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Evaluation of bias free rainfall forecasts and Kalman filtered temperature forecasts of T-80 model over Indian monsoon region

RASHMI BHARDWAJ, ASHOK KUMAR* and PARVINDER MAINI*

Department of Mathematics, Guru Gobind Singh Indraprastha University, Delhi, India

**National Center for Medium Range Weather Forecasting, NOIDA, UP, India*

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e mails : rb_22@rediffmail.com; ashok@ncmrwf.gov.in; pmaini@ncmrwf.gov.in

सार – धरातलीय मौसम घटकों के स्थान विशेष के निष्पक्ष मध्यम अवधि पूर्वानुमान प्राप्त करने के लिए राष्ट्रीय मध्यम अवधि मौसम पूर्वानुमान केन्द्र में पूर्वानुमान विकसित की है। इस कार्य के लिए उपयोग में लाई गई आधारभूत सूचना राष्ट्रीय मध्यम अवधि मौसम पूर्वानुमान केन्द्र में प्रचालित आम प्रयोग में आने वाले मॉडल (जी. सी. एम.) टी.–80 / टी.–254 से प्राप्त हुए आउटपुट है। इस सिस्टम का अत्याधिक अनिवार्य कारक प्रत्यक्ष निदर्श आउटपुट (डायरेक्ट मॉडल आउटपुट) है। इसके विषय में यहां संक्षेप में बताया गया है। डायरेक्ट मॉडल आउटपुट (डी. एम. ओ.) पूर्वानुमान, जी. सी. एम. से प्रागुक्त धरातलीय मौसम घटक से प्राप्त हुए हैं। यहाँ जिन दो महत्वपूर्ण मौसम प्राचलों के बारे में विस्तार से विवेचन किया गया है वे हैं वर्षा और तापमान। इन दोनो मौसम प्राचालों के प्रति पहले से ही पूर्वाग्रह हैं। यधपि वर्षा के आरम्भिक मान (थ्रेश होल्ड बैल्यूज) के आधार पर बिना किसी पूर्वाग्रह के तकनीक को अपनाने से वर्षा के पूर्वानुामन के प्रति पूर्वाग्रह में कमी आई है और तापमान पूर्वानुमान देने के बिना किसी पूर्वाग्रह के द्विप्राचल कालमन फिल्टर का प्रयोग किया गया है। बिना किसी पूर्वाग्रह के पूर्वानुमान देने के लिए उपयोग में लाई गई तकनीक को यहाँ विस्तार से बताया गया है। अंततः मानसून 2007 के दौरान कालमान फिल्टर्ड तापमान पूर्वानुमान और बिना किसी पूर्वाग्रह के वर्षा का पूर्वानुमान देने के लिए पूर्वानुमान कौशल के मूल्याकंन को यहाँ प्रस्तुत किया गया है।

ABSTRACT. A forecasting system for obtaining objective medium range location specific forecast of surface weather elements is evolved at National Centre for Medium Range Weather Forecasting (NCMRWF). The basic information used for this is the output from the general circulation models (GCMs) T-80/T-254 operational at NCMRWF. The most essential component of the system is Direct Model Output (DMO) forecast. This is explained in brief. Direct Model Output (DMO) forecast is obtained from the predicted surface weather elements from the GCM. The two important weather parameters considered in detail are rainfall and temperature. Both the weather parameters have biases. While the bias from the rainfall is reduced by adopting bias removal technique based upon threshold values for rainfall and for removing bias from temperature forecast a two parameter Kalman filter is applied. The techniques used for getting bias free forecast are explained in detail. Finally an evaluation of the forecast skill for the Kalman filtered temperature forecast and bias free rainfall forecast during monsoon 2007 is presented.

Key words – NCMRWF, GCM, DMO, Kalman filter, Bias free.

1. Introduction

Historically, weather forecast in India was mainly issued in qualitative terms with the help of conventional methods using satellite data and synoptic information about the location of interest. As these forecasts are subjective and cannot be used for risk assessment in quantitative terms, hence the work for developing an objective medium range local weather forecasting system was started first time in India at NCMRWF. An R-40 general circulation model with a resolution of $2.8° \times 1.8°$ was installed for this purpose in 1989. Later on a T-80 general circulation model at the resolution of 1.5×1.5 was made operational in 1993.

An objective forecast is a forecast which does not depend on the subjective judgement of the person issuing it. Strictly speaking, an objective forecasting system is one which can produce one and only one forecast from a specific set of data. The objective forecast for rainfall and

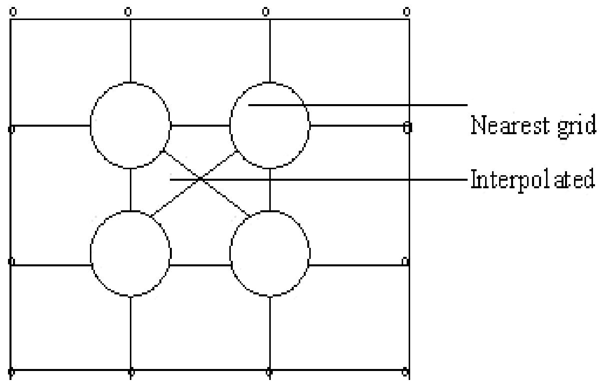

Fig. 1. Area considered around a grid point for deciding the relative importance of nearest grid and the interpolated DMO forecast values for a particular location

maximum/minimum temperature is directly obtained from general circulation model operational at NCMRWF and is called the direct model output (DMO) forecast. The DMO forecast suffer from biases and systematic errors. Rainfall and temperature are the most important surface weather parameters in day-to-day life. Hence a system for removing the biases from these parameters has been developed at NCMRWF. The bias free forecast is operationally used for providing the final local weather forecast for these surface parameters at NCMRWF. In the present study bias free direct model output (DMO) forecast based upon T-80 Model is explained in detail.

Section 2.1 describes the procedure for obtaining the rainfall and temperature forecast obtained from the NWP model. Section 2.2 discusses the Kalman filter approach used to obtain the bias free temperature forecast. In Section 2.3, the method to obtain the bias free rainfall forecast is presented. Section 2.4 describes skill scores used for evaluation of the forecast. Section 3 gives the results and discussions in the light of skill scores for the Kalman filtered temperature forecast and bias free rainfall forecast during monsoon 2007. Section 4 discusses the conclusions.

2. Data and methodology

2.1. *Direct model output (DMO) forecast*

2.1.1. *Nearest grid and interpolated forecast values*

As the forecasts are obtained at Gaussian grids and not at a particular location, hence the simplest way to get forecast at a specific location is to use the interpolated value from the four grid points surrounding it. But if the location is very near to a grid point, then the forecast at that grid point can also be taken as the forecast for the location. In order to decide as to which forecast among the two should be given more weightage for a location, it is necessary to know the distance of the location from the four grid points surrounding it. If the distance of the location from the nearest grid is less than one-fourth of the diagonal distance between any two grid points, then more importance is given to the nearest grid forecast values otherwise the interpolated value is considered, Fig. 1 (Kumar *et al*., 1999).

2.1.2. *DMO Forecast*

DMO forecast values of both types *i.e.* nearest grid and interpolated, for each location of interest are obtained. Five day forecast for the following parameters is obtained by using forecast values at each time step of 15 minutes.

(*i*) Rainfall (24 hours accumulated) (mm)

(*ii*) Maximum Temperature (°C)

(*iii*) Minimum Temperature (°C)

Here, the validity of the forecast values for a particular day is for the subsequent 24 hours starting from 0300 UTC [0830 hrs (IST)] of that day. As at NCMRWF the T-80 model is run only for 7 days based on 0000 UTC analysis, hence only the 24, 48, 72, 96, 120 hours forecasts are obtained. The forecast thus obtained are biased and bias needs to be removed.

2.1.3. *Bias free DMO forecast*

For getting bias free DMO forecast during any season, the forecasted and observed values of the predictand during recent one or two seasons are considered and correction factors are obtained by trial and error method so that the skill of the forecast gets maximised. Same correction factors are used while obtaining the bias free DMO forecast during current season. During present study correction factors are initially calculated based upon monsoon season (June, July, August and September) of 2001, 2002 and 2003 and later on calibrated on 2005 and 2006 monsoon seasons.

2.2. *Kalman filter approach for temperature forecast*

2.2.1. *Basis (Anders O. Persson, 1991)*

It is a common fact that NWP models exhibit systematic errors in the forecasts of the near surface weather parameters. The 2m-temperatures for example are often systematically biased, though the magnitude of the bias varies with geographical location and time of the season. Such systematic errors may not only be due to short comings in the physical parameterization but also depend on the sub-grid location of the station. Individual mountains or different parts of a large city with their specific climate can hardly be fully resolved in any NWP model.

Mathematically a correction formula for a given station and for the specific lead time can be formulated as

$$Y = \mathrm{X1} + \mathrm{X2}^{*}\ \text{Temperature forecast}$$

If X1 and X2 were constant over the seasons they could be computed with good accuracy by linear regression techniques. Normally X1 and X2 are varying in time, mainly due to seasonal variations and changes in the atmospheric model. Values of X1(τ) and X2(τ) typical at time τ may not be representative a couple of weeks later. Thus we always have to update our estimations of X1(τ) and X2(τ).

One solution would be to store observed and forecasted data from the last thirty to forty days and every day perform a linear regression analysis. The obtained mean values for X1(τ) and X2(τ), would then be assumed to be valid even some days in the future. To avoid storage of old data a recursive regression technique could be used applying weights to make more recent data have a larger impact. X1 and X2 would then reflect more recent conditions. However, in a pure statistical sense this method is only a way to smooth the data, the weights pushing the emphasis towards a more recent time. In contrast to simple smoothing and filtering techniques, Kalman filter actually tries to estimate today's value, in light of historical data. Thus a simple one parameter Kalman filter can be applied for more efficient smoothing and removing the biases (systematic errors) in the temperature forecasts.

2.2.2. *Kalman filter equations*

The Kalman filter consists of two sets of equations: the observation equation and the system (or prognostic) equation.

(a) *The observation equation*

Let TFC (τ) be the forecasted value and TOBS (τ) the verifying observation at a certain location and time of the year τ.

The observed forecast error is then

$$\mathrm{TFC}\ (\tau) - \mathrm{TOBS}\ (\tau) = Y(\tau) \qquad (1)$$

Where $Y(\tau)$ is the time varying bias and can be assumed to be a stochastic variable, which contains noise, *i.e.*, factors that we can not describe: errors in synoptic part of the forecast, deficiencies in the physical parameterization and unexplained small scale disturbances.

$$Y(\tau) = \mathrm{X1}(\tau) + v(\tau) \qquad (2)$$

Where X1(τ) is the applied correction and $v(\tau)$ is the unexplained, non-systematic noise. A part of this noise might be explained by another statistical model *e.g.*, containing more predictors. For example the bias might seem to be dependent on the forecasted parameter, TFC(τ) or function of it:

$$Y(\tau) = \mathrm{X1}\ (\tau) + \mathrm{X2}\ (\tau)^{*}\mathrm{TFC}\ (\tau) + v\ (\tau) \qquad (3)$$

Equations (2&3) are examples of observation, since they relate the observed errors to the statistical error model. If there is only a bias in the forecasts, then X2 = 0. If there are only non-systematic errors both X1 and X2 will be equal to zero.

(b) *The system (or prognostic) equation*

So far we have only considered the static part of the Kalman filter. The "clue" of the Kalman filter is a second stochastic and dynamic model that tries to describe the time evolution of the model coefficients X(τ) in the form

$$\mathrm{X}\ (\tau+1) = \mathrm{A}\ (\tau)^{*}\ \mathrm{X}(\tau) + u\ (\tau) \qquad (4)$$

Where A (τ) is a time dependent transition matrix, known a priori, describing how X evolves from one time period to the next during the season and $u(\tau)$ is a stochastic variable describing the "model noise", *i.e.*, those part of the model development we do not know a priori.

Since we do not know the "ideal" coefficients X (τ) and u (τ), we have to make estimates:

X (τ / τ) and e (τ / τ) is the corresponding co-variance of X.

In our applications A (τ) = 1 for all times τ, because we lack any theory (or even empirical formulas) describing how the coefficients develop over time. In other words, we will apply estimates valid "today" as a forecast some days ahead.

All changes in X will in our examples be due to random /unexplained variations due to the noise u (τ). Both v (τ) and u (τ) as well as e (τ / τ) are supposed to be normally distributed and uncorrelated with means 0 (white noise) and standard deviations D(τ), C(τ) and Q(τ) respectively.

2.2.3. *Definitions of the time prefixes*

Time prefixes may be confusing, the following principles will be used,

τ = the seasonal time when a numerical forecast is verified.

Y (τ) = the observed error between the TFC and TOBS at time (τ), not between The Kalman filtered and corrected value and TOBS.

X (τ -1/ τ -1) = last estimated value of the coefficients valid at (τ -1)

X (τ / τ -1) = last estimated value of the coefficients valid at (τ) but made at time (τ -1)

X (τ / τ) = the estimated model coefficients at (τ) after Kalman filtering *i.e.*, (update of X [τ-1/ τ-1)]

X (τ +1/ τ) = estimated coefficients for the next time step.

X (τ) = "true'' value of X.

- Thus prefix (τ) always denotes true values of which only *Y*(τ) can be observed.

- Prefix (τ / τ) denotes model values.

- Prefix (τ / τ-1) denotes estimated value at (τ) using information up to (τ-1). This can later be updated to (τ / τ) and form a better estimation of the true value.

It is important to note that (τ +1) does not necessarily denote a +24 hour forecast , but forecast for any lead time.

2.2.4. *Updating the coefficients*

Using Eqn. (2) at time (τ -1), we make a prediction error *Y* at time (τ) assuming that v (τ / τ -1) = 0.

$$Y(\tau / \tau -1) = X(\tau / \tau -1) \tag{5}$$

i.e., the last available verification TFC-TOBS. Any difference between the predicted *Y* (τ / τ -1) and observed value *Y* (τ) must of course make us update X.

Let us introduce δ (to be derived later), having the property 0< δ(τ)<1 so that

$$X(\tau / \tau) = X(\tau / \tau -1) + \delta(\tau) * [Y(\tau) - Y(\tau / \tau -1)] \tag{6}$$

This is the recursive formula to update our estimate of X.

For the current available TFC we apply correction (4) assuming u (τ +1) = 0

$$X(\tau +1/ \tau) = A(\tau) * X(\tau / \tau) \tag{7}$$

And combined with Eqn. (6) and remembering that X (τ / τ -1) = *Y* (τ / τ -1) in the 1-dimentional case

$$X(\tau +1)/\tau) = A(\tau) * \{X(\tau / \tau -1) + \delta(\tau) * [Y(\tau) - Y(\tau/\tau-1)]\}$$

$$= A(\tau) * [X(\tau / \tau-1) + \delta(\tau) * Y(\tau) - X(\tau / \tau-1)]$$

$$= [A(\tau) - \delta(\tau)] * X(\tau / \tau -1) + \delta(\tau) * Y(\tau) \tag{8}$$

2.2.5. *Updating the co-variances*

Also the error in our estimate Eqn. (8) follows a recursive equation. Let

Let e (τ) as stated above denotes this error:

e (τ +1) = X (τ +1) – [X(τ +1) / τ]

so from Equations (6) and (8)

$$\begin{aligned} e(\tau+1) &= A(\tau)^* X(\tau) + u(\tau+1) - [A(\tau) - \delta(\tau)]^* X(\tau/\tau-1) - \delta(\tau)^* Y(\tau) \\ &= A(\tau)\,[X(\tau) - X(\tau/\tau-1)] + u(\tau+1) + \delta(\tau)^* X(\tau/\tau-1) + \delta(\tau)^*[X(\tau) + v(\tau)] \\ &= [A(\tau) - \delta(\tau)]^* [X(\tau) - X(\tau/\tau-1)] + u(\tau+1) - \delta(\tau)^* v(\tau) \\ &= [A(\tau) - \delta(\tau)]^* e(\tau) + u(\tau+1) - \delta(\tau)^* v(\tau) \end{aligned} \tag{9}$$

If $Q(\tau) = \mathrm{cov}(e)$, $D(\tau) = \mathrm{cov}(v)$ and $C(\tau) = \mathrm{cov}(u)$ then

$$Q(\tau+1) = [A(\tau) - \delta(\tau)]^* Q(\tau)^*[A(\tau) - \delta(\tau)] + C(\tau) + \delta(\tau)^* D(\tau)^* \delta(\tau) \tag{10}$$

2.2.6. *Derivation of δ(τ)*

Derive $\delta(\tau)$ by minimizing the variance of estimated errors:

$$\mathrm{Var}\,[X(\tau+1) - X(\tau+1/\tau)] \tag{11}$$

Use Eqn. (4) $X(\tau+1) = A(\tau)^* X(\tau) + u(\tau)$

And Eqn. (8) $X(\tau+1/\tau) = [A(\tau) - \delta(\tau)]^* X(\tau/\tau-1) + \delta(\tau)^* Y(\tau)$

and (1) $Y(\tau) = X(\tau) + v(\tau)$

which yields

$$\begin{aligned} &\mathrm{var}\,\{A(\tau)^* X(\tau) + u(\tau) - [A(\tau) - \delta(\tau)]^* X(\tau/\tau-1) - \delta(\tau^*[X(\tau) + v(\tau)]\} \\ &= \mathrm{var}\,\{A(\tau) - \delta(\tau)^* X(\tau) + u(\tau) - [A(\tau) - \delta(\tau)]^* X(\tau/\tau-1) - \delta(\tau)^* v(\tau)\} \\ &= \mathrm{var}\,[A(\tau) - \delta(\tau)]^* X(\tau) - X(\tau/\tau-1) + u(\tau) - \delta(\tau)^* v(\tau) \\ &= \mathrm{var}\,[A(\tau) - \delta(\tau)]^* e(\tau) + u(\tau) - \delta(\tau)^* v(\tau) \end{aligned} \tag{12}$$

or

skipping τ -indices

$$\mathrm{var}\,[(A-\delta)^* e + u - \delta^* v] \tag{13}$$

Since $e(\tau)$, $u(\tau)$ and $v(\tau)$ are uncorrelated their products can be can be deleted, we can express (13) using $\mathrm{var}(e) = Q$

$$Q^*A^{**}2 + Q^*\delta^{**}2 - Q^*2^*A^*\delta + C + \delta^{**}2^*D$$

Now we differentiate with respect to δ and put expression = 0

$$2^*Q^*\delta - 2^*Q^*A + 2^*\delta^*D = 0$$

which ends up into

$$(Q + D)^*\delta = QA \;=>\; \delta = QA/(Q + D) \tag{14}$$

Expressed in τ

$$\delta(\tau) = A(\tau)^* Q(\tau)/[D(\tau) + Q(\tau)] \tag{15}$$

2.2.7. *Obtaining the forecast*

The values of $X(\tau + 1/\tau)$ is obtained by using the values $X(\tau/\tau-1)$ and $Y(\tau)$ by using equation (8). $A(\tau)$, $D(\tau)$, $Q(\tau)$ and delta(τ) are also calculated at each step by using equation (15). After obtaining the values of X's by using the last 40 days data. These values of X's are used for obtaining the bias value to be used on 41st day by using the equation (3), assuming noise as zero. These biases are obtained for 24, 48, 72, 96 and 120 hour forecasts separately and are used for getting the bias free temperature forecasts.

2.3. *Bias free rainfall forecast*

For rainfall optimal threshold value is set so as to maximise the skill score. Optimal threshold value means that if the forecasted rainfall amount is less than the threshold then forecasted value is taken as zero other wise it is taken as the forecasted rainfall amount.

Let Th be a hit and trail threshold value for deciding rain/no rain cases. That is Th be the threshold up to which the rainfall is taken as zero and beyond the Th value rainfall is taken as actual value then if the forecasted value for rainfall series during a season is denoted as R_{fi}, i = 1,2, …….*n*. Let. Value 1 is taken for rainfall case and let it is denoted by *Y* and no rain *i.e.*, 0 cases are denoted as N.

Similarly observed value for rainfall series during the season is denoted by R_{oi} , *I* = 1,2, …..,*n* ; then consider the threshold value as 0.1 mm and the derived values are denoted by the variable *Y* for rainfall and N for no rain cases.

Hanssen and Kuipers (HK) score, as defined in Para 2.4, is maximised by varying the value of Th, based upon the data from previous season and the same Th value is applied for the forecasted rainfall values for the current season.

2.4. *Skill scores used*

The ratio score and HK score are used for the verification of yes/no rainfall forecasts. The scores used for verification of rainfall forecast are the ratio score and Hanssen and Kuipers (H.K.) skill scores. The ratio score (RS) measures the percentage of correct forecasts out of total forecasts issued. The Hanssen and Kuipers' discriminant (HK) is the ratio of economic saving over climatology.

H.K Score can be explained by the following contingency table.

	Observed	
Forecasted	*Rain*	*No Rain*
Rain	YY	YN
No Rain	NY	NN

Ratio Score = (YY + NN) / N

H. K. Score = (YY*NN-YN*NY)/(YY+YN)*(NY+NN)

If the H. K. Score is closer to 1 then the forecasts are the best and when the H.K. Score is near 0 or less than 0 then the forecasts are bad.

For quantitative precipitation hit rate is used as the measure of skill. While defining the hit rate, only the four categories are considered for observed and as well as for forecasted rainfall (quantitative precipitation). These categories are defined as fallows,

o_1 , f_1 ; less than threshold (Th) is no rain

o_2, f_2 ; greater than Th and less than 3.5 cm is light to moderate rain

o_3, f_3 ; greater than 3.5 cm and less than 12.5 cm is heavy rain

o_4, f_4 ; greater than 12.5 cm is very heavy rain.

Then a 4 × 4 contingency table is defined as fallows,

	o_1	o_2	o_3	o_4
f_1	a	b	C	D
f_2	E	f	G	H
f_3	I	j	K	L
f_4	m	n	O	P

Then the hit rate for quantitative precipitation is defined as ,

H = (a + f + k + p)/N

where N is the total of all the frequencies shown in the table.

Hit rate for different categories of rainfall *viz*., light to moderate, heavy and very heavy is calculated as no. of matching cases divided by total no of observed rainfall cases in a particular rainfall category.

Rainfall categories are taken as;

Light to moderate rain	:	Threshold value to 3.5 cm
Heavy	:	more than 3.5 cm to 12.5 cm
Very Heavy	:	more than 12.5 cm

TABLE 1

Skill score for 24 hr rainfall forecast, Monsoon (June – September 2007)

S. No.	Station	Bias free			DMO		
		Ratio (%)	HK	Hit Rate for QP	Ratio (%)	HK	Hit Rate for QP
1	Ahmedabad	60	0.20	0.56	60	0.17	0.51
2	Akola	66	0.25	0.65	60	0.10	0.57
3	Amritsar	56	0.10	0.54	40	-0.05	0.36
4	Bhopal	74	0.47	0.68	60	0.22	0.55
5	Bhubaneshwar	61	0.28	0.55	59	-0.01	0.59
6	Bikaner	68	0.24	0.67	30	-0.09	0.19
7	Bangalore	59	0.17	0.57	44	-0.07	0.41
8	Chennai	64	0.28	0.62	55	0.02	0.52
9	Coimbatore	61	0.18	0.62	41	-0.04	0.41
10	Dehradun	70	0.38	0.52	65	0.20	0.49
11	Delhi	60	0.21	0.57	47	0.13	0.45
12	Guwahati	70	0.36	0.56	66	0.06	0.56
13	Gwalior	60	0.20	0.59	52	0.08	0.49
14	Hissar	61	0.29	0.55	41	0.14	0.37
15	Hyderabad	57	0.11	0.53	55	0.07	0.58
16	Imphal	57	0.14	0.51	54	0.04	0.75
17	Indore	65	0.31	0.58	58	0.11	0.49
18	Jabalpur	65	0.32	0.59	60	0.18	0.55
19	Jodhpur	61	0.31	0.61	34	0.11	0.32
20	Jaipur	61	0.17	0.57	44	0.10	0.41
21	Jammu	55	0.10	0.49	51	0.04	0.48
22	Mumbai	82	0.46	0.62	79	0.00	0.62
23	Patna	69	0.37	0.62	58	0.06	0.49
24	Panaji	69	0.41	0.44	65	0.00	0.65
25	Pune	71	0.34	0.65	69	0.00	0.65
26	Raipur	63	0.22	0.57	60	0.07	0.55
27	Ranchi	60	0.15	0.52	54	0.00	0.57
28	Shillong	64	0.23	0.49	61	0.00	0.61
29	Udaipur	68	0.32	0.66	40	0.07	0.37
30	Varanasi	63	0.18	0.58	52	0.14	0.47

TABLE 2

Skill score for 72hr rainfall forecast, Monsoon (June – September 2007)

S. No.	Station	Bias free			DMO		
		Ratio (%)	HK	Hit Rate for QP	Ratio (%)	HK	Hit Rate for QP
1	Ahmedabad	64	0.30	0.61	59	0.17	0.51
2	Akola	60	0.20	0.57	58	0.04	0.56
3	Amritsar	56	0.10	0.62	53	0.07	0.51
4	Bhopal	58	0.15	0.56	55	0.11	0.45
5	Bhubaneshwar	55	0.10	0.57	51	0.00	0.56
6	Bikaner	56	0.10	0.63	30	-0.02	0.26
7	Bangalore	59	0.20	0.59	52	0.09	0.49
8	Chennai	61	0.22	0.51	55	0.03	0.52
9	Coimbatore	58	0.13	0.56	43	-0.01	0.43
10	Dehradun	75	0.52	0.56	62	0.27	0.49
11	Delhi	55	0.10	0.54	50	0.05	0.48
12	Guwahati	65	0.28	0.53	60	0.16	0.52
13	Gwalior	58	0.20	0.59	39	0.07	0.35
14	Hissar	61	0.15	0.48	43	0.09	0.40
15	Hyderabad	55	0.10	0.49	50	-0.04	0.50
16	Imphal	56	0.16	0.53	52	0.07	0.72
17	Indore	55	0.11	0.55	50	0.10	0.49
18	Jabalpur	64	0.27	0.63	58	0.05	0.50
19	Jodhpur	65	0.35	0.63	44	0.20	0.42
20	Jaipur	66	0.35	0.61	44	0.10	0.41
21	Jammu	58	0.14	0.58	51	0.08	0.56
22	Mumbai	73	0.44	0.63	69	0.12	0.68
23	Patna	57	0.15	0.59	57	0.05	0.46
24	Panaji	62	0.20	0.43	59	0.00	0.63
25	Pune	72	0.37	0.68	65	0.00	0.65
26	Raipur	64	0.25	0.55	61	0.02	0.50
27	Ranchi	57	0.15	0.50	51	0.00	0.52
28	Shillong	70	0.55	0.54	60	0.05	0.56
29	Udaipur	56	0.16	0.57	44	0.14	0.39
30	Varanasi	55	0.11	0.45	47	0.07	0.42

TABLE 3

Skill score for 120hr rainfall forecast, Monsoon (June – September 2007)

S. No.	Station	Bias free			DMO		
		Ratio (%)	HK	Hit Rate for QP	Ratio (%)	HK	Hit Rate for QP
1	Ahmedabad	64	0.30	0.60	64	0.26	0.54
2	Akola	60	0.20	0.59	59	0.08	0.57
3	Amritsar	58	0.10	0.57	51	-0.07	0.49
4	Bhopal	58	0.10	0.50	54	0.09	0.47
5	Bhubaneshwar	55	0.15	0.50	51	-0.06	0.54
6	Bikaner	56	0.10	0.60	30	-0.04	0.25
7	Bangalore	55	0.14	0.55	48	0.03	0.43
8	Chennai	58	0.15	0.50	51	0.07	0.46
9	Coimbatore	56	0.10	0.46	43	-0.01	0.42
10	Dehradun	63	0.27	0.52	62	0.20	0.51
11	Delhi	55	0.10	0.51	47	0.09	0.44
12	Guwahati	62	0.20	0.52	60	0.09	0.57
13	Gwalior	60	0.26	0.56	38	0.02	0.33
14	Hissar	61	0.29	0.50	47	0.18	0.44
15	Hyderabad	55	0.10	0.53	51	-0.05	0.51
16	Imphal	58	0.23	0.50	54	0.04	0.73
17	Indore	58	0.17	0.51	55	0.06	0.44
18	Jabalpur	55	0.10	0.59	52	0.05	0.49
19	Jodhpur	59	0.10	0.54	35	-0.01	0.35
20	Jaipur	60	0.22	0.61	44	0.09	0.41
21	Jammu	55	0.14	0.51	49	-0.03	0.46
22	Mumbai	66	0.22	0.58	62	0.04	0.65
23	Patna	56	0.10	0.47	52	0.07	0.47
24	Panaji	57	0.34	0.41	55	0.00	0.62
25	Pune	58	0.15	0.63	55	-0.01	0.66
26	Raipur	55	0.10	0.45	50	0.03	0.53
27	Ranchi	61	0.20	0.50	55	0.03	0.51
28	Shillong	65	0.40	0.56	60	0.11	0.57
29	Udaipur	56	0.13	0.43	38	0.00	0.32
30	Varanasi	55	0.11	0.47	50	0.09	0.44

TABLE 4

Skill score for rainfall categories and active & weak Monsoon for 24hr forecast (June – September 2007)

S. No.	Station	Hit rate for rainfall category			Hit rate for monsoon		
		No rain	Light to moderate	Heavy	Very heavy	Active periods	Weak periods
1	Ahmedabad	0.62	0.59	0.18	-	0.68	0.49
2	Akola	0.42	0.86	0..00	-	0.74	0.61
3	Amritsar	0.57	0.52	0.00	-	0.46	0.60
4	Bhopal	0.67	0.76	0.00	0.00	0.69	0.63
5	Bhubaneshwar	0.74	0.51	0.00	0.00	0.58	0.52
6	Bikaner	0.70	0.47	-	-	0.68	0.66
7	Bangalore	0.65	0.50	0.00	-	0.60	0.59
8	Chennai	0.57	0.70	0.00	-	0.54	0.65
9	Coimbatore	0.79	0.40	-	-	0.57	0.62
10	Dehradun	0.64	0.66	0.05	0.00	0.47	0.54
11	Delhi	0.55	0.66	0.00	0.00	0.45	0.58
12	Guwahati	0.59	0.61	0.00	-	0.71	0.54
13	Gwalior	0.71	0.40	0.00	-	0.56	0.62
14	Hissar	0.53	0.69	0.00	-	0.49	0.61
15	Hyderabad	0.50	0.59	0.00	-	0.49	0.55
16	Imphal	0.50	0.52	0.00	-	0.62	0.52
17	Indore	0.79	0.46	0.12	0.00	0.54	0.61
18	Jabalpur	0.70	0.61	0.00	-	0.50	0.60
19	Jodhpur	0.60	0.74	0.00	-	0.55	0.64
20	Jaipur	0.68	0.42	0.00	-	0.60	0.56
21	Jammu	0.57	0.48	0.00	-	0.58	0.49
22	Mumbai	0.59	0.76	0.12	0.00	0.58	0.61
23	Patna	0.70	0.68	0.09	-	0.49	0.66
24	Panaji	0.71	0.58	0.04	0.00	0.58	0.39
25	Pune	0.64	0.70	0.22	-	0.70	0.61
26	Raipur	0.52	0.70	0.11	0.00	0.47	0.58
27	Ranchi	0.47	0.60	0.14	-	0.54	0.54
28	Shillong	0.47	0.60	0.14	0.00	0.43	0.53
29	Udaipur	0.70	0.62	0.20	-	0.57	0.72
30	Varanasi	0.74	0.38	0.00	-	0.66	0.51

TABLE 5

Skill score for rainfall categories and active & weak monsoon for 72hr forecast (June – September 2007)

S. No.	Station	Hit rate for rainfall category			Hit rate for monsoon		
		No rain	Light to moderate	Heavy	Very heavy	Active periods	Weak periods
1	Ahmedabad	0.76	0.57	.0.09	-	0.55	0.62
2	Akola	0.66	0.53	0.00	-	0.53	0:56
3	Amritsar	0.70	0.43	0.00	-	0.60	0.65
4	Bhopal	0.58	0.59	0.25	0.00	0.53	0.58
5	Bhubaneshwar	0.62	0.63	0.00	0.00	0.64	0.52
6	Bikaner	0.63	0.61	-	-	0.55	0.66
7	Bangalore	0.61	0.60	0.00	-	0.71	0.53
8	Chennai	0.48	0.57	0.00	-	0.51	0.53
9	Coimbatore	0.66	0.43	-	-	0.54	0.58
10	Dehradun	0.80	0.60	0.09	0.00	0.61	0.52
11	Delhi	0.50	0.64	0.00	0.00	0.40	0.57
12	Guwahati	0.55	0.52	0.57	-	0.61	0.52
13	Gwalior	0.58	0.67	0.00	-	0.61	0.57
14	Hissar	0.56	0.31	0.00	-	0.43	0.50
15	Hyderabad	0.34	0.62	0.00	-	0.37	0.53
16	Imphal	0.62	0.52	0.00	-	0.59	0.51
17	Indore	0.75	0.42	0.25	0.00	0.57	0.56
18	Jabalpur	0.70	0.67	0.00	-	0.66	0.59
19	Jodhpur	0.63	0.68	0.00	-	0.57	0.64
20	Jaipur	0.59	0.68	0.00	-	0.57	. 0.59
21	Jammu	0.84	0.34	0.00	-	0.61	0.58
22	Mumbai	0.88	0.72	0.12	0.00	0.58	0.61
23	Patna	0.70	0.62	0.00	-	0.37	0.63
24	Panaji	0.57	0.55	0.12	0.00	0.58	0.32
25	Pune	0.65	0.74	0.22	-	0.65	0.68
26	Raipur	0.55	0.65	0.00	0.00	0.53	0.55
27	Ranchi	0.47	0.58	0.12	-	0.46	0.50
28	Shillong	0.75	0.56	0.29	0.00	0.57	0.51
29	Udaipur	0.56	0.63	0.40	-	0.65	0.52
30	Varanasi	0.60	0.53	0.00	-	0.44	0.57

TABLE 6

Skill score for rainfall categories and active & weak Monsoon for 120hr forecast (June – September 2007)

S. No.	Station	Hit rate for rainfall category				Hit rate for monsoon	
		No rain	Light to moderate	Heavy	Very heavy	Active periods	Weak periods
1	Ahmedabad	0.71	0.62	0.00	-	0.58	0.61
2	Akola	0.58	0.62	0.00	-	0.58	0.59
3	Amritsar	0.66	0.35	0.00	-	0.51	0.61
4	Bhopal	0.49	0.53	0.25	0.00	0.50	0.46
5	Bhubaneshwar	0.58	0.52	0.00	0.00	0.53	0.47
6	Bikaner	0.62	0.53	-	-	0.53	0.63
7	Bangalore	0.58	0.53	0.00	-	0.69	0.47
8	Chennai	0.43	0.57	0.00	-	0.51	0.47
9	Coimbatore	0.48	0.43	-	-	0.37	0.47
10	Dehradun	0.71	0.62	0.05	0.00	0.50	0.54
11	Delhi	0.51	0.55	0.00	0.00	0.43	0.54
12	Guwahati	0.55	0.55	0.14	-	0.42	0.59
13	Gwalior	0.54	0.68	0.00	-	0.56	0.56
14	Hissar	0.52	0.50	0.00	-	0.40	0.54
15	Hyderabad	0.49	0.60	0.00	-	0.49	0.57
16	Imphal	0.59	0.49	0.00	-	0.54	0.48
17	Indore	0.59	0.53	0.00	0.00	0.46	0.54
18	Jabalpur	0.76	0.53	0.11	-	0.68	0.52
19	Jodhpur	0.59	0.38	0.00	-	0.55	0.53
20	Jaipur	0.62	0.66	0.00	-	0.47	0.67
21	Jammu	0.84	0.15	0.00	-	0.48	0.52
22	Mumbai	0.87	0.66	0.06	0.00	0.50	0.58
23	Patna	0.39	0.65	0.08	-	0.23	0.56
24	Panaji	1.00	0.48	0.15	0.00	0.58	0.31
25	Pune	0.62	0.71	0.00	-	0.59	0.62
26	Raipur	0.77	0.30	0.00	0.00	0.42	0.44
27	Ranchi	0.51	0.55	0.20	-	0.40	0.56
28	Shillong	0.72	0.59	0.36	0.00	0.53	0.53
29	Udaipur	0.46	0.43	0.00	-	0.41	0.46
30	Varanasi	0.36	0.71	0.00	-	0.38	0.51

TABLE 7

Skill score for 24hr minimum temperature forecast, monsoon (June – September 2007)

S. No.	Station	Kalman Filtered		DMO	
		MAE	ME	MAE	ME
1	Ahmedabad	1.16	-0.03	1.50	0.28
2	Akola	1.37	-0.21	1.67	1.51
3	Amritsar	2.17	-0.32	4.72	4.70
4	Bhopal	1.33	0.06	1.48	1.29
5	Bhubaneshwar	1.69	-0.29	1.77	1.59
6	Bikaner	2.04	0.14	2.04	0.14
7	Bangalore	1.04	0.01	0.83	0.23
8	Chennai	1.47	-0.38	1.88	1.71
9	Coimbatore	0.87	-0.04	0.97	0.66
10	Dehradun	1.78	0.21	1.73	1.35
11	Delhi	2.04	-1.14	2.16	-0.04
12	Guwahati	1.00	-0.32	1.03	-0.52
13	Gwalior	1.79	-0.72	1.80	0.67
14	Hissar	2.14	-0.27	2.17	1.09
15	Hyderabad	1.34	-0.06	1.60	1.49
16	Imphal	0.79	-0.20	0.81	0.63
17	Indore	1.50	-0.24	2.15	2.06
18	Jabalpur	1.50	-0.28	2.12	1.99
19	Jodhpur	1.87	0.12	1.84	0.01
20	Jaipur	1.87	0.22	3.46	3.39
21	Jammu	1.82	1.19	2.16	1.87
22	Mumbai	1.19	-0.50	1.12	-0.03
23	Patna	1.32	-0.46	1.76	-0.74
24	Panaji	0.94	-0.19	2.11	2.10
25	Pune	0.69	0.05	0.62	0.09
26	Raipur	1.55	0.14	2.12	2.04
27	Ranchi	1.14	0.08	1.86	1.77
28	Shillong	1.02	-0.06	2.15	-2.11
29	Udaipur	1.56	-0.02	1.77	0.40
30	Varanasi	1.52	-0.85	1.67	-0.65

TABLE 8

Skill score for 72hr minimum temperature forecast, monsoon (June – September 2007)

S. No.	Station	Kalman Filtered		DMO	
		MAE	ME	MAE	ME
1	Ahmedabad	1.34	-0.08	1.59	0.25
2	Akola	1.61	-0.67	1.64	1.47
3	Amritsar	2.46	-1.00	4.40	4.35
4	Bhopal	1.44	-0.03	1.54	1.29
5	Bhubaneshwar	1.78	-0.59	1.63	1.30
6	Bikaner	2.38	-0.73	2.38	1.51
7	Bangalore	1.13	-0.18	0.93	-0.38
8	Chennai	1.47	-0.31	1.69	1.43
9	Coimbatore	0.90	-0.23	0.81	-0.39
10	Dehradun	1.47	-0.43	1.71	1.40
11	Delhi	2.02	-0.95	2.00	-0.08
12	Guwahati	1.24	-0.74	1.37	-0.79
13	Gwalior	1.79	-0.80	1.88	0.82
14	Hissar	2.35	0.05	2.07	1.12
15	Hyderabad	1.25	0.20	1.33	1.23
16	Imphal	1.04	-0.12	0.90	0.01
17	Indore	1.79	-0.20	2.14	1.98
18	Jabalpur	1.43	-0.53	1.94	1.70
19	Jodhpur	1.66	0.23	2.06	0.87
20	Jaipur	1.80	0.53	3.64	3.74
21	Jammu	1.88	0.62	2.08	1.45
22	Mumbai	1.07	-0.21	1.12	-0.01
23	Patna	2.01	-1.37	2.11	-0.95
24	Panaji	1.01	-0.21	2.05	2.03
25	Pune	0.84	-0.10	0.67	0.12
26	Raipur	2.37	-0.92	1.91	1.66
27	Ranchi	1.43	-0.03	1.83	1.65
28	Shillong	1.25	-0.78	2.51	-2.47
29	Udaipur	1.76	0.25	1.96	0.44
30	Varanasi	1.86	-1.13	2.11	-0.83

TABLE 9

Skill score for 120hr minimum temperature forecast, monsoon (June – September 2007)

S. No.	Station	Kalman Filtered		DMO	
		MAE	ME	MAE	ME
1	Ahmedabad	1.56	-0.58	1.57	0.14
2	Akola	1.49	-0.47	1.53	1.26
3	Amritsar	2.86	-0.96	4.34	4.30
4	Bhopal	2.01	0.22	1.83	1.40
5	Bhubaneshwar	1.79	-0.76	1.47	1.16
6	Bikaner	2.04	-0.14	2.04	0.14
7	Bangalore	0.84	-0.32	0.83	-0.39
8	Chennai	1.39	-0.54	1.62	1.32
9	Coimbatore	0.93	-0.24	0.85	0.35
10	Dehradun	1.74	-0.45	1.68	1.12
11	Delhi	2.39	-1.88	1.84	-0.15
12	Guwahati	1.25	-0.61	1.52	-1.15
13	Gwalior	2.44	-1.34	1.92	0.88
14	Hissar	2.25	-0.35	2.04	1.06
15	Hyderabad	1.05	-0.13	1.15	1.00
16	Imphal	0.99	-0.24	0.87	-0.25
17	Indore	2.27	-0.84	2.16	1.97
18	Jabalpur	1.69	-0.92	2.07	1.74
19	Jodhpur	1.99	0.18	2.27	0.96
20	Jaipur	1.88	-0.44	3.85	3.79
21	Jammu	1.97	0.35	2.13	1.16
22	Mumbai	1.23	-0.12	1.25	-0.06
23	Patna	2.03	-1.52	2.16	-0.96
24	Panaji	1.19	-0.08	1.97	1.96
25	Pune	0.85	-0.17	0.75	0.01
26	Raipur	1.42	-0.18	1.71	1.52
27	Ranchi	1.56	-0.08	1.81	1.58
28	Shillong	1.51	-1.16	2.73	-2.69
29	Udaipur	2.09	-0.84	2.00	0.44
30	Varanasi	2.12	1.02	2.16	-0.78

TABLE 10

Skill score for 24hr maximum temperature forecast, monsoon (June – September 2007)

S. No.	Station	Kalman Filtered		DMO	
		MAE	ME	MAE	ME
1	Ahmedabad	1.73	0.63	1.81	0.34
2	Akola	1.89	0.86	2.01	1.25
3	Amritsar	2.11	0.26	4.15	4.09
4	Bhopal	2.00	-0.09	2.21	1.98
5	Bhubaneshwar	2.89	-0.97	2.89	2.56
6	Bikaner	1.64	-0.32	1.67	-1.01
7	Bangalore	1.51	-0.27	2.02	1.82
8	Chennai	1.89	-0.06	1.87	0.55
9	Coimbatore	1.49	0.05	1.73	-0.89
10	Dehradun	2.24	0.58	2.09	1.44
11	Delhi	2.08	-0.37	2.45	-0.22
12	Guwahati	1.89	-0.31	2.15	-1.47
13	Gwalior	1.61	-0.19	1.69	-0.16
14	Hissar	2.17	0.21	2.72	-0.37
15	Hyderabad	1.69	0.26	1.79	1.31
16	Imphal	1.62	0.34	1.68	-0.78
17	Indore	1.75	0.13	2.08	1.53
18	Jabalpur	1.98	-0.20	3.33	3.26
19	Jodhpur	1.53	-0.17	1.70	-0.13
20	Jaipur	1.73	0.09	1.75	3.39
21	Jammu	2.03	-0.04	2.16	0.00
22	Mumbai	1.66	-0.48	1.68	-1.22
23	Patna	2.22	0.72	2.20	0.10
24	Panaji	1.13	0.14	1.16	0.30
25	Pune	1.51	-0.12	2.13	-1.95
26	Raipur	2.25	-0.36	3.99	3.89
27	Ranchi	1.88	-0.39	1.91	1.50
28	Shillong	1.43	-0.08	1.93	-1.78
29	Udaipur	1.58	0.33	1.77	-0.38
30	Varanasi	1.98	0.02	2.04	-0.08

TABLE 11

Skill score for 72hr maximum temperature forecast, monsoon (June – September 2007)

S. No.	Station	Kalman Filtered		DMO	
		MAE	ME	MAE	ME
1	Ahmedabad	2.06	-0.33	2.21	0.46
2	Akola	1.82	0.16	2.23	1.42
3	Amritsar	2.89	0.69	5.11	5.07
4	Bhopal	2.06	-0.64	2.44	1.94
5	Bhubaneshwar	2.89	-0.92	2.82	1.99
6	Bikaner	2.33	-0.67	2.41	-0.51
7	Bangalore	1.73	-0.51	1.80	1.41
8	Chennai	1.80	0.21	1.84	0.10
9	Coimbatore	1.73	-0.28	2.16	-1.43
10	Dehradun	2.64	0.80	2.78	1.63
11	Delhi	2.84	-0.60	2.98	-0.03
12	Guwahati	2.24	-0.46	2.69	-2.03
13	Gwalior	2.28	-0.87	2.28	-0.42
14	Hissar	2.80	-0.80	2.81	0.08
15	Hyderabad	1.82	0.02	1.81	1.18
16	Imphal	2.15	0.10	2.25	-1.14
17	Indore	2.14	-0.23	2.29	1.58
18	Jabalpur	2.44	-0.53	3.44	3.14
19	Jodhpur	2.56	-1.39	2.64	-0.10
20	Jaipur	2.14	-0.15	2.16	0.10
21	Jammu	2.10	0.64	4.16	4.06
22	Mumbai	1.59	-0.49	1.58	-1.12
23	Patna	2.33	-0.22	2.62	0.11
24	Panaji	1.26	0.04	1.30	0.27
25	Pune	1.50	-0.41	2.00	-1.77
26	Raipur	2.55	0.23	4.15	3.82
27	Ranchi	2.09	-0.29	2.21	1.56
28	Shillong	1.79	-0.28	2.48	-2.28
29	Udaipur	2.31	-0.30	2.41	-0.37
30	Varanasi	2.69	-0.51	2.80	-0.25

TABLE 12

Skill score for 120hr maximum temperature forecast, monsoon (June – September 2007)

S. No.	Station	Kalman Filtered		DMO	
		MAE	ME	MAE	ME
1	Ahmedabad	2.18	0.46	2.21	0.30
2	Akola	2.05	0.42	2.11	1.20
3	Amritsar	2.98	0.19	5.58	5.51
4	Bhopal	2.49	-0.78	2.59	1.95
5	Bhubaneshwar	2.47	-0.03	2.57	1.77
6	Bikaner	2.43	-0.38	2.49	-0.11
7	Bangalore	1.67	-0.35	1.75	1.10
8	Chennai	1.85	-0.46	1.85	-0.33
9	Coimbatore	1.89	-0.50	2.43	-1.80
10	Dehradun	2.86	-0.62	2.88	1.80
11	Delhi	2.49	-0.96	2.94	0.35
12	Guwahati	2.36	0.26	3.09	-2.38
13	Gwalior	2.38	-0.90	2.40	-0.20
14	Hissar	2.70	-0.83	2.76	0.65
15	Hyderabad	1.93	-0.10	1.95	0.86
16	Imphal	2.17	0.07	2.29	1.60
17	Indore	2.72	-0.64	2.82	1.47
18	Jabalpur	2.73	-0.48	3.44	2.95
19	Jodhpur	2.34	-0.14	2.36	0.05
20	Jaipur	2.49	-0.42	2.50	0.52
21	Jammu	2.43	0.78	4.51	4.27
22	Mumbai	1.77	-0.35	1.89	-1.41
23	Patna	2.56	-0.01	2.72	-0.05
24	Panaji	1.29	-0.03	1.44	0.06
25	Pune	1.69	-0.24	2.32	-2.11
26	Raipur	2.89	-0.08	3.99	3.53
27	Ranchi	2.43	-0.77	2.49	1.40
28	Shillong	1.95	-0.24	2.86	-2.64
29	Udaipur	2.87	-0.69	2.98	-0.33
30	Varanasi	2.65	-1.71	2.88	-0.22

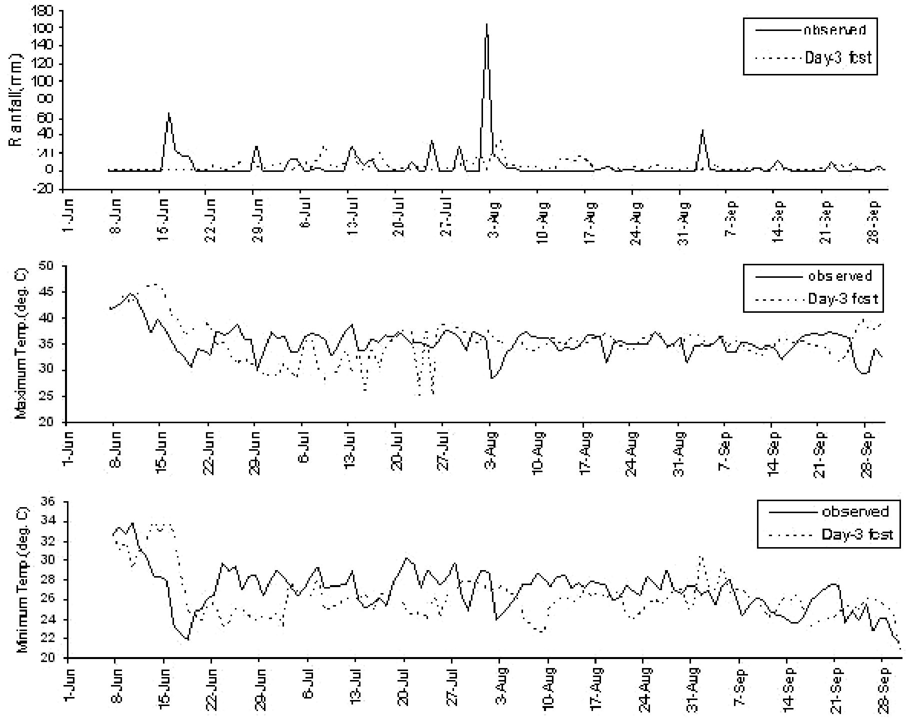

Fig. 2. Observed and Day-3 forecasts for rainfall and maximum/minimum temperature at Delhi

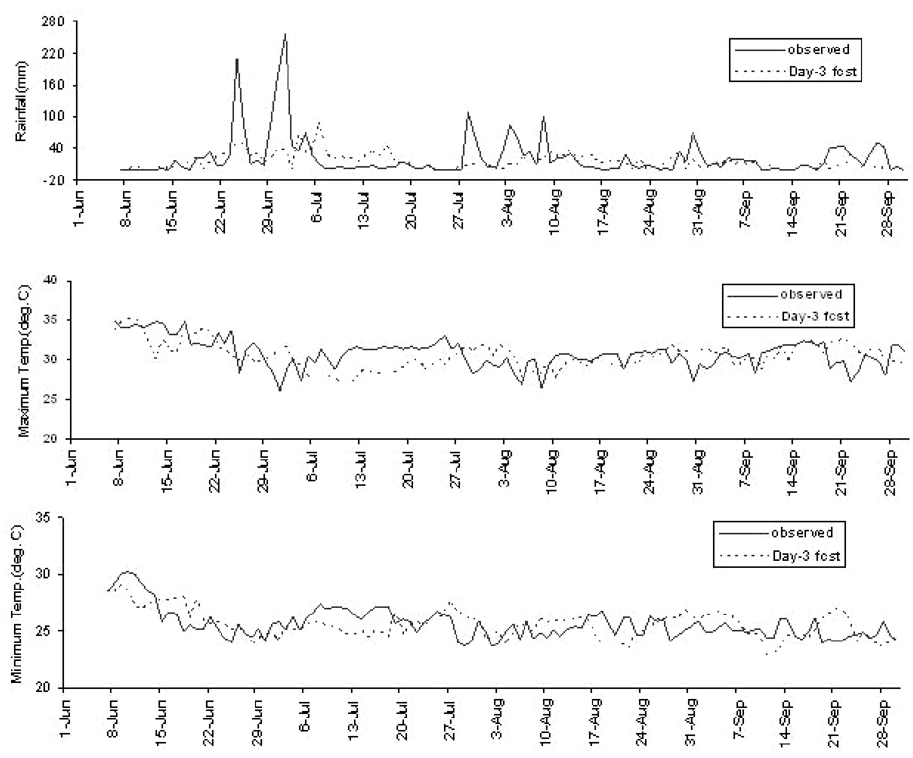

Fig. 3. Observed and Day-3 forecasts for rainfall and maximum/minimum temperature at Mumbai

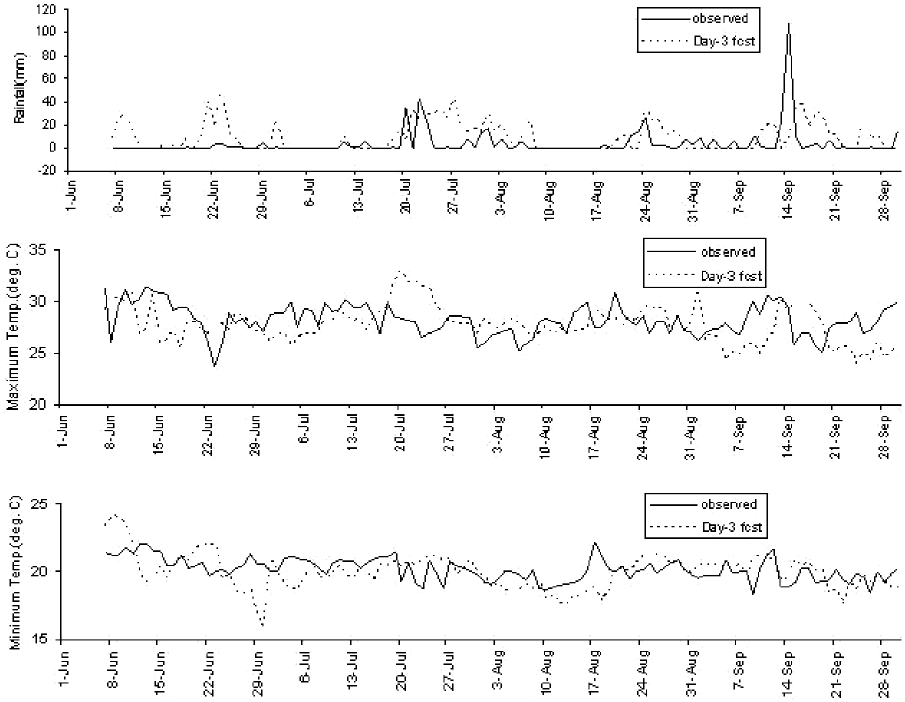

Fig. 4. Observed and Day-3 forecasts for rainfall and maximum/minimum temperature at Bangalore

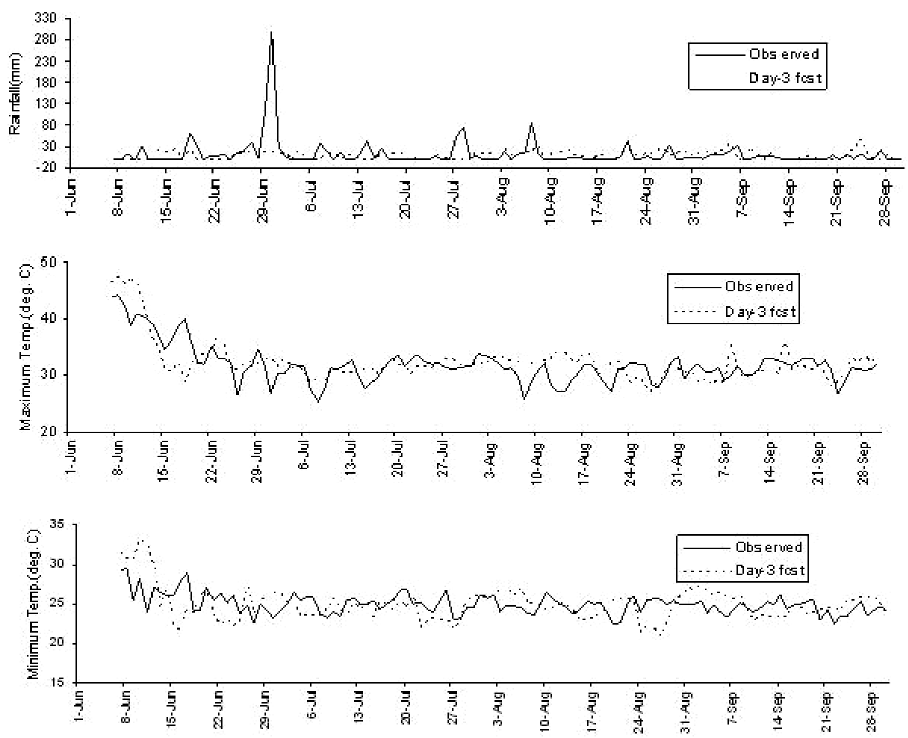

Fig. 5. Observed and Day-3 forecasts for rainfall and maximum/minimum temperature at Raipur

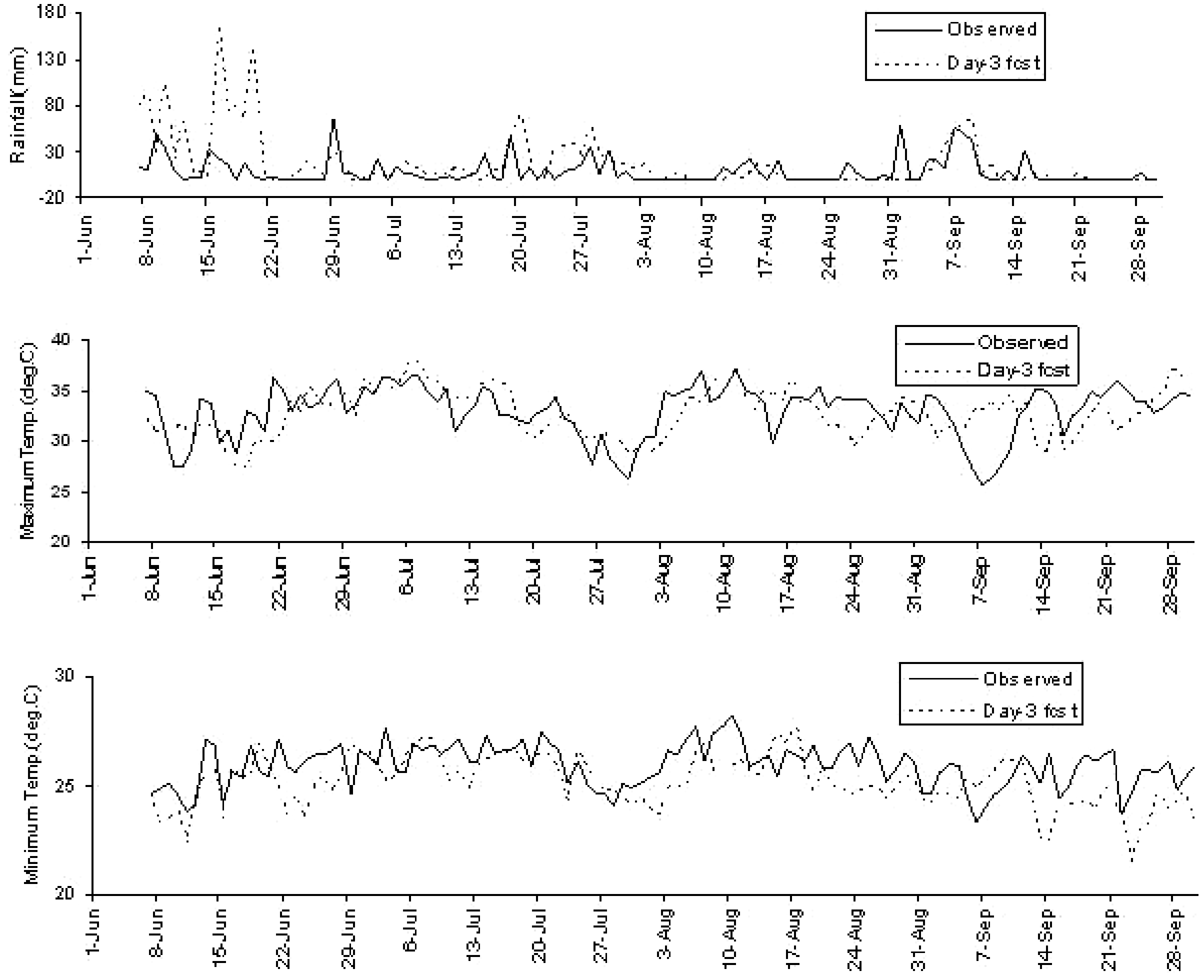

Fig. 6. Observed and Day-3 forecasts for rainfall and maximum/minimum temperature at Guwahati

Hit rates are also calculated for the active and weak monsoon periods during the monsoon season.

The active and weak monsoon period during the monsoon season are defined as follows;

Active monsoon periods	:	The periods with positive rainfall anomaly that is having rainfall more than or equal to normal.
Weak monsoon periods	:	The periods with negative rainfall anomaly that is having rainfall less than normal.

The skill scores used for maximum and minimum temperatures are mean absolute error (MAE) and mean error (ME). For defining these scores, if f_k, k = 1,......,n are the forecast values and o_k, k = 1,....,n are the observed values, then mean absolute error (MAE) is defined as,

$$\mathrm{MAE} = \frac{1}{n}\sum_{k=1}^{n}|f_k - o_k|$$

and mean error (ME) is defined as,

$$\mathrm{ME} = \frac{1}{n}\sum_{k=1}^{n}(f_k - o_k) = \bar{f} - \bar{o}$$

3. Results and discussion

Forecast skill scores for bias free rainfall and systematic error free temperature forecasts are obtained for monsoon season 2007 (Ebert and Mcbride, 2000). For making the verification study compact, these scores are obtained for the 30 stations for which the data could be easily obtained and which are a good sample out of total 70 stations for which the forecast procedure is developed, as these covers almost all the regions of the country. Ratio and HK score are calculated for bias free rainfall forecast. Hit rate for quantitative precipitation, active and weak monsoon and different categories of rainfall are also obtained. The mean absolute error (MAE) and mean error (ME) are calculated for systematic error (bias) free Maximum and Minimum temperatures forecasts. These skill scores are obtained for 24, 48, 72, 96 and 120 prediction hours. These scores are presented for 24, 72 and 120 prediction hours in Tables 1 to Table 12.

3.1. *Rainfall*

It would be worth mentioning here that rainfall being highly variable and discrete, it is not always desirable to make all the values of rainfall as bias free as compared to observations. But if we remove the bias in rainfall series for marginal rains that is discarding the small rainfall values or adjusting the threshold values for rain and no-rain in the developmental data set, such that Hanssen & Kuiper's skill score gets maximized, then definitely we have a higher skill in terms of yes/no rainfall in evaluation data set as indicated from results in Table 1 to Table 3.

For bias free rainfall forecast (Table 1 to Table 3), the ratio scores varies from 55 to 82 percent and HK skill score varies from 0.1 to 0.5. In case of quantitative precipitation, the hit rate for bias free rainfall forecast varies from 0.43 to 0.68. These scores are showing the higher value as compared to the skill scores for DMO forecast for almost all the stations, as is clear from the values in the relevant tables.

The main reason for this is the fact that T-80 model gives marginal rains on the no-rain days and these marginal rainfall values are reduced to zero after comparing with the optimal threshold values which maximizes the HK skill scores.

The hit rates (Table 4 to Table 6) for different categories of rainfall indicates that the hit rates for no-rain and light to moderate category of rain are quite high, these varies from 0.47 to 1.00 for no-rain and 0.42 to 0.86 for light to moderate rainfall and the hit rates for heavy and very heavy category are very low. In fact as the hit rates for even heavy rainfall category are very low, hence the higher resolution NWP models like T-254 (nearly 50 km resolution) and UK Met Office; UKMO (nearly 40 km resolution) are being installed, so that the rainfall amounts could be predicted with more degree of accuracy.

Similarly, the hit rates for active and weak monsoon indicates that for the stations having less number of rainy day it is more for weak monsoon as compared to active monsoon, where as for the stations with more number of rainy days it is more for active monsoon as compared to weak monsoon.

3.2. *Minimum temperature*

For Kalman filtered minimum temperature forecast (Table 7 to Table 9), the MAE varies from 0.87 to 2.86 and ME varies -1.88 to 1.19 and most of the values of MAE varies from 1.0 to 1.75 and the values of ME varies from -0.5 to 0.5. Although the skill decreases with the increase in prognostic hours, but these skill scores indicates that Kalman filtered temperature forecasts are having better skill as compared to DMO forecasts and are a definite improvement over DMO forecasts.

3.3. *Maximum temperature*

For Kalman filtered maximum temperature forecast (Table 10 to Table 12), the MAE varies from 1.13 to 2.98 and ME varies from -1.71 to 0.86 and most of the values of MAE varies from 1.25 to 2.00 and the values of ME varies from -0.5 to 0.5. In this case also the skill decreases with prognostic hours, but the skill scores for Kalman filtered maximum temperature forecasts are showing better skill as compared to DMO forecasts for almost all the stations.

3.4. *Time series comparison*

The time series comparing daily forecast versus observation for rainfall and maximum and minimum temperature for the selected stations *viz*., Delhi ,Mumbai, Bangalore, Raipur and Guwahati, representing different aerial zones of the country, are illustrated as Fig. 2 to Fig. 6. These figures indicate a fairly good match between the observed and forecasted values for most of the stations throughout the monsoon season. Although there are a very few cases in Fig. 2 for Delhi and Fig. 4 for Bangalore, mostly during the initial phase of monsoon period that is June to July, where there are large differences between observed and Day-3 forecasts in the series for maximum and minimum temperatures, these could be attributed to either the formation of a spurious low leading to cloudy conditions in the forecast which is not actually formed or not predicting a low which is actually formed leading to the cloudy conditions.

4. Conclusions

Although the skill falls with the prognosis time, the overall skill scores indicate the potential of the bias free rainfall forecast and Kalman filtered systematic error free temperature forecast to be used as an automated forecast(Kumar and Maini, 1993, 1996) which could be directly issued to the users. The users can have a moderately higher confidence in these forecasts after knowing the fact that rainfall forecasts are having HK scores up to 0.5 and for maximum temperature forecasts MAE varies from 1.25 to 2.00 for most of the stations and for minimum temperature forecast MAE varies from 1.00 to 1.75. At present the forecasts for maximum/minimum temperature and rainfall using the above mentioned methodology is obtained on operational basis for 70 Major cities and is put regularly on NCMRWF website *www.ncmrwf.gov.in.*

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