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District level value-added dynamical-synoptic forecast system for rainfall

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सार – इस शोध–पत्र में वर्षा से संबंधित जिला स्तरीय मानों पर आधारित गतिकीय सिनाप्टिक पूर्वानुमान की पद्धति और उसके प्रयोगात्मक परिणामों को प्रस्तुत किया गया है। इसके पहले इस तकनीक का उपयोग वर्ष 2005 की मानसून पूर्व की ऋतु, दक्षिणी पश्चिमी मानसून ऋतु और मानसून के पश्चात की ऋतु के दौरान हुई जिलेवार वर्षा का पूर्वानुमान लगाने के लिए किया गया था। उक्त 2005 के पूर्वानुमान के लिए टी.–80,एम. एम. 5, राष्ट्रीय मध्य अवधि मौसम पूर्वानुमान केन्द्र (एन. सी. एम. आर. डब्ल्यू. एफ.) के. ई. टी. ए. और भारत मौसम विज्ञान विभाग में कार्यशील एम. एम. 5 गतिकीय निदर्शों का समन्वित रुप से उपयोग किया गया था। पूर्वानुमान में समन्वित रुप से योगदान देने वाले सभी निदर्शों के मानों का अलग–अलग मूल्यांकन करके उनसे प्राप्त हुए वर्षा के पूर्वानुमानों का उपयोग करके गतिकीय पूर्वानुमान तैयार किया गया है। परिचालन लक्षणों, उर्ध्वाधर वेग, उपग्रह से प्राप्त सूचना सिनाप्टिक चार्टों और जलवायु विज्ञान आदि जैसे अन्य निदर्शों का आकलन करके गतिकीय पूर्वानुमानों को मान आधारित (वेल्यू एडिड) सिनाप्टिक मौसम पूर्वानुमानों में परिवर्तित किया गया है। वर्ष 2005 में किए गए पूर्वानुमान के अनुभव से यह पता चला है कि समन्वित रुप से योगदान देने वाले निदर्शों से अलग–अलग प्राप्त हुए वर्षा के पूर्वानुमानों की निपुणता की तुलना में मान–आधारित (वेल्यू एडिड) गतिकीय सिनाप्टिक प्रणाली के 24, 48, 72 घंटों के जिला स्तरीय वर्षा के पूर्वानुमान कहीं अधिक निपुणता से तैयार किए जा सकते हैं।

ABSTRACT. The paper presents the methodology and trial results of the district level value-added dynamical-synoptic forecast for rainfall. The technique was tried for forecasting districtwise rainfall during Pre-monsoon, Southwest Monsoon and Post monsoon seasons of 2005. The constituent dynamical models were T-80, MM5, ETA of the National Centre for Medium Range Weather Forecasting (NCMRWF) and the MM5 model operational at India Meteorological Department, New Delhi. The dynamical predictions were prepared using the rainfall predictions of the constituent models by assigning different weights. The dynamical predictions were converted into value-added synoptic-weather forecasts by taking into account other inputs like circulation features, vertical velocity, satellite information, synoptic charts and climatology etc. The experience during 2005 has shown that the value-added dynamical-synoptic system can produce 24, 48, 72 hours district level rainfall forecast of greater skill than the skills of the constituent models.

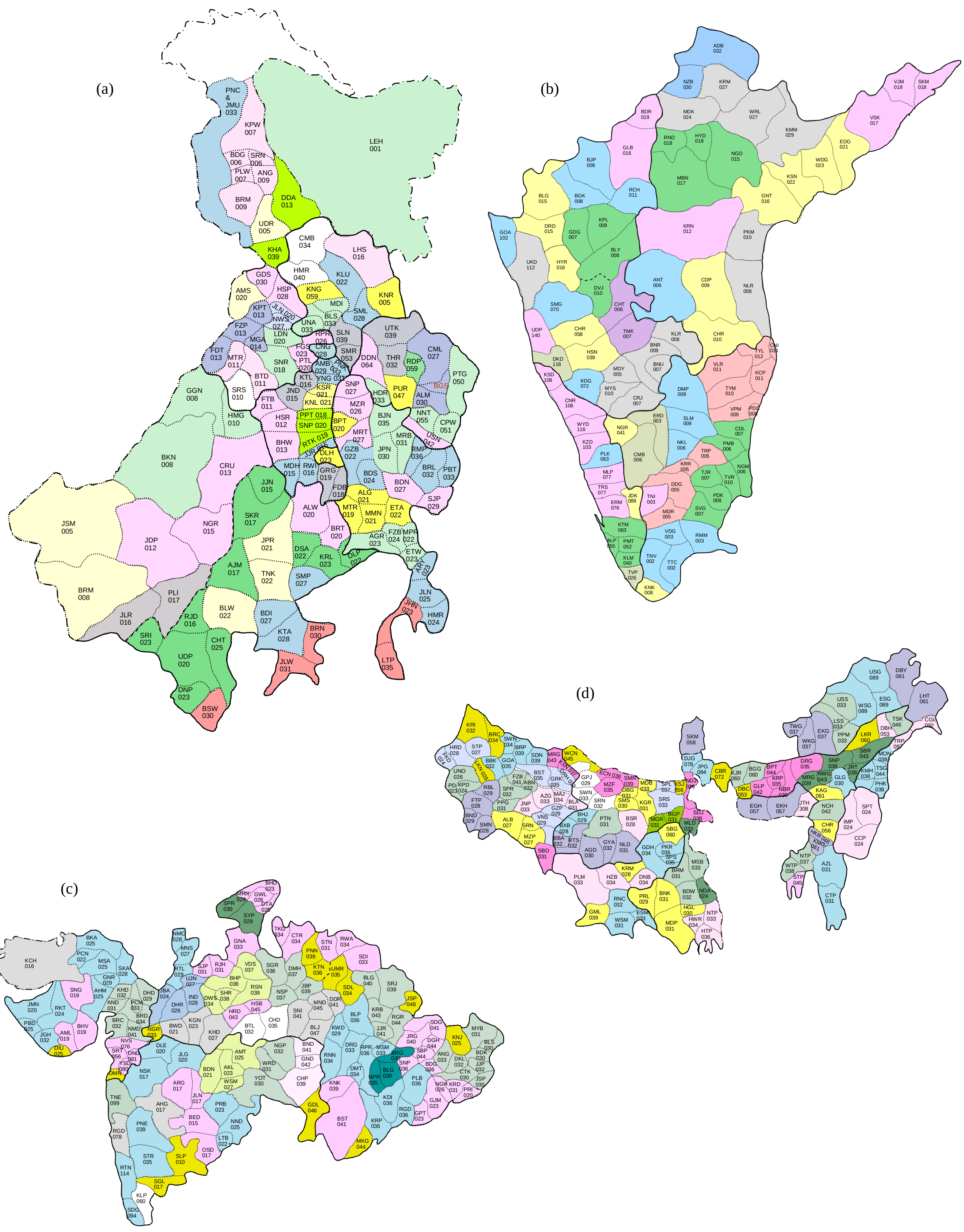
Key words – Super ensemble, Prediction, Value-added dynamical-synoptic forecast, Constituent model, Validation, Skill improvement.

1. Introduction

The weather forecast for smaller spatial resolution such as district level is required by many users in the country. It is especially needed for agricultural applications. To meet this requirement the Annual Cyclone Review (ACR)-2005 held on 18 January, 2005 recommended the constitution of a group of experts in the fields of Numerical Weather Prediction (NWP) and Synoptic Meteorology for the development of a district level forecast system in the India Meteorological Department (IMD). Consequently, the group was constituted in March, 2005 with a specific task of generation of 24, 48 and 72 hr weather forecast for each district in India.

Initially, it was planned to develop the forecast system for rainfall. Other meteorological parameters will be included in due course. The group started the work with examination of characteristics of rainfall of different districts beginning from April. The neighbouring districts of a sub-division having similar rainfall distributions were clubbed into one cluster. Figs. 1(a-d) shows the clusters of districts for the month of July. Clustering of districts has proved to be of immense use in the value-addition.

For district level forecast it was necessary to utilize the model outputs at finer grid resolutions. Availability of fast computer systems led a number of groups to work on different versions of numerical weather prediction (NWP) models. The fifth generation mesoscale model MM-5 developed by the National Centre for Atmospheric Research (NCAR), USA has become popular (Dudhia, 1993) for mesoscale studies. The model is very flexible and can be run at different resolutions, normally ranging from 50 to 5 km with various (optional) cumulus parameterization schemes. Regional models are favoured over the global models for mesoscale regional prediction



Figs. 1. (a-d). Clusters of districts for the month of July

because their resolution can be increased without much computational expenditure. A comparative performance of few regional models (also called limited area model) namely RAMS, MM-5, U.S. Navy Operational Regional Prediction System (NORAPS), and Relocated Window Model (RWM) was reported by Cox *et al*. (1998). The study ranks RAMS marginally ahead of MM-5.

The traditional NWP models are built on a foundation of deterministic modelling which start with some initial conditions. The inherent limitation to these NWP models is that they neglect small scale effects and they parameterize complicated physical processes and interactions. The models lose skills because they describe only in an approximate way the exact law of physics and because of the growth of the inevitable uncertainty in the initial conditions. In view of these facts, a new approach known as ensemble forecasting was introduced in the 1990s (Molteni *et al*., 1996; Toth and Kalnay, 1997; Zhang and Krishnamurti, 1997 etc.). In this method, forecasts are made with different models and different initial conditions, and are combined into a single forecast to take into account the uncertainty in the models' physical parameterization schemes and initial conditions. The ensemble forecasting approach, in concert with the statistical technique has come into vogue in weather and seasonal climate forecasting.

In ensemble forecasting, the main issue relates to the removal of the collective errors of multi-models participating in the making of an ensemble. The major drawback of the straight average approach of assigning an equal weight of 1.0 to each models is that it may include several poor models. The mean of these poor models degrades the over all results. To address this problem of ensemble forecasting, Krishnamurti *et al*. (2000a, 2000b) introduced a multimodel super ensemble technique that shows a major improvement in the prediction skills. In the super ensemble approach, weight is assigned to each model based on spatial and temporal performance of respective models. The procedure can be used for the variables such as winds, temperature, pressure, precipitation and humidity. The resulting super ensemble reduces forecast errors below those of constituent models. According to Krishnamurti *et al*. (2000b) the super ensemble is able to provide roughly 20% improvement over the best model.

In the present study, the technique developed for district level forecast is based on daily data sets from operational MM-5, ETA and T-80 models of National Centre for Medium Range Weather Forecasting (NCMRWF) and from the MM-5 model operational at IMD New Delhi. The rainfall charts of this model were available and the same have been utilized. The horizontal resolution of NCMRWF MM-5 model is 30 km and it is run with the initial and boundary conditions from T-80 model. The ETA model is run at the resolution of 55 km. IMD MM-5 model is run at the horizontal resolution of 45 km with the initial and boundary conditions of NCEP Global Forecast System. The major difference between the MM-5 model run at NCMRWF and the MM-5 model run at IMD is in the initial and boundary values. At NCMRWF, the initial and boundary fileds are obtained from the outputs of the global T-80 model and boundary values are updated at every 12 hours interval. Interpolation of T-80 outputs (horizontal resolution around 175 km over the tropics) to MM-5 resolution is not suitable to retain the meso scale properties in the initial field itself. Moreover, the meso scale properties at the lateral boundaries is not captured properly due to the updatation of boundary values at the longer time interval. Whereas at IMD the initial and boundary conditions are obtained from the Global Forecast System (GFS) outputs (at the resolution of 1° × 1° of National Centre for Environmental Prediction) to run the MM-5 model at the resolution of 45 km over a single domain covering the area between Lat. 25° S to 45° N / Long. 30° E to 120° E. The boundary conditions are updated at every 6 hours interval. As such, MM5 at IMD is run with better initial field and boundary values. Again, as the model is run over a large integration domain, boundary effect over the Indian region may be very little.

Out of two versions of MM5, namely the NCMRWF-version and NCEP-version being run at IMD, New Delhi, we have selected IMD version for studying the comparative performances. A procedure was developed to convert daily grid point rainfall outputs of each of these models into district rainfall by computing areal average rainfall for each district (total rainfall divided by number of grids falling in that district). The corresponding observed areal average rainfall for each district was computed utilizing daily rain-gauge observations. The rainfall for each district is computed by assigning different weights to the constituent models. The predictions are converted into value-added forecasts after considering the inputs from ECMWF flow pattern, satellite information, climatology, synoptic charts etc.

2. Methodology

As pointed out earlier the district level forecast system is being developed based on the principles of super-ensemble method. Model outputs of different

TABLE 1

District level value-added dynamical-synoptic forecast format

Name of the state	Name of the district	District index	Forecast (Rainfall in mm)																		Realized (Actual) (Rainfall in mm)		
			T-80 (NCMRWF)			MM5 (IMD)			MM5 (NCMRWF)			ETA (NCMRWF)			Dynamical F/C			Value-added dynamical F/C					
			Day-1	Day-2	Day-3	Day-1	Day-2	Day-3	Day-1	Day-2	Day-3	Day-1	Day-2	Day-3	Day-1	Day-2	Day-3	Day-1	Day-2	Day-3	Day-1	Day-2	Day-3
Anda-man & Nicobar	Anda-man	01001																					
	Nicobar	01002																					

numerical models are utilized for generation of district level quantitative forecast of rainfall. While examining the performance of individual models it was found that each model had certain strengths and weaknesses. For instance some models were able to provide good forecasts in certain regions but in some areas they had some inherent problems. Similarly, some models were able to predict light rainfall correctly but failed badly in case of heavy rainfall. It is well known that monsoon rainfall over India has very high spatial variability. Based on trials on real-time basis during the Pre-monsoon, SW Monsoon and Northeast Monsoon-2005 the strengths and weaknesses of different models of NCMRWF and IMD were identified. This helped in the statistical intervention and determination of 'weights' for rainfall forecast of different models. The weights were determined objectively by computing the correlation coefficients C_n between the model predicted and actual rainfall. The weights, W_n were obtained from the following equation:

$$W_n = \frac{C_n}{\sum_{i=1}^{4} C_i} \qquad n = 1,.........4$$

The dynamical prediction which is the 'weighted mean' of different model forecasts takes into account the forecasts of all constituent models. The validation results in different situations showed that the method is capable of generating 24, 48 and 72 hr forecasts of greater accuracy than the accuracies of the individual constituent models. To begin with the weights were computed on the basis of monthly data sets which have been used in the computation of dynamical predictions during succeeding months. In future the weights will be worked out on the basis of bigger data sets being generated in the system.

TABLE 2

Rainfall forecast categories used in value-added dynamical-synoptic forecast

Category	Forecast range	Type of rainfall*
1	No Rain	No Rain
2	< 1 cm	Light
3	1-2.5 cm	Moderate
4	2.5-4.5 cm	Moderate
5	4.5-6.5 cm	Rather heavy
6	6.5-12.5 cm	Heavy
7	12.5-20 cm	Very Heavy
8	> 20 cm	Exceptionally Heavy

* These categories have been defined keeping in view the requirements of value-added dynamical-synoptic forecast and the existing IMD's classification

The aim is not a mere generation of 'weighted mean' prediction. The experiences in the fields of synoptic meteorology, satellite applications etc. are being utilized in the value-addition. The dynamical predictions are modified wherever considered necessary and the final value-added forecast is prepared. It may be pointed out that due to limited experience the value-addition is not free from subjectivity at present. It would be possible to make the process objective when sufficient amount of data pertaining to different seasons/situations become available in future. The major inputs to the value-addition are IMD's synoptic charts, satellite information, climatology and the NWP products. Other than precipitation, the circulation patterns predicted by Europian Centre For Medium Range Weather Forecast (ECMWF) have been found very useful in value-addition, especially in the event of heavy rainfall over West Coast of India and concentrated rainfall associated with disturbances like Tropical Cyclones (TCs), Monsoon Depressions (MDs),

TABLE 3

Forecast validation results for all the districts of India

S. No.	Season/ Synoptic situation	F/C date and validity	Skill Percentage														
			Day-1					Day-2					Day-3				
			Very good		Skillful	Not Skillful	Poor	Very Good		Skillful	Not Skillful	Poor	Very Good		Skillful	Not Skillful	Poor
			(0)	(±1)	(±2)	(±3)	(±4 and ±5)	(0)	(±1)	(±2)	(±3)	(±4 and ±5)	(0)	(±1)	(±2)	(±3)	(±4 and ±5)
1	Pre-monsoon	13 May (14,15,16 May)	89	9	2	0	0	85	12	3	0	0	89	9	2	0	0
2	Pre-monsoon (Just before onset over Kerala)	24 May (25,26,27 May)	63	32	5	0	0	69	27	4	0	0	60	36	4	0	0
3	Southwest monsoon (Onset phase)	8 June (9,10,11 June)	51	39	10	0	0	54	35	11	0	0	51	39	10	0	0
4	Southwest monsoon (Onset phase)	9 June (10,11,12 June)	55	39	6	0	0	58	32	10	0	0	60	30	10	0	0
5	Southwest monsoon (Active phase)	30 June (1,2,3 July)	56	22	11	6	5	54	32	10	3	1	55	31	10	4	0

Mid-Tropospheric Cyclones (MTCs), etc. The experience has shown that the tracks of systems predicted by ECMWF were closer to actual which helped in the identification of districts which were likely to receive heavy/very heavy rainfall amounts. The predicted location of low level jet core at 850 hPa over the Arabian Sea was found to be related to heavy rainfall zones over the west coast. The relationship was extensively used for forecasting heavy rainfall cases along the west coast. The statistical correlations between different jet parameters and west coast rainfall are being studied comprehensively and the detailed results will be reported in a future publication. The technique used so far is based on the predicted location of jet hitting the west coast. The districts situated within 1.5° of this location were delineated for very heavy rainfall amounts and the method yielded good value-added forecasts. Thus the present system based on dynamical-cum synoptic approach differs from the super ensemble method adopted by Krishnamurti *et al* (2000a, 2000b) in which an objective technique is used to arrive at the super-ensemble. The trials have shown that value-added forecast scores handsomely over the individual dynamical model predictions. The forecast format is given in Table 1.

3. Validation

Validation of any quantitative forecast for smaller spatial scales is not an easy task. On several occasions the actual weather information is not available from some districts. Development of an appropriate validation method for any forecast for spatial scale of 40-50 km is in itself an interesting exercise. Several techniques may be adopted for this purpose. The accuracy of any forecast will depend upon the criteria used in the validation. In the present system we have adopted an objective method. All available observations from a particular district are picked up by the computer by specifying the boundary of the district. Then the actual rainfall is compared with the quantitative forecast for that district. Other methods using objective analysis will also be tried in future.

3.1. *Quantitative rainfall forecast categories*

In value-added dynamical-synoptic forecast system the forecast is given quantitatively in different ranges that cover various types of rainfall amounts. The conventional

TABLE 4

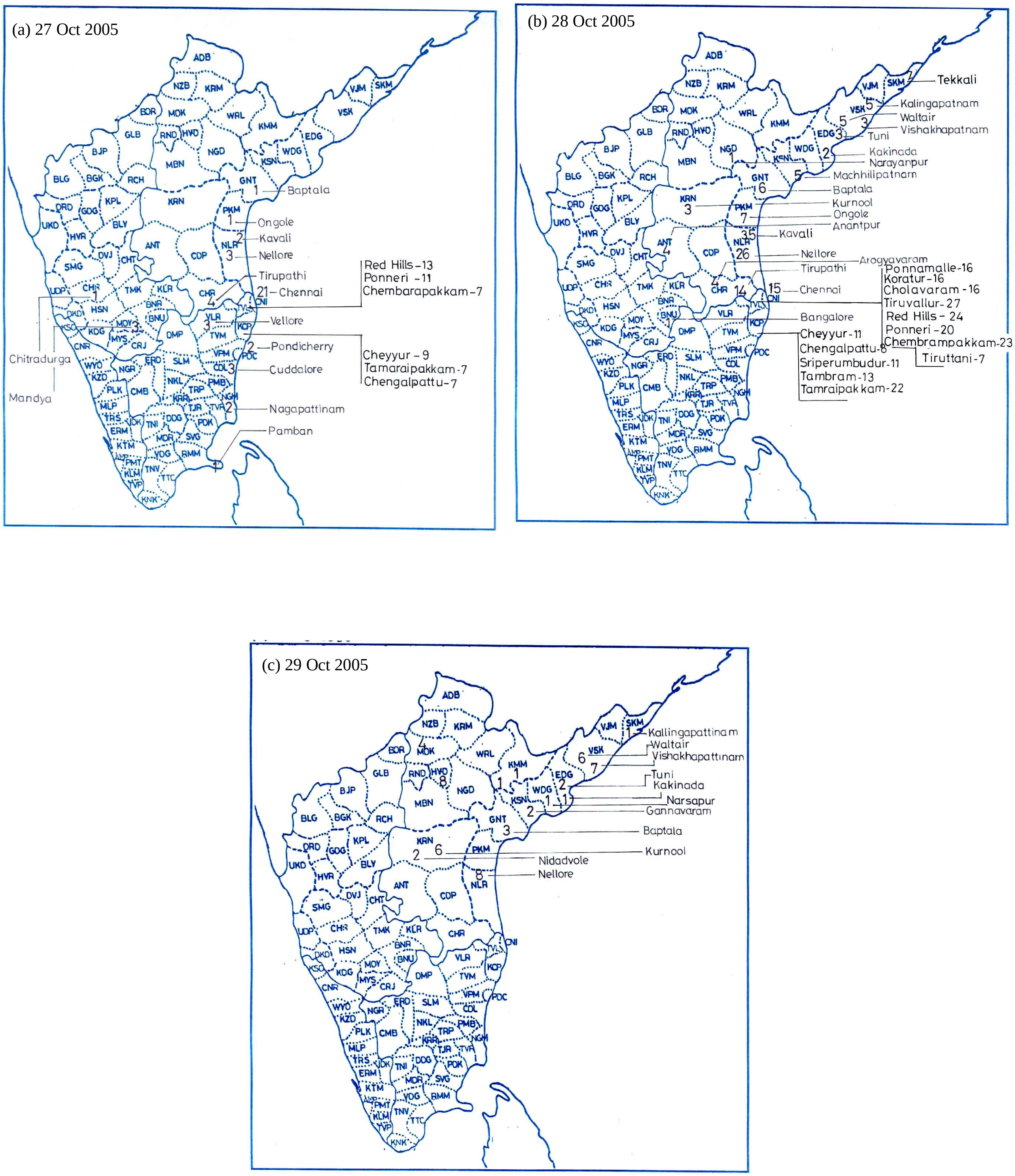
Performances of models and value-added dynamical-synoptic 3-day forecast for the districts affected by the Bay of Bengal cyclone of 17-25 September, 2005. The numbers indicate the rainfall category

Date	State	Affected districts (heavy to very heavy rainfall)	Rainfall						Difference in category between value-added dynamical F/c and actual
			T-80	MM5(IMD)	ETA (NCMWRF)	T-170 (NCMWRF)	Value-added dynamical F/c	Actual	
20 Sep	Andhra Pradesh	East Godavari	2	3	3	4	6	7	-1
		Khammam	2	1	3	6	6	7	-1
		Visakhapatnam	3	3	3	3	7	7	0
		Krishna	2	1	2	2	2	7	-5
21 Sep	Andhra Pradesh	Khammam	3	2	3	6	7	6	1
		Medak	3	2	2	2	6	7	-1
		Nizamabad	3	2	2	2	7	6	1
		Karimnagar	3	2	2	2	7	6	1
	Maharashtra	Ratnagiri	3	2	6	2	6	6	0
22 Sep	Gujarat	Dangs	2	2	3	2	4	6	-2
	Maharashtra	Nasik	2	4	4	2	5	6	-1
		Thane	2	3	6	3	6	6	0
23 Sep	Maharashtra	Thane	3	3	6	7	7	6	1
	Goa	North Goa	3	3	3	6	4	6	-2
24 Sep	Gujarat	Patan	2	1	1	1	5	6	-1
		Kheda	3	2	4	2	5	6	-1
25 Sep	Uttaranchal	Almora	2	2	2	2	5	6	-1
		Nainital	2	2	2	2	5	6	-1
		Tehri Garhwal	2	2	2	2	5	6	-1
		Dehradun	2	1	2	2	2	6	-4

TABLE 5

Performance of models and value-added dynamical-synoptic 3-day forecast during Deep Depression of northeast monsoon, 2005. The numbers indicate the rainfall category

Date	State	Affected districts (heavy to very heavy rainfall)	Rainfall						Difference in category between value-added dynamical F/c and actual
			Models' prediction						
			T-80	MM5(IMD)	ETA (NCMWRF)	T-170 (NCMWRF)	Value-added dynamical F/c	Actual	
27 Oct	Tamil Nadu	Chennai	2	2	3	2	4	7	-3
		Tiruvallur	2	2	3	2	4	6	-2
		Kanchipuram	2	3	3	2	4	6	-2
28 Oct	Tamil Nadu	Chennai	3	2	6	4	6	7	-1
		Tiruvallur	3	3	3	4	6	7	-1
		Kanchipuram	3	2	6	4	6	7	-1
	Andhra Pradesh	Nellore	3	3	2	4	6	7	-1
		Prakashan	3	3	2	2	6	6	0
		Srikakulam	2	3	1	2	4	6	-2
29 Oct	Andhra Pradesh	Nellore	2	2	6	4	7	6	1
		Visakhapatnam	2	3	3	1	6	6	0
		Hyderabad	2	3	1	2	2	6	-4



Figs. 2. (a-c). 24 Hours rainfall

TABLE 6

Comparative skills of different models and value-added dynamical-synoptic forecast during Bay of Bengal cyclonic storm 17-25, September 2005. Numbers in brackets indicate the skill during Deep Depression of 26-29 October 2005

S. No.	Model	Skill Category			
		Very good (0 and ±1)	Skillful (±2)	Not Skillful (±3)	Poor (±4 and ±5)
1	T-80	0 (0)	0 (0)	7 (1)	13 (11)
2	MM5 (IMD)	0 (0)	1 (0)	3 (5)	16 (7)
3	ETA	3 (3)	2 (0)	3 (3)	12 (6)
4	T-170	4 (0)	0 (1)	2 (4)	14 (7)
5	Value-added dynamical F/c	16 (7)	2 (3)	0 (1)	2 (1)

moderate rainfall category is broken into two ranges and exceptionally heavy rainfall is covered under category 8 (>20cm). The rainfall forecast categories are given in Table 2.

3.2. *Criteria for validation*

The following objective criteria has been used in the forecast validation. The forecast is categorized as 'very good' if the difference in categories between value-added dynamical forecast and actual rainfall is 0 or ±1, 'skillful' if the difference is ±2, 'not skillful' if the difference is ±3 and 'poor' if the difference is ±4 or ±5. The results presented in subsections 3.3 and 3.4 differ in the sense that the results of section 3.3 pertain to the evaluations for all 586 districts of India whereas the results of section 3.4 pertain to specific synoptic situations like Tropical Cyclone/Depression. Thus the evaluations in 3.4 are based on differences in value-added forecast or model predictions with the actual rainfall over the affected districts only (*i.e.*, the districts receiving heavy to very heavy rainfall).

3.3. *Validation results*

Real-time trials of value-added dynamical forecast commenced in Pre-monsoon 2005. The validation results presented in Table 3 show that the accuracy of 3-day forecast can reach up to 85-90% during the pre-monsoon. During the onset phase of SW monsoon-2005, the accuracy (zero difference in category between value-added dynamical forecast and actual) of 3-day forecast varied between 51-60%.

Though there is a clear drop in the accuracy between pre-monsoon and monsoon onset periods, it is felt that with further experience 60-70% accuracy of quantitative district-wise rainfall forecast is achievable for the country as a whole. During the active phase of monsoon (1-3 July 2005) when the country was affected by a Monsoon Depression (MD) and a Mid-Tropospheric Cyclone (MTC) the skill decreased further though a 55% accuracy of 3 day forecast was achieved. It may be mentioned that the SW Monsoon had covered the entire country by 30 June and some forecasts for 1-3 July were not skillful. However, for the country as a whole it was possible to achieve high percentages of 'very good' and 'skillful' forecasts. The success rates decreased when the evaluations were made only for these districts which were affected by synoptic systems like cyclone/depression.

3.4. *Tropical cyclone case of SW Monsoon-2005*

3.4.1. *Formation and track of movement*

During the Southwest Monsoon season-2005 a low pressure area formed over north Andaman Sea and adjoining east central Bay of Bengal on 16th September. Moving northwards it concentrated into a depression over northeast Bay of Bengal near Lat. 20.5° N / Long. 90.5° E on the morning of 17^{th}. It further intensified into a cyclonic storm and crossed Andhra Pradesh coast near Kalingapatnam in the morning of 19^{th}. Moving in a westerly/west-northwesterly direction it weakened into a depression over west Madhya Pradesh near Khandwa. Moving westward it further weakened into a well marked low pressure area over north Maharashtra and adjoining south Gujarat and southwest Madhya Pradesh on 22^{nd}. Thereafter the low pressure area moved in a north/north-northeasterly direction and lay over west Uttar Pradesh and adjoining Uttaranchal on 25^{th} morning. It become unimportant over the same area by the morning of 26^{th} September. The system caused widespread rainfall with heavy to very heavy falls in several districts of a number of meteorological subdivisions (Table 4). Developments in the life-history of this system led to a significant improvement in total monsoon rainfall over the country.

3.4.2. *Value-added dynamical-synoptic forecast during the cyclonic period*

Table 4 shows the performance of models and value-added dynamical-synoptic forecast during the cyclonic period. The cyclonic storm yielded very heavy rainfall amounts over the coastal districts of Andhra Pradesh from Visakhapatnam to Krishna on 20^{th} September. As revealed by Table 4 the constituent models T-80 and IMD-NCEP MM5 version could not predict such heavy rainfall amounts over these districts. This was mainly due to the models' failure in the cyclone track prediction resulting in displaced maximum rainfall zones. The model predictions during cyclonic situations for smaller spatial scales like district level becomes a challenging task as an error of 40-50 km in the prediction of cyclone centre would shift the focus of heavy rainfall zone. This is what exactly happened during the cyclonic storm of September 2005 monsoon. The comparative skills of different models and value-added dynamical forecast is presented in Table 6.

As mentioned earlier IMD-NCEP MM5 version has been selected for studying the comparative performances. NCMRWF MM5 version's performance was slightly better than T-80 and poorer than the IMD-NCEP version for cases studied here. The value-added dynamical method showed good skill in the forecast of district level heavy rainfall amounts. As revealed by Table 4 majority of the forecasts were within 0 and ±1 category. The major inputs to the value-addition were the forecast charts of the ECMWF, especially the sea level chart and the flow pattern at 850 hPa, climatology and the satellite imageries. The track predicted by ECMWF was closer to actual as compared to other models due to which its outputs were useful in the identification of heavy rainfall districts. However, with further experience only it would be possible to assign weights objectively to these model outputs. Same is the case with the vertical velocity field at 700 hPa predicted by COLA which was also useful in the identification of districts that were likely to receive heaviest rainfall amounts. It is seen from Table 4 that for value-added dynamical-synoptic forecast on 20^{th} September two coastal districts of Andhra Pradesh, namely East Godavari and Visakhapatnam and one interior district, Khammam were identified for maximum rainfall. The actual rainfall amounts received subsequently showed that the maximum rainfall occurred over these districts. However, very heavy rainfall belt extended upto Krishna which could not be anticipated in value-added dynamical forecast prepared on 19^{th} September. Needless to mention, none of the models predicted heavy rainfall over Krishna district for 20^{th} September.

Over the interior districts of Andhra Pradesh also the value-added dynamical forecasts of heavy rainfall turned out to be correct where again models failed to predict the heavy rainfall amounts. Subsequently, during the depression stage also the districts receiving heavy rainfall were correctly identified. Even when the system recurved northeastward as a low pressure area on 23^{rd} September the maximum rainfall belt forecast was correct with only exception of Dehradun where heavy rainfall occurred on 25^{th} September but the forecast rainfall was only light.

As revealed by Table 6, out of total 20 events of heavy to very heavy rainfall the value-added dynamical method generated 16 'very good' forecasts during the cyclonic period (a score of 80%) followed by T-170's 20% and ETA's 15%. T-80 and MM5 could not produce a single 'very good' prediction. None of the predictions of T-80 could be categorized even 'skillful' whereas MM5 produced only one 'skillful' prediction. All models taken together could produce 7 'very good' and 3 'skillful' forecasts whereas the value-added method yielded 16 'very good' and 2 'skillful' forecasts showing a significant skill improvement.

The experience during the cyclone period established the importance of value-addition in dynamical-synoptic forecasting at district level. None of the models, T-80, MM5, ETA etc could predict such high amounts of rainfall over several affected districts. But after consideration of the ECMWF's flow patterns, climatology, satellite imageries etc. the value-added rainfall amounts were quite close to the actual over a good number of districts due to which the value-added dynamical-synoptic forecast produced the lowest root mean square errors over the country during the cyclonic period of September-2005. With further experience it would be possible to assign weights objectively to these products to minimize the subjectivity in the value-addition. Sufficient data pertaining to cyclonic cases are to be generated for this purpose which is being done.

3.5. *Deep Depression case of northeast monsoon, 2005*

3.5.1. *Bay of Bengal Deep Depression 26-29 October 2005*

A low pressure area formed over southeast and adjoining southwest Bay of Bengal on the morning of 25th October and became well marked in the evening. It concentrated into a depression and lay centred at 0300 UTC of 26th October near Lat. 12.0° N / Long. 84.5° E about 500 km east-southeast of Chennai. It further intensified into a Deep Depression and lay centered at 2330 UTC near Lat. 12.5° N / Long. 84.0° E about 400 km eastsoutheast of Chennai. It moved westnorthwestwards and lay centred at 0300 UTC of 27th October near Lat. 13° N / Long. 82.5° E about 250 km east of Chennai. The system moved northwestward after 1200 UTC and crossed south Andhra Pradesh coast near Ongole around 0800 UTC of 28th October. It weakened into a depression over the same area by 1200 UTC. Remaining practically stationary it weakened into a low pressure area in the evening of 28th. Under the influence of this system heavy to very heavy rainfall occurred in 3 north coastal districts of Tamil Nadu and 5 districts of Andhra Pradesh. The rainfall distribution during this period is given in Figs. 2 (a-c).

3.5.2. *Performances of models and value-added dynamical-synoptic forecast*

Performances of different models and value-added dynamical-synoptic method during the Deep Depression period from 27-29 October, 2005 are presented in Tables 5 and 6. The Deep Depression caused heavy to very heavy rainfall over three districts of Tamil Nadu, namely Chennai, Tiruvallur and Kanchipuram on 27th and 28th October and five districts of Andhra Pradesh namely Nellore, Prakasham, Visakhapatnam, Srikakulam and Hyderabad on 28th and 29th October. T-80 and T-170 could predict only light rainfall over Tamil Nadu districts on the 27th. ETA and value-added dynamical-synoptic method both forecast was moderate rainfall over Tamil Nadu districts. Thus none of the models including the dynamical-synoptic one could predict such heavy rainfall amounts over coastal Tamil Nadu on 27th. On 28th October though all models showed an increase in the rainfall over coastal Tamil Nadu but the predicted amounts were of moderate category only. However, ETA predicted heavy rainfall over two districts. The value-added forecasts were very close to actual over all the three districts. Over coastal Andhra Pradesh districts of Nellore and Prakasham also the heavy rainfall forecast was given by the value-added dynamical-synoptic method but over Srikakulam none of the models including the value-added one could predict the heavy rainfall. The heavy rainfall over extreme north coastal Andhra Pradesh appears to be a secondary rainfall maximum zone which could not be anticipated as the Deep Depression was located over south coastal Andhra Pradesh and adjoining north Tamil Nadu coast. On 29th October, ETA predicted heavy rainfall over Nellore while the value-added dynamical-synoptic forecast was very heavy. All models including the value-added method failed to predict the heavy rainfall over Hyderabad on 29th October.

Table 5 shows that during the Deep Depression period of 27-29 October, 2005 there were 12 cases of heavy to very heavy rainfall over the districts of Andhra Pradesh and Tamil Nadu out of which 9 cases were predicted well by the value-added dynamical-synoptic method. Barring ETA's prediction of heavy rainfall over Nellore on 29th none of the constituent models could predict such heavy amounts. The error of value-added dynamical-synoptic forecast was minimum. This again demonstrates the importance of value-addition in dynamical forecasting.

It is seen from Table 6 that out of 12 heavy to very heavy rainfall events the value-added method generated 7 'very good' forecasts (a score of about 58%). However, large number (5 out of 12) were within ±2 to ±4 category. Among the constituent models ETA's performance was satisfactory with a score of 25% of 'very good' forecast. Generally, the success rate was lower during the northeast monsoon system. However, more comprehensive analysis would be required with more number of cases to arrive at definite conclusions about relative success/failure rates in different seasons and different type of synoptic situations. The skill improvement due to value-addition was significant during northeast system also which is evident from Table 6. Out of 12 events all models could produce only 3 'very good' and 1 'skillful' forecasts whereas the value-added method generated 7 'very good' and 3 'skillful' forecasts.

4. Future plans and requirements

4.1. *Operationalisation*

The real-time trials of district level dynamical forecast during Pre-monsoon, SW Monsoon and Northeast Monsoon 2005 have shown that with limited resources and manpower it was possible to generate 3-day forecasts for each district of India having far greater accuracies than the individual constituent models or the existing conventional synoptic methods. The district-wise selection of gridded model forecasts and actual (realized) rainfall data are completely computerized. The quantitative dynamical forecast is being computerized simultaneously by assigning different 'weights' to different model forecasts. On real-time basis it is possible to complete this exercise every day including the value-addition provided the model outputs of all constituent models are available within 6-7 hours of analysis time. It is worth mentioning here that the model outputs of ECMWF and COLA based on 0000 UTC are generally available by 0600 UTC.

4.2. *Requirements*

(*i*) Availability of real-time model predictions and outputs within 6-7 hrs of observations time. It may be mentioned that 48 and 72 hrs forecasts will have better utility compared to 24 hrs forecast as the value-added forecasts will not be ready up to 12 hrs after the observation time even if model predictions are available on time.

(*ii*) Suitable manpower for the district-level forecast unit / division. A strong group having comprehensive research experience in the fields of weather forecasting and numerical weather prediction related developmental work would be required.

(*iii*) Necessary computational and related facilities. The district level forecast group should have direct access to the grid-point forecasts of all constituent models and the real-time observations.

(*iv*) District-wise daily/weekly climatologies of relevant meteorological parameters. Preparation of district-wise daily/weekly climatology for meteorological parameters like rainfall, maximum and minimum temperature, cloud cover, humidity wind etc involves a voluminous data processing work and possession of such climatologies will be a clear advantage for IMD in the value-addition. It may be pointed out that due to comprehensive forecasting experience and availability of huge data resource, IMD is better equipped to prepare the district level value-added forecasts.

(*v*) Necessary communication facilities for quick dissemination of the forecast to different units of IMD and the users. A feedback mechanism would be essential for constant improvement of the forecast system.

5. Concluding remarks

The district level value-added dynamical-synoptic forecast system was able to generate 3-day rainfall forecasts of greater accuracy than the constituent NWP models. The experience has shown that the value-addition utilizing the synoptic, climatological, satellite and NWP inputs (other than rainfall) improved the dynamical prediction computed on the basis of rainfall predictions of different models. The root mean square errors of value-added forecasts were lowest when all the districts of the country were considered as 'no rain' cases improved the forecast skills. When the forecasts were evaluated for the districts affected by the systems like cyclone or depression the accuracy decreased. It is possible to improve the forecast accuracy when more data sets pertaining to different synoptic situations and seasons become available in future. The success rates were higher during the monsoon system as compared to the northeast monsoon system. However, more comprehensive evaluations based on sufficiently large number of cases/situations would be required to arrive at definite conclusions about the variability of success/failure rates in different synoptic situations and seasons. It is proposed to refine the district level rainfall forecast technique further by considering bigger data sets being generated. It is also planned to develop similar techniques for other meteorological parameters like maximum/minimum temperatures, humidity, cloud cover etc.

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