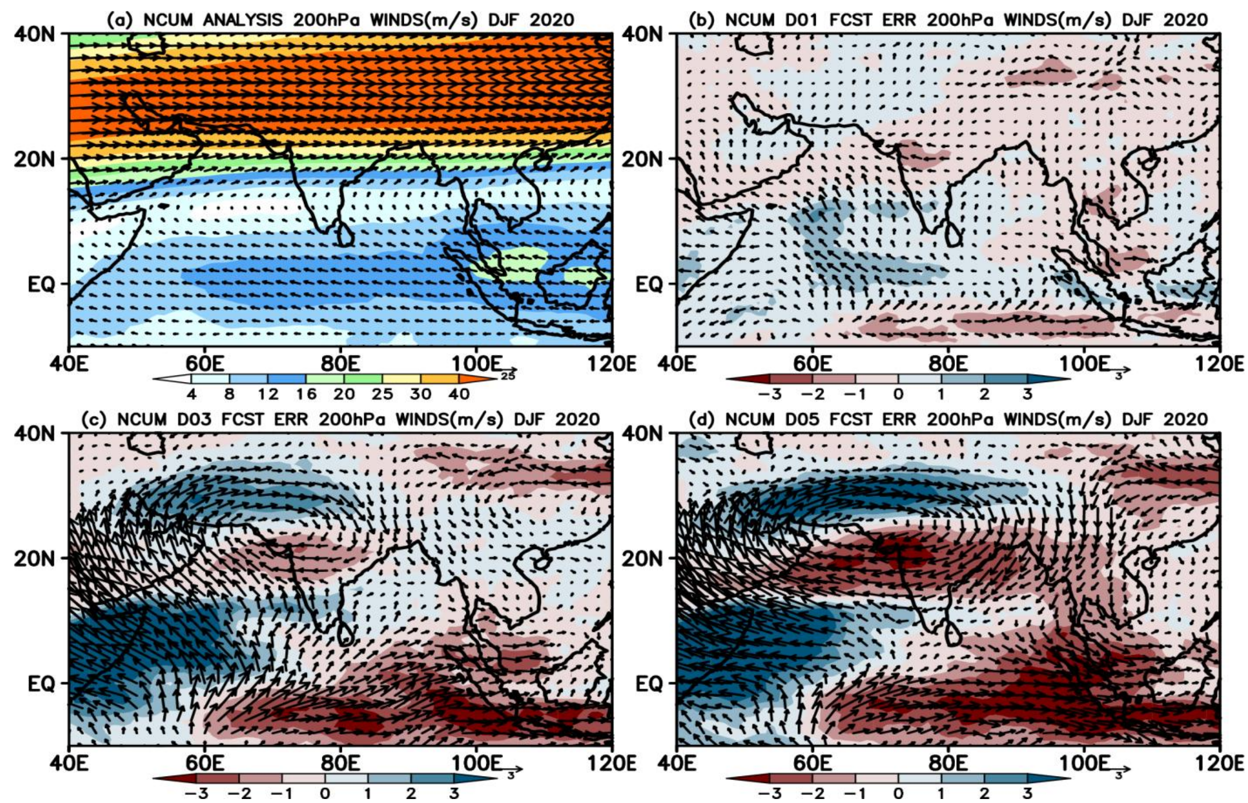


Figure 10. (a) Mean winds at 200 hPa and systematic errors in (b) Day-1 (c) Day-3 and (d) Day-5 forecasts during DJF 2020

Mean winds at 500 hPa level shows strong westerlies between 30-40N and these westerly winds penetrated over central Indian region. Errors in winds at 500hPa level are relatively small in Day-1 forecasts. The westerly wind bias seen over northern parts of India and easterly wind bias south Bay of Bengal and AS seems enhancing in Day-3 and Day-5 forecasts. The enhanced winds exhibit cyclonic circulation just above equator in Day-5 forecast around 500hPa level, which is noteworthy.Systematic errors at 200 hPa level winds show enhanced divergent circulation centered around north western parts of India is seen in Day-3 and similar spatial pattern in winds is also seen in Day-5 with enhanced error magnitudes (Figure 10 c-d)

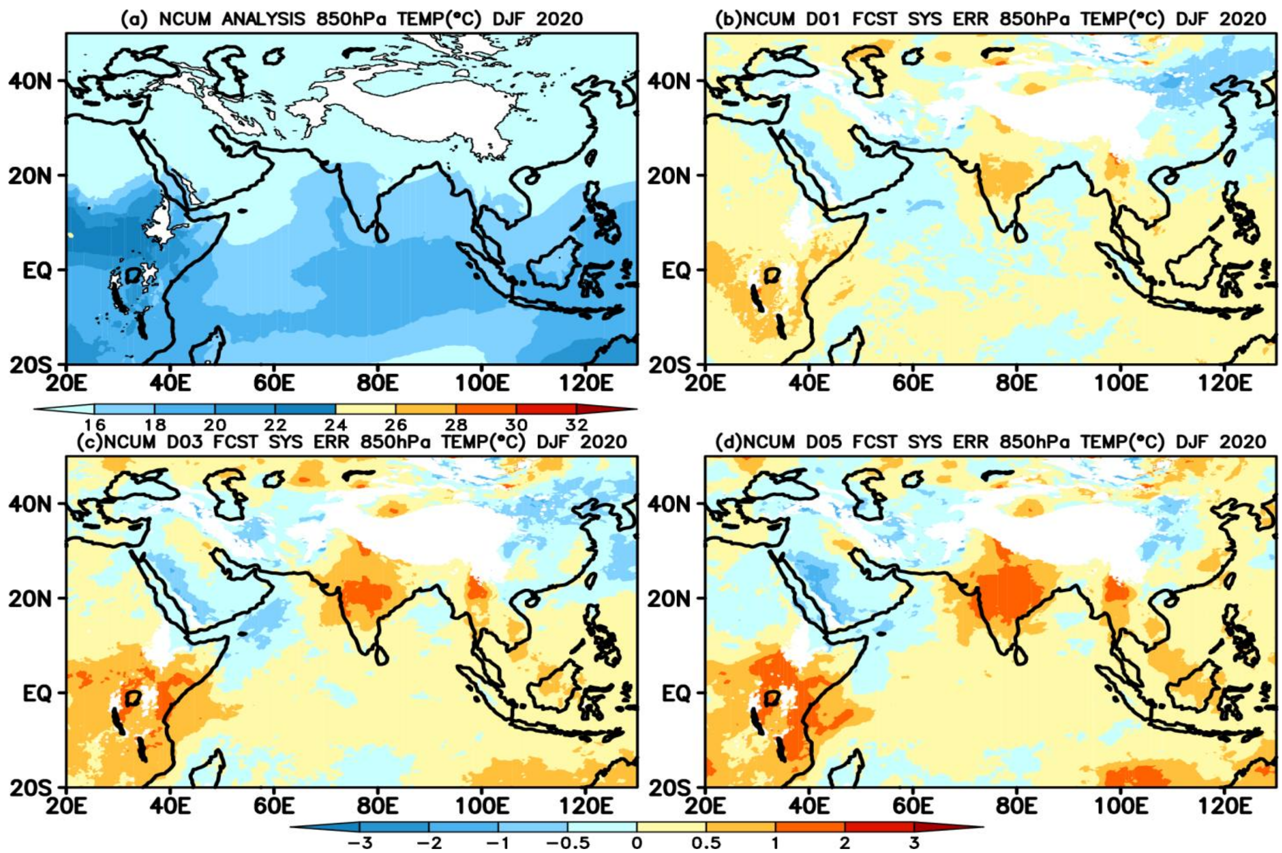


Figure 11. (a) Mean Temperature at 850 hPa and systematic errors in (b) Day-1 (c) Day-3 and (d) Day-5 forecasts during DJF 2020.

4.2 Temperature and Relative humidity:

Spatial map of seasonal mean temperature from NCUM analysis at 850hPa shows warm and cold temperatures over south and northern parts of India and surrounding oceanic regions respectively (Figure 11a). Model errors show warm bias (~1 C) occupied over most of the Indian land mass and the magnitude of this bias is increasing (Figure 11 c-d). These error incrementsat 850hPa temperatures are also more prominent over eastern African regions. On a similar note, temperature errors at 700 hPa also show warm bias (~0.5C) over most of the Indian land region. Interesting to see that the bias over AS region reverse sign and now exhibits warm bias compared to 850hPa level. This warm bias over AS is consistent in all the forecast times upto Day-5. BoB region also exhibits change in sign from Day-1 to Day-5.

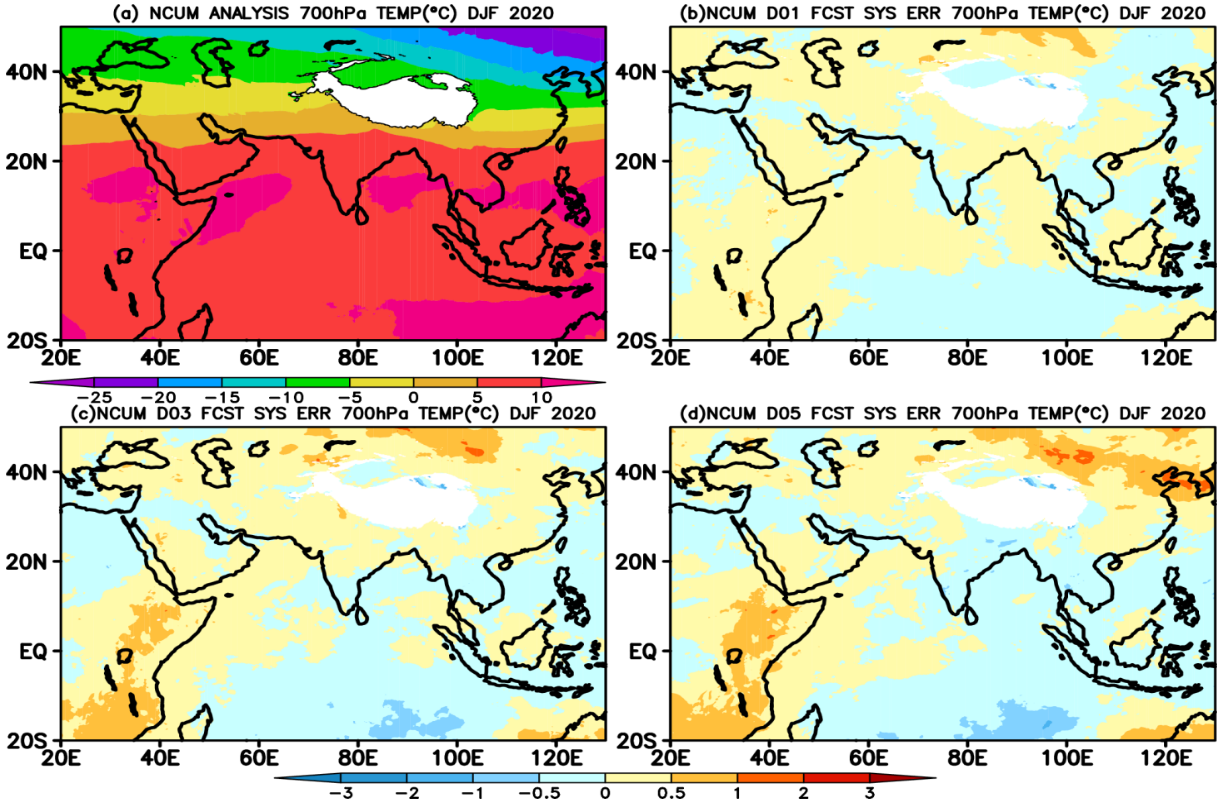


Figure 12. (a) Mean Temperature at 700 hPa and systematic errors in (b) Day-1(c) Day-3 and (d) Day-5 forecasts during DJF 2020

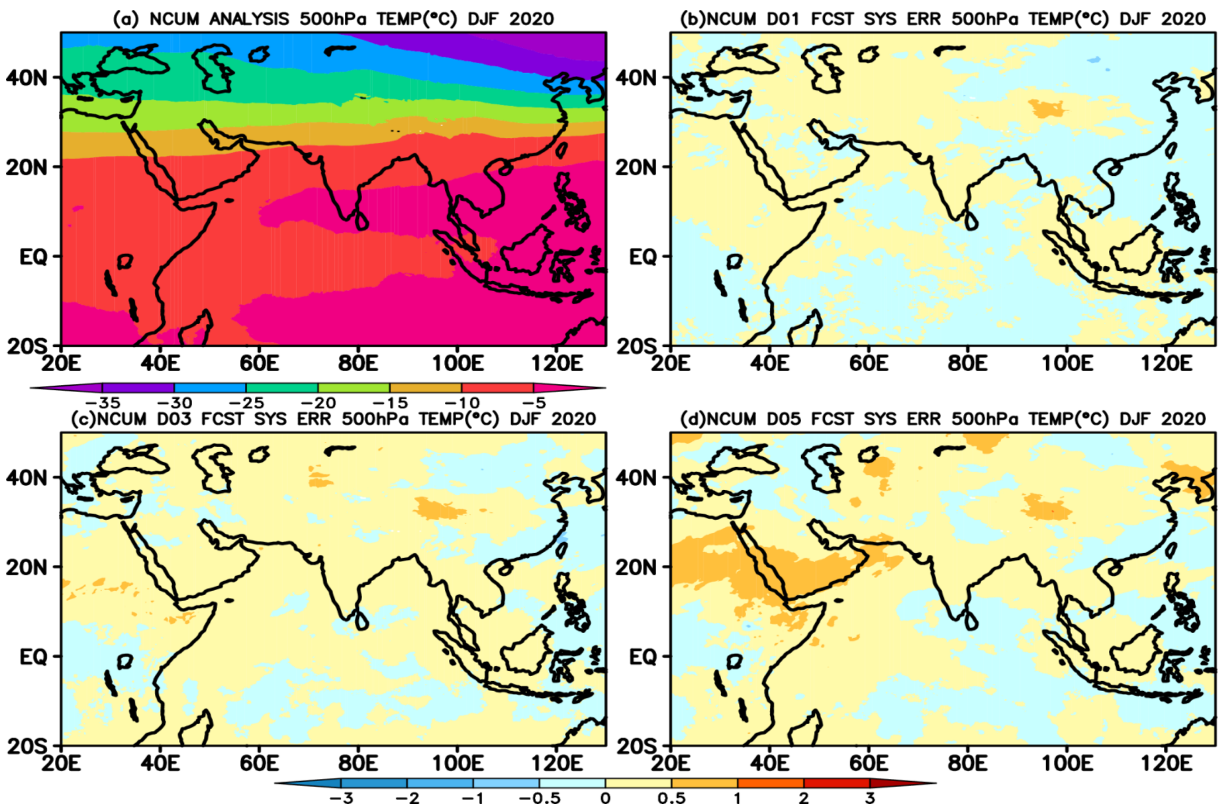


Figure 13. (a) Mean Temperature at 500 hPa and systematic errors in (b) Day-1 (c) Day-3 and (d) Day-5 forecasts during DJF 2020.

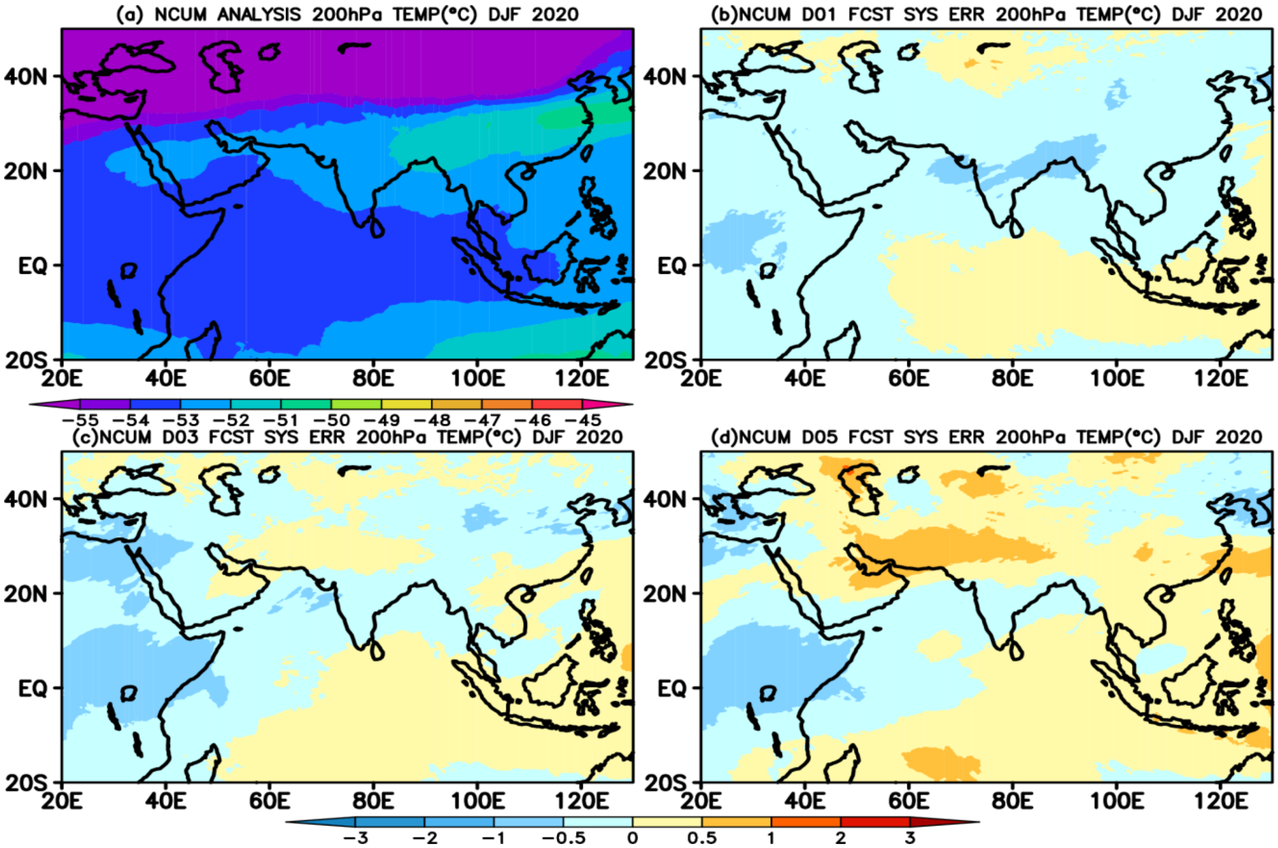


Figure 14. (a) Mean Temperature at 200 hPa and systematic errors in (b) Day-1 (c) Day-3 and (d) Day-5 forecasts during DJF 2020.

Systematic errors over 500 and 200 hPa level show warm and cold bias over Indian land region and surrounding oceanic regions respectively. The cold bias over central Indian region at 200 hPa level is perhaps due to the presence of anticyclonic circulation which brings cold air from midlatitudes at northward flank (Fig 10c-d).

Seasonal mean RH at 850 and 700 hPa levels show largevalues > 90% over equatorial regions and relatively less RH values over Northern parts of the Indian subcontinent. Maximum in RH values are concentrated over MC. Systematic errors show large dry bias over Indian land regions over 850hPa level and the dryness is enhancing with forecast times. (Figure 15c-d). Omni presence of strong north easterlies over open oceanic regions of AS and BoB and increased evaporation could be one primary reason for the positive RH values over these regions (Figure 15c-d). In contrary, most of the Indian subcontinent and surrounding oceanic regions are exhibits moist bias as evidenced by positive RH values, except Africa and west Arabian regions.

In next section a brief description of systematic errors present in the model forecasts are given for key surface variables of 2m Temperature; 10m winds and precipitable water vapor (PWAT). The errors are computed against the NCUM analysis

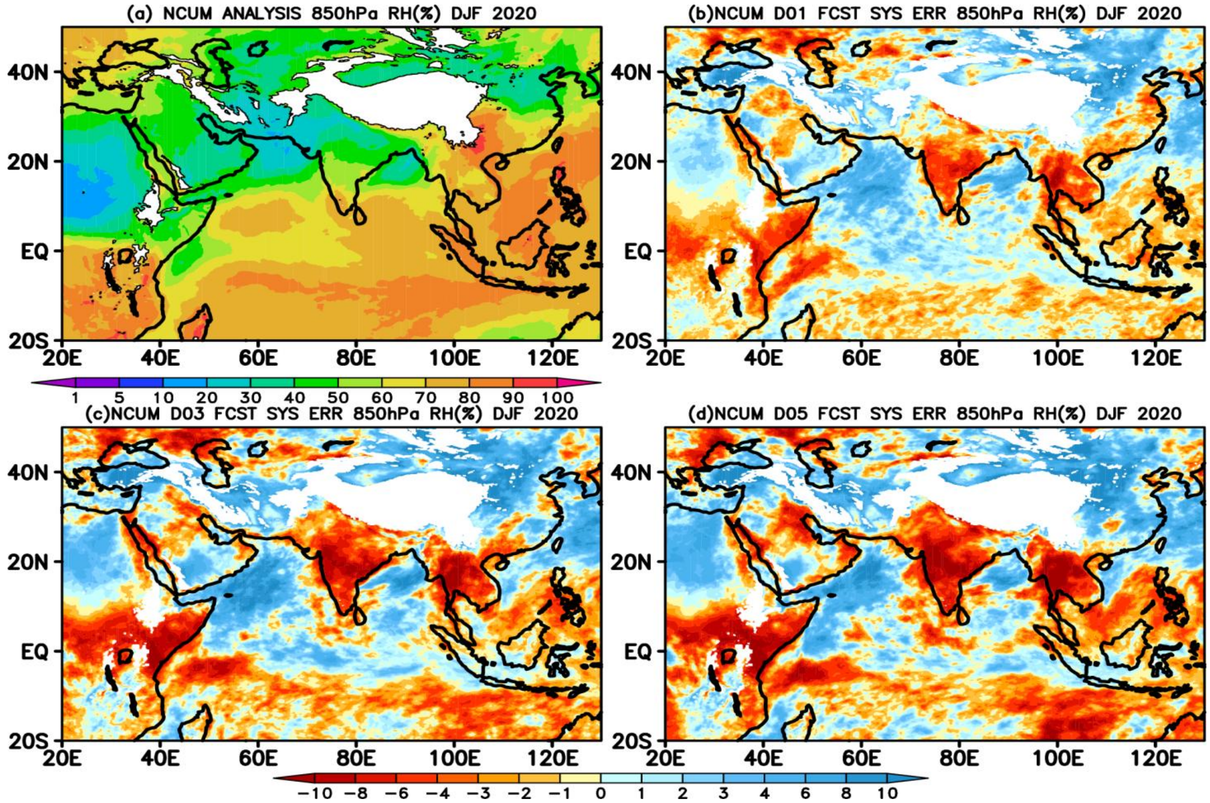


Figure 15. (a) Mean Relative Humidity at 850 hPa and systematic errors in (b) Day-1 (c) Day-3 and (d) Day-5 forecasts during DJF 2020

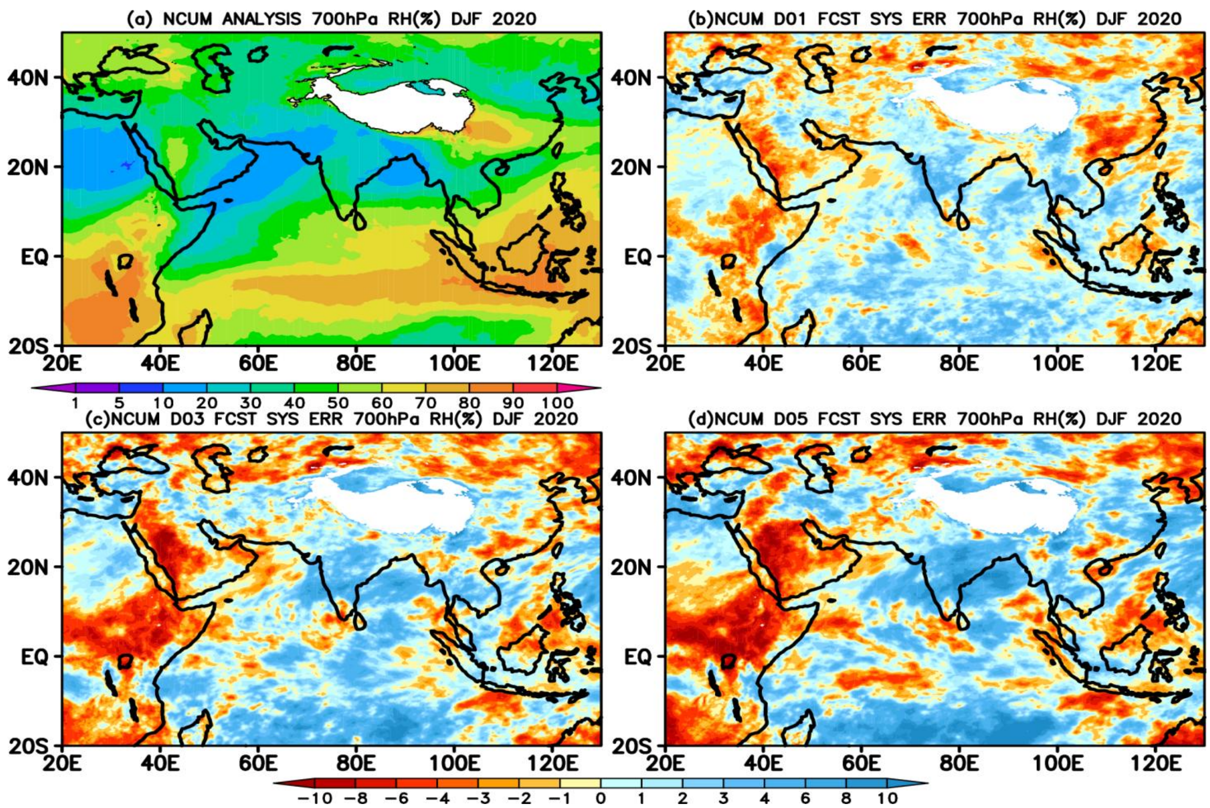


Figure 16. (a) Mean Relative Humidity at 700 hPa and systematic errors in (b) Day-1 (c) Day-3 and (d) Day-5 forecasts during DJF 2020

.4.3 surface (10m) winds:

Seasonal mean winds at 10m level from analysis show presence of strong North easterlies over Bay of Bengal (BoB) and Arabian sea (AS) with maximum winds around open AS; African coast and South China Sea. Reversal of these north easterlies to westerlies after crossing the equator is also noted in the analysis. The systematic errors in the forecasts (Figure 18 b-d) depicts few notable features; 1) The North easterlies which are noticed in Day-1 (Fig 18b) is changing its direction to southerlies with lead time and it is clearly seen Day-5 (Fig 18d). 2) The north westerly wind bias over northern AS in Day-1 is enhancing its strength with forecast lead time. 3) On a similar note, the easterly wind bias seen around equator and south of the equator are also getting intensified with forecast time.

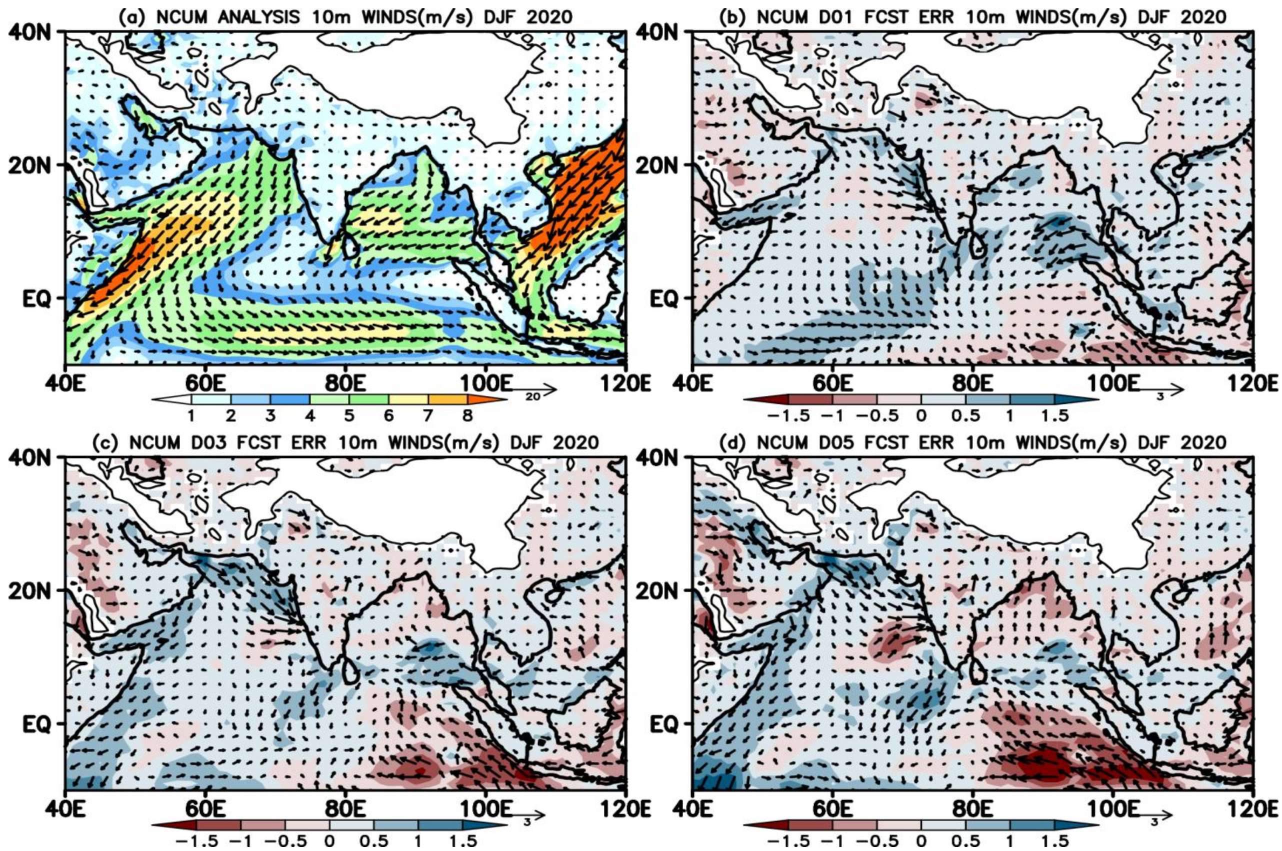


Figure 18. (a) Mean winds at 10m height and systematic errors in (b) Day-1 (c) Day-3 and (d) Day-5 forecasts during DJF 2020

4.4 Temperature at 2m:

Seasonal temperature pattern over Indian region show cold temperatures (12-15 ^{o}C) on the North and warm temperatures (>25 ^{o}C) towards south. Systematic errors show a relatively warm bias over Indian land regions and north of 40 ^{o}N latitude regions. Interestingly these warm biases are increasing with lead time especially over Indian region. This can be attributed to the dry north westerly winds from Northwest entering into Indian land

and North AS (Fig 18 c-d). In addition, most of the oceanic regions of BoB and AS exhibiting warm bias of the range 0-0.5 °C in all the forecast times. In addition, model temperature errors also exhibit a cold bias over west of the AS. It is noted that the magnitude of bias is increasing with forecast lead time, which is note worthy.

4.5 Total precipitable water (PWAT):

Seasonal mean PWAT shows a large value (> 60mm) around the equatorial regions, especially over Maritime continent owing to the presence of winter time MJO active conditions over these regions. In contrary most of the northern and central Indian regions are dry with very less PWAT values (5-15mm). However, over extreme South east peninsular India exhibits moderate PWAT values around 35-40 mm due to the effect of northeast monsoon conditions. Systematic error in PWAT shows a column dry over Indian land regions in Day-1, this dryness in column is enhancing forecast times and its magnitudes are maximum in Day-5 (Figure 20c-d). Large positive PWAT biases are seen over BoB; AS and over equatorial regions. This excess column water could be one reason for excess rainfall over these regions (Fig 18).

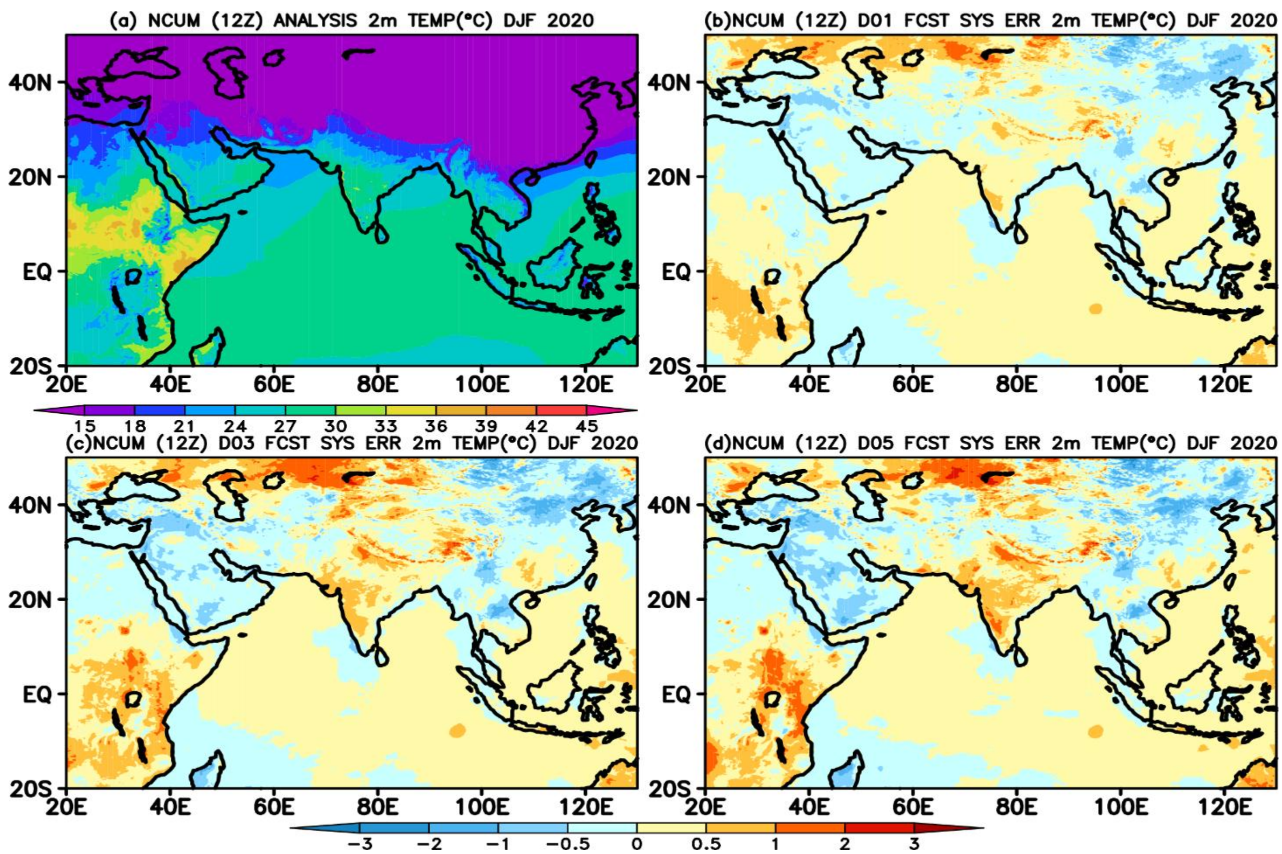


Figure 19. (a) Mean Temperature at 2mt height and systematic errors in (b) Day-1 (c) Day-3 and (d) Day-5 forecasts during DJF 2020

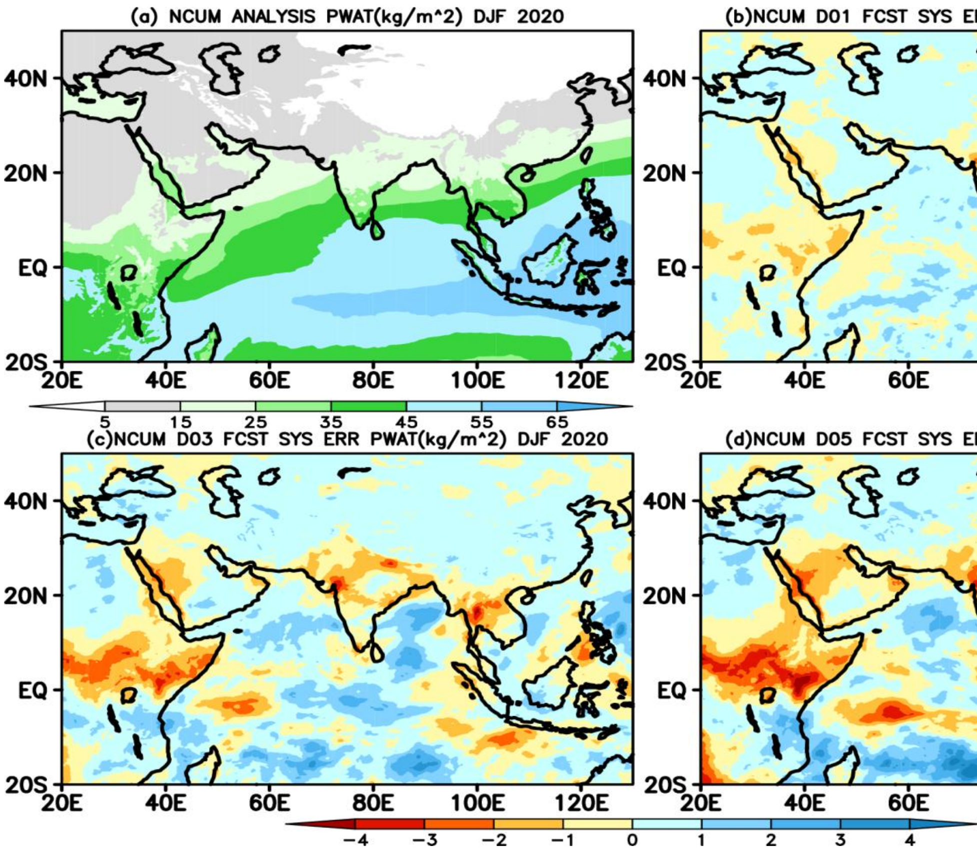


Figure 20. (a) Mean precipitable water content (PWAT) up to model levels and systematic errors in (b) Day-1 (c) Day-3 and (d) Day-5 forecasts during DJF 2020

5. Rainfall Forecast Verification

Verification of NCUM-G model rainfall forecasts is presented in this section for DJF 2020-21. The daily accumulated rainfall forecasts are verified against the NCMRWF-IMD merged Satellite and gauge rainfall product. The discussion presented in this section is confined to mean and mean error (ME) over India region. Further, this section also quantifies forecast skill using standard verification metrics, namely, POD, FAR, CSI which are described in standard text books (Wilks, 2011, Jolliffe and Stephenson, 2012) and SEDI, a metric for extreme and rare events (Stephenson et al 2008, Ashrit et al 2015b, Sharma et al 2021).

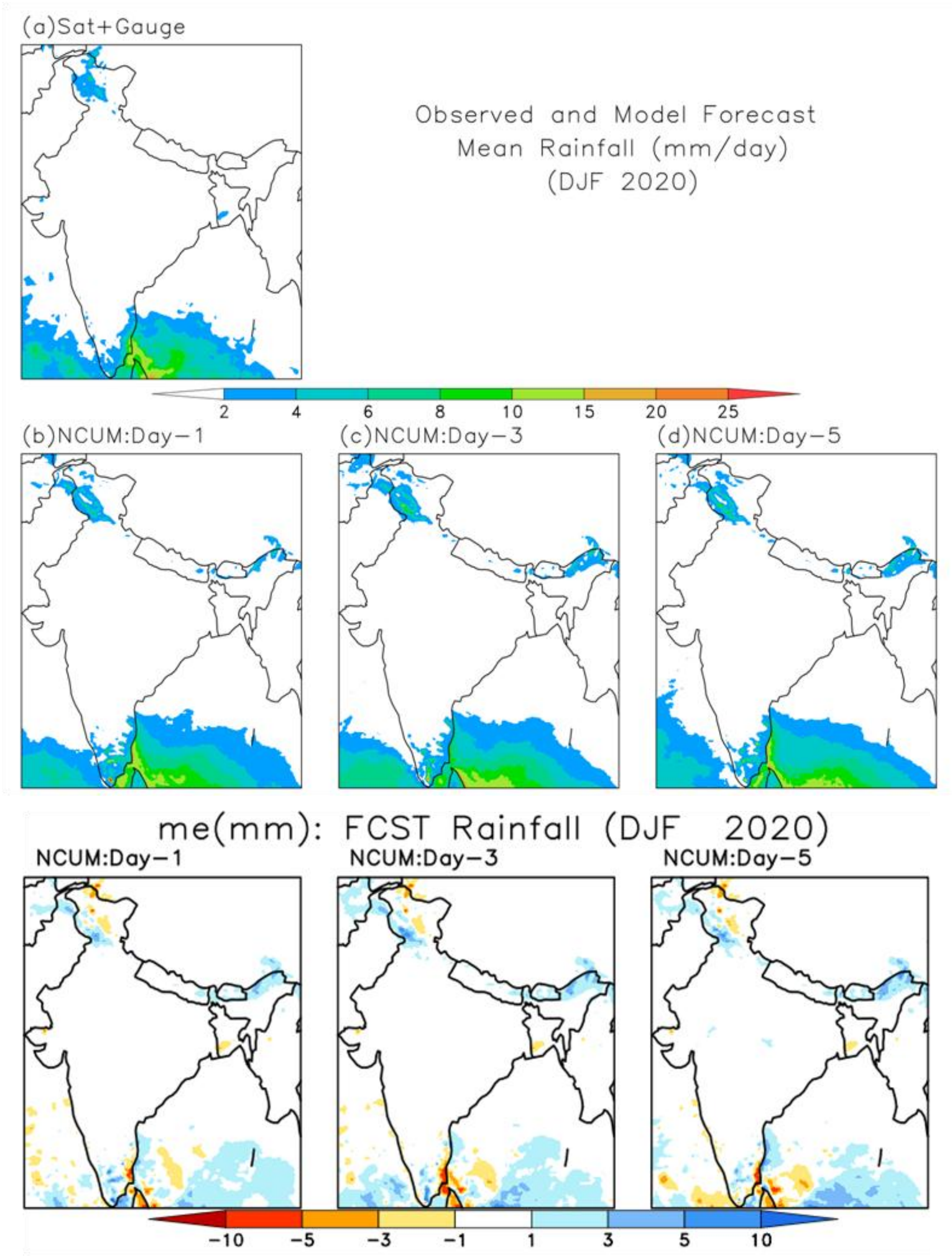


Figure 21. Accumulated DJF rainfall in (a) Observations and (b) Day-1 (c) Day-3 and (d) Day-5 forecasts. Bottom panels (e), (f) and (g) show Mean Error (ME) in Day-1, Day-3 and Day-5 forecasts respectively.

5.1 Mean and Mean Error

The observed and forecast mean rainfall during DJF 2020-21 is shown in Figure 21. Observations indicate the highest mean rainfall exceeding 12mm/day is seen over southern parts of peninsular India and equatorial oceanic regions. Another moderate rainfall (2-4 mm/day) region is seen over Jammu and Kashmir region where the effect of western disturbances is more prominent which brings significant amount of rain occur over these regions. The panels in the middle row, Figure 21 b-d show Day-1, Day-3, and Day-5 NCUMG forecast rainfall averaged during DJF period. The observed peak in rainfall amounts are well predicted in all the forecast times. However, it is found that the NCUM forecast overestimates rainfall amountsand spatial distribution over oceanic regions around equator and J & K region. Apart from this most of the Indian subcontinent is dry with no convection in both observations and forecasts. Now, to further quantification forecast mean errors (ME) are computed against the observations. The panels in the bottom row show rainfall mean error (ME) (Figure 21 e-g) in predicted rainfall indicating wet bias (blue) over southern parts of the oceanic regions consistent with the mean rainfall pattens (Figure 20 b-d). Small dry bias regions are noticed over Sri Lanka and some parts of Tamilnadu in the rainfall forecasts and the magnitude of dry bias is increases with lead time (Figure 21 e-g).

5.2 Categorical score of rainfall:

To further quantifying the model rainfall forecasts, all Indian categorical scores are computed. The categorical approach of verifying QPF is generally based on the 2 x 2 contingency table which is evaluated for each threshold. Verification scores are presented for rainfall of up to 30mm/day. For different rainfall thresholdsPOD and FAR show decrease and increase in scores respectively. The BIAS score (frequency bias) indicates that forecasts overestimate the frequency at various thresholds. The values of PSS, and SEDI all are high for rainfall up to 3-5 mm/day suggesting reasonable skill. PSS score shows a very sharp decrease as the threshold varies. Overall, the skill is not bias-free. For higher rainfall thresholds (> 10 mm/day), there is no frequency bias is almost constant, but the skill is low as indicated by CSI, PSS, and SEDI (Figure 22).

5.3Categorical scores for T_{min} at 2m

Similar analysis as discussed in above section 6.1 is repeated for minimum temperature thresholds. Interestingly the POD and PSS scores for Tmin thresholds remains nearly constant up to 20-22 C with values less than 0.4. However, the scores slightly increase at rainfall 22-24C in both POD and PSS (Figure 23). FAR scores over all India as whole shows relatively large values >0.6 up to temperature thresholds 18-20C, later a gradual decrease is noticed in all the forecast times (Figure 23).

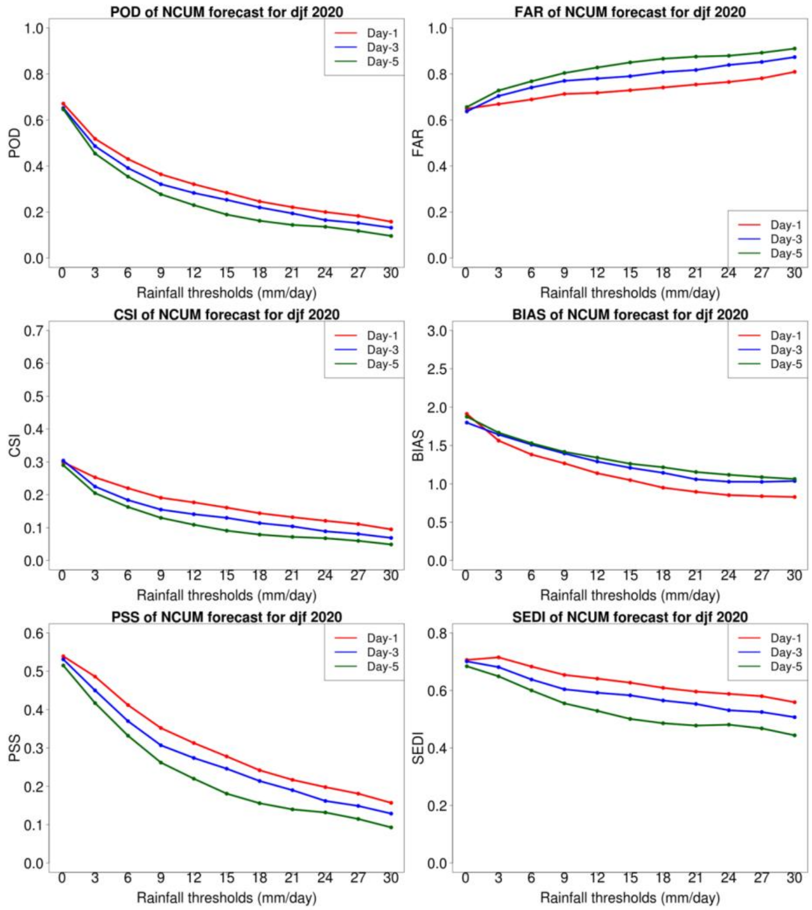


Figure 22. Categorical all India Rainfall scores POD (*top left*), FAR (*top right*), CSI(*middle left*), BIAS (*middle right*), PSS (*bottom left*) and SEDI (*bottom right*).

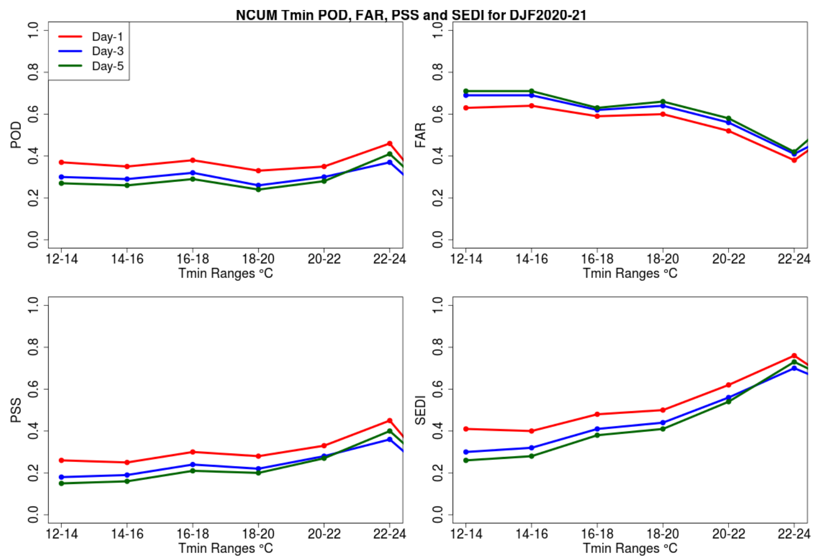


Figure 23. Categorical all India T_{min} scores POD (*top left*), FAR (*top right*), PSS (*bottom left*) and SEDI (*bottom right*).

6. Significant Weather:

6.1 CS "Burevi" 30Nov-05Dec2020

6.1.1 Forecast Tracks and Strike Probability

This section gives a brief summary report on the verification of the NCMRWF model forecasts for the recent CS 'BUREVI' that developed during 30Nov-05Dec2020 over Bay of Bengal (BoB). Verification of forecast tracks and intensity is presented for NCMRWF Unified Models; NCUM-G(12km grid resolution),NEPS-G mean (12km grid resolution) and NCUM-R (4km grid resolution) for both 00UTC and 12UTC runs. Forecast tracks and verification is presented for model predicted tracks against IMD best track data. Figure 24 shows the observed and predicted tracks based on 00UTC of 30 November 2020. The model predicted tracks indicate that the system would cross the coast remarkably close to the observed position (first over Sri Lanka and then India). The forecast track errors are discussed in the next section. The strike probability and member tracks (Figure 25) based on the 23 member NEPS-G ensemble indicate that the cyclone would cross the coast of Sri Lanka near Triconomalee followed by Tamil Nadu coast near Rameshwaram.

6.1.2 Forecast Track Errors

The NCUM-G, NEPS-G and NCUM-R tracks based on 00 and 12UTC forecasts from 28 Nov -04 December 2020 have been used in the verification. Table 1 summarizes the track errors at different lead times. The track error components of Direct Position Error(DPE), Along Track Error (ATE) and Cross Track Error (CTE) are shown in Figure 27. Mean initial position error is least in NCUM-R whereas at higher lead times (24 h and above) NEPS-G shows the lowest errors. DPE has further been compared against the IMD official forecast error and it is evident that at 72h forecast NCMRWF model NEPS-G has relatively lesser DPE.

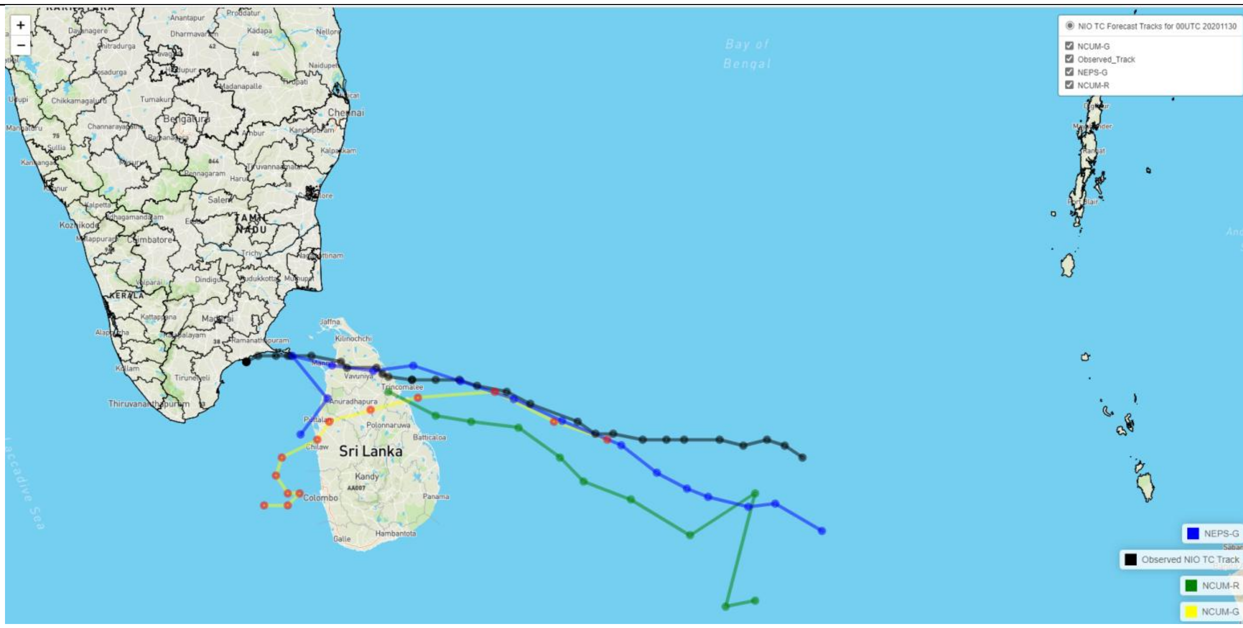


Figure 24. Observed and forecast tracks based on 00UTC on 30th November 2020

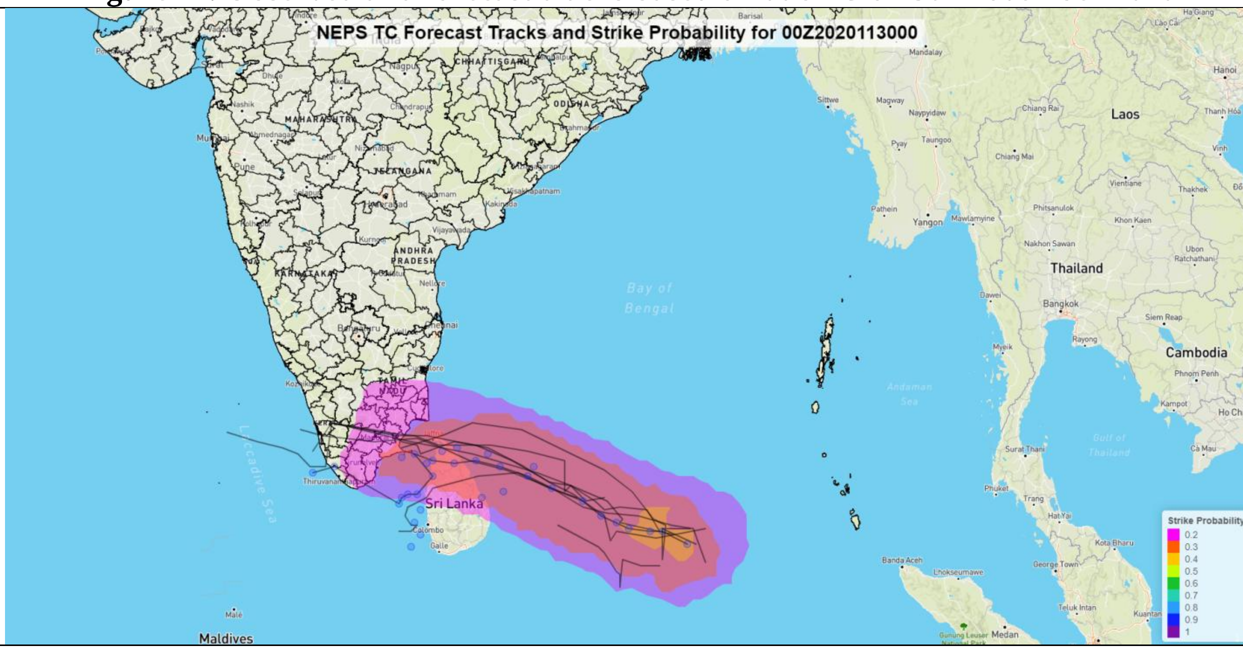


Figure 25 NEPS-G strike probability and member tracks

Table 1. Forecast Track Errors NCUM-G, NCUM-R and NEPS-G (numbers below the row indicate number of forecast points).

Model/Fcst hr	0	12	24	36	48	60	72	84	96	108	120
NCUMG	**96**	**107**	**86**	**91**	**93**	**133**	**130**	**177**	**160**	**213**	**160**
	7	8	8	7	4	6	7	7	7	7	6
NCUMR	**81**	**93**	**86**	**128**	**159**	**177**	**190**				
	9	9	8	9	10	8	8				
NEPSG	**115**	**94**	**76**	**73**	**79**	**80**	**113**	**120**	**155**	**178**	**130**
	9	10	10	10	10	10	10	10	10	9	7

Table 2: Error in the forecast landfall time and position

	Landfall Position Error			Landfall Time Error		
Forecast Hour	**NCUM-R**	**NCUM-G**	**NEPS-G**	**NCUM-R**	**NCUM-G**	**NEPS-G**
0-24	53	40	30	12	12	12
24-48	45	42	20	-6	9	12
48-72	47	14.5	54.5	6	6	0
72-96			5			0

(Forecast time – Observed time) **[-ve early +ve delay].**

Table 2 summarizes the landfall error in terms of position and time. NCMRWF model NEPS-G was able to predict the landfall accurately in terms of time and position 72-96 h before with least error of approximately 5 km. Landfall time error was zero for NEPS-G predicted on 30th November and 1stDecember

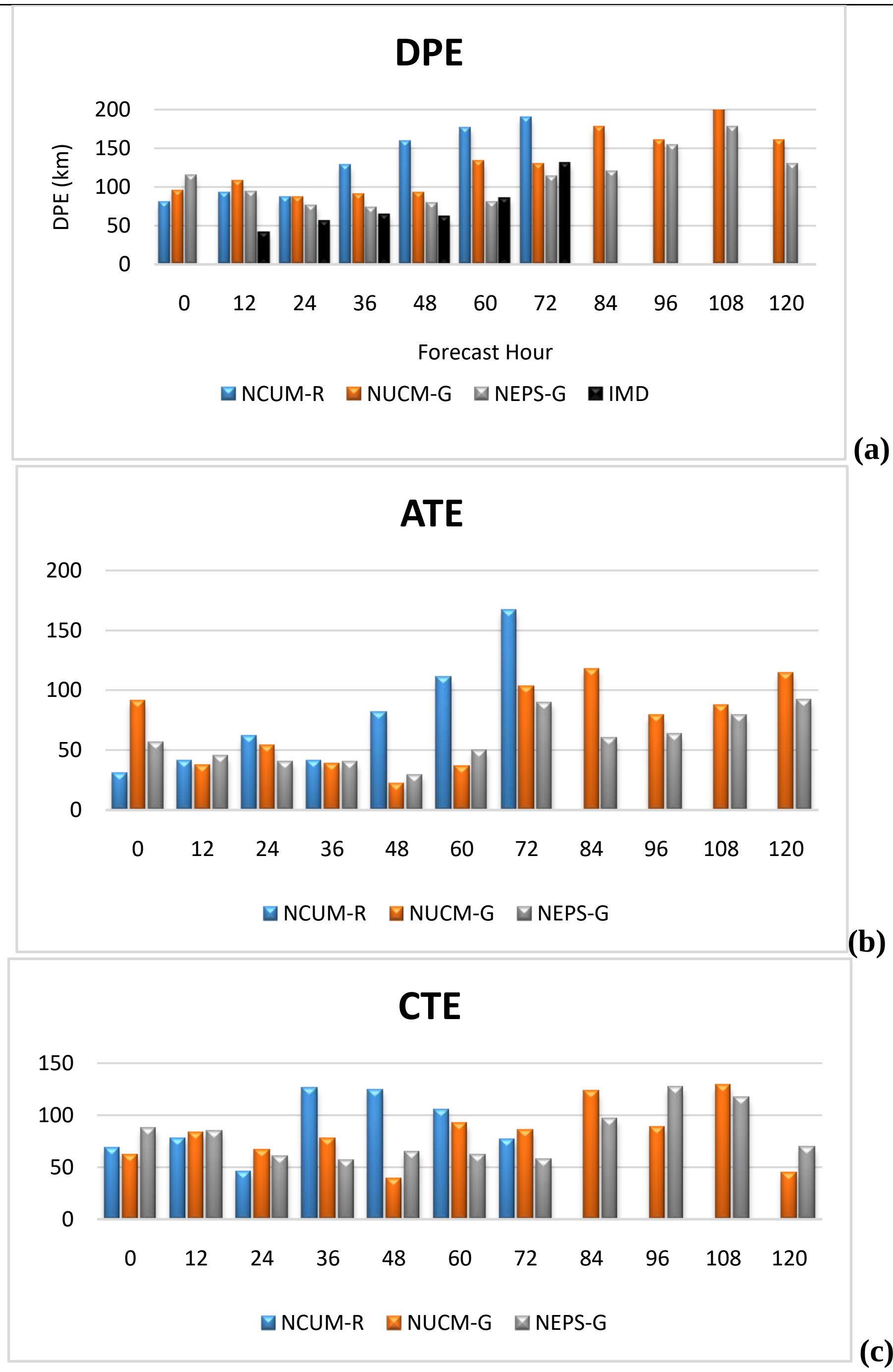
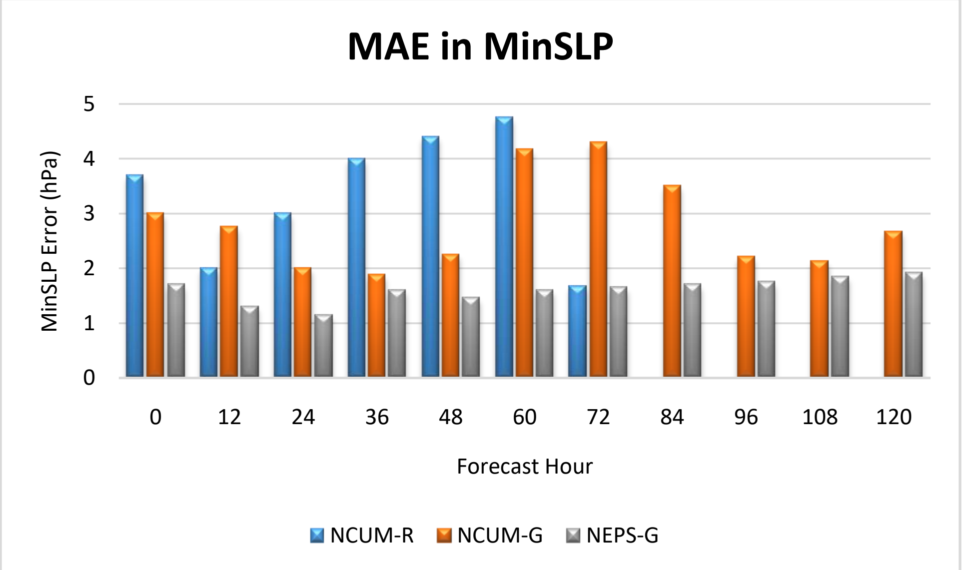


Figure 26. Track forecast errors(a) Direct position error (b) along track error and (c) cross track error in km

6.1.3 Intensity Forecast (Min SLP and Max Wind):

The mean absolute error in Min SLP and MSW for the three models is shown in Figure 28. Least average error in MinSLP is evident at all the forecast lead times in NEPS-G. Error in MSW is relatively higher and again NEPS-G has edge over the other two models at all the forecast lead times. At higher lead times (24 - to 72-h) NEPS-G has even lower intensity error than that of IMD official forecast errors.



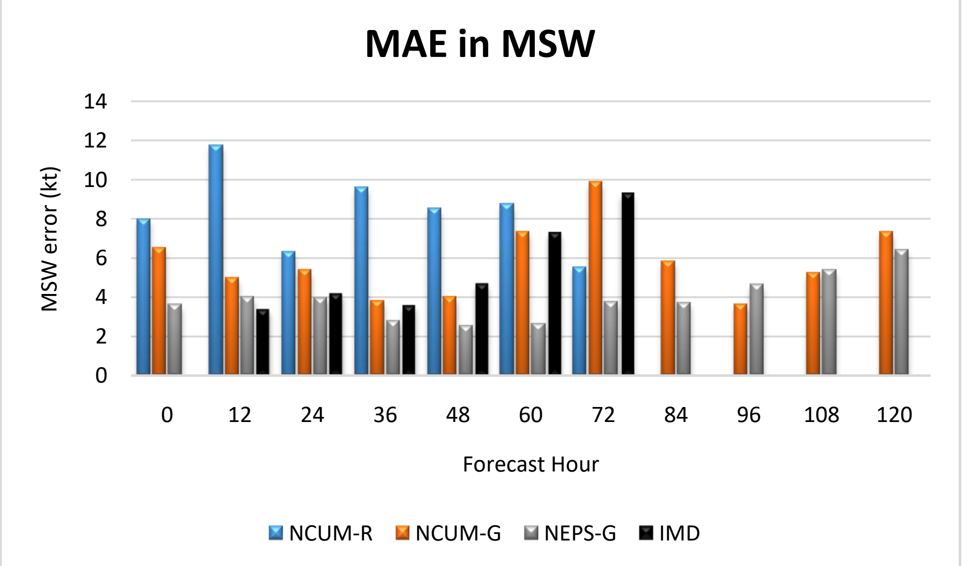


Figure 27. Mean Absolute Error (MEA) in MinSLP(hPa) and MSW(kt) at different forecast lead times

6.1.4 Verification of Strike Probability

Verification of strike probability is presented using ROC and Reliability diagram (attributes diagram). The Reliability diagram (Figure29) gives a comparison of forecast probability against the observed frequencies. A perfect match will show all points along the diagonal 1:1 line. Points above diagonal suggest underestimation (lower forecast probabilities) while points below the diagonal suggest over estimation (higher forecast probabilities). For the case of CS Burevi, NEPS-G strike probability verification is presented for 23 member lagged ensemble. Figure 29 shows the reliability and ROC plots for the strike probability verification. It is seen from the figure that the reliability curve lays in the skillful region and very close to the diagonal line of perfect reliability. However, for higher probabilities i.e., (0.6) it is seen that the NEPSG model is under forecasting with the observed frequencies being higher than the forecast probabilities. Figure 29 shows the ROC, the model shows skill as the curve is away from the diagonal line of no resolution. Also, the area under the ROC is 0.83 which shows reasonable skill.

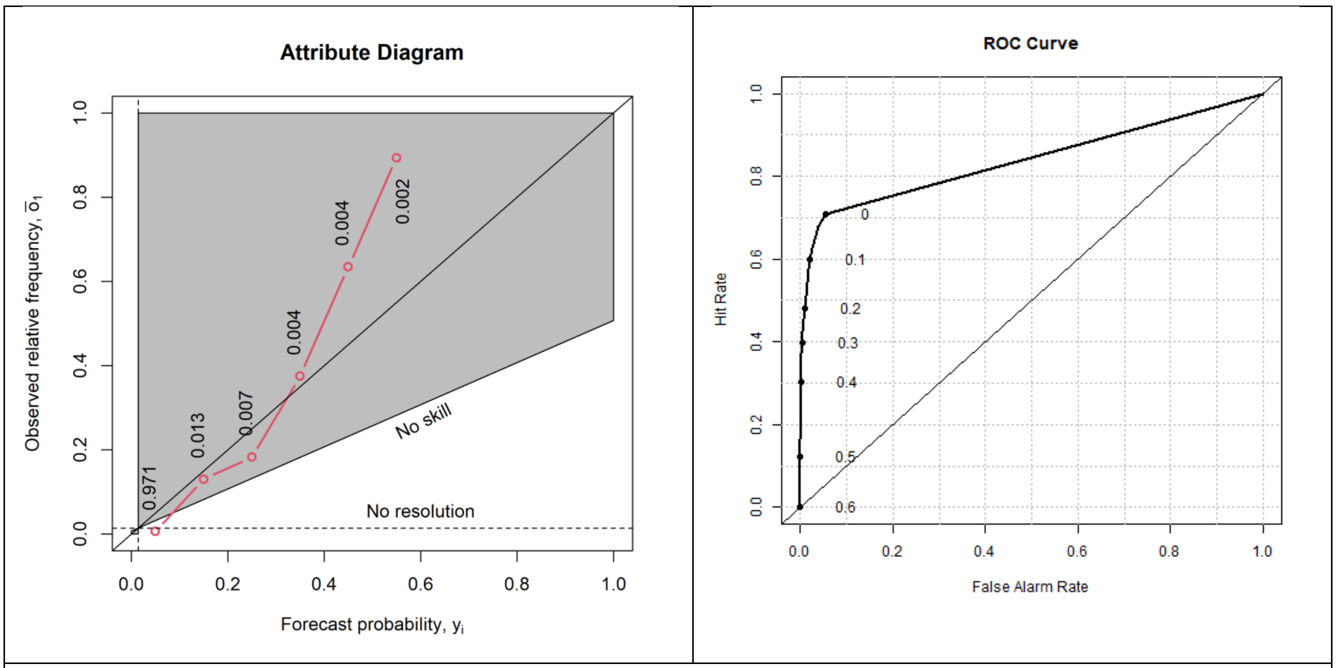


Figure 28. Verification of strike probability using reliability diagram (left) and ROC curve (right) for the case of CS 'Burevi'

6.1.5 CRA Verification of Rainfall Forecasts

Contiguous rain areas (CRA) verification is a spatial verification method (Ebert and Gallus 2009). This method focuses on individual weather systems and verifies the properties of the forecast objects, which allows estimation of location error of the forecast entity. Detailed description of the method with application over India can be found for UM Rainfall forecasts over India (Ashrit et al 2015a) and MoES Models (NCUM & GFS) in Sharma et al., (2020). Here, NCUM-G rainfall forecasts corresponding to the CS ‘Burevi’ on 4th Dec 2021 are discussed briefly using CRA verification for 40 and 80 mm/day rainfall objects (Figure 29). For the 40mm/day CRA, the forecast shows a good match with observations as seen from scatter plot, average rain rate (~55mm/day in both), rain volume (~4 km^3) in both. However, the maximum rain is hugely underestimated and the RMSE is 69mm/day. The forecast rainfall object is shifted southward by 1.75°. Contribution to RMSE from error due to displacement is 38.4% For 80mm/day CRA forecast shows rather poor match in terms of scatter and underestimated average rain rate, maximum rain and rain volume. The RMSE for 80 mm/day CRA is higher at 98mm/day compared to the same in 40 mm/day CRA. The forecast object is displaced southwestwards [0.75°W and 2°S] leading to 46% contribution to total error.

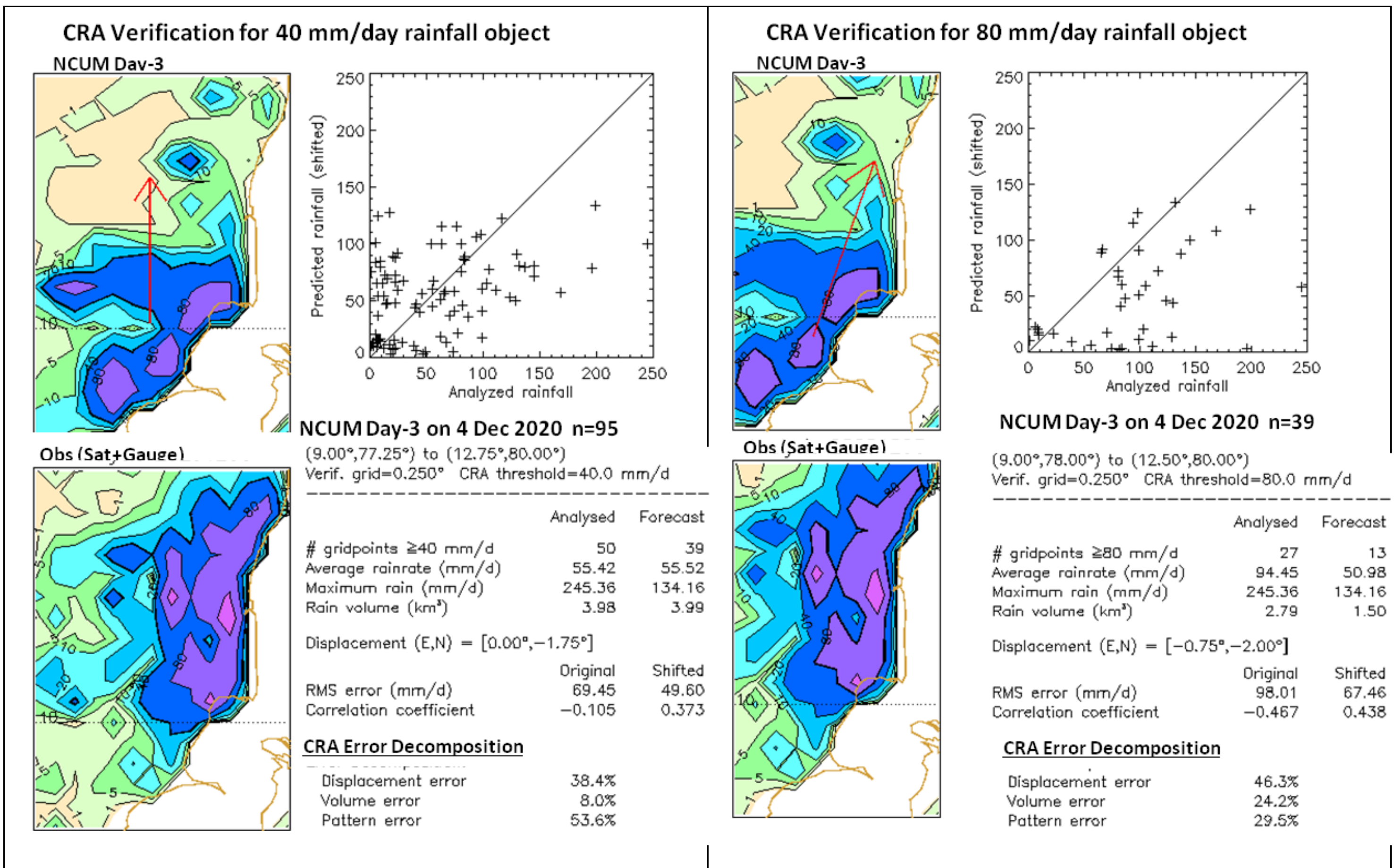


Figure 29. CRA verification of NCUM Day-3 rainfall forecasts valid on 4th Dec 2020 following landfall for CS ‘Burevi’ over Tamil Nadu coast. Results for 40 (left) and 80mm/day (right) rainfall objects are shown.

6.2 Cold Waves & Western Disturbance:

6.2.1 Verification of Tmin & Western disturbance:31Dec 2020 and 29 Jan 2021

Figure 30 shows the observed and forecast minimum temperature on 31st Dec 2020. Large part of north India shows Tmin lower than 10°C in the observations which is accurately predicted in each of the forecasts. Minimum temperature <4°C is seen in the observations over Northwest India. The NCUM-G forecasts successfully predict the low Tmin values over northwest India. However, the model forecasts show low temperatures over a larger area. Similarly, Figure 31 shows the observed and forecast Tmin on 29th Jan 2021. The forecasts show a reasonable match with the observations. Both the cases considered are associated with passing Western disturbance. For the first case Figure 32 shows 500 hPa winds to show passing western disturbance in the form of a trough in the westerlies over J & K region. Similarly for the case of 29th Jan 2021, the trough in the westerlies is rather prominent. Thus, in both the cases, NCUM model forecasts clearly indicate the location and intensity of the trough and WD formation. Particularly in case 2, the strong north westerlies, are accurately predicted in the model.

6.2.2 Observed and forecast daily Tmin time series: 22-23 Dec 2020 ans 22-23 Jan 2021

Further, verification of the Tmin forecasts based on the NEPS ensemble is shown for several locations over Northwestern India. Observed Tmin data is obtained from SYNOP stations over India via the GTS network. Figure 34 shows the forecasts with IC=22 & 23 Dec 2020. The NEPS control (red), ensemble mean (blue) and ensemble members (green) are compared with the observations (black). Observed Tmin generally lies within the spread of ensemble members. Ensemble mean shows very good match with the observations and successfully predicts sharp rise/fall in value consistent with observations. The sharp drop in observed Tmin in New Delhi (Jodhpur) by about 6°C (8°C) between 30 & 31st (28-30) Dec 2020 is accurately predicted. Similarly for another case of cold wave in January 2021 is shown in Figure 35 for IC=22-23 Jan 2021. Prolonged spell of low Tmin is indicated in the forecasts consistently. The sharp drop in observed Tmin in Udaipur by about 6°C between 25 & 26th Jan 2021 is accurately predicted. Prolonged low observed temperatures over Dehradun during 23-31Jan and Churu after 25th Jan 2021 are well represented in the NEPS forecasts.

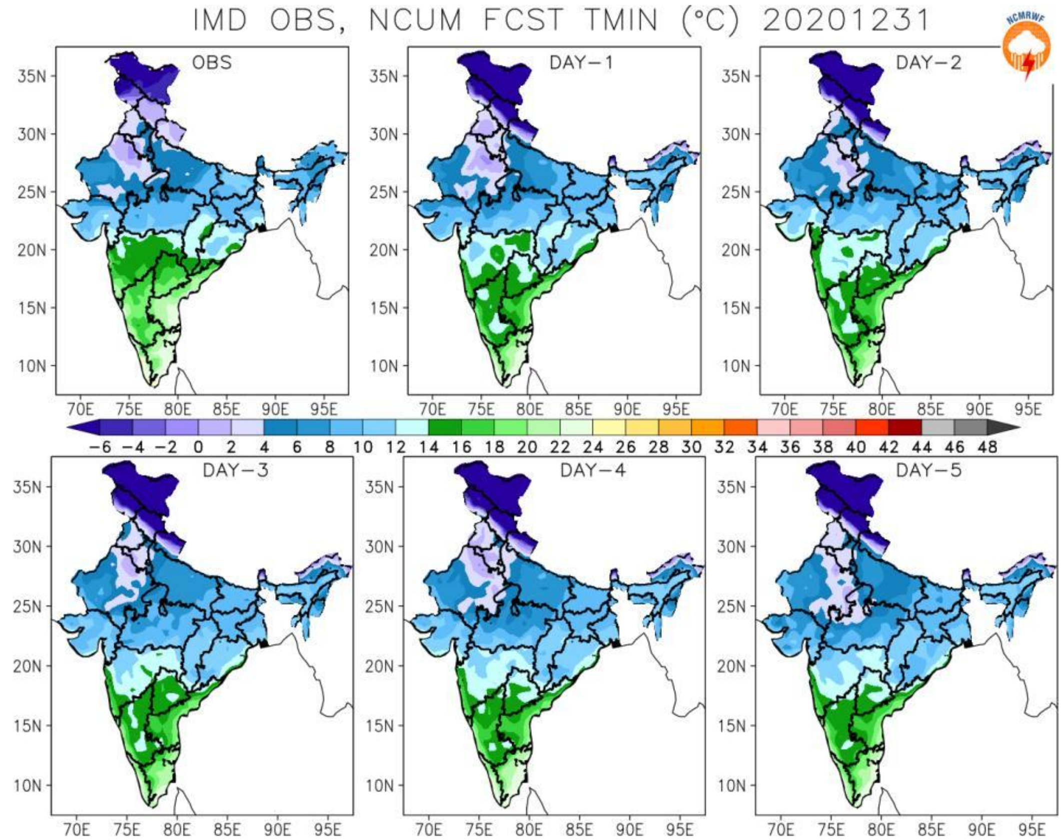


Figure 30 Observed and forecast Tmin valid on 31st Dec 2020 over India

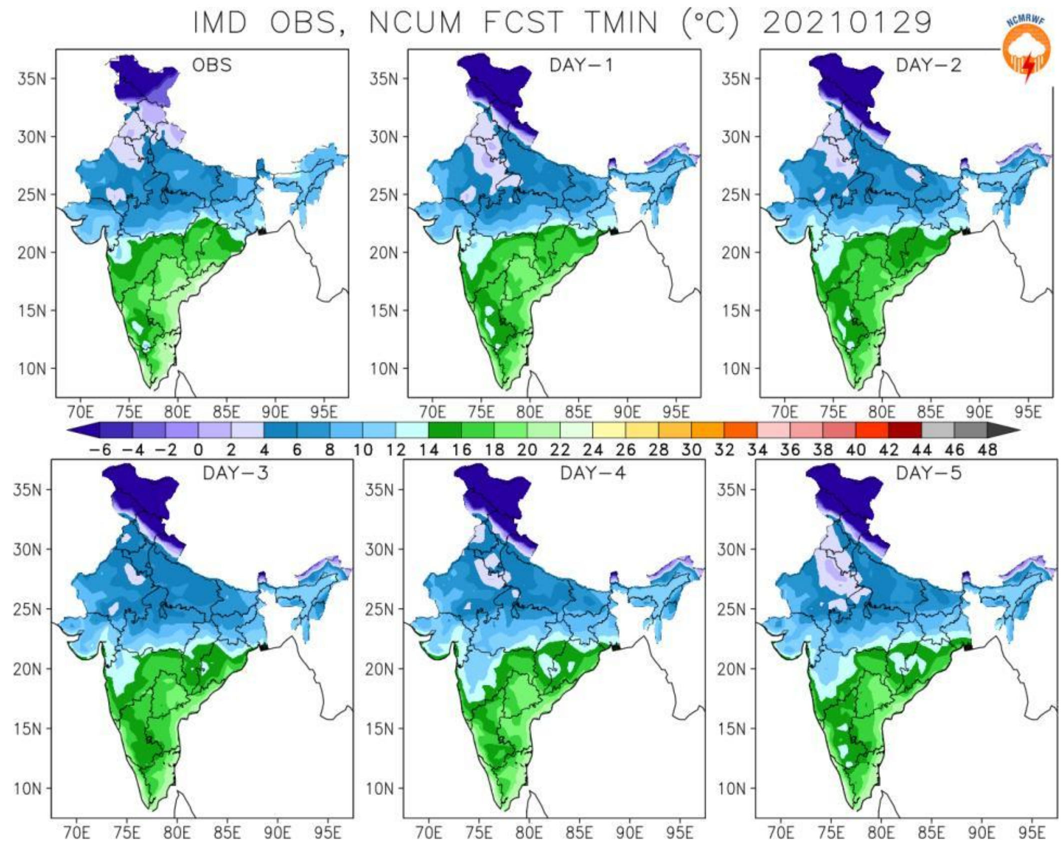


Figure 31 Observed and forecast Tmin valid on 29th Jan 2021 over India

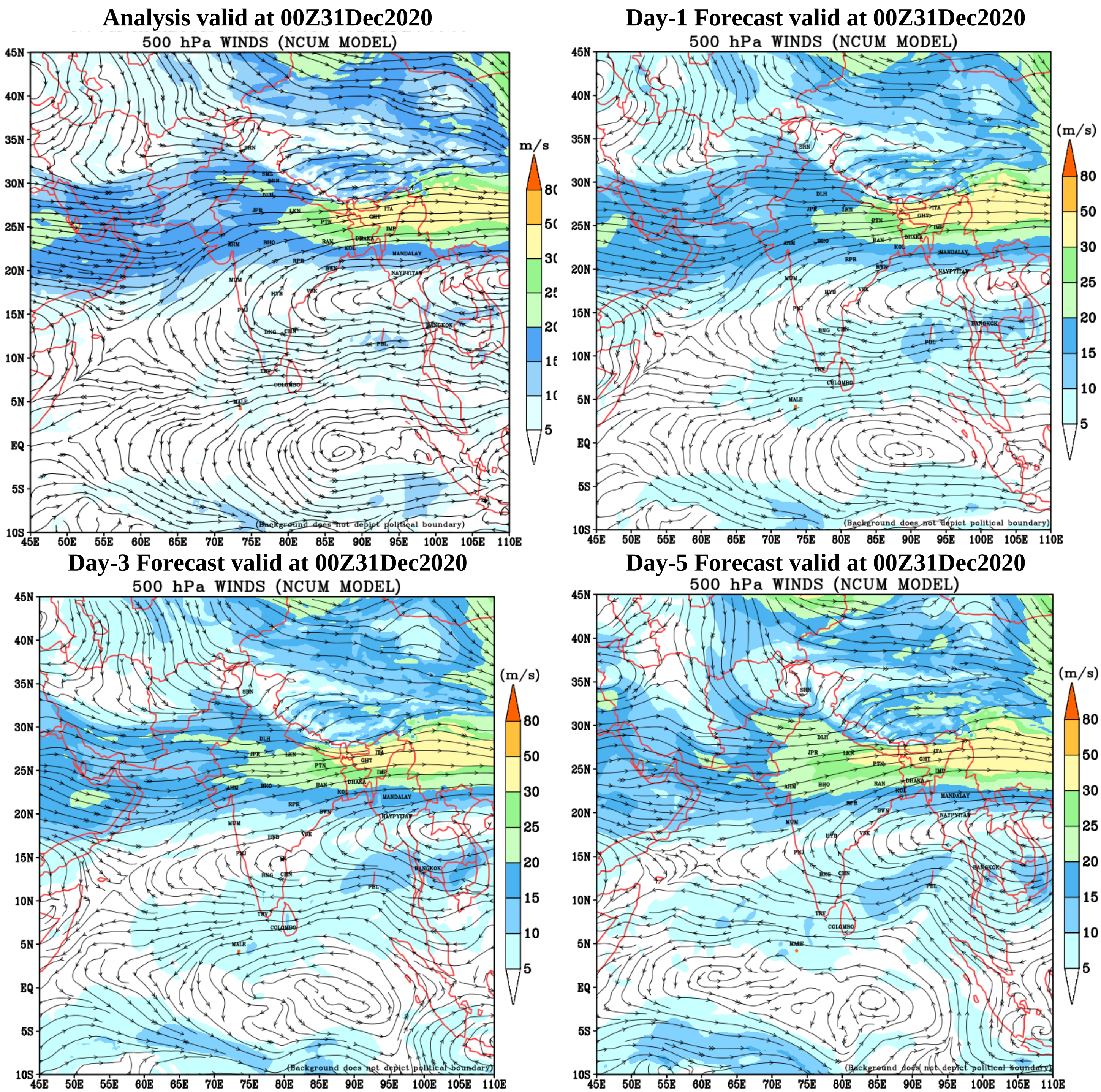


Figure 32 NCUM Winds at 500 hPa in the NCUM analysis and Day-1, Day-3 and Day-5 forecasts valid on 31Dec2020

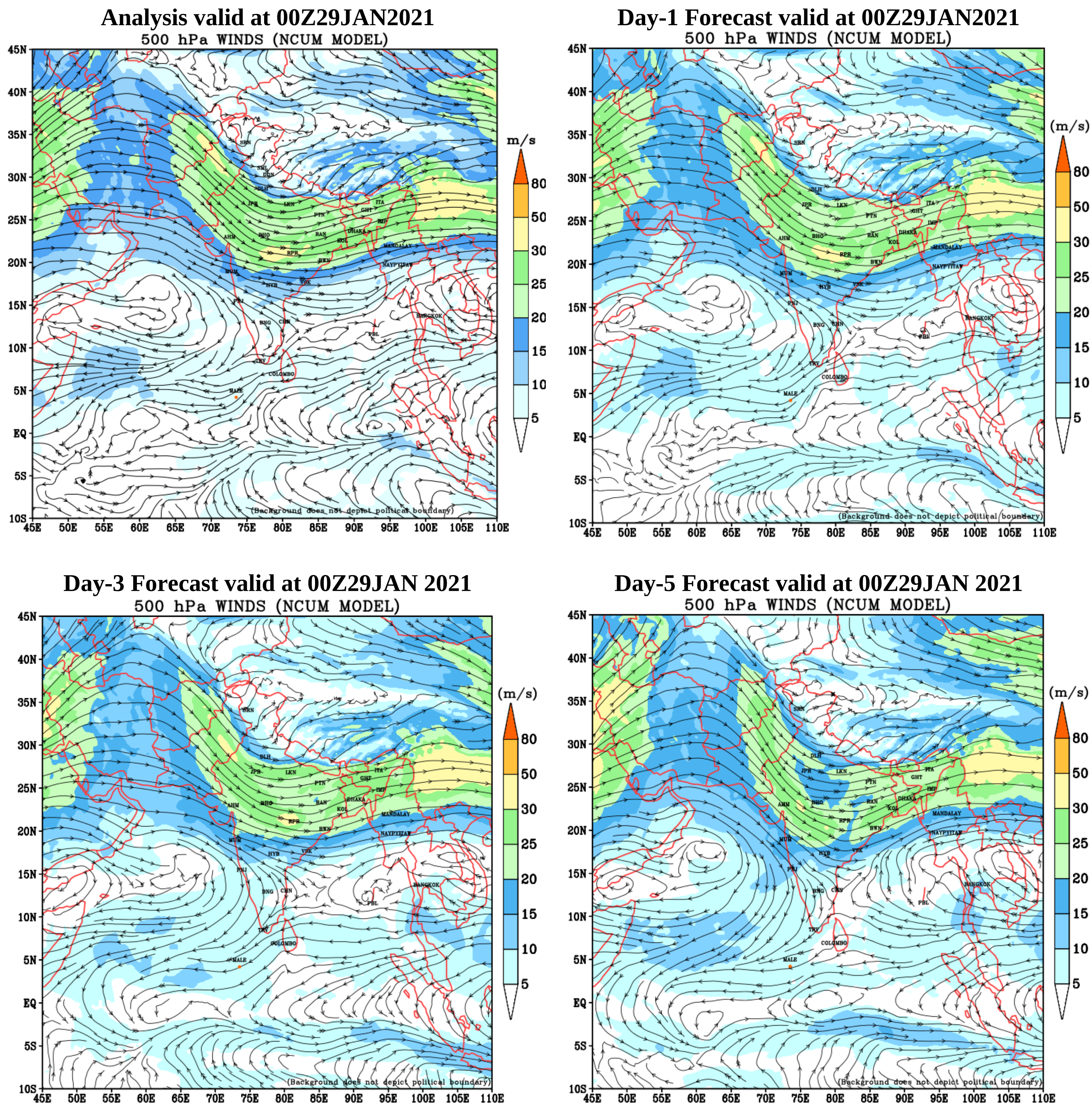


Figure 33 NCUM Winds at 500 hPa in the NCUM analysis and Day-1, Day-3 and Day-5 forecasts valid on 29Jan2021

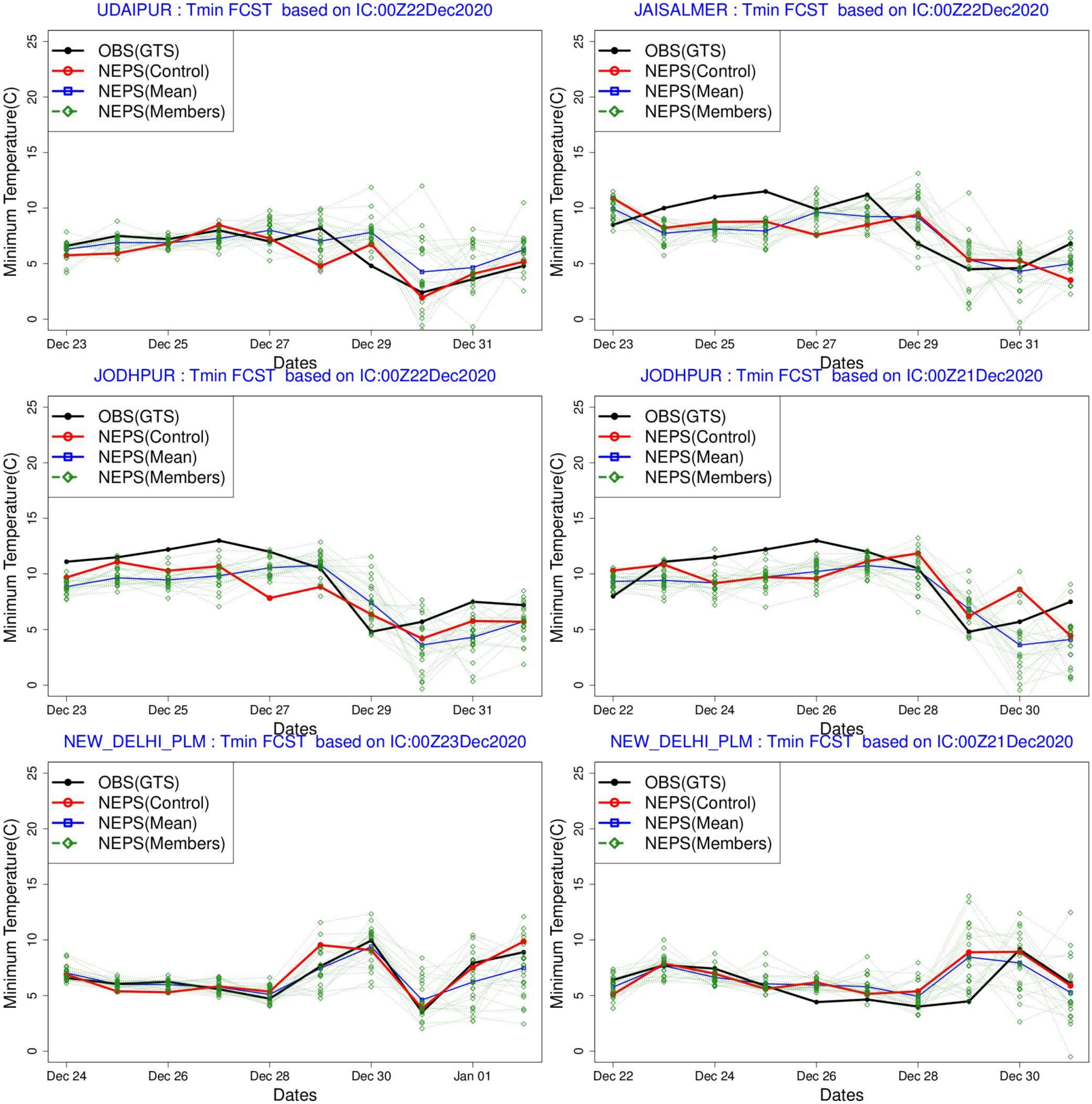


Figure 34 Observed and NEPS-G forecast Tmin over different cities over North India during the cold wave conditions of late Dec 2020.

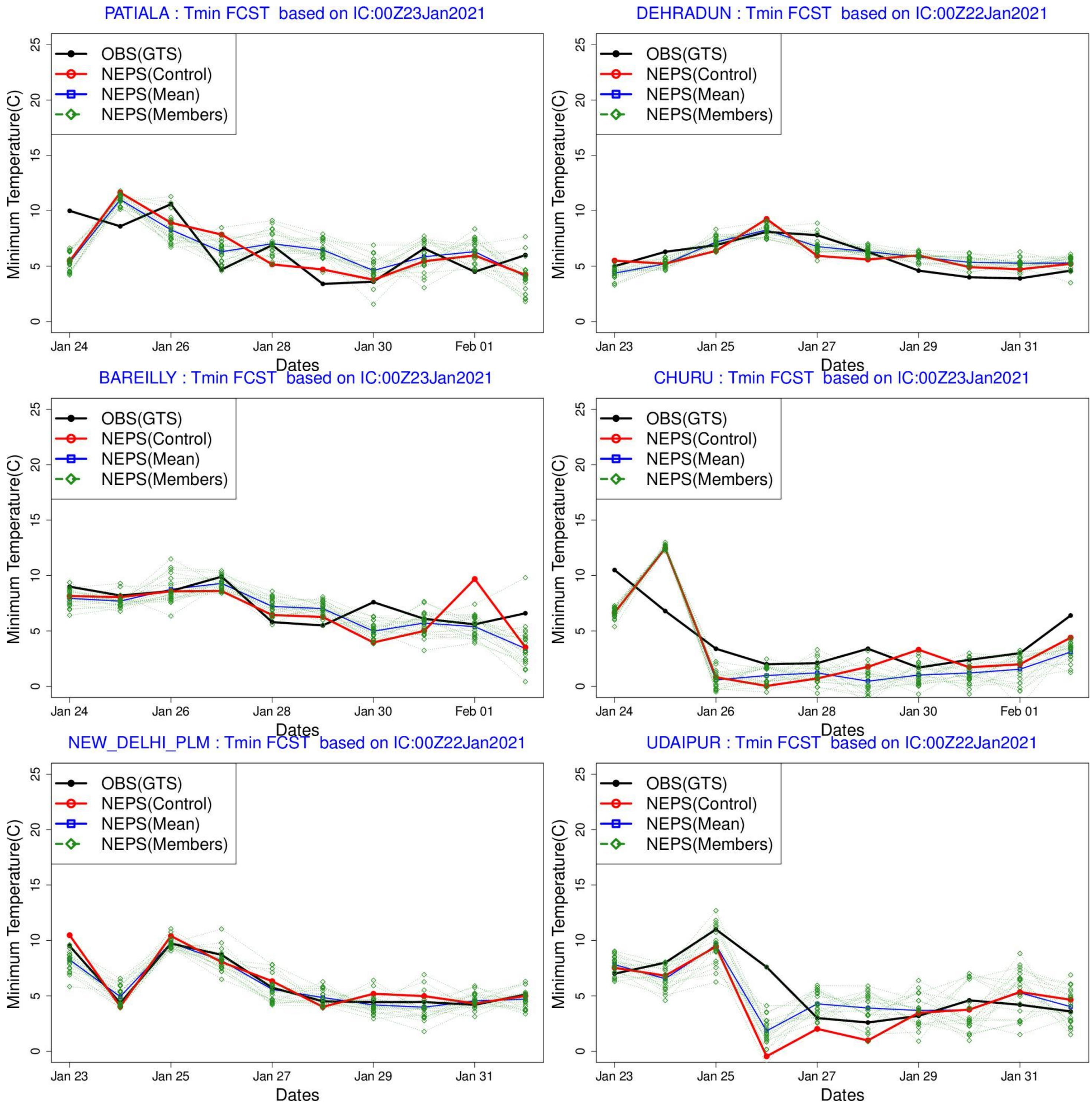


Figure 35 Observed and NEPS-G forecast Tmin over different cities over North India during the cold wave conditions of late Jan 2021.

7. Summary and Conclusions

This report documents performance of the NCMRWF model forecasts during winter season DJF 2020-21. The verification results are presented to address (a) forecasters and (b) model developers. The information on biases in the forecast winds, temperature humidity, rainfall, etc., are crucial for the forecasters to interpret the model guidance for forecasting. Additionally, information on recent improvements in the model skill adds to confidence in the model forecasts. The results of the study can be summarized below.

NCUM-G Mean analysis and anomalies during DJF 2020-21

- *The low-level wind anomalies at 850 and 700 hPa show presence of anticyclonic circulation over the Central Indian region indicating high pressure and subdued convection. Penetrating westerlies from higher latitude having relatively large magnitudes w.r.t ERA5 climatology towards Indian subcontinent is evident. The anomalous easterlies are clearly discernible prevailing from the west Pacific to middle eastern region in the north India in the upper troposphere. In the equatorial regions, the upper tropospheric winds are quite strong with magnitudes of more than 6m/s in winter 2020-21.*
- *Low level (850 and 700 hPa) temperature anomalies indicate the winter 2020-21 is warmer than the climatology with magnitudes between 1-2K in north India. The warmer temperatures stretch from northwest to southeast India covering the Indo-Gangetic plains.*
- *DJF2020-21 indicates the higher percentage of RH compared to the climatology in the south India, and lower seasonal mean over northern plains. The Oceanic regions of Bay of Bengal and Arabian seas also shown positive anomalies in the humidity distribution for the winter period and negative anomalies are noted in the equatorial regions.*

NCUM-G Systematic Errors

- *Systematic errors in winds at 850 hPa from Day-1 forecasts shows an easterly wind bias over south Bay of Bengal. A westerly wind bias over south of the equator around 60E and easterly wind bias around the maritime continent (MC) is also noted. With forecast lead times these errors in low-level winds enhances and this could be due to the enhanced convective activity around the equatorial regions during winter season. Westerly wind bias is more prominent at 700 hPa level over central India in Day-3 and Day-5 forecasts.*
- *Model errors show warm bias (~1 C) occupied over most of the Indian land mass and the magnitude of this bias is increasing. These error increments at 850hPa temperatures are also more prominent over eastern African regions. On a similar note, temperature errors at 700 hPa also show warm bias (~0.5C) over most of the Indian land region. Interesting to see that the bias over AS region reverse sign and now exhibits warm bias compared to 850hPa level.*
- *Systematic errors show large dry bias over Indian land regions over 850hPa level and the dryness is enhancing with forecast times. Omni presence of strong north easterlies over open oceanic regions of AS and BoB and increased evaporation could be one primary reason for the positive RH values over these regions. On contrary, most of the Indian subcontinent and surrounding oceanic regions are exhibits moist bias as evidenced by positive RH values, except Africa and west Arabian regions.*
- *Systematic errors in surface winds at 10m level show North easterlies in Day-1 is changing its direction to southerlies with lead time and it is clearly seen Day-5.*

- *Systematic errors in 2m temperature show a relatively warm bias over Indian land regions and north of 40 ^{o}N latitude regions. Interestingly these warm biases are increasing with lead time especially over Indian region. This can be attributed to the dry north westerly winds from Northwest entering into Indian land and North AS.*
- *Systematic error in PWAT shows a column dry over Indian land regions in Day-1, this dryness in column is enhancing forecast times and its magnitudes are maximum in Day-5. Large positive PWAT biases are seen over BoB; AS and over equatorial regions. This excess column water could be one reason for excess rainfall over these regions).*

Rainfall Forecast Verification

- *NCUM forecast overestimates rainfall amounts and spatial distribution over oceanic regions around equator and J & K region. Rainfall mean error (ME) show wet bias over southern parts of the oceanic regions consistent with the mean rainfall patterns. Small dry bias regions are noticed over Sri Lanka and some parts of Tamil Nadu in the forecasts and the magnitude of dry bias increases with lead time.*
- *For different rainfall thresholds (3-30mm/day) POD (FAR) shows decrease (increase) in value respectively.POD >= 0.5 for rainfall up to 6 mm/day. The BIAS score (frequency bias) indicates that forecasts overestimate the frequency all thresholds. The values of PSS, and SEDI all are high for rainfall up to 3-5 mm/day suggesting reasonable skill. PSS score shows a very sharp decrease as the threshold varies.*
- *Interestingly the POD and PSS scores for Tmin thresholds remains nearly constant up to 20-22 C with values less than 0.4. However, the scores slightly increase at rainfall 22-24C in both POD and PSS. FAR scores over all India as whole shows relatively large values >0.6 up to temperature thresholds 18-20C, later a gradual decrease is noticed in all the forecast times.*

Verification for Significant Weather

Bay of Bengal CS 'Burev' (30th Nov-5th Dec 2020), Western Disturbances and Cold waves formed significant weather events of DJF 2020-21

- *For the CS 'Burevi', the mean initial position error is least in NCUM-R whereas at higher lead times (24 h and above) NEPS-G shows the lowest errors.*
- *Error in MSW is relatively higher and again NEPS-G has edge over the other two models at all the forecast lead times. At higher lead times (24 - to 72-h) NEPS-G has even lower intensity error than that of IMD official forecast errors.*
- *NEPSG model is under forecasting while ROC the area under the ROC is 0.83 which shows reasonable skill.*
- *The spatial verification of Day-3 rainfall valid on 4th Dec 2020 shows RMSE of 69 and 98 mm/day for 40mm/day and 80mm/day thresholds respectively. Forecasts have southward and southeastward displacement by about 2° leading to significant contribution to total error.*
- *For the Western Disturbance, the forecast show accurate prediction of trough in the westerlies at 500 hPa up to 5 days ahead. Associated low temperatures are accurately predicted in the NEPS-G ensemble mean. Ensemble members have reasonable spread around the observations indicating reliability in ensemble forecasts.*

References

Ashrit, R., Elizabeth Ebert, Ashis K. Mitra, Kuldeep Sharma, Gopal Iyengar and E.N. Rajagopal 2015a: Verification of Met Office Unified Model (UM) quantitative precipitation forecasts during the Indian Monsoon using the Contiguous Rain Area (CRA) method. NMRF/RR/03/2015

Ashrit R, Sharma K, Dube A, Iyengar G R, Mitra A K and Rajagopal E N 2015b: Verification of short-range forecasts of extreme rainfall during monsoon; Mausam 66 375–386, 607.

Barker, D., 2011. Data assimilation-progress and plans, MOSAC-16, 9-11 November 2011, Paper16.6.

Ebert, E.E. and W.A. Gallus, 2009: Toward better understanding of the contiguous rain area (CRA) method for spatial forecast verification. Wea. Forecasting, 24, 1401-1415.

Hersbach H, Bell B, Berrisford P, et al. 2020: The ERA5 global reanalysis. Q J R Meteorol Soc. 2020;146:1999–2049. https://doi.org/10.1002/qj.3803

Jolliffe, I. T., and D. Stephenson, 2012: Forecast Verification: A Practitioner's Guide in Atmospheric Science, John Wiley & Sons, Ltd

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/01/2019, 17p.

Kumar Sumit, M. T. Bushair, Buddhi Prakash J., Abhishek Lodh, Priti Sharma, Gibies George, S. Indira Rani, John P. George, A. Jayakumar, Saji Mohandas, Sushant Kumar, Kuldeep Sharma, S. Karunasagar, and E. N. Rajagopal 2020: NCUM Global NWP System: Version 6 (NCUM-G:V6), NMRF/TR/06/2020

Mitra, A. K., A. K. Bohra, M. N. Rajeevan and T. N. Krishnamurti, 2009: Daily Indian precipitation analyses formed from a merged of rain-gauge with TRMM TMPA satellite derived rainfall estimates, J. of Met. Soc. of Japan, 87A, 265-279.

Mitra, A. K., I. M. Momin, E. N. Rajagopal, S. Basu, M. N. Rajeevan and T. N. Krishnamurti, 2013, Gridded Daily Indian Monsoon Rainfall for 14 Seasons: Merged TRMM and IMD Gauge Analyzed Values, J. of Earth System Science, 122(5), 1173-1182.

Sharma K., S. Karunasagar and Raghavendra Ashrit 2020: CRA Verification of GFS and NCUM Rainfall Forecasts for Depression cases during JJAS 2018. /NMRF/RR/05/2020

Sharma, K., Ashrit, R., Kumar, S. et al. Unified model rainfall forecasts over India during 2007–2018: Evaluating extreme rains over hilly regions. J Earth Syst Sci 130, 82 (2021). https://doi.org/10.1007/s12040-021-01595-1

Srivastava A K, Rajeevan M and Kshirsagar S R 2009: Development of a high resolution daily gridded temperature data set (1969–2005) for the Indian region; Atmos. Sci. Lett. 10 249–254, https://doi.org/10.1002/asl.232

Stephenson D.B., B. Casati, C.A.T. Ferro and C.A. Wilson, 2008: The extreme dependency score: a non-vanishing measure for forecasts of rare events. Meteorol. Appl., 15, 41-50.

Walters, D., and co-authors: The Met Office Unified Model Global Atmosphere 6.0/6.1 and JULES Global Land 6.0/6.1 configurations, Geosci. Model Dev., 10, 1487–1520, https://doi.org/10.5194/gmd-10-1487-2017, 2017

Wilks D S 2011 (eds) Statistical methods in the atmospheric 807 sciences; 3rd edn, Elsevier, 676p