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RESEARCH REPORT

Performance of NCMRWF Forecast Models in Predicting the Uttarakhand Heavy Rainfall Event during 17 – 18 June 2013

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10	Abstract (100 words)	On 17th June 2013 the state of Uttarakhand received more than 340 mm of rainfall, which is 375% above the daily normal (65.9 mm) rainfall during monsoon. This caused heavy floods in Uttarakhand as well as unprecedented damage to life and property. In this study we aim at assessing the performance of two deterministic forecast models run at NCMRWF (T574 and NCUM) in predicting the heavy rainfall observed over Uttarakhand region of India during 17th -18th June 2013. Verification of the synoptic features in forecasts of the two models suggests that NCUM accurately captures the circulation features as compared to T574. This is further confirmed by verification of the quantitative Precipitation Forecast (QPF) statistics using standard scores like POD, ETS and HK. Further verification based on CRA (Contiguous Rain Area) technique also confirms better skill of NCUM over T574 in terms of forecast highest rainfall amounts, volume and average rain rate. While precise prediction of heavy rainfall events is a challenge using the high resolution deterministic models, predictions/guidance based on the 'ensemble forecast system' have shown immense promise in recent years. For the first time in India an initiative is taken up at NCMRWF to issue probabilistic forecasts of the rainfall based on the 20 member Global Ensemble Forecast System (GEFS). This approach shows some promise in Day 3 and Day 5 forecasts.
11	Security classification	Non-Secure
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13	Key Words	*Kedarnath Flood, T574, NCUM, Unified Model, Verification, CRA, Ensemble, Probabilistic, Monsoon*

Contents

Abstract

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Verification of the synoptic features in forecasts of the two models suggests that NCUM accurately captures the circulation features as compared to T574. This is further confirmed by verification of the quantitative Precipitation Forecast (QPF) statistics using standard scores like POD, ETS and HK. Further verification based on CRA (Contiguous Rain Area) technique also confirms better skill of NCUM over T574 in terms of forecast highest rainfall amounts, volume and average rain rate.

While precise prediction of heavy rainfall events is a challenge using the high resolution deterministic models, predictions/guidance based on the ‘ensemble forecast system’ have shown immense promise in recent years. For the first time in India an initiative is taken up at NCMRWF to issue probabilistic forecasts of the rainfall based on the 20 member Global Ensemble Forecast System (GEFS). This approach shows some promise in Day 3 and Day 5 forecasts.

1. Introduction

Over the Indian subcontinent, the amount of rainfall received during the monsoon season (June to September) is very crucial for the agriculture and in turn for the economy. In the past couple of years, there have been several cases of heavy rainfall (3-12cm/day) events over India. The most recent events (June 2013) are the heavy rainfall observed in Maharashtra (approximately 300% more than the average during 1st to 16th June 2013 in Mumbai and adjoining areas) and Uttarakhand (approximately 800% more than the average during 13th to 19th June 2013 in Kedarnath and adjoining areas) states of India. The floods in Uttarakhand region led to a massive destruction of property and loss of life; as reported in a report from the Ministry of Home Affairs (Disaster Management Division) approximately 580 people lost their lives, more than 60,000 were left stranded and approximately 100,000 people were affected (http://www.ndmindia.nic.in/flood-2013/floodsJune-2013.htm, http://www.ndmindia.nic.in/flood-2013/floodsJuly-2013.htm, http://nidm.gov.in/PDF/DU/2013/June/19-06-13.pdf). Thus, issuing a reliable short to medium range (3-7 days) prediction is of utmost importance for heavy rainfall events leading to catastrophic floods, disruption of transport over the affected regions. These warnings could help the authorities to take necessary measures to reduce the damage to life and property.

In the last couple of decades, several sophisticated numerical weather prediction (NWP) models have been developed around the world, which include many complex physical processes and advanced data assimilation schemes. In India, National Centre for Medium Range Weather Forecasting (NCMRWF) provides daily weather predictions based on two NWP models: T574 (Global Forecast System[GFS]), NCUM (NCMRWF Unified Model). In addition, Global Ensemble Forecast System (GEFS) with a 21 ensemble members is used to generate probabilistic predictions. Accuracy of prediction of high risk events, i.e., the reliability of the forecast, is also a very important part of forecasting weather.

The upper Himalayan territories of Himachal Pradesh and Uttarakhand are mainly covered with forests and mountains. These areas besides being important pilgrimage centres are also famous as tourist attractions especially during the hot summer months of the Indian subcontinent. During 14th to 17th June 2013 Uttarakhand received heavy rainfall, and this when combined with the melting snow (due to high temperature during summer season) resulted in an aggravation of floods in this region (Kedarnath and adjoining areas). On 17th June alone, the state of Uttarakhand received more than 340 mm of rainfall (37 cm/day in Dehradun; as reported in the Climate Diagnostics Bulletin of India, June 2013 [CDBI-June 2013]), which is 375% more than the daily normal (65.9 mm). IMD reported a weekly departure of about 847% in the rainfall volume for the week ending on 19th June 2013 in Uttarakhand (http://www.imd.gov.in/section/hydro/dynamic/rfmaps/WeekByWeekRain.htm).

This study aims at comparing the performance of NCUM and T574 models over Uttarakhand region during 17th -18th June 2013. The methodology used for verification of rainfall over India includes calculating the standard verification statistics like Probability of Detection (POD), Equitable Threat Score (ETS), Hanssen and Kuipers Discriminant (HK) (Hanssen and Kuipers, 1965). Along with these statistics, CRA (Contiguous Rainfall Area) method is also used for spatial verification of rainfall over Uttarakhand. This method uses a pattern matching technique to determine the location error, as well as errors in area, mean and maximum intensity, and spatial pattern (detailed description is given in section 4).

1.1 Synoptic features as observed during 17-18 June 2013

Some major synoptic features observed on the 17th and 18th of June 2013 were taken from the weekly weather watch issued by the India Meteorological Department on the 19th of June 2013 and are listed below:

- The axis of monsoon trough was seen to be passing through Bikaner, Gwalior, Gaya and Imphal and across the Gangetic West Bengal.
- A low pressure area which originated over northwest Bay of Bengal moved eastwards and was seen over Odisha on 13th June. It intensified into a well marked low pressure area. This system sustained its northwestward movement till 18th June and weakened into a cyclonic circulation over Haryana and adjoining west Uttar Pradesh.
- A western disturbance (WD) in the form of a trough in mid tropospheric level was observed around west Rajasthan on 16th June. This WD moved eastwards (towards east Rajasthan) and on 18th June it was observed near northern regions of India (Punjab, Haryana, Uttarakhand and adjoining areas). This system finally moved away eastwards on 19th June 2013.

Some of the above mentioned synoptic features are shown in Figure 1 which depicts the 850 and 500 hPa analysis wind from 15th to 18th of June 2013 obtained from NCUM. The analysis obtained from T574 is similar to that of NCUM (Figures not shown). The 850 hPa analyses wind (Figure 1(a-d)) shows low pressure system which was observed on 15th June near the east coast of India moving northwestwards from 16th to 18th of June. On 18th June, this system is located near western region of Uttar Pradesh and eastern parts of Haryana. The 500 hPa analysis wind from 15th to 18th June (Figure 1(e-h), shows the eastward movement of the WD in the form of a trough over north India.

While the synoptic events captured in the analyses of both the models are very similar, the forecasts from the two models differ. The Day 3 forecast wind at 850 and 500 hPa from T574 and NCUM valid on 17th and 18th of June are shown in Figure 2 (similarly the Day-5 forecasts are shown in Figure 3). The lower level winds (850 hPa) from both the models show the cyclonic flow associated with the low pressure system in the forecasts. The location of this low pressure system in Day 3 and Day 5 forecasts of NCUM (valid on 17th and 18th of June, Figure 2 (a, b) and 3(a, b)) is matching with the location in the analysis (Figures 1(c, d)). However, the Day 3 and Day 5 forecasts of T574 (Figures 2(c, d) and 3(c, d)) show a stronger low pressure system much to the southwest of the observed location (Figures 1 (c, d)). The trough at 500 hPa associated with the WD is seen in the forecast of both models on 17th and 18th (Figures 2 (e, h) and Figure 3(e-h)). Although the Day 3 and Day 5 forecasts of both models predict the trough in the westerlies over north India, T574 forecasts are dominated by the cyclonic circulation over Gujarat (western India).

2. Observations

Observed rainfall used for verification of the model forecasts is the IMD-NCMRWF merged satellite gauge (NMSG) data (Mitra et al. 2009, Mitra et al. 2013). This rainfall data is a merged product of satellite estimates (TRMM) and rain gauge observations (IMD) at 0.5degree resolution, accumulated for 24 hours daily at 03UTC. The forecast rainfall from T574 and NCUM are 24-hour accumulations valid at 03UTC to match with the observations. However, the forecast rainfall from GEFS is 24-hour accumulations valid at 00 UTC.

3. NWP Models at NCMRWF

This study attempts to compare the forecasts made by two deterministic models run at NCMRWF and their respective skills in predicting high rainfall event. The models under consideration are:

1. Global Forecast System (T574) with T574L64 resolution (~22 km in tropics)
2. NCMRWF Unified Model (NCUM) with N512L70 resolution (~25 km in Mid-latitudes)

Additional details on the models' configuration and forecast products are available at (www.ncmrwf.gov.in). This report attempts to summarize the detailed intercomparison and verification of rainfall predictions of T574 and NCUM models for the 17th and 18th of June 2013. Probabilistic Quantitative Precipitation Forecasts (PQPF) based on GEFS is also examined during the same period.

4. Verification Methods

The evaluation and intercomparison of model rainfall forecasts is carried out with standard verification statistics listed in the end of section 1. Based on the contingency table involving number of hits, correct negatives, misses and false alarms, for different rainfall ranges (10-20 mm and 20-40 mm), POD, ETS and HK score were computed (Stefano and Marco, 2008).

Spatial verification of the rainfall forecasts is carried out using the CRA (contiguous rain area) method. The CRA method is an object-oriented verification procedure suitable for gridded quantitative precipitation forecasts (QPFs). In the CRA framework a weather system is defined as a region bounded by a user specified isopleth (entity) of precipitation in the union of the forecast and observed rain field. The forecast and observed entities need not overlap, but they must be associated with each other, which means that they should be close to each other. For each entity that can be identified in forecast and observations, the CRA method uses pattern matching techniques to determine the location error, as well as errors in area, mean and maximum intensity, and spatial pattern. The total error can be decomposed into components due to location, volume, and pattern error. To estimate the location error, the forecast field is horizontally translated over the observed field until the best match is obtained. The location error is then simply the vector displacement of the forecast. The error due to volume represents the bias in mean intensity and the pattern error accounts for differences in the fine structure of the forecast and observed fields. CRA method was developed for estimating the systematic errors in the rainfall forecasts (Ebert and McBride 2000; Ebert and Gallus 2009). It was one of the first methods to measure errors in predicted location and to separate the total error into components due to errors in location, volume and pattern. The steps involved in CRA technique are described in Ebert and Gallus (2009).

In this study, the CRA method is used for verification of the rainfall forecast over Uttarakhand region. The verification is carried out over common grids of 0.5° resolution. All grids over the neighboring seas and over Himalayas above 4000 m were masked out.

5. Verification of Model Forecasts

5.1 Synoptic features and rainfall

A qualitative summary of verification and intercomparison is presented first mainly involving the synoptic features of the rainfall system. This is followed by a verification of quantitative precipitation forecast (QPF) statistics to quantify the forecast biases in the two models.

Figures 4 and 5 show the observed and predicted rainfall along with circulation and geopotential height at 600 hPa for T574 (approx. 3480 m AMSL; location of flooding). Observed station rainfall (Dehradun), highest observed gridded (NMSG) rainfall and model predicted rainfall amounts for 17th and 18th June are also presented in Table 1. Figure 4 depicts the Day 1, Day 3 and Day 5 forecasts valid on 17th June 2013. Day 1 and Day 3 forecasts show moderate to high rainfall amounts over Uttarakhand and adjoining areas. Day 5 forecasts also show light rainfall over this region (the amount of rainfall is not as high as seen in Day 1 and Day 3 forecasts). However, the highest amount of observed precipitation (Table1; Figure 4(a)) is not captured by the model. From Figure 5 it can be seen that for 18th June, models predicted very high amounts of rainfall (Table 1) in Uttarakhand only in the Day 3 forecast. However, this was absent in the Day 1 and Day 5 forecasts (Figures 5 (d)). For both the dates, Day 3 forecasts shows a small area of heavy rainfall (>16 cm), but this is absent from the Day 5 forecasts.

Figures 6 and 7 show zoomed plot of the observed and model predicted rainfall wind and geopotential height at 600h Pa over Uttarakhand region for 17th and 18th of June

2013 respectively. Day 3 forecasts for 17th June show heavy rainfall (20 cm/day; Table 1) near the reported area of disaster. The plots also show that there is some degree of consensus between the observed and model predicted circulation patterns and geopotential height for Day 1 and Day 3 for 17th June whereas the comparison is poor beyond Day 1 in the case of forecast valid for 18th June. The model is intensifying the inland low pressure system and its position is also much to the southwest of the observed location. In T574 (Figure 4-7) forecasts of the flow is dominated by the cyclonic circulation over Gujarat and Rajasthan particularly in Day 3 and Day 5.

A similar analysis is presented for NCUM (Figures 8-11). Figure 8 and table 1 valid for 17th June show that the observed highest rainfall amounts are underestimated by approximately 50% for Day 1, Day 3 and Day 5 forecasts for 17th June. The rainfall pattern is also slightly displaced from its observed location in the Day 1, Day 3 and Day 5 forecasts. However, the model predicted rainfall for 18th of June shows that the amount of rainfall (maximum amount; Table 1) is nearly accurate for Day 1 and Day 3 forecasts (the observed highest rainfall amount are overestimated by 0.06% for Day 1 and underestimated by 20% for Day 3 forecast). Further the circulation (Figures 10 and 11) shows that the low pressure system is forecasted with moderate intensity and its location is also correctly predicted in Day 5 forecasts.

5.2 Verification of QPF statistics

Figures 12 and 13 show the POD, ETS and HK score in the form of bar graphs for Day 1 to Day 5 forecasts of T574 and NCUM valid for 17th and 18th June respectively. These statistics were calculated for two different rainfall thresholds (10-20 mm; left panels and 20-40 mm; right panels) for both the models. These statistics were calculated based on a contingency table, which contains the number of hits, correct negatives, misses and false alarms.

POD is defined as the fraction of observed events that were also correctly forecasted; therefore a high POD indicates good forecast skill of a model. From the two figures, it is seen that POD is consistently higher for NCUM (Day 1 to Day 5) for the forecast valid on 17th. However, for the forecast valid on 18th of June, for 10-20 mm rainfall threshold NCUM consistently shows a higher POD than T574 as in the previous case. On the other hand, for 20-40 mm rainfall threshold T574 shows a higher POD for

Day 1 and Day 2 forecasts as compared to NCUM. For Day 3 to Day 5 forecasts, in the same rainfall threshold, NCUM once again shows a higher POD than T574.

Threat Score (TS or Critical Success Index [CSI]) measures the fraction of observed and/or forecast events that were correctly predicted. It can be thought of as the accuracy when correct negatives have been removed from consideration, i.e., TS is only concerned with forecasts that count. TS depends on climatological frequency of events (poorer scores for rarer events) since some hits can occur purely due to random chance. Therefore, ETS was designed to help offset this tendency. ETS measures the fraction of events that are correctly predicted accounting for hits by random chance. For 17th June ETS is higher for Day 1 to Day 5 forecasts obtained from NCUM. For the Day 1 and Day 2 forecasts valid on 18th June, ETS in T574 is higher for both the rainfall thresholds. However, for Day 3 to Day 5 NCUM shows a higher ETS as compared to T574 for both the rainfall thresholds. Also ETS decreases with increasing forecast lead time for both the models. HK score, also known as the True Skill Score (TSS), is defined as the difference between the hit rate and the false alarm rate (Hansen and Kuiper, 1965). A high HK score indicates more hits relative to false alarms. In this case NCUM shows a higher HK score for the forecast valid on 17th June. The HK score for NCUM is much closer to 1 (a perfect score) for Day 1 and Day 2 forecasts and decreases after this for 10-20 mm rainfall threshold. However, for 20-40 mm rainfall threshold the score values are lower for both the models. For Day 1 forecast valid on 18th June, T574 shows a higher HK score than NCUM, but from Day 2 to Day 5 forecasts NCUM shows better skills than T574.

5.3 CRA Verification for Rainfall on 17th and 18th June 2013

As a first step of CRA analysis entities (defined in section 4) based on rainfall rates were obtained. As an example: during the southwest monsoon season large parts of India regularly receive widespread rainfall in excess of 10 mm/day. Rainfall exceeding lower thresholds (1, 2 and 5 mm/day) spreads the CRA across large geographical areas, CRAs defined by higher thresholds of 10, 20, 40 and 80 mm/day are used to isolate the events corresponding to a region and are associated with specific rain systems (offshore trough, monsoon trough, Bay of Bengal low pressure etc.).

As a next step, a pattern matching technique is used for estimating the location error. Here the forecast field is horizontally translated over the observed field until the best match is obtained. The location error is then simply the vector displacement of the forecast. The best match between the two entities can be determined either: (a) by maximizing the correlation coefficient, (b) by minimizing the total squared error, (c) by maximizing the overlap of the two entities, or (d) by overlaying the centres of gravity of the two entities. For a good forecast, all the methods should give very similar location errors. In the present study the best match is determined by maximizing the correlation. The mean squared error (MSE) and its decomposition (location error, volume error and pattern error) are done as shown below:

$$MSE_{Total} = (F - O)^2 + (s_O - rs_F)^2 + (1- r^2)^2\, s_F \quad (1)$$

where F (s_F) and O (s_O) are the mean (standard deviation) values of the forecast and observed precipitation respectively before obtaining the best match via shifting the forecast.

The spatial correlation between the original forecast and observed features (r) increases to an optimum value (r_{OPT}) in the process of correcting the location via pattern matching. The contribution to total error due to displacement, volume and pattern errors are estimated as:

$MSE_{Displacement} = 2s_Fs_O\,(r_{OPT} - r)$,

$MSE_{Volume} = (F' - O')$, and (2)

$MSE_{Pattern} = 2s_Fs_O\,(1 - r_{OPT}) + (s_F - s_O)^2$

where F′ and O′ are the mean values after shifting.

Figures 14-16 and Figures 17-19 show the CRA verification statistics for T574 and NCUM for Day 1, Day 3 and Day 5 forecasts valid for 17th and 18th of June respectively. The values tabulated in Figure 14-16 and 17-19 correspond to the region of heavy rainfall (>=40 mm/day CRA).

The figures also summarize the observed and forecast average rain rate (mm/day), maximum rain (mm/day) and rain volume (km^3). From Day 1, Day 3 and Day 5 forecast (Figure 14-16) of T574 it can be seen that the average rain rate and rain volume are largely underestimated. The percentage error in the average rain rate and the rain volume for T574 on 17th of June ranges from 50% (Day 1 forecast) to 73 % (Day 5 forecast). For 18th June the error ranges from 39% in the Day 1 forecast to 56% in the Day 5 forecast. On the other hand NCUM forecast for 17th (Figure 14-16) and 18th (Figure 17 and 18) show that the average rain rate and the rain volume match better than T574 with the observed values. The percentage error in the average rain rate and rain volume for Day 1 and Day 5 forecast valid on 17th June is 13% and 17% respectively. However, for Day 3 forecast the percentage error is 25%. For 18th June, Day 1 and Day 3 forecasts show a small percentage error in average rain rate and rainfall volume (ranges from 0.06% to 18%). Day 5 forecast, from NCUM (Figure 19), valid on 18th June shows a poor match between the forecast and observations (60% error).

The figures 14-19 also show the RMSE and Correlation Coefficient (CC) for the original and shifted rainfall (i.e., before and after the CRA procedure). The two tabulated values of CC are a direct indicator of forecast accuracy. For forecasts with large errors improvement in CC from analyzed (left) to forecast (right) is large (Grams et al., 2006). For accurate forecasts this change is small as evident in Figure 18 for NCUM forecast. Additionally CRA verification provides decomposition of forecast errors in terms of displacement, volume and pattern error (section 5.2). Displacement and pattern errors are associated with errors in dynamics (predicted flow) while volume error is associated with errors in physics (moisture) treatment. These components provide guidance for model developers when the statistics of error components are studied for large sample of cases. In this case study for two days the CRA statistics (displacement, volume and pattern errors) should be interpreted with caution.

5. Ensemble Prediction

Global Ensemble Forecast System (GEFS) is an ensemble prediction system that is currently running at NCMRWF. The most important product of an ensemble prediction system is the probability of occurrence of a particular event. In the case of rainfall observed in Uttarakhand on 17th and 18th of June 2013 we have tried to see with what probability the rainfall was predicted by GEFS. We are only presenting the figures for forecasts valid on 18th June as the predictions for 17th June show very similar patterns and probabilities. Figure 20 shows the spatial plots for rainfall probabilities valid on 18th June 2013 within the range 5 – 10 cm/day. From this figure, it is observed that for Day 1 and Day 3 there is a 65% to 95% chance of getting 5 to 10 cm of rainfall. For Day 5 forecast valid on 18th June the probability ranges from 35% to 65% for the same rainfall range (5-10cm/day) and rainfall area is also seen to be shifted towards north of the actual locations. Day 7 and Day 9 again show the same rainfall range with a lower probability (5% to 35%) and a shift in the rainfall band. Figure 21 (Figure 22) shows the Day 3 (Day 5) forecast postage stamp plot for 18th June. It is seen that most of the members are showing high rainfall (exceeding 16 cm/day) in northern regions of India. The location of observed rainfall in Uttarakhand is not very well captured in these plots and a reason for this may be the displacement of rainfall area in the T574 (parent deterministic model for GEFS) forecasts. Looking at the postage stamp plots of ensemble members from GEFS, from Day 5 and Day 6 forecasts valid on 18th June 2013, it was observed that there were some members that were predicting high rainfall within the vicinity of the area under consideration. However, the number of members predicting this was small and therefore this result was not reflected in the probabilistic rainfall output. Even for Day 7 forecast valid on 18th June, rainfall in excess of 8-16 cm/day was predicted by some GEFS members.

6. Conclusions

Based on the above observations and statistics we can draw the following conclusions about the performance of T574 and NCUM:

1) The rainfall event in Uttarakhand is captured in the models-
    i. Day-1 and Day-2 in T574 for 17th and 18th
    ii. Day-1 through Day-5 in NCUM for both 17th and 18th
2) The circulation associated with the rainfall in Uttarakhand is captured in -
    i. Analysis valid for 15-18 June 2013 generated from both the models (T574 and NCUM) was able to capture the interactions between the low pressure system and the WD which is also well described in the weather report of 19th June 2013 by IMD.
    ii. T574 forecasts (Day-1 and Day-2) valid for 17th and 18th. For all other forecasts, the flow is dominated by the intense low pressure system over Gujarat.
    iii. NCUM forecasts (Day-1 through Day-5) valid for 17th and 18th. The flow is consistently dominated by the mid-latitude trough (WD) and interaction with the low over North India.

3) Based on various verification scores, NCUM shows better skill as compared to T574 for Day 1 to Day 5 forecasts valid on 17th June as well as Day 3 to Day 5 forecasts valid on 18th June. However, T574 shows better skills for Day 1 and Day 2 forecasts valid on 18th June.

4) From the CRA verification statistics of average rain, rain volume and maximum rain it can be concluded that NCUM performs better in predicting rainfall as compared to T574 for this event. The percentage error in average rain rate and rain volume for T574 ranges from 50% to 80% on 17th June and 40% to 56% on 18th June. On the other hand for NCUM for 17th June the percentage errors in Day 1 and Day 5 forecasts are lower than those in Day 3 forecast. For 18th June the percentage error for Day 1 and Day 3 forecasts ranges from 0.06% to 18% and for Day 5 is 60%.

5) Global Ensemble Forecast System shows some promising results in terms of probabilities of the rainfall events. However, due to the lower resolution of the GEFS (1°x1°) and fewer ensemble members, its outputs are not seen to have forecast skills as good as the other deterministic models mentioned in this report. There is an ongoing effort for making GEFS outputs better by correcting model bias and downscaling the outputs. Probabilistic verification statistics are being generated to enable ascertaining the effect of ensembles in forecasting extreme events.

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http://www.imd.gov.in/section/nhac/forecast_7days/archive/ai17062013mor.pdf

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http://www.ndmindia.nic.in/flood-2013/floodsJuly-2013.htm

Disaster Update by the National Institute of Disaster Management (NIDM):

http://nidm.gov.in/PDF/DU/2013/June/19-06-13.pdf

Date	Observed Rainfall (cm/day)		Forecast Rainfall (cm/day)					
			Day 1		Day 3		Day 5	
	Station (Dehradun)	Gridded (NMSG)	T574	NCUM	T574	NCUM	T574	NCUM
17-06-2013	37.0	24.9	12.9	14.7	20.3	10.5	6.8	15.3
18-06-2013	28.0	28.6	11.9	28.8	27.9	22.9	18.0	9.9

Table 1: Observed and forecast rainfall on 17th and 18th June.
Observed station rainfall is recorded at Dehradun while the observed (NMSG) gridded and forecast rainfall amounts are the highest rainfall over the region of Uttarakhand (i.e., in a 2°x2° grid box encompassing Uttarakhand)

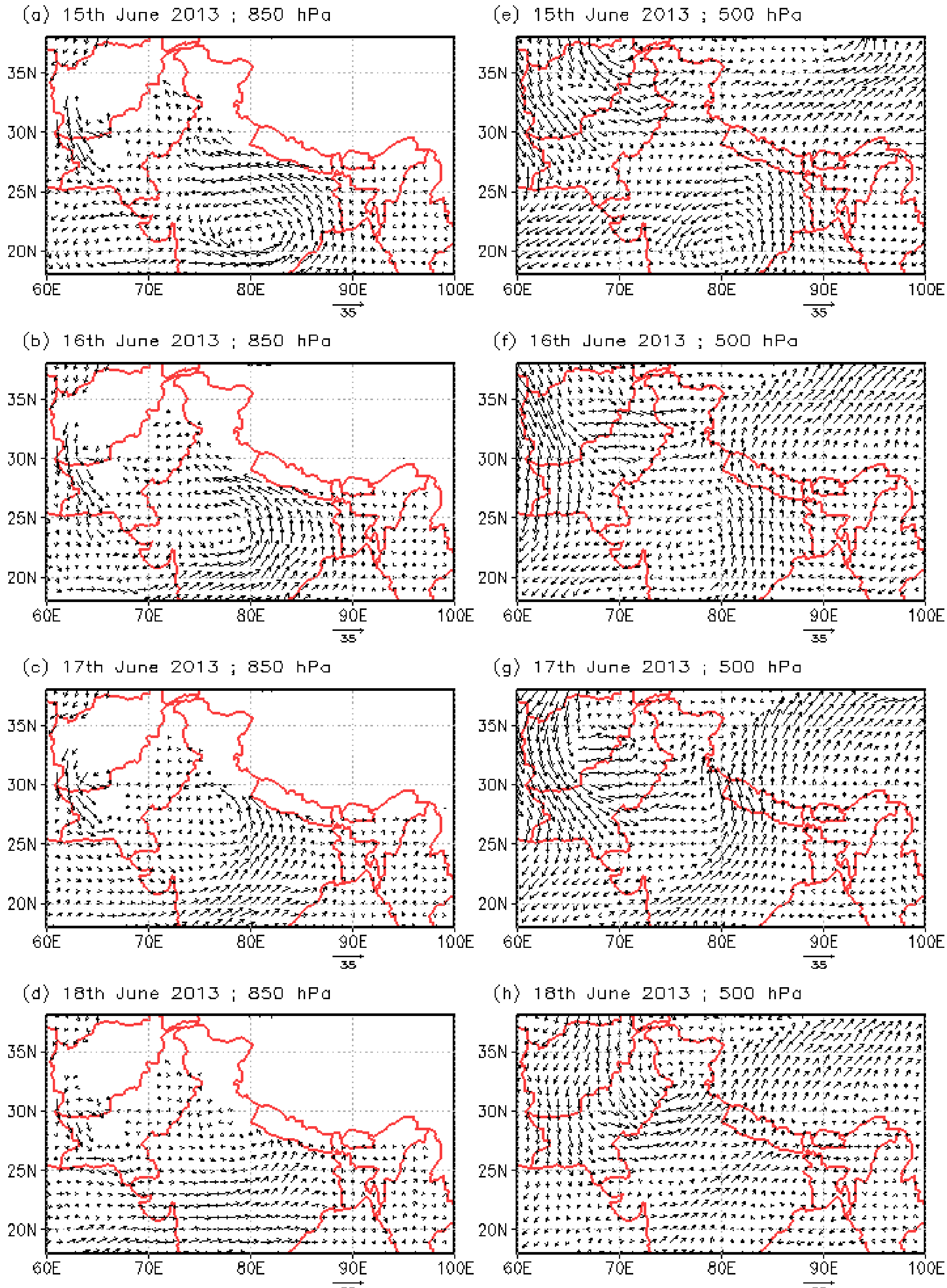


Figure 1: 850 hPa (a-d) and 500 hPa (e-h) Wind Analysis (m/s) from NCUM for 15th, 16th, 17th and 18th June 2013

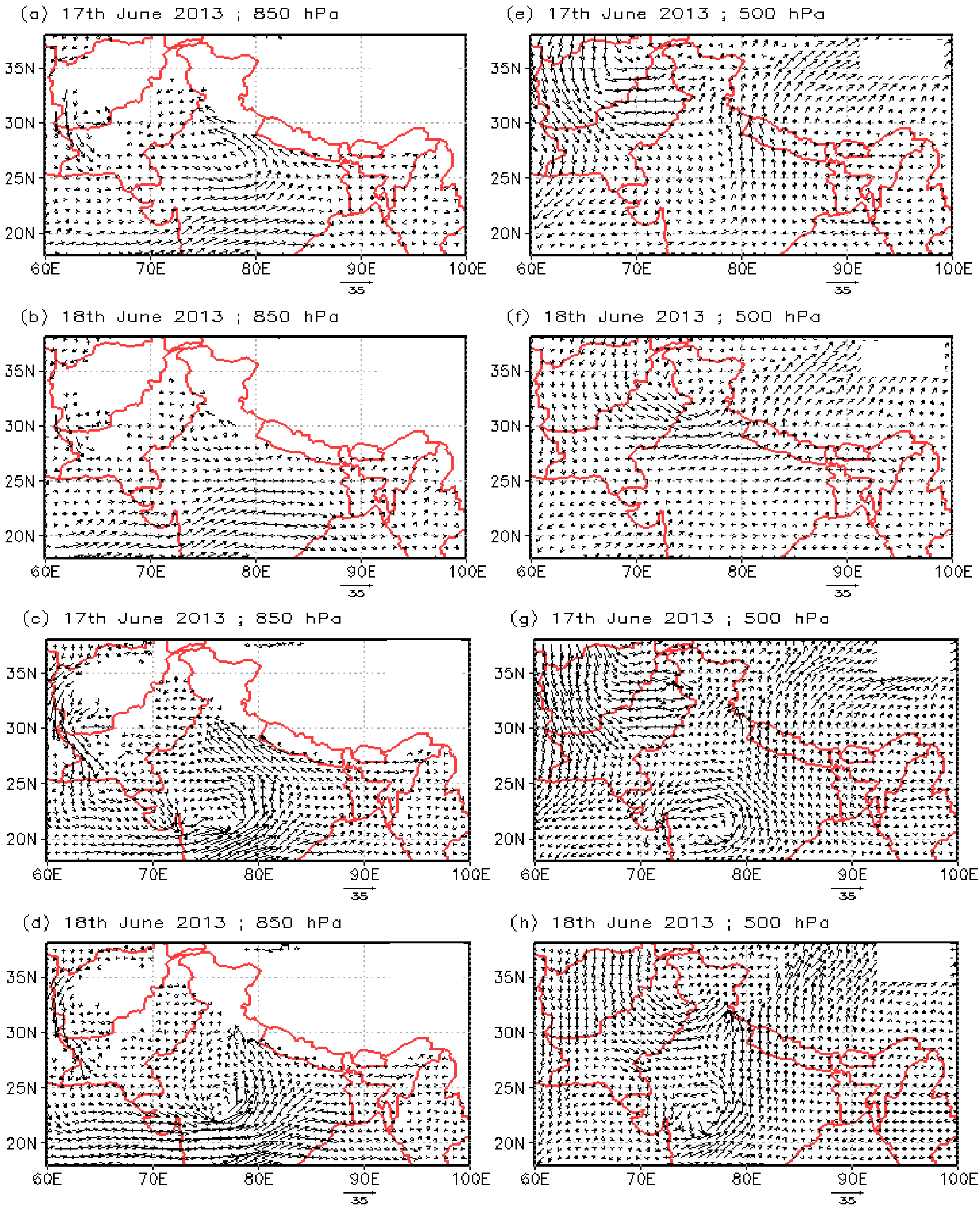


Figure 2: Day 3 forecast 850 hPa and 500 hPa Wind (m/s) from NCUM and T574, valid on 17th and 18th of June 2013

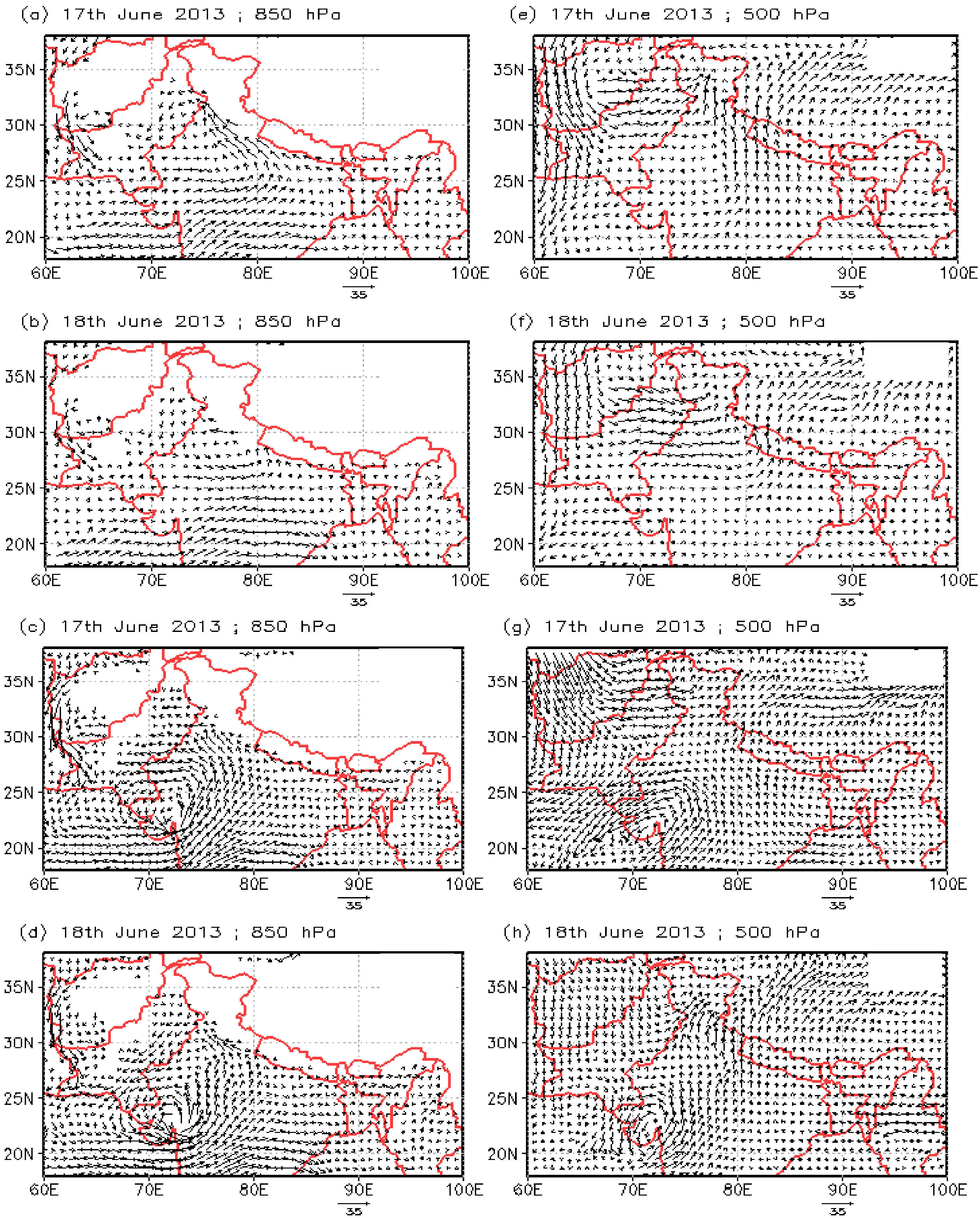


Figure 3: Day 5 forecast of 850 hPa and 500 hPa Wind (m/s) from NCUM and T574, valid on 17th and 18th of June 2013

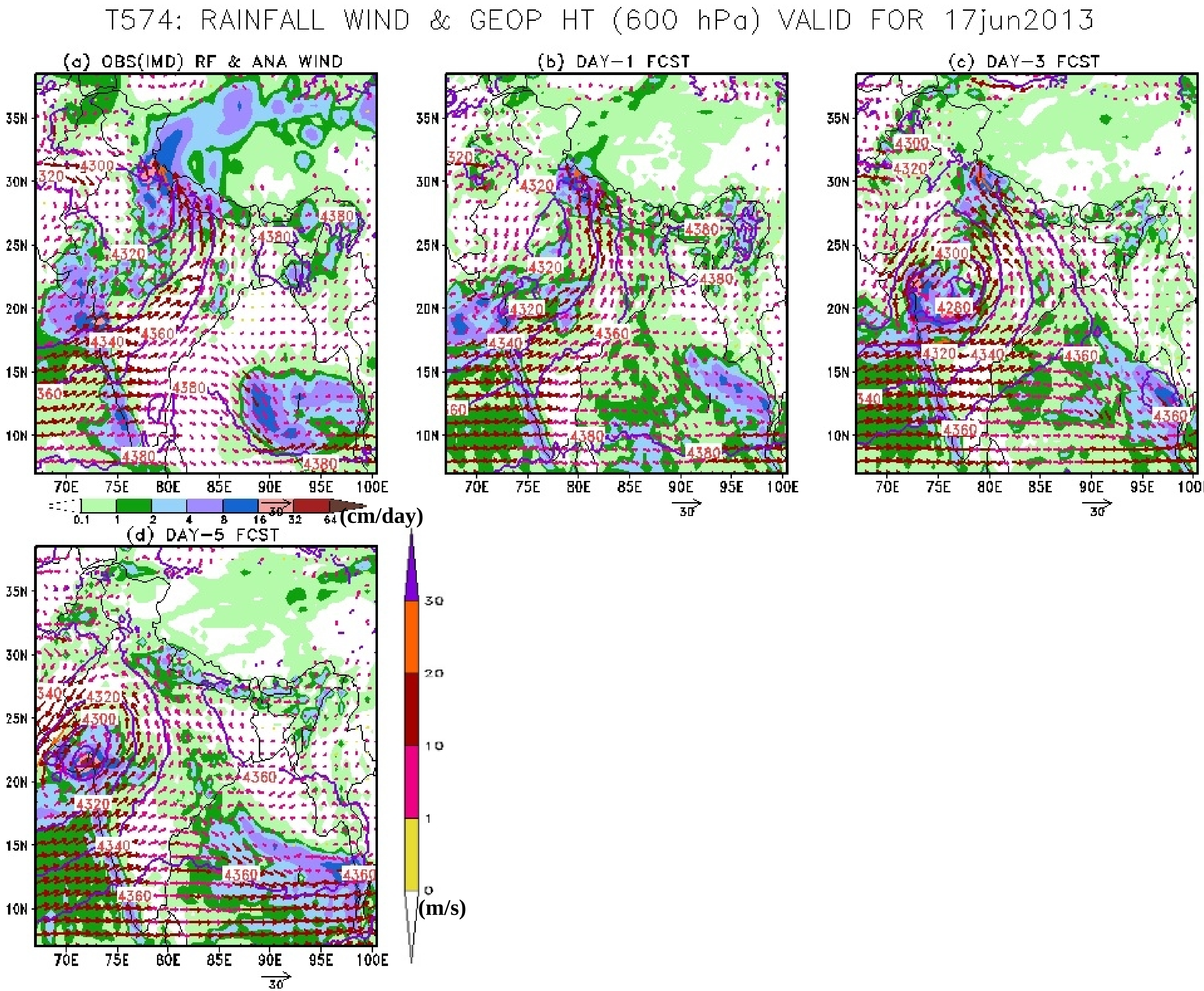


Figure 4: Observed and T574 Model Predicted rainfall (cm/day) over Indian region valid for 03Z17June 2013

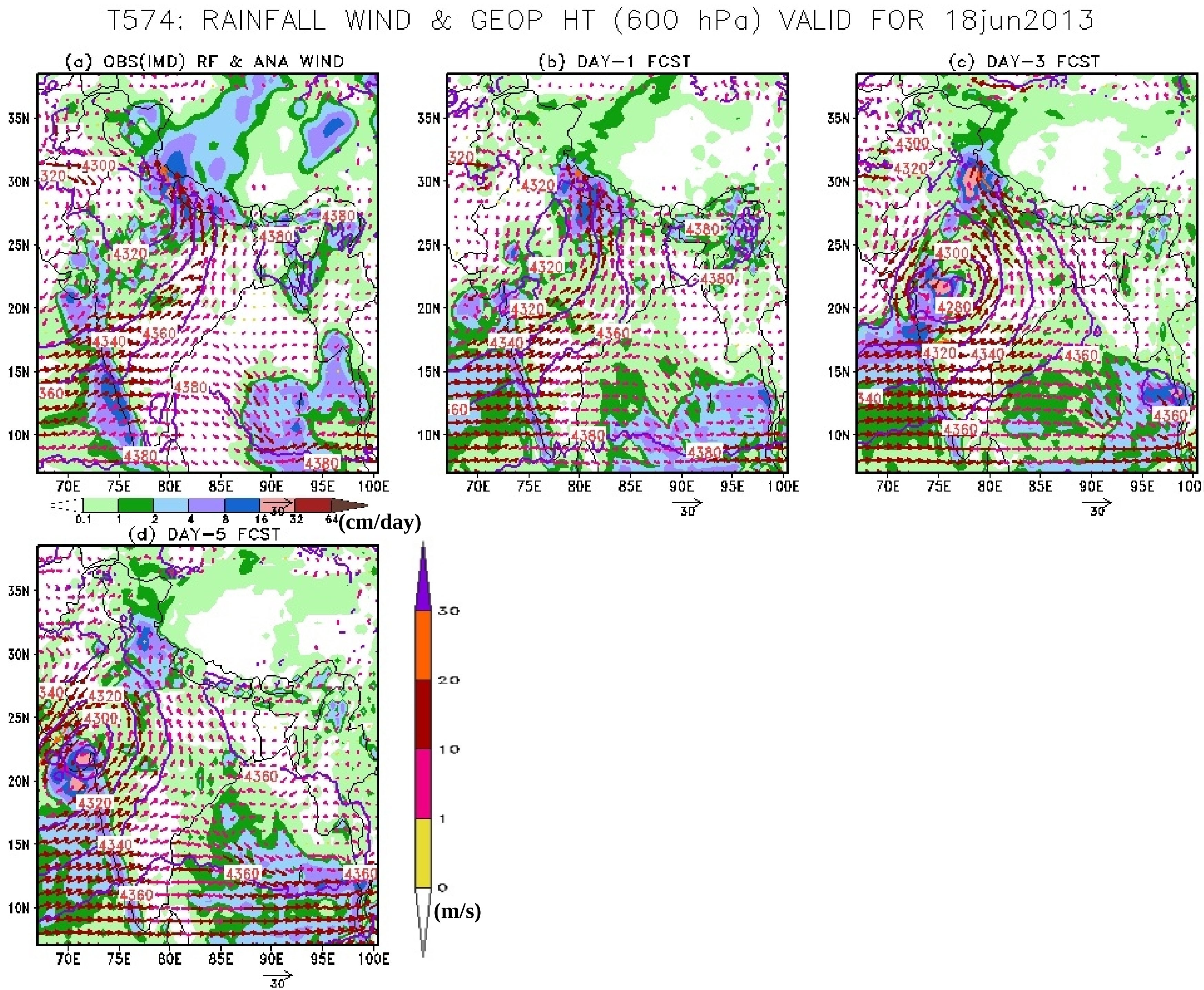


Figure 5: Observed and T574 Model Predicted rainfall (cm/day) over Indian region valid for 03Z18June 2013

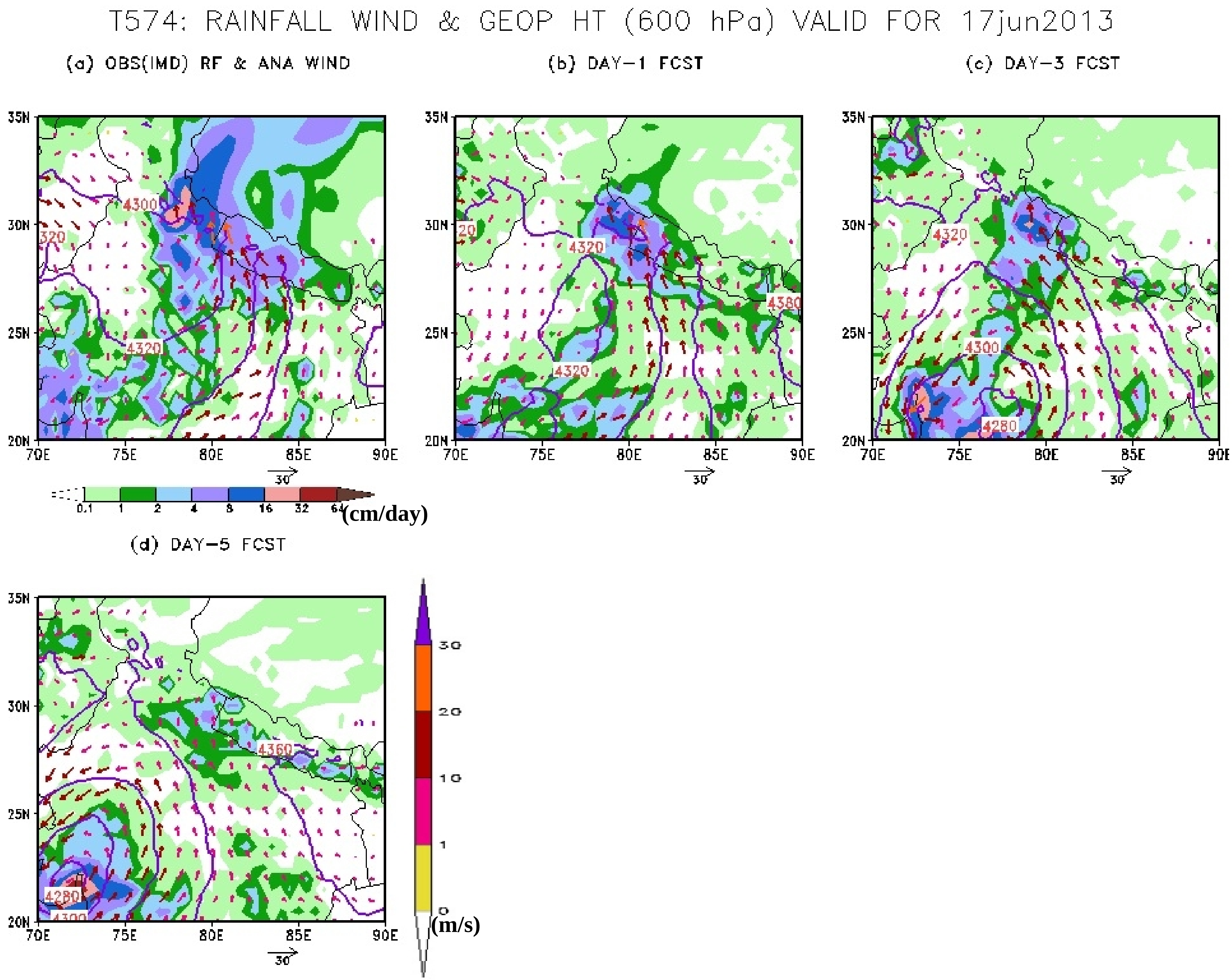


Figure 6: Observed and T574 Model Predicted rainfall (cm/day), 650 hPa circulation (m/s) and geopotential height over Indian region valid for 03Z17June 2013

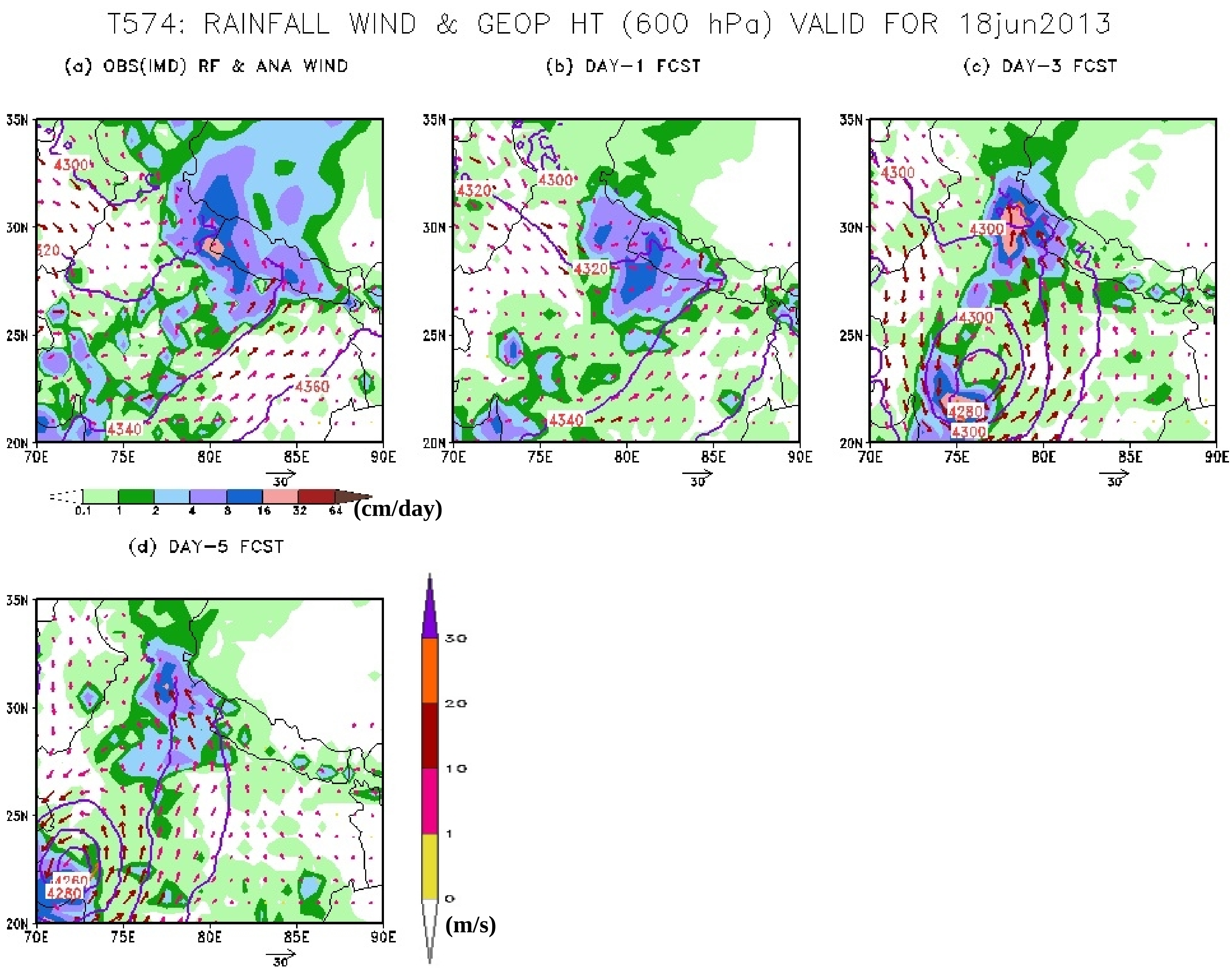


Figure 7: Observed and T574 Model Predicted rainfall (cm/day), 650 hPa circulation (m/s) and geopotential height over Indian region valid for 00Z18June 2013

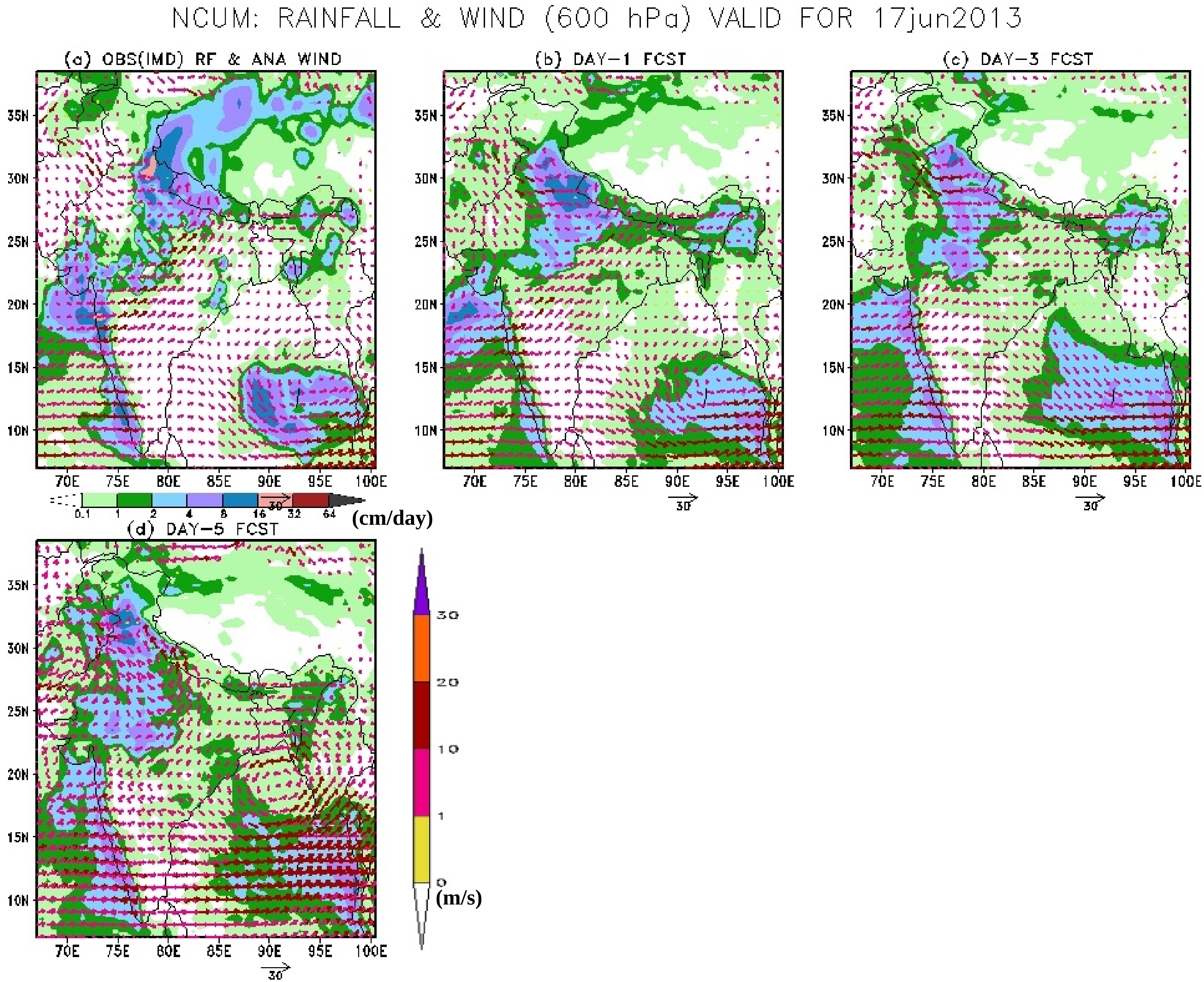


Figure 8: Observed and NCUM Model Predicted rainfall (cm/day) over Indian region valid for 03Z17June 2013

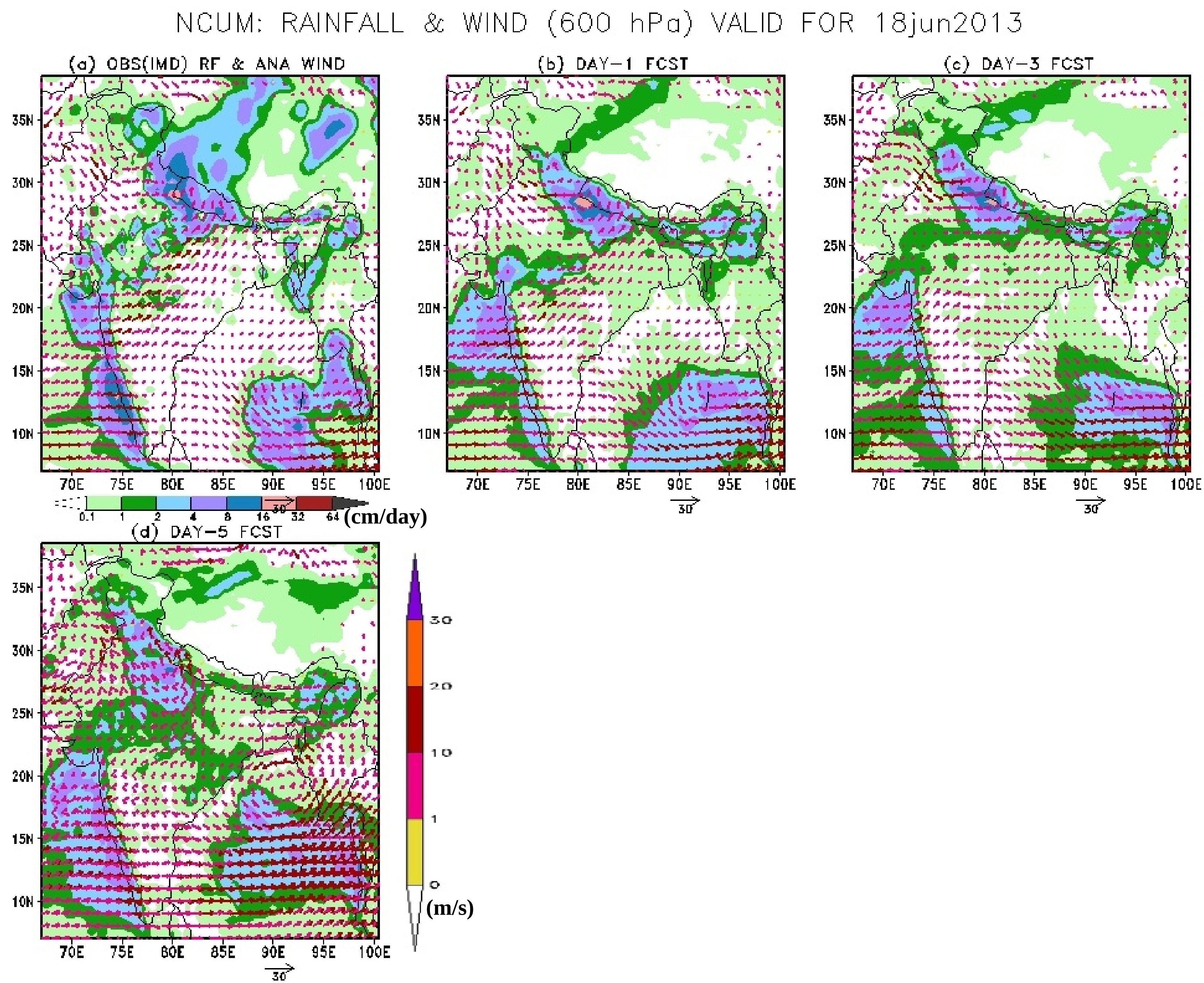


Figure 9: Observed and NCUM Model Predicted rainfall (cm/day) over Indian region valid for 03Z18June 2013

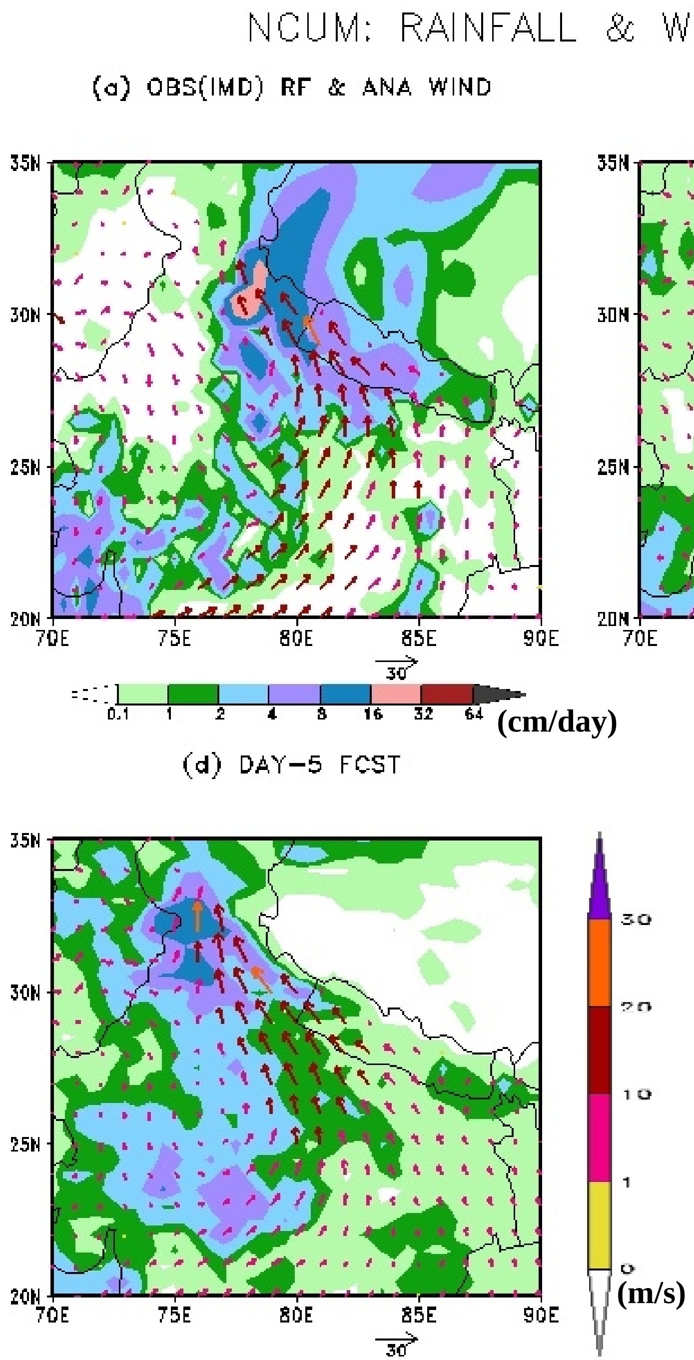


Figure 10: Observed and NCUM Model Predicted rainfall (cm/day) and 600 hPa circulation (m/s) over Indian region valid for 03Z17June 2013

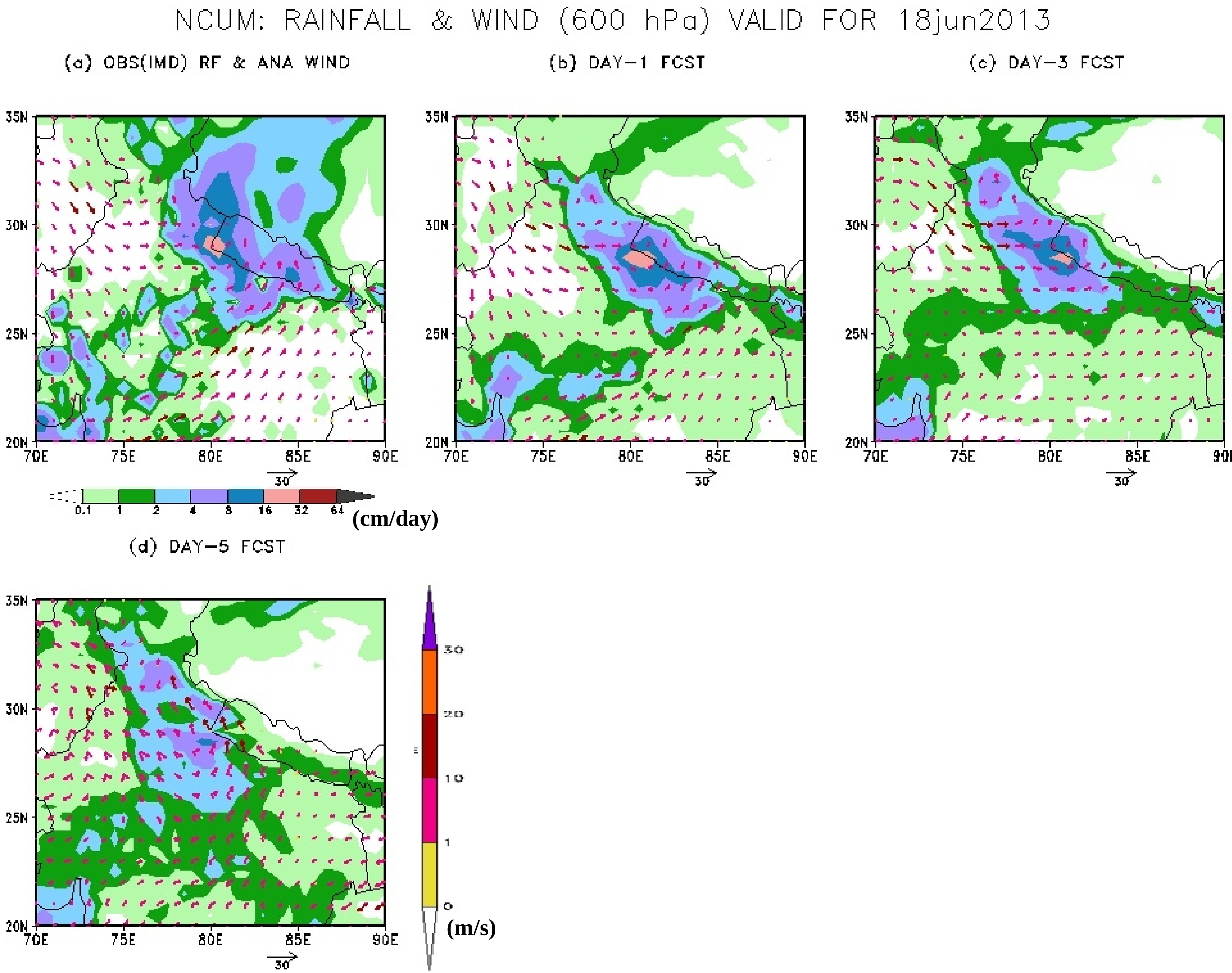


Figure 11: Observed and NCUM Model Predicted rainfall (cm/day) and 600 hPa circulation (m/s) over Indian region valid for 00Z18June 2013

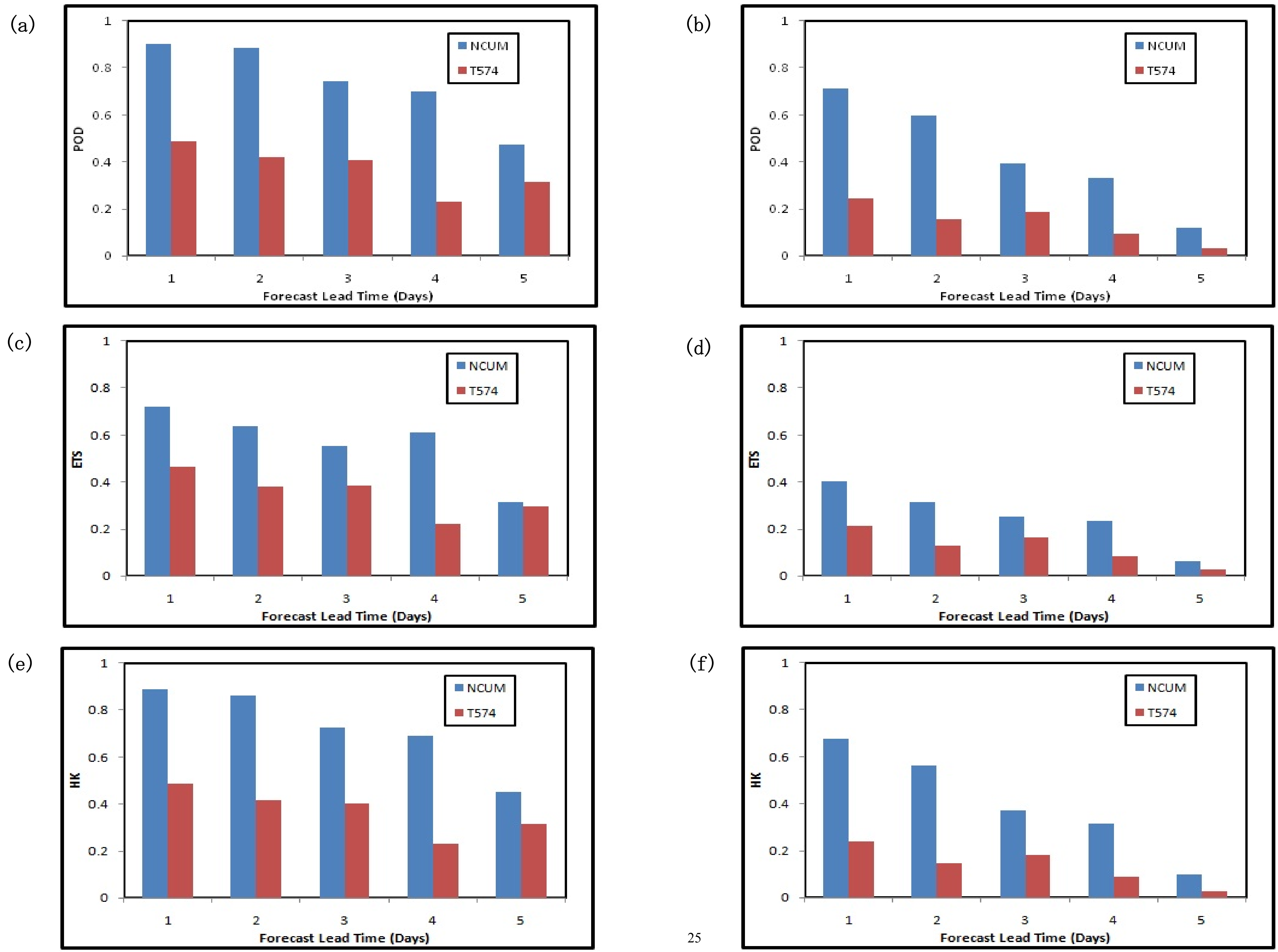


Figure 12: Bar graphs showing the various statistics for T574 and NCUM for Day 1 to Day 5 forecasts valid for 17th June 2013 based on 10-20 mm (a,c and e) and 20-40 mm (b, d and f) rainfall thresholds.

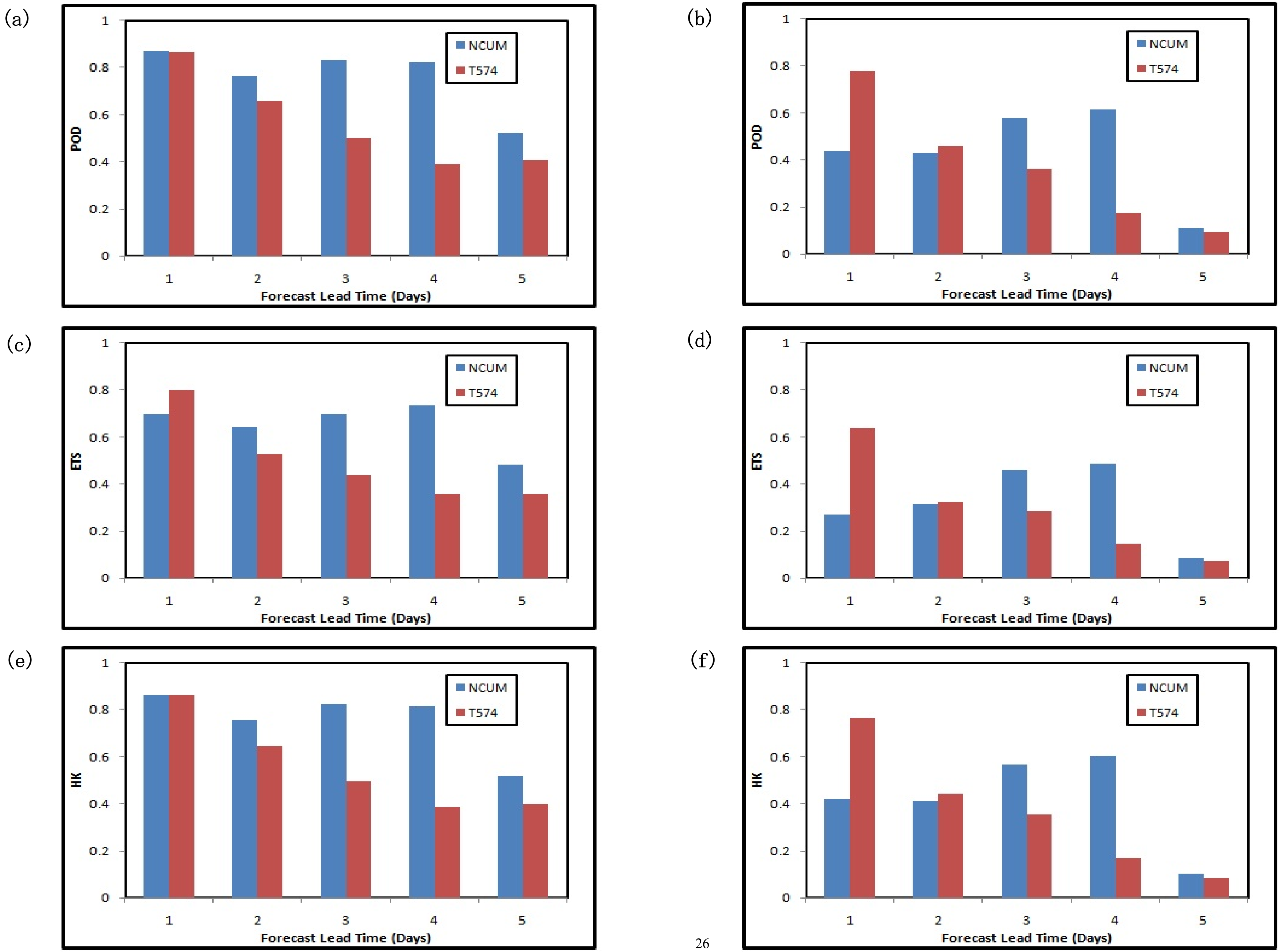
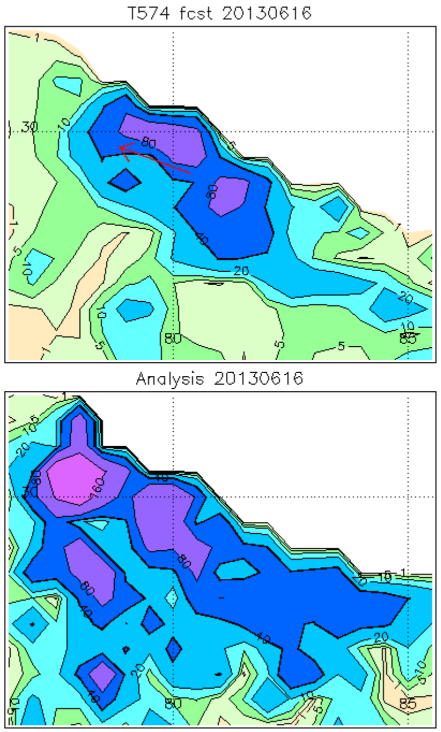
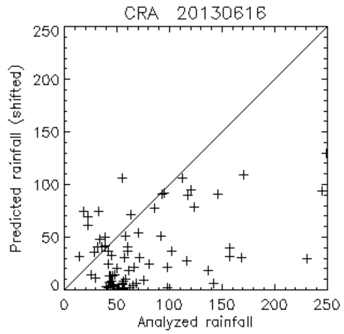


Figure 13: Bar graphs showing the various statistics for T574 and NCUM for Day 1 to Day 5 forecasts valid for 18th June 2013 based on 10-20 mm (a,c and e) and 20-40 mm (b, d and f) rainfall thresholds.





T574 00–24 fcst 20130616 n=78
(26.00°,77.00°) to (31.50°,85.00°)
Verif. grid=0.500° CRA threshold=40.0 mm/d

	Analysed	Forecast
# gridpoints ≥40 mm/d	65	22
Average rainrate (mm/d)	73.83	34.48
Maximum rain (mm/d)	248.72	129.25
Rain volume (km³)	15.55	7.26

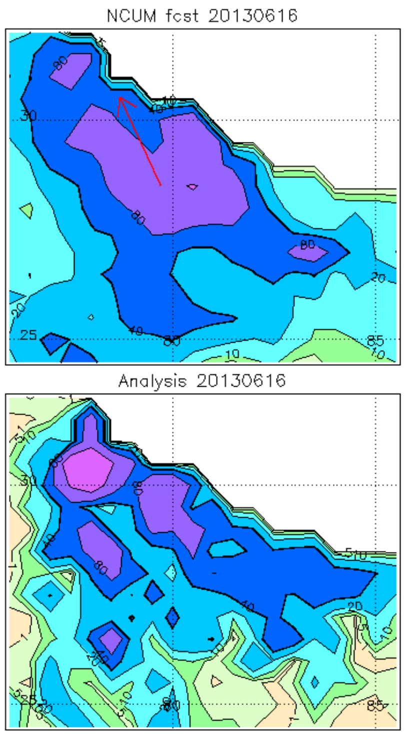
Displacement (E,N) = [1.50°,−0.50°]

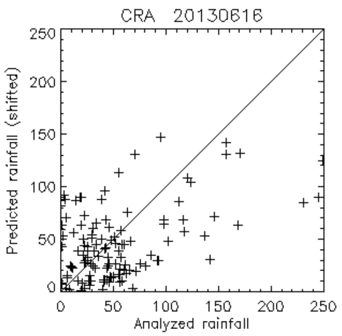
	Original	Shifted
RMS error (mm/d)	71.52	60.48
Correlation coefficient	0.060	0.440

Displacement may be wrong – correlation not signif.

Error Decomposition:

Displacement error	23.5%
Volume error	35.8%
Pattern error	40.7%





NCUM 00–24 fcst 20130616 n=121
(25.00°,76.50°) to (31.50°,85.00°)
Verif. grid=0.500° CRA threshold=40.0 mm/d

	Analysed	Forecast
# gridpoints ≥40 mm/d	66	91
Average rainrate (mm/d)	53.02	45.64
Maximum rain (mm/d)	248.72	146.87
Rain volume (km³)	17.41	14.98

Displacement (E,N) = [1.00°,−2.00°]

	Original	Shifted
RMS error (mm/d)	54.22	46.21
Correlation coefficient	0.229	0.445

Displacement may be wrong – >25% of fcst removed

Error Decomposition:

Displacement error	24.7%
Volume error	4.4%
Pattern error	71.0%

Figure 14: CRA comparison between analysis and Day 1 rainfall obtained from T574 and NCUM for 03Z of 17 June 2013

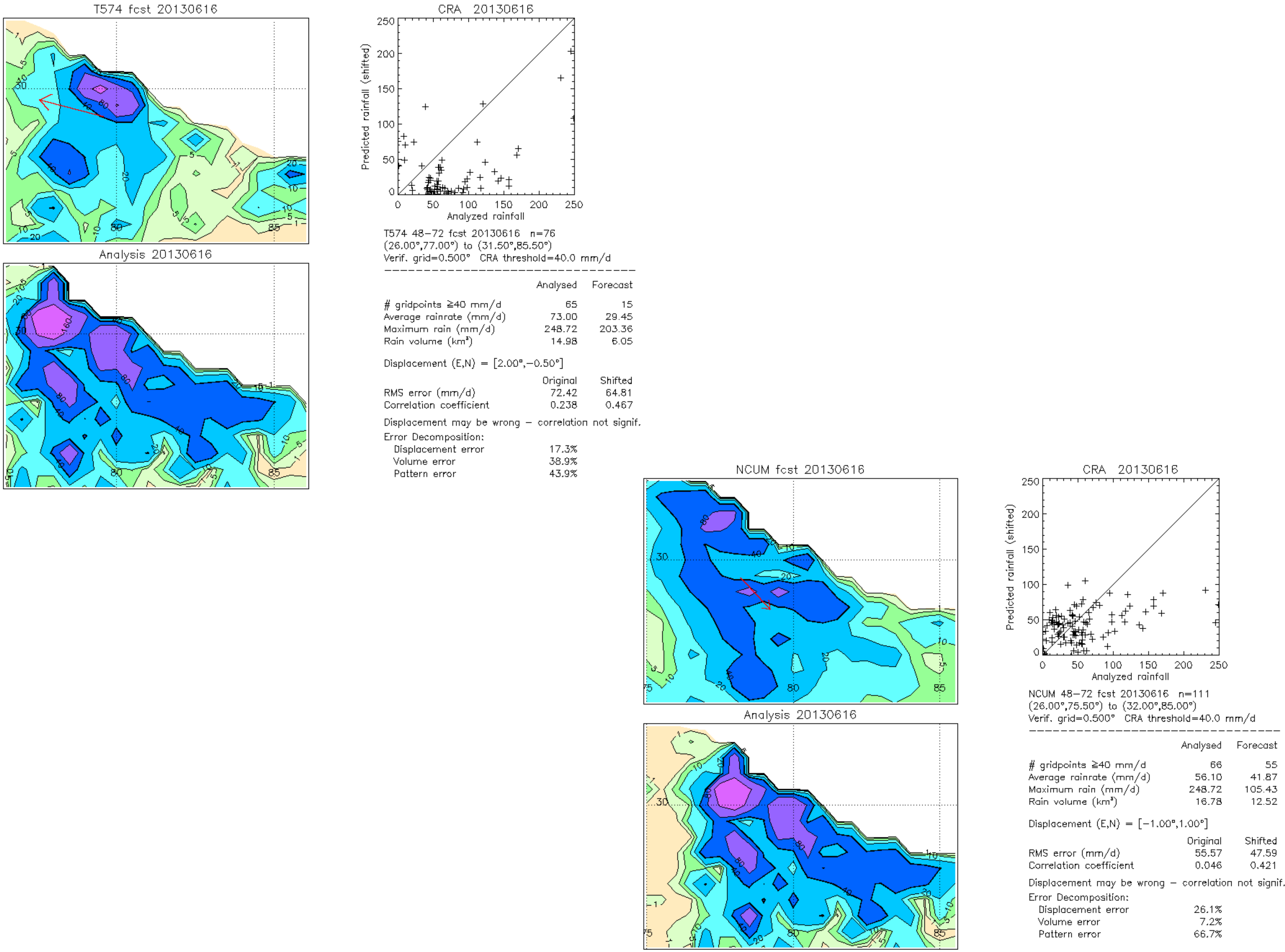
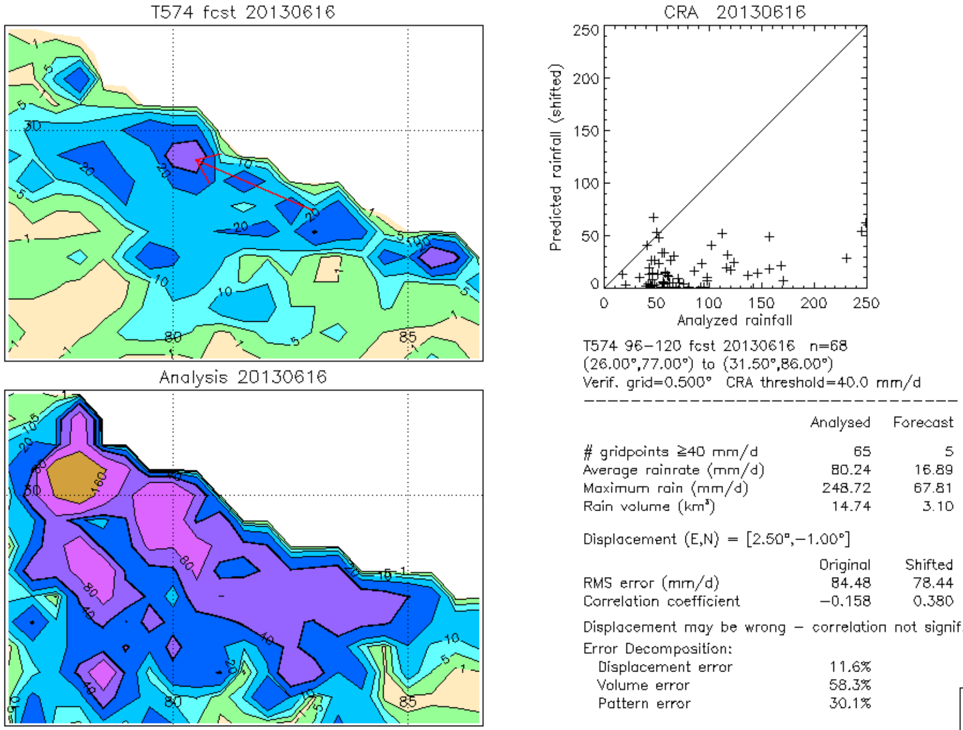


Figure 15: CRA comparison between analysis and Day 3 rainfall obtained from T574 and NCUM for 03Z of 17 June 2013



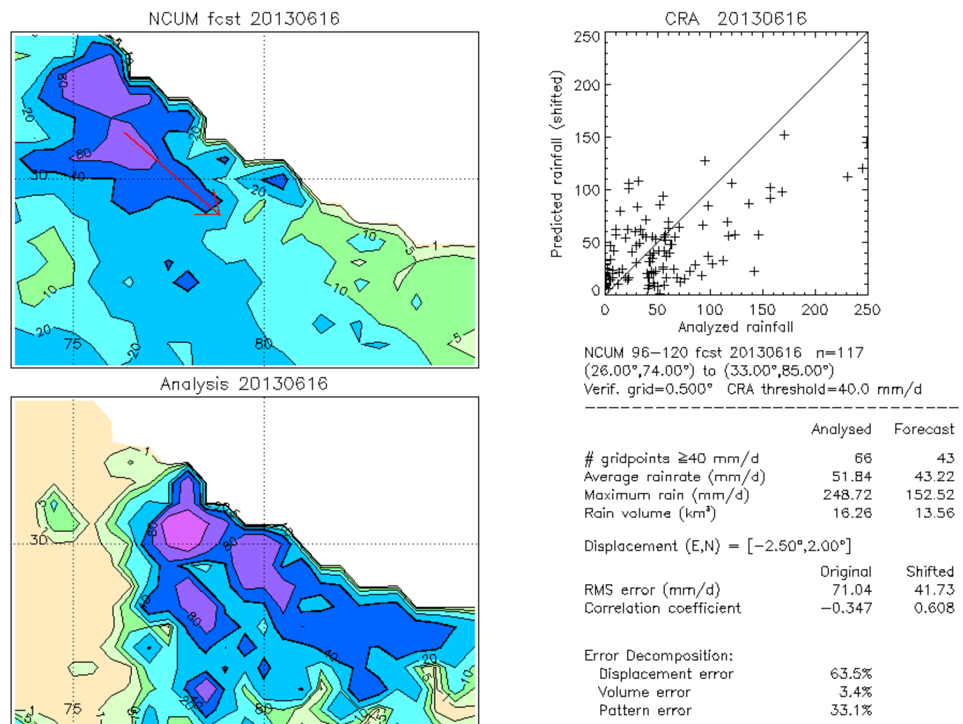


Figure 16: CRA comparison between analysis and Day 5 rainfall obtained from T574 and NCUM valid for 03Z of 17 June 2013

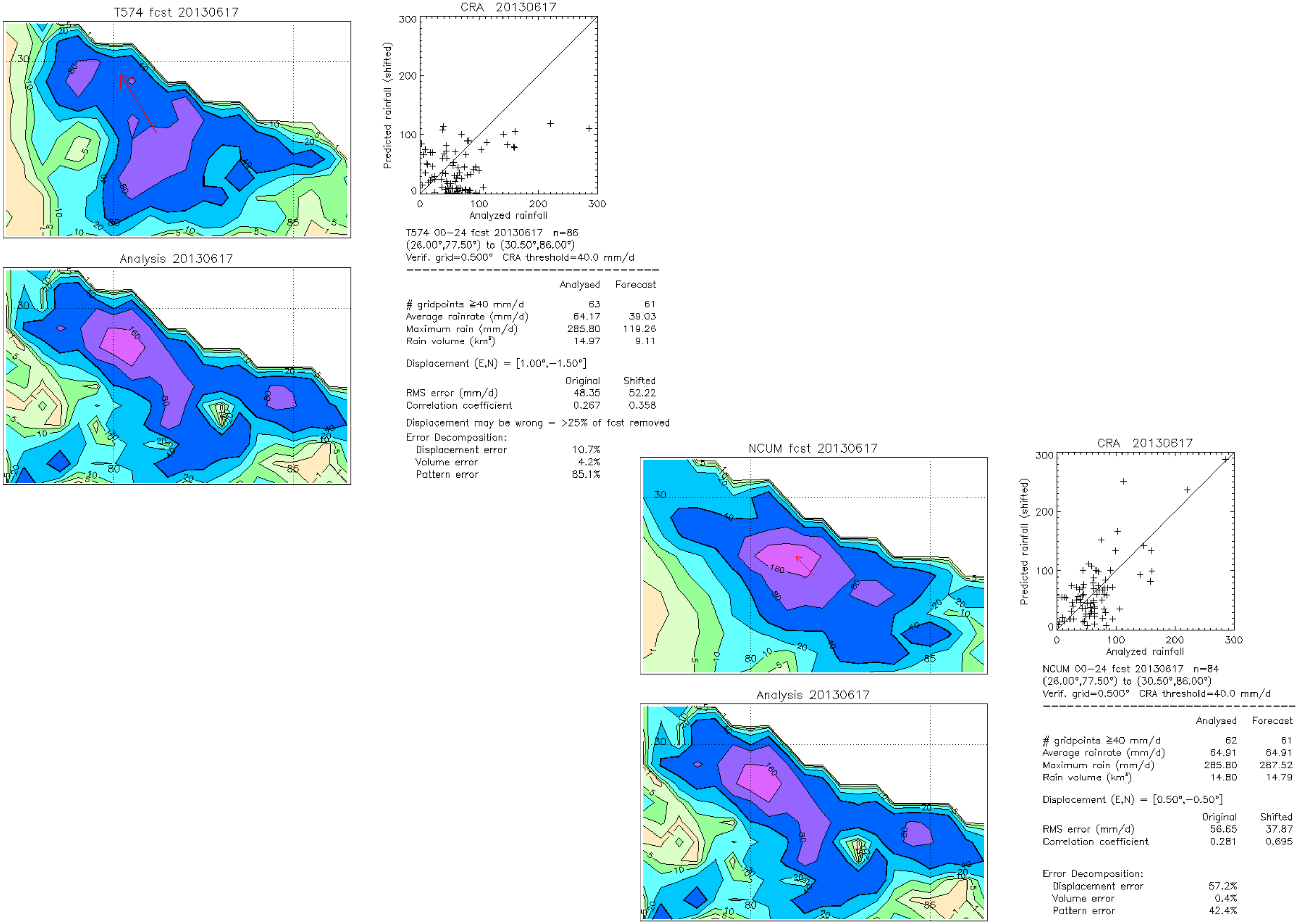


Figure 17: CRA comparison between analysis and Day 1 rainfall obtained from T574 and NCUM valid for 03Z of 18 June 2013

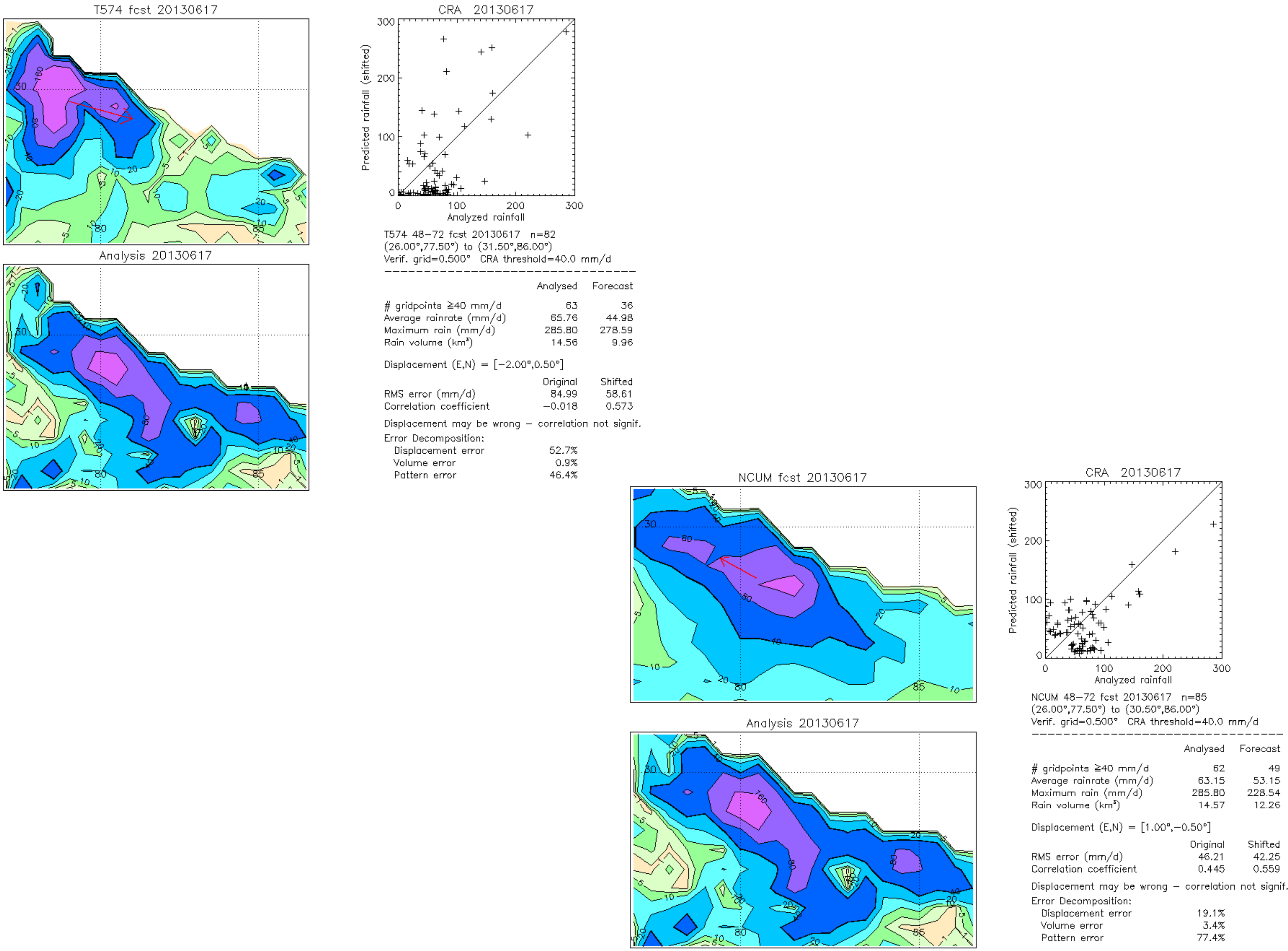


Figure 18: CRA comparison between analysis and Day 3 rainfall obtained from T574 and NCUM valid for 03Z of 18 June 2013

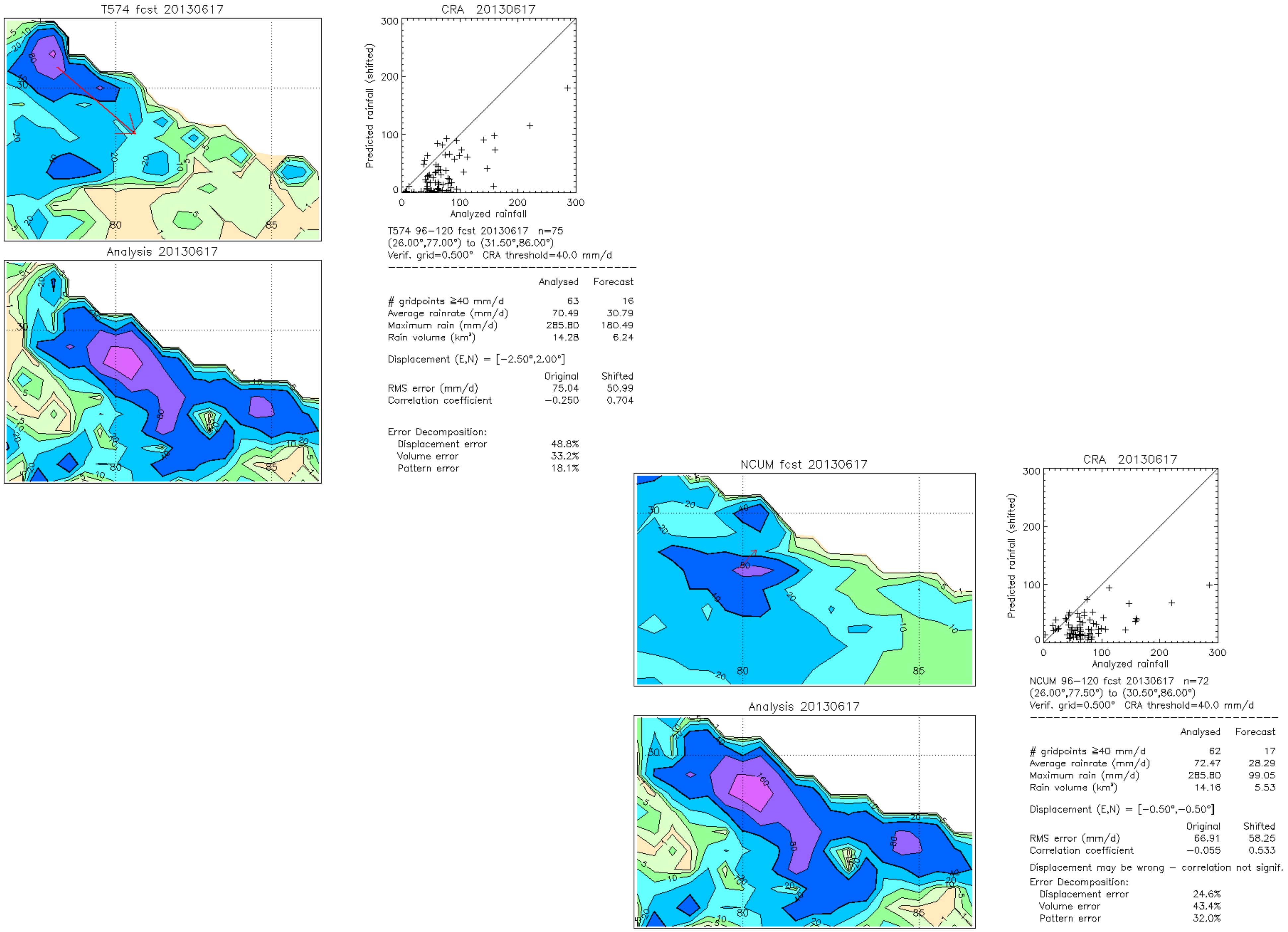


Figure 19: CRA comparison between analysis and Day 5 rainfall obtained from T574 and NCUM valid for 03Z of 18 June 2013

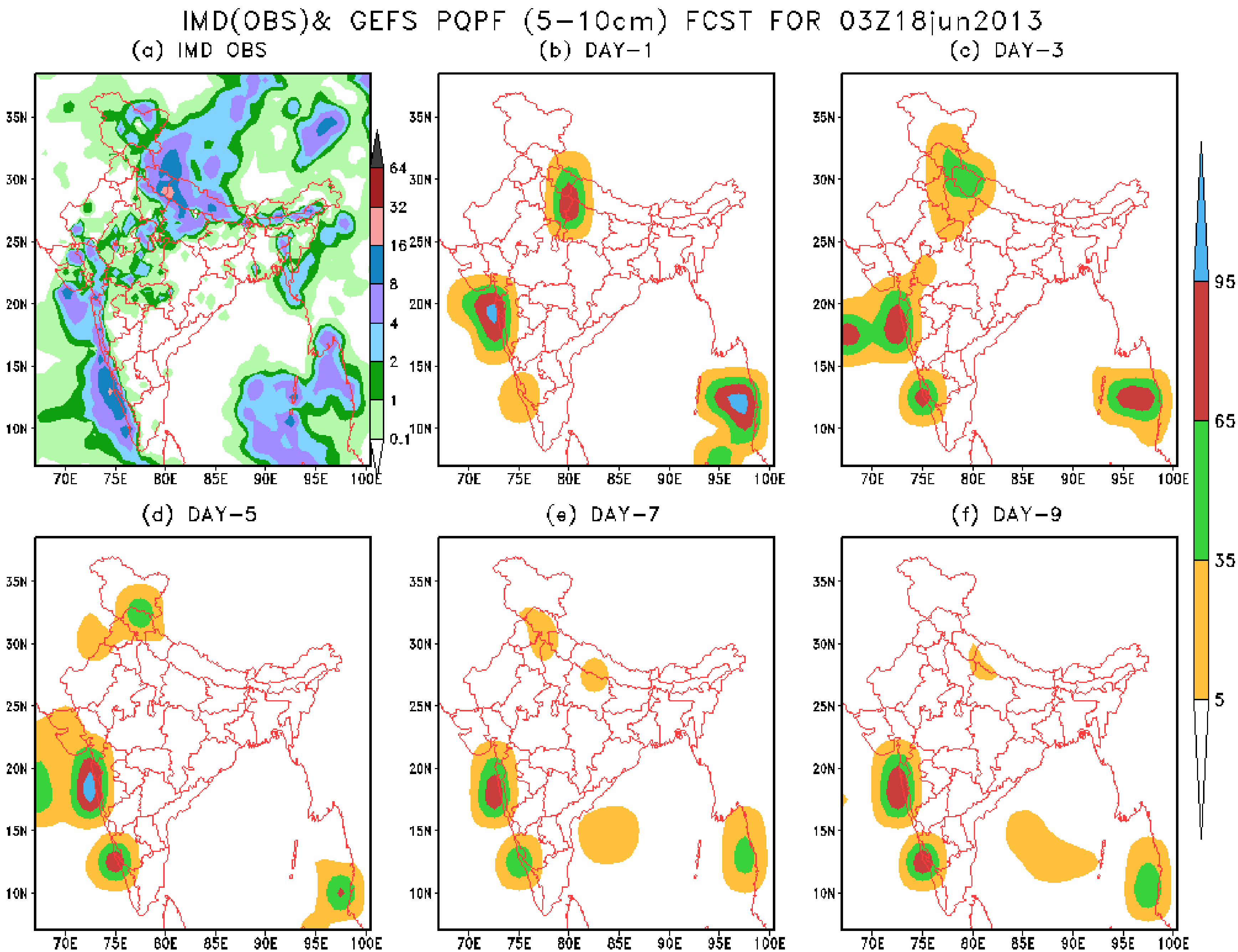


Figure 20: GEFS, probabilistic rainfall for 5 to 10 cm/day range for 18 June 2013 (Day 1 to Day 9)

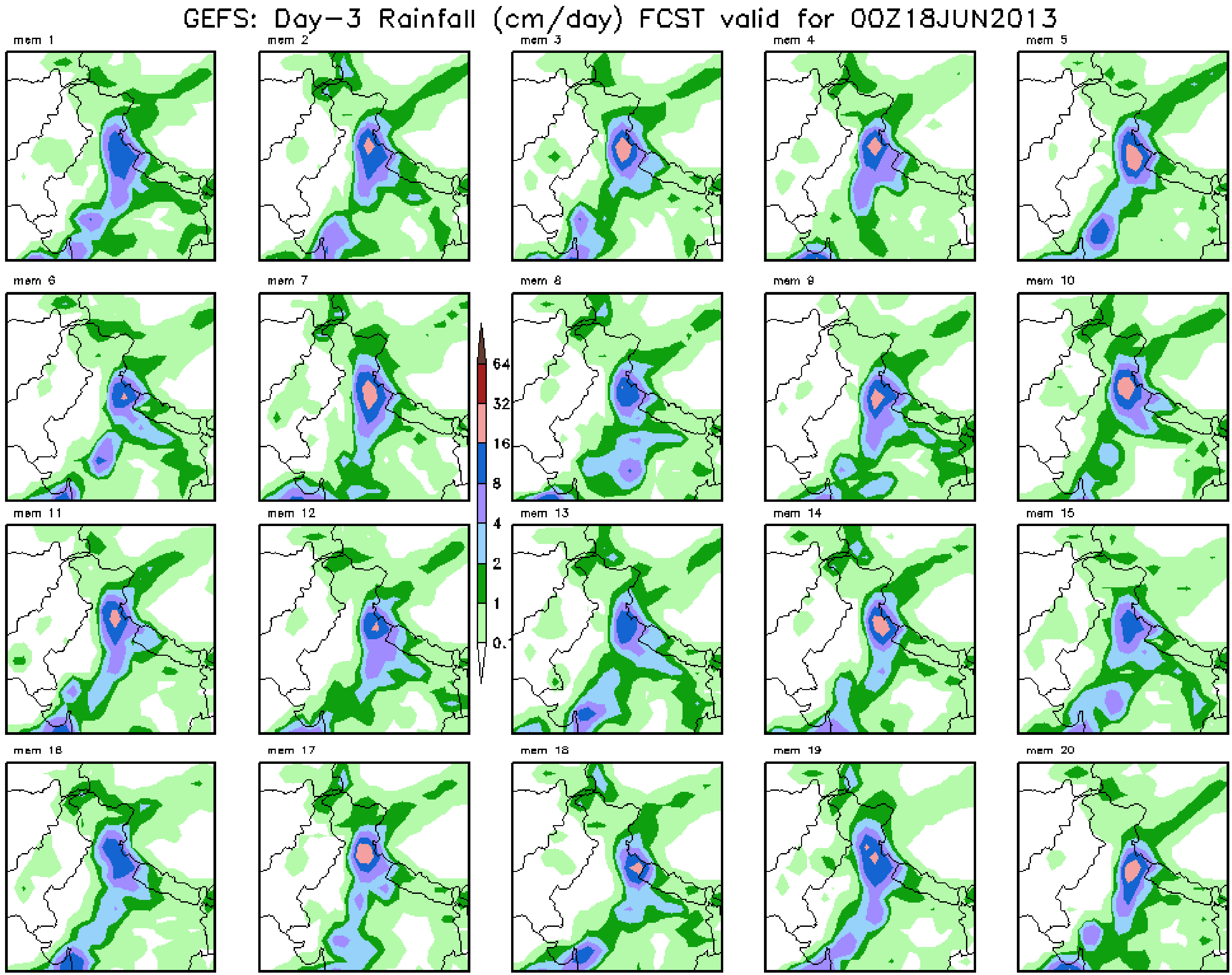


Figure 21: Postage Stamp picture showing rainfall (cm/day) from 20 ensemble members of GEFS Day 3 forecast valid on 18 June 2013

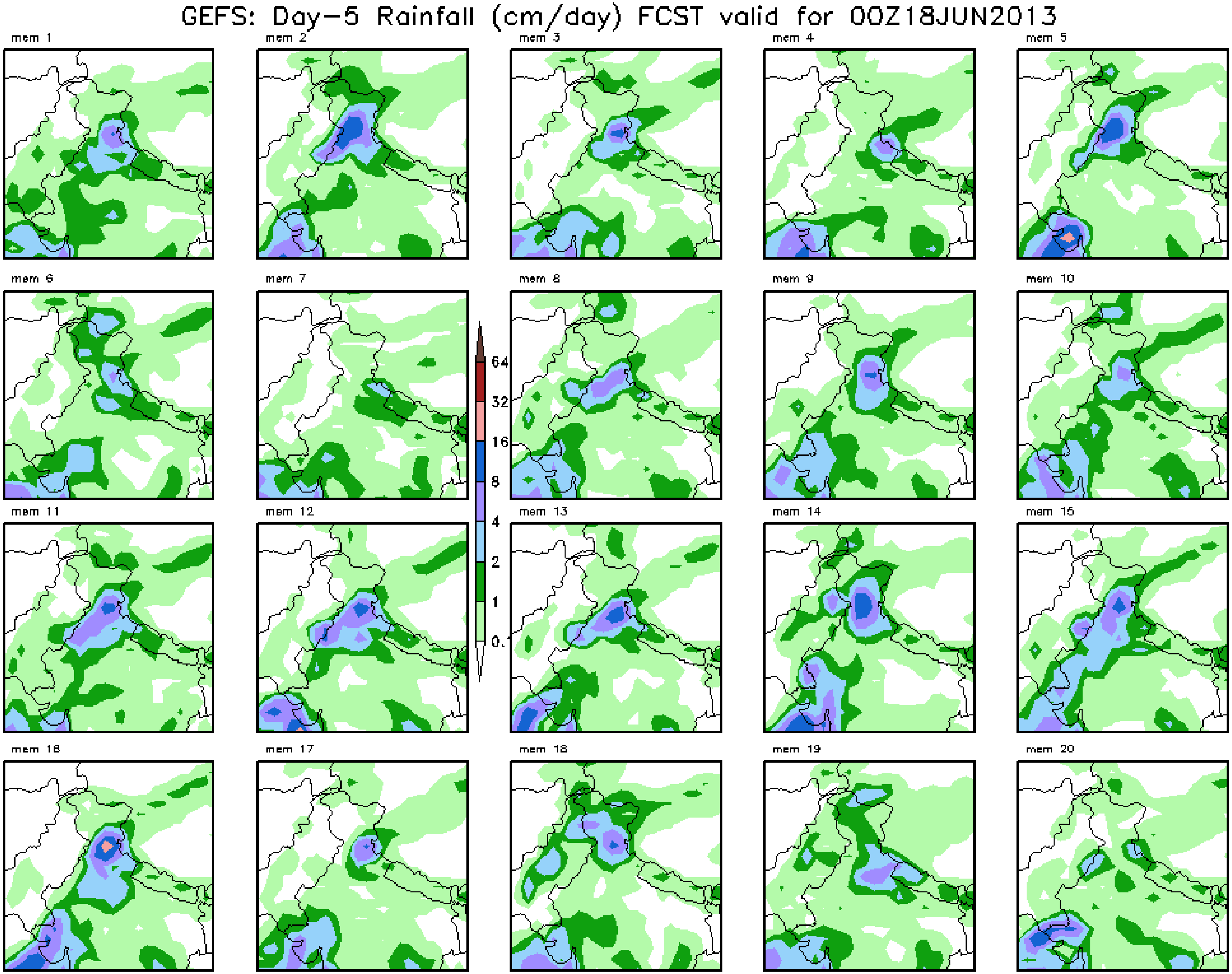


Figure 22: Postage Stamp picture showing rainfall (cm/day) from 20 ensemble members of GEFS Day 5 forecast valid on 18 June 2013