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RESEARCH ARTICLE

Reconstruction of missing monthly temperature observations in Jaffna, Sri Lanka

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Abstract: A well known method of estimating missing temperature observations has been refined and applied to estimate monthly temperature with a higher accuracy. The estimates are based on the temperature departures of stations in the same geographical regions from their standard normal. The method was successfully applied for reconstructing the missing monthly temperature records at the Meteorological Station, Jaffna (80°02'E, 9°41'N) during the period 1980 − 2000 where large gaps in weather observations can be seen. With the available past data, it is shown that the accuracy of estimates is ± 0.3 °C and over 90 % of the estimates are within ± 0.5 °C from the observed values. Although the method can be applied to any region having a cluster of meteorological stations, the method depends on the density of the stations in the proximity of the target station and the availability of data in the nearby stations.

Keywords: Mean temperature, missing data, standard departure, weather stations.

INTRODUCTION

Temperature is one of the most important meteorological parameters that has profound effects on many natural and human systems on Earth. The temperature data are used by meteorologists and hydrologists to study the water availability in the atmosphere, evapotranspiration, melting of ice and heat losses by large buildings (Islam *et al*., 2000). The literature shows that uninterrupted time series data of climatic parameters are required in order to conduct climate related research studies particularly in modelling and prediction (DeGaetano *et al*., 1995). Although Sri Lanka has a reasonable infrastructure consisting of 22 main meteorological stations with many of the stations having climate observations dating back to 1870s, a number of these stations in the northern and eastern parts of Sri Lanka experienced difficulties in recording data during the period 1980 − 2000 due to the conflict situation. Specially, the meteorological station in Jaffna (80°02'E, 9°41'N), which is the main meteorological station to maintain weather records for the northern peninsula, although having over 100 years of continuous weather recordings, was unable to collect data during the period from 1984 to 2000. Although the weather observations have been resumed from 2001, no attempts have been reported on the reconstruction of missing observations. Estimation of the missing data is an important part of post conflict measures to bring back the stations in the northern part of the island to normalcy. The main objective of this work is to reconstruct the missing monthly temperature in Jaffna for the period 1980 − 2000.

The estimation of missing temperature data or identifying observational errors, is an important task for climatologists and for those who work in related disciplines (Kemp *et al*., 1983; DeGaetano *et al*., 1995; Huth & Nemesova, 1995). It is particularly important for regions where meteorological stations are scarce and the measurements are questionable. In the past, a number of researchers have used a variety of techniques based on the area, period and availability of data in the neighbouring stations to estimate missing temperature data. In general, the methods of estimating missing temperature data can be divided into three broad categories; (i) within the station, (ii) between stations, and (iii) regression based techniques (Allen & DeGaetano, 2001). The within station method is one of the simplest methods to estimate missing observations. This involves taking the average of the temperature records of previous and following days. In the other two methods, one or more neighbour stations are used to estimate the missing values at the target stations.

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Xia *et al*. (1999) have discussed the results of six different methods to calculate missing values of forest climate data. They used the following techniques; (1) simple arithmetic averaging; (2) inverse distance interpolation; (3) normal ratio method; (4) single best estimator; (5) multiple regression analysis, least absolute deviations criteria, and (6) closest station method. The first method is commonly used to calculate missing meteorological data. The missing data are estimated by arithmetically averaging the data of the five closest weather stations around the target station. The inverse distance method is also a popular method in which the data of neighbour stations are averaged according to the weights of the inverse of the distance between the neighbour station and the target station. The normal ratio method depends on the spatial correlation of the closest station, and the missing data are estimated as a combination of variables with different weights, which are calculated using the correlation coefficient. In the single best estimator method, the closest neighbouring station that has the highest positive correlation with the target station is used to estimate the missing data. The multiple regression analysis is an advanced statistical approach to estimate the missing data. In this method, two or more stations are used to establish a multiple regression equation to calculate the target station data.

Kemp *et al*. (1983) evaluated seven different techniques for estimating missing values of daily maximum and minimum temperatures. The seven methods can be divided into three distinct categories: (1) within station technique, which utilizes data from adjacent days to predict missing values, (2) between station technique, which employs the mean difference to predict missing values, and (3) regression techniques, which utilize the between-station correlation and regression coefficient to predict missing values. They concluded that the selection of the most appropriate technique depends on the type of data, size of the gap of the weather record and the availability of surrounding stations' data to include in the analysis. However, as reported by the authors, the between-station regression based approach generates significantly smaller errors compared to the other methods.

The prominent methods of estimating missing data depend upon the statistical properties of the data. In climatology, the two most important factors are the spatial and temporal correlation between the stations. The most appropriate technique will also depend on the purpose for which the data are to be used. In this paper, results of a refined method based on the between-stations technique that was successfully applied to reconstruct the missing monthly temperature data in the Jaffna meteorological station, which had virtually no records between 1984 and 2000 is presented.

DATA SAMPLE

Monthly temperature records from 5 stations (target station – Jaffna; neighbouring stations – Mannar, Anuradhapura, Puttalam and Trincomalee) having approximately 100 years of data or more were extracted from the published data records (Yoshino & Suppiah, 1982) for the present analysis. These stations were selected from the same geographical region to ensure similar climatic conditions to those prevailing in the northern part of Sri Lanka. The recent data records used in the study were obtained directly from the Department of Meteorology, Sri Lanka.

Temperature records of the target station (Jaffna) are not available for the period from 1984 – 2000 due to the conflict situation and frequent hostilities in this part of the country. The data from the neighbouring station Mannar also consisted of a substantial number of missing records during the period 1991 − 1997. Therefore, Mannar was not used in the temperature reconstruction work for the months where the data were missing. The remaining three stations had only a very few missing temperature records and these were filled by considering the temperature records of the same months recorded in adjacent years at the same stations. Thus, the analysis in this study is based on monthly temperature data at

Table 1: Summary of monthly temperature data used in this study

	Station	Period (years)	Latitude (N^o)	Longitude (E^o)	Altitude (m)	Duration (years)
1	Jaffna	1951 − 1980	9.68	80.03	3.1	30
2	Mannar	1951 − 2000	8.98	79.92	3.6	50
3	Anuradhapura	1951 − 2000	8.35	80.38	92.5	50
4	Puttalam	1951 − 2000	8.03	79.83	2.1	50
5	Trincomalee	1951 − 2000	8.58	81.25	23.9	50

five stations during the period 1951 − 2000. The period 1951 − 1980 was used to validate the model. The model was used to reconstruct the missing temperature records at Jaffna during the period 1981 − 2000. The duration of data records together with the latitude, longitude and altitude of stations are given in Table 1.

METHODOLOGY

In this study, a method developed by Steurer (1985) based on the between-stations technique for estimating daily maximum and minimum temperatures was refined and adopted to estimate the missing monthly temperatures in Jaffna. The method assumed that for a given day, stations having similar geographical conditions will have temperatures that will deviate from their standard normal by similar amounts. Thus, for monthly temperatures it was assumed that for the five selected stations, Jaffna, Mannar, Anuradhapura, Puttalam and Trincomalee, the temperature will deviate from their standard normal by similar amounts. For monthly temperature, the standard departure Z for station n was defined as:

$$Z_n = \frac{T_n - \bar{T}_n}{S_n} \quad ...(01)$$

Where, n represents any station in the same climate division, T_n is the monthly temperature, $\bar{T}_n$ is the longterm mean monthly temperature and S_n is the standard deviation of monthly temperature values. For a given month and a climate division, the average monthly standard departure expected at the target station can be calculated by combining the standard departures from all the neighbouring stations without including the target station as:

$$Z_{ave} = \frac{1}{N}\sum Z_n \quad ...(02)$$

Where, N is the total number of stations used. Since 4 neighbouring stations to Jaffna were selected in this study, $N = 4$. The minimum requirement is to have data from at least one neighbouring station although three is recommended. Thus, the missing monthly temperature at the target station can be estimated by:

$$T_j = Z_{ave} \times S_j + \bar{T}_j \quad ...(03)$$

Where, j represents the target station, and $\bar{T}_j$ and S_j are the long-term mean monthly temperature and its standard deviation, respectively. The accuracy of the estimates can be verified by calculating the standard deviation of the difference between the estimated values and observed values.

When calculating the combined standard departure Z_{ave}, it has been assumed that the contribution from each neighbouring station is equal. This may not be strictly true even if the stations are selected from a similar climate division. The standard departures in stations close to the target station may show higher correlation compared to distant stations. In addition, since the method is applied to monthly temperature values, seasonal variability in temperature can affect the accuracy. For example, throughout the year, the increase and the decrease of the temperature cycle between a pair of stations may not follow a linear pattern. These effects can be minimized in the above model by introducing a parameter, which can adjust the average monthly deviation from the expected linear behaviour (mean shift, if any) and using weights, which correspond to the strength of the correlation between the stations. Thus, the refined average monthly standard departure expected at the target station is:

$$Z_w = \frac{\sum\left(Z_n - \bar{\delta}_{n,m}\right) \times w_n}{\sum w_n} \quad ...(04)$$

Where, $\bar{\delta}_{n,m}$ is the mean shift for the month m for a given station n, introduced to compensate for the deviations in the Z_n values due to seasonal effects and w_n is the square of the reciprocal of the standard deviation σ_n of the differences in the standard departures between the target station and each of the stations used in the calculation. That is:

$$w_n = \left(\frac{1}{\sigma_n}\right)^2 \quad ...(05)$$

With this change, the missing values at the target station can be estimated by using the revised formula:

$$T_j = Z_w \times S_j + \bar{T}_j \quad ...(06)$$

In this study, thirty years of monthly temperature data (from 1951 to 1980) were used to test the accuracy of the above model.

RESULTS AND DISCUSSION

The northern peninsula, where Jaffna is located, belongs to the Dry Zone of Sri Lanka and the average temperature in Jaffna is one of the highest in the country. During the period under consideration, the highest mean monthly temperature was observed during the month of April (29.7 °C) and the lowest mean monthly temperature was observed during the month of January (25.5 °C). The range of mean monthly temperature can vary by approximately 2.0 °C while the range of variation of mean monthly temperature within a year is limited to roughly 6.0 °C. As shown in Table 2, the temperature variability in the other stations selected for this work is also similar to the variation seen in Jaffna. In general, there is no high temperature variability in the northern part of the country.

In order to understand the strength of the correlation between the target station and the neighbouring stations, the standard departures (Z) of temperatures were calculated for the period 1951 − 1980 separately for all five stations with non-missing observations. Figure 1 shows the histograms of the difference between the standard departure of temperatures in the target station and each of the selected neighbouring stations, Mannar, Anuradhapura, Puttalam and Trincomalee. The Z values of each station follow a normal distribution. As expected, the difference in standard departures $Z_j - Z_n$ also follows a normal distribution.

The best agreement between the standard departures was found to be between the stations Jaffna and Mannar. Between these two stations, the agreement of the standard departures is within ± 0.5 for 95 % of the cases. The poorest agreement in standard departures was seen between the Jaffna and Trincomalee stations where only 73 % of the cases were within ± 0.5. Thus, when calculating the average standard departure by combining the standard departures of all neighbouring stations, higher weight should be assigned to Mannar. The estimated standard deviations (σ_i) of the difference between the standard departures $Z_j - Z_n$, between

Table 2: Mean monthly temperature variability (1951 − 1980)

	Station	Highest temperature °C	Lowest temperature °C	Monthly variability °C	Annual variability °C
1	Jaffna	30.8	24.2	± 0.41	± 1.44
2	Mannar	30.4	25.1	± 0.42	± 1.17
3	Anuradhapura	30.2	24.1	± 0.58	± 1.53
4	Puttalam	30.2	24.7	± 0.45	± 1.19
5	Trincomalee	31.5	24.8	± 0.53	± 1.72

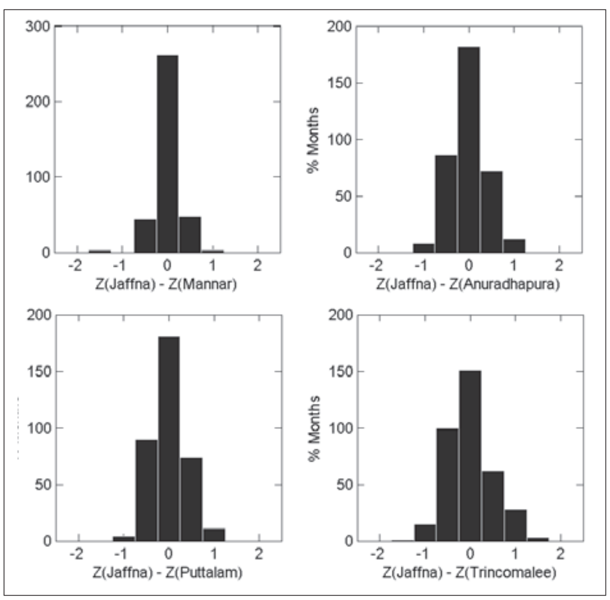

Figure 1: Histograms of the difference between standard departures estimated based on monthly temperature values at Jaffna and four neighbouring stations (1951 − 1980)

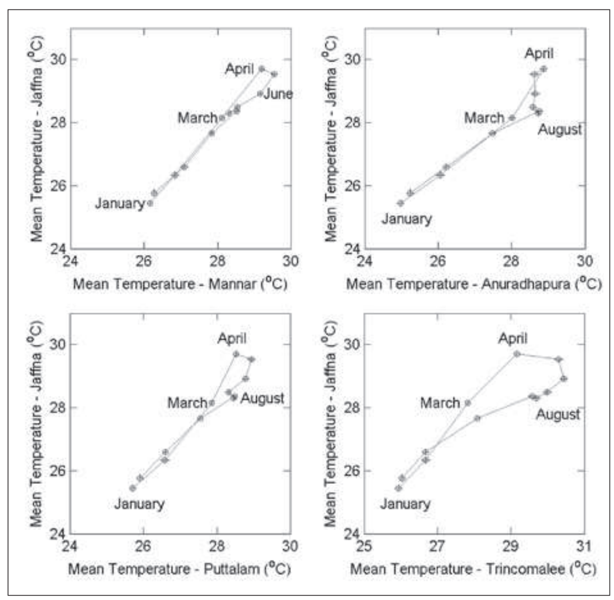

Figure 2: Seasonal correlation of long-term monthly mean temperatures in Jaffna and four neighbouring stations (1951 − 1980)

Jaffna and each of the neighbouring stations Mannar, Anuradhapura, Puttalam and Trincomalee are 0.28, 0.39, 0.38 and 0.48, respectively.

In order to investigate the effect of seasonal temperature variations on standard departures, the correlation between the monthly temperatures at the target station and the neighbouring stations were analysed. The mean monthly temperature variations between the target station and the neighbouring stations are shown in Figure 2. The error bars in the figure represent the error of the mean temperature observed for each month (i.e., σ/√K, where σ is the standard deviation and K is the number of observations). The data showed that, in all five stations in the northern region, Jaffna, Mannar, Anuradhapura, Puttalam and Trincomalee, the mean monthly temperature increases from January and reach a maximum towards the months of April/May/ June and then decreases up to December. The cycle of temperature change during the year is depicted by the solid line connecting the data points.

It can be seen that Jaffna and Mannar have the best agreement compared to the agreement of Jaffna with the other stations. In general, the data points tend to spread outward from the expected linear trend line at high temperatures and come together at lower temperatures. The departure from the linear trend in these graphs, especially at higher temperatures is evident in the difference in standard departures shown in Figure 1.

Table 3: Estimated values of mean shifts necessary to compensate for the seasonal temperature variations between the target station and neighbouring stations

Month	Mean shift ($\bar{\delta}_{n,m}$)			
	Mannar	Anuradhapura	Puttalam	Trincomalee
January	- 0.09	+0.04	+ 0.00	- 0.21
February	- 0.04	- 0.06	- 0.12	- 0.03
March	+ 0.14	- 0.06	+ 0.08	+ 0.58
April	+ 0.29	+ 0.46	+ 0.60	+ 0.89
May	- 0.12	+ 0.51	+ 0.15	+ 0.10
June	- 0.21	+ 0.07	- 0.15	- 0.40
July	+ 0.02	- 0.20	- 0.06	- 0.44
August	+ 0.07	- 0.42	- 0.31	- 0.42
September	- 0.06	- 0.40	- 0.30	- 0.29
October	+ 0.04	- 0.05	+ 0.01	+ 0.09
November	- 0.08	+ 0.03	+ 0.06	+ 0.16
December	+ 0.04	+ 0.09	+ 0.06	- 0.04

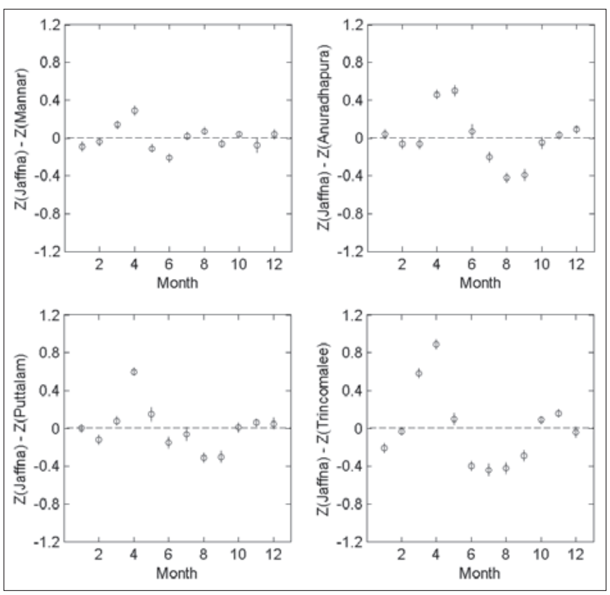

Figure 3: Monthly variation of mean shift in standard departures of temperature observed in Jaffna and neighbouring stations (1951 − 1980). The mean shifts are caused by seasonal temperature variations between the stations. The dotted line is drawn to guide the eye.

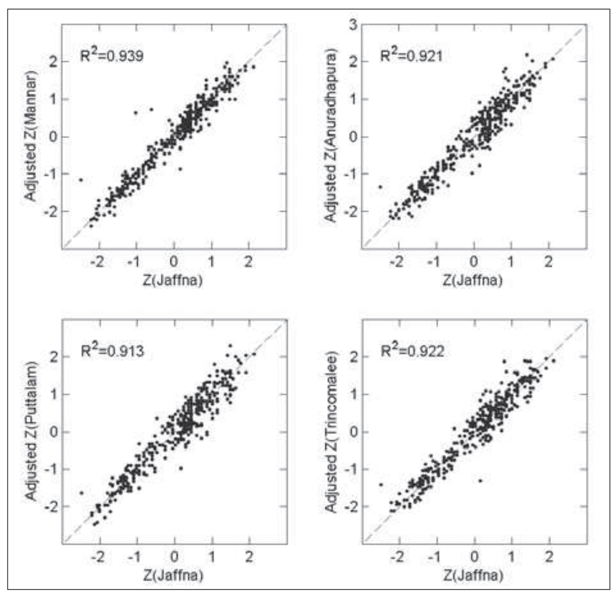

Figure 4: Correlation between standard departures of temperature in Jaffna and adjusted standard departures of temperature in neighbouring stations (1951 − 1980). Adjustments are based on mean shifts calculated for each month separately to compensate for the seasonal effects.

The seasonal temperature correlation is an indicator for the temporal relationship between Jaffna and the other neighbouring stations. A higher positive correlation coefficient will indicate a better estimator for the target station to calculate the missing value.

The seasonal variations show that, in order to obtain the best agreement, an adjustment is necessary for standard departures when estimating the temperature at Jaffna from the neighbouring stations. In order to estimate the monthly mean shift ($\bar{\delta}_{n,m}$) necessary to adjust the standard departures, the difference in standard departures between Jaffna and each of the neighbouring stations was computed by month and depicted in Figure 3. The error bars represent the error in estimating the mean shifts. In general, mean shifts are positive for March and April and negative for August and September. Table 3 shows the estimated values of mean shifts necessary to compensate for the seasonal temperature variations observed between the target station and the neighbouring stations.

As expected, Mannar shows the smallest mean shifts whereas Trincomalee shows the largest. The mean shifts fluctuated between + 0.89 and - 0.44 (mean shifts larger than one standard deviation are underlined in Table 3). The standard deviations of the difference in temperature departures for individual months vary between 0.15 and 0.37, indicating an overall error around ± 0.3. Thus, the results should be improved by adjusting the standard departures of neighbouring stations to compensate for the mean shifts observed for each month.

Figure 4 illustrates the correlation between the Z values of Jaffna and the adjusted Z values after correcting the mean shifts given in Table 3 for all four stations. The dashed line represents the expected 45 degree gradient between the estimated and the observed values. Any departure from this line will indicate an offset. The standard deviation of the difference between the adjusted Z values and the observed values will indicate the accuracy of predicting the missing values. When the whole year is considered, the higher deviation is observed at higher temperature values. Between Jaffna and Mannar, the agreement of the standard departures is within ± 0.5 for 96 % of the cases. The poorest agreement in standard departures, which was seen between Jaffna and Trincomalee stations earlier, improved to having 94 % of the cases within ± 0.5. With this change, the estimated standard deviations σ_i of the difference between standard departures $Z_j - Z_n$ for Jaffna and each of the neighbouring stations Mannar, Anuradhapura, Puttalam and Trincomalee improved to 0.25, 0.29, 0.30 and 0.28, respectively making the temperature correlation between all stations nearly the same. The corresponding weights w_n are, 16, 12, 11 and 13, respectively.

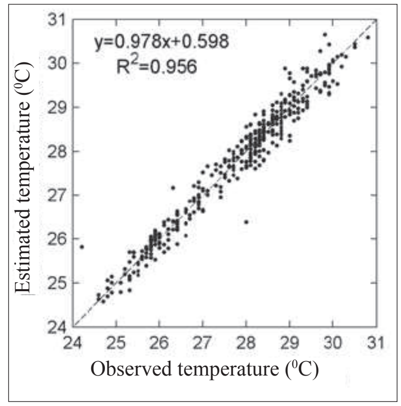

Figure 5: Correlation between observed temperature and estimated temperature in Jaffna (1951 − 1980). The dotted line is the best fit to the data. The standard deviation between observed and estimated temperature difference is 0.3 °C

The correlation between the observed and estimated monthly temperatures in Jaffna is shown in Figure 5. The gradient of the fitted line is 0.98 with a squared correlation of 0.96. The mean monthly temperature $\overline{T_j}$ and standard deviation S_j for Jaffna are 27.8 °C and 1.43 °C, respectively. Over 90 % of the estimated values are within ± 0.5 °C of the actual values. The standard deviation of the difference between the actual and predicted values is 0.30 °C. The data were also tested for any systematic temperature-dependent bias in the estimates. However, no such significant bias was detected. It can be seen that there are a few outliers with large deviations from the expected $x = y$ line. At this point, it is not clear whether they are real or due to some errors in the observations. The accuracy also was tested by using 3 stations instead of 4 stations by systematically removing one station at a time. Even when the Mannar station was not included in the calculation, the error in reconstruction was increased only marginally. This is an indication of the robustness of the proposed model.

In order to compare the accuracy of the refined method with the original method developed by Steurer (1985), the same calculation was repeated without using the means shifts introduced to compensate for seasonal effects and the weights introduced to incorporate the strength of the correlations between the stations (equation 4). The original method produced 0.40 °C as the standard deviation of the difference between the actual and predicted values. Thus, the increased accuracy of the refined method is about 25 %.

The model was used in reconstructing the missing data for Jaffna for the period 1981 − 2000 (Table 4). The

Table 4: Reconstructed missing monthly temperature values in Jaffna based on observations at Mannar, Anuradhapura, Puttalam and Trincomalee stations from 1981 − 2000. From 1991 − 1997 Mannar data were not available and hence remaining three stations have been used. The estimated error in the reconstruction is ± 0.30 °C.

Year	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
1981	25.7	26.5	29.5	30.2	29.7	28.5	28.5	28.4	27.7	27.9	27.0	25.9
1982	25.9	26.7	28.7	30.5	29.6	29.0	28.8	28.9	28.8	27.8	26.9	25.9
1983	26.0	27.4	29.2	31.2	30.5	29.8	29.5	29.1	28.4	28.4	26.7	25.9
1984	25.8	26.0	28.0	29.3	29.9	28.8	27.4	28.0	27.4	27.5	26.4	25.8
1985	26.2	26.6	28.5	30.4	29.8	28.1	28.2	28.3	28.1	28.1	26.2	26.0
1986	25.3	26.6	28.1	30.1	29.8	29.5	28.9	28.2	28.4	27.9	26.8	26.8
1987	26.2	26.4	29.2	30.4	30.0	30.0	29.6	29.2	29.2	27.9	27.4	26.7
1988	26.5	27.3	29.5	29.9	30.6	29.2	28.7	28.5	28.0	28.9	26.6	26.5
1989	26.3	26.3	28.2	30.8	30.4	28.7	28.1	28.6	28.5	28.4	27.1	26.6
1990	25.6	28.0	29.4	31.2	29.6	29.2	28.7	28.3	29.0	28.3	27.3	26.2
1991	26.2	26.8	29.2	30.4	30.7	28.7	29.1	29.1	29.3	27.9	26.9	26.3
1992	25.9	26.9	28.7	30.7	29.8	29.1	28.6	28.6	28.5	27.8	27.0	25.6
1993	25.8	27.1	28.7	30.1	29.9	29.4	28.4	28.8	28.9	27.8	26.6	25.7
1994	26.0	26.6	28.4	30.1	30.5	29.3	29.0	28.9	28.8	27.3	26.7	26.2
1995	26.3	27.0	29.0	29.8	29.8	29.5	29.1	28.8	29.2	28.9	27.2	26.4
1996	26.5	27.0	29.1	30.2	30.9	28.6	28.9	28.6	28.2	28.0	27.2	26.1
1997	26.3	27.1	29.2	30.6	30.3	29.6	29.8	29.5	28.9	28.4	27.6	27.5
1998	27.2	28.6	30.1	31.9	30.8	30.4	29.3	28.9	29.0	29.0	27.8	26.6
1999	25.8	27.4	29.0	29.8	29.8	28.9	29.0	29.0	29.3	27.7	27.3	26.2
2000	26.1	27.2	28.4	30.5	30.7	29.1	29.2	28.3	28.4	28.2	27.3	26.4

error in the reconstructed data was ± 0.3 °C. Since the data from Mannar was not available during the period from 1991 − 1997, data from the remaining stations were used to reconstruct the Jaffna monthly temperature values for this period. The same technique can be applied to reconstruct the missing data or validate the observations in Mannar or any other station in the region.

CONCLUSION

In this study, results on the reconstruction of missing monthly temperature data at the Jaffna meteorological station during the period from 1981 − 2000 are presented. The estimates are based on the temperature departures from their standard normal at the stations in the same geographical region. It is shown that monthly temperature data at Jaffna can be estimated with an accuracy of ± 0.3 °C using 30 years of temperature data recorded in the meteorological stations at Mannar, Anuradhapura, Trincomalee and Puttalam. The method allows the user to estimate the temperature with the available observations even if some observations are missing in the nearby stations. In estimating the monthly temperature in Jaffna, the observations in Mannar play a vital role and it has the best temporal correlation with Jaffna. The observations at stations other than Mannar show some seasonal effects. It is shown that by calculating the mean shifts to compensate for the seasonal variations and using weights corresponding to the strength of the correlations between the target and neighbouring stations, the estimation can be improved. The results show that 91 % of the estimated values are within the range of ± 0.5 °C of the actual values.

Although this method can be applied to any region having a cluster of meteorological stations, it has been shown elsewhere (Huth & Nemesova, 1995) that the results can be improved by using techniques such as the principal component analysis and the cluster analysis to classify and identify stations belonging to the same climate divisions. The mean shifts used in this paper allow users to combine data from stations in a wider geographical area. Currently we are in the process of developing a technique to estimate missing daily maximum and minimum temperature in Jaffna using artificial neural networks.

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