VARIATIONS AND TRENDS IN TURKISH SEASONAL HEATING AND COOLING DEGREE-DAYS

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Abstract. The potential effect of climate change on energy demand is important especially for the developing and non-oil-producing countries. Cooling and heating degree-day (CDD and HDD) concepts are among the most significant meteorological variables related to residential energy consumption. This paper presents the spatial and temporal characteristics of Turkish seasonal CDD and HDD in the context of climate change. CDD and HDD are defined objectively by truncation of the temperature series at any constant base temperature level. This leads to surpluses and deficits as deviations. The surpluses are instances for cooling and the deficits for heating. Depending on temperature fluctuations, the degree-day statistics at any location show local and seasonal variations. In this study, regional variations of seasonal HDD and CDD are mapped for Turkey and their relations to local topography and climatic features are examined with conclusive interpretations. The sequential version of Mann–Kendall rank statistic is applied to demonstrate any existence of possible nonlinear trends in accumulated HDD and CDD over the seasons. Spatially coherent and statistically significant trends of HDD and CDD appear in some regions of Turkey. In general, the sign of the trends is inconsistent with General Circulation Models (GCM) predictions.

1. Introduction

Spatial and temporal variations of temperature influence many human activities such as agriculture, architecture, power generation and use, melting of snow that supports water resources and the effects of freezing and icing on transportation systems, flowering and harvesting dates, electrical power for heating or cooling in large cities and air-conditioning services. Additional loads on electrical power for heating or cooling in the big cities are all related to relative values of expected daily temperature with respect to a design level, i.e., threshold (EPRI, 1983).

The intensity of the heating or cooling periods versus their length (Şen et al., 1998) is frequently represented by the accumulation of temperature units below/above the plant growth or human comfort thresholds (Figure 1). Truncation of daily temperature time series at a constant level, i.e., base temperature, gives rise to two types of events, which in practical climatic and heat engineering terminology correspond to heating degree-day (HDD) and cooling degree-day (CDD) amounts.

On the other hand, climate change has long been predicted to result from increasing greenhouse gases in the atmosphere. Some of the studies have focused in the context of ecosystems (Gates, 1993; Tegart et al., 1990; Kadıoğlu et al.,

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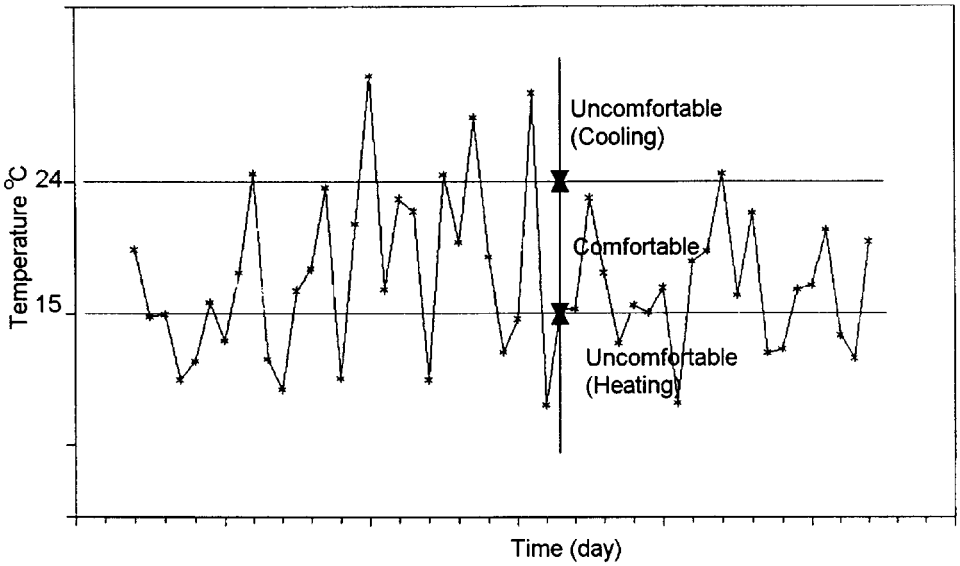

Figure 1. Temperature series truncation, and cooling and heating degree-days definition.

1997) and agriculture (Singh et al., 1998; Sykes and Prentice, 1996; Lenihan and Neilson, 1995; Bootsma, 1994). Energy production has been responsible for being the main source of atmospheric concentrations of the greenhouse gases, among which carbon dioxide plays a dominant role. Reducing the amount of heating fuel consumption will cause reduction in CO_2 emissions or vice versa. The problem of climate change is also related to energy consumption and emissions of greenhouse gasses. It is uncertain how climatic change may impact energy consumption for building heating or cooling in Turkey. However, it is important to determine what degrees of changes in climate variability are important for energy consumption in any country.

Turkey is located at the eastern corner of Southern Europe, and chosen as a representative region by the Intergovernmental Panel on Climate Change (IPCC) among five regions in the world (IPCC, 1991). Three high resolution general circulation models (GCMs), namely, Canadian Climate Center (CCC), Geophysical Fluid Dynamics Laboratory (GFDL) and United Kingdom Meteorological Office (UKMO) models have been applied over Turkey by IPCC. According to predictions of these models, temperatures are expected to increase by 2 °C in winter and 2–3 °C in summer. In other words, the GCMs predictions suggest a decrease in HDD and an increase in CDD over Turkey. However, a change in mean (or a trend in) HDD/CDD need not indicate necessarily a change in climatic means; it could be due to changes in the cumulative probabilities (CDFs). On the other hand, CDF estimates from GCM simulations are not very reliable, to say the least. Furthermore, analysis of trends in HDD and CDD in any country may serve as a surrogate in

detecting climate changes, because they represent control of the required energy in buildings throughout the year.

Although IPCC (1991) used models to give the most reliable regional patterns, the current general circulation models (GCMs) have well-documented limitations in simulating regional climate changes (e.g., Dickinson, 1989; Mitchell et al., 1991). The analyses of the instrumental records may help to clarify some of these uncertainties (Lachenbruch and Marshall, 1986; Jones and Jiusto, 1980). Several statistical techniques were used for the trend search in climate series in Turkey (Kadıoğlu, 1997), who has analyzed the changes in the mean seasonal daily maximum and minimum temperatures over Turkey and has stated that the air temperature trends over Turkey are not the same as the predictions of GCMs. In contrast, the trend of temperature analyzed by Mann–Kendall depends on the location and season.

This study presents the regional and national heating and cooling demands related to seasonal and annual weather conditions through actual daily temperature measurements in Turkey. The spatial variations in trends of HDD and CDD were analyzed by considering the daily mean temperature records and a sequential version of Mann–Kendall rank statistic. The procedural methods in this paper are similarly applicable in any part of the world.

2. Data Features

The seasonal mean, minimum and maximum un-smoothed daily temperatures of shelter level air are used in this study. The mean daily temperature data from 255 stations are considered to calculate and depict the spatial variations of seasonal totals of HDD and CDD. Stations are selected on the basis of completeness and reliability of records in addition to the availability of at least 3 years of complete daily records. The station locations are shown in Figure 2. Seventy-four stations are chosen out of 255 for studying temporal variations of HDD and CDD over Turkey. The locations of these representative stations are shown in Figure 3. These stations have various periods of records, but none of them is shorter than 45 years. Herein, meteorological seasons are defined conventionally as 3-month periods.

Daily temperatures are collected routinely from principal Turkish State Meteorological Works (Devlet Meteoroloji İşleri, DMİ) stations all over Turkey. The maximum, minimum and mean daily temperature data obtained from DMİ are scrutinized through statistical control techniques (such as, non-parametric Swed and Eisenhart, and Kruskal–Wallis homogeneity tests) for their reliability.

Although in many parts of the world spatial homogeneity is not assured by the station network, in Turkey the stations are scattered almost homogeneously. This point has been confirmed by the counting procedure of stations after dividing the whole study area into different square subareas. It was noticed that the number of stations falling within each subarea is not significantly different at 5% relative

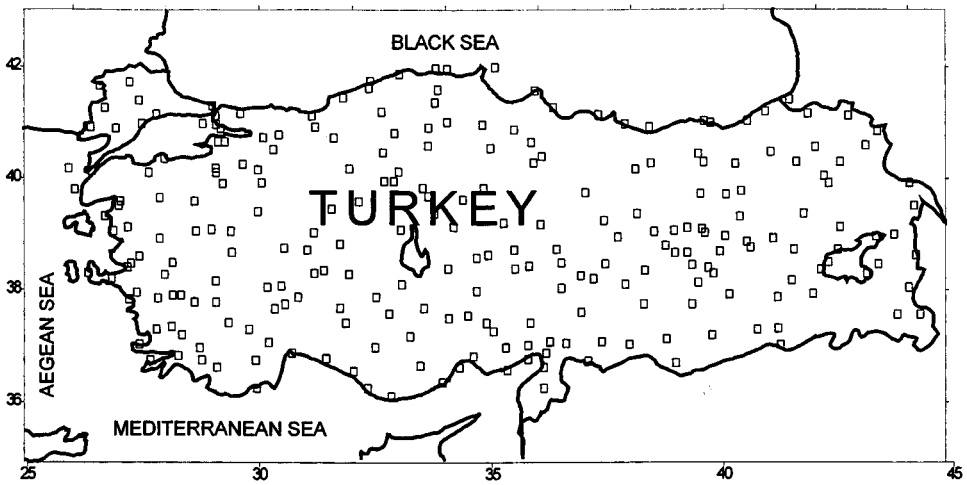

Figure 2. Location map and station locations used in degree-days calculations.

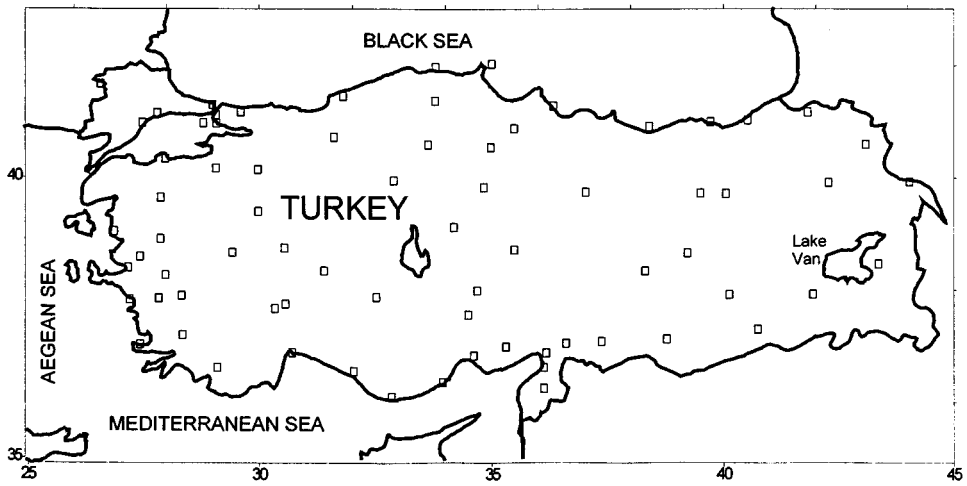

Figure 3. Station locations used in the Mann–Kendall trend test analysis.

error level. On the other hand, local effects such as proximity to surface water bodies (lakes, rivers, sea, oceans) temperature lapse rates and topographical features are expected to introduce heterogeneity. This is one of the focal points in this research which tries to relate regional monthly degree-day (DD) values and, especially, maps of morphological and climatological features. Possible changes during recording period in each station may introduce a systematic bias into the temperature measurements but such effects have been eliminated from the data used in this study.

3. Methods

3.1. DEGREE-DAYS

The first analytical approach to DD formulation was started by Thom (1952). Standard statistical analysis was applied in order to obtain the relationship between the means of the daily temperature records and DD derived therefrom. Thom (1954) further explained the relationship between mean temperature and the mean DD for truncation (base) level of 65 °F (19 °C). Later, Thom (1962) developed equations for obtaining mean monthly DD above any base level temperature by the standard deviation of monthly average temperatures. Quayle and Diaz (1980) have observed that HDD are directly related to site-specific total energy and heating oil-consumption for individual residences. Guttman (1983) analyzed the variability of population weighted seasonal HDD for 48 states within U.S.A. He concluded that the prediction of future heating-energy demand is dependent not only on historical averages but also on the variability of the climate. Later, Guttman and Lehman (1992) modeled the mean daily degree-hours by assuming a normal probability distribution for temperatures. Furthermore, a risk assessment of unusual weather-related heating energy demand is provided empirically by Şen and Kadıoğlu (1998a,b). Recently, theoretical assessment formulations are given by Kadıoğlu and Şen (1999).

In general, definition of DD requires on one hand, historical temperature records $T_1, T_2, \ldots, T_i, \ldots, T_n$ where n is the record length, and on the other hand, a constant level of comparison as the base temperature, T_B. Truncation of the temperature series at T_B level leads to two types of occurrences. These are the surpluses when $T_i - T_B \geq 0$ and deficits in the case $T_i - T_B < 0$. It is to be noticed that these two events are complementary and mutually exclusive, which, according to basic probability theory implies that summation of their probability of occurrences is equal to one.

For design purposes, in practice, if the outside temperature T_o at time i is greater than the inside temperature T_i, then the required temperature reduction by cooling is expressed as

$$T_{ci} = (T_o - T_i)\,. \tag{1}$$

Similarly, the temperature rise needed for heating becomes

$$T_{hi} = (T_i - T_o)\,. \tag{2}$$

Note that in these expressions T_i has been considered as equivalent to base temperature, T_B. The temperature differences $(T_i - T_o)$ are related to heat loss through insulation for a building. The recommended inside temperature T_i is a function of the time of day, usage purpose, degree of occupant activity, duration of occupation, presence of radiant heat sources, and outside conditions.

An uninterrupted sequence of cooling (heating) amounts preceded and succeeded by at least one heating (cooling) amount is called the cooling (heating) duration. For a season, the summation of the daily cooling amounts is referred to as the seasonal CDD value in the literature and if the number of days in the season is m_d, then in general the CDD is defined as

$$\mathrm{CDD} = \sum_{i=1}^{m_d} T_{c,i} \,, \tag{3}$$

which has the same unit as the temperature. In Equation (3), i indicates the initial time of the cooling period. Similarly, the seasonal HDD is given by

$$\mathrm{HDD} = \sum_{i=1}^{m_h} T_{h,i} \,, \tag{4}$$

where m_h is the seasonal number of days in the season.

The choice of base temperature depends on various climatic variables (humidity, wind regime, etc.) for the particular region. As a boundary condition parameter, especially for heating systems, the base temperature will depend strongly on local building technologies. For instance, depending on design parameters, a well-ventilated home needs almost no heating between 12.8 °C (55 °F) and 18.3 °C (65 °F) in the United States of America (Quirk, 1981). On the other hand, in relatively hot climates such as in Jordan, 18.3 °C is not a suitable base temperature for HDD, but recommended base value is 15.5 °C; in the Kingdom of Saudi Arabia depending on different regions within the country, it ranges between 17.8 °C and 21.1 °C (El-Shaarawi and Masri, 1996). An appropriate value is already adopted in Turkey as 15 °C is by Gültekin (1995), Gültekin and Kadıoğlu (1997), and Kadıoğlu et al. (1999).

Considering the importance of humidity increase with temperature and spatial variability of humidity during hot periods, it is not possible to adopt one high temperature threshold all across Turkey because it is surrounded three sides by large water bodies which are humidity generators in summer months. Hence, it is necessary to take one constant high temperature threshold for coastal areas and another for inland. However, adaptation of different high temperature thresholds for different regions does not hinder the application of the methodology in this paper.

For the purpose of this paper, the temperature series are truncated at different base levels (15 °C and 24 °C) for calculations of HDD and CDD, respectively. The results are presented in the form of contour maps, which show regional variations. Due to the space limitation, only seasonal and annual DD number spatial features will be explained with their relevance to local and regional climatic as well as topographic effects.

3.2. TREND EXISTENCE ANALYSIS

In general, previous trend studies have analyzed the instrumental data for locating climate trends mostly through the parametric statistical methods, such as moving averaging (Jones and Jiusto, 1980) and linear regression methods as well as two-phase regression models (Solow, 1987). The dependency of these methods on the shape of the distribution underlying the observations requires time consuming data transformation work, if they are not normally distributed. However, the Mann–Kendall rank statistic, which is a non-parametric test, is different from the others. It does not give the functional form of trends but their possible existences in a given data. Besides, it depends on the ranks of the data rather than actual measurements. In this test, the departures from a Gaussian normal frequency distribution are not needed to be a concern at all (Sneyers, 1990).

The parametric techniques are based on the assumption of independent observations and they cannot be valid for correlated sequences. However, non-parametric tests, such as those based on the ranks rather than the magnitude of the observations, are not dependent on the correlation structure. Since the temperature data have significant serial correlation structure, it is then necessary to use a non-parametric statistical trend analysis.

The time series of the calculated HDD and CDD are analyzed in order to identify meaningful long-term trends by making use of the sequential version of Mann–Kendall technique, which does not show the functional form of the trend but its existence only (Sneyers, 1990; Kadıoğlu, 1997).

4. Discussion of Results

The calculated seasonal spatial and temporal variations of HDD and CDD according to Equations (3) and (4) are mapped in Figure 4 for identification and interpretation of spatial features. For contour mapping purpose the Kriging technique is used to create a regularly spaced grid based on the irregularly spaced stations in the study area. On the other hand, the contour values in Figures 5 and 6 show spatial variation the Mann–Kendall trend test statistics at ± 1.96 ($\sim \pm 2.0$) standard values which correspond to $\alpha = 0.05$ significance level.

4.1. SPATIAL VARIABILITY OF SEASONAL HDD AND CDD

Turkey is located in the general subtropical region of the world with its very ragged topography surrounded on three sides by different seas. According to the advancement of different air currents toward Turkey, the HDD and CDD spatial distributions take their characteristic shapes as shown in Figure 4 for seasonal and annual variations. Their patterns are directly related to topographic, meteorological and climatological features of the region. Since mean daily temperature generally

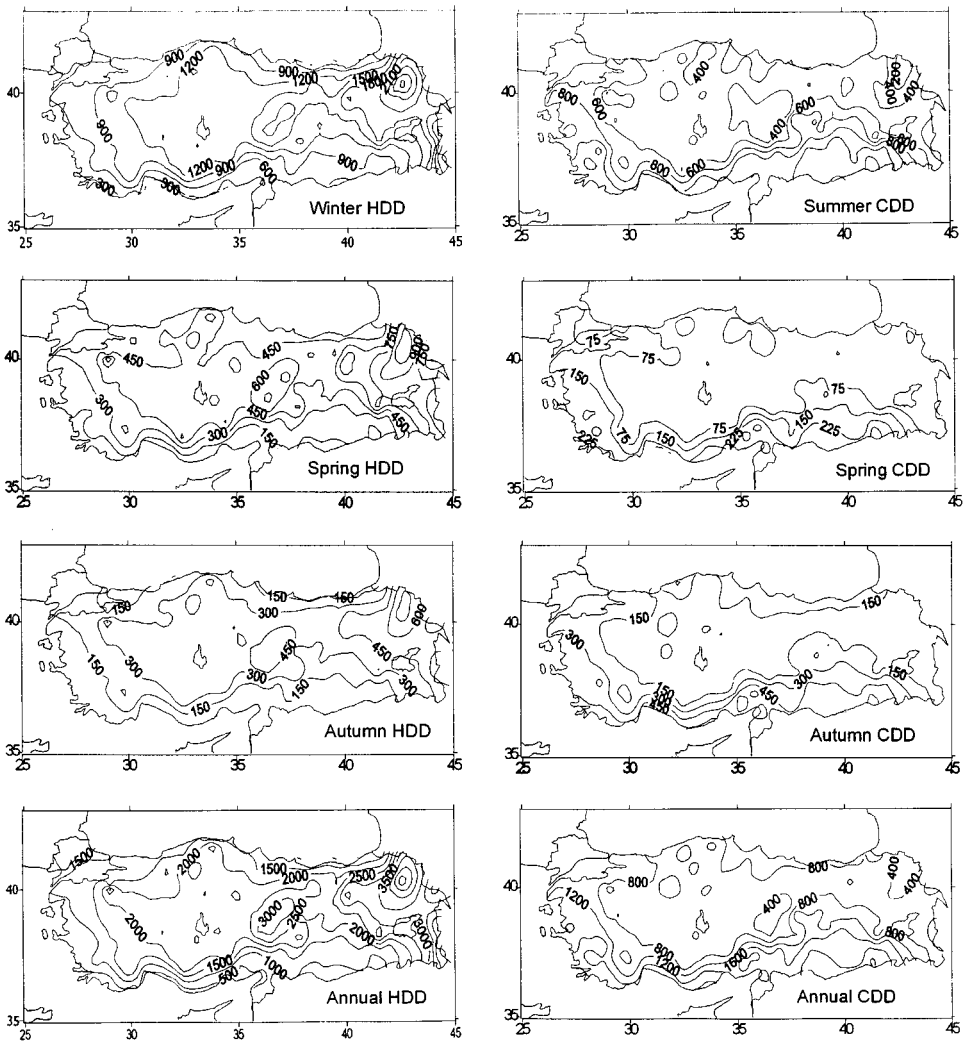

Figure 4. Seasonal and annual totals of HDDs and CDDs during 1930–1996.

does not drop below 15 °C in summer and exceed 24 °C base temperature in winter, they are excluded from the analysis.

In general, HDD amounts are greater than CDD in each season and annually the difference between the two is significant. For instance, in the northeastern regions annual HDD reaches up to 3500 °C whereas the same region needs 400 °C CDD energy. On the other hand, simultaneously as some parts of Turkey needs cooling, some other parts require heating. This is tantamount to saying that there is a continuous energy demand in Turkey for heating and cooling purposes. Furthermore, HDD has extensive appearance over all the country in all seasons whereas CDD

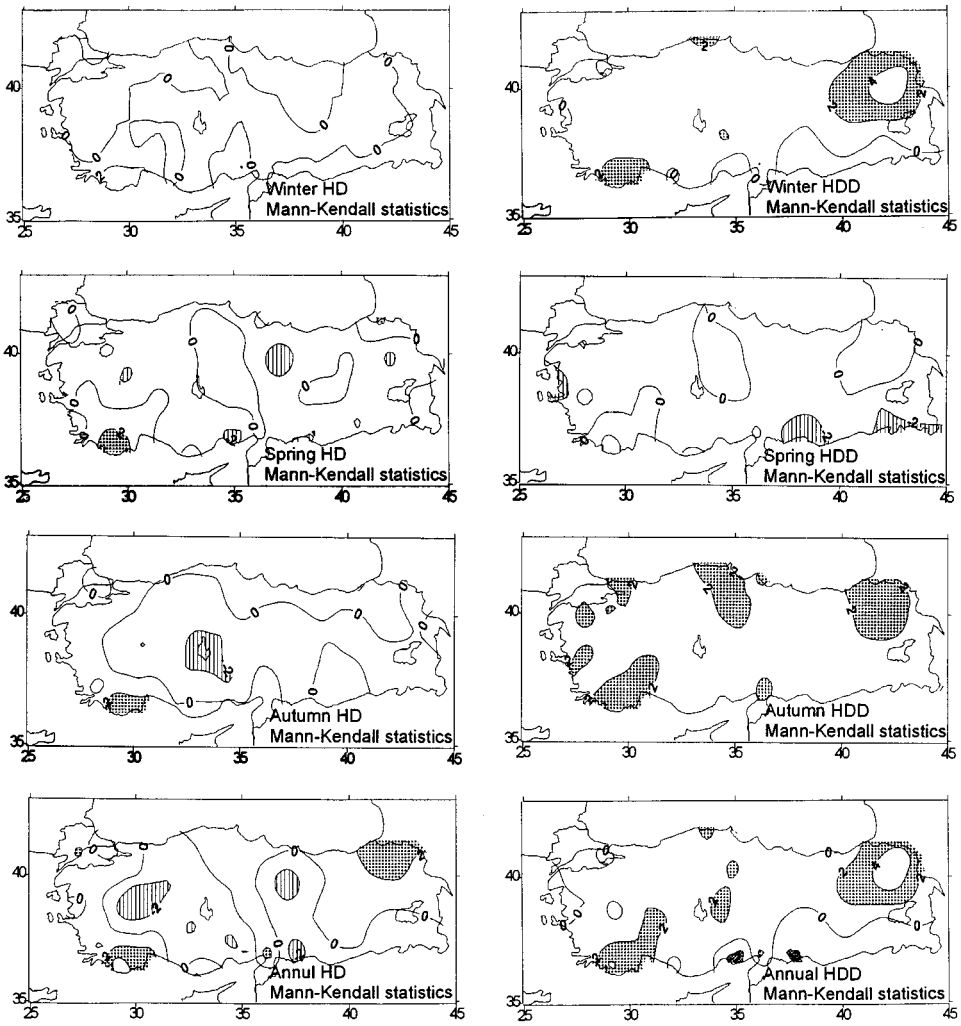

Figure 5. Seasonal and annual Mann–Kendall trend test statistics of HD number and HDD during 1930–1996. Dot and vertical line shading mark regions of warming and cooling, respectively, with a significant trend occurrence (95% level).

requirements appear significantly in the southern and western regions as obvious from spring CDD maps in Figure 5.

Figure 4 yields that at the 15 °C base temperature extreme cold conditions prevail in the eastern parts of Anatolia in winter. This region has the maximum HDD amounts centered at eastern Anatolia, which has its fame as 'mustache-icing'. However, towards the south and southeast where the largest lake of Turkey, namely, Lake Van, is situated comparatively moderate conditions appear due to the mild effect of free surface water body on the HDD value. Such an effect plays a retardation role in the expansion of HDD contours towards the southern parts

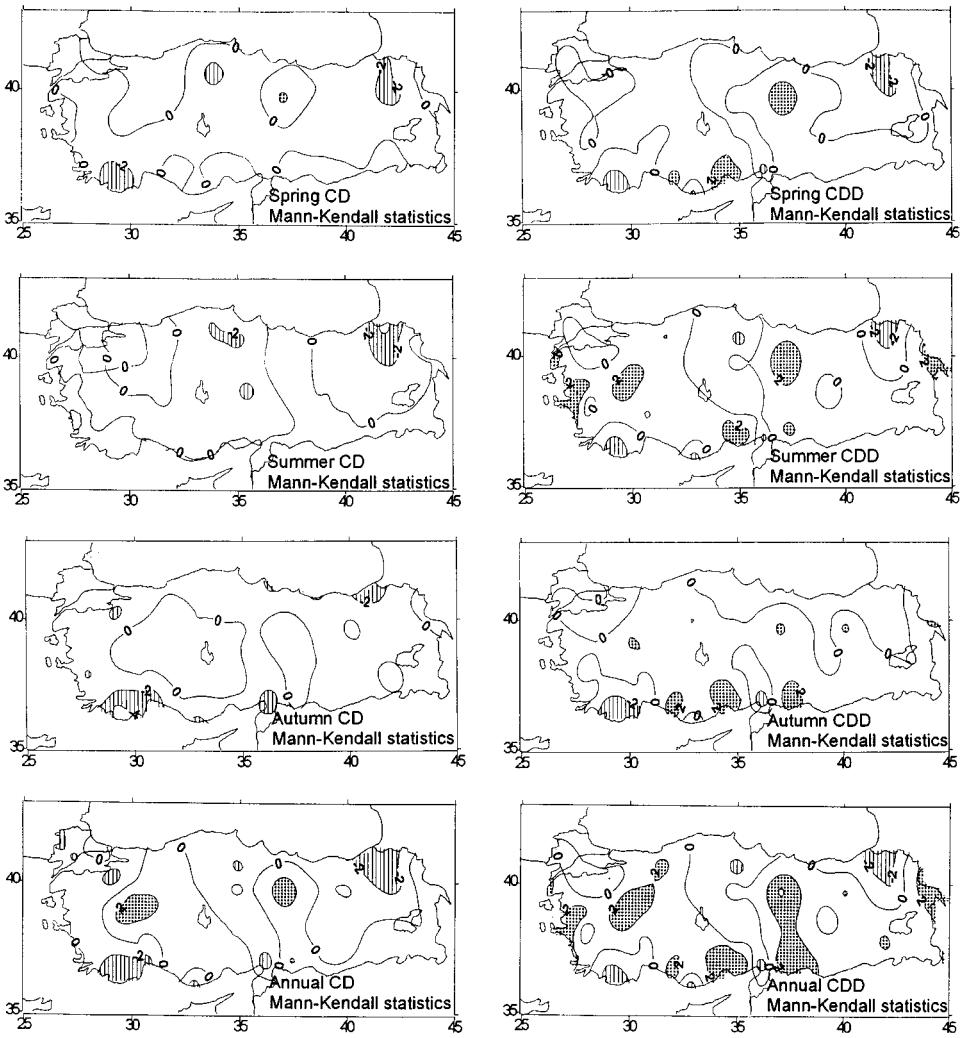

Figure 6. Seasonal and annual Mann–Kendall trend test statistics of CD number and CDD during 1930–1996. Dot and vertical line shading mark regions of warming and cooling , respectively, with a significant trend occurrence (95% level).

of the region (Kadıoğlu et al., 1997). The peak HDD values in eastern Turkey at about 2500 m above mean sea level are confined between the Black Sea and Lake Van. Hence, the influence of water heat storage on the temperature from these two surface water bodies is very obvious.

The autumn HDD map reflects more or less the same features as in spring, but HDD has lower values. This is equivalent to saying that autumn months are warmer than spring months. These maps also show very distinctively the penetration of cold air masses from the eastern provinces, which is under the influence of Siberian high pressure center during wintertime. Furthermore, in the northwest

just to the south of the Marmara Sea, there is a small circle of HDD at the very famous skiing center of Turkey called Uludağ. Still the heating effect of Lake Van appears in the eastern parts. In this map, none of the equal HDD lines reaches the coastal lines and they are confined to the area between the Taurus mountains in the south parallel to the Mediterranean Sea and the Isfendiyar mountains that run parallel to the Black Sea coast in the north (see Figure 4). Hence, extension of HDD equal lines towards the west is due to the penetration of cold continental polar air masses from the northeastern parts of Turkey originating from Siberia. There are some HDD indications on the European side of Turkey. Penetrations of maritime arctic and polar air masses become distinctive through the northwestern European part of Turkey. The only area that is not influenced is the Aegean coastal plain because of the warm and moist air transfer from the Aegean Sea toward inland along various river valleys that run perpendicular to the coastal line. At first glance, annual HDD gives the impression that this pattern matches almost completely with the topographic features, i.e., elevations except the eastern part of Turkey. Since the weather is warmer, the effect of the inland water body (Lake Van) disappears in the east. In general, the higher the elevation the bigger the HDD in this map.

Only winter HHD exhibits rather uniform and coastal-line parallel contours. This implies penetration of local moist air from the surrounding seas inland. It can be concluded that micro and local climatic effects play a dominant role in shaping HDD contours at this temperature base level than global climatic features. In Figure 4, for annual HDD, although coastal effects remain almost the same inland contours are rather heterogeneous. This implies that local but continental microclimate varies depending on the existing topographic features especially on diurnal time scale and local climatic changes.

As for CDD, their spatial variations are somewhat similar to the HDD, but CDD along the Eastern Black Sea coast behaves very different than that of the HDD patterns. CDD are highest over the Southeastern Anatolia and lowest over the eastern Anatolia in summer months.

4.2. SPATIO-TEMPORAL TREND EXISTENCE IN HDD AND CDD

In order to be able to assess the regional trend existence in the HDD and CDD variations, Mann–Kendall statistics are mapped at 5% significance level for various seasons in addition to the annual variations. Figures 5 and 6 show HD number with HDD and CD number with CDD spatio-temporal variations, respectively.

For instance in Figure 5, during winter there are trend occurrences of HDD in the northeastern part and southwest corner of Anatolia at 5% statistical significance level. The trend in the southwest corner of Anatolia is parallel to the trend in the number of heating days (HD) over the same area. There is no significant change in the other parts of Turkey in winter as well as in annual HDD. Likewise, the map of CDD in spring shows that there is a statistically significant decrease in both CD number and CDD in the east corner of Turkey (Figure 6). Additionally,

a decreasing trend has been estimated at 5% significance level in the southwestern corner of the Mediterranean region. Since, in general, the eastern Anatolia has the highest HDD in Turkey, the increasing trend of HDD over this region is important. Furthermore, Figure 5 shows that the summer cooling need is higher than any other season in Turkey. The decreasing trends in CD number and CDD exist only over the northeastern corner of Turkey in summer and spring seasons. On the other hand, in autumn, no statistically significant trend existence is observed over most of the country. A small area with decreasing trend existence appears in the southwestern part of Turkey during autumn. However, after summer, the cooling trend occurrence has not been determined in northeast of Anatolia, except in the Mediterranean region. The CDD decreases in some parts of the country for all seasons. It is found that the CDD decreases significantly in the eastern parts of Turkey during all seasons. Decrease in the annual values of CDD during warm parts of the year gives a favorable contribution to the energy demand.

Significant cooling trend possibilities have been determined in spring and summer seasons (Figure 6). In general, decreasing temperature has been observed along the coastal regions of southwestern Turkey only. This is a very important effect, because air conditioning demand is very high in this regions. Decrease of temperature in the future can cause significant effects on the electric consumption, because of the extensive air conditioning that results from cooling in houses and tourist complexes.

Furthermore, from the calculated values of HDD during autumn, one can observe a significant increase in all Black Sea coasts of Turkey. The increase of HDD during autumn might imply extension of the cold season period in the Black Sea region. Comparatively, greater warming effects have occurred in spring and winter minimum temperature records rather than maxima (Kadıoğlu, 1997).

In general, there is a great socio-economical concern in Turkey that the consequences of climate change might endanger the agricultural crop products, tourism, as well as historical and archeological interests that lie in the lowland coastal areas especially along the Aegean and Mediterranean Seas. Among the archeology wealths are remnants of old Greek, Byzantium and Ottoman periods, which could be partially submerged into the water due to possible sea level rise. On the other hand, Turkey as an agricultural country may suffer severely due to the climatic zone shifts toward the north hence becoming under the influence of more desertic climates as a result of climate change. It is expected in the future that the heating degree days in Turkey will increase as a consequence of global climate change.

5. Conclusions

Temperature records are necessary for many human related activity assessments through the heating and cooling degree-days (HDD and CDD). The application of

degree-day (DD) methodology is achieved for 255 temperature stations scattered all around Turkey. These stations are homogeneously distributed over the country with no biases and they are checked for reliability through simple statistical tests prior to treatment for HDD calculations. Maps of seasonal and annual HDDs and CDDs are presented and related to the local and regional climatology of the country. Analyses of 50-year long daily temperature records at 74 Turkish sites have been carried out in order to identify statistically significant trend occurrences in seasonal and annual heating day (HD) number, cooling day (CD) number, HDD and CDD by making use of a sequential Mann–Kendall rank statistics version. The DD approach, therefore, focused on the causes of climatic sensitivity on residential energy consumption.

This paper presents the relationships between the regional distribution of HDD and CDD at the base temperature levels of 15 °C and 24 °C, respectively. HDD and CDD maps prepared in this manner reflect many patterns concerning surface features, micro and macroclimate variations. It is observed that in regions of continental climate within Turkey, differences increase between the HDD and CDD.

On the other hand, it is concluded that spatially coherent, statistically significant and decreasing trends of HDD and CDD exist over the southwest coastal and northeast areas of Turkey for almost all seasons. In other words, the energy needed to cool buildings has been decreasing over the southwest coast throughout the year. On the other hand, there is a discernible increase in energy demand for building heatings over the northeast Anatolian regions of Turkey in all seasons.

These reductions (excesses) in the accumulated CDD (HDD) above 24 °C (below 15 °C) are somewhat inconsistent (at least in direction) with the predictions concerning warmer air temperatures over Turkey by the three high resolution General Circulation Models' $2 \times CO_2$ simulations (IPCC, 1991). In other words, our analyses of DD patterns from historical climate records do not provide empirical support for the model simulations.

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