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Forecasting minimum temperature during winter and maximum temperature during summer at Delhi

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A knowledge of minimum temperature during winter and maximum temperature during summer is a very useful for individuals, as well as for organisations whose workers and machines have to operate in the open, e.g. the armed forces, railways, roadways, tourism, etc. Accurate forecasts of minimum temperature during winter help in the prediction of cold-wave conditions and those of maximum temperature during summer help in the prediction of heat-wave conditions over northern India. Models for forecasting the minimum temperature during December and the maximum temperature during May at Delhi have been developed using surface and upper-air meteorological data from 1984–89. The results of testing the models on independent data from recent years (1994–95) are presented. The results are encouraging and more than 80% of the forecasts are correct within ±2 °C. Possible reasons for large deviations are also investigated.

1. Introduction

Northwestern parts of India are frequently affected by cold-wave conditions in winter months (December–February) and heat waves in summer months (April–June), leading to acute human discomfort and sometimes loss of life. A knowledge of minimum temperature, particularly in the winter season, is of value to many institutions and individuals. For instance, low minimum temperatures may lead to intense winter inversions close to the ground; these increase the residence time and concentration of pollutants such as smoke in the atmospheric boundary layer, leading to conditions of poor visibility. Over hilly areas, such as Jammu and Kashmir, Ladakh, Himachal Pradesh and the Hills of West Uttar Pradesh, a knowledge of the minimum temperature is helpful in predicting frost, which is of use to agriculturists, horticulturists, tourism and the public at large. Prediction of daily maximum temperature in the summer months is useful for providing warning of heat-wave conditions and hence human discomfort. Also, advance information of maximum temperature in the summer months helps agriculturists and water-management experts in planning water and energy requirements. Minimum and maximum temperatures at a specific location depend upon the season, the synoptic condition and local parameters including topography.

The following definitions are used for cold waves and heat waves:

- During winter months (Dec.–Feb.), a location with normal minimum temperature less than or equal to 10 °C is defined as being under moderate cold-wave conditions when the minimum temperature is 3 to 4 °C below normal. Similarly, if the temperature is 5 °C or more below normal, then it becomes a severe cold-wave condition. For a location with normal minimum temperatures of more than 10 °C, the limits for variation are 5–6 °C to be a moderate cold wave, and 7 °C or more for severe cold-wave conditions.
- During summer months (Apr.–Jun.), a location with normal maximum temperature of more than or equal to 40 °C is considered to be under moderate heat-wave conditions when the maximum temperature is 3 to 4 °C above normal. The situation with a temperature of 5 °C or more above normal is referred to as severe heat-wave conditions. For a location with a normal maximum temperature less than 40 °C, the limits are 5–6 °C for a moderate heat wave and 7 °C or more for severe heat-wave conditions.

The extreme weather conditions such as cold-wave and heat-wave conditions are often observed over the northwest (NW) India and Gangetic Plains during the winter and summer seasons respectively. In this study, Delhi is selected as a representative station in NW India for the development of objective methods of predicting minimum temperature in winter and maximum temperature in summer. Considering its geographic location, population and human activity, as well as the availability of quality surface and upper-air meteorological observations, Delhi is the best location in NW India for this study.

In India, the deterministic approach for forecasting minimum and maximum temperature is in the developmental stage.

- Dhanna Singh & Jaipal (1983) developed a method for forecasting the minimum temperature over Delhi. Since their technique requires a subjective deduction of the direction of the advecting wind as a potential predictor, the technique is not totally objective.
- Mohan *et al.* (1989) developed a method for forecasting the maximum temperature over Ozar, situated in Maharashtra.
- Raj (1989) evolved a scheme for predicting minimum temperature at Pune by analogue and regression methods.
- Charantoris & Liakatas (1990) have studied minimum temperature forecasts employing Markov chains.
- Vashisth & Pareek (1991) have used a partial objective method to forecast minimum temperatures at Jaipur and South Rajasthan.
- Attri *et al.* (1995) have used a multiple regression method for forecasting minimum temperature at Gangtok based on the knowledge of dew-point temperature, amount of cloud, and the maximum and minimum temperature recorded on the previous day.

All these studies pertaining to minimum and maximum temperature forecasting in India are either semi-objective or subjective in nature. Also, for a given location, a method for forecasting both minimum and maximum temperature is not available. Short-range, deterministic, location-specific forecasts of meteorological parameters can be carried out using either a meso-scale numerical model, which requires a large computing resource and a meso-scale network of observations, or a simple statistical approach based on a reasonably long record of reliable data. Though the former approach is more attractive, it demands a lot of R & D effort and resources. In this study an attempt is made to develop deterministic statistical models for forecasting minimum and maximum temperatures at a specific location (Delhi) in the NW Indian plains. In this attempt the time-frame of the forecast is restricted to 24 hours or less in view of the limitation in forecast skill and its usefulness in meeting operational requirements.

2. Data and analysis procedure

In order to obtain a reliable and relatively long record of data, a meteorological station situated in the north-eastern periphery of Delhi at a distance of about 15 km from central Delhi (henceforth referred to as Delhi) was selected as the exact location to be used for this study. As a representative period for NW India, the month of December was selected for the minimum temperature because the lowest minimum temperatures are encountered from mid-December to mid-January. Similarly, the month of May was selected for forecasting the maximum temperature because in some years the arrival of the monsoon is early and by the first fortnight of June the temperature comes down. Hence, for developing the forecast models for predicting minimum and maximum temperatures, six years of data (1984–89) for the months of December for minimum and May for maximum temperature have been utilised. The performance of the models was evaluated with independent data from May and December from recent years (1994 and 1995).

In general, at Delhi the minimum temperature occurs close to 0830 IST (Indian Standard Time; the difference between IST and UTC is 5 hours and 30 minutes) and the maximum close to 1430 IST, which happen to be part of three-hourly observing sequence. In the formulation of the model equations for minimum and maximum temperatures, the upper-air observations corresponding to 0530 and 1730 hours IST, which are available about two to three hours after the RS/RW ascents, are utilised. Hence, 12 and 24 hours for minimum temperatures in December, and 9 and 18 hours for maximum temperatures in May, have been chosen as lead times of the forecasts on the basis of availability of data, usefulness and operational requirements. The 24-hour forecast of minimum temperature is issued at 0830 IST (0300 UTC) and the 12-hour forecast at 2030 IST (1500 UTC), both valid for the next day. Similarly, for the maximum temperature the 18-hour forecast is issued at 2030 IST valid for the next day and the 9-hour forecast at 0530 IST (0000 UTC) valid for the same day.

During the process of selecting the data it was ensured that there were no gaps and standard quality control checks were rigorously implemented. In the process of checking the quality of the data, space, time and synoptic condition consistency checks were used. The individual data gaps were closed by using linear interpolation of the previous and subsequent observations of meteorological parameters and also using consistency of time, space and synoptic conditions. The data from stations surrounding the selected place of study were also taken into consideration, so that the advection effects could be fully taken into account. The data selected for the study consisted of surface and upper-air data at Delhi (the location selected for development of models), and the surrounding stations utilised are

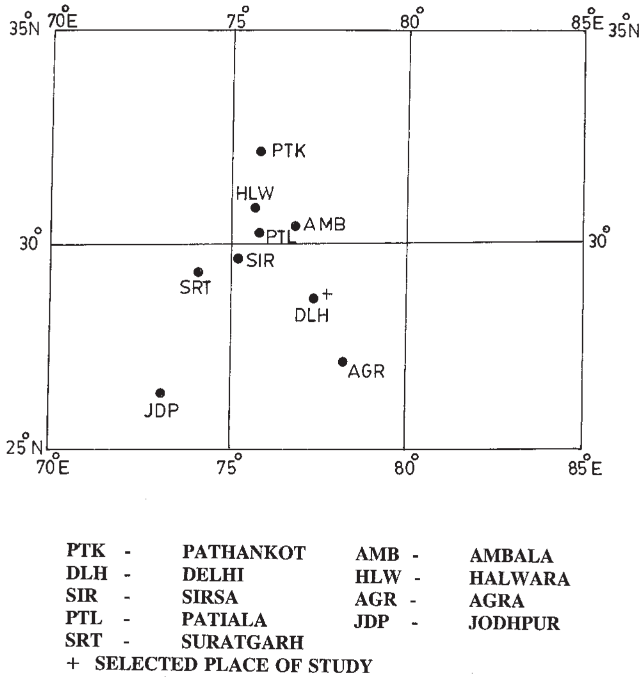

Figure 1. *Locations of meteorological stations from where data has been used in this study.*

Halwara, Ambala, Patiala, Jodhpur, Sirsa and Suratgarh, Pathankot and Agra. The geographical locations of these stations are given in Figure 1. The list of potential predictors and their notations used in this study are given in Table 1.

3. Climatology of minimum and maximum temperature

Since minimum and maximum temperatures depend considerably on the local features as well as on the moving synoptic systems (advective processes), it was decided to carry out a climatological study to find out the statistical distribution of temperatures and their relationship with potential predictors. For studying the climatological characteristics, the developmental sample as well as the independent sample data are utilised.

3.1. Minimum temperature

The frequency distribution of minimum temperature during the month of December is given in Figure 2. This indicates that the distribution is close to normal with a slight skewness to the right. The skewness is due to higher minimum temperatures, which occur mainly due to the passage of western disturbances. The sample statistics are given in Table 2. Averages of three-hourly synoptic time temperatures during the month of December are studied and it showed that the minimum temperature occurs between 0530 IST (0000 UTC) and 0830 IST (0300 UTC), which is to be expected, as it is well known that the minimum temperature occurs just after sunrise.

Correlation studies of minimum temperature with previous three-hourly synoptic observations of dry bulb

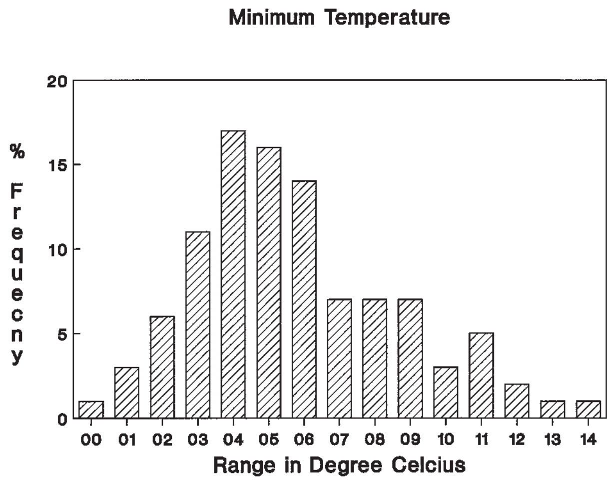

Figure 2. *Frequency distribution of minimum temperature in December.*

Table 1. *List of potential predictors and their notations used in this study*

	Predictors and their notations	Stations	Total
Surface	Dry bulb (*TT*) and dew point (*TD*) temperatures, maximum (*T*max) and minimum (*T*min) temperatures and their 24 hour changes (ΔTT, ΔTD, ΔTmax, ΔTmin), dew point depression (DPD), relative humidity (RH), total cloud amount (TTLN), zonal (*U*s) and meridional (*V*s) components of wind	Delhi, Ambala, Sirsa, Halwara, Pathankot, Jodhpur, Suratgarh	70
Upper-air	Dry bulb (*TT*) and dew point (*TD*) temperatures, mixing ratio (*w*), zonal (*U*) and meridional (*V*) components of wind at standard pressure levels (850, 70, 500, 400, and 300 hPa) and thermal advection, wind shear, lapse rate, between different levels from surface to 300 hPa	Delhi, Patiala, Jodhpur	118
Persistence	Maximum (*T*max)/minimum (*T*min) temperatures	Delhi	1
Total number of predictors			189

Table 2. *Statistics of minimum and maximum temperatures using data from 1984–89 and 1994–95*

	Minimum	Maximum
Mean	6.0	40.9
Standard deviation	2.9	3.7
Highest	14.4	47.6
Lowest	0.2	28.0
Range	14.2	19.6
Modal value	4.8	40.8

and dew point temperatures, humidity, cloudiness and winds made during the previous 24-hours are given in Table 3. This shows that the minimum temperature is positively correlated with dry bulb and dew point temperatures, relative humidity and cloudiness. An increase in cloudiness, especially during night times during winter, decreases the heat loss due to long-wave radiation and hence the rate of fall of temperature decreases, giving higher minimum temperatures. The correlation coefficients of minimum temperature with dry bulb and dew point temperatures are high, of the order of 0.6 to 0.9, and the correlations are of the order of 0.2 to 0.5 with relative humidity and cloudiness respectively.

As shown in Table 3, minimum temperature has a negative correlation with *U*, the zonal component of wind, which indicates that higher values of minimum temperature are associated with easterly winds (*U* negative), while a lower minimum temperature is associated with the westerly component of the wind (*U* positive). Similarly, minimum temperature has a positive correlation with *V*, the meridional component of the wind, which indicates that southerly winds increase the minimum temperature and northerly winds decrease the minimum temperature.

It may be noted that the minimum temperature over the NW Indian region is linked to the synoptic systems. With the approach of a western disturbance over a NW Indian station, dry bulb and dew point temperatures and cloudiness increase, winds become easterly to southerly in the lower tropospheric levels and this leads to a rise in minimum temperature. After the passage of the system, the sky becomes clear, dry bulb and dew point temperatures decrease, winds become dry and cold from the west to north and this leads to a fall in the minimum temperature. The correlation study clearly supports this behaviour of the minimum temperature.

3.2. Maximum temperature

The distribution of maximum temperature during the month of May is given in Figure 3, from which it is seen that there is almost a normal distribution with a skewness in this case to the left. The skewness is due to low values of maximum temperatures which occur during the passage of a system. The sample statistics are given in Table 2. Three-hourly averages of temperatures during the month of May are examined and it is observed that the maximum temperature occurs between 1430 IST (0900 UTC) and 1730 IST (1200 UTC), though it is understood and known to occur after or close to 1430 IST.

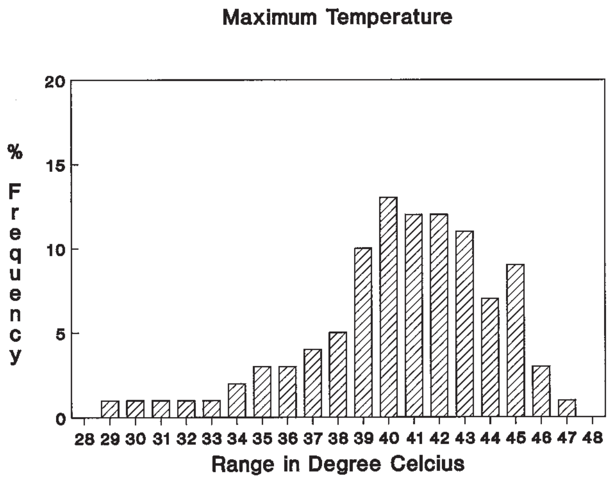

Figure 3. *Frequency distribution of maximum temperature in May.*

Table 3. *Correlation of minimum temperature and surface/upper-air parameters*

	Previous day								Same day	
Time (IST)	0230	0530	0830	1130	1430	1730	2030	2330	0230	0530
Predictor										
TT	0.56	0.60	0.63	0.28	0.10	0.35	0.75	0.80	0.89	0.85
TD	0.62	0.66	0.67	0.58	0.58	0.53	0.72	0.80	0.86	0.92
RH	0.23	0.16	0.24	0.33	0.42	0.29	0.15	0.19	0.15	0.04
*T*min					0.70					
TTLN	0.39	0.34	0.35	0.30	0.39	0.39	0.44	0.47	0.51	0.47
*U*s				–0.34	–0.35					
*V*s				0.22	0.25					
*U*850						–0.14				
*V*850						0.32				

To understand the relation between maximum temperature and other surface parameters, correlation studies were carried out with three-hourly synoptic observations made during the previous 24 hours of dry bulb and dew point temperatures, relative humidity, cloudiness and winds. The results are given in Table 4. The maximum temperature has a positive correlation of 0.4 to 0.8 with the dry bulb temperature but a negative correlation with dew point temperature and relative humidity. This negative correlation indicates that during summer there is an increase in moisture content in the atmosphere, which may be due to large-scale advection from relatively cool water bodies such as seas, lakes, rivers etc., resulting in a decrease of the maximum temperature. The cloudiness has a negative correlation of 0.2 to 0.4 with the maximum temperature. As increase in cloudiness during daytime decreases the incoming short-wave radiation, reducing the rate of rise of temperature, and hence the maximum temperature decreases.

As far as the winds are concerned, the maximum temperature is positively correlated with *U* and negatively correlated with *V* unlike in the case of minimum temperature. The correlation coefficients are of the order of 0.4 for *U* and –0.2 for *V*, at the surface as well as at 850 hPa. This indicates that when the winds are easterly (negative *U*), the maximum temperature decreases and when the winds are westerly (positive *U*) the maximum temperature increases. The contribution to the increase or decrease of minimum and maximum temperatures over a station/region is determined by the dominance of *U* or *V*.

Like the minimum temperature, the maximum temperature over NW Indian region is also linked to the synoptic systems. During the passage of western disturbances, the dew point, humidity and cloudiness increase and the winds at the surface and in the lower tropospheric levels become easterlies, resulting in a reduction of maximum temperature. After the passage of the disturbance, the sky becomes clear, winds become westerlies to north-westerlies, humidity and dew point fall and hence the maximum temperature increases.

The climatological study shows that over the selected place of study, the minimum and maximum temperatures are synoptic-system linked and the correlation studies clearly indicates the effect of movement of such disturbances across the station.

4. Development of models

Short-range, location-specific, deterministic prediction of surface weather elements is one of the challenging problems in weather forecasting. Further, the impact of orographical and topographical features makes the prediction more difficult. In order to provide such specific forecasts, it is necessary to develop mesoscale models which require a large number of observations to be taken at frequent intervals and at numerous locations (mesoscale network) surrounding the specific location. Hence, this approach puts a large demand on computer resources. In addition, a better understanding of mesoscale physical processes and their inclusion in the model makes it a difficult task. On the other hand, for short-range forecasts, statistical methods can meet the requirement at a specific location. Glahn (1982) has reviewed the use of such methods in the short-range prediction of various weather elements at specific locations in the USA. Since the objective of this study is to forecast minimum and maximum temperature 9 to 24 hours in advance, the input would consist of observational data available at the time that the forecast is prepared. This situation can be expressed as:

$$Y_t = f\,[X_0]$$

where Y_t is the estimate (forecast) of the predictand (minimum/maximum temperature in this case) at time *t* (length of forecast, say 24 hours) and X_0 is a vector of observational data at time '*0*' (the observations are not necessarily made at time '*0*' but must be made

Table 4. *Correlation of maximum temperature and surface/upper-air parameters*

	Previous day								Same day	
Time (IST)	0230	0530	0830	1130	1430	1730	2030	2330	0230	0530
Predictor										
TT	0.46	0.40	0.78	0.76	0.73	0.80	0.67	0.67	0.62	0.50
TD	–0.07	–0.09	–0.08	–0.01	–0.13	–0.15	–0.12	–0.10	–0.10	–0.13
RH	–0.55	–0.51	–0.53	–0.53	–0.51	–0.54	–0.51	–0.61	–0.68	–0.64
*T*max					0.74					
TTLN	–0.34	–0.33	–0.34	–0.31	–0.35	–0.30	–0.28	–0.28	–0.34	–0.36
*U*s				0.41	0.45					
*V*s				–0.19	–0.30					
*U*850						0.45				
*V*850						–0.28				

available at that time). Since minimum/maximum temperature have a considerable component due to local effects, it became essential to develop an independent method of forecasting minimum/maximum temperature at the selected place of study. A multiple regression approach was used in this study for the selection of statistically significant predictors; for this a stepwise regression method following Draper & Smith (1981) was utilised.

In order to develop multiple regression equations for forecasting minimum and maximum temperatures, 189 potential predictors are utilised as listed in Table 1. These consisted of surface and upper-air observations and associated derived parameters.

As a first step, all the 189 potential predictors are subjected to screening in the forecast of minimum and maximum temperatures. It may be noted that many of the parameters are inter-correlated and every one is measured with a certain degree of observational error. Therefore, it is necessary to identify a few potential predictors which can explain most of the variance of the predictand. This is accomplished by a forward method of selection by multiple regression, in which significant predictors are picked in a stepwise fashion. As a result, a small number of predictors can be selected which contain practically all the linear predictive information of the entire set with respect to a specific predictand and satisfy a statistical significance test. In this study the Fishers' F-test is utilised to select significant predictors at the 95% confidence level. The stepwise procedure continues by adding one predictor at a time to the model. All the predictors included in the model are re-checked, and at this stage any predictor that is not statistically significant in the presence of other predictors is removed. The procedure terminates when the new predictor fails to reduce the variance at least by 0.5% or does not satisfy statistical significance at the prescribed 95% confidence level ($F = 3.29$). In this procedure, it is found that not more than eight predictors out of 189 are retained into the final multiple regression equations for prediction of Tmin/Tmax.

4.1. Minimum temperature

The minimum temperature forecast equations for 12-hour and 24-hour forecasts are given in Table 5, along with variance explained by the selected predictors and their cumulative variance. Table 5 shows that in the 12-hour forecast five predictors have been selected and the 24-hour forecast equation contains six predictors. The 24-hour forecast may be treated as an early forecast and if needed the 12-hour forecast may be used to update the earlier forecast, particularly during the passage of a western disturbance (sudden change of temperature in 12-hour time). Also note that all the predictors selected indicate a relationship between

Table 5. *Minimum temperature forecast model: equation, predictors and reduction of variances*

12-hour forecast issued at 2030 IST
Equation
$$Y = -4.3280 + (0.475001 \times A1) + (0.385540 \times A2) + (0.266501 \times A3) + (0.225608 \times A4) + (0.036429 \times A5)$$

S1 No.	Predictor	Time (IST)	Level	Place	VE	CVE
A1	*TD*	2030	Surface	Delhi	54.0	54.0
A2	*TT*	2030	Surface	Ambala	10.6	64.6
A3	*w*	1730	850 hPa	Delhi	4.3	68.9
A4	TTLN	2030	Surface	Delhi	3.2	72.1
A5	DPD × Wind	2030	Surface	Delhi	2.1	74.2
					MCC = 0.86	

24-hour forecast issued at 0830 IST
Equation
$$Y = 1.4862 + (0.289333 \times B1) + (0.476186 \times B2) + (0.290734 \times B3) + (0.067632 \times B4) - (0.176244 \times B5) + (0.163340 \times B6)$$

S1 No.	Predictor	Time (IST)	Level	Place	VE	CVE
B1	*T*min		Surface	Halwara	52.4	52.4
B2	*T*min		Surface	Delhi	6.6	59.0
B3	Δ*TT*	1730	Surface	Halwara	2.6	61.6
B4	Δ*TD*	0530	850 hPa	Delhi	1.5	63.1
B5	Δ*T*min		Surface	Halwara	1.0	64.1
B6	Δ*TT*	2330	Surface	Halwara	1.0	65.1
					MCC = 0.81	

VE – Variance Explained, CVE – Cumulative VAriance Explained, MCC – Multiple Correlation Coefficient moisture at the selected place of study and temperature at stations to the northwest of Delhi. The increase in moisture will lead to higher minimum temperature, which normally happens at the approach of a western disturbance, while the role of stations to the northwest indicates that after the passage of the western disturbance, colder temperatures to the northwest of selected place of study become important as an advection mechanism.

4.2. Maximum temperature

The 9-hour and 18-hour forecast equations for maximum temperature in May are given in Table 6, along with the variance explained by the predictors. It is evident from Table 6 that persistence is quite significant in forecasting maximum temperature, and that moisture also plays an important role. Cloudiness or moisture in May at the selected place of study can be associated with the arrival of a western disturbance. Thus, the maximum temperature usually rises at the approach of a western disturbance, provided it advects dry westerly or northerly wind. The maximum temperature falls if there is an increase in cloudiness or moisture or precipitation. This aspect of maximum temperature in summer is opposite to that of minimum temperature in winter.

5. Results and discussion

The models developed for forecasting minimum and maximum temperatures are tested with developmental data for May and December of 1989, and independent data sets for the months of May and December of 1994 and 1995.

5.1. Minimum temperature

The 12-hour and 24-hour minimum temperature forecasts along with the actual values for December 1989, 1994 and 1995 are given in Figures 4 and 5. It may be noted that the model responds very well to the variation in the actual minimum temperature. The error analysis of the forecasts for both the developmental and the independent data sets is given in Tables 7 and 8. From Figures 4 and 5 and Tables 7 and 8 it is found that 60–70% of the forecasts are correct to within ±1 °C and about 80–90% of the forecast are within ±2 °C of the actual value.

The reasons for the large deviations have been analysed for the developmental as well as the independent data sets. For example, on 21 December 1989, the minimum temperature observed is 11.8 °C, the values for 12-hour and 24-hour forecasts are 9.8 °C and 8.4 °C, respect-

Table 6. *Maximum temperature forecast model: equation, predictors and reduction of variances*

9-hour forecast issued at 0530 IST
Equation
$$Y = 18.4910 + (0.23023 \times A1) - (0.54155 \times A2) + (0.176916 \times A3) + (0.120642 \times A4) + (0.145034 \times A5) + (0.127014 \times A6)$$

S1 No.	Predictor	Time (IST)	Level	Place	VE	CVE
A1	*TT*	1730	Surface	Delhi	66.9	66.9
A2	TTLN	0530	Surface	Ambala	7.7	74.6
A3	*TT*	2030	Surface	Delhi	3.8	78.4
A4	*TT*	1730	800 hPa	Delhi	2.0	80.4
A5	DPD	0230	Surface	Delhi	1.2	81.6
A6	*TT*	2030	Surface	Ambala	1.0	82.6
					MCC = 0.91	

18-hour forecast issued at 2030 IST
Equation
$$Y = 13.0731 + (0.36684 \times B1) + (0.243409 \times B2) - (0.121005 \times B3) + (0.119024 \times B4) - (0.080357 \times B5) - (0.296618 \times B6) + (0.269886 \times B7) + (0.220624 \times B8)$$

S1 No.	Predictor	Time (IST)	Level	Place	VE	CVE
B1	*T*max		Surface	Delhi	69.7	69.7
B2	*TT*	1730	Surface	Delhi	2.8	72.5
B3	*TT*	1130	Surface	Ambala	1.5	74.0
B4	*TT*	1730	700 hPa	Delhi	1.0	75.0
B5	*TD*	1130	Surface	Delhi	1.0	76.0
B6	*TT*	1430	Surface	Delhi	1.0	77.0
B7	*TT*	1730	Surface	Delhi	0.9	77.9
B8	*TT*	0830	Surface	Delhi	0.9	78.6
					MCC = 0.89	

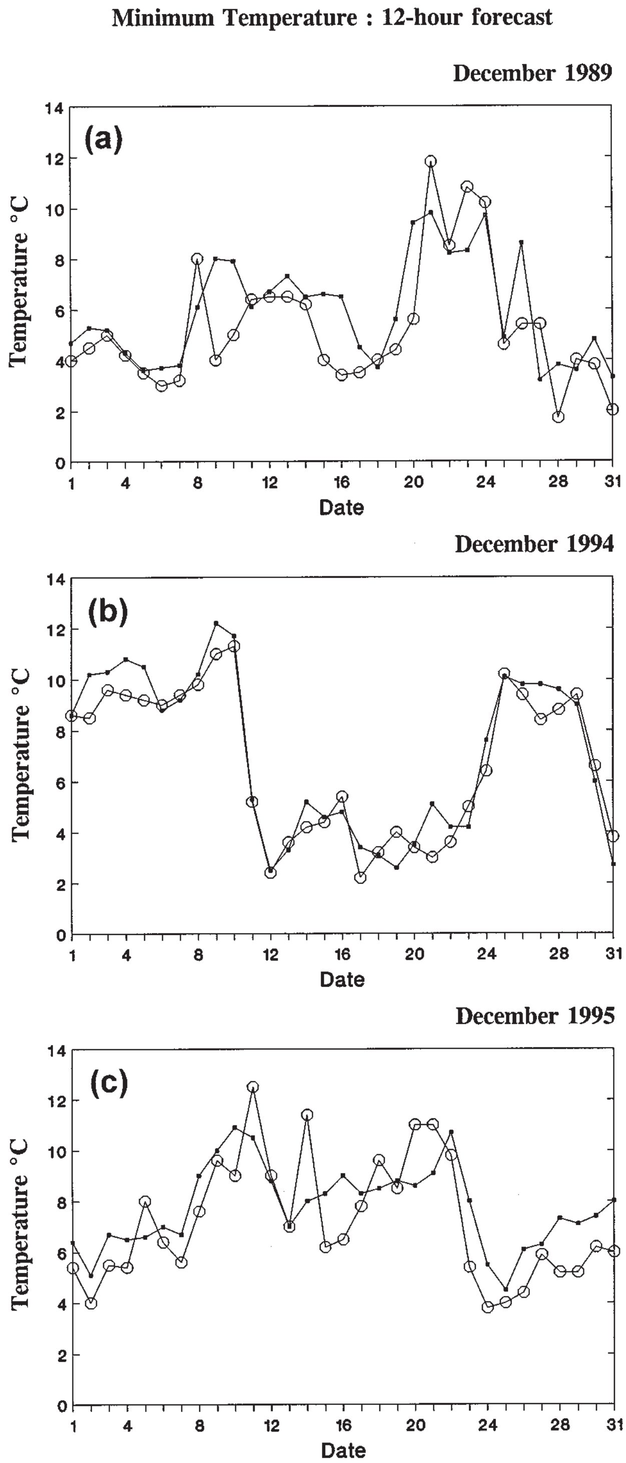

Figure 4. *Observed (–○–) and 12-hour forecast (–■–) minimum temperature for* (a) *December 1989,* (b) *December 1994 and* (c) *December 1995.*

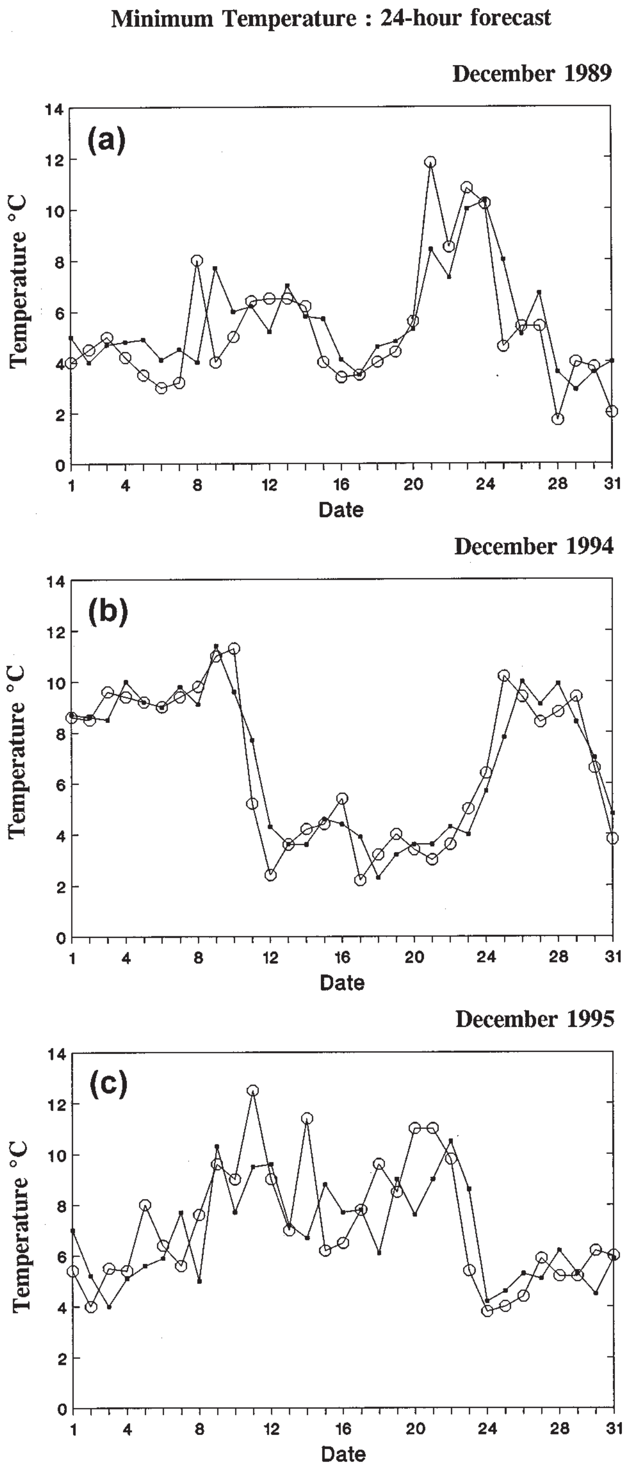

Figure 5. *Observed (–○–) and 24-hour forecast (–■–) minimum temperature for* (a) *December 1989,* (b) *December 1994 and* (c) *December 1995.*

ively. Thus, the 12-hour forecast deviated by 2.0 °C and the 24-forecast by 3.4 °C. On analysis, it is found that thundershowers occurred with overcast sky conditions between 0500 and 0830 hours IST on that day, during which period the daily minimum temperature occurs. The precipitation is not included as a forecast element in the equation and this caused the large deviation. The forecast model does not include any synoptic processes such as rain, thunderstorm, change of surface wind, etc. in the forecast equation for minimum temperature. Similarly, an example from the independent data of 1994 indicates that on 17 December 1994, the observed minimum temperature is 2.2 °C and the 12-hour forecast issued for this is 4.8 °C, resulting in a deviation of 2.6 °C. On investigation, it is found that the dry bulb temperature at 2030 IST happened to be higher by

Table 7. *Error analysis and skill scores for minimum temperature (12-hour forecast)*

Error range	Development data	Test data		
		Dec. 1989	Dec. 1994	Dec. 1995
0.0–1.0	101 (65%)	19 (61%)	24 (77%)	10 (32%)
1.1–2.0	38 (25%)	04 (13%)	06 (20%)	15 (49%)
2.1–3.0	15 (09%)	05 (16%)	01 (13%)	05 (16%)
3.1–4.0	00 (00%)	03 (10%)	—	01 (03%)
4.1–5.0	01 (01%)	—	—	—
⩾5.1	—	—	—	—
Total	155 (100%)	31 (100%)	31 (100%)	31 (100%)
ABS	1.15	1.22	0.75	1.35
RMS	1.51	1.63	0.91	1.58
P-ABS	1.59	1.55	1.36	1.65
P-RMS	2.24	2.31	1.96	2.14
SKILL (%)	55	50	78	45
CC	0.86	0.73	0.94	0.78

ABS – Absolute error
RMS – Root mean square error
P-ABS – Absolute error assuming persistence
P-RMS – RMS error assuming persistence
SKILL – Skill score
CC – Correlation coefficient

Table 8. *Error analysis and skill scores for minimum temperature (24-hour forecast)*

Error range	Development data	Test data		
		Dec. 1989	Dec. 1994	Dec. 1995
0.0–1.0	74 (48%)	17 (55%)	15 (48%)	19 (61%)
1.1–2.0	48 (31%)	10 (32%)	06 (20%)	09 (29%)
2.1–3.0	19 (12%)	—	08 (26%)	03 (10%)
3.1–4.0	08 (05%)	04 (13%)	02 (06%)	—
4.1–5.0	06 (04%)	—	—	—
⩾5.1	—	—	—	—
Total	155 (100%)	31 (100%)	31 (100%)	31 (100%)
ABS	1.44	1.16	1.34	1.03
RMS	1.93	1.58	1.71	1.23
P-ABS	1.81	1.55	1.65	1.13
P-RMS	2.31	2.31	2.00	1.41
SKILL	32	53	29	22
CC	0.89	0.75	0.72	0.83

2.0 °C than on earlier or subsequent days. This alone resulted in the estimate of minimum temperature being higher by 1 °C.

Similarly, all departures of more than 2.0 °C, both for developmental and independent data sets, were investigated. In most cases, it was found that the rapid movement of synoptic systems associated with rain, thunderstorm, etc., which passed across the station in time frame of less than the selected range of the forecast (12-hour and 24-hour), resulted in a sudden change in certain predictors of the forecast equations which lead to such large deviations. Further analysis of forecast and actual values for 1994 indicate that day-to-day minimum temperature variations are quite homogeneous in nature as indicated by the root mean square error (rmse) value assuming persistence alone. Thus, the performance of the forecast equations with the independent data set of 1994 is found to be better than the developmental sample.

5.2. Maximum temperature

The 9-hour and 18-hour maximum temperature forecasts for the month of May for one year of the developmental sample data of 1989 and independent data sets of 1994 and 1995 are given in Figures 6 and 7. Once again, it is found that the model responds effectively to the variations. The error analysis of the forecasts for both the developmental and the independent data sets is given in Tables 9 and 10. It is observed from Figures 6 and 7 and Tables 9 and 10 that 60–70% of the forecasts are correct to within ±1 °C.

As was found for minimum temperature, there are days when the forecasts deviated by more than 2 °C,

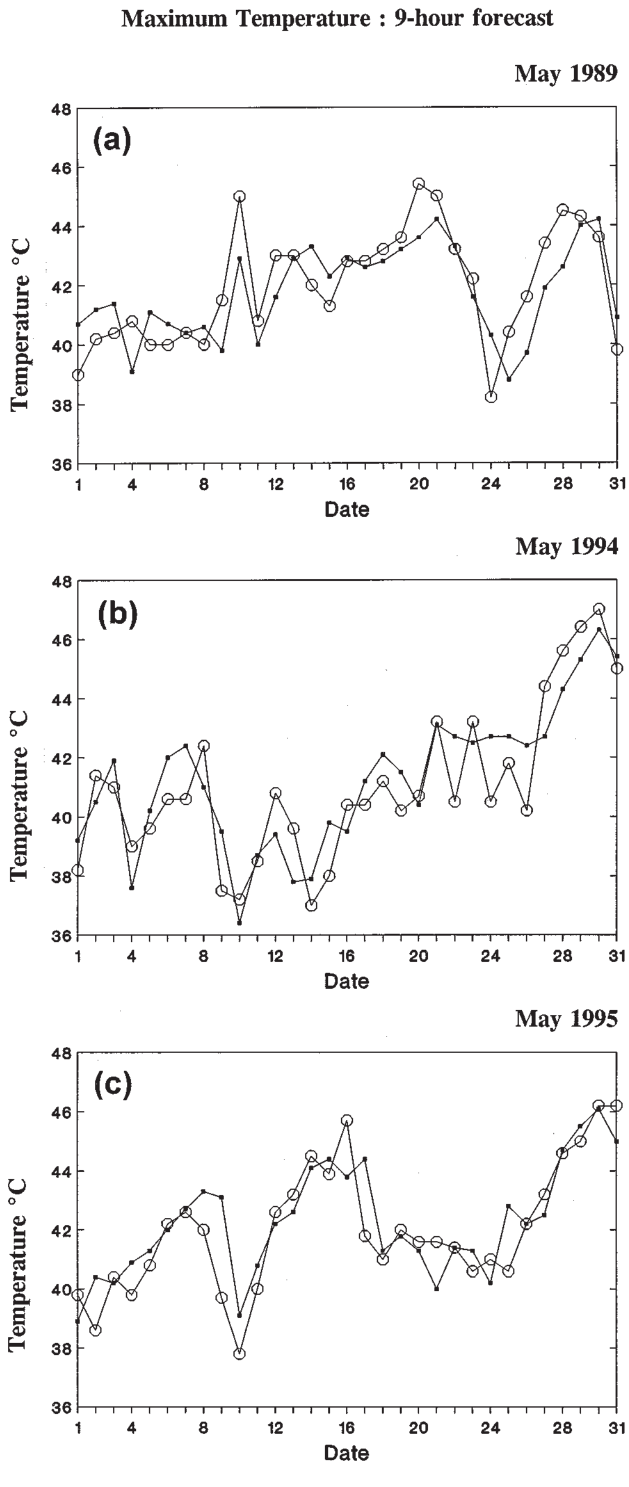

Figure 6. *Observed (–○–) and 9-hour forecast (–■–) maximum temperature for* (a) *May 1989,* (b) *May 1994 and* (c) *May 1995.*

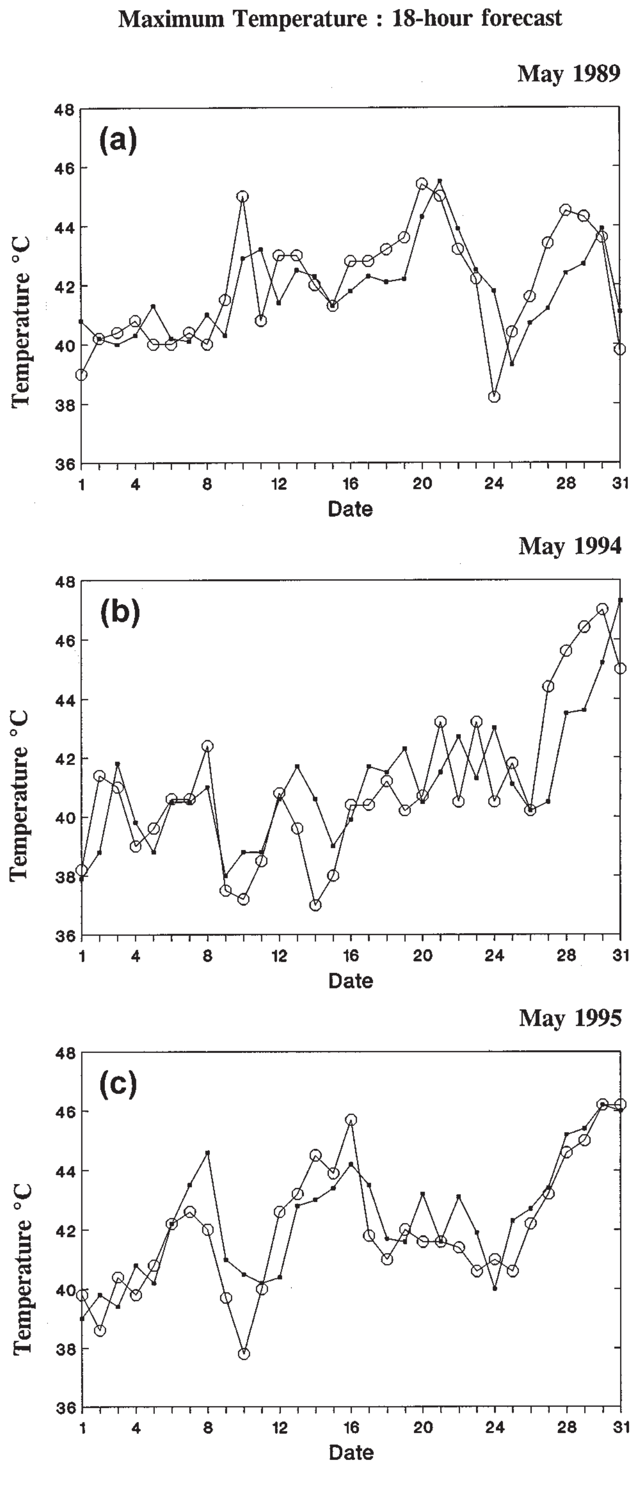

Figure 7. *Observed (–○–) and 18-hour forecast (–■–) maximum temperature for* (a) *May 1989,* (b) *May 1994 and* (c) *May 1995.*

even on a time scale of 9 hours. Analysis of these large errors reveal that very rapid and large changes, particularly during the time scale of less than 9 hours or 18 hours could be responsible for the large departures. Such changes are mainly attributed to rapid movement/ intensification of the synoptic systems associated with rainfall, thunderstorms or duststorms, which in turn sharply change certain predictors of the forecast equations. For example, on 24 May 1989, the observed maximum is 38.2 °C. The 9-hour and 18-hour forecasts issued for this are 40.3 °C and 41.8 °C, respectively. Thus, the 9-hour forecast deviated by 2.1 °C and the 18-hour forecast by 3.6 °C. The analysis of the data revealed that on this particular day, precipitation had taken place between 0700 and 0735 hours IST and thundery activity between 1430 and 1500 hours IST. This resulted in the actual maximum temperature being significantly lower than

Table 9. *Error analysis and skill scores for maximum temperature (9-hour forecast)*

Error range	Development data	Test data		
		May 1989	May 1994	May 1995
0.0–1.0	82 (53%)	17 (55%)	16 (51%)	20 (65%)
1.1–2.0	48 (31%)	12 (39%)	12 (39%)	07 (23%)
2.1–3.0	13 (08%)	02 (06%)	03 (10%)	02 (06%)
3.1–4.0	07 (05%)	—	—	02 (06%)
4.1–5.0	05 (03%)	—	—	—
⩾5.1	—	—	—	—
Total	155 (100%)	31 (100%)	31 (100%)	31 (100%)
ABS	1.31	1.02	1.19	0.96
RMS	1.72	1.21	1.32	1.21
P-ABS	1.81	1.76	1.65	1.13
P-RMS	2.31	1.29	2.03	1.41
SKILL	45	53	57	30
CC	0.91	0.77	0.87	0.84

Table 10. *Error analysis and skill scores for maximum temperature (18-hour forecast)*

Error range	Development data	Test data		
		May 1989	May 1994	May 1995
0.0–1.0	74 (48%)	16 (52%)	15 (48%)	19 (61%)
1.1–2.0	48 (31%)	09 (29%)	06 (20%)	09 (29%)
2.1–3.0	19 (12%)	05 (16%)	08 (26%)	03 (10%)
3.1–4.0	08 (05%)	01 (03%)	02 (06%)	—
4.1–5.0	06 (04%)	—	—	—
⩾5.1	—	—	—	—
Total	155 (100%)	31 (100%)	31 (100%)	31 (100%)
ABS	1.44	1.07	1.34	1.03
RMS	1.93	1.35	1.71	1.23
P-ABS	1.81	1.29	1.65	1.13
P-RMS	2.31	1.76	2.00	1.41
SKILL	32	41	29	22
CC	0.89	0.68	0.72	0.83

the forecast produced by the equations. Similarly, in the independent data set of May 1994, on 27 May the maximum temperature observed is 44.4 °C and the 18-hour forecast for maximum temperature is 40.5 °C; thus, the forecast deviated by 3.9 °C. On investigation, it is found that the dry bulb temperatures at 1430 and 1730 IST are 2 to 4 °C lower than the previous and subsequent days, which resulted in the forecast maximum being significantly lower than the actual. Other cases of significant departure of forecast both in the dependent and independent samples are also examined, which confirms the above reasonings. This indicated that large deviations are mainly associated with rapid changes in the predictors of the equations which are within the 9–18 hours scale.

In Tables 7–10, the skill scores of the forecast are estimated as:

$$\text{Skill Score} = \left[1 - \frac{\text{RMSE}_m^2}{\text{RMSE}_p^2}\right] 100\%$$

where RMSE_m and RMSE_p stands for rmse of the model prediction and of the persistence respectively. A positive value of skill score stands for a better performance of the model over persistence, while a negative value of skill score indicates that the model does not have skill even to match the persistence. Though there are a few occasions with the forecast errors of minimum/maximum temperature exceeding 2 °C, the skill scores given in Tables 7–10 clearly indicate that the developed equations have positive skill and perform better than the persistence with dependent as well as independent data sets.

6. Conclusions

In this study, equations for forecasting minimum and maximum temperatures have been developed using the multiple regression method and are tested with independent data sets. The following are the main conclusions drawn from this study:

(a) Minimum and maximum temperatures are well predicted by the forecast model equations, as in 65% of the cases the errors are within the limit of ±1 °C and about 90% of cases are within ±2 °C.
(b) The verification of the model equations indicates that in each of the cases there is definite positive skill in the forecast produced by the models over the persistence.
(c) On a few occasions large deviations of the forecast are observed. These are mainly attributed to rapid movement of synoptic systems associated with rain, thunderstorms, etc.

The models developed for location-specific, short-range forecasting of minimum and maximum temperatures at Delhi for the months of December and May respectively are of practical use. They also enable cold and heat wave conditions over the region to be forecast.

In the present study only historical data has been used to develop the statistical models. The model equations do not use the forecast parameters from Numerical Weather Prediction (NWP) models. It is possible to improve the forecast with incorporation of the NWP products, to develop Model Output Statistics (MOS) or Perfect Prog Method (PPM) techniques to forecast minimum and maximum temperatures.

Further improvement can be achieved through incorporation of weather elements such as rain, thunderstorm, strong surface wind, etc., predicted by other methods in the present model equations. This process could reduce cases of large forecast errors of minimum/maximum temperature prediction associated with rapid movement/intensification of synoptic systems.

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