Minimum temperature forecast at Manali, India

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Northern India is comprised of complex Himalayan mountain ranges having different altitude and orientation. Knowledge of minimum temperature in this region during winter months is very useful for assessing human comfort and natural hazards. In the present study, Perfect Prognostic Method (PPM) is used for forecasting minimum surface temperature at one of the stations, Manali, in Pir Panjal range of Himalayas. Firstly, a statistical dynamical model is developed for assessing next day's temperature category, i.e. ≤ 0°C or >0°C. Once the category is known, then temperature forecast model is developed for that category. Statistical dynamical models are developed for winter season, December, January, February and March (DJFM) using multivariate regression analysis. Model is developed with data of DJFM for 12 years (1984–96) and tested with data of DJFM for the year 1996–97. Analysis data from National Center for Environmental Prediction (NCEP), US, station surface and upper air data of three stations of India Meteorological Department (IMD), India and surface data at Manali are used. Four experiments are carried out with four different sets of predictors to evaluate performance of the models with independent data sets. They are: (i) NCEP reanalysis data, (ii) operational analyses from the National Center for Medium Range Weather Forecasting (NCMRWF) in India, (iii) day 1 forecast with a T80 global spectral model at NCMRWF and (iv) forecasts from the regional mesoscale model MM5 day 1 forecast. A comparison of skill is drawn among these four set of experiments. It is found that best prediction for temperature category is made with an accuracy of 71.2% with MM5 day 1 forecast as predictors in temperature category forecast model. Further, temperature forecast model for ≤ 0°C category selects only station data and shows skill of 62.1% with independent data, whereas, model for >0°C category selected predictor from numerical analysis also. Here MM5 day 1 forecast makes best prediction with 90.0% skill.

KNOWLEDGE of minimum temperature is one of the important weather parameters during winter season for assessing human comfort and natural hazard in snowbound areas of northwest India. Also, this is a very useful information for organization where men and machines are employed to operate in open, viz. for defence forces, agriculture, tourism, etc. Future projection of minimum temperature is useful in prediction of cold wave conditions, avalanche release and critical human comfort index. Over hilly areas such as Jammu and Kashmir, Himachal Pradesh and Uttaranchal, knowledge of minimum temperature is helpful in predicting frost, which is of use to many people at large. Minimum temperature at a specific location depends upon the season, the synoptic conditions and local parameters including topography.

Various researchers have carried out studies on temperatures. Dhanna Singh and Jaipal[1] developed a subjective method for forecasting minimum temperature over Delhi. Woodcock[2] described some experimental MOS forecasts of daily maximum and minimum temperature for seven Australian cities. Raj[3] evolved a scheme for predicting minimum temperature at Pune by analogue and regression methods. Mohan *et al.*[4] developed a method for forecasting maximum temperature over Ozar situated in Maharastra using maximum and dew point temperature of the previous day. Chrantorois and Liakatas[5] have studied minimum temperature forecasts employing Markov chains. Vashisht and Pareekh[6] have given a partial objective method to forecast minimum temperature at Jaipur and South Rajasthan. Attri *et al.*[7] have given a multiple regression method for forecasting minimum temperature at Gangtok based on knowledge of dew point temperature, cloud amount, maximum and minimum temperature recorded on previous day. Skill score performances and accuracy of location-specific temperature forecasts are carried out by Sanjeeva Rao *et al.*[8]. Kumar and Maini[9] have carried out statistical interpretation (SI) forecast of GCM to improve location-specific medium range local weather forecast. Mohanty *et al.*[10] employed regression techniques for forecasting maximum and minimum temperatures at Delhi during summer and winter season respectively. Raj[11] employed forecast schemes based upon statistical techniques to forecast daily summer maximum temperature at Chennai. Statistical model is developed to forecast minimum and maximum temperature at Manali[12]. A set of optimal number of predictors is chosen from a large number of parameters by employing stepwise forward screening. Maini *et al.*[13] have carried out statistical interpretation of T-80 model's output and verified the skill of location-specific forecast for the 1997 monsoon season for a number of stations in India.

All these studies pertaining to temperature forecasting in India are based on a classical method. Also for a site and time-specific forecast location, these methods or models use real

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time observations. In the present study numerical model outputs are used to develop temperature forecast. Firstly, a probabilistic temperature category forecast model is developed, which will determine that either temperature will fall in ≤ 0°C category or will fall in >0°C category (hereafter called category I and category II respectively). Then, secondly, a statistical dynamical model based on Perfect Prog Method (PPM) is developed to forecast minimum temperature for that category. For this purpose, time frame of forecast is restricted to 24 hours. Since northwest India is worst affected by cold temperature conditions during winter, therefore December, January, February and March (DJFM) months are considered for developing deterministic models. Data used for the study are presented followed by characteristics of minimum surface temperature at Manali. Results pertaining to the study are discussed and conclusions are outlined.

Data used

For site and time-specific category and temperature forecast models, Manali (long 77°13′27″, lat 32°19′27″ and altitude 2192 m) is chosen for the study (Figure 1). This site is situated in Pir Panjal range in Himachal Pradesh. Further, long and continuous past data sets are available for this site, which is suitable for the statistical model development.

In this study, 12 years' data (1984–96) for DJFM is used for developing stable statistical dynamical models for category and temperature forecast. The developed model is tested with independent data sets of DJFM for the period 1996–97. Reanalysis data of National Center for Environmental Prediction (NCEP), US, surface and upper air data of Patiala, Jodhpur and Delhi from India Meteorological Department,

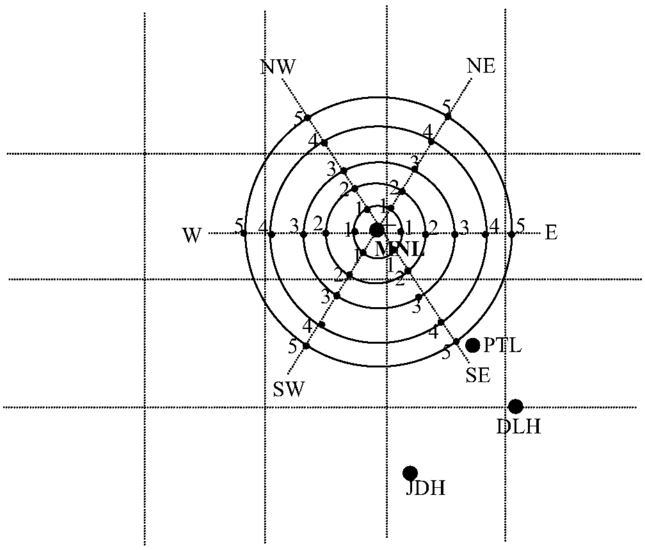

Figure 1. The location of meteorological stations from which data have been used in this study. PTL, Patiala; DLH, Delhi; JDH, Jodhpur. The MNL, Manali is the selected place of study and is indicated by +. NCEP analysis data is interpolated at locations numbered from 1 to 5 along various geographical directions and are marked by •.

(IMD) is used for the model development. The NCEP reanalysis data is global data with resolution of 2.5° lat × 2.5° long. grid in vertical pressure levels. IMD upper air data is station data in vertical pressure levels. For development of model equations, basic fields, viz. geopotential height (gpm), dry bulb temperature (TT), u and v component of wind, vertical velocity and moisture at 850, 700, 500, 300 and 200 hPa levels from NCEP reanalysis fields and upper air fields from IMD data sets are considered. Further, derived parameters are also taken into consideration to account for various shear/gradients in vertical. These derived parameters include vorticity, advection of various fluxes and various meteorological indices. IMD station data and NCEP analysis data considered for study are observed at 0000 UTC and 1200 UTC (Table 1). Further, as being a very coarse grid, from topographic and terrain conditions' point of view, NCEP analysis data are interpolated at site and around it on five concentric circles with increasing radius from 0.5° to 2.5° with an interval of 0.5°. Then six station points, at each circle around the sites are selected by starting anticlockwise from east direction with 60° intervals, as shown in Figure 1. Due to interpolation of data, maximum atmospheric circulation at and around the site will be taken care of.

In order to develop a multiple regression equation, a total of 3364 potential predictors, as shown in Table 1, consisting of surface and upper air observations and derived parameters are utilized. During the process of selecting the potential predictors, care has been taken to avoid data gaps. The individual data gaps are filled by using linear interpolation between previous and subsequent meteorological observations. Also, quality control checks are utilized. Checks are made on the space, time and synoptic condition consistency.

Temperature is categorized in two categories. This is done to stratify the temperature forecast. If recorded temperature is ≤ 0°C then it is considered as 0 and if it is > 0°C then it is considered as 1 for category forecast. In this manner, firstly, the next day's category is forecasted by model and then temperature forecast model is developed for that category only. The category forecast is initiated at 0300 UTC, hereafter supposed as 0000 UTC, for the next 24 hours. The temperature forecast model is initiated at the same time for category which is predicted by category forecast model. It is found that a separate model for forecasting the category and then temperature of that category give consistently better results than including it as a category in the discriminant procedure.

Characteristics of minimum temperature at Manali

Minimum temperature considerably depends upon local features and moving synoptic systems (advective processes). Studying characteristic features of minimum temperatures is to find out their distribution and relationship with potential predictors. Only developmental sample is considered for characteristic studies of temperature at Manali.

Table 1. List of potential predictors and their notations used in the present study. The total number of predictors is 3364

Predictors and their notations	Stations	Time	Total
Surface data			
Dry bulb (TT) and dew point (TD) temperature, saturation mixing ratio (SM), mixing ratio (MR), dew point depression (DPD), relative humidity (rh), wind speed (ff), wind direction (dd), zonal (u) and meridional (v) component of wind	Delhi Patiala Jodhpur	–12 UTC and 00 UTC	60
Dry bulb (TT), maximum and minimum temperatures (T_{Max} and T_{Min}), wind speed (ff), wind direction (dd)	Manali	–12 UTC and 03 UTC	10
Upper air data			
Dry bulb (TT) and dew point (TD) temperature, saturation mixing ratio (SM), Mixing ratio (MR), dew point depression (DPD), relative humidity (rh), wind speed (ff), wind direction (dd), zonal (u) component and meridional (v) component of wind at standard pressure levels (850, 700, 500 hPa), dry bulb and potential temperature differences between different levels from surface to 300 hPa, mean of relative humidity and saturation mixing ratio between various levels, derived wind shear term between various levels	Delhi Patiala Jodhpur	–12 UTC and 00 UTC	498
Stability indices			
Showalter index, Rackliff's index, Jefferson's modified index, Convective index of REEP, George index, Vertical total index, Cross total index, Totals total index, Modified George index, Modified vertical total index, Modified cross total index, Modified totals total index, Potential wet bulb index, Lifted index, Potential instability index, Severe weather threat index	Delhi Patiala Jodhpur	–12 UTC and 00 UTC	96
NCEP interpolated data			
Geopotential height (gpm), dry bulb temperature (TT), zonal (u) and meridional (v) component of wind, vertical (w) component of wind and moisture (q) at standard dynamical pressure levels (850, 700, 500, 300 and 200 hPa)	30 stencil points	–12 UTC 00 UTC and 12 UTC	2700
		Total	3364

In time description '–' indicated that observation is recorded before forecast issuing time, which in present case is considered as 00UTC, and '+' sign indicates that observation is recorded after forecast issuing time (which naturally is numerical model output).

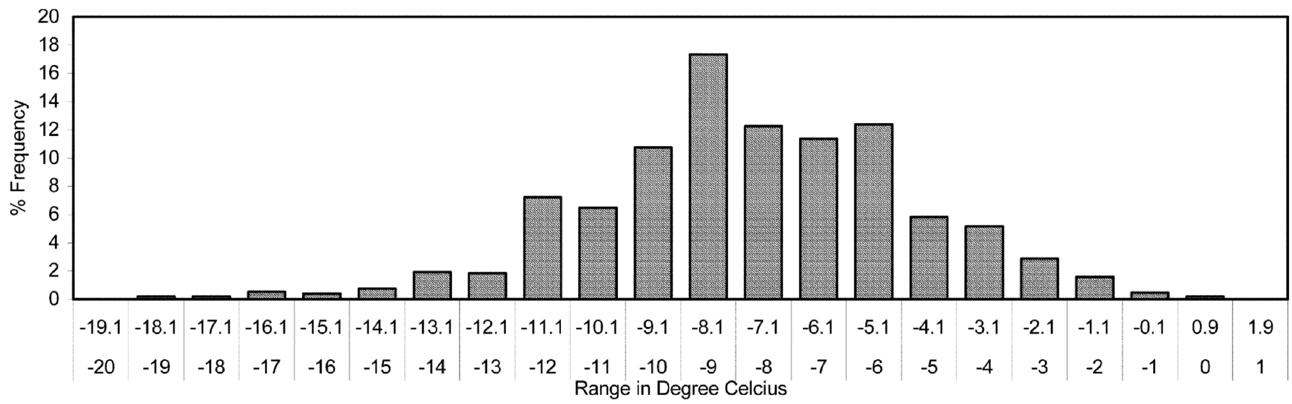

Figure 2. Frequency distribution of minimum temperature for development data set (DJFM, 1984–96).

Table 2. Statistics of minimum temperature for developmental data set (DJFM,1984–96) and independent data set (DJFM, 1996–97)

	Manali			
	Below or equal to 0°C		Above 0°C	
	Development data	Independent data	Development data	Independent data
Mean	–1.8	–2.1	2.8	3.0
Standard deviation	1.84	1.92	2.98	2.24
Highest	0.0	0.0	9.8	9.0
Lowest	–9.6	–9.0	0.0	0.0
Range	9.6	9.0	9.8	9.0

Frequency distribution of minimum temperature during DJFM is shown in Figure 2. The figure indicates that the distribution of minimum surface temperature is close to the normal at Manali. The sample statistics are given in Table 2. Minimum temperature at Manali shows higher degree of variability and is having spread in temperature distribution. It also depicts the high range of distribution of minimum temperature. Table 3 shows persistence of minimum temperature in 24 hours. Absolute change in 24 hours in observed minimum temperature is presented here. Most of the changes are found in the lower error range, i.e. in the range 0.0–2.0°C. But some of the events had shown persistence of ≥ 5.1°C. These particular occasions are accounted just after clearance of sky, after a passage of Western Disturbances (WDs), due to which significant fall in temperature is seen.

Correlation studies of minimum temperature with synoptic observations and numerical model outputs in future state are presented in Tables 4 and 5. These show that the minimum temperature is governed much by persistence. Further, minimum temperature is positively correlated with dry bulb and dew point temperatures, relative humidity and moisture. During the passage/presence of a synoptic weather system, especially during nighttime in winter, increase in cloudiness leads to heat loss due to long wave radiation and hence the rate of fall in temperature. Similarly, minimum temperature is positively correlated with dry bulb temperature. Minimum temperature shows variable signs of correlations with wind components. Again it is indicative of local topography effects as Manali is situated in a complex and variable topography.

It may be noted that minimum temperature over northwest Indian region is linked to synoptic systems. With the approach of a WD over northern Indian stations, dry bulb and dew point temperatures and cloudiness increase and this leads to rise in minimum temperature. After the passage of the system, the sky becomes clear; a fall is registered in dry bulb and dew point temperature, wind direction changes to northwesterly and all these leads to a fall in minimum temperature. The correlation study clearly supports this behavior of minimum temperature.

Result and discussion

Performance of model development and verification are discussed in the following paragraphs. First category forecast model is discussed followed by temperature forecast model.

Model development and verification for minimum temperature

Manali records minimum temperatures below and above 0°C during winter season. For making suitable temperature forecast, attempt is made to stratify the model development for category I and category II. By assuming so, a probabilistic forecast is derived at, by using Multiple Discriminant Analysis (MDA) technique, category which states the next day's temperature will either be in category I or category II. Predictand (minimum temperature) is converted either in 0 or 1 for category I and category II respectively. It is assumed that during developmental process if minimum temperature is below (or equal to) 0°C then predictand is 0 and if minimum temperature is above 0°C then predictand is 1. Once the knowledge of next day's probable category is known, forecasting equations are generated for the temperature values for that particular category. In this way we will have two model equations, one for category forecast and another for temperature forecast.

Table 6 shows skill scores and sensitivity of category forecasts. Skill scores for dependent and four independent data sets of IMD–NCEP analysis, IMD–NCMRWF analysis, IMD–T80 day-1 forecast and IMD–MM5 day-1 forecast are also presented. It is seen that developmental sample (DJFM, 1984–96) shows best performance of correct forecast with higher skills. Whereas in case of independent data samples IMD–MM5 day-1 forecast combination shows 61% probability of detection with 1.18 model bias and 61.2 percent correct forecast. Once state of next day's category is known, minimum temperature forecast for that category is generated. For development sample (DJFM 1984–96), 539 days are found when minimum temperature was recorded in category I and 913 days are found when minimum temperature was recorded in category II. While verification (DJFM 1996–97), 72 days are forecasted in category I and 49 days are forecasted in category II. Then, minimum temperature forecast model for respective category is developed and verified for those many days only and are illustrated in succeeding paragraphs. The procedure for development, verification and results are given in following paragraphs.

Skill scores of forecast are estimated as,

$$\text{Skill score} = \left[1 - \frac{RMSE^2_{\text{Forecast}}}{RMSE^2_{\text{Pers}}}\right] * 100\%, \quad (1)$$

where $RMSE_{\text{Forecast}}$ and $RMSE_{\text{Pers}}$ stand for root mean square error of the model prediction and persistence respectively. A positive value of skill score stands for a better performance of the model over the persistence and a negative value of the skill score indicates that the model does not have skill even to match the persistence. Skill scores clearly indicate that the developed equations have positive skill and perform better than the persistence with dependent as well as independent data sets.

Minimum temperature forecast for category I

At Manali minimum temperatures are normally recorded below or equal to 0°C during winter season for considerable

Table 3. Persistence: Absolute change in observed maximum temperature in 24 hour

	Manali			
	Below or equal to 0°C		Above 0°C	
Error range	Development data	Independent data	Development data	Independent data
0.0–0.1	264 (50%)	41 (57%)	419 (45.9%)	16 (32.6%)
1.1–2.0	120 (22.3%)	20 (27.8%)	281 (30.8%)	12 (24.5%)
2.1–3.0	79 (14.66%)	5 (6.94%)	99 (10.8%)	8 (16.3%)
3.1–4.0	20 (2.60%)	1 (1.38%)	74 (8.10%)	4 (8.16%)
4.1–5.0	14 (2.60%)	3 (4.16%)	37 (4.05%)	2 (4.08%)
≥ 5.1	42 (7.79%)	2 (2.81%)	3 (0.32%)	7 (14.3%)
Total	539 (100%)	72 (100%)	913 (100%)	49 (100%)

Table 4. Equation, prediction, variance explained and correlation coefficient for forecasting minimum temperature below or equal to 0°C at Manali

$$Y = -0.0899 + 0.9889*\, M(T_{\min-1})^{-0300\mathrm{UTC}}_{\mathrm{surface}} + 0.1035*\, J(u)^{+00\mathrm{UTC}}_{\mathrm{surface}} - 0.0612*\, J(v)^{+00\mathrm{UTC}}_{\mathrm{surface}} - 0.001289*\, J(dd)^{+00\mathrm{UTC}}_{\mathrm{surface}} + 0.0356*\, J(ff)^{+00\mathrm{UTC}}_{\mathrm{surface}} + 0.0612*\, J(TD)^{-12\mathrm{UTC}}_{\mathrm{surface}} - 0.0229*\, J(r)^{+00\mathrm{UTC}}_{\mathrm{surface}} + 0.0153*\, D(r)^{+00\mathrm{UTC}}_{900\,\mathrm{hPa}} + 0.0048*\, D(\Delta TT)^{-12\mathrm{UTC}}_{500-300\,\mathrm{hPa}}$$

Predictor	Type of data	Variance explained	Cumulative variance	Correlation coefficient
$M(T_{\min-1})^{-0300\mathrm{UTC}}_{\mathrm{surface}}$	STN	98.54	98.54	+1.00
$J(u)^{+00\mathrm{UTC}}_{\mathrm{surface}}$	STN	0.08	98.62	+0.05
$J(v)^{+00\mathrm{UTC}}_{\mathrm{surface}}$	STN	0.36	98.98	+0.03
$J(dd)^{+00\mathrm{UTC}}_{\mathrm{surface}}$	STN	0.18	99.16	–0.02
$J(ff)^{+00\mathrm{UTC}}_{\mathrm{surface}}$	STN	0.07	99.23	–0.01
$J(TD)^{-12\mathrm{UTC}}_{\mathrm{surface}}$	STN	0.03	99.26	+0.11
$J(r)^{+00\mathrm{UTC}}_{\mathrm{surface}}$	STN	0.02	99.28	+0.12
$D(r)^{+00\mathrm{UTC}}_{900\,\mathrm{hPa}}$	STN	0.01	99.29	+0.09
$D(\Delta TT)^{-12\mathrm{UTC}}_{500-300\,\mathrm{hPa}}$	STN	0.01	99.30	+0.12
		Multiple correlation coefficient = 0.99		

Table 5. Equation, prediction, variance explained and correlation coefficient for forecasting minimum temperature above 0°C at Manali

$$Y = -73.9850 + 0.470098*\, M(T_{\min-1})^{-0300\mathrm{UTC}}_{\mathrm{surface}} - 0.113782*\, E5(TT)^{+12\mathrm{UTC}}_{500\,\mathrm{hPa}} + 0.044615*\, P(DPD)^{+00\mathrm{UTC}}_{850\,\mathrm{hPa}} - 0.075812*\, P(\Delta TT)^{-12\mathrm{UTC}}_{850-700\,\mathrm{hPa}} + 0.183522*\, E5(TT)^{+12\mathrm{UTC}}_{700\,\mathrm{hPa}} + 0.005411*\, NW1(gpm)^{+00\mathrm{UTC}}_{200\,\mathrm{hPa}} - 0.16818*\, E3(q)^{+00\mathrm{UTC}}_{200\,\mathrm{hPa}} - 0.061067*\, P(ALT)^{+00\mathrm{UTC}}_{\mathrm{surface}} - 0.081864*\, J(r)^{+00\mathrm{UTC}}_{\frac{\mathrm{Surface}+900\,\mathrm{hPa}+850\,\mathrm{hPa}}{3}}$$

Predictor	Type of data	Variance explained	Cumulative variance	Correlation coefficient
$M(T_{\min-1})^{-0300\mathrm{UTC}}_{\mathrm{surface}}$	STN	32.87	32.87	+0.57
$E5(TT)^{+12\mathrm{UTC}}_{500\mathrm{hPa}}$	NANA	5.97	38.84	+0.39
$P(DPD)^{+00\mathrm{UTC}}_{850\mathrm{hPa}}$	STN	1.55	40.39	+0.23
$P(\Delta TT)^{-12\mathrm{UTC}}_{850-700\mathrm{hPa}}$	STN	1.13	41.52	–0.11
$E5(TT)^{+12\mathrm{UTC}}_{700\,\mathrm{hPa}}$	NANA	0.64	42.16	+0.35
$NW1(gpm)^{+00\mathrm{UTC}}_{200\,\mathrm{hPa}}$	NANA	0.76	42.92	+0.40
$E3(q)^{+00\mathrm{UTC}}_{200\,\mathrm{hPa}}$	NANA	0.75	43.67	+0.19
$P(ALT)^{+00\mathrm{UTC}}_{\mathrm{surface}}$	STN	0.78	44.45	+0.01
$J(r)^{+00\mathrm{UTC}}_{\frac{\mathrm{Surface}+900\,\mathrm{hPa}+850\,\mathrm{hPa}}{3}}$	STN	0.5	44.95	–0.02
		Multiple correlation coefficient = 0.67		

time. As such there is a great variation in minimum temperature at Manali which at times dips as low as – 10°C.

24 hours minimum temperature forecast equation for temperature below or equal to 0°C, variance explained, cumulative variance explained and correlation coefficients are depicted in Table 4. In the present case all the selected predictors are for real time stations observations. Model exhibits multiple correlation coefficients of 0.99 and cumulative variance explained is 99.30. Model shows very strong resistance and robustness towards prediction of minimum temperature in category I. Persistence itself contributes maximum for projection of next day's minimum temperature.

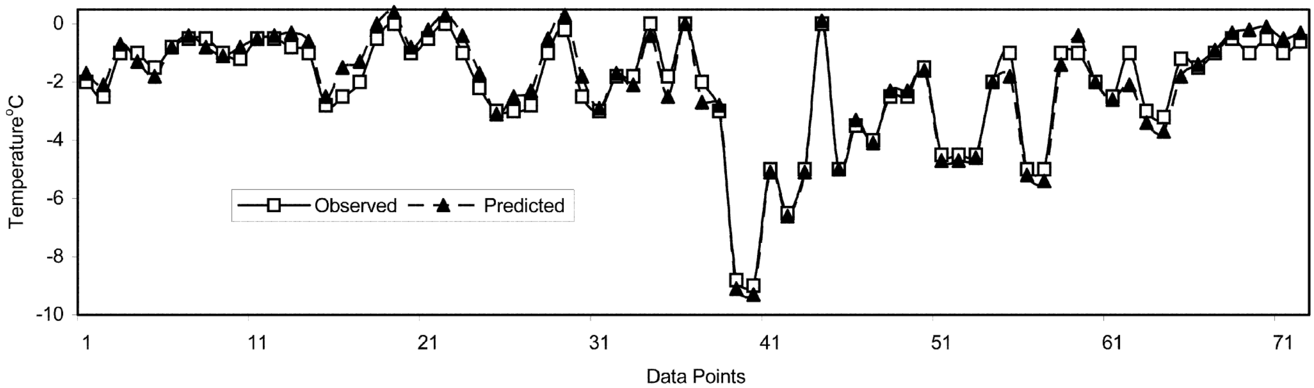

Figure 3. Observed and 24-hour forecast of minimum temperature below or equal to 0°C at Manali for DJFM 1996–97.

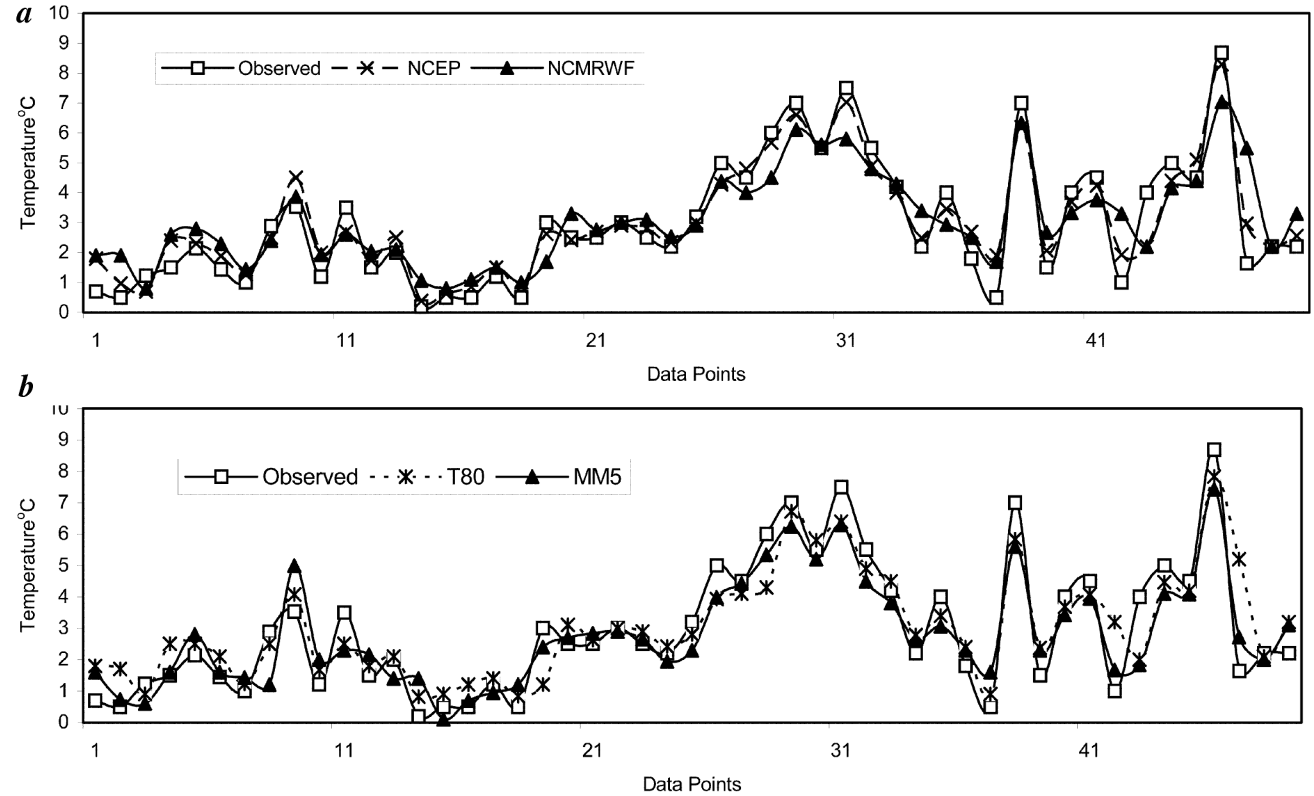

Figure 4. Observed and 24-hour forecast of minimum temperature above 0°C at Manali. ***a***, NCEP analysis and NCMRWF analysis ***b***, MM5 and T80 day 1 forecast for DJFM 1996–97.

Figure 3 shows comparison between model forecast of minimum temperature in category I with observed. It is seen that the model does reasonably well and make very close predictions. Error analysis and skill scores are shown in Table 7. It is seen that 75% forecast is within ±2°C and only very few cases show large deviations from the actual. Model shows reasonably good skill score with independent data sets and shows correlation coefficients of 0.99.

Minimum temperature forecast for category II

During winter season (DJFM) Manali exhibits the most rapid change in minimum temperature. Here statistical dynamical model is generated for prediction of minimum temperature in category II. The results are described in the following paragraphs.

Table 5 shows 24 hour prediction equation, variance explained; cumulative variance explained and selected predictors. It is seen that model selects real time station observations and numerical model outputs as potential predictors. The model shows multiple correlation coefficient of 0.67 and cumulative variance explained of 44.95.

Figure 4 shows the comparison between observed and four independent data sets. It is seen that the model predicts reasonably well and forecast values are quite close to the observed. Further, distribution and pattern of temperature are found

Table 6. Verification measures of models for forecasting minimum temperature below (or equal to) 0°C or above 0°C

Measure	Dependent data (DJFM 1984–96)	Independent data (DJFM 1996–97) IMD–NCEP analysis	IMD–NCMRWF analysis	IMD–T80 day 1 fcst	IMD–MM5 day 1 fcst
Probability of detection (POD)	0.66	0.61	0.39	0.53	0.61
False alarm rate (FAR)	0.21	0.43	0.72	0.53	0.48
Miss rate (MR)	0.34	0.39	0.61	0.47	0.39
Correct non-occurrence (C-NON)	0.71	0.68	0.32	0.60	0.61
Critical success index (CSI)	0.56	0.42	0.19	0.33	0.39
True skill score (TSS)	0.37	0.29	–0.29	0.13	0.22
Heidke skill score (HSS)	0.35	0.29	–0.28	0.13	0.22
Bias (BIAS)	0.83	1.08	1.39	1.12	1.18
Per cent correct (PC)	67.91	65.29	34.71	57.02	71.16

Table 7. Error analysis and skill scores for minimum temperature below or equal to 0°C at Manali

Error range	Development data (DJFM 1984-96)	Independent data (DJFM 1996-97)
0.0–1.0	538 (99.81)	35 (48.61)
1.1–2.0	0 (0.0)	19 (26.38)
2.1–3.0	1 (0.18)	10 (13.88)
3.1–4.0	0 (0.0)	6 (8.33)
4.1–5.0	0 (0.0)	2 (2.77)
≥ 5.1	0 (0.0)	0 (0.0)
Total	539 (100%)	72 (100%)
ABS	0.07	0.83
RMS	0.15	1.06
P-ABS	1.48	1.14
P-RMS	2.21	1.72
CC	0.99	0.85
Skill (%)	99.51	62.05

Table 8. Error analysis and skill scores for minimum temperature above 0°C at Manali

Error range	Dependent data (DJFM 1984–96)	Independent data (DJFM 1996–97) IMD–NCEP analysis	IMD–NCMRWF analysis	IMD–T80 day 1 fcst	IMD–MM5 day 1 fcst
1.0–1.0	536 (58.71)	17 (35.4)	18 (36.7)	19 (38.8)	19 (38.8)
1.2–2.0	257 (28.15)	23 (46.9)	20 (40.8)	21 (42.9)	23 (46.9)
2.1–3.0	89 (9.75)	4 (8.2)	6 (12.2)	5 (10.2)	2 (4.1)
3.1–4.0	29 (3.18)	4 (8.2)	2 (4.1)	1 (2.0)	1 (2.0)
4.1–5.0	2 (0.22)	0 (0.0)	2 (4.1)	2 (4.1)	2 (4.1)
≥ 5.1	0 (0.0)	0 (0.0)	1 (2.0)	1 (2.0)	2 (4.1)
Total	913 (100%)	49 (100%)	49 (100%)	49 (100%)	49 (100%)
ABS	1.10	0.92	0.90	1.17	0.98
RMS	1.41	1.11	1.0	1.5	1.18
P-ABS	1.33	1.79	1.66	1.84	1.89
P-RMS	1.75	2.64	2.60	2.60	2.64
CC	0.67	0.859	0.81	0.86	0.89
Skill	35.26	82.34	82.34	67.58	89.97

to be similar barring a few events where deviations are found to be reaching > 3°C. Error analysis and skill scores for minimum temperature in category II are depicted in Table 8. It is seen that MM5 day-1 forecast model gives best performance and forecast 85.7% cases within ± 2°C. Also the model shows reasonable skill score and shows correlation coefficients 0.89. Overall the model performance gives quite a satisfactorily result.

Conclusions

In this study, equations for forecasting minimum temperature are developed based on perfect prog method. Results are tested with independent data sets. Broad conclusions are given below.

Minimum temperature is well predicted at Manali, as 50 to 80% cases are well predicted within ± 2°C. The verification of the model outputs are compared with four independent data sets, viz. IMD-NCEP analysis, IMD-NCMRWF analysis, IMD-T80 day-1 forecast and IMD-MM5 day-1 forecast. It is found that IMD–MM5 day-1 forecast provides the best performance. All the results show definite positive skill in forecast produced by the model over the persistence. On a few occasions large deviations of the forecast are observed. These are mainly attributed to rapid movement of synoptic systems associated with precipitation, thunderstorm, etc. Manali is surrounded by variable topography. The local wind circulation plays a crucial role in defining the local weather. It has been attempted to insert these features into the model.

The models developed for location-specific, short range forecasting of minimum temperatures at Manali for December, January, February and March are of much practical use for inhabitants of the region and defence purposes. This will enable to infer severity of the cold conditions during winter season over the mountainous region. Further improvement can be achieved through incorporation of weather element as precipitation amount and type, cloud characteristics, surface winds, closed grid data on model output statistics basis. This process will reduce cases of large forecast errors of minimum temperature prediction associated with passage/ presence of the synoptic weather systems.

1. Dhanna Singh and Jaipal, S., *Mausam*, 1983, **34**, 185–188.
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ACKNOWLEDGEMENTS. We acknowledge National Center for Environmental Prediction (NCEP), USA, India Meteorological Department (IMD), and National Center for Medium Range Weather Forecasting (NCMRWF), and Snow & Avalanche Study Establishment (SASE) Manali, for providing valuable data.