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Analysis of temperature series: estimation of missing data and homogeneity test

Mahmut Firat,[a]* Fatih Dikbas,[b] A. Cem Koc[b] and Mahmud Gungor[b]
[a] *Faculty of Engineering, Civil Engineering Department, Inonu University, 44258 Malatya, Turkey*
[b] *Faculty of Engineering, Civil Engineering Department, Pamukkale University, 20017 Denizli, Turkey*

ABSTRACT: In this study, missing value analysis and homogeneity tests were applied on the 267 meteorological stations having temperature records throughout Turkey. The monthly and annual mean temperature data of stations operated by the Turkish State Meteorological Service (DMI) for the period 1968–1998 were considered. For each station, each month was analysed separately and the stations with more than 5 years missing values were eliminated. The missing values of the stations were extrapolated by the Expectation Maximization (EM) method using the data of the nearest gauging station (reference station). In consequence of the analysis, annual mean temperature data are obtained by using the monthly values. These data have to be hydrologically/statistically reliable if they are to be used in later hydrological, meteorological, climate change and estimation studies. For this reason, the Standard Normal Homogeneity Test (SNHT), the (Swed-Eisenhart) Runs Test and the Pettitt homogeneity test were applied to detect inhomogeneities in the annual mean temperature series. Each test was evaluated separately and inhomogeneous stations were determined.

KEY WORDS monthly mean temperature; annual mean temperature; estimation of missing temperature data; EM method; homogeneity test; SNHT

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1. Introduction

The accuracy and reliability of the model results in climate change studies, classification, flood and drought modelling, water resources planning and modelling related to hydrology and meteorology varies according to the quality of the data used. Inhomogeneities may occur in time series of meteorological observations due to changes in the methodology used, the conditions around the station and the reliability of the measurement tool. An homogeneous climate series may be defined as a series only influenced by the variations in climate. For this reason, the data taken from the observation stations should be tested for reliability and homogeneity prior to their use in the research studies. The data length and missing values in the stations to be used in regional studies, the number of stations representing the area and the quality of the data are also very important in the development of an accurate model. For a better representation of an area it is important to complete the series of the stations having missing values due to various reasons. Many methods, such as time series models, Markov models, multiple regression models, the nearest neighbour (KN) algorithm, neural networks and genetic algorithms are proposed in the literature for missing data analysis. Ustaoglu *et al*. (2008) applied three different artificial neural network (ANN) methods to forecast daily mean, maximum and minimum temperature time series.

In the present study the Expectation Maximization (EM) algorithm is used for completing the series of stations with missing values. The EM algorithm combines statistical methodology with algorithmic applications and it receives interest in the solution of missing value problems (Dempster *et al*., 1977). The EM algorithm is a general method for incomplete data and it provides a best estimate of the missing value and the unknown parameters of a data model. In the application of this method, the missing values are initially calculated by using the estimated model parameters. Nelwamondo *et al*. (2007) carried out a comparative study by using artificial neural networks and EM method for completing missing values. Schneider (2001) used the EM method for the completion and analysis of the missing values in climate series. Kim and Ahn (2009) applied the EM method to forecast the missing values in daily precipitation series. They recommended that the EM method can be applied successfully for missing data analysis.

The homogeneity tests of time series may be classified in two groups as the 'absolute method' and the 'relative method'. In the first method, the test is applied for each station separately. In the second method, the neighbouring (reference) stations are also used in the testing (Wijngaard *et al*., 2003). In the present study, the absolute method is used for testing homogeneity because the temperature observations in a very wide area are

* Correspondence to: M. Firat, Faculty of Engineering, Civil Engineering Department, Inonu University, 44258 Malatya, Turkey.
E-mail: mfirat@gmail.com

used and missing values exist. In the literature, many methods have been proposed for testing the homogeneity of meteorological variables such as precipitation and temperature (Ducré-Rubitaille *et al.*, 2003; Klingbjer and Moberg, 2003; Tomozeiu *et al.*, 2005; Staudt *et al.*, 2007; Modarres, 2008). Wijngaard *et al.* (2003) used the Standard Normal Homogeneity Test (SNHT), Buishand test, the Pettitt test and the Von Neumann test for testing the homogeneity of daily precipitation and temperature series.

Mihajlovic (2006) used the SNHT method to test the homogeneity of monthly total precipitation series used in analysis. Hanssen-Bauer and Førland (1994) applied homogeneity analysis on the 75 year precipitation series of 165 stations in Norway by using the SNHT method. Tayanc *et al.* (1998) carried out a comparative evaluation by using the Kruskall–Wallis and Wald–Wolfz methods to determine the inhomogeneous structure in the Turkish temperature series. Slonosky *et al.* (1999) used various methods to test the homogeneity of surface pressure series of 51 stations with long observation periods in Europe. In that study, it was stated that the SNHT method shows a very good performance when a suitable reference series is obtained for comparison-evaluation and correction. Tuomenvirta *et al.* (2000) used the SNHT method to test the reliability and homogeneity of the monthly maximum and minimum temperature series. Yıldırım *et al.* (2004) tested the homogeneity of precipitation and riverflow series by using the Kruskall–Wallis method in their study. Freiwan and Kadiodlu (2008) used the annual, seasonal and monthly maximum and minimum precipitation series to analyse climate change in Jordan. The Runs test was applied before the analysis to test the homogeneities of the annual, seasonal and monthly precipitation series.

The main purposes of the present study are: (1) to complete missing values in the temperature series recorded by meteorological gauging stations, and, (2) to detect inhomogeneities in temperature series of meteorological stations to obtain reliable climatic data for future studies such as climate change, classification, flood and drought modelling, water resources planning, and modelling related to hydrology and meteorology. The monthly total temperature values are considered to complete the missing values using the EM method. The SNHT, Swed-Eisenhart Runs and Pettitt tests were used to detect the inhomogeneities in temperature series. The inhomogeneous temperature series were determined by comparing the results of all three methods and making a general evaluation throughout Turkey.

2. Expectation maximization (EM) method

The EM algorithm, proposed by Dempster *et al.* (1977) to solve the problems faced in the maximum likelihood methods, combines statistical methodology with algorithmic application and it receives attention for the solution of various missing value problems. The EM algorithm is an iterative method to estimate unknown parameters of the data model. Finding the model parameters is easy when the missing values are known. Similarly, when the parameters are known, it is possible to make estimations for the missing values. The EM algorithm was proposed based on the reciprocal dependence between the model parameters and the missing values. If the data space is properly chosen, the EM algorithm can estimate the missing data values effectively. The EM algorithm consists of two main steps: the conditional expectation step (called E-step) and the maximization step (called the M-step). The E-step calculates the conditional expectations of missing data given observed data and estimates of model parameters. The M-step finds the estimates of the model parameter to maximize complete – data log likelihood function from the E-step. These steps are iterated until the iterations converge (Schneider, 2001). The EM algorithm alternates the expectation and maximization steps for updating the estimate, θ_n, of the unknown parameters θ at iteration. The conditional expectations of missing data in observed series and estimates of model parameters in the E-step are calculated by Equation (1):

$$Q(\theta_0|\theta_n) = E_{Z|x,\theta_n}[\log L(\theta; x, z)] \quad (1)$$

where, $L(\theta; x, z)$ is the likelihood function, θ is the parameter vector, θ_n is the estimate of the model parameters, x is observed data, z is the missing data. In the M-step, the model parameters can be calculated using Equation (2) to maximize complete–data log likelihood function from the E-step:

$$\theta^* = \arg_\theta \max Q(\theta|\theta_n) \quad (2)$$

The flow chart for the EM algorithm is demonstrated in Figure 1.

3. Homogeneity test

The quality and reliability of the data obtained from the meteorological stations depend on many factors. Meteorological gauging stations are influenced by the location of the station, the tool and method used and the observation quality, and the time series might gain an inhomogeneous structure. For this reason, the reliability and quality of the data to be used in the modelling of hydrology and water resources processes should be tested statistically. It can be stated that the natural structure of the observation values is not deteriorated when the precipitation time series has an homogenous structure. The homogeneity methods such as the 'absolute method' and 'relative method' are used to detect the inhomogeneities in time series. In the second method, neighbouring (reference) stations are used for the testing process (Wijngaard *et al.*, 2003), but it is very difficult to find reference stations with a high correlation and

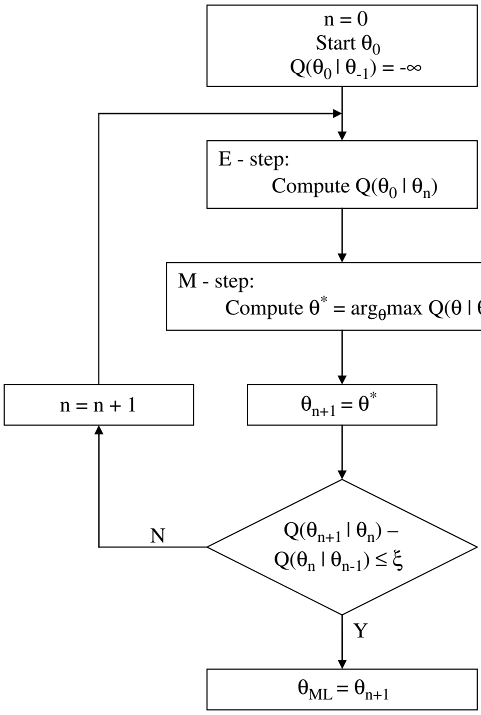

Figure 1. The flow chart for EM algorithm.

an homogeneous structure in the studies covering very wide regions (Tayanc *et al*., 1998). For this reason, in the present study in which the temperature gauging stations throughout Turkey covering a very broad area, are used and there are missing observation records, the first test is used for homogeneity.

The Standard Normal Homogeneity Test (SNHT), (Swed-Eisenhart) Run and Pettitt tests are used for the determination of the inhomogeneous temperature series for the annual total temperature values of the stations making observations throughout Turkey. The SNHT was proposed by Alexandersson (1986) to determine inhomogeneous structure in time series. The SNHT detects the inhomogeneous structures at the beginning and/or towards the end of the series. The mathematical structure and detail of the SNHT method can be obtained from several studies (Alexandersson, 1986; Alexandersson and Moberg, 1997; Gonzalez-Rouco *et al*., 2001). The Pettit test is a nonparametric test that detects one change point the observed time series and more sensitive to detect the inhomogeneous structures in middle of the time series. The Swed and Eisenhart (1943) Run test is a non-parametric procedure used in determining a time series (Deniz *et al*., 2011). To apply the Run test for time series data, first a critical value is determined. For meteorological data the median is generally used as the critical value. Higher and lower values than the critical value of the time series are then determined. Upper values signed as positive and lower values are signed as negative. The number of changes between the positive and negative values is called the run and runs should satisfy the normal distribution.

4. Study area and available data

The monthly annual temperatures recorded at meteorological stations located in Turkey were used in this study. Turkey is situated over a transition region between polar and tropical air masses with Mediterranean climate characteristics in a subtropical climate zone. The temperature difference between summer and winter is high, the precipitation generally occurs in spring and winter and dry periods dominate summers. The annual mean temperature, which is between 3.6 and 20.1 °C, depends on location and elevation (Deniz *et al*., 2011). The temperature series measured at 267 meteorological stations operated by the Turkish State Meteorological Service (DMI) throughout Turkey for the period 1968–1998 was used to complete the missing values and to detect the inhomogeneities. This time range was determined by evaluating the records of the stations for using as much stations as possible. Monthly mean temperature records are obtained by daily mean temperature data at the stations. Similarly, the annual mean temperature data are calculated by using monthly mean temperature data. The geographical locations of stations are shown in Figure 2a.

5. Results and discussion

5.1. Missing value analysis

In the first phase of this study, the missing values in the series of meteorological stations were determined and they were completed by using the EM algorithm. To complete the missing values, the nearest neighbouring stations to the station with missing values are used. For this, each month of the year is evaluated separately and estimations were made by using the long year monthly mean series of the station with missing values and the neighbouring station. The results of the estimation are evaluated by looking at the correlation coefficient and the runs of the time series of the estimated and neighbouring stations.

In the scope of this study, because of space restrictions, only the steps for the completion of the missing values of Bandırma station (station no 17114) located in western Turkey are given (Figure 2b). It was determined that the monthly total temperature values between 1 January and 31 December 1973 are missing in this station. For completing the missing temperature values of station 17114, each neighbouring station was evaluated one by one to find the most suitable reference station. For this, the missing value situations of the neighbouring stations and the correlations between the data of the station 17114 and its neighbours were evaluated. According to the criteria above, the Balıkesir station (station no 17152) was chosen as a reference station for completing the missing values in station 17114. The comparison of the monthly mean temperature series of the stations 17114 (Bandırma) and 17152 (Balıkesir) is given in Figure 3 and estimations for each month are made separately.

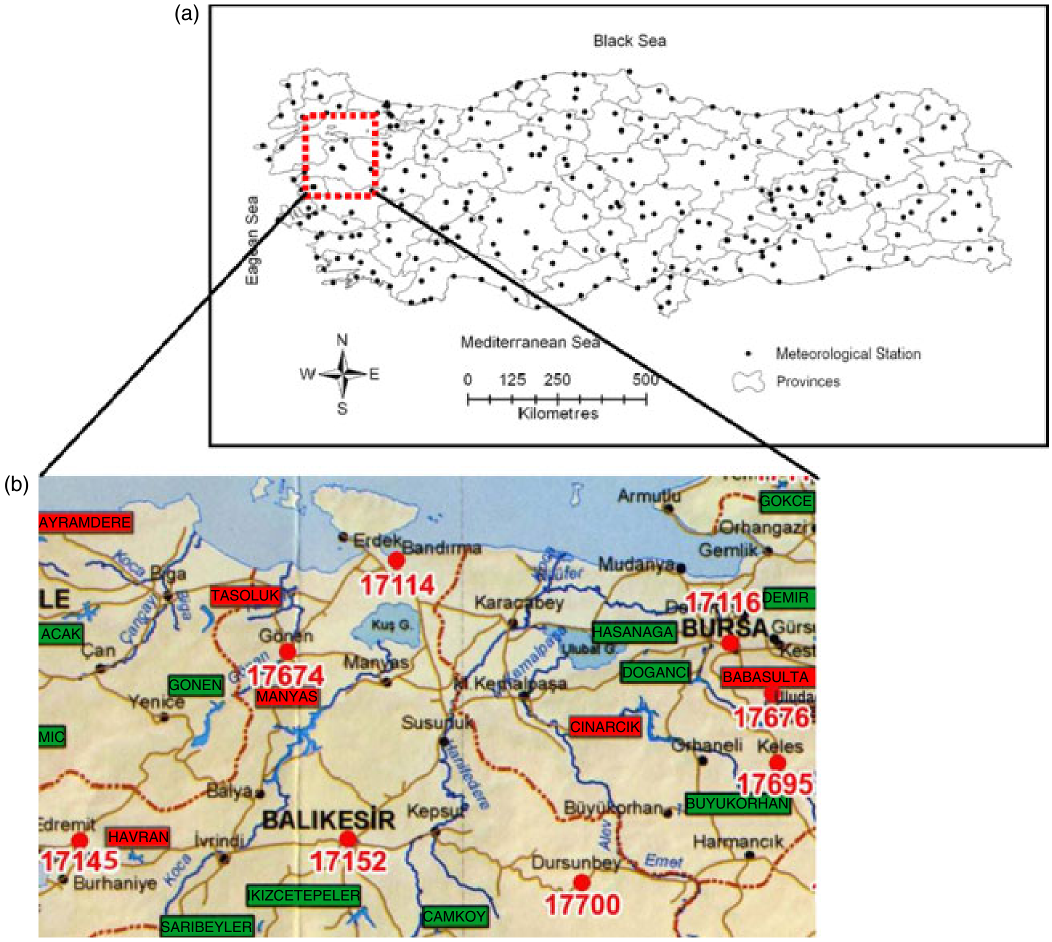

Figure 2. (a) The locations of meteorological stations. (b) The locations of 17 114 (Bandırma) and 17 152 (Balıkesir) stations. This figure is available in colour online at wileyonlinelibrary.com/journal/met

Similarly, the same process is repeated for the remaining months and the missing values are completed. For evaluating the performance and results of the EM method in the completion of missing values of 1973 water year at station 17114, the data between 1995 and 1998, which is testing data set 1, were used as test data. The performance of the EM method for testing this data set were evaluated according to statistical criteria such as, correlation coefficient (CORR), Efficiency (E), and Normalized Root Mean Square Error (NRMSE) given Equations (3) and (4):

$$\mathrm{NRMSE} = \frac{\left[\sum_{i=1}^{N} \frac{(\mathrm{WD}_{Y_i} - \mathrm{WD}_{D_i})^2}{N}\right]^{0.5}}{(1/N)(\sum_{i=1}^{N}(\mathrm{WD}_{D_i}))} \tag{3}$$

$$E = \frac{E_1 - E_2}{E_1} \quad E_1 = \sum_{t=1}^{N}(\mathrm{WD}_D - \overline{\mathrm{WD}_D})^2,$$

$$E_2 = \sum_{t=1}^{N}(\mathrm{WD}_Y - \mathrm{WD}_D)^2 \tag{4}$$

where N is the number of records, WD_Y is the estimated temperature, WD_D is the field observed temperature, $\overline{\mathrm{WD}_D}$ is the average of the monthly temperature. The CORR is a commonly used statistic and provides information on the strength of linear relationship between the observed and the computed values. The E parameter is one of the widely employed statistics to evaluate model performance. The values of CORR and E close to 1.0 indicate good model performance. The NRMSE statistic indicates a model's ability to predict a value away from the mean.

The performance evaluation criteria calculated for testing data set 1 were indicated in Table I. Also, the results obtained with the EM method for the flow observations in 1973 were compared and evaluated for stations 17114 and 17152. Figure 4(a) shows the estimation results of the EM method for the 1995–1998 period comparatively. As can be seen in Figure 4(a), the EM method has a good performance for the test data set. The data estimated by the EM method are in very good agreement with the observation data. Here, firstly, the testing of the model performance with the test data set was accomplished. It can be seen in Table I, the values of CORR and E are very close to unity and the value of NRMSE is very small. According to these criteria, the EM method has shown a good performance for testing data set.

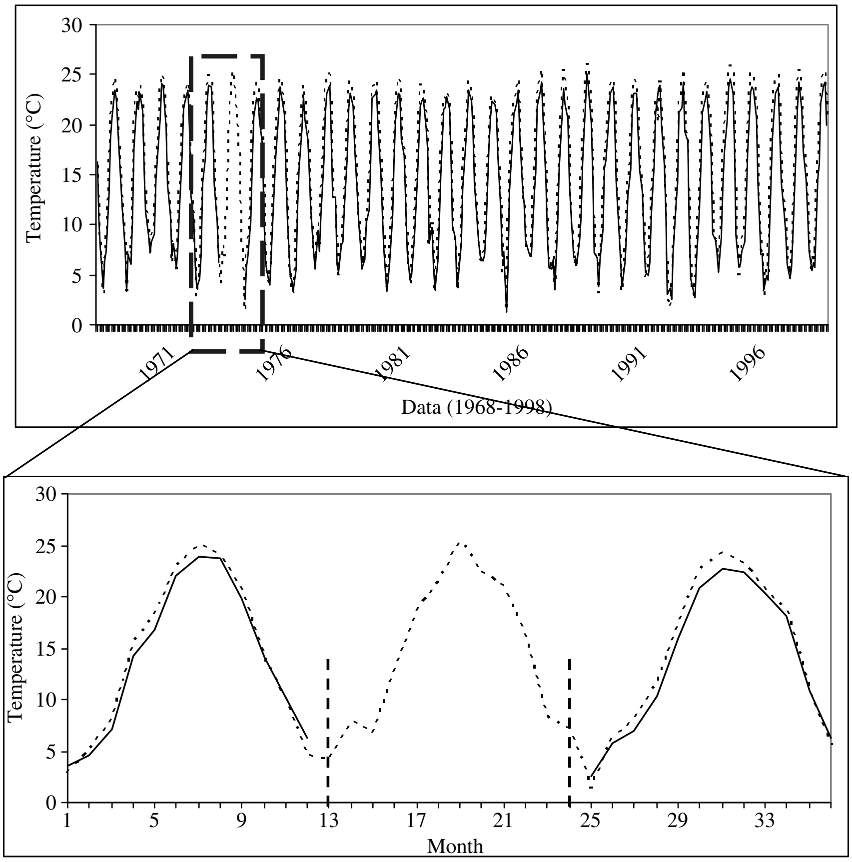

Figure 3. Monthly mean temperature series of the stations 17 114 and 17 152.

Table I. Model performances for the test data sets.

Testing set	Method	Criteria		
		NRMSE	E	CORR
Testing set I	EM	0.505	0.988	0.995
Testing set II	EM	0.054	0.979	0.987

Secondly, half of the total data set (between 1968 and 1983, with 15 years data length, data of 1973 missing) was used in the construction of the model, and the remaining half (between 1984 and 1995, with 15 years data length), which is testing data set 2, was used in the testing of the EM method. Performance evaluation criteria for the test data set 2 are calculated and given in Table I. It can be seen from the results that the CORR and *E* values calculated for both testing data sets are very close to each other, but the NMRSE value calculated for the test data set 2 is lower than the value for test data set 1. Figure 4(b) shows the comparison of the EM method results and observation values for the test data set 2. According to this result, as the results obtained for both of the test data sets are very close to each other, the results obtained for the first data set are used in the remaining sections. After testing the performance of the model with these evaluations, the missing data of 1973 are estimated. Figure 5 shows the comparison of the results of the EM method for the station 17114 with the observed values of the station 17152 in 1973.

As can be seen from the figure, there is a good correspondence between the estimated values of station 17114 and the observed temperature values covering 1 January to 31 December 1973. Also, after the estimation, the correlation between the two stations is calculated. Figure 5 shows the correlations obtained for each month after the process of missing value completion made between the stations 17114 and 17152. It can be said that the EM method has shown good performance in the completion of the missing values in the monthly mean temperature data. As a result of the analysis, 38 stations were eliminated because they had missing values for more than 5 years. In the investigation of the temperature data, no missing values were found in 124 temperature series but missing values were detected and completed for the remaining 105 stations. In Figure 6, the stations having no missing values, the stations of which the missing values were completed and the stations having too many missing values are shown on the same map.

Figure 6 shows that a majority of the stations with missing values are found in eastern Turkey. Similarly, the eliminated stations, because they have too many missing values, are also generally in the eastern part of Turkey. In the completion of the missing values, the distance between the stations to be completed and to be used in the completion, geographical location, the climate properties

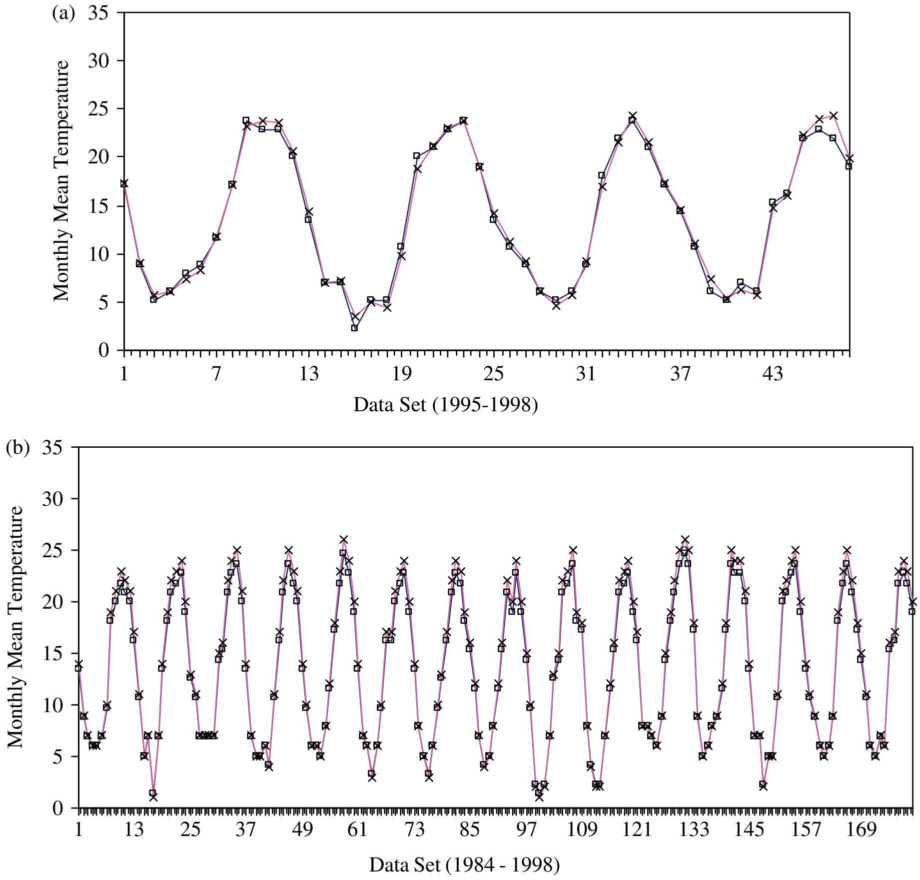

Figure 4. Comparison of results of EM and observations. This figure is available in colour online at wileyonlinelibrary.com/journal/met

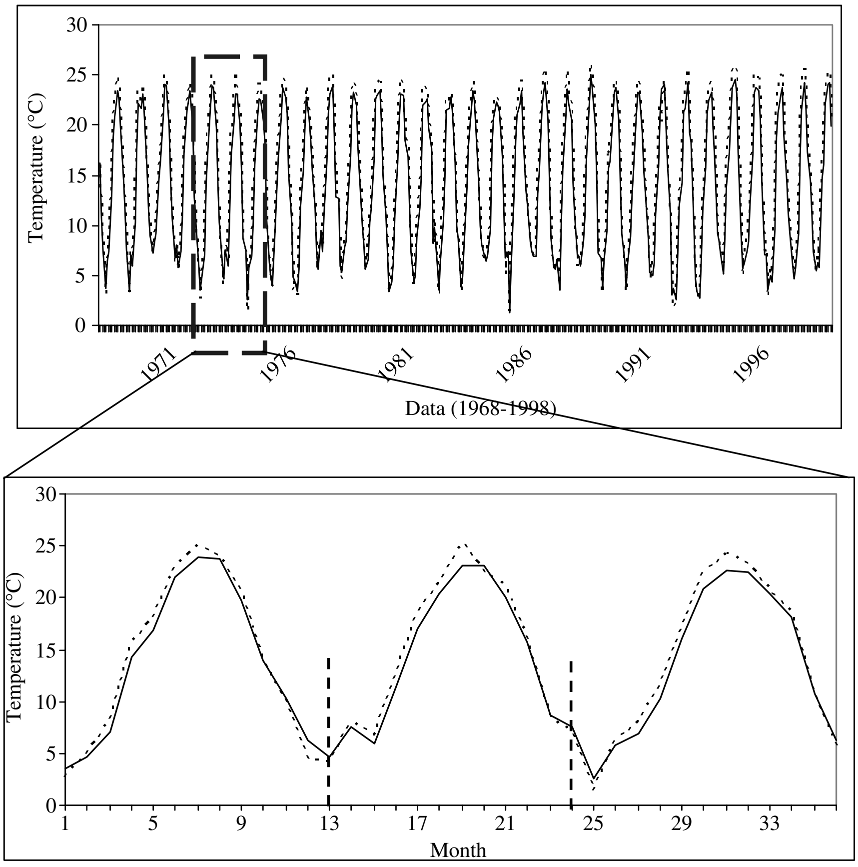

Figure 5. Comparison of the temperature series of the completed and neighbouring station.

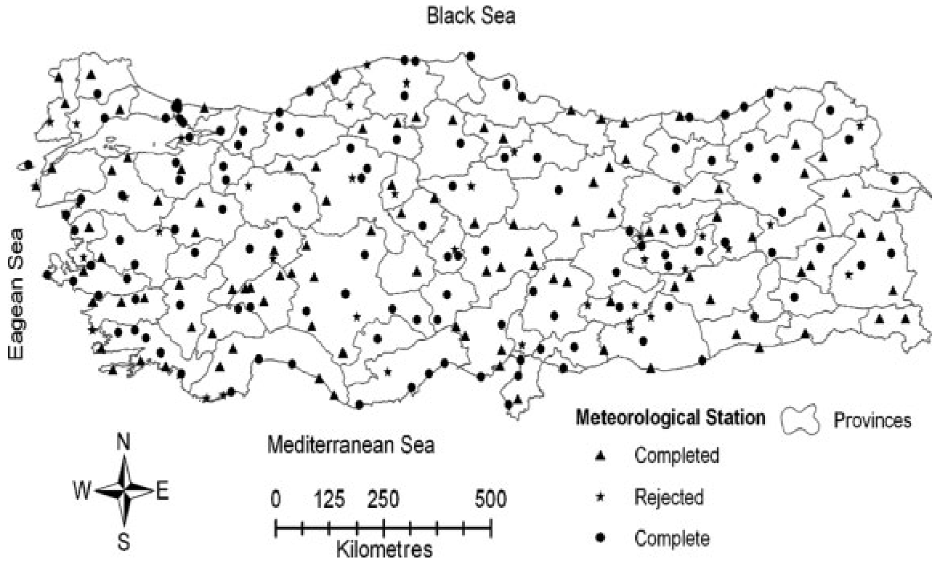

Figure 6. The distribution of the stations after the completion of the missing values.

of the location of the station are quite important for the model results. Especially, in the Central Anatolian region where arid climate is effective, it was very hard to find suitable reference stations for completing the missing values in summer months. After making completions with the EM method for each station, the obtained results are evaluated by calculating correlations and by comparing the runs of the series of both stations. According to the obtained results, it is thought and proposed that the EM method can successfully be used for completing the missing values in temperature series. After completing the missing values annual mean temperature values are calculated and homogeneity tests started.

5.2. Homogeneity test

As stated above, the homogeneity of the annual mean temperature series of the stations throughout Turkey were tested for the whole 1968–1998 period. The annual mean temperature series for 229 stations were calculated by using monthly data. The SNHT, Swed-Eisenhart Runs and Pettitt tests were applied separately to detect the inhomogeneities in the temperature time series. The results of each method were evaluated for a significance level of 95% and the break years were determined. The evaluation of the SNHT results and the details of the criteria to be considered in the determination of the inhomogeneous series or years are given in the study made by Khaliq and Quarda (2007). Table II shows the list of inhomogeneous stations and the comparative test statistics calculated by the three methods.

In Table II, it is seen that the number of stations passing the critical test value at a 95% significance level as a result of the application of the Pettitt test has been 24. The results shown in the table indicate that the inhomogeneous structure is generally observed between 1983 and 1987, and in 1994. As can be seen from the table, an inhomogeneous structure was detected in 1994 at eight stations, in 1983 at three stations, in 1984 at three stations and in 1985 at three stations by using the Pettitt test. Table II shows that only six stations are found to be inhomogeneous as a result of the Runs test. It can be stated from the evaluation of the results given in Table II that the SNHT and Pettitt methods are more precise than the Swed-Eisenhart test in the determination of inhomogeneity.

Table II shows that data at 26 stations were found to be inhomogeneous as a result of the application of the SNHT method, at a significance level of 95%. In the evaluation of the SNHT results, the stations with a test statistic higher than 7.54 are considered to be inhomogeneous for a 31 year data series. The table shows that the inhomogeneity was detected at three stations in 1976, four in 1992, eight stations in 1994 and at six stations between 1983 and 1988.

It is also seen in the table that in some stations both the SNHT and Pettitt tests detected inhomogeneity in the same year. Inhomogeneous structure was detected by both of the tests in 1994 for stations 17 172, 17 237, 17 248, 17 296, 17 340, 17 375, 17 676 and 17 872. It is seen from the map that these stations are in the same region. It can be deduced from these findings that the inhomogeneous structure might be related to the variations of natural meteorological conditions. Figures 7 and 8 show the locations of the homogeneous and inhomogeneous stations determined by the application of the SNHT and Pettitt methods, respectively.

Figure 7 shows that inhomogeneity was detected in 1994 at stations 17 296, 17 237 and 17 375, which are close to each other and located in western Turkey. Similarly, the series of the stations 17 248, 17 330 and 17 340 located in southern Turkey were found to be inhomogeneous in 1994. Also, the years in which homogeneity deteriorated are between 1985 and 1987 at stations 17 750, 17 884, 17 926, 17 992 located in western Turkey. According to these results, it can be thought that the

Table II. Comparison of results of methods at 95% significance level.

Break year (test statistics) at 95% significance level							
Station Number	SNHT	Pettitt	Runs test	Station Number	SNHT	Pettitt	Runs test
17 096	1988 (14.34)	1988 (160)	–	17 835	1982 (10.11)	1982 (152)	–
17 172	1994 (7.60)	1994 (160)	–	17 850	1984 (150)	–	–
17 237	1994 (8.9)	1994 (41)	–	17 872	1994 (9.74)	1994 (144)	–
17 248	1994 (7.98)	1994 (130)	–	17 882	1985 (15.88)	1983 (192)	−2.16
17 261	1977 (7.65)	1977 (134)	–	17 884	1986 (7.8)	1985 (164)	–
17 282		1994 (32)	–	17 922	–	1985 (130)	–
17 296	1994 (8.3)	1994 (148)	–	17 926	–	1987 (124)	–
17 298	–	1984 (128)	–	17 830	1992 (8.20)	–	–
17 300	1976 (14.76)	1976 (164)	–	17 668	1992 (7.66)	–	–
17 310	–	1984 (170)	–	17 812	1982 (8.12)		–
17 330	1992 (7.85)	1994 (130)	–	17 820	1972 (8.82)	–	–
17 340	1994 (13.74)	1994 (85)	–	17 676	1994 (9.36)		–
17 375	1994 (11.61)	1984 (178)	–	17 906	1992 (7.60)	–	–
17 606	1976 (7.7)		–	17 920	1979 (10.2)	–	–
17 622	1983 (8.23)	1983 (130)	–	17 114	–	–	2.2
17 628	1987 (8.81)	1983 (126)	–	17 050	–	–	2.2
17 648	–	1977 (136)	–	17 054	–	–	2.2
17 750	–	1985 (152)	–	17 112	–	–	2.2
17 810	1982 (8.47)	1982 (136)	–	17 056	–	–	2.2

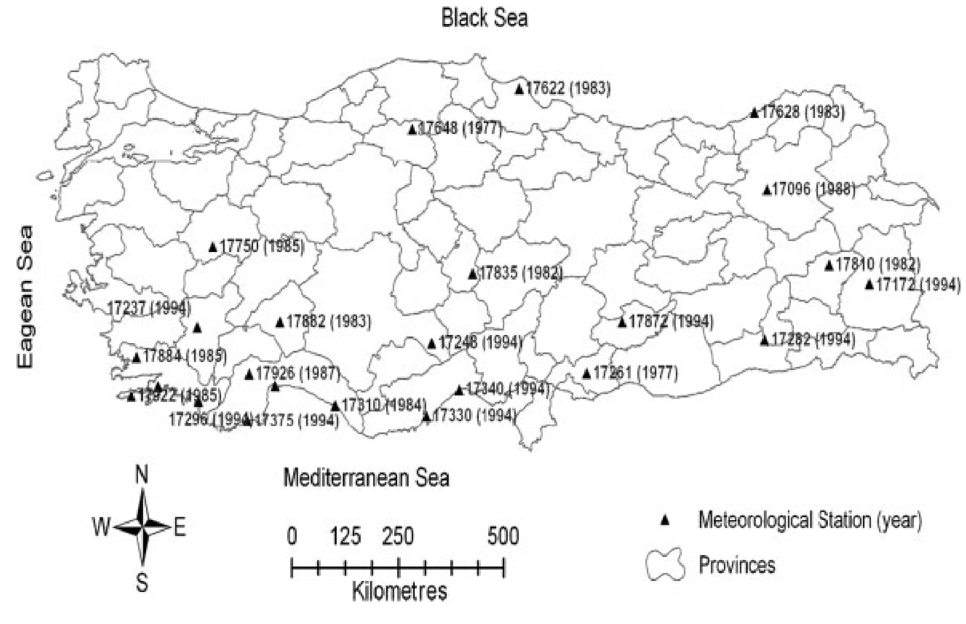

Figure 7. Homogeneity test results of Pettitt test for temperature series (the inhomogeneous stations and years).

inhomogeneous structure detected in the same year for the stations which are close to each other might be related to climatic variations.

Figure 7 shows the break years in stations 17 248, 17 296, 17 330, 17 340, 17 375 and 17 906 located in southern Turkey. Similarly it was determined that there is inhomogeneity between 1985 and 1986 at stations 17 850, 17 882 and 17 884 located in the same region. Inhomogeneity was also determined in 1982 at the neighbouring stations 17 810 and 17 812 located in eastern Turkey.

Figures 7 and 8 also show that there are homogeneous stations around the inhomogeneous stations. Inhomogeneity was not detected in other neighbouring stations for the year in which inhomogeneity was detected. According to these results, it can be stated that the inhomogeneity of these stations are not caused by climatic variation but by other environmental conditions.

In this study, three different methods were used for testing the homogeneity of annual mean temperature series. With the application of these methods, inhomogeneous structures were detected in 38 stations of which the natural structures were deteriorated due to various reasons. In Table II, it is possible to compare the sensitivity of tests for detecting inhomogeneity. The detected breaks

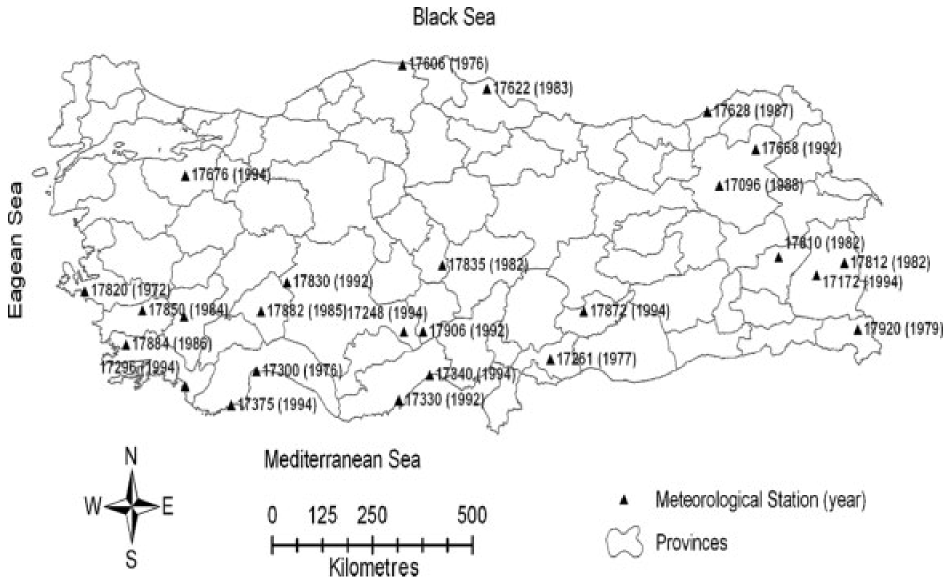

Figure 8. Homogeneity test results of SNHT method for temperature series (the inhomogeneous stations and years).

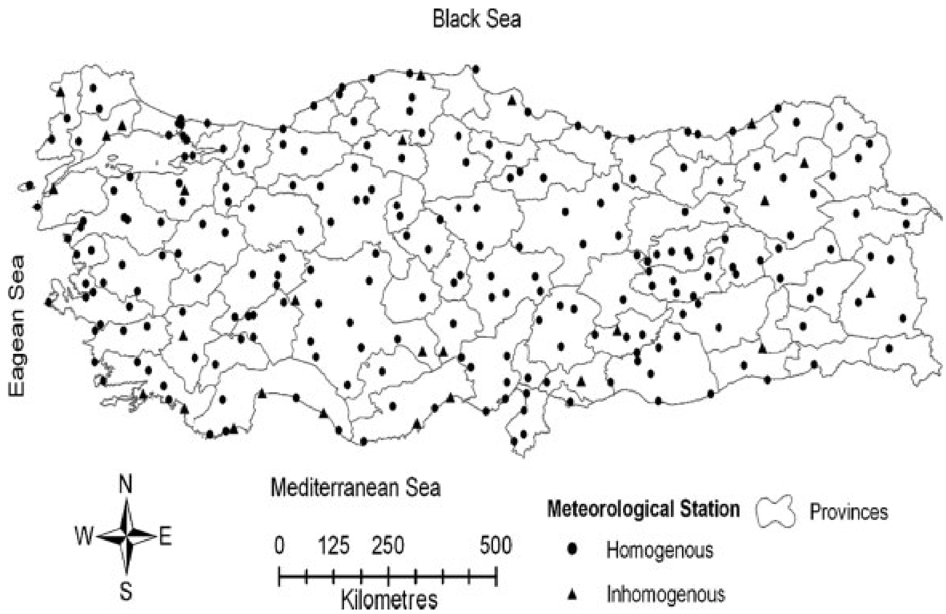

Figure 9. The stations with and without homogeneous structure according to the homogeneity tests.

captured by the Pettitt test appeared in the middle of the 1968–1998 period, whereas the results of SNHT indicate the inhomogeneities which mostly appeared at the beginning or end of the records (Martinez *et al*., 2010).

In conclusion of the missing value analysis and homogeneity tests, 38 of 267 stations were eliminated because they had too many missing values. On the other hand, no missing values were found in 124 temperature stations but missing values were detected and completed for the remaining 105 stations. After the missing value analysis, homogeneity tests were applied for 229 stations and it was detected that homogeneity was lost in 38 stations and inhomogeneous structure was not detected in the remaining 191 stations. The locations of these homogeneous and inhomogeneous stations are shown together in the map in Figure 9.

As a result of this study it was experienced that the SNHT and Pettitt tests give more precise results in the determination of the inhomogeneous structure of temperature series. The results show that the SNHT and Pettitt tests can be successfully applied in the determination of the inhomogeneous structure in series. It is also thought that the outputs obtained from this study will constitute a reference for the studies to be made in Turkey on hydrology and meteorology.

6. Conclusions

In this study, missing value analysis and homogeneity tests were applied for the temperature series of 267 meteorological stations operated by DMI throughout Turkey for the period 1968–1998. Firstly, the missing values in the series were determined, and then the missing values in the temperature series were completed by using the EM method. For the completion of the missing values, the series of the nearest neighbouring stations were used. The results of estimation were evaluated and decisions were made by examining the correlation co-efficients and the runs of the series of the estimated station and the neighbouring station. In the analysis, 38 stations were eliminated because they had missing values for more than 5 years, 124 stations had no missing values and missing temperature values were completed in the remaining 105 stations. The results showed that the EM method can be successfully applied to complete the missing values in the series. In the second phase of the study, homogeneity tests were applied using the Standard Normal Homogeneity Test (SNHT), and Pettitt and Swed-Eisenhart Runs tests to detect the inhomogeneities in the annual mean temperature series. The results of each of the above testing methods were evaluated separately and the break years in the series were determined at a significance level of 95%. At a significance level of 95%, inhomogeneous structure was detected in 26 stations with the application of the SNHT method on annual mean temperature series. It was also determined as a result of the application of the Pettitt test that the number of stations passing the critical test values is 24 at a significance level of 95%. The application of the Swed-Eisenhart Runs test indicated inhomogeneity in only six stations. With the application of the aforementioned methods, inhomogeneity was detected in data from 38 stations of which the natural characteristics were deteriorated by various reasons and 191 stations were found to be homogeneous. As a result of the study, it was seen that the SNHT and Pettitt tests are more sensitive in the determination of inhomogeneity in series. The obtained results show that these methods can be used successfully in the homogeneity tests of temperature series. It is also our opinion that the outputs of this study will constitute a reference for the studies in Turkey on hydrology and meteorology.

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