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Research Paper

The synergy of ambient air quality and thermal discomfort: A case study of Greater Cairo, Egypt

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ABSTRACT

The interaction between thermal discomfort and air pollution poses significant challenges for human health and environmental well-being. When there is a high level of air pollution, it can worsen thermal discomfort by trapping heat in the atmosphere. This paper aims to study this interaction in arid megacities during different weather events. Weather data and air pollution were utilized to evaluate air quality, thermal discomfort levels, their impact, and their relationship at three separate sites (Qaha, Naser City, and 6th of October City). The ambient air quality is determined by measuring the levels of particulate matter (PM10), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2). The work included a statistical analysis of the discomfort index (DI) and the air quality index (AQI) for each city and their linkage with the weather. The air quality evaluation revealed that a significant portion of the population in Qaha frequently experienced discomfort and were exposed to unhealthy levels of air pollution. The results show that most of the population in all three cities experience discomfort at least some of the time with varying degrees. In Qaha, 28.97% of the population experiences no discomfort, while 25.41% experiences severe stress. In Nasr City, 32.15% of the population experiences no discomfort, while 20.21% experiences severe stress. The 6th of October City, 33.76% of the population experienced no discomfort, while 16.65% experienced severe stress. Noted that certain months, specifically June to September, are associated with higher levels of discomfort, affecting more than 50% of the population. Seasonal variations in discomfort can be due to a range of factors, including weather, climate, and environmental conditions. The temporal variation in discomfort reflects the challenges people face when transitioning from colder to hotter seasons.

***Keywords**:* The discomfort index, Air Quality Index, particulate matter (PM10), Nitrogen dioxide (NO2), and Sulfur dioxide (SO2).

The interaction between thermal discomfort and air pollution poses significant challenges for human health and the environment. Accumulating evidence has shown that climate change and air pollution pose multiple health threats to humans through complex and interacting pathways. Several studies have enhanced our knowledge of the health effects of particulate air pollution. These studies, along with others, have contributed significantly to our understanding of the adverse health effects associated with particulate air pollution and emphasize the urgent need for effective mitigation strategies to protect public health (Ostro *et al*., 2018, Xiao and Gao, 2021).

Air pollution is a significant concern for health in Egypt. Studies have shown that air pollution levels in cities, such as Alexandria and Cairo, exceed national standards and pose health risks to the population (Zaki, 2011). The main sources of air pollution in Egypt include fuel usage, burning operations, and automobile exhaust. Additionally, the economic losses from respiratory diseases caused by air pollution are a concern, emphasizing the need for effective pollution treatment and prevention of environmental health risks. Particulate matter and lead pollution present grave concerns in the urban areas of numerous developing nations. An assessment comparing risks, conducted in Cairo in 1994, identified these two pollutants as particularly alarming. Furthermore, an examination of the potential economic advantages linked to the regulation of

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these pollutants indicates that their economic harm is substantial (Lowenthal *et al*., 2014).

Some studies have contributed to focusing on the environmental concerns of Egyptians living in different regions, focusing on issues such as dirty streets, air and water pollution, and noise. The paper emphasizes the need for public participation and individual responsibility in achieving environmentally sound development plans (Mostafa *et al*., 2018,). Most of the Middle Eastern and North Africa (MENA) region is a hot and dry climate, so, extreme weather tends to heat waves, as a period of abnormally hot weather. Also, a wide desert in MENA leads to a high frequency of exposure to airborne pollutants (Bauer *et al.*, 2019). Megacities like Cairo, often found in the MENA region, are characterized by rapid urbanization, extensive industrialization, and high population density. These factors contribute to elevated levels of air pollution and other environmental challenges. The study focuses on examining the extent to which different weather conditions exacerbate air pollution in such urban areas. This study delves into the relationship between different weather conditions and the degradation of air quality in a megacity within the Middle East and North Africa (MENA) region. The specific objective is to understand how various weather patterns impact the deterioration of air quality.

MATERIALS AND METHODS

Study area

Greater Cairo (GC) is a megacity situated in the northeastern region of Egypt. It encompasses three major urban administrative divisions: Cairo, Giza, and Al-Qalubiya. These three divisions together form the Greater Cairo metropolitan area, which is home to a significant population and faces numerous challenges associated with urbanization, industrialization, and air pollution (Mostafa *et al*., 2018). The eastern region of GC consists of barren desert and bare land, while the western region includes cultivated land in the Nile Delta and Nile River. The ambient air quality and thermal discomfort index were assessed at three distinct locations: Qaha, Naser City, and 6th of October City. Each of these locations possesses unique environmental characteristics (Fig. 1).

Qaha is situated in the Qalyubia Governorate, which is located approximately 25 kilometers to the north of Cairo, it is described as a “semi-urban small village,” suggesting that while it may have some urban-like characteristics, it is not a fully developed urban area. Nasr City is situated on the eastern outskirts of Cairo and is characterized by a mix of different types of areas and structures. 6th of October City is described as a satellite city of Giza and create new urban centers or hubs to alleviate the pressures on the capital.

Meteorological and pollution data

The data includes concentrations of three specific air pollutants: Particulate matter less than 10 micrometers (PM10): These are tiny airborne particles with a diameter less than 10 micrometers, which can have a significant impact on air quality and human health, nitrogen dioxide (NO_2): This is a harmful gas that can be present in the air due to various human and natural activities, sulphur dioxide (SO_2): Another harmful gas, sulfur dioxide, is a product of the combustion of sulfur-containing fuels and can contribute to air pollution. The data collection took place over a specific time frame, spanning from January 1, 2010, to December 31, 2019. This decade-long duration allows for an extended analysis of air quality trends and patterns. The air quality data was collected at three distinct geographical locations. The Egyptian Environmental Affairs Agency’s (EEAA) National Network for Ambient Air Quality Monitoring was responsible for monitoring and documenting these pollutants. In this study, the daily average of PM10, as well as the daily maximum hourly values of NO_2 and SO_2, were utilized as indicators of air quality. These pollutant concentrations were employed in the calculation of the air quality index (AQI) (Lotayef, 2019).

The climatic data were obtained through a combination of sources, including the Egyptian weather service and NASA POWER reanalysis products. These sources provided data on daily surface maximum and minimum temperatures, solar radiation, wind speed, relative humidity, and precipitation. The characteristics of the data used in the study are reanalyzed data. The NASA POWER system combines information from several sources: direct measured data, satellite data, wind soundings, and data derived from assimilated data systems. Results from some research showed that there is good agreement between NASA POWER reanalysis and observed data for all parameters, except for wind speed (Rodrigues and Braga, 2021, Horn and Dasgupta, 2023, Halimi *et al.,* 2023).

Exploratory data analysis was employed to elucidate and visually represent the levels of air quality and thermal discomfort. Exploratory data analysis involves techniques to summarize, describe, and visualize data in order to discover patterns, trends, and potential insights. In this case, the primary focus of the analysis was to shed light on the levels of air quality and thermal discomfort.

Air quality evaluation

The Egyptian Environmental Affairs Agency’s (EEAA) provided the daily average of PM10, the maximum hourly average of NO_2, and the maximum hourly average of SO_2 should not exceed 150 µg m^{-3}, and 300 µg m^{-3}. These standards serve as regulatory guidelines to safeguard air quality and, by extension, the health and well-being of the population. The United States Environmental Protection Agency (EPA) created the air quality index (AQI) as a color-coded system to categorize daily air quality. Table 1 presents the AQI breakpoints, which range from 0 to 500. The daily value of each pollutant was converted to its corresponding AQI, and the highest value among them was chosen to represent the daily air quality (Horn and Dasgupta, 2023).

The various averaging times for the different pollutants in Table 1 have been determined. In general, the maximum concentration of any given pollutant with different averaging times within a one-month period can be approximated as (the maximum concentration observed for the shortest averaging time) raised to the power of n, where n is less than 1 (Venkatram, 2002). Intuitively, when considering longer averaging times, it becomes clear that the maximum observed concentration will be lower than that for shorter averaging times. Similarly, this difference will continue to decrease as the averaging windows become longer (Horn and Dasgupta, 2023).

Table 1: Table of AQI breakpoints for each pollutant into color coded categories

AQI Class (Daily)	Color (Code)	AQI (Range)	PM10 µg m^{-3} (Daily)	NO_2 ppb (Hour)	SO_2 ppb (Hour)
Good	Green	0 - 50	0 - 54	0 - 53	0 – 35
Moderate	Yellow	51 - 100	55 - 154	54 - 100	36 - 75
Unhealthy for sensitive groups	Orange	101 - 150	155 - 254	101 - 360	76 – 185
Unhealthy	Red	151 - 200	255 - 354	361 - 649	186 – 304
Very unhealthy	Purple	201 - 300	355 - 424	650 - 1249	305 – 604
Hazardous	Maroon	301 - 500	425 - 604	1650 - 2049	605 - 1004

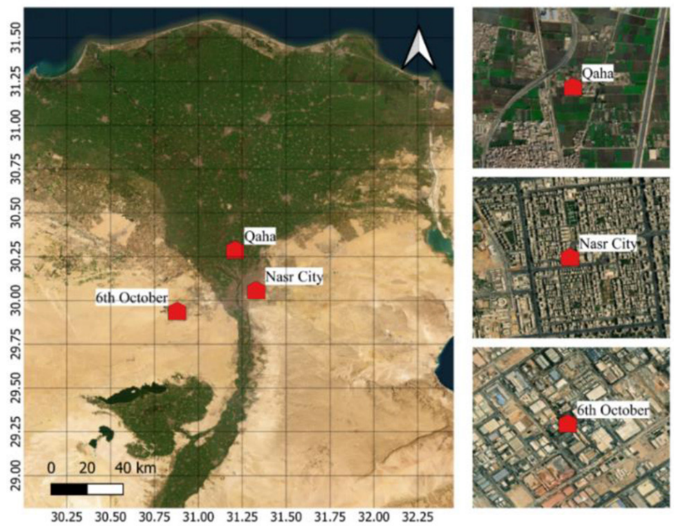

Fig. 1: Map of the study locations (Qaha, Naser City, and 6th of October City).

Thermal discomfort evaluation

Thom's discomfort index (DI) is a heat stress index used to assess human comfort or discomfort in hot and humid weather conditions. The index considers both temperature and humidity, making it useful for evaluating heat-related discomfort. Thom's discomfort index is a useful tool for understanding the combined effects of temperature and humidity on human comfort or discomfort. It's often used in fields like meteorology, occupational health, and climate science to evaluate heat stress and inform decisions related to safety and well-being in hot and humid environments (Pandey 2018).

The formula for calculating Thom's discomfort index is as follows:

$$DI\ (°C) = T – 0.55\ (1 - RH\ \%)\ (T – 14.4)$$

Where: DI = Thom's discomfort index (°C), T = temperature (°C), and RH = relative humidity (%).

The resulting DI value is used to assess heat-related discomfort. Higher DI values indicate greater discomfort, especially in hot and humid conditions. The DI values falls within a range of 1 to 6, where a value of 1 indicates no discomfort, and a value of 6 represents a state of medical emergency. Table 2 illustrates the impact of DI on human health according to discomfort index (Saha *et al*. 2016, Talukdar *et al*., 2017).

Table 2: Thom's discomfort conditions according to discomfort index (DI) and their effects on human health

DI Class	DI range	Effect on Human Health
DI 1	DI < 21	No discomfort
DI 2	21 ≤ DI < 24	Less than 50 % of the population feels discomfort
DI 3	24 ≤ DI < 27	More than 50 % of the population feels discomfort
DI 4	27 ≤ DI < 29	most of the population suffers from discomfort
DI 5	29 ≤ DI < 32	Everyone feels severe stress
DI 6	DI ≥ 32	State of a medical emergency

RESULTS AND DISCUSSION

Air quality evaluation

Each pollutant was evaluated individually by calculating its index value. The daily average PM10 was used to calculate its corresponding index, denoted as I(PM10). The daily maximum value of hourly averages for both NO_2 and SO_2 was also used to calculate I(NO_2) and I(SO_2), respectively. The daily AQI for a location is determined by the highest value among I(PM10), I(NO_2), and I(SO_2). Table 3 represents the values of I(PM10), I(NO_2), and

Table 3: AQI values for each pollutant in three locations

AQI (%)	PM_{10}			NO_2			SO_2		
	Qaha	Nasr	6th October	Qaha	Nasr	6th October	Qaha	Nasr	6th October
Good	1.5	11.4	5.8	86.8	88.4	95.1	98.2	98.7	98
Moderate	61.2	74.8	71.4	13.2	11.6	4.9	1.8	1.3	2
Unhealthy for sensitive groups	26.5	11.1	15.8	0	0	0	0	0	0
Unhealthy	7.5	1.7	4.3	0	0	0	0	0	0
Very unhealthy	1.2	0.5	0.7	0	0	0	0	0	0
Hazardous	2.2	0.5	2.0	0	0	0	0	0	0

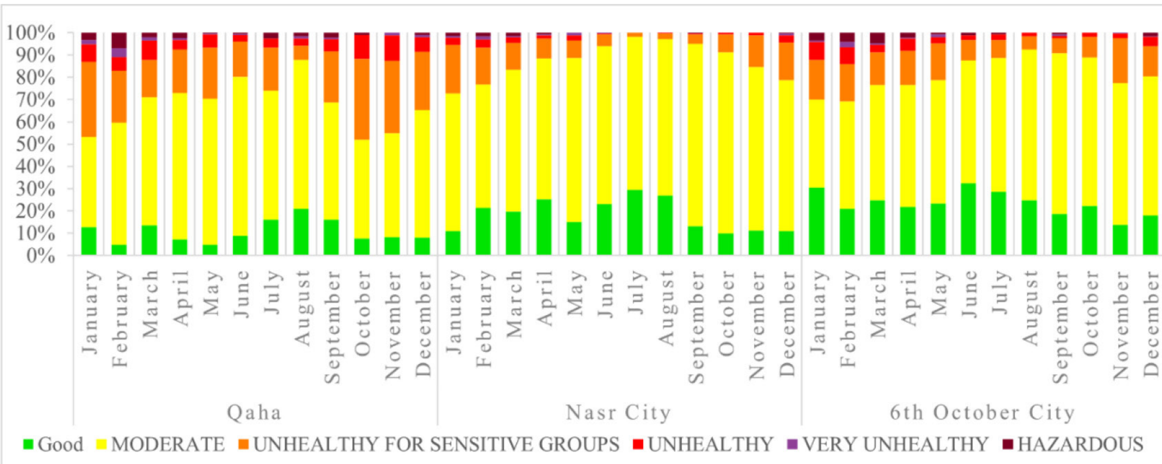

Fig. 2: The frequency of AQI for each location/ monthly

I(SO_2) from 2010 to 2019 in three locations. From the table, the calculated values of I(NO_2) and I(SO_2) fall within the "good" to "moderate" classes. Qaha exhibits the highest level of gas pollution in comparison to the other two locations. In a scientific context, this suggests that the concentrations of these two air pollutants, NO_2 and SO_2, are generally at levels that are considered acceptable for human health. However, the paragraph also mentions that Qaha has the highest level of gas pollution when compared to the other two locations. This indicates that, although the pollution levels are within "good" to "moderate" classes, Qaha still has a relatively higher concentration of these gases compared to the other locations.

The classification into these categories depends on predefined concentration thresholds for pollutants. In this context, "good" signifies that the pollution levels are at their lowest and pose minimal risk to human health, while "moderate" suggests that pollution levels are slightly higher but still generally acceptable. The fact that Qaha has the highest level of gas pollution indicates that even within this acceptable range, there are variations in pollution levels among the different locations studied. Noted that, in contrast to the higher gas pollution levels observed in Qaha, the 6th of October City experiences the least amount of gas exposure. This indicates that the levels of nitrogen dioxide (NO_2) and sulfur dioxide (SO_2) in the air are notably lower in the 6th of October City compared to Qaha. This observation is important because lower gas exposure generally corresponds to better air quality, which can have positive implications for public health. Additionally, found that the values of I(PM10) indicate particulate contamination in all three locations, with Qaha displaying the highest values and the 6th of October City showing the lowest values. The fact that Qaha has the highest values of I(PM10) implies that it experiences the highest levels of particulate contamination among the three locations, which can be detrimental to air quality and human health. In contrast, the 6th of October City has the lowest values for I(PM10), suggesting that it has the least particulate contamination and, consequently, better air quality in terms of particulate matter. These observations are crucial for assessing the air quality and potential health risks in these locations.

Fig. 2 shows the frequency of AQI calculated in the three locations and the monthly variation in the frequency for each location. The results showed that the air quality in Qaha was the worst of the three cities, with 10.52% of days classified as good, 56.09% of days classified as moderate, 23.71% of days classified as unhealthy for sensitive groups, 6.69% of days classified as unhealthy, 1.05% of days classified as very unhealthy, and 1.94% of days classified as hazardous. Nasr City was slightly better than Qaha, with 18.02% of days classified as good, 69.47% of days classified as moderate, 10.02% of days classified as unhealthy for sensitive groups, 1.56% of days classified as unhealthy, 0.45% of days classified as very unhealthy, and 0.48% of days classified as hazardous. However, the air quality in 6th of October City was the best of the three cities, with 23.25% of days classified as good, 58.36% of days classified as moderate, 12.74% of days classified as unhealthy for sensitive groups, 3.47% of days classified as unhealthy, 0.57% of days classified as very unhealthy, and 1.61% of days classified as hazardous. However, the air quality in all three cities was poor, with a significant proportion of days classified as unhealthy or worse. The results of analyzing the monthly variation of ambient air quality in the three cities in GC show that air quality

Table 4: Extreme values of meteorological parameters

Location	T ºC				RH %			
	Min	10%	90%	Max	Min	10%	90%	Max
Qaha	2.0	11.1	35.3	46.4	4.4	19.5	89.9	100
Nasr City	1.4	10.4	34.5	45.4	4.3	18.9	88.4	100
6th October City	1.3	10.0	33.8	45.4	4.1	20.0	91.8	100

Table 5: Presents the frequency of DI categories during different weather conditions

Location		DI 1	DI 2	DI 3	DI 4	DI 5
	Normal	23.7%	24.8%	27.9%	23.6%	0.1%
Qaha	Cold	100.0%	0.0%	0.0%	0.0%	0.0%
	Hot	0.0%	0.0%	0.0%	65.5%	34.5%
	Normal	27.7%	25.3%	32.7%	14.3%	0.0%
Nasr City	Cold	100.0%	0.0%	0.0%	0.0%	0.0%
	Hot	0.0%	0.0%	0.8%	87.4%	11.8%
	Normal	29.7%	24.6%	36.0%	9.7%	0.0%
6th October City	Cold	100.0%	0.0%	0.0%	0.0%	0.0%
	Hot	0.0%	0.0%	3.0%	89.3%	7.7%

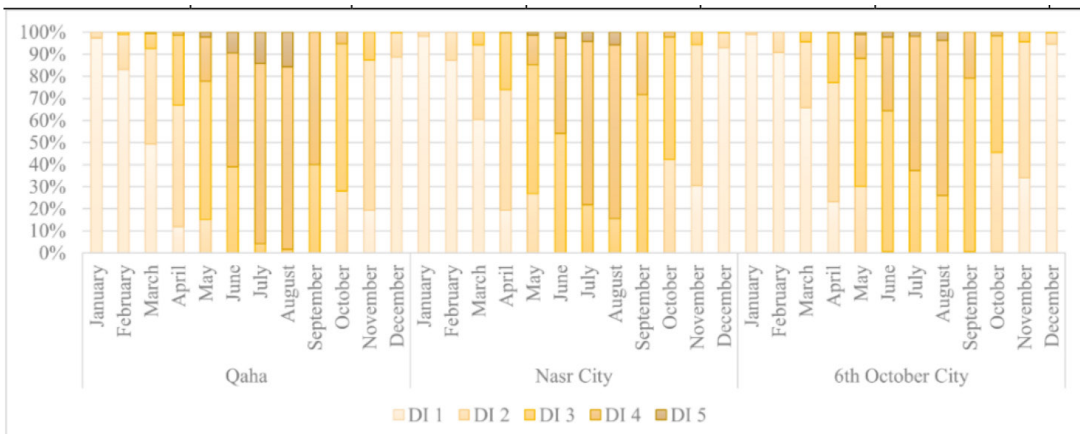

Fig. 3: The frequency of DI classes for each location/ monthly

in all three cities is significantly worse in the winter than in the summer. This is likely due to a combination of factors, which can contribute to air pollution. In the summer months, the air quality improves. The observation that air quality in all three cities in GC is significantly worse in the winter than in the summer is a common phenomenon and can be scientifically explained by several factors:

- Temperature inversion: in many regions, especially during the winter months, temperature inversions can occur. This is when a layer of warm air traps cooler air near the surface, preventing pollutants from dispersing. This stagnant air can lead to the accumulation of pollutants, resulting in poorer air quality.

- Winter weather conditions, such as calm winds and low atmospheric mixing, can limit the dispersion of pollutants. In contrast, summer often brings more turbulent atmospheric conditions, which help disperse pollutants, improving air quality. Stagnant air masses during the winter, the movement of air masses can be more sluggish, and this can contribute to the accumulation of pollutants in specific areas. In contrast, the dispersion of pollutants is often more effective in summer due to more dynamic air circulation patterns. Increased combustion: during the winter, there is typically an increase in the combustion of fossil fuels for heating, both in residential and industrial settings.

Thermal discomfort identification

Thermal discomfort is a term used to describe the conditions in which people find themselves uncomfortable due to the temperature and humidity levels in their environment.. Thom's discomfort Index (DI) was used for this assessment process. The assessment of thermal discomfort conditions using Thom's discomfort index and the presentation of extreme weather conditions are important steps in understanding how temperature and humidity affect human comfort and well-being in different locations. This knowledge can guide efforts to create more comfortable and healthy living and working environments. It classifies conditions into different categories or classes, which provide insights into the level of discomfort experienced by individuals in specific weather conditions. Table 4 shows data on extreme weather conditions, specifically temperature (TºC) and relative humidity (RH%), for each of the study locations. It then highlights the occurrence of both extremely cold and extremely hot weather conditions in these

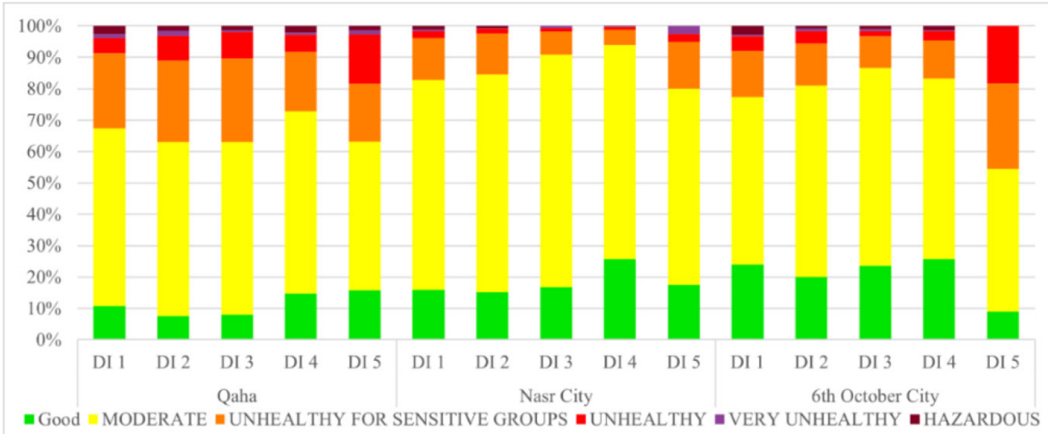

Fig. 4: The synergy between AQI and DI in different weather conditions at three locations

locations. Fig. 3 illustrates how the DI classes vary spatially and temporally across the study locations. The frequency of each DI class provides valuable information about the prevalence of thermal discomfort conditions in these areas over time. Notes that DI 6, which represents a medical emergency state, was not recorded in the study locations. The results show that most of the population in all three cities experience discomfort at least some of the time. It is noted that Fig. 3 reveals that a significant portion of the population in all three cities experiences discomfort to varying degrees. In Qaha, 28.97% of the population experiences no discomfort, while 25.41% experiences severe stress. In Nasr City, 32.15% of the population experiences no discomfort, while 20.21% experiences severe stress. The 6th of October City, 33.76% of the population experienced no discomfort, while 16.65% experienced severe stress.

Fig. 3 highlights a seasonal variation in discomfort levels within the population. This suggests that certain months, specifically June to September, are associated with higher levels of discomfort, affecting more than 50% of the population. Seasonal variations in discomfort can be due to a range of factors, including weather, climate, and environmental conditions. D3 and D4 were recorded in the spring months, due to the monsoon such as Khamsin's hot and dusty wind. The frequency of DI courses during severe cold, extremely hot, and typical weather situations is shown in Table 5. Extremely hot weather causes considerable pain in at least half of the population. According to Thom's DI categories. The temporal variation examination reveals that most participants in the studied locations had no discomfort throughout the winter months (December to March). However, when the temperature rose throughout the summer months (May to September), an increasing number of individuals began to complain. By July and August, more than half of the population was in pain. The temporal variation in discomfort reflects the challenges people face when transitioning from colder to hotter seasons, emphasizing the need for strategies to cope with extreme heat in regions unaccustomed to such conditions. During winter months (December to March), discomfort is low. In contrast, discomfort increases during the summer months (May to September) because of the physiological and psychological challenges posed by extreme heat. Increased Heat-Related Illness it leads to more than half of the population being in pain during July and August indicating a potential increase in heat-related illnesses and discomfort during the hottest months of the year.

The synergy of AQI and DI

Fig. 4 shows the synergy between DI and AQI in different weather conditions; three weather periods: extremely cold, extremely hot, and normal or regular conditions. The results showed that in extremely cold weather, only DI 1 was recorded. The good AQI was 13.39%, 18.10%, and 26.33% for Qaha, Naser City, and 6th of October City, respectively. These values indicate poor air quality in all three cities during extremely cold weather. In extremely hot weather, DI 3, DI 4, and DI 5 were recorded. The good AQI recorded the lowest percentage during DI 5 than during DI 4, which was 16.00%, 17.50%, and 9.09% for Qaha, Naser City, and 6th of October City, respectively. These values suggest that higher DI is associated with lower AQI in extremely hot weather. In normal weather conditions, the synergy of DI and AQI was not clear as in extreme weather. However, DI 5 was not recorded during normal weather except for Qaha, which had 100% moderated AQI. A study was conducted to examine the influence of mixing layer height on air pollution. The analyses reveal that the associations between pollutant concentrations and mixing layer height (MLH) are least pronounced within street canyons. Furthermore, the correlations at the urban background stations are more substantial during the winter season compared to the summer season, and they are also more substantial at the urban stations in comparison to the rural stations (Schäfer *et al*., 2006). Another study was conducted to investigate the impact of mixing layer height on air pollution and the thermal discomfort index in the three cities. The study found that the relationship between AQI and DI varies depending on the weather conditions. In cold weather, DI is lower, even when AQI is high. In hot weather, DI is higher, even when AQI is not as high. This is due to different reasons such as the temporal variation of the atmospheric mixing height (Geiß *et al*., 2017).

CONCLUSION

The results of this study show that most of the population in all three cities in Egypt experience discomfort at least some of the time. Air quality in all three cities was poor, with most days falling into the unhealthy for sensitive groups or unhealthy categories. The highest levels of air pollution were found in Qaha, followed by Nasr City and 6th October City. The main pollutant responsible for air pollution in these cities was (PM10). The results suggest that DI and AQI are synergistic in extreme weather conditions. The air quality management strategies should focus on reducing emissions from vehicles and other sources of pollution in extreme weather conditions. This suggests a need for strategies to mitigate the health impacts of extreme heat, such as heat waves.

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***Authors contribution*: M. Abd El-Ha. Mohamed:** Conception and design of study, Acquisition of data, Analysis and/or interpretation of data, Drafting the manuscript, Revising the manuscript; **M. M. A. hwehy:** Conception and design of study, Acquisition of data, Analysis and/or interpretation of data, Drafting the manuscript, Revising the manuscript; F. **I. Moursy:** Analysis and/or interpretation of data: Revising the manuscript; **A. M. El-tantawi:** Drafting the manuscript, Revising the manuscript.

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