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Index-based evaluation of the relationship between bioclimatic comfort levels and air quality levels of particles and sulfur dioxide in Şanlıurfa Province (Turkey)

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Abstract

The aim of this study is (i) to reveal the bioclimatic comfort zones depending on the Discomfort Index (DI) in Şanlıurfa province with the help of geographic information system (GIS), and (ii) to determine the relationship between bioclimatic comfort levels and Air Quality Index (AQI) levels in the Şanlıurfa city. For all analyzes made in the study, annual and monthly average values of meteorological (temperature, relative humidity, wind speed) and air pollutant parameters (for PM_{10} and SO_2) between the years 2006–2021 were used. In this context, meteorological parameters, air pollutant parameters, temporal changes of DI and AQI (for PM_{10} and SO_2) parameters were determined by Mann-Kendal (MK) trend analysis and the relationships between all these parameters were determined by Pearson correlation analysis. The most suitable ($21 \leq DI < 24$) months in terms of bioclimatic comfort in Şanlıurfa province were June and September. In the Şanlıurfa city, annual and monthly average AQI_{PM10} values were generally in the “good” and “moderate” class, while AQI_{SO2} values were in the “good” class in all years and all months. While the annual average temperature values showed a statistically significant increase, the annual average wind speed and PM_{10} and AQI_{PM10} values showed a statistically significant decrease. There was a negative “weak” correlation ($r = -0.028$) between DI and AQI_{PM10}, and a positive “moderate” correlation between DI and AQI_{SO2} ($r = 0.449$; $p < 0.05$). In addition, correlations between DI, PM_{10}, and SO_2 were significant at the $p < 0.05$ level.

Keywords DI · AQI · Bioclimatic comfort · Air pollutant · GIS

Introduction

Urbanization is a concept that forces governments, municipalities, and city planners to adapt to these great changes by reshaping the structure of cities (Cetin et al. 2019). With urbanization, energy transfer (radiation, convection, conduction), thermal conditions (specific heat, albedo), humidity conditions (evaporation, surface flow, precipitation), and air circulation systems are changing. These changes revealed the difference between cities and the natural environment (Gungor et al. 2021). Scenarios of increased air temperature caused by global warming can exacerbate thermal discomfort and adversely affect living conditions in many regions around the world (Marx et al. 2021).

Thermal comfort indices, which are widely used in bioclimatology studies, play an important role in understanding the effects of urbanization on the natural environment. These indices are based on the measurement of human responses to meteorological parameters (Gungor et al. 2021). The thermal comfort index is a bioclimatic indicator that reflects the level of thermal comfort/discomfort within a climate regime over a given period of time. The American Society of Heating, Refrigeration, and Air Conditioning Engineers defines thermal comfort as “a state of mind that expresses satisfaction with the thermal environment and is evaluated by subjective evaluation” (Oroud 2022). Climate has a direct impact on human comfort, as environmental conditions affect the

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heat balance between the human body and the environment and are the source of possible thermal discomfort conditions (Poupkou et al. 2011). Many researchers (Roshan et al. 2019; Ahmadi and Ahmadi 2017; Cetin and Sevik 2020; Gungor et al. 2021; Vinogradova 2020) have demonstrated the thermal comfort properties of study areas by using different bioclimatic indices based on GIS [Physiological Equivalent Temperature (PET), Thermo Hygrometric Index (THI), Universal Thermal Climate Index (UTCI), and DI].

Clean air is an essential condition for human survival (WHO 2006). However, with the rapid development of urbanization and industrialization, air pollution has become a global environmental problem affecting human health (Landrigan et al. 2018; Luo et al. 2020). In the last 20 years of the twentieth century, a statistically significant increase trend was observed on heat waves and their duration, so studies revealing the relationship between thermal comfort and air quality gained great importance (Nastos and Matzarakis 2008).

Air quality can be expressed depending on air pollutant concentration values. The most common pollutants causing air pollution are sulfur dioxide (SO_2) and particulate matter (PM). While the main source of SO_2 is fuels containing high sulfur, the main source of PM is unburned fuels and fuel combustion inefficiency (İçağa and Sabah 2009). Air quality assessment procedures at the international level are set by the indexes. The first index adopted by the United States Environmental Protection Agency (US-EPA) was the Pollution Standard Index (PSI). In 1999, EPA replaced the PSI index with two new sub-indexes, the Air Quality Index (AQI) containing ground-level ozone and fine particles (Lanzafame et al. 2015). The AQI is a useful tool for characterizing pollution levels in an area and informing citizens about pollution levels in an adequate and understandable manner, as well as a tool to be used by relevant authorities to carry out a series of assessments [World Health Organization (WHO) 2006]. The AQI is a color-coded scale that simplifies different pollutant concentrations into a single numerical value that reflects overall air quality, health effects, vulnerable groups, and necessary precautions (Zaib et al. 2022). AQI can be calculated for ground level ozone, particulate matter, carbon monoxide, sulfur dioxide, and nitrogen dioxide parameters (EPA 2009). Kassomenos et al (1999) proposed an air quality index based on European Union (EU) directives to determine the effects of air quality on human health. Murena (2004) developed and implemented an air pollution index in Naples (Italy). Kirkilis et al. (2007) developed an air quality index for Athens (Greece).

According to their potential and importance to cause adverse health and/or environmental effects, air pollutants in Turkey generally consist of two air pollutants, PM_{10} and SO_2. PM is recognized as an important component of ambient air as it plays a vital role in human health and air quality (Dinoi et al. 2017). PM with an aerodynamic diameter less than 10 µm is called PM_{10} (Talbi et al. 2018). Industries, coal and biomass burning, vehicles, and petroleum resources are among the largest sources of PM_{10} (Li et al. 2018). Like most pollutants, SO_2 has both natural and anthropogenic sources (Ray and Kim 2014). On a global scale, SO_2 emissions from anthropogenic activities are approximately ten times higher than SO_2 emissions from natural sources (Qiao et al. 2018).

There are not many studies combining thermal comfort and air quality on sustainable cities and biometeorology. To address this gap, a unified decision support framework for thermal comfort and air quality indices will promote an environmentally sustainable urban landscape and improve the health and well-being of the urban population (Fahad 2021). Mavrakis et al. (2012), in their study on the Thriassion Plain in Greece, revealed high levels of thermal disturbance and increased air pollution levels, and found a significant correlation between DI and AQI. Poupkou et al. (2011) found a strong relationship between thermal comfort and poor air quality in the Thessaloniki Region (Greece), based on the DI and the Common Air Quality Index (CAQI), with an increase in temperature in summer. In a study conducted in 5 important cities of China (Beijing, Xining, Nanjing, Kunming, and Guangzhou), it has been determined that air pollution levels worsen thermal comfort levels in all seasons, especially in winter in Nanjing, thermal comfort decreases by 30.30% and this was due to air pollution (Zhang et al. 2021).

As in many parts of the world, Turkey has faced rapid urban growth in recent years. Rapid urbanization causes the deterioration of the ecological balance in urban areas (Adıguzel et al. 2020). Monitoring of air pollutants is very important to manage air quality in cities. The Ministry of Environment, Urbanization, and Climate Change (Turkey) has developed the National Air Quality Observation Network by establishing air quality measurement stations to improve the air quality management system in Turkey. With the help of this network, data on pollutant parameters are recorded in real time. However, both the number of measured parameters and the availability of retrospective data are still limited (Büke and Köne 2016).

In this study, bioclimatic comfort zones depending on the DI in Şanlıurfa province were mapped with the help of GIS, and the relationships between bioclimatic comfort levels (DI) and air quality levels (AQI) were determined in Şanlıurfa city.

Material and methods

Study area

The study area covers the provincial border of Şanlıurfa located in the Southeastern Anatolia Region of

Turkey (36°41′28″–37°57′50″ northern latitudes and 37°49′12″–40°10′00″ east longitudes). The Turkey-Syria land border forms the south of the province, and Syrian territory is located in the south of the province. Ranking 7th in terms of surface area, Şanlıurfa province has a surface area of 18,765 km^2. The altitude of Şanlıurfa city is 518 m. Şanlıurfa is one of the provinces included in the Southeastern Anatolia Project (SAP). The province is at the center of an important water-based regional development project in terms of developing water and soil resources under the influence of natural climate change. In addition, the province has regional and international importance with its cultural, historical, and natural resources, where Göbeklitepe, the oldest temple in the world, belonging to the end of the Paleolithic age is located (Bengisu 2020). The study area is under the influence of very different air masses, which vary according to the summer and winter conditions, as is the case in Turkey in general. In general, the province is under the influence of cold air masses in the north in winter, and under the influence of hot air masses in the south in summer. In other words, the study area is under the influence of desert heat with the Basra cyclone entering Anatolia in the summer season. In addition, dust storms from the Sahara and Syrian deserts in the south of the province affect the province negatively, especially in spring and autumn. When precipitation is added to these dust winds, muddy precipitation is common in the region (Dogan et al. 2020). Annual average temperature values of the districts in the study area; For Şanlıurfa city, Akçakale, Ceylanpınar, Bozova, Birecik, Hilvan, and Siverek are 18.5 °C, 18.3 °C, 18.2 °C, 17.1 °C, 17.8 °C, and 16.6 °C, respectively. The annual average precipitation is 459.8 mm, 291.5 mm, 312 mm, 404.2 mm, 375.5 mm, 434.3 mm, and 569.1 mm for Şanlıurfa city, Akçakale, Ceylanpınar, Bozova, Birecik, Hilvan, and Siverek, respectively (İrcan and Duman 2021). The height of the study area above sea level varies between 231 and 1978 m (Fig. 1).

Data supply and software

The basic data of this study consists of meteorological parameters (temperature, relative humidity, and wind speed) and air pollutant parameters (PM_{10} and SO_2) that affect health the most. For the bioclimatic comfort analysis of Şanlıurfa province, the temperature (T) and relative humidity (RH) parameters of 7 meteorology stations between the years 2006 and 2021 were used. The wind speed (WS) parameter was used together with other meteorological parameters to reveal the climatological condition of the study area. Detailed information about the meteorology stations is given in Table 1, and the spatial distribution of the stations is shown in Fig. 1. The annual average pressure of the province of Şanlıurfa is 948.8 mb and this value does not differ much for all months. Annual average temperature values of all stations are shown in Table 1. Twelve-month average values were obtained by using the monthly average values for the climate parameters in the relevant time period, which were obtained from the Şanlıurfa Meteorology Provincial Directorate. PM_{10} and SO_2 values measured by 1 air quality measurement station in Şanlıurfa city belong to the years 2006–2021. These data were obtained as monthly average values from the Ministry of Environment, Urbanization, and Climate Change/National Air Quality Monitoring Network (Ankara/Turkey) (Table 2). The calculated AQI (for PM_{10} and SO_2 pollutants) is equivalent to the air quality index developed by the United States Environmental Protection Agency (US EPA). At the air quality data station located in the central district of Şanlıurfa, verification (validation) processes on the data are carried out regularly, taking into account the calibration and alarm information of the devices. Accordingly, monthly and annual reports are prepared for the evaluated data, and the raw data (PM_{10} and SO_2) obtained from the air quality monitoring network (for Turkey) are published simultaneously at www.havaizleme.gov.tr, and data on PM_{10} and SO_2 pollutants are used in this study.

Excell 2017 was used for DI calculation and AQI calculation with all analyzes of temperature, relative humidity, and wind speed parameters and air pollutant parameters used in the study. While ArcGIS 10.8 and SPSS Statistics 23 were utilized obtaining spatial distribution maps of meteorological parameters and bioclimatic comfort analysis and trend analysis and correlation analysis of PM_{10} and SO_2 pollutant parameters, respectively.

Method

Three methods were preferred in the realization of the aim of this study. These methods are bioclimatic comfort analysis based on the DI, MK trend analysis (Skirienė and Stasiškienė 2021), and Pearson correlation (Skirienė and Stasiškienė 2021) analysis. These methods were used as reference methods, taking into account the previous studies on the environment and climate. Among these methods, MK trend analysis and Pearson correlation analysis methods are automatic methods that analyze with the help of software, and the bioclimatic comfort analysis (DI) method is a manual method based on simple calculation with the help of Excell 2007 software. The first step of the method applied in this study is to reveal the bioclimatic comfort zones according to the DI, which is determined according to the temperature and relative humidity parameters for the provincial border of Şanlıurfa. The second step of the method is to determine the relationship between the bioclimatic comfort levels obtained for the city border of Şanlıurfa and the air pollutant levels. Within the scope of the study, information

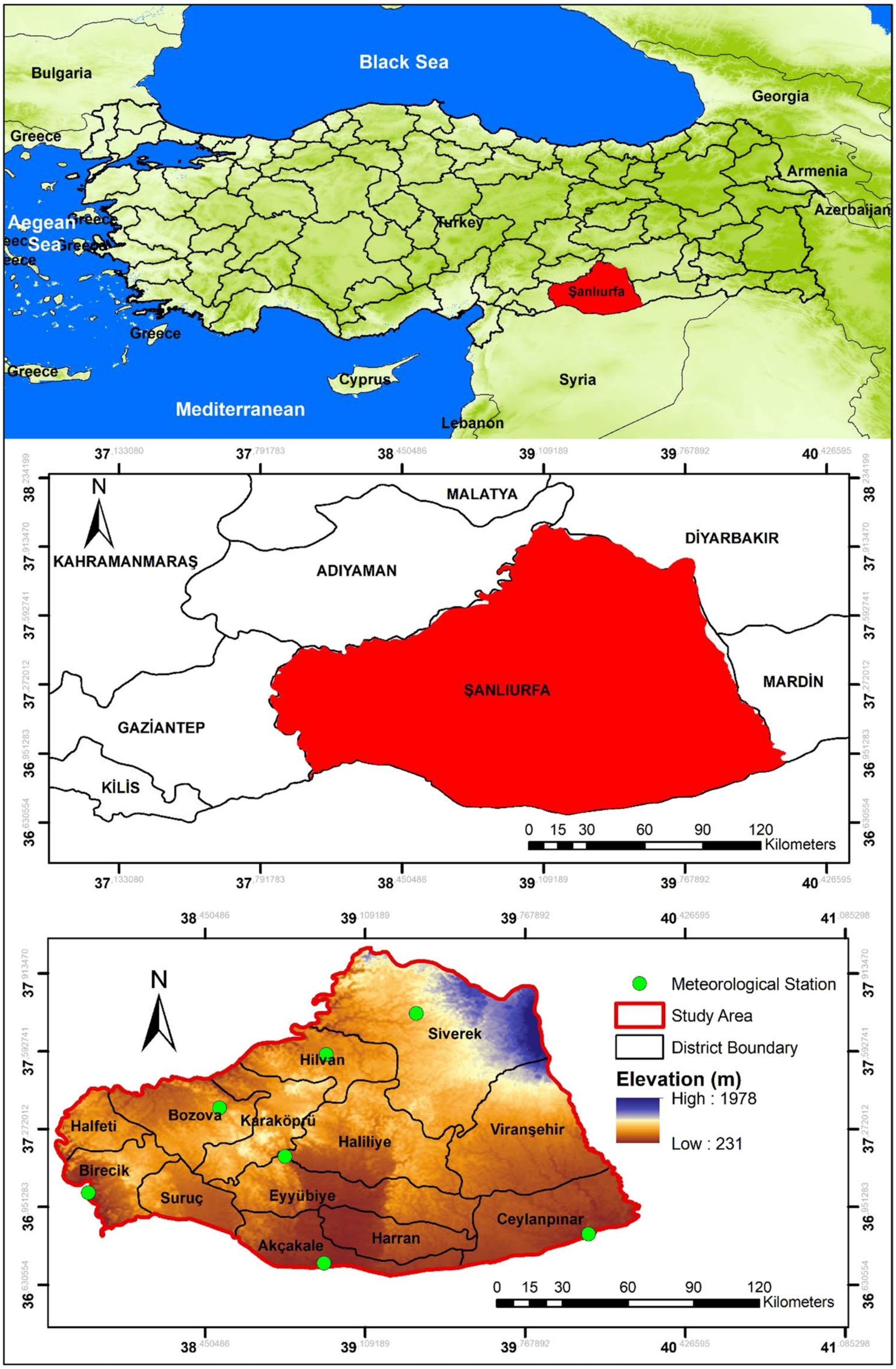

Fig. 1 Location of study area, spatial distribution of meteorological stations, and elevations in the study area

on the calculation of DI values, the creation of spatial distribution maps of climate parameters and DI, trend analysis of meteorological and air pollutant parameters and correlation analysis are given below.

Bioclimatic comfort analysis based on Discomfort Index

The most commonly used bioclimatic index in urban climate studies to describe the level of thermal sensation a

Table 1 The average meteorological data of Şanlıurfa province in the climate period (2006–2021)

Meteorology station code	Meteorology station name	Latitude	Longitude	Altitude (m)	AAT (°C)*	AARH (%)[a]	AAWS (m/s)[a]
17,270	Şanlıurfa	37.16	38.78	550	19.52	47.27	1.45
17,912	Siverek	37.75	39.32	801	17.26	50.15	1.69
17,914	Hilvan	37.58	38.95	589	17.13	52.58	1.11
17,944	Bozova	37.36	38.51	622	17.64	51.20	1.72
17,966	Birecik	37.01	37.97	347	18.50	55.46	1.10
17,968	Ceylanpınar	36.84	40.03	360	19.17	53.75	2.11
17,980	Akçakale	36.72	38.94	365	18.91	51.54	1.85

[a] Annual average values were obtained using monthly average values, annual average temperature: AAT, annual average relative humidity: AARH, annual average wind speed: AAWS.

Table 2 Twelve-month average air pollutant data of Şanlıurfa city for the climate period (2006–2021)

Month	Pollutant Concentration (µg/m^3)	
	PM$_{10}$	**SO$_2$**
Jan	141.46	53.49
Feb	132.94	51.61
Mar	68.98	14.92
Apr	49.52	9.79
May	41.0.45	8.08
Jun	28.85	9.45
Jul	25.67	8.22
Aug	28.04	9.06
Sep	51.84	10.73
Oct	71.95	13.76
Nov	79.99	17.68
Dec	131.53	54.57

person experiences due to the changing climatic conditions of an urban area is Thom's DI (Zauli Sajani et al. 2008). The DI is an index that reflects the proportional contribution of air temperature and relative humidity to human thermal comfort. DI, which presents a general assessment of comfort conditions especially in outdoor spaces, reveals the information necessary for comfort and energy purposes. DI is calculated with the help of the following formula (Eq. 1) (Adiguzel et al. 2020; Polydoros and Cartalis 2014).

$$\mathrm{DI}(°\mathrm{C}) = \mathrm{T} - (0.55 - 0.0055 * \mathrm{RH}) * (\mathrm{T} - 14.5) \tag{1}$$

where DI is the discomfort index, T is the temperature (°C), and RH is the relative humidity.

Bioclimatic conditions of the outdoor environment can be evaluated using thermal indices; it is affected by diferent climatic factors such as air temperature, relative humidity, wind speed, and mean radiant temperature (Roshan et al. 2019; Balogun and Daramola 2019). In this study, DI was used to determine suitable areas of Şanlıurfa in terms of bioclimatic comfort taking into account the outdoor conditions. By using the monthly average values of T and RH parameters in the relevant time period, 12-month values of DI were obtained. The bioclimatic comfort zones of Şanlıurfa province were evaluated based on the DI values calculated for 12 months. Table 3 shows the thermal evaluation ranges for DI. According to Table 3, evaluation intervals of DI are divided into 8 groups. According to DI levels, DI values in the 18–21 °C range represent the "comfortable" category, while DI values in the 21–24 °C range represent the "optimum" category (Ziaul and Pal 2019).

GIS-based bioclimatic comfort mapping

The inverse distance weighting (IDW) method in the spatial analysis module of ArcGIS 10.8 software was used to create the spatial distribution maps of the bioclimatic comfort zones depending on the DI calculated within the scope of the study. Calculated DI values taken into account in the evaluation of bioclimatic comfort zones were reclassified with the help of ArcGIS 10.8 software according to the evaluation intervals of DI in Table 3. Spatial distribution maps of

Table 3 Thermal perceptions of discomfort index used in the study (Ziaul and Pal 2019)

Thermal perception	DI Level (°C)
Extremely uncomfortable	$\mathrm{DI} < 12$
Uncomfortable	$12 \leq \mathrm{DI} < 15$
Partially uncomfortable	$15 \leq \mathrm{DI} < 18$
Comfortable	$18 \leq \mathrm{DI} < 21$
Optimum	$21 \leq \mathrm{DI} < 24$
Partially Uncomfortable	$24 \leq \mathrm{DI} < 27$
Uncomfortable	$27 \leq \mathrm{DI} < 30$
Extremely Uncomfortable	$30 < \mathrm{DI}$

bioclimatic comfort zones related to DI were created according to the reclassification values.

AQI

AQI is a term used to express the level of health risk due to air pollution and explains air quality in a simple and understandable way (Monteiro et al. 2017). AQI is a quantitative measure used to properly report on the air quality of different components in relation to human health (Feng et al. 2013). AQI is an index used for daily reporting of air quality. Air quality is measured with the help of a network of measuring devices that record certain pollutant concentrations. These raw measurement values can be converted to AQI values using the developed standard formulas. AQI recommended by EPA (2000) has a scale that can vary between 0 and 500, and AQI values in terms of health concern levels are grouped as 0–50 (good), 51–100 (moderate), 101–150 (unhealthy for sensitive groups), 151–200 (unhealthy), 201–300 (very unhealthy), and 301–500 (dangerous). The purpose here is to convert the pollution concentration to a number between 0 and 500. AQI can be calculated with the following formula (Fang et al. 2015):

$$\begin{gathered} \mathrm{AQI} = [(\mathrm{I_{hi}} - \mathrm{I_{low}})/(\mathrm{BP_{hi}} - \mathrm{BP_{low}})] * (\mathrm{C_p} - \mathrm{BP_{low}}) + \mathrm{I_{low}} \\ \text{Final AQI} = \max(\mathrm{AQI_1}, \mathrm{AQI_2}, \mathrm{AQI_3} \mathrm{AQI_n}) \end{gathered} \tag{2}$$

Here, AQI = Air Quality Index, C_p: concentration of pollutant, BP_{hi}: breakpoint greater than or equal to the pollutant concentration, BP_{low}: breakpoint less than or equal to the pollutant concentration, I_{hi}: AQI corresponding to BP_{hi}, I_{low}: AQI corresponding to BP_{low}.

Results and discussion

Spatial distribution of climate parameters (T, RH, and WS) for Şanlıurfa province

Figure 2 shows the spatial distribution of the average temperature values for the 12 months between 2006 and 2021 in Şanlıurfa province. The lowest temperature value (3.93 °C) in the study area was observed in Hilvan district in January, while the highest temperature value (32.95 °C) was observed in July in the Şanlıurfa city (Eyyübiye). Wide temperature differences are observed throughout the study area during these 2 months in the relevant time period. All 12-month temperature values in Siverek and Hilvan districts, located in the north of the study area, are lower than other district depending on the altitude. When moving from the north to the south of the study area, an increase in temperature values s observed in general during the 12-month period. When an evaluation is made for Şanlıurfa city (Eyyübiye), which is close to the southern part of the study area, the lowest temperature value (6.23 °C) was observed in January, and the highest temperature value (32.95 °C) was observed in July. When all districts are taken into account, the average temperature values for the summer months (June-July–August) are between 29.62 and 31.68 °C, while the average temperature values for the winter months (December-January–February) vary between 5.32 and 7.74 °C. Şanlıurfa city (Eyyübiye) is the district center with the highest average temperature values in summer and winter months (Fig. 2). Due to the Mediterranean climate prevailing in the study area, it is seen that there are no extreme winter temperatures in the region, and the temperatures reach maximum values in spring and summer. It is observed that as one moves from the south to the north of the study area, changes in climate comfort conditions occur depending on the altitude increase and terrestrial conditions.

Relative humidity values in the study area vary between 28 and 76%. The highest relative humidity value (75.83%) was observed in Ceylanpınar district in December, while the lowest relative humidity value (28.25%) was observed in Şanlıurfa city (Eyyübiye) in July. While the average relative humidity values for the summer months (June-July–August) are between 30.27 and 39.8%, the average relative humidity values for the winter months (December-January–February) vary between 65.64 and 74.81%. The district centers with the highest (39.8%) and lowest (30.27%) average relative humidity values in summer are Birecik and Şanlıurfa city (Eyyübiye), respectively. The district centers with the highest (74.81%) and lowest (65.64%) average relative humidity values in winter months are Ceylanpınar and Şanlıurfa city (Eyyübiye), respectively. Although the relative humidity values rise above 65% in the winter months, it falls below 35% in the summer months (Fig. 3).

When the distribution map of the 12-month average wind speed data of the province between 2006 and 2021 (Fig. 4) is examined, it is seen that the average speed values vary between 0.5 and 3.00 m/s. The lowest average wind speed values (0.86–1.77 m/s) are in the autumn months; the highest average wind speed values (1.37–2.49 m/s) were determined in the summer months. The district center with the lowest average wind speed (0.70 m/s) is Hilvan (in November), and the highest (2.72 m/s) district center is Ceylanpınar. While the average wind speed values are high especially in the south and inner parts of the study area in summer months, the average wind speed values in the west (Birecik and Halfeti) and north (Hilvan) of the study area are low especially in February, October, November and December.

Spatial distribution of bioclimatic comfort zones for Şanlıurfa province

The bioclimatically comfortable zones in Şanlıurfa were evaluated according to the DI used in the study. According

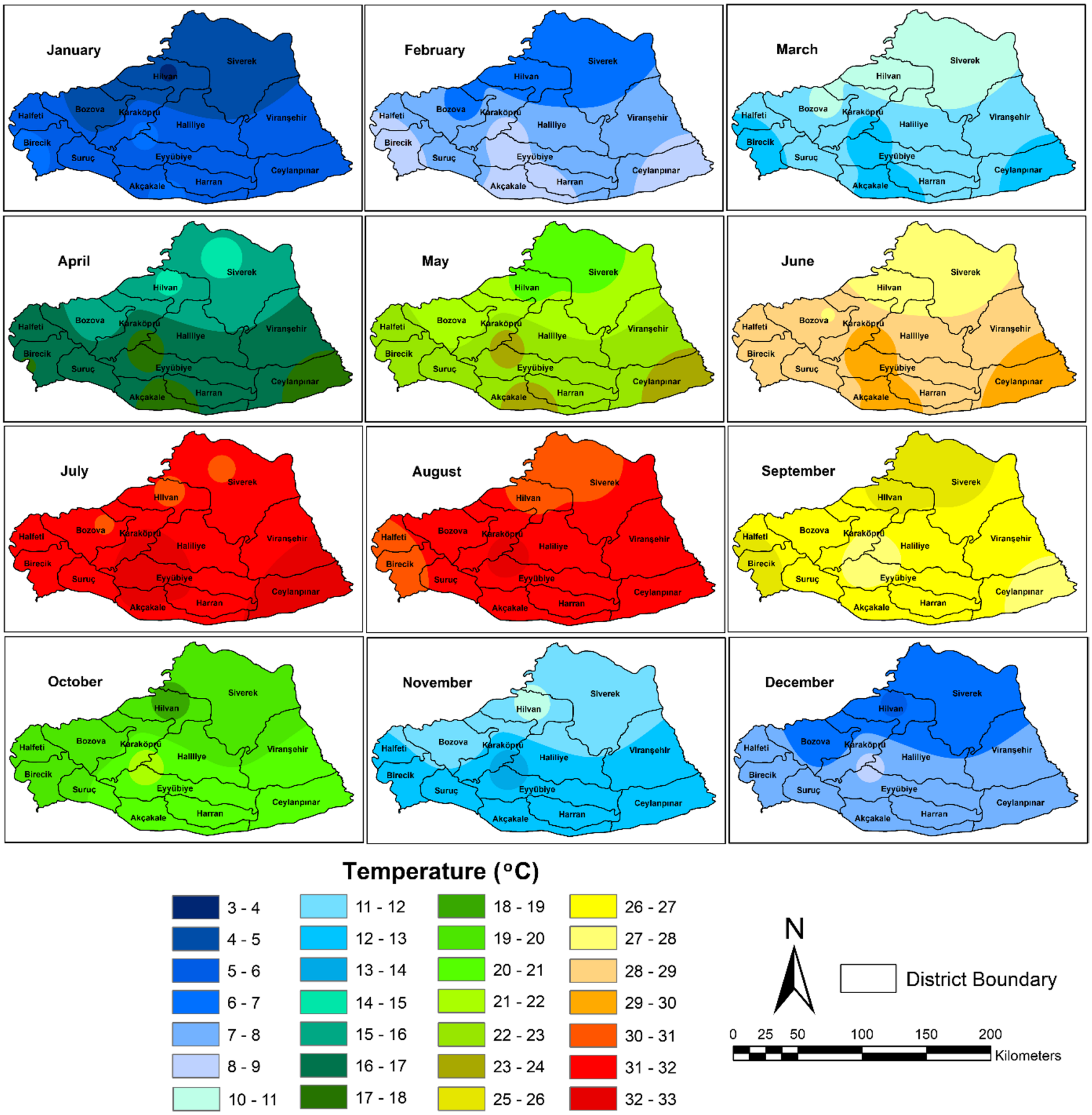

Fig. 2 Spatial distribution of average monthly temperature (from 2006 to 2021) in Şanlıurfa province

to the spatial distribution map obtained according to DI (Fig. 5), it was observed that extremely uncomfortable (DI < 12) zones were dominant in the entire study area in December, January, and February. Moreover, some of Hilvan and Siverek districts in November; all of Bozova, Hilvan, and Siverek districts in March; and some of Haliliye, Karaköprü, and Viranşehir districts were located in extremely uncomfortable (DI < 12) zones. The whole study area was represented by the category of partially uncomfortable (24 ≤ DI < 27) in July and August, the optimum (21 ≤ DI < 24) in June and September, and comfortable (18 ≤ DI < 21) in May. In October, large parts of Hilvan and Siverek districts and a small part of Bozova district were represented by the category of partially uncomfortable (15 ≤ DI < 18). Except for these three districts specified for October, all districts are in the comfortable (18 ≤ DI < 21) category. While some parts of Hilvan and Siverek districts were represented with the category of uncomfortable

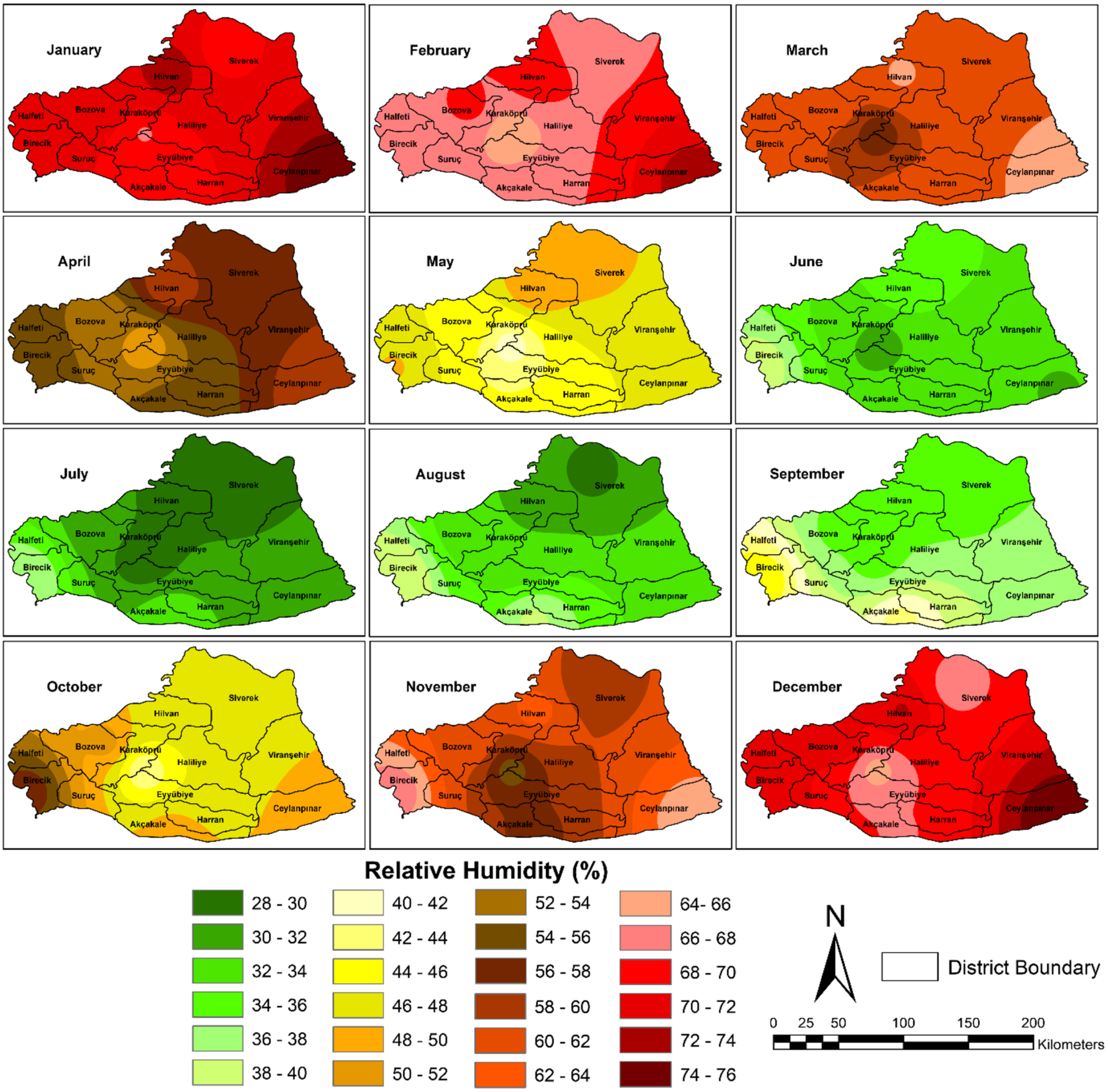

Fig. 3 Spatial distribution of average monthly relative humidity (from 2006 to 2021) in Şanlıurfa province

(12 ≤ DI < 15) in April, other parts of these two districts and all districts other than these two districts were located in partially uncomfortable zones (15 ≤ DI < 18). When a general evaluation is made in terms of bioclimatic comfort for the province of Şanlıurfa, June and September were determined as the optimum months, while October and May were determined as comfortable months.

In a study conducted by Kolbüken (2018), bioclimatic comfort conditions in Şanlıurfa province were evaluated for the 2013–2015 time period. The researcher used THI for the bioclimatic comfort analysis of the province and emphasized that April and October are the months when there is no thermal stress on people and comfortable thermal conditions (THI = 15–20 °C) prevail. The optimum zones we obtained according to DI in our study supported the researcher's results for October. The reason for the different values in terms of bioclimatic comfort in these two studies for April. The time intervals and the bioclimatic indices used are different. The prevailing air masses and facade systems in Şanlıurfa, province where continental Mediterranean climate characteristics are observed, have greatly affected the seasonal weather and bioclimatic

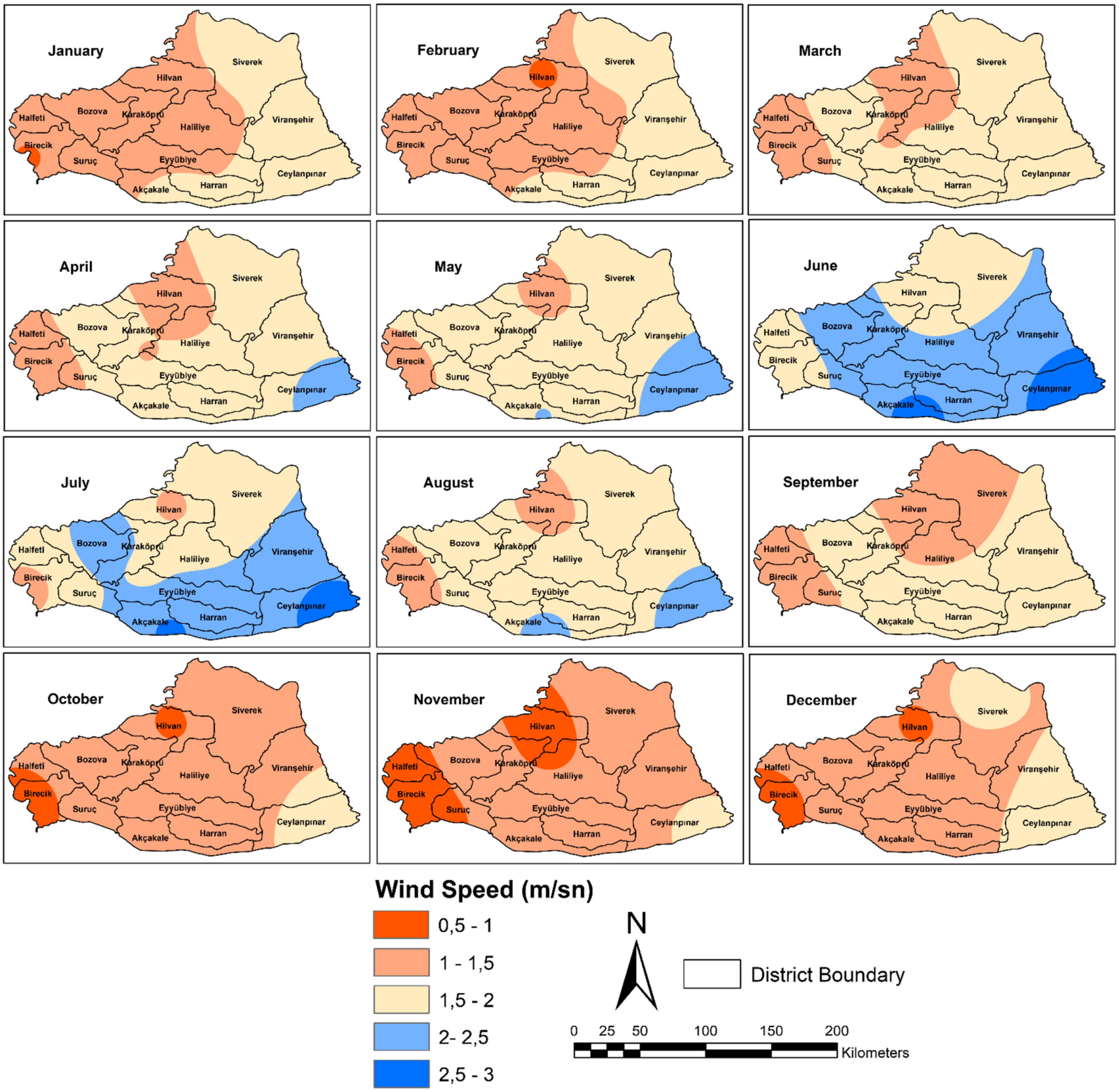

Fig. 4 Spatial distribution of average monthly wind speed (from 2006 to 2021) in Şanlıurfa province

conditions of the province (Kolbüken 2018). Gungor et al. (2021) revealed the bioclimatic characteristics of Mersin province using the PET index. According to the results of the researchers, September and May were determined as the optimum months in terms of bioclimatic comfort. The monthly PET results for Mersin, which has similar climatic characteristics to Şanlıurfa, supported the monthly DI results in our study.

Analysis of climate parameters for Şanlıurfa city

In Şanlıurfa city, the annual average temperature values for 16 years vary between 18.37 and 20.69 °C. The highest average annual temperature (20.69 °C) was seen in 2010, while the lowest annual average temperature (18.37 °C) was observed in 2011. While the month with the highest monthly average temperature value (32.96 °C) was July, the month

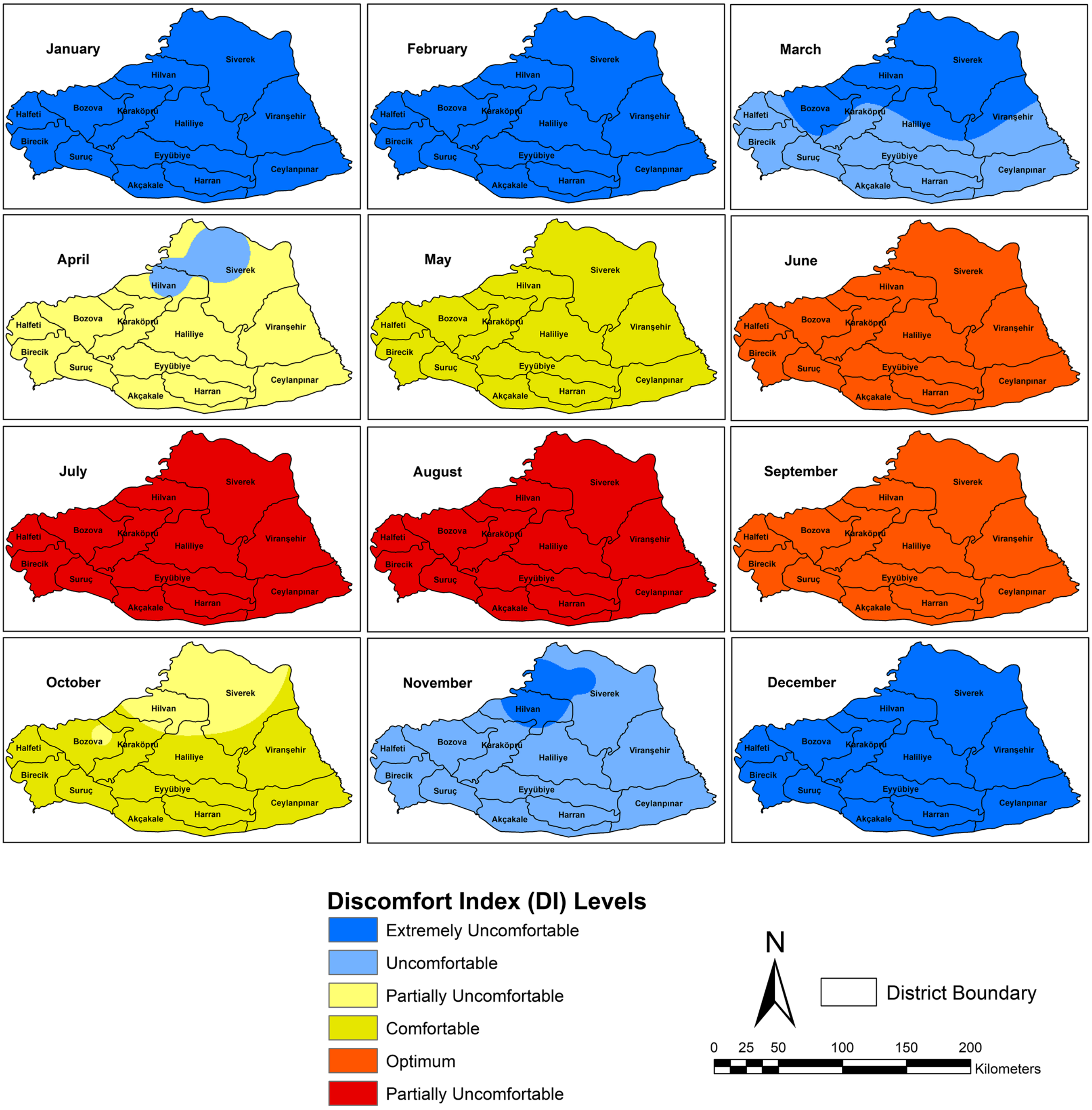

Fig. 5 Spatial distribution of bioclimatic comfort zones (from 2006 to 2021) in Şanlıurfa province

with the lowest monthly average temperature value (6.23 °C) was January. The highest annual average relative humidity (54.48%) and wind speed (1.73 m/s) were observed in 2007 and 2008, respectively. The highest monthly average relative humidity (67.84%) and wind speed (2.07 m/s) were observed in January and July, respectively (Fig. 6a, b, c; Fig. 7a, b, c).

Cetin (2015) and Zengin et al (2010) defined the range of 15–20 °C in terms of temperature parameter, the range of 30–65% in terms of relative humidity, and the range of 0–5 m/s in terms of wind speed parameter as "comfortable" in terms of bioclimatics. In the evaluation based on the annual average values, the years except 2010, 2018, 2020, and 2021 are "comfortable" according to the temperature values. All years were in the "comfortable" category according to humidity and wind speed values. According to monthly average values, April is "comfortable" in terms of temperature; In terms of relative humidity, the months except December, January and July were determined as

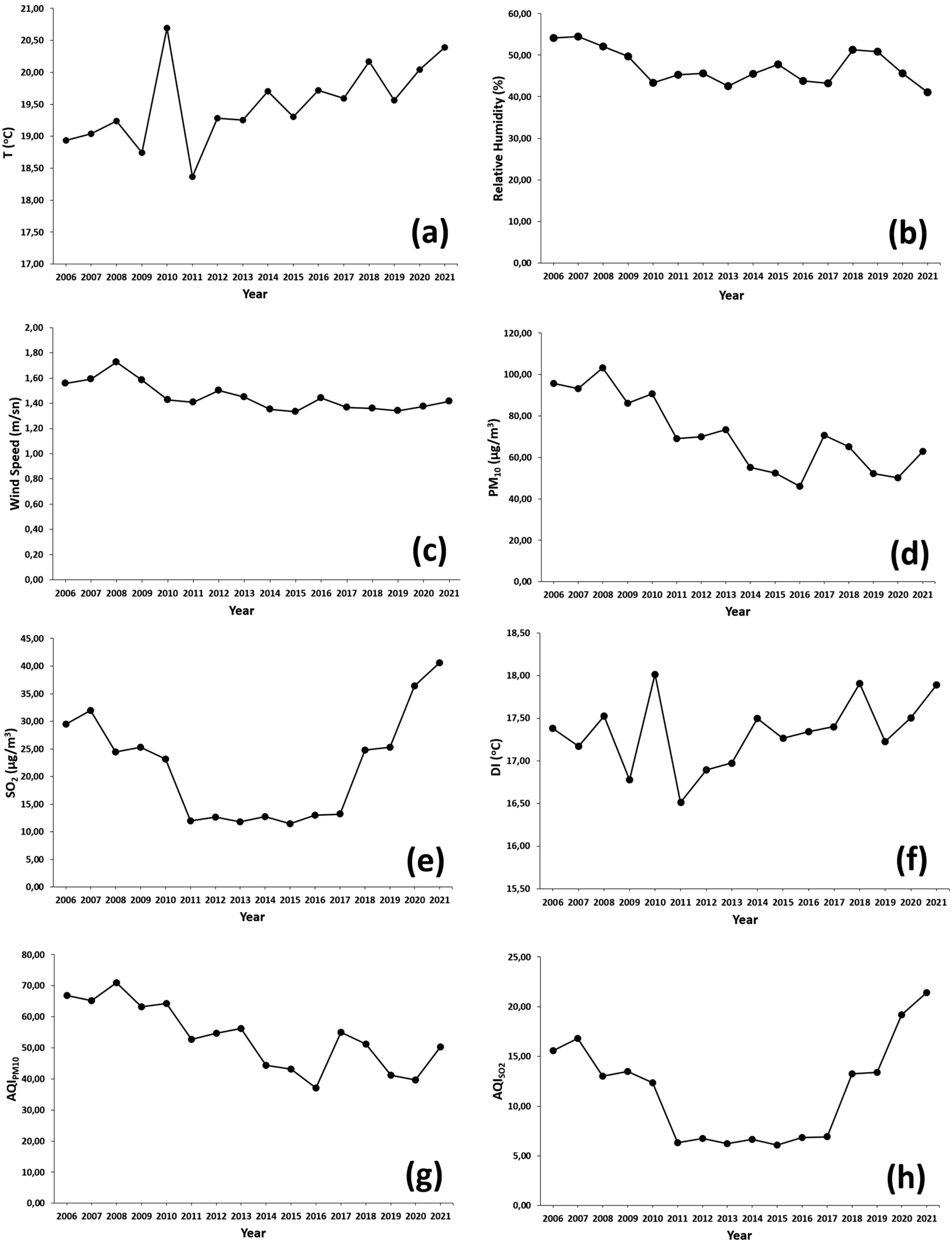

Fig. 6 Annually average values of meteorological parameters, air pollutants, DI, and AQI in Şanlıurfa city: **a** temperature, **b** relative humidity, **c** wind speed, **d** PM_{10} concentration, **e** SO_2 concentration, **f** DI, **g** AQI_{PM10}, **h** AQI_{SO2}

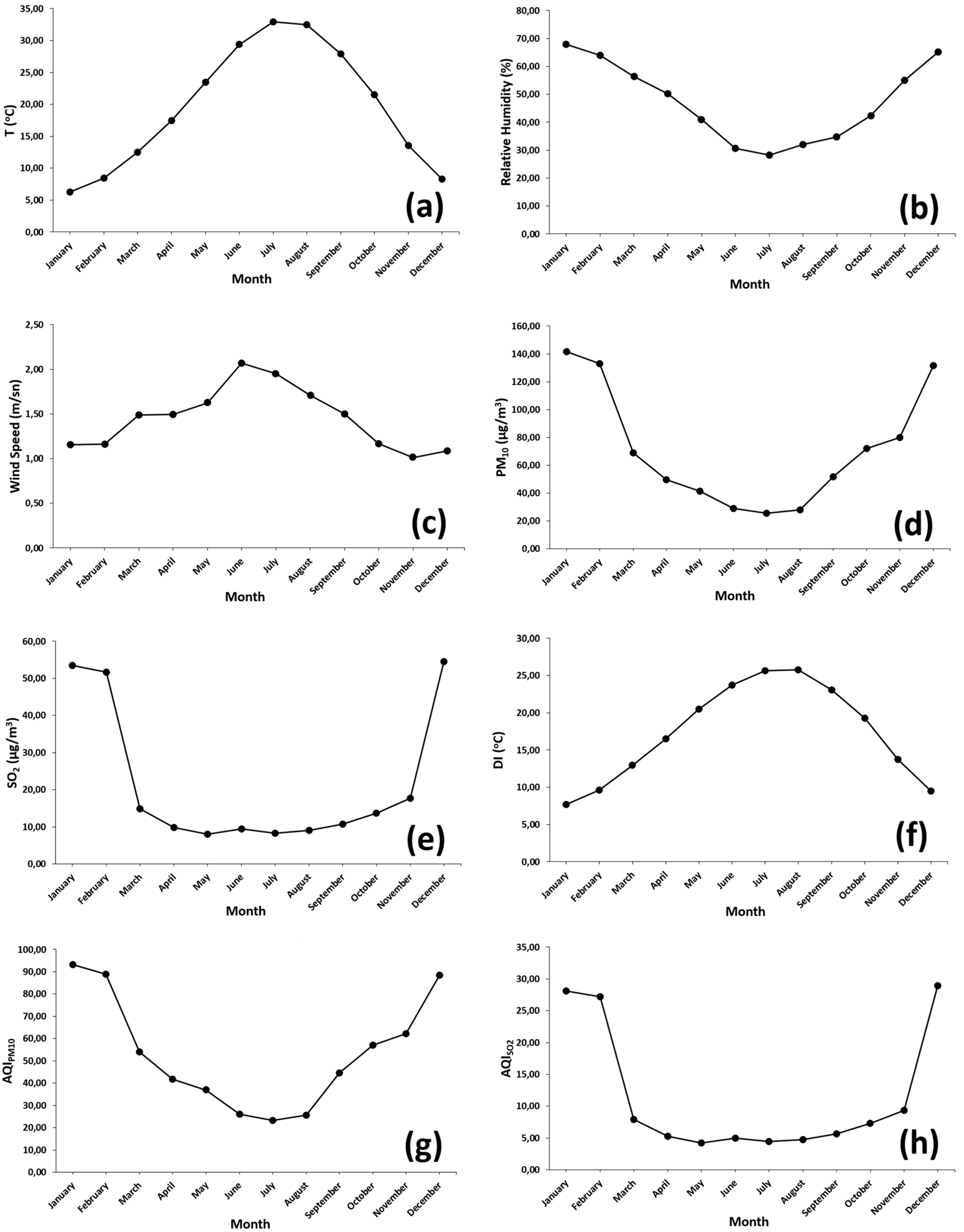

Fig. 7 Monthly average values of meteorological parameters, air pollutans, DI, and AQI in Şanlıurfa city: **a** temperature, **b** relative humidity, **c** wind speed, **d** PM_{10} concentration, **e** SO_2 concentration, **f** DI, **g** AQI_{PM10}, **h** AQI_{SO2}

"comfortable" and in terms of wind speed, all months were determined as "comfortable" (Fig. 6a, b, c; Fig. 7a, b, c).

Bioclimatic comfort analysis for Şanlıurfa city

Annual average DI values vary between 16.51 and 18.02 °C. Except for the DI value in 2010 (18.02 °C), DI values for all years are in the range of $15 \leq DI < 18$, and DI values for these years are defined as "partially uncomfortable" in terms of bioclimatics. The DI value for 2010 was categorized as "comfortable." When the monthly average DI values are examined, it is seen that the DI values vary between 7.69 and 25.75 °C. According to the DI evaluation range, December, January, and February were represented by the "extremely uncomfortable ($DI < 12$)" category; November and March were "uncomfortable ($12 \leq DI < 15$)"; April was "partly uncomfortable ($15 \leq DI < 18$)"; October and May were comfortable ($18 \leq DI < 21$)"; September and June were "optimum ($21 \leq DI < 24$)"; July and August were "partly uncomfortable ($24 \leq DI < 27$)" (Fig. 6f; Fig. 7f).

Air quality analysis for Şanlıurfa city

The PM_{10} and SO_2 values measured by the air quality measurement station in Şanlıurfa city were evaluated within the scope of the air quality standards determined by the WHO (2006). Annual average PM_{10} values between 2006 and 2021 exceeded the WHO (2006) air quality standard (annual average PM_{10} exposure: 20 µg/m^3) in all years. The 24-h monthly average PM_{10} values, which were determined according to the 24-h daily average values, exceeded the WHO (2006) air quality standard (24-h daily average PM_{10} exposure: 50 µg/m^3) in January, February, March, September, October, November, and December. Depending on the annual average values, the highest PM_{10} value (103.33 µg/m^3) was observed in 2008, and the highest PM_{10} value (141.45 µg/m^3) was observed in January, depending on the monthly average values. The year and month with the lowest PM_{10} values are 2016 (46.11 µg/m^3) and July (25.66 µg/m^3), respectively (Fig. 6d; Fig. 7d). Annual average SO_2 values exceeded the standard value determined by WHO (2006) for SO_2 (24-h daily average SO_2 exposure: 20 µg/m^3) in all years except 2011, 2012, 2013, 2014, 2015, 2016, and 2017. Monthly average SO_2 values were above the relevant standard value in January, February, and December. Depending on the annual average values, the highest SO_2 value (40.57 µg/m^3) was seen in 2021, and the highest SO_2 value (54.57 µg/m^3), depending on the monthly average values, was observed in December. The year and month with the lowest SO_2 values are 2015 (11.47 µg/m^3) and May (8.08 µg/m^3), respectively (Fig. 6e; Fig. 7e). The biggest reasons for the change in PM_{10} and SO_2 concentrations between certain years in 9 provinces in the Southeastern Anatolia Region of Turkey; transition from coal to natural gas for heating purposes, increase in the number of vehicles in traffic and population growth (Dogan and Atbinici 2022).

By using the concentration values of PM_{10} (24 h average) and SO_2 (1 h average) parameters belonging to the air quality monitoring station, with the help of the AQI calculation formula proposed by the EPA (2000), the annual and monthly average of the AQI for PM_{10} and SO_2 between the years 2006–2021 values were obtained. Depending on the annual and monthly average values calculated for the PM_{10} parameter, the highest AQI value (AQI_{PM10}) was in 2006 (71) and January (93.25), respectively; the lowest AQI value (AQI_{PM10}) was seen in 2019 (41.25) and July (23.31), respectively. In Şanlıurfa city, the use of coal for heating was switched to a clean energy natural gas system in 2010. When Fig. 6 d, e, g, and h is examined, the reason why both PM_{10} and SO_2 parameters were higher between 2006 and 2010 is the use of coal for heating in this time period. There are many studies on air pollution levels being higher in the winter months. These studies have been generally associated with an increase in coal use, civil heating, electricity generation, fossil fuel burning, industrial activity, vehicle exhausts, and adverse/stagnant meteorological conditions (Ma et al. 2019; Chen et al. 2019; Bilal et al. 2021). In a study conducted in 2022, the spatial–temporal changes of air quality in 5 cities of China (Shaanxi, Xinjiang, Gansu, Ningxia, and Qinghai) were determined. In this study, it was found that the highest AQI values according to seasonal changes increased due to the burning of coal for heating purposes in winter (Zaib et al. 2022). It has been determined that there are great differences in air pollution levels in Tehran (Iran) in cold and hot seasons, and it has been determined that both PM_{10} and SO_2 values increase due to the coal used for heating in the cold season (Amini et al. 2014).

For Şanlıurfa city, according to the annual average AQI values (AQI_{PM10}) calculated for the PM_{10} parameter, the AQI_{PM10} values for the years 2014, 2015, 2016, 2019, and 2020 are in the "good (0–50)" class, while all the years other than these years are "moderate (51–100)" class. According to the monthly AQI_{PM10} values, the months of April, May, June, July, August, and September are in the "good (0–50)" class; October, November, December, January, February, and March are represented by the "moderate (51–100)" class (Figs. 6g and 7g). Depending on the annual and monthly average values calculated for the SO_2 parameter, the highest AQI value (AQI_{SO2}) is in 2021 (21) and December (28.93), respectively. The lowest AQI value (AQI_{SO2}) was seen in 2011, 2013, and 2015 (6) and May (4.25), respectively. The monthly and annual average AQI values (AQI_{SO2}) calculated for the SO_2 parameter were included in the "good (0–50)" class in all years and all months (Figs. 6h and 7h). According to the AQI_{PM10} and AQI_{SO2} values calculated for all years and all months, the index pollutant was determined to be PM_{10}.

Saharan dust particles can adversely affect air quality in many parts of the world, such as the western and eastern Mediterranean, Europe, the Caribbean basin, the US, and South America. Different approaches have been used to identify and determine dust source regions such as remote sensing, surface dust observations, orbital analyzes, and mineralogical tracers (Kaskaoutis et al. 2019). In a study conducted in Morocco and Mauritania, the presence of strong Saharan dust storms was determined based on the HYSPLIT model, and the PM_{10} value was measured as 372 µg/m^3 (Qor-el-aine et al. 2021). In a study conducted for Şanlıurfa, using the HYSPLIT model, it was determined that dust was transported from the deserts in the Sahara, Syria, and Arabian Peninsula, especially in spring and autumn (Dogan et al. 2020). PM_{10} concentration values were above the WHO (2006) standards in the spring and autumn months due to the atmospheric particles transported from the Sahara and Syrian deserts to the study area (Fig. 7d).

Trend analysis for Şanlıurfa city

According to the annual average values, temperature, DI, SO_2, and AQI_{SO2} values between 2017 and 2021 increased, while relative humidity, wind speed, PM_{10}, AQI_{PM10}, and SO_2 and AQI_{SO2} values between 2006 and 2011 decreased (Fig. 6). Table 4 shows the MK (Mann 1945; Kendall 1975) trend analysis results for temperature, relative humidity, wind speed, DI, PM_{10} and SO_2, AQI_{PM10}, and AQI_{SO2} between 2006 and 2021. In cases where $p < 0.05$ and $p < 0.01$ conditions were met, increases and decreases in the trends of the parameters were found to be statistically significant. Monthly average temperature values increased in all months except July, but these increases were not statistically significant. According to the annual average temperature values, statistically significant increases were observed in the positive direction at the level of $p < 0.01$ ($r = 0.550$). A general decrease was observed in the monthly and annual average relative humidity values, and the decreases were statistically significant only in September ($p < 0.05$, $r = -0.400$) and October ($p < 0.05$, $r = -0.450$). Wind speed values decreased in all months except January. According to the monthly average wind speed values, the decreases in March ($r = -0.452$), April ($r = -0.498$), June ($r = -0.390$), July ($r = -0.432$), and November ($r = -0.441$) at $p < 0.05$ significance level showed statistical significance. Annual average wind speed values showed a decreasing trend at $p < 0.01$ significance level ($r = -0.517$). Monthly average DI values decreased in June, July, and August, while monthly average DI values and annual average DI values increased in all months other than these months. Increases and decreases in monthly and annual average DI values were not statistically significant. Monthly average PM_{10} values for all months and annual average PM_{10} values showed a decreasing trend. The decrease in the annual average PM_{10} values ($r = -0.650$) and the monthly average PM_{10} values of January, February, March, April, November, and December showed statistical significance at the $p < 0.01$ level. Monthly average values of SO_2 parameter were determined at $p < 0.05$ level in April ($r = 0.383$), and significant increasing trends were determined at $p < 0.01$ level in May ($r = 0.633$), June ($r = 0.567$), July ($r = 0.583$), August ($r = 0.550$), and September ($r = 0.500$) months. The increase in annual average SO_2 values was not statistically significant. The decreases in monthly average AQI_{PM10} values and annual average AQI_{PM10} values for the months of January, February, March, April, May, November, and December showed significance at the $p < 0.01$ level. Increases in monthly average AQI_{SO2} values for May, June, July, August, and September were found to be statistical significant at the $p < 0.01$ level, but decreases in annual average AQI_{SO2} values were not statistically significant (Table 4).

Pearson correlation analysis for Şanlıurfa city

The correlations between meteorology and air pollution parameters and the DI and AQI values calculated based on these parameters were revealed with the help of Pearson correlation analysis (Table 5). When the relations between the parameters mentioned here were evaluated according to Kibena et al (2014), there was a positive "strong" correlation between temperature and DI ($p < 0.01$, $r = 0.887$), a negative "weak" correlation between temperature and PM_{10} ($p < 0.01$, $r = -0.286$), a positive "moderate" correlation between RH and WS ($p < 0.05$, $r = 0.480$), a positive "strong" correlation between PM_{10} and WS ($p < 0.01$, $r = 0.815$), a positive "strong" correlation between AQI_{PM10} and WS ($p < 0.01$, $r = 0.784$), a positive "strong" correlation between AQI_{PM10} and PM_{10} ($p < 0.01$, $r = 0.992$), and a positive "strong" correlation between AQI_{SO2} and SO_2 ($p < 0.01$, $r = 1.000$).

There was a weak negative correlation ($r = -0.028$) between DI and AQI_{PM10} and a positive "moderate" correlation ($r = 0.449$) between DI and AQI_{SO2}, and these correlations were statistically significant at the $p < 0.05$ level. In addition, correlations between DI and PM_{10} and SO_2 were also significant at the $p < 0.05$ level. Hysenaj and Duraj (2021) stated that there is a strong negative correlation ($r = -0.876$) between temperature and PM_{10}, PM_{10} values increase in winter, peak in December–January, and the lowest value is in August. Hysenaj (2019) emphasized that vehicle emissions also increase PM_{10} values. According to Hysenaj and Duraj (2021), there is a weak correlation ($r = 0.21$) between RH and PM_{10}, which was defined as a positive relationship. When the RH value reaches 75%, it rises to a threshold value of PM_{10} and then the correlation

Table 4 Results of the MK test for the temperature (T), relative humidity (RH), wind speed (WS), discomfort index (DI), air pollutant concentrations (PM_{10} and SO_2), and AQI (for PM_{10} and SO_2)

Parameter	Kendalls value	Months												Annually average
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
T (°C)	r	0.346	0.269	0.042	0.117	0.168	−0.245	0.120	0.017	0.247	0.315	0.243	0.202	**0.550****
	p	0.064	0.149	0.822	0.528	0.367	0.190	0.526	0.928	0.189	0.094	0.191	0.279	0.003
	Trend													▲
RH (%)	r	−0.017	−0.183	0.017	−0.233	−0.300	−0.092	−0.226	−0.150	**−0.400***	**−0.450***	−0.159	0.100	−0.333
	p	0.928	0.322	0.928	0.207	0.105	0.620	0.224	0.418	0.031	0.015	0.392	0.589	0.072
	Trend									▼	▼			
WS (m/sn)	r	0.019	−0.221	**−0.452***	**−0.498***	−0.088	**−0.390***	**−0.432***	−0.045	−0.248	−0.120	**−0.441***	−0.382	**−0.517****
	p	0.924	0.252	**0.021**	**0.012**	0.647	**0.043**	**0.025**	0.817	0.207	0.543	**0.024**	0.060	**0.005**
	Trend			▼	▼		▼	▼				▼		▼
DI (°C)	r	0.333	0.283	0.050	0.083	0.133	−0.267	−0.100	−0.100	0.017	0.083	0.233	0.233	0.267
	p	0.072	0.126	0.787	0.653	0.471	0.150	0.589	0.589	0.928	0.653	0.207	0.207	0.150
	Trend													
PM_{10} (μg/m^3)	r	**−0.617****	**−0.650****	**−0.567****	**−0.550****	**−0.400***	−0.100	**−0.383***	−0.133	−0.050	−0.050	**−0.533****	**−0.550****	**−0.650****
	p	**0.001**	**0.000**	**0.002**	**0.003**	**0.031**	0.589	**0.038**	0.471	0.787	0.787	0.004	0.003	0.000
	Trend	▼	▼	▼	▼	▼		▼				▼	▼	▼
SO_2 (μg/m^3)	r	- 0.333	−0.183	0.167	**0.383***	**0.633****	**0.567****	**0.583****	**0.550****	**0.500****	0.300	0.150	−0.250	0.100
	p	0.072	0.322	0.368	**0.038**	**0.001**	**0.002**	**0.002**	**0.003**	**0.007**	0.105	0.418	0.177	0.589
	Trend				▲	▲	▲	▲	▲	▲				
AQI_{PM10}	r	**−0.628****	**−0.655****	**−0.577****	**−0.561****	**−0.410****	−0.111	−0.356	−0.126	−0.050	−0.034	**−0.518****	**−0.561****	**−0.650****
	p	0.001	0.000	0.002	0.003	0.007	0.556	0.058	0.499	0.787	0.857	0.006	0.003	0.000
	Trend	▼	▼	▼	▼	▼						▼	▼	▼
AQI_{SO2}	r	−0.329	−0.222	0.153	0.259	**0.565****	**0.574****	**0.550****	**0.578****	**0.498****	0.276	0.155	−0.288	0.067
	p	0.078	0.239	0.415	0.194	**0.005**	**0.003**	**0.004**	**0.003**	**0.004**	0.146	0.413	0.124	0.719
	Trend					▲	▲	▲	▲	▲				

**Correlation is significant at the 0.01 level (2-tailed).

*Correlation is significant at the 0.05 level (2-tailed).

Table 5 Pearson correlation coefficients between temperature, relative humidity, wind speed, DI, air pollutant concentrations (PM_{10} and SO_2), and AQI (for PM_{10} and SO_2)

Parameter	Pearson Correlation	T (°C)	RH (%)	WS (m/sn)	DI (°C)	PM_{10} (μg/m^3)	AQI_{PM10}	SO_2 (μg/m^3)	AQI_{SO2}
T (°C)	r	1							
	p	0.000							
RH (%)	r	−0.413	1						
	p	0.112	0.000						
WS (m/sn)	r	−0.425	0.**480***	1					
	p	0.101	0.0**49**	0.000					
DI (°C)	r	0.**887****	−0.089	−0.190	1				
	p	0.0**00**	0.742	0.480	0.000				
PM_{10} (μg/m^3)	r	−0.2**86****	0.467	0.**815****	−0.1**16***	1			
	p	0.0**03**	0.068	0.0**00**	0.0.**02**	0.000			
AQI_{PM10}	r	−0.287	0.416	−0.**784****	−0.**280***	0.9**92****	1		
	p	0.281	0.109	0.0**00**	0.0**43**	0.0**00**	0.000		
SO_2 (μg/m^3)	r	0.329	0.300	0.243	0.**248***	0.230	0.193	1	
	p	0.213	0.260	0.365	0.0**27**	0.391	0.473	0.000	
AQI_{SO2}	r	0.330	0.303	0.246	0.**449***	0.235	0.199	**1.000****	1
	p	0.212	0.254	0.359	0.0**36**	0.381	0.461	0.0**00**	0.000

**Correlation is significant at the 0.01 level (2-tailed).

*Correlation is significant at the 0.05 level (2-tailed).

ends. RH affects the natural precipitation process of PM_{10}, whereby moisture particles adhere to PM_{10} and accumulate atmospheric PM_{10} concentration (Hysenaj and Duraj 2021). According to Xu et al (2020), AQI values are affected by the temperature at which the AQI concentration will be low during the summer. While AQI values are high in winter, AQI values decrease in summer, which improves air quality. Mavrakis et al. (2021) have found a significant positive correlation ($r = 1.00$) between T and DI, a negative correlation between RH and DI ($r = -0.57$), a positive "strong" correlation between DI and AQI ($p < 0.01$, $r = 0.81$), and a positive "strong" correlations between PM_{10} and SO_2 and AQI values ($p < 0.01$, $r = 0.86$; $p < 0.01$, $r = 0.59$). Poupkou et al. (2011) emphasized that daily DI values (≥ 24 °C) may be related to increasing temperature rather than relative humidity, and that there is a strong correlation between these DI values and high and very high AQI values.

This strong correlation is an indication that the high PM_{10} concentrations are due to a Sahara dust transport episode. The calm conditions in the area favored high PM_{10} concentrations (Mavrakis et al. 2021). Although there was a positive correlation between SO_2 and PM_{10}, this correlation was not statistically significant. This may indicate that the contributions to these two pollutants from PM sources are not the same. The positive correlation of PM_{10} with WS indicates that this parameter contributes to the increase of pollutant concentration (Adesina et al. 2022). It can be seen that there is a negative linear correlation between PM_{10} and temperature, the content of these pollutants will decrease as the temperature increases. This negative correlation indicates that the temperature change has a large effect on the PM_{10} content (Di and Li 2019). Decreasing and increasing outdoor temperature influence the weather stability and as a result disturb outdoor PM concentration. Different studies report inverse relationship between ambient temperature and outdoor PM species concentration (Chan, 2002). Air quality in coastal cities is mainly affected by monsoons or other climatic conditions such as atmospheric pressure. Air quality in coastal cities is mainly affected by monsoons or other climatic conditions such as atmospheric pressure. The diffusion effect of the wind can cause a positive correlation between PM_{10} and SO_2 pollutants and wind speed (Li et al. 2021). While temperature is negatively related to AQI, relative humidity has a positive effect on AQI (Qin et al. 2020). Having wind speed is used to take advantage of the use of low wind weather. Wind speed is a factor that increases in atmospheric air conditions (Afzali et al. 2014). Low wind speed affects PM_{10} in the atmosphere. Extensive ventilation of air masses at stations and removal of air pollutants over a remote area can cause a negative correlation between wind speed and PM_{10} (Tella et al. 2021). Since the DI parameter is directly related to temperature, it is quite normal to have a negative correlation between PM_{10} and DI. The results of the correlation analysis for Şanlıurfa city supported the literature information mentioned above.

Conclusion

This study revealed the correlation and temporal variation of thermal comfort and air quality levels in Şanlıurfa province. GIS-based bioclimatic comfort mapping based on DI was obtained only for Şanlıurfa province border, and all other analyzes conducted in the study were performed for Şanlıurfa city (Eyyübiye). Considering the general climatic characteristics of Şanlıurfa, when going from the south to the north of the study area, it is observed that the climate comfort conditions change depending on the altitude increase and terrestrial conditions. In terms of bioclimatic comfort in Şanlıurfa, according to monthly average DI values, June and September were the optimum months, while October and May were the comfortable months. According to the monthly average temperature, relative humidity, and wind speed parameters of the Şanlıurfa city, April was "comfortable" in terms of temperature. The months except December, January, and July were determined as "comfortable" in terms of relative humidity, and all months were determined as "comfortable" in terms of wind speed. Due to increasing temperature and decreasing relative humidity, DI values decreased partially over a 16-year period, and DI values were defined as partially uncomfortable ($15 \leq DI < 18$) in terms of bioclimatic comfort during this period. For those living in the Şanlıurfa city, December, January and February were extremely uncomfortable ($DI < 12$) months in terms of thermal discomfort. According to the results of the trend analysis, while the increase in temperatures was statistically significant ($p < 0.01$), the increases in DI were insignificant; decreases in wind speed, PM_{10}, and AQI_{PM10} were significant ($p < 0.01$); decreases in relative humidity and AQI_{SO2} were insignificant. Fluctuations in SO_2 values due to both increases and decreases were emphasized as insignificant. The results of the MK trend analysis test revealed statistically significant increases and decreases when the conditions of $p < 0.05$ and $p < 0.01$ were met. According to the results of Pearson correlation analysis revealing the relationship between thermal comfort and air quality levels, there was a weak negative correlation ($p < 0.01$) between DI and AQI_{PM10}, and a moderate positive correlation ($p < 0.01$) between DI and AQI_{SO2}. According to this analysis, it was determined that SO_2 concentration had a significant effect on air quality.

GIS-based bioclimatic comfort mapping is very important in terms of creating local strategy plans in urban areas for adaptation to climate change studies and integrating them into regional plans and policies. It can be said that there is a positive relationship between the poor air quality caused by high PM_{10} and SO_2 levels that may have been transported from the Sahara Desert to Şanlıurfa province and thermal disturbance conditions. Establishment of urban climate and air quality monitoring systems is very important in terms of measures to be taken in the coming years in order to accurately evaluate and associate the relationships between bioclimatic conditions and air pollutant levels in cities. In other provinces with climatic conditions similar to Şanlıurfa, the importance of long-term bioclimatic comfort conditions in semi-arid regions should be revealed and necessary plans should be made considering the negative effects of climate change. Emphasis should be placed on research combining thermal comfort and air quality to improve the health and well-being of the urban population and achieve environmentally sustainable urbanization.

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Data availability Data are available upon request on the corresponding author.

Code availability Not applicable.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no conflict of interest.

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