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Research Article

An Assessment of Long-Term Urban Heat Island Impact on Istanbul's Climate

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Abstract

It is critical to investigate the relations between urban heat island, population growth, and changes in the urban land use due Megacity Istanbul's significant urban population increase and rapid rate of its unplanned urbanization. The aim of this work is to study the local climate change and the effects of urbanization on urban climate of megacity Istanbul. Temporal variations of urban heat island (UHI) and UHI intensity in Istanbul were analyzed by using air temperature data measured by five meteorology stations for the period of 1951–2020. Minimum, maximum, and mean temperature data of Istanbul were used to understand the possible impacts of urbanization on the climate of the megacity. In addition, Corine Land Cover (CLC) datasets for the years 1990, 2000, 2012, and 2018, were used to visualize the spread of urban cover throughout the city. Seasonal observation data were statistically tested for monotonic trends. Significant upward trends in temperature were found in all selected stations, both rural and urban. The air temperature in urban areas, densely populated residential areas of the Istanbul, has increased more in years compared to its rural parts. The results showed an increase in night time (minimum temperature) temperature in both urban and rural stations between 0.010 – 0.047 °C yr^{-1} and an increase in daytime (maximum temperature) in all stations between 0.026 – 0.034 °C yr^{-1}. The urban heat island impact increased over time in Istanbul with the expansion of the urban areas toward rural areas further reducing green areas.

Keywords: Urban Heat Island, Urban Temperature Trends, Climate Change, Istanbul

Introduction

Urbanization is a complex transformative process that converts formerly rural areas into urban settlements causing a shift in population from rural to urban areas. General population and migration trends show that the majority of the world's population is urban since more than half of the world's people already living in urban areas (UN, 2018). Size of the population living in cities, as well as the number of cities, will continue to grow, driven mainly by migration from rural to urban areas and from abroad as well as the urbanization of formerly rural areas (Lerch, 2017).

The population size and growth rate of urban areas highlight environmental problems, one of which is exposure to effects of climate change, caused by urbanization. Urban population is exposed to the effects of climate change at an elevated level due to modifications on the surface radiation and energy balances generally due to irregular urbanization and lack of planning the expansion of the cities. An example of this is the heat absorption of concrete urban surfaces which modifies micro climatic properties leading to increase in air temperature within urban areas compared to their neighboring areas and close proximity rural areas (Oke 1982). This difference in surface and air temperatures between an urban area and its surroundings is called urban heat island (UHI) (Landsberg, 1981; Oke 1982, 1987; Roth et al., 1989; Voogt and Oke, 2003; Arnfield, 2003; Imhoff et al., 2010; Yang et al., 2016; Sobstyl et al., 2018; Philipps et al., 2022; Çolakkadıoğlu, 2023).

In previous studies, UHI is result of lack of vegetation and surface moisture, atmospheric pollution levels, canyon/tunneling effects of buildings, and concrete surface areas (Vailshery, 2013; Czarnecka and Nidzgorska-Lencewicz, 2014; He, 2018; Ulpiani, 2021). Urbanization often coupled with industrialization induce drastic changes in local and regional climatic characteristics. Greatly reduced vegetation cover and dense irregular urban areas trap high amounts of heat with more heat being added continuously from anthropogenic sources further reinforcing UHI intensity (Oke, 1987; Karaca et al., 1995a and b; Chen et al., 2006). In literature, virtually every city that has been studied have experienced long-term increases in UHI intensity have also been subjected to large population increases (Karaca et al., 1995a, 2000; Ezber et al., 2007; Ozdemir et al., 2012; Kaya et al., 2012, Dihkan et al., 2018; Das, 2022) especially in the developing countries where the population growth is tremendous.

The aim of this study is to investigate the impact of urban heat island intensity, fueled by rapid irregular urbanization, high volume of migration, and population increase, on Istanbul's local climate. Trends and drastic changes that occurred in the Istanbul's climate within the last fifty years were studied and effects of urbanization, urban heat island, and climatic results were discussed.

Materials and Methods

Istanbul has ranked among the largest cities in the world. Address Based Population Registration System of The Turkish Statistical Institute (TurkStat) reported Istanbul Metropolitan Municipality's population as 15,462,452 (at the end of 2020) (Figure 1), making up 18.49% of Türkiye's total population. Additionally, Istanbul has the highest population density with 2,910 persons per square kilometer (TurkStat, 2020). In Figure 1, population trend of Istanbul over the years, between 1927-2020, is given. Population trend starts to show a significant increasing trend after 1960s. From the same figure a sharper upward trend can be observed after 1980s when urbanization, irregular for the most part, rate also increases.

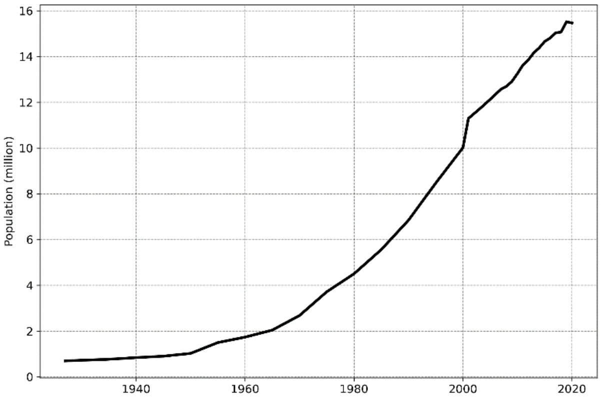

Fig. 1. Population of Istanbul between 1927-2020.

Geographically, Istanbul is located in the northwestern Türkiye on two continents, Europe and Asia, divided by the Bosphorus strait which is connecting the Black Sea with the Marmara Sea. Istanbul has a total area of 5,460.85 km2, 3,474.35 km² of its being European side (25 districts) and 1,868.87 km² Asian side (14 districts). Total urban area of the city is 2,576.85 km², 47.18% of total area. Most of the urban areas are relatively recent due to rapid growth during the second half of the 20th century, with its sharp population increase after 1980s (Figure 1), main reason of this growth is the mass migration from Anatolia. Urbanization direction is generally in a South - North direction along both shores of the Bosphorus and East – West direction parallel to the Marmara Sea. Effects of rapid urbanization can be seen at northern regions in last decade, i.e. the shore of the Black Sea where is still relatively less populated than southern regions. It should be noted that with the opening of the third Bosphorus Bridge and the new airport (Istanbul Airport) will result in further northern expansion and reduction of the northern forested areas in Istanbul.

In Figure 2, five meteorological stations that were selected for this study are shown. These stations are operated by the Turkish State Meteorological Service (TSMS) and selected due to their long observation records. In Table 1, location, elevation, data period, and characterization of the stations are given. In this study, two urban (Kadıköy and Florya), and three rural (Sarıyer, Şile, and Kumköy) stations were used (Figure 1). The datasets contain monthly averages of maximum, minimum, and mean temperatures. Precipitation and wind data weren't used since the aim of the study is to detect major urbanization effect on local climate. These climatic variables are subjects of other studies. One of the main reasons to focus on temperature is the variations in temperature are also good indicators of climatic variations. Temperature time series alone include wide range of climatic changes for micro-scale to macro-scale. Measurements in each station starts from a different date (Table 1). Study period was chosen as 1951 to 2020. Stations had small discontinuities (0.39 to 1.44 percent) as well as duplicates. Duplicates were removed and missing data were gap filled, using observations as predictors of missing data, by interpolating the data of the same month from the previous and the following year (Alexandersson, 1986).

Fig. 2. Location of meteorology stations

Urban classification was done by taken into several criteria, most importantly, population and urban area to total area of the district – neighborhood. The areas classified as urban are Florya and Kadıköy. Florya is located in the southern coast of the European part of Istanbul a part of Bakırköy district. It used to be neighbor of the Ataturk airport, which was one of the busiest airports in Europe until its closure in 2019. Florya is a fairly affluent residential area and has a station along the Marmaray Intercontinental Commuter Line. Other urban area is the district of Kadıköy where is located in the Asian side of Istanbul, the northern shore of the Marmara Sea. Kadıköy is the cultural center of the Asian side of Istanbul and host of more than 500.000 residents.

Three locations that were classified as rural are Sarıyer (Kireçburnu), Kilyos-Kumköy, and Şile. Both Kireçburnu and Kilyos-Kumköy are located in the same district, Sarıyer, however they have distinct differences in meteorological and topological characteristics due to their locations within the district. In this study Sarıyer station will be referred as Kireçburnu since this station is usually referred as such, located close to district center (Figure 2) and Kilyos-Kumköy will be referred as Kilyos for the sake of clarity, a typical coastal rural area located on the shores of the Black Sea even though it has experienced a slight increase in population in the past decades. Şile is another coastal rural area and a district of Istanbul on the Black Sea coast of the Asian side. Kireçburnu, Kilyos, and Şile, three rural stations, are characterized by forest areas, one- or two-story buildings, and low-density residential areas whereas Florya and Kadiköy, urban areas, characterized by dense residential and commercial buildings and limited green spaces.

Table 1. The characteristics and the classifications of the stations

Stations	Latitude	Longitude	Elevation (m)	Type	Data Years
KİLYOS	41.25N	29.03E	38	Coastal-Rural	1951-2020
KİREÇBURNU	41.14N	29.05E	59	Coastal-Rural	1949-2020
ŞİLE	41.16N	29.60E	83	Coastal-Rural	1939-2020
KADIKÖY	40.98N	29.01E	5	Urban	1929-2020
FLORYA	40.97N	28.78E	37	Coastal-Urban	1937-2020

Table 2. Linear change in temperature (mean, minimum, maximum) over the years

1951-2020	**Average temperature change (°C yr^{-1})**	**1951-2020**	**Average temperature change (°C yr^{-1})**
Stations	T_{mean}	**Stations**	T_{mean}
KİLYOS	0.0195	KİLYOS	0.0195
KİREÇBURNU	0.0179	KİREÇBURNU	0.0179
ŞİLE	0.0126	ŞİLE	0.0126
KADIKÖY	0.0294	KADIKÖY	0.0294
FLORYA	0.0253	FLORYA	0.0253

Additionally, in order to visualize the spread of the urban canopy Copernicus Land Monitoring Service (CLMS)'s CORINE Land Cover (CLC) datasets (CLMS, 2023) were used. Years 1990, 2000, 2006, 2012, and 2018 are available through these datasets. CLC datasets are based on the classification of satellite images. Datasets spatially cover Europe including Türkiye. It has 44 classes in the hierarchical 3-level CLC nomenclature; minimum mapping unit (MMU) for status layers is 25 hectares; minimum width of linear elements is 100 meters. In this study, classes that were used are as the following; 111 - Continuous urban fabric, 112 - Discontinuous urban fabric, 121 - Industrial or commercial units, 133 - Construction sites, and 141 - Green urban areas.

Results

Time series of all stations show a slight increasing trend (Figure 3). From Table 2, it can be seen that Kadıköy has the highest mean temperature increase with 0.0294 °C yr^{-1} and highest minimum temperature increase with 0.0468 °C yr^{-1}. However, maximum temperature was observed in Kilyos station with 0.0342 °C yr^{-1}. Second highest mean and minimum temperatures were recorded by Florya station with 0.0253 °C yr^{-1} and 0.0311 °C yr^{-1}, respectively. For maximum temperature the second highest values were observed in Şile station with 0.0278 °C yr^{-1}. Highest values of mean and minimum temperatures are both observed in urban stations while maximum temperature values were observed in rural stations. These results agree with the effect of urbanization and impact of UHI since in urban areas minimum temperature increase significantly more than rural stations due to drastic change in land cover and land use, generally shrinking green spaces and greater urban surface area. None of the stations showed a cooling trend, only varying degrees of warming.

In Figure 3, time series of maximum and minimum temperatures of the selected stations were given. The gap between the maximum and the minimum temperatures in rural stations are more or less the same throughout the years. However, in urban stations this gap between maximum and the minimum temperatures are getting narrower especially in the last two decades. For example, minimum temperature increase in rural areas is range between 0.0104 – 0.0215 °C meanwhile in urban stations this range is 0.0311 – 0.0468 °C. This clearly shows the impact of urbanization on local climate. Since minimum temperature, night time temperatures, is a good proxy of urban heat island effects it gives useful information between different stations (Karaca et al., 1995 a and b). This in fact applies to the two urban stations that were selected for this study. There is a clear difference in minimum temperatures between them with Kadıköy having the higher values (0.0468 °C yr^{-1}) than Florya (0.0311 °C yr^{-1}) which physically makes sense considering Kadıköy is more densely and irregularly urbanized. In Florya most buildings are one- or two-stories while Kadıköy has no floor restrictions amplifying UHI effects. Same difference can be observed among rural stations too. Kireçburnu which is located close to the center of Sarıyer district has significantly higher minimum temperature (0.0215 °C yr^{-1}) compared to Şile station (0.0104 °C yr^{-1}) but slightly higher compared to Kilyos station (0.0192 °C yr^{-1}) which is also located in the same district, Sarıyer, but north of Kireçburnu at the coast of Black Sea. Şile is a coastal rural area and the least urbanized compared to all other stations in this study so the results actually agree with urbanization levels. However, even though Şile is the least urbanized area among other stations, still, a sharp increase in temperature can be observed after 2005. In recent years northern forested and less populated rural parts of Istanbul such as Şile is going under heavy urbanization mainly due to rapidly increasing population and northern expansion of the city.

In Figure 4, UHI intensity differences between urban and rural stations (T_{urban} - T_{rural}) are given. In the same figure, crossing points of the T_{min} and T_{max} lines signify the impact of urbanization. These points showed the time when urbanization started to affect the local climate and air temperature. For the most urban (Kadıköy) and rural (Şile) stations there is significant trend dictated by urbanization and rapidly increasing population. The highest minimum and mean temperature differences were these two stations with 0.0364 °C yr^{-1}, 0.0167 °C yr^{-1}, respectively (Table 3).

In general, all urban – rural differences have an increasing T_{min} and T_{mean} trend of different magnitudes based on their urbanization level. For the maximum temperature differences there is a declining trend for all comparisons but Florya – Kireçburnu (0.0004 °C yr^{-1}) which doesn't have any significant trends which can be attributed to the urban structure of Florya. The highest difference in Tmax was between Florya and Kilyos. These stations are located in southern part of Istanbul on the coast of Marmara Sea (Florya) and located on northern part of Istanbul on the coast of Black Sea (Kilyos) which might explain the maximum temperature difference.

Based on the speed of urbanization and population increase rate minimum temperatures over time will increase meaning night time air temperature will increase leading to higher average temperatures overall (Table 2). Kadıköy – Şile is the clearest example of this, rapid urbanization in Kadıköy lead to sharp increase in night time temperature exceeding day time temperature differences starting from 1997 with a widening gap between day and night time differences. From Table 3 it can be seen that mean temperature difference is also increasing which is another sign of urbanization's impact on local climate.

Table 3. Linear change of difference between urban and rural stations (mean, minimum, maximum temperature) over the year

1951-2020	Average temperature change (°C yr^{-1})		
Station Difference	**Tmean**	**Tmin**	**Tmax**
FLORYA – KİLYOS	0.0050	0.0112	-0.0078
KADIKÖY -KİREÇBURNU	0.0115	0.0253	-0.0009
KADIKÖY - ŞİLE	0.0167	0.0364	-0.0018
KADIKÖY - FLORYA	0.0040	0.0156	-0.0013
FLORYA - KİREÇBURNU	0.0074	0.0096	0.0004

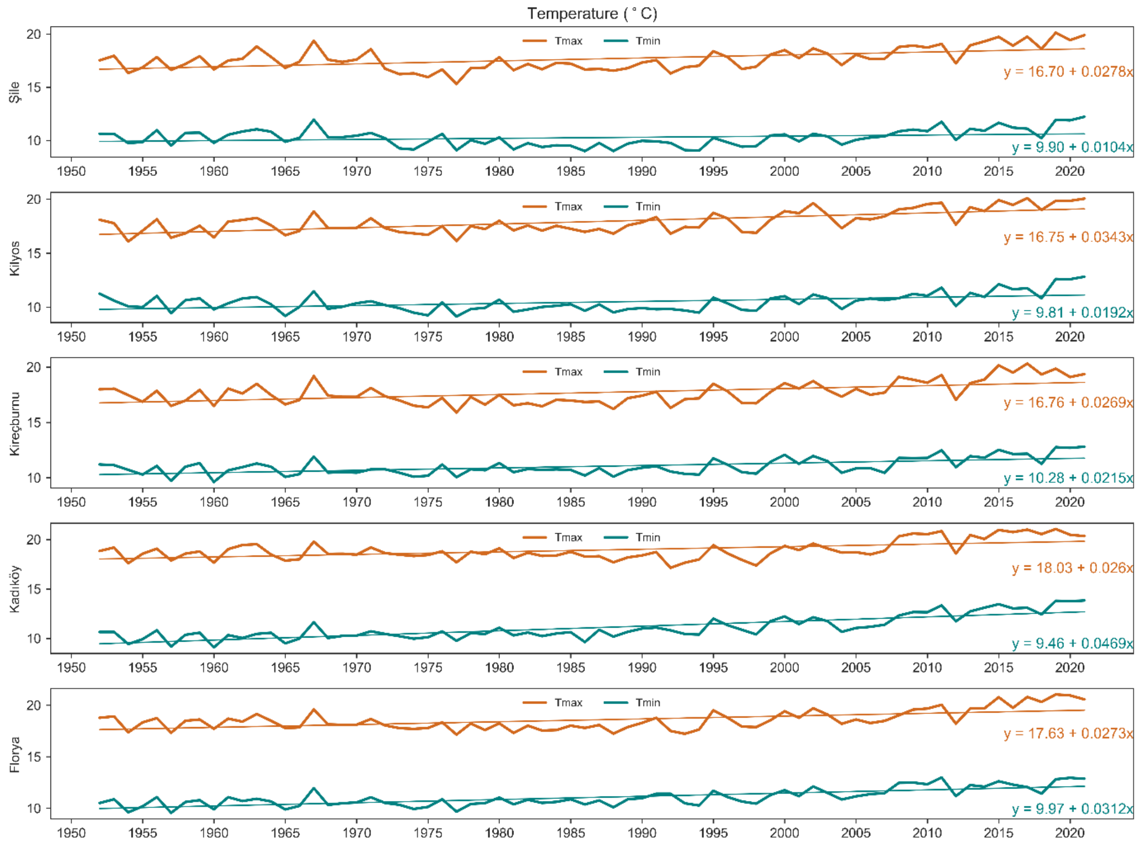

Fig. 3. Maximum and minimum temperature time series of selected stations.

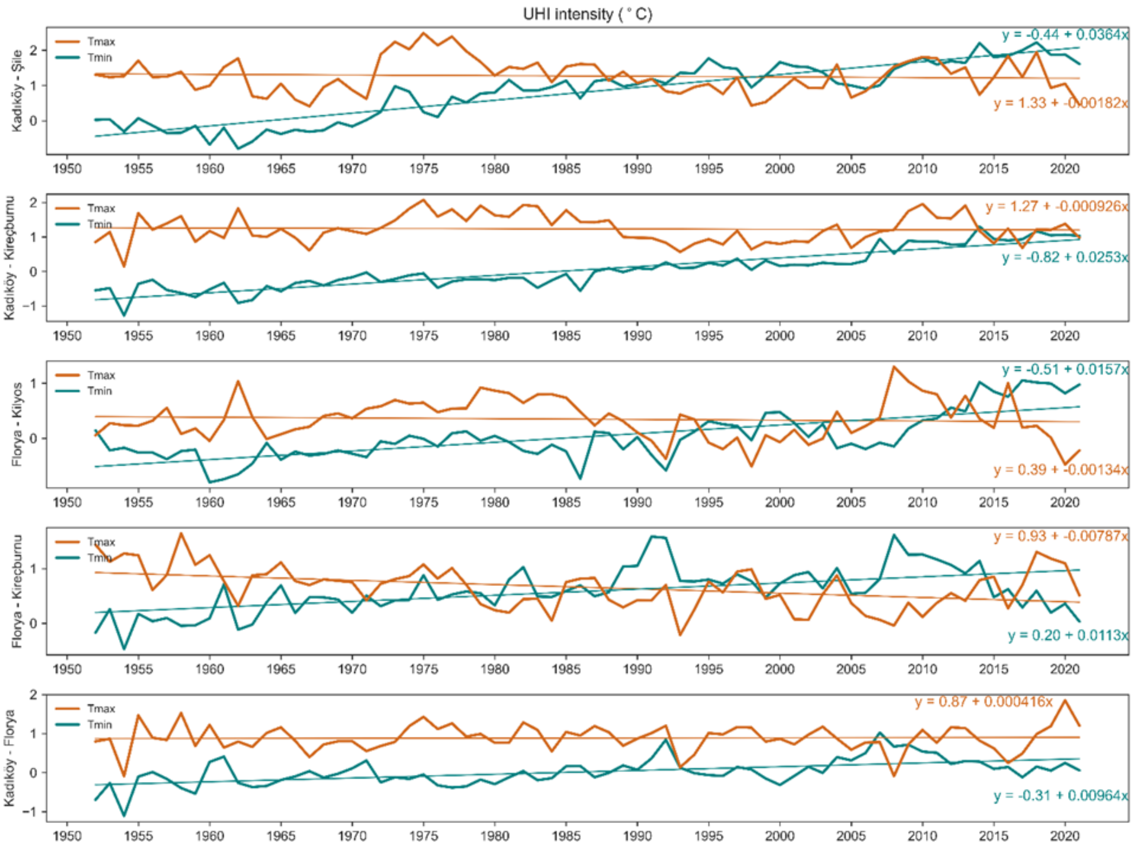

Fig. 4. UHI intensity (Urban – Rural Difference) time series

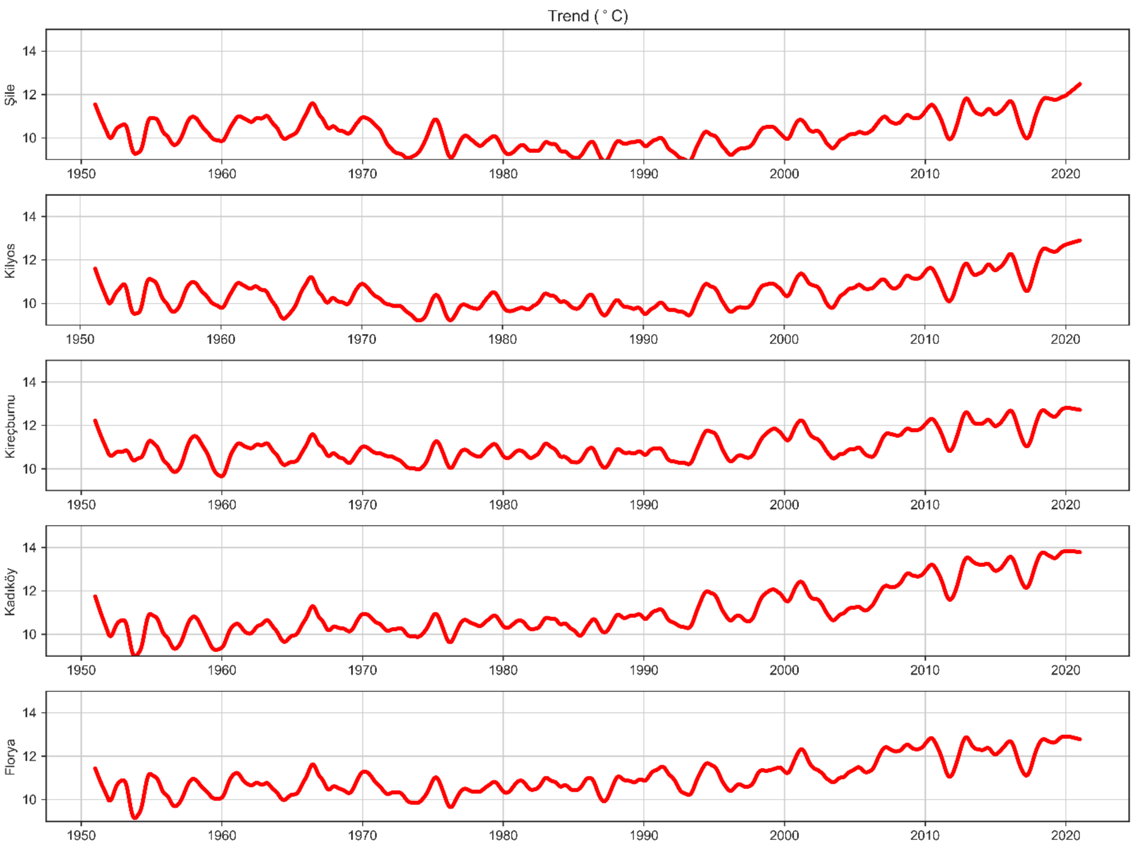

Fig. 5. Seasonal and Trend decomposition using Loess for each station

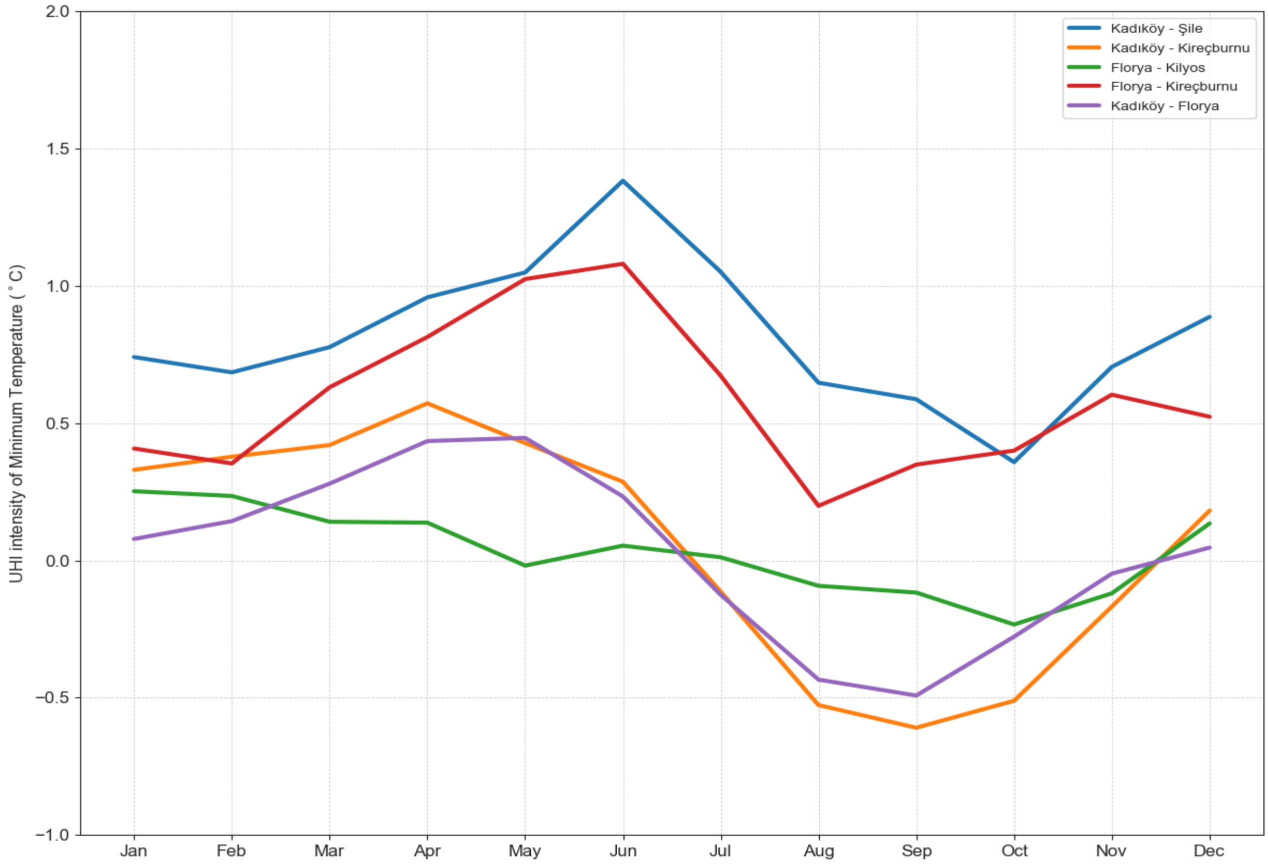

Fig.6. UHI nighttime (minimum temperature) intensity.

In this study, the underlying trends in the temperature data were also examined using Seasonal and Trend decomposition using Loess (STL) method. It is used for decomposing a time series data into three components; seasonality, trend, and residual. By removing the regular recurring patterns that happen at a fixed interval of time the overall tendency is revealed. In this study's perspective it is the underlying trends of night time temperature differences between urban and rural locations.

Figure 5 displays the trends in minimum temperatures for the study stations. Urban stations are showing a n significant increasing trend towards the present day with Kadikoy having the steeper trend among other stations. From the same figure it can be easily seen that the trends for every station after year 2000 are increasing. Significance of this year is that the irregular urbanization sped up which can also be seen in the land use change maps too. In Figure 6, the UHI intensity of minimum temperatures for each month (average of 1951-2020) were given to show the urban and rural differences for different seasons. Results shown in this figure are supporting the other indicators of UHI impact. Kadikoy has the biggest difference in month of June with 1.4 °C. Significance of summer months' minimum temperature difference is that due to urbanization cities cannot cooldown during night time. Similar effects can be seen during winter months too. In addition to build up due to urban density other factors such as residential heating also are in effect during the colder months.

Urban canopy spread over time is also in agreement with the observed meteorological data. In Figure 7, land cover for 1990 (a), 2000 (b), 2012 (c), 2018 (d) were given for megacity Istanbul. CLC datasets have 44 classes, in this study, only five classes were used to calculate the urban spread. These classes are generally good indicator of urban core, for Istanbul the urban core mainly consist of densely populated and rapidly urbanized places such as Golden Horn, Historical Pennisual, Anatolian side mainly Uskudar and Kadikoy, Northern parts of Bosphorous Sarıyer, Maslak, etc. Difference between the area of these urban related classes are as follows; 1990-2000 39%, 2000-2012 11.32%, 2012-2018 9.98%, 1990-2018 70.35%. The most significant change is between 1990 – 2000 which is also the time period of rapid urbanization. From the Figure 7 the direction of the urban spread can be seen from Bosphorous to outwards on both western and eastern parts of the city. One of the reasons for this outward expansion is the construction of the bridges over the Bosphorus and development of road infrastructure and at the same time, peripheral growth accelerated due to rural migration (Dokmeci and Berkoz, 1994).

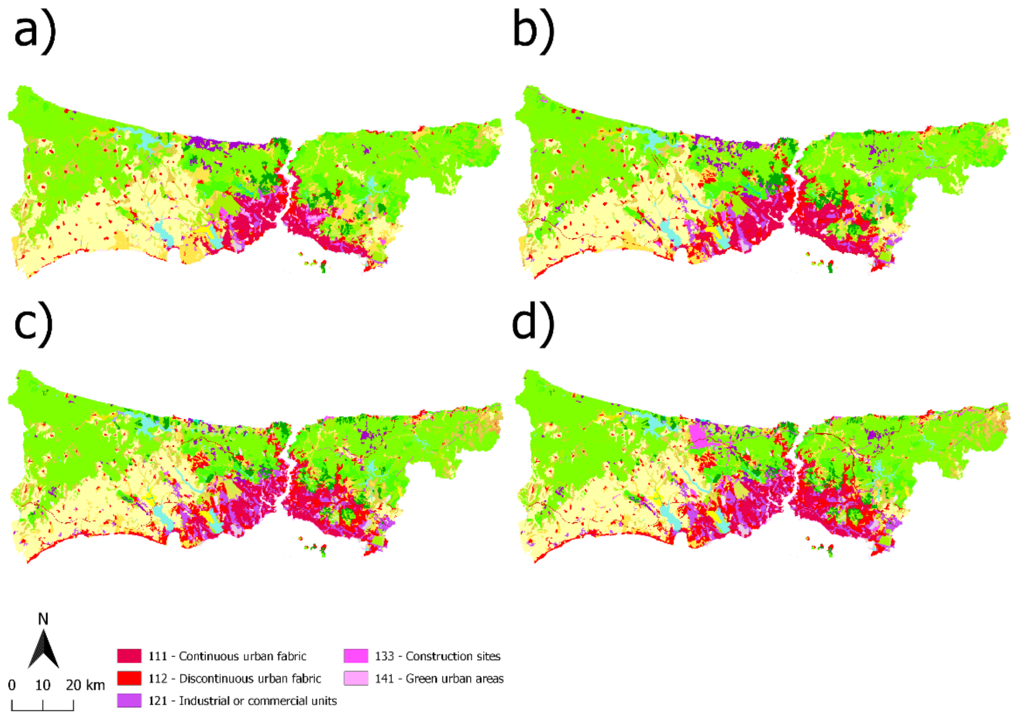

Fig. 7. Corine Land Cover images for a) 1990, b) 2000, c) 2012, d) 2018

Discussion and Conclusion

In this study, impact of urbanization and UHI on megacity Istanbul was investigated from a meteorological perspective. In recent literature, the increased interest in UHI can be seen since it is a common problem caused by the rapidly increasing urban areas worldwide, especially in megacities such as Istanbul. UHI in particular refers to the differences in temperature between urban and rural areas. This difference is more apparent on minimum air temperature values which can also be referred as night time temperatures.

In previous studies that was conducted on effects of UHI in Istanbul was concluded that impact of UHI could be detected by the changes occur in minimum temperature (Karaca et al., 1995 a; Karaca et al., 1995 b; Unal et al., 2020). Results of this study showed that an increasing trend in night time temperatures over the period of 1951-2020 in all selected stations but more significantly in urban stations pointing out the underlying impact of urbanization in Istanbul. It should be noted that both day time and night time temperatures were found to have an increasing trend showing the impact of expansion of urban areas towards surrounding rural and green areas. Some of the major examples of this expansion are the new Istanbul Airport, the third Bosporus bridge (Yavuz Sultan Selim bridge), and the third highway ring (Kuzey Marmara Otoyolu).

Compared to other similar studies, results of this study are in parallel with their results and support the hypothesis of a relation between an increasing trend in minimum temperature and urbanization in Istanbul. The increasing long-term trends of minimum temperature hinting a possible climatic change towards a stronger UHI. No cooling trends were observed in contrast to previous studies mainly due to the differences between study periods. Selected period of this study is nearly 70 years, starting from 1951 to the end of 2020, expanding upon existing literature by taking into account the recent years providing a picture of how UHI and urbanization rapidly changing for the worse.

Istanbul is an old city with an ever-increasing population and located on an active fault line. It is suggested that the government policies should take the results of this study along with previous studies, not only meteorological studies but also socio-economic and urban planning studies, and an extremely destructive earthquake looming in relatively near future take into serious consideration. Moreover, instead of a disjoint plan for different regions of Istanbul it is better to plan for a complete reconstruction of the whole city.

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