Assessment of air pollution at Greater Cairo in relation to the spatial variability of surface urban heat island

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Abstract

Greater Cairo, Egypt, which lies in the apex of the Nile Delta, is one of the most populated regions in the world. Air pollution is a profound environmental issue prevailing in the urban/rural landscapes of this crowded megacity. The objectives of the present study were to utilize remotely sensed data in order to address the seasonal variations of the nocturnal surface urban heat island intensity (SUHII) as extracted from the American Moderate Resolution Imaging Spectroradiometer (MODIS) satellite and the related seasonal distribution of selected air pollutants, including nitrogen dioxide (NO₂), sulphur dioxide (SO₂), and carbon monoxide (CO) as extracted from the European TROPOspheric Monitoring Instrument (TROPOMI) for the period from 2018 to 2021. It is observed that there is clear nocturnal urban heat island over Greater Cairo, particularly at the administrative districts dominated by urban land use with high density of population and at the industrial and power generation locations. The highest SUHII is observed during winter. On the other hand, the selected pollutants also represent an urban pollution island (UPI) capping the regions of high SUHII. At the seasonal level, the highest NO₂ correlation with the SUHII occurs during spring ($R^2 = 0.59$), while the CO correlates maximum during winter ($R^2 = 0.51$). Nonetheless, the seasonal SO₂ distribution is poorly related to the SUHII as this specific pollutant is significantly associated with the industrial land use. Climatic and topographic factors could intensify the distribution of air pollution in the study area. Results of this study demonstrate the significance of geospatial technology tools in the subtle analysis and addressing regional air pollution. The outputs are also of a paramount implication on the management of urban environment and the adaptation of urban air quality.

Keywords SUHII · Cairo · NO₂ · SO₂ · CO · Spatial technologies

Introduction

Two important urban climate phenomena occur in urban landscapes, namely: the urban heat island (UHI) and the urban pollution island (UPI). The former refers to the warmer temperatures in urban land compared to the adjacent rural areas due to human activities (Ulpiani 2021), while the latter is linked to the emissions of pollutants into the urban atmosphere with more observable loads than at the surroundings (Crutzen 2004). UHI is generally different from the surface urban heat island (SUHI). UHI is usually measured for air temperature records obtained from ground meteorological stations at the standard 2-m height, while SUHI is acquired by satellite derived land surface temperature (LST) data (Alqasemi et al. 2021; Dewan et al. 2021). Moreover, the SHUI intensity (SUHII) denotes the difference between LST in urban land and LST in rural areas (Zhao et al. 2017). Generally, UHIs and UPIs are correlated and linked to the

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combustion processes from transport, industry, and other human activities (Ulpiani 2021; Li et al. 2007). Yet, they occur in a complex and intimate pattern of feedbacks at regional and local scales (Oke 1982). Ideally, there are two mechanisms by which large urban landscapes could affect local, regional, and global climates (Baklanov et al. 2016). The first one denotes the influence of urban heating upon the local air circulation, whereas the second mechanism involves the emissions of pollutants that have subsequent effects on climate. Therefore, a systematic understanding of the UHI and UPI configurations and driving forces is critical for formulating efficient mitigation and adaptation strategies (Zhou et al. 2018).

The assessment and monitoring of UHI and UPI allow policymakers to evaluate these phenomena and seek ways to minimize their risk. Remote sensing is a powerful tool to study regional changes in LST, and hence the SUHI. However, spatial and temporal resolutions, in terms of the coarse pixel size, the frequency of data acquisition, and the lengths of temporal coverage could be significant limitations to remotely sensed data. Nevertheless, the development and improvement of thermal remote sensing provide a good means to compensate the flaws observed in conventional monitoring of UHI (Pongrácz et al. 2010; Weng 2009). The Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the first Earth Observing System (EOS) platform (called *Terra*), which was launched in 1999, provided a new era for global studies of atmosphere, land, and ocean processes (Wan et al. 2002). The other counterpart of *Terra* was launched in 2002 with the name *Aqua*. Both platforms provide daily images for the entire earth at 36 wavebands, covering the wavelength spectrum from the visible to the thermal infrared with local crossing times at approximately 01:30 and 13:30 for the *Aqua* and 10:30 and 22:30 for the *Terra* satellite. MODIS is therefore capable of acquiring nighttime observations of the land surface temperatures, which is advantageous to the Landsat satellite as the UHI is better observed at nighttime (Zhao et al. 2017). MODIS images were widely utilized to study the UHI in numerous studies (e.g., Wang et al. 2008; Imhoff et al. 2010; Clinton and Gong 2013; Cheval and Dumitrescu 2015; Miles and Esau 2017; Shastri et al. 2017; Campelo et al. 2018; El-Kenawy et al. 2020; Al-Fazari et al. 2021; Alqasemi et al. 2021).

According to the World Health Organization (WHO 2016), deaths from air pollution diseases approach about 6.5 million with up to 92% of the global population residing in areas of air quality exceeding the WHO limits. The urban structure is responsible for reducing air circulation and lowering the wind speed while enhancing the vertical eddy mixing, which promotes concentrations of pollutants in the urban atmosphere (Ulpiani 2021). Monitoring air pollution in urban landscapes is therefore crucial in urban environment

for health considerations. Most common air pollutants in urban environment include: nitrogen dioxide (NO₂), sulfur dioxide (SO₂), carbon monoxide (CO), aerosols, and other secondary pollutants. Major sources of these pollutants are from the industry, transportation facilities, power generation plants, heating appliances and stoves. Remote sensing technology could play a critical role in monitoring air quality at national, regional and global scales (Geddes et al. 2015; Lin et al. 2015). The emergence of the TROPOMI/Sentinel-5 Precursor satellite, which was launched in October 2017 by the European Commission Copernicus Programme, for monitoring the earth, was the milestone for monitoring the atmosphere at a daily basis. Since July 2018, the TROPOMI delivered calibrated data from its nadir-viewing spectrometer that measures reflected sunlight in the ultraviolet (UV), visible (VIS), near-infrared (NIR), and shortwave infrared (SWIR) with the spectral bands in the UV and VIS spectra for monitoring atmospheric gasses at 7×3.5 km spatial resolution (improved to 5.5×3.5 km after August 6, 2019) along a swath of 2600 km (Shikwambana et al. 2020). Sentinel-5P is a near-polar orbiting sun-synchronous satellite flying at an altitude of 817 km above the earth's surface in an ascending node with an equator crossing time at 13:30 (local time) offering daily worldwide coverages. Monitoring air pollutants by TROPOMI could occur by three different data streams: the near-real-time (NRTI), the Offline (OFFL) mode, and the Reprocessing (RPRO) stream. The OFFL and RPRO data are usually available within a few days after acquisition, while the NRTI data are available within just 3 h from the time of acquisition. Many previous studies on air pollution were conducted using this satellite, particularly addressing the lockdown period synchronized with the COVID-19 pandemic with the previous years (e.g., Alqasemi et al. 2021; El Kenawy et al. 2021; Mehmood et al. 2021; Tyagi et al. 2021).

Investigations of the SUHI and UPI using nocturnal remote sensing are generally little and inconsistent in Egypt at the time where there is a global concern and interest about the impact of urbanization on regional climate and urban air quality. Quantifying and mapping the distribution of air pollutants in high urban sprawl landscapes are also crucial from the human health prospective. In Egypt, most studies related to the mapping and monitoring of air pollution were carried out using ground measurements, fixed monitoring stations, modeling, and interpolation techniques (El-Dars et al. 2004; Abu-Allaban et al. 2007; Ahmed et al. 2018; Abbass et al. 2020). Meanwhile, the SUHI studies were mostly accomplished using daytime satellite data (e.g., Effat and Hassan 2014; Hereher 2017). The study performed by El-Kenawy et al. (2020) using MODIS nighttime data proved a notable increase in SUHI over the Greater Cairo region. The present study aims to link the spatial extent of the nighttime SUHI with UPI in the GC region based on remotely sensed

data. Specifically, the objectives of this investigation are to study the spatial and temporal variability of the nighttime surface urban heat island and to correlate these variations with the seasonal magnitude of air pollution, with particular insight on the following primary pollutants: NO₂, SO₂, and CO. MODIS and Sentinel 5P data utilized in this study were acquired for the last 3 years. In this investigation, we pursue a robust geospatial analysis of both LST and air pollutants by means of remote sensing and Geographical Information Systems (GIS).

The study area

The term megacity refers to the urban agglomerations with a population exceeding 10 million (Baklanov et al. 2016). In this context, Cairo, the capital of Egypt, is one of these megacities of the world, where the total population is more than 20 million (El-Kenawy et al. 2020). The metropolitan area is literally known as the Greater Cairo (hereafter referred to as the GC), which occupies a total area of 2670 km² and occurs in three governorates (Cairo, Giza, and Qalyubia). This administrative union consists of 69 units ranging in area from 0.8 to 22 km² and in population from 10,500 to 96,000 (2016 National census). Recently, the GC has expanded by constructing new urban communities at the west known as the 6th of October district in 1979 and the New Cairo at the east, which was established in 2000. These two districts grew very rapidly, but their landscape design was significantly different from the old city in many aspects including the wide streets, low house heights, low density of population, and the occurrence of gardens and green spaces. In this context, Hereher (2012) reported that the urban mass of Greater Cairo was doubled in less than 30 years from 234 km² in 1973 to more than 550 km² in 2006. The GC is one of the most polluted cities in the world, with extremely high levels of air pollutants (Wheida et al. 2018). According to the World Bank (Swanson, 2007), Cairo was the worst city in the world in terms of the concentrations of the particulate materials emitted from the burning of the agricultural wastes during the fall season. In 2019, the concentrations of particulate matter in Egypt averaged 18 µg/m³ compared to 12.3 µg/m³ in France and 7.7 µg/m³ in Canada (IQAir 2020, <https://www.iqair.com/world-air-quality>). The GC is bordered from the west and east by two limestone plateaus (Giza and Al-Muqatam, respectively) (Fig. 1). From a climatic point of view, Greater Cairo is located in the extratropical zone, with hot and dry summers and moderate and dry winters (BWh) according to the Köppen–Geiger classification (Peel et al. 2007). Based on the meteorological records for the period 1983–2019 (El Kenawy et al. 2021), the mean annual temperature is about 22 °C, while the mean annual rainfall is about 20 mm. The summer

maximum temperature commonly exceeds 30 °C, while the winter minimum temperatures occasionally fall below 10 °C (El Kenawy et al. 2019). Wind speed as measured by the meteorological station of Cairo International Airport east of Cairo (Hamouda 2012) reveals an average speed of about 4 m/s with the maximum value of about 25 m/s during winter. According to Favez et al. (2008) and Mahmoud et al. (2008), the northwest, north, and northeast winds dominate all the yearlong. However, the southwest winds significantly occur during winter and spring. These southwest winds are locally called the *Khamasin*, which are associated with dust storms affecting the Greater Cairo and the entire Nile Delta region (Aboel Fetouh et al. 2013).

The GC hosts more than one-third of the total national industry in Egypt, and major industrial activities include iron and steel, cement, fertilizers, equipment, food and brick manufacturing, and power plants (Robba 2003). The most important industrial regions occur in Helwan (#53 in Fig. 2), Tebeen (#22 in Fig. 2) in the south, and Shubra Al-Khima (#67 in Fig. 2) in the north. Although the GC is the major metropolitan region in Egypt, some of its districts are dominated by agricultural fields, such as Monshat El-Kanater (#63 in Fig. 2) in the northwest and Badrasheen (#14 in Fig. 2) in the south. The western block of the GC, which is known as the 6th of October (#4, 10, and 12 in Fig. 2) was established at the early 1980s, and the eastern protrusions of the city, such as the New Cairo (#43, 48, and 50 in Fig. 2) communities, were established in the year 2000.

Materials and methods

MODIS Terra LST data

This study relied on a collection (July 2018–March 2021) of the 8-day composites of the LST product from the MODIS Terra satellite (MOD11A2.V6). Satellite data were downloaded from the Land Processes Distributed Active Archive Center of the United States Geological Survey (<https://lpdaac.usgs.gov/>). The acquisition time of each image is at 10:30 AM and 10:30 PM every day. We selected the nighttime (10:30 PM) LST layer rather than the daytime image as the SUHI is mostly determined by the behavior of both surface temperature and sensible heat flux (Li et al. 2019a). In addition, although the air pollution exists during the daytime and nighttime over the study area, it was difficult to elaborate a strong relationship between air pollutants and SUHI during daytime because of the nature of the heat emissions during daytime, which reflect the intrinsic behavior of the landscape rather than the human activity. Moreover, the intensity and distribution of SUHI are impacted more by anthropogenic heat releases, which are more pronounced during nighttime, mainly due to the emission of longwave

Fig. 1 A Google Earth map of Egypt showing the location of Greater Cairo and a satellite image dated May 2021 with the administrative boundary of Greater Cairo (red line). Note the occurrence of urban landscape and the rural agricultural lands

radiation from heating and cooling appliances in the absence of the sun (Zhou et al. 2014). A total of 103 MODIS images (from July 2018 to March 2021) were processed in order to extract the nighttime LST for the study area. The images are of high quality as they are composite data, and they were originally processed at NASA laboratories for amending any atmospheric disorders during image acquisition. Individual nighttime layers were extracted and compiled in a seasonal pattern, where a mean seasonal image was eventually produced. Hence, the value of each pixel in an image for a given season represents the mean values of all records of this pixel in this season. The temperatures in each image were also converted to degree Celsius. The study area was clipped in the mean seasonal images to yield the mean seasonal values of LST for the study area. Typically, the SUHII was determined by identifying a reference pixel in each season's LST image in the rural area outside the urban masses, and the LST of the reference pixel was then subtracted from the LST for the urban land mass using the following equation: (Cui et al. 2019)

$$\text{SUHII} = \text{LST}_{\text{urban}} - \text{LST}_{\text{rural}}$$

Seasonal surface urban heat island intensity (SUHII) maps were prepared, where the seasonal SUHII variation was displayed and classified.

TROPOMI/Sentinel-5p data

The TROPOMI daily global observations are used for monitoring the concentrations of atmospheric constituents. Recent literature has shown that measurements of TROPOMI are quite well associated with actual ground measurements of air pollutants (Lorente et al. 2019; Griffin et al. 2019). Zeng et al. (2019) also calibrated a selection of TROPOMI product at a global scale with independent pollution measurements from NASA similar sensors. The TROPOMI Monitoring Instrument is a passive sun backscatter imaging spectrometer that allows for the acquisitions of 8-band imagery at higher spatial resolution than the predecessors. The Sentinel-5p data are available to

Fig. 2 An administrative map of the Greater Cairo region showing the population density at the 69 different districts. Sources of the population data are from the Central Agency for Public Mobilization and Statistics (<https://www.capmas.gov.eg>. Accessed on 5/5/2021)

users at two different processing levels: L1B, as radiometrically corrected top-of-atmosphere (TOA) radiances, and L2 of multiple layers including radiance, solar irradiance, and products for aerosols, clouds, and different pollutants (i.e., total columns of O_3 , SO_2 , NO_2 , CO , and CH_4) (Virghileanu et al. 2000). Sentinel-5P provides a quality band, with values ranging from 0 (poor) to 1 (excellent), which is important for pixel filtering and data quality verification (e.g., elimination of cloud interference) (El-Kenawy et al., 2021).

In this study, the TROPOMI Offline stream of NO_2 , SO_2 , and CO columns of daily datasets was used for the period from July 2018 to March 2021 (the period of duty of this satellite) on a monthly basis. The retrieval scheme of these pollutants could be found in Borsdorff et al. (2018), Theys et al. (2019), and Cheng et al. (2019). The TROPOMI data were extracted using the Earth Engine Code Editor. From the daily images, we obtained the monthly average image by dividing the total records of each pixel for a given month by the number of the days for the this month. Then, we obtained

the seasonal and annual profiles of the study area in order to explore the spatial variability of each pollutant.

We also performed an overlay analysis in a GIS environment in order to determine the overall severity of pollution known as the multi-pollution index (MPI), which was proposed by Gurjar et al. (2008) to consider the combined impact of air pollutants. In this analysis, the distribution of the annual concentration of each of the three pollutants (NO_2 , SO_2 , and CO) was obtained for the entire study area using the monthly profile for each pollutant. The annual map of each pollutant was classified into three classes (low, moderate, and high) using the percentile classifier. This classifier is a method designed to optimize the data and classify their values. In this study, we classified the annual image of each pollutant into three classes, which correspond to the three percentiles as Low (< the 33rd percentile), Moderate (33rd–66th percentiles), and High (> 66th percentile). An overlay analysis was then performed to determine the annual spatial variability of the three pollutants together, where a final map was produced. In this final map, another

classification was applied using the 33rd and 66th percentiles to yield the overall spatial distribution of the Low (< the 33rd percentile), Moderate (33rd–66th percentiles), and High (> 66th percentile) pollution categories.

Statistical analysis

In order to delineate the correlation between the SUHII obtained from the MODIS data and the different air pollutants obtained from the TROPOMI/Sentinel 5P, statistical relationships were conducted to calculate the regression coefficient (R^2) between the seasonal SUHII with their counterparts of each pollutant. To carry out this regression analysis, the locations of 3930 points representing the total pixels in each seasonal image were selected in the study area. The values of the seasonal record of each pixel in the SUHII and the counterpart value in the three pollutant (NO_2 , SO_2 , and CO) images were extracted using the locations of the assigned points, then the regression analysis was performed between the SUHII (as an independent variable) and each of the three pollutants (NO_2 , SO_2 , and CO) (as dependent variables) in order to determine the regression coefficient.

Results

Population density and SUHII

Fig. 2 shows the density of population of the GC, which ranges from 302 to more than 93,000 inhabitants/km² with the most agglomerations in the downtown districts. The highest density is observed in Dar El-Salam (#54 in Fig. 2), Hadayek El-Koba (#52 in Fig. 2), Bolak E-Dakror (#11 in Fig. 2), and Ain Shams (#59 in Fig. 2) (> 70,000 capita/km²). On the other hand, the least density of population is observed in the newly urban communities at the west and east of the GC. These low density districts hold less than 200 capita/km², such as in the New Cairo, the 6th of October, El-Shorouk, and Badr cities. The accelerated population growth in Cairo in the last two decades is associated with an increase in car ownership and air conditioning units. According to Aboelata and Sodoudi (2020) and Attia and Evrad (2012), car ownership in Cairo increased from 16 cars/100 persons in 2013 to 25 cars/100 persons in 2014, and the annual sale of air-conditioning units increased from 54,000 units between 1996 and 2006 to 766,000 units between 2006 and 2010. This socioeconomic change associated with the population and urban sprawl entailed extra energy consumption and significantly modified the regional urban climate of the study area.

The spatial distribution of the nocturnal SUHII in the study area clearly coincides with that of the density of population. Fig. 3 reveals conspectus seasonal SUHII patterns

for the study period. Generally, there is a considerable difference between the rural and urban heat island intensity. The SUHII for the winter shows a concentration of the heat island exclusively at the districts of the high density of population with heat intensity of more than 6 °C greater than the rural areas. In this consensus, the SUHII is maximum during winter with the highest (> 6.5 °C) at Zamalek, Bolak, and Rod El-Farag as people heat buildings during winter. In addition, during spring, the distribution of the SUHII is comparable to the winter season. The difference between LST of rural and urban lands (SUHII) approaches 5.6 °C during spring, with highest locations at Omraniya and Imbaba. In summer, there is a spread of the SUHII throughout the majority of the study area, which could be interpreted by the human activities that extend to a late hour of the day during this season, particularly the extensive use of air condition units. Maximum summer SUHII occurs at El-Omraniya and El-Basateen (> 5.3 °C). In contrast, the fall season witnesses the least SUHII in the study area. The highest value (4.7 °C) is observed to occur at Zamalek, Bolak, Rod El-Farag, and Azbakiya. Comparing the results of this study with a previous investigation for mapping UHI of the GC using daytime data acquired from the Landsat satellite (Effat and Hassan 2014) indicates the efficiency of the nocturnal MODIS images for mapping UHI, while the daytime Landsat data recorded highest LST at desert region east of Cairo rather than in urban lands in the downtown. Moreover, El-Hattab et al. (2018) and Hereher (2017) reported high UHI south of the GC due to the influence of industrial land use upon the LST in the region.

Distribution of air pollutants

Nitrogen dioxide (NO_2) is one of the main air quality pollutants of concern in urban and industrial areas, and it is responsible for tens of deaths annually in Cairo (Wheida et al. 2018). The seasonal distribution of the NO_2 (Fig. 4) reveals a good agreement with the dense buildings and the nocturnal SUHII over the GC. Specifically, the winter season witnesses the highest concentrations of NO_2 over the study area, where the tropospheric NO_2 gas approaches 325 $\mu\text{mol}/\text{m}^2$. The high dependence upon the heating fuel during cold months could be the driver of this increase of the NO_2 gas. During this season, the NO_2 concentration is more localized at the northern districts with maximum concentration, which is observed at Nasr City (# 44 in Fig. 2) near Cairo Airport, where the winds significantly blow from the north direction. Moreover, the wind speed during the spring season is the greatest over the GC. Remarkably, the concentration of NO_2 in the spring season is generally lower than in winter. It approaches its maximum load during spring at Sayeda Zeinab district (221 $\mu\text{mol}/\text{m}^2$). Interestingly, the summer season witnesses the least concentration of NO_2 gas in the

Fig. 3 The seasonal distribution of SUHII (°C) in Greater Cairo region for the period July 2018 to March 2021. Numbers refer to the districts of the Greater Cairo. Names of these numbers are shown in Fig. 2

troposphere (from surface up to ~10 km above the GC); however, it becomes much widespread over the northern and southern parts of the capital with its maximum concentration ($177 \mu\text{mol}/\text{m}^2$), where it is observed at Monshat Nasr (#63 in Fig. 2). The concentration rises again during the fall to reach its maximum value of $255 \mu\text{mol}/\text{m}^2$ at El-Khalifa region. As this pollution is closely related to the emissions from transportation means and heating requirements, this may interpret its high concentrations in crowded regions with the highest population density.

Regarding the concentrations of SO_2 gas in the troposphere of the study area, this pollutant is mostly linked to the industrial and power generation facilities, rather than the population density and its activity. This is quite observable at Shubra Al-Kheima north of Cairo, where major textile, smelters, chemical, petroleum industries, and electricity generation plants occur. These industrial operations mostly use high sulfur heavy fuel, which produce SO_2 emissions and rendered the region a hotspot location for SO_2 emissions (Moseholem 1992). During winter, this pollutant reaches a value of $669 \mu\text{mol}/\text{m}^2$, while in spring, the concentration

increases up to its absolute maximum seasonal concentration ($810 \mu\text{mol}/\text{m}^2$) (Fig. 5). The emissions decrease again in the summer and fall. Although the overwhelming concentration of SO_2 is related to the emissions from specific industrial activities at Shubra Al-Kheima, yet some other residential areas have surprisingly experienced relatively high SO_2 concentrations, such as New Cairo, the 6th of October, and El-Badrasheen. The interpretation of the extraordinary high concentrations of SO_2 in the new urban communities is the huge use of trucks fueled by diesel for creating new asphalt roads and construction purposes. The minimum and maximum concentrations during the winter and spring seasons, respectively conform with the observations of EL-Dars et al. (2004) at Shubra Al-Kheima who reported a maximum ambient value of up to $1219 \mu\text{g}/\text{m}^3$ during April.

The concentrations of carbon monoxide (CO) pollutant are likely to resemble the distribution of population density and NO_2 pollutant (Fig. 6). However, the CO is much contingent to the middle and southern districts of GC. Emissions of CO include motor vehicles and industrial activities. The concentration of this pollutant is relatively constant (~

Fig. 4 The seasonal distribution of NO_2 concentration ($\mu\text{mol}/\text{m}^3$) in Greater Cairo region for the period July 2018 to March 2021. Numbers refer to the districts of the Greater Cairo. Names of these numbers are shown in Fig. 2

36 part per billion, ppb) through the majority of seasons, except for the spring where the concentration is at its peak level (40 ppb). This is confirmed by Mostafa et al. (2018) who reported from a 5-year monthly averages that the tropospheric cycles of the CO enforce this pollutant to be in its peak concentration during spring. Maximum concentration of CO in winter, spring, summer, and fall seasons is observed at El-Omraniya, Misr El-Kadima, El-Basateen, and Misr El-Kadima, respectively.

The multi-pollutant index (MPI) in this study, which was produced by merging the individual annual maps of the three pollutants (NO_2 , SO_2 , and CO) and eventually obtaining a map reflecting the overall distribution of these pollutants collectively, indicates a high concentration of air pollution in the heavily populated districts and forming what is called an urban pollution island (UPI) in these highly populated regions of the GC. Fig. 7 shows this MPI map with most polluted regions (red colors), which highlight this UPI. This island extends also to the industrial belt at Helwan and Tebeen south of Cairo. The rural districts, such as Monshat El-Kanater in the northwest, reveal the lowest polluted

regions due to the dominance of agricultural land. The newly constructed urban communities, such as the 6th of October at the west and some districts of the New Cairo at the east, show low to moderate levels of air pollution due to the low population densities and the relatively artificial green belts and gardens in these communities.

Statistical relationships

The regression analysis of the seasonal SUHII versus the studied air pollutants (NO_2 , SO_2 , and CO) at GC are shown in Figs. 8, 9, and 10, respectively. Fig. 8 clearly reveals a positive relationship between SUHII and NO_2 meaning that the concentrations of this pollutant are directly proportionate to the human activities. The relationship is maximum during the spring ($R^2 = 0.59$) and minimum during the fall season ($R^2 = 0.23$), while the regression coefficients (R^2) for the winter and summer are 0.48 and 0.29, respectively.

The regression relationship between the SUHII and SO_2 (Fig. 9) indicates a poor correlation, which reflects the low influence of urban landscape upon the distribution of this

Fig. 5 The seasonal distribution of SO_2 concentration ($\mu\text{mol}/\text{m}^3$) in Greater Cairo region for the period July 2018 to March 2021. Numbers refer to the districts of the Greater Cairo. Names of these numbers are shown in Fig. 2

pollutant. As mentioned earlier, the spread of SO_2 is intimately linked to the industrial land use, which occur mostly at Shubra Al-Kheima in the north and Tebeen in the south. Statistically, this linkage between the SUHII and SO_2 is very small for all seasons, and it is close to zero.

The relationship between the SUHII and CO is shown in Fig. 10. Generally, this pollutant relatively correlates with the SUHII during winter ($R^2 = 0.51$) and spring season ($R^2 = 0.46$). However, this relationship is weak during the fall ($R^2 = 0.31$) and summer ($R^2 = 0.19$). It is clear that the NO_2 and CO have their highest correlations during the winter and spring seasons.

Discussions and conclusions

Greater Cairo is one of the biggest cities in the world, where more than twenty millions of people settle in this megacity. Millions of vehicles and thousands of industrial facilities, which are fueled by diesel and gasoline, release tremendous emissions of pollutants, such as NO_2 , CO, SO_2 , annually into

the city atmosphere. Traffic congestion and unregulated control of exhaust emissions from older vehicles (17% of private cars and 32% of taxis are over 25 years old) significantly contribute to this indigenous problem in Cairo (Abbass et al. 2020). The Egyptian Environmental Affairs Agency (EEAA) has installed a network of fixed monitoring units for measuring air quality parameters in residential, industrial, and road-sides. Although many studies addressed the distribution of air pollution over the GC depending on the data provided by the EEAA or similar in situ measurements (Safar and Labib 2010; Mostafa et al. 2018; Wheida et al. 2018), the present study is among the few that elaborate remotely sensed data for a regional investigation (e.g., Abdelsattar et al. 2021). The population density in the GC reveals a concentration at the downtown districts, whereon the heart of this megacity pulses. In accordance, the spatial distribution of the SUHII is clearly observed to correlate with the population density. In contrast, newly urban communities with green belts and wide interbuilding spaces reveal lower SUHII due to the conditioning effect of vegetation (Aboelata and Sodoudi 2020). In addition, the UPI clearly covers the most populated

Fig. 6 The seasonal distribution of CO concentration (ppb) in Greater Cairo region for the period July 2018 to March 2021. Numbers refer to the districts of the Greater Cairo. Names of these numbers are shown in Fig. 2

Fig. 7 The multi-pollution index (MPI) map of the GC with the locations of the low, moderate, and high pollution. Note the red color indicates regions with high overall pollution, which refers to the urban pollution island (UPI)

Fig. 8 The seasonal relationship between the SUHII and NO₂ pollutant over GC

Fig. 9 The seasonal relationship between the SUHII and SO₂ pollutant over GC

55 districts out of the total 69 districts of the GC. There is a general consensus that the pollution concentrations of the studied parameters are high during winter and spring. This could be attributed to many reasons including topographic and climatic influences. The wind generally ranges from gentle breeze to weak speed, where pollutants are likely to accumulate rather than dilute over Cairo's atmosphere. This

is clearly obvious during the harvesting season of the rice crop in September and October and the illegal burning of the rice straws, which tremendously impact the atmosphere of Cairo by forming what is recently known in Egypt by the black clouds (Li et al. 2019b). Barry (1992) reported that air pollution concentrations are at the peak when the wind speed becomes low, stable weather with low vertical

Fig. 10 The seasonal relationship between the SUHII and CO pollutant over GC

turbulence and high humidity, which is the case to occur at Cairo during winter and spring seasons. Moreover, Aboel Fetouh et al. (2013) attributed the high concentrations of air pollutants during winter and spring in Cairo to the stable weather associated with temperature inversion during this cold period. In this context, Ahmed et al. (2018) observed that the maximum monthly air pollution occurs in February. The SUHII is also observed to be maximum during winter because the cloud cover is usually most frequent during this season and the radiated heat from the surfaces are being trapped by clouds and by the high humidity in the troposphere. Topographic setting was reported to influence the distribution of air pollutants and enhance thermal inversion (Carvalho et al. 2006). The eastern (Al-Muqatam) and western (Giza) plateaus bounding the urban mass are responsible of the stagnation of air masses over the city, which eventually confine the pollution levels in the lower atmosphere (Aboel Fetouh et al. 2013). The emissions of air pollutants synchronized by the climatic and topographic influences triggered the formation of a notable urban pollution island over the troposphere of the GC region during all seasons, with major concentration within the highly populated and industrialized regions. In a conclusion, it is clearly observed that air pollution, particularly NO_2 and CO, directly correlates with the SUHII as these pollutants are emitted mainly from transportation within the urban masses and from human activities, while the SO_2 has low correlation with the SUHII because this specific pollutant is mostly related to the industrial facilities. The present study is limited to the data provided by remotely sensed sources; however, another

attempt is required to validate space-based measurements with in situ and station measurements using detailed records from the different districts in the GC region.

Author contribution Conceptualization: MH and AEK; data visualization: RE and MH; manuscript writing: MH; data availability and design of the methodology: AA and MH.

Availability of data and materials Data utilized in this research are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate The authors declare that they followed the ethics in scientific research.

Consent for publication Not applicable

Competing interests The authors declare no competing interests

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