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Forecasting maximum and minimum temperature over airports with special relevance to aviation in flight planning

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सार— मद्रास में ग्रीष्मकालीन ऋतु (मार्च से मई) के दौरान स्वसमाश्रयण के माध्यम से तथा अनुकूली फिल्टरकारी और कालमैन फिल्टरकारी पद्धति के प्रयोग द्वारा वैमानिक एवं अवैमानिक प्रयोजनों के लिए अधिकतम और न्यूनतम तापमान का पूर्वानुमान लगाने का प्रयास किया गया है। इन फिल्टरकारी तकनीकों का वर्णन संक्षेप में किया गया है और उनसे प्राप्त हुए परिणामों की तुलना जलवायु विज्ञान और प्रस्थायित्व (पेरसिस्टेंस) की पद्धति के साथ की गई है। मद्रास में ग्रीष्मकालीन ऋतु के दौरान अनुकूली फिल्टरकारी मॉडल निर्गम का उपयोग करते हुए कालमैन फिल्टर से अधिकतम और न्यूनतम तापमान की दिन प्रतिदिन की बारम्बारता का पूर्वानुमान लगभग 90 प्रतिशत तक प्रभावी रहा है। चूँकि तटवर्ती स्टेशन मद्रास में इस मॉडल का निष्पादन अच्छा रहा अतः इसी मॉडल का प्रयोग तमिलनाडु के अन्तर्देशीय हवाईअडडे वाले स्टेशन त्रिची (मद्रास से 300 किमी. दक्षिण पश्चिम में) पर इसकी प्रभावकारिता का पता लगाने के लिए किया गया है। यह 2° सें. के घटवढ़ की यथोचित उपयुक्तता के साथ अधिकतम और न्यूनतम तापमान की प्रागुक्ति करने में 90 प्रतिशत से अधिक प्रभावी रहा है।

ABSTRACT. Forecasting of maximum temperature and minimum temperature for aviation and non-aviation purpose has been attempted through auto regression and by employing the method of adaptive filtering and Kalman filtering during the hot weather season (March to May) over Madras. The filtering techniques have been outlined and the results are compared with the method of climatology and persistence. The Kalman filter, using the model output of adaptive filtering, forecasts well the day-to-day variability of maximum and minimum temperature during hot weather season over Madras with an efficiency close to 90%. As the model performs reasonably well over Madras, a coastal station, the same has been tried over Trichy (300 km southwest of Madras), an inland airport station in Tamilnadu to ascertain its efficacy. The efficiency is better than 90% in predicting maximum and minimum temperature within an accuracy of ± 2°C.

Key words — Auto Regressive process, Adaptive filtering, Kalman filter, Model output statistics, Persistence, Madras airport, Trichy airport.

1. Introduction

The atmospheric temperature with its diurnal and spatial variability affects the living conditions of all living beings on the earth. Though the indoor temperature can be controlled to the safe and comfortable living conditions due to technological advancement on knowing the variability of temperature, the information on outside temperature is inevitable to have a proper planning of day-to-day work. As prolonged exposure to extreme hot and cold temperature may not only cause discomfort and inefficiency in working environment but also succumbs human beings to heatwave and coldwave conditions, the forecast information on maximum temperature during summer and minimum temperature during winter with a reasonable degree of accuracy will be of prophylactic value to the public.

The optimal, economic and efficient flight planning at all stages of the flight operations, *viz*, take-off, ascent, cruise and landing requires a thorough knowledge of actual and expected weather. The lift of the aircraft in the take-off/ ascent state depends on the air density which in turn depends on the temperature of the surface and at runway. Temperature at the ground also plays an important role in the 'power setting' by the engine to overcome its weight during the take-off phase. An increase of temperature reduces the power setting and power developed may not be sufficient to effect a take-off on the available runway. Hence take-off weight has to be decreased when the temperature, at the time

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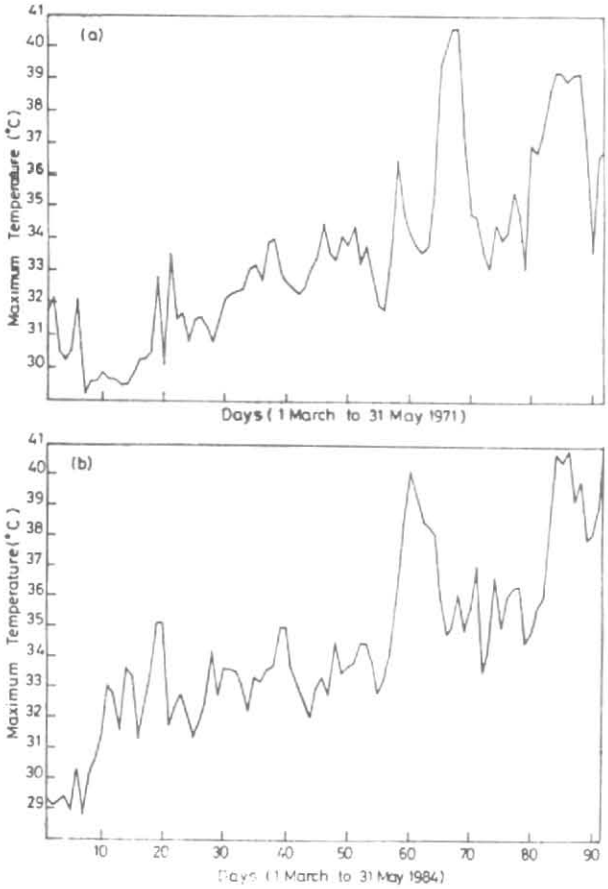


Figs. 1(a &b). Plot of daily Maximum temperature over Madras airport (a) March - May 1971 (b) March - May 1984

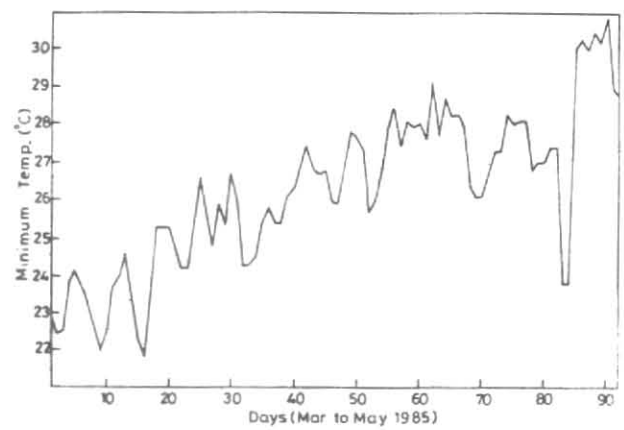


Fig. 2. Plot of daily minimum temperature over Madras airport during March - May 1985

of take-off, increases (Rama Sastry, 1984). An increase of 1° C temperature during take-off may warrant a decrease of atleast 200 kg of take-off gross weight of the aircraft (Menon, 1991). The fuel consumption increases exponentially with rise of temperature, from 67 kg (for 1° C error in forecasting at the time of take-off) to as high as 2000 kg when the forecast temperature deviates on the higher side from the actual by more than 5°C during all stages of the aircraft operations (WMO, 1969). Hence it is absolutely imperative to offload some quintals or even few tonnes of cargo load to effect take-off at the scheduled departure time when the actual temperature appreciably deviates on the positive side from that was forecast.

The long haul (international) passenger and cargo flights operations are normally restricted to night/early hours, in view of the fact that the air temperature is minimum, so as to carry maximum passenger and cargo load. However the short haul or domestic flights operations continued to be throughout the day to cater to the passenger requirements. Though the frequency of aircraft operations is relatively minimum between 1300 and 1500 hrs IST (the period during which maximum temperature occurs) for obvious seasons, an attempt has been made in this paper to forecast maximum temperature during hot-weather season (March to May) as a few aircraft incident/ accident have been reported during this period. Forecasting of night minimum temperature also has been attempted in this study to cater to the long haul flight operations. However forecasting of surface temperature and pressure at synoptic and auxilliary synoptic hours (0000, 0300, 0600 ....2100 UTC) and intervening periods have not been attempted here and they are being considered separately as the methodology of forecasting the same is different in view of the well established diurnal variation.

2. Data

The daily maximum and minimum temperature, rainfall recorded by the Meenambakkam (Madras) airport meteorological office for the period March to May 1971 to 1985 have been obtained from the National Data Centre (NDC), India Meteorological Department (IMD), Pune. The maximum and minimum temperature recorded at Trichy airport (300 km southwest of Madras) during March - May, 1980-1993 have been collected from the climatological section, Regional Meteorological Centre, Madras. The upper air RS/RW data (0000 and 1200 UTC) of Madras and the 3 hourly surface observations, in standard code format, in respect of Meenambakkam, Cuddalore (250 km south of Madras), Trichy observatories for the period 1984 and 1985 have also been obtained from NDC, Pune and considered in this study.

3. Time series analysis

A plot of daily maximum temperature as recorded at Madras airport during two typical years 1971 and 1984 is shown in Fig. 1. Though persistency is commonly observed, the absolute value of deviation of daily maximum temperature from the previous days's value exceeding even 4° C is not at all uncommon. Similar is the case in respect of

TABLE 1

Forecast verification of maximum and minimum temperature over Madras during 1985 by an auto regressive process of order 4

	Absolute error (°C)	Frequencies of Observed								
		Maximum temperature					Minimum temperature			
		A	B	C	D	Total	E	F	A	Total
F	≤ 0.50	8	15	6	0	29	7	29	2	38
O R	0.51-1.00	13	10	2	0	25	8	21	0	29
E	1.01-1.50	6	6	0	0	12	4	7	1	12
C	1.51-2.00	2	5	3	0	10	1	4	1	6
A S	> 2.00	2	8	2	0	12	2	1	0	3
T	Total	31	44	13	0	88	22	62	4	88

A : 30-35° C ; B : 35 - 40 °C ; C : 40 - 45 °C; D : > 45 °C ; E : 20 - 25 ° C ; F : 25 - 30° C

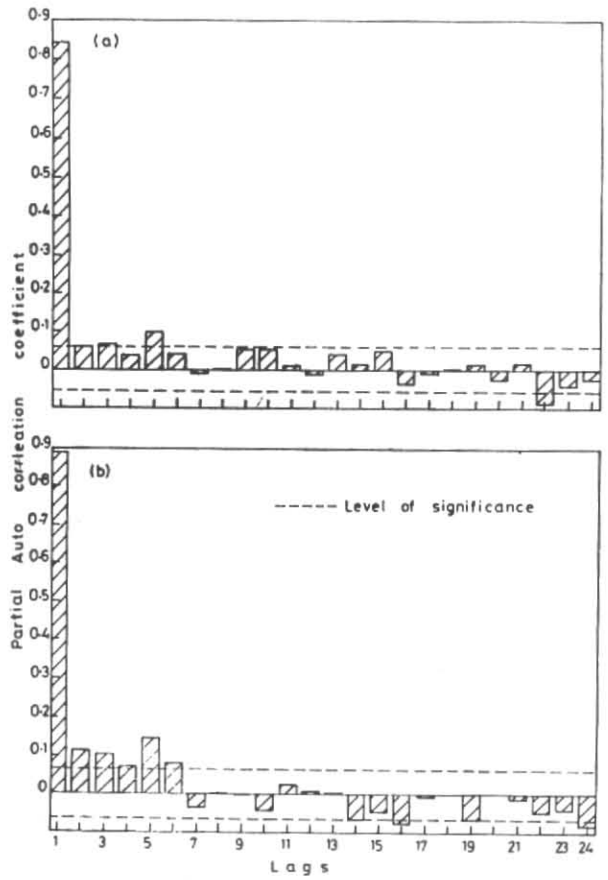
minimum temperature also (Fig. 2). The maximum and minimum temperature series have been subjected to correlogram analysis with a view find out the presence of signal, if any, of forecast value. As the Auto Correlation Coefficient (ACC) of lag 1 in respect of maximum temperature was 0.841 (0.888 for minimum temperature) and the ACCs of subsequent lags were gradually dropping to zero, we infer that potential exists for univariate prediction. The method of persistency alone yielding 55 to 70% accuracy of forecast with an absolute error of less than or equal to 1° C on different years.

4. Methodology and computation

Forecasting of surface minimum temperature was attempted by Roodenburg (1984) utilising step-wise forward multiple regression technique based on cloud amount, sunshine duration, wind speed direction and maximum temperature of the previous day. Significant variation of maximum and minimum temperature over Bombay was carried out by Manral (1983) based on wind direction and speed on a qualitative analysis. Dhanna Singh and Jaipal (1983) studied the predictability of minimum temperature over Delhi by employing multiple regression technique. In the present study, the univariate and multivariate analysis are being attempted.

4.1. *Auto regressive process*

The Partial Auto Correlation Coefficient Function (PACF) were computed for maximum and minimum temperature series and depicted in Fig. 3. The exponential decreasing and dropping to zero of ACCs and significant spikes of PACFs upto lag 6 based on the development period data sample (1971 to 1982) suggest that the data can be modelled as an Auto Regressive (AR) process of orders 3 to 6. The model coefficients were estimated through the Marquardt (1963)compromise as given in Alan Pankratz (1983). The AR (4) model Root Mean Squared Error (RMSE) was 1.65 (which is very much comparable with the standard deviation of the maximum temperature series, *viz.*, 2.85°C). The corresponding values in respect of minimum temperature series were 1.16 and 2.35° C respectively. The verification of forecast for the year 1985 is tabulated in Table 1. The model equation for the maximum temperature is



Figs. 3 (a &b). Correlogram of partial auto correlation function of (a) Maximum temperature (b) Minimum temperature (March -May, 1971-82)

$$T_t = 0.848\ T_{t-1} + 0.080\ T_{t-2} - 0.020\ T_{t-3} + 0.096\ T_{t-4} \quad (1)$$

where, T_t is the maximum temperature at day t.

TABLE 2

Forecast verification of maximum and minimum temperature over Madras during March - May 1985 by an adaptive filter algorithm of order 4

	Absolute error (°C)	Frequencies of Observed								
		Maximum temperature					Minimum temperature			
		A	B	C	D	Total	E	F	A	Total
FORECAST	≤ 1.00	21	24	8	0	53	14	50	2	66
	1.01 - 2.00	8	12	3	0	23	6	11	2	19
	2.01 - 4.00	1	8	0	0	9	2	0	0	2
	4.01 - 6.00	1	0	2	0	3	0	1	0	1
	> 6.00	0	0	0	0	0	0	0	0	0
	Total	31	44	13	0	88	22	62	4	88

A : 30 - 35 °C ; B : 35 - 40 °C ; C: 40 - 45 °C ; D : > 45 ° C ; E : 20 - 25 ° C ; F : 25 - 30 ° C

TABLE 3

The year-wise performance of Adaptive Filtering process of various orders in forecasting maximum and minimum temperature over Madras

Order of AF process	1983		1984		1985		1971-'82 Model
	% C.F.	RMSE	% C.F.	RMSE	% C.F.	RMSE	RMSE
			(a) Maximum temperature				
3	91.0	1.427	86.5	1.179	84.3	1.437	1.408
4	88.6	1.395	84.1	1.172	86.4	1.436	1.402
			(b) Minimum temperature				
3	75.2	1.399	88.8	0.841	91.1	1.124	0.963
4	73.9	1.370	90.9	0.835	84.1	1.088	0.949
5	83.9	1.385	90.8	0.816	82.8	1.064	0.938
6	74.7	1.375	90.7	0.811	83.7	1.071	0.930

C.F : Correct Forecast, R.M.S.E. : Root Mean Squared Error

The model equation for the minimum temperature is

$$T_t = 0.688\, T_{t-1} + 0.182\, T_{t-2} - 0.023\, T_{t-3} + 0.153\, T_{t-4} \qquad (2)$$

where T_t is the minimum temperature at day t.

4.2. *The method of generalised adaptive filter algorithm*

The method of Adaptive Filtering (AF) can be thought of as an improved version of estimating the coefficients of Box-Jenkins Auto Regressive (AR)/ Moving Average (MA) process. The time series (X_t) can be modelled as $X_t = \sum_{i=1}^{p} \phi_i\, X_{t-i} + e_t$ where, t is the time period and p is the order of the filtering process. The coefficients ϕ_i (i = 1,2,3 .....p) can be estimated on non-linear least square approach to minimize the error e_t (Wilde and Beighter, 1964 and Makridakis and Wheelwright, 1978). The method starts with some initial value of ϕ_i (i = 1,2,3....p) and by repeatedly applying the recurrence relationship $\phi'_i = \phi_i + 2\, K\, e_t\, X_{t-i}$ (i = 1,2 ......, p) and ($t = p+1$, ... n) where ϕ'_i is the newly adapted parameter and K is the learning constant which speeds up the adaptation, the coefficients ϕ_i are estimated. Convergence is guaranteed when K is chosen to fall in the range $[0, 1/(\sum_{i=1}^{p} X_i^2)_{max}]$ according to Widrow (1966). The mechanism is truly self adaptive since the parameters are getting automatically adjusted as and when the new data is made available. The iterations can be stopped when the new Mean Squared Error (MSE) is no longer less than the old one by 0.0001 or any arbitrary value so desired for individual forecasting applications. The quite interesting feature of the adaptive filtering is that it enjoys the positive characteristics of the exponential smoothing filters besides it can work well even in a non-stationary data series (Wheelwright and Makridakis, 1973).

The data pertaining to 1971 to 1982 have been used to develop the model coefficients and that of 1983 to 1985 are used for verification. The value of K was varied from 0.001 to 0.150 in steps of 0.001 to find out the optimal value of K that ensures minimum MSE. The value of learning constant (K) thus obtained for this model was 0.018 based on the maximum and minimum temperature series of 1971-82.

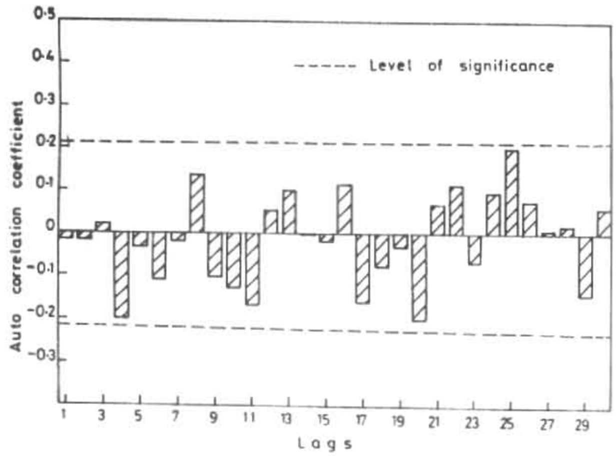


Fig. 4. Correlogram of residual series of adaptive filtering (order 4) model in predicting minimum temperature (March - May 1984) over Madras airport

Table 2 lists the performance of the model AF (3) and AF (4) for the year 1985. The forecast accuracy have been computed based on the IMD criteria for issuing qualitative forecasts so that this model can be used for issuing non-aviation (local) forecast also. For this purpose the daily means were consulted from the published records of IMD. The departure from normal value can be classified as

(a) + 1° C : Normal (NC)

(b) + 1 to + 2° C : Slight Rise (SR)

(c) + 2 to + 4° C : Moderate Rise (MR)

(d) + 4 to + 6° C : Large Rise (LR)

(e) > 6° C : Heat wave

(f) - 1 to - 2° C : Slight Fall (SF)

(g) - 2 to - 4° C : Moderate Fall (MF)

(h) - 4 to -6° C : Large Fall (LF)

(i)< = - 6° C : Cold Wave

The model RMSE of AF(3) and AF (4) are 1.408 and 1.402 respectively for maximum temperature. The test period RMSE and the forecast efficiency within the qualitative / quantitative errors are summarised in Table 3. The correct forecast is taken as the one which could forecast the maximum (minimum) temperature in the ranges mentioned as NC, SR (SF), MR (MF) etc. Though the individual year's performance of AF (3) seem to better than AF (4) in predicting maximum temperature during 1983 and 1984, the AF (4) model can be considered appropriate as its model as well as test period RMSE is lesser than that of AF (3). The model equation of AF (4) is

$$T_t = 0.847T_{t-1} + 0.074T_{t-2} - 0.019T_{t-3} + 0.103T_{t-4} \quad (3)$$

where T_t is the maximum temperature at day t.

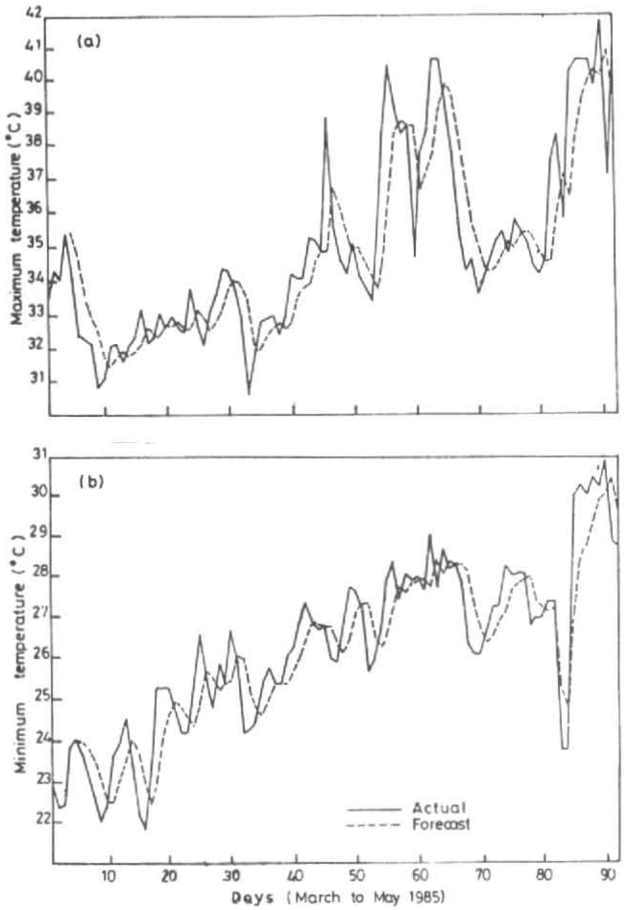


Fig. 5. Comparison of Kalman filter forecast with observed (a) Maximum temperature (b) Minimum temperature (March - May 1985) over Madras airport

The parameters of AF model got stabilised in predicting the minimum temperature at order 6, as can be inferred from Table 3, due to its minimum RMSE. However the ACCs of the residual series of AF (4) showed no significant spike. A plot of ACCs of residual series of AF (4) for a typical year 1984 is shown in Fig 4. Since a good model should be parsimonious, AF (4) model, which has performed relatively well, can be considered appropriate in forecasting minimum temperature. The model equation is

$$T_t = 0.686T_{t-1} + 0.178T_{t-2} - 0.024T_{t-3} + 0.167T_{t-4} \quad (4)$$

where T_t is the minimum temperature at day t.

From Tables 1 through 3, it can be concluded that both AR and AF processes of order 4 have predicted well with an efficiency exceeding 85%. However, as the RMSE of AF (4) model is lower than that AR (4), the AF (4) model can be used to forecast maximum and minimum temperature over Madras. The model efficiency in predicting maximum (minimum) temperature within an absolute error of 1° C during March to May 1997 was 65.9% (72.7%) and within an absolute error of 2° C was 90.9% (93.2%) respectively.

TABLE 4

Frequencies of forecast class using Adaptive Filtering and Kalman Filter falling within the observed (persistence) categories

		Observed Class																	
		1983						1984						1985					
		a	b	c	d	e	Total	a	b	c	d	e	Total	a	b	c	d	e	Total
		(a) Maximum temperature																	
FORECAST	a	47	2	0	0	0	49	51	6	0	0	0	57	50	3	0	0	0	53
	b	3	21	1	0	0	25	4	16	2	0	0	22	5	16	2	0	0	23
	c	0	3	10	1	0	14	0	2	7	0	0	9	0	1	8	0	0	9
	d	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	1	2	3
	e	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total		50	26	11	1	0	88	55	24	9	0	0	88	55	20	11	2	0	88
		(b) Minimum temperature																	
FORECAST	a	48	7	0	0	0	55	67	3	0	0	0	70	61	5	0	0	0	66
	b	10	11	3	0	0	24	4	11	1	0	0	16	7	12	0	0	0	19
	c	0	1	4	2	0	7	0	0	2	0	0	2	0	1	1	0	0	2
	d	0	0	0	2	0	2	0	0	0	0	0	0	0	0	0	0	1	1
	e	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total		58	19	7	4	0	88	71	14	3	0	0	88	68	18	1	0	1	88

a : Absolute Error (A.E) ≤ 1.0 °C ; b : A.E 1.01 - 2.00 °C; c : A.E 2.01 - 4.00 °C ; d : A.E 4.01 - 6.00 °C; e : A.E > 6.0 °C

TABLE 5

Forecast verification of maximum and minimum temperature over Trichy during March-May 1993 by an adaptive filter algorithm of order 4

		Frequencies of Observed							
		Maximum temperature					Minimum temperature		
	Absolute error	A	B	C	D	Total	E	F	A	Total
FORECAST	≤ 1.00	8	53	6	0	67	16	41	0	57
	1.01 - 2.00	1	16	1	0	18	4	19	0	23
	2.01 - 4.00	0	2	1	0	3	6	1	0	7
	4.01 - 6.00	0	0	0	0	0	1	0	0	1
	> 6.00	0	0	0	0	0	0	0	0	0
	Total	9	71	8	0	88	27	61	0	88

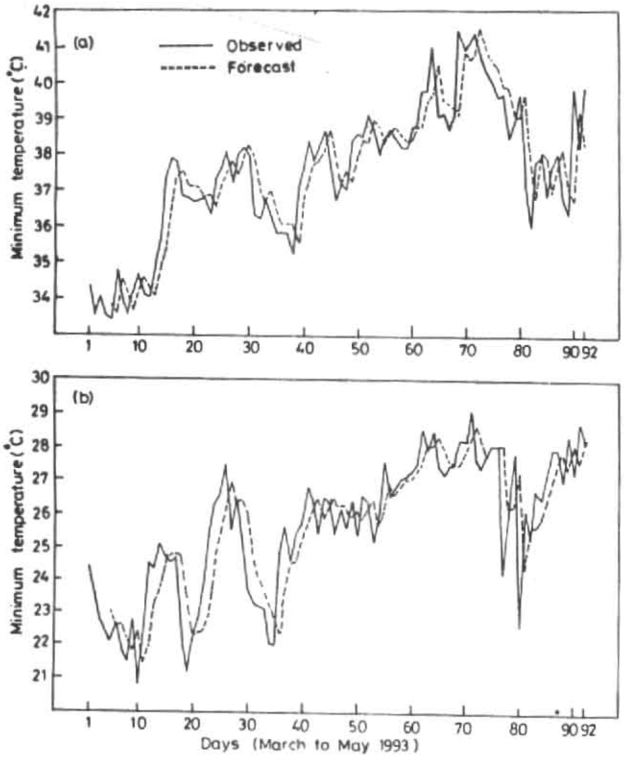
A : 30 - 35 ° C ; B : 35 - 40 ° C C : 40 - 45 ° C ; D : > 45 °CE : 20 - 25 ° C ; F : 25 - 30 ° C

4.3. *Kalman filtering*

The Kalman filter is a statistical method to correct the forecast of a weather element based on the recent data. It is both adaptive and recursive, as the changes are independent of length of past data and the new data modifies the model coefficients (WMO, 1992). The Kalman filter equation can be described as

$$F_{t+1} = W_t X_t + (1-W_t)F_t \quad (5)$$

where, F_t is the forecast at time t, X_t is the variable at time t and W_t the weight of the Kalman filter to be estimated. W_t can be found out by adaptive and recursive methods by considering a long time series. The consistent value of W_t, on considering large volume of sample data, may be used to forecast the series in the test (independent) period. The weight W_t can be expressed as the ratio of variance of actual and forecast data. Kalman filtering consists of combining two independent estimates, one based on prior knowledge and the other a prediction based on new information (data) to form a weighted estimate. It is similar to Bayesian approach, which combines prior and sampling information to form a posterior distribution. This filtering approach has grown out of control engineering. Detailed information can be obtained from the celebrated papers of Kalman (1960)



Figs. 6(a&b). Comparison of adaptive filter forecast with observed (a) Maximum temperature (b) Minimum temperature (March - May 1993) over Trichy airport

and Harrison and Stevens (1971). The estimated W, according to Makridakis and wheelwright (*loc. cit*) is

$$W^* = \sigma^2_F / (\sigma^2_F + \sigma^2_x) \quad (6)$$

where σ^2_F and σ^2_x are the variances of forecast and actual value.

The forecast (F_t) issued by AF (4) model has been considered to estimate the weight of the Kalman filter recursively. Though the performance of the filter leads to almost same results obtained by the earlier methods, the trend in day to day variability could be explained better in this filtering. For instance, there was an abrupt rise in the minimum temperature by 6.2° C on 24th May 1985 (see the value of day 85 in Fig. 2). Kalman filter could predict a rise of 3.3° C on that day due to its attractive negative feed back mechanism whereas the method of persistency could not predict even a single degree rise in temperature. The results of Kalman filter output are presented in Table 4. A comparison of Kalman filter forecast and the observed values of maximum and minimum temperature during the year 1985 is shown in Fig. 5. If we consider the forecast category falling one stage below the observed class also as correct forecast (as normally this criteria is followed in verification of forecast by research workers), then predicting the maximum and minimum temperature using AF (4) model and utilising this model output as an input to Kalman filtering may yield a forecast efficiency better than 90%. As such this model can be considered as the model output statistics (MOS) on a local scale-by considering univariate time series alone — perhaps similar to the MOS coined using Numerical Weather Prediction (NWP) model output which require data on regional / global scale.

The maximum temperature over a station is affected by the onset of sea breeze, continental airmass advection (Atkinson, 1981 ; Haltines and Martin 1957). The air mass flux arriving / passing through Madras was computed from surface upto 850 hPa (as the air mass flux in these levels can influence the surface maximum temperature) for 0000 UT for the period March to May 1984 and 1985. The order of air mass flux was varying between 8.33×10^5 to 9.654×10^5 metric tonne per second. The multivariate analysis using surface parameters at synoptic and auxiliary synoptic hours of Madras, Cuddalore, Trichy and Nellore and Upper air data of Madras, for the period 1984-85, to predict the maximum temperature have been attempted. However due to lack of sufficient upper air and surface data and in view of high order of the air mass flux, multiple regression analysis could not reveal clear cut signals. Hence we decided to attempt the model based on dynamical parameters on receipt of adequate data.

4.4. *Forecasting over Trichy airport*

As the AF model discussed in section 4.2 correctly forecasts maximum and minimum temperature in more than 85% of the cases over Madras, a coastal station, the same technique was adapted to predict maximum and minimum temperature over Trichy, an inland airport station. The method of persistency along yields an efficiency varying between 66 and 72% in predicting maximum and minimum temperature. After conducting the timeseries analysis listed in sections 3 and 4.1, the maximum and minimum temperature data of 1981 to 1991 were subjected to develop the AF model coefficients and that of 1992 and 1993 have been used for validation. The efficiency of the AF model of order 4 has been tabulated in Table 5. Here again, the AF(4) model predicted maximum (minimum) temperature in 76% (64.8%) within an absolute error of 1° C and 96.9% (90.9%) within an absolute error of 2° C. The AF(4) model equation for predicting maximum temperature is

$$T_t = 0.692T_{t-1} + 0.122T_{t-2} - 0.010T_{t-3} + 0.199T_{t-4} \quad (7)$$

where T_t is the maximum temperature at time t. The model RMSE is 1.38° C.

The AF(4) model equation to predict minimum temperature is

$$T_t = 0.536T_{t-1} + 0.226T_{t-2} + 0.103T_{t-3} + 0.139T_{t-4} \quad (8)$$

where T_t is the minimum temperature at time t. The model RMSE is 1.33°C. A typical plot of observed and AF(4) predicted maximum and minimum temperature during March - May, 1993 has been depicted in Fig. 6. From

Table 5 and Fig. 6, it can be concluded that the AF model can conveniently be used to forecast maximum and minimum temperature with a good degree of accuracy.

5. Results

The autoregressive process of order could forecast the maximum temperature / minimum temperature over Madras during hot weathers season (March to May) in more than 60% case within an absolute error of less than 1°C. The efficiency of adaptive filtering is somewhat better than 80% in forecasting different categories of the rise and fall of maximum and minimum temperature. The combination of adaptive filtering and Kalman filter can be used to forecast maximum and minimum temperature quantitatively and qualitatively with an efficiency close to 90%. This method can be used for issuing aviation as well as non-aviation forecasting of maximum and minimum temperature over Madras during hot weather season. The AF (4) model has an efficiency of more than 70% (90%) in predicting maximum and minimum temperature within ± 1°C (± 2 °C).

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