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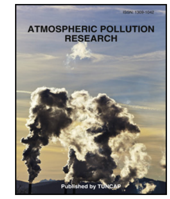

Air quality (AQ) identification by innovative trend diagram and AQ index combinations in Istanbul megacity

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A R T I C L E I N F O

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A B S T R A C T

Istanbul is one of the megacities with population over 14 million, where the most intensive economic and social human activities take place in Turkey with unprecedented energy consumption and extravagant life style. These activities cause air pollutant emissions and concentrations increases under the additional effects of greenhouse gasses and waste heat with their impacts on ecosystems, climate change and air quality.

In order to control and improve the air quality at different quarters of Istanbul City, various air pollutants are monitored for effective combat. For this purpose, time series records of the pollutants (particulate matter < 10 µm in diameter such as dust, pollen, mold, etc. (PM10), carbon monoxide (CO), sulfur dioxide (SO_2) and nitrogen dioxide (NO_2)) are subjected to innovative trend diagram (ITD) analysis coupled with the air quality index (AQI) classification according to the US Environmental Protection Agency health status. Linguistic AQI classes are considered for pollutant levels with linguistic trend interpretations through the ITD diagram. The combination of ITD and AQI provides opportunity to detect trends at each class. The application of the methodology is presented for Esenler and Beşiktaş stations on the European, and Kadıköy and Ümraniye stations on the Asian sides of Istanbul City.

1. Introduction

Today, over half of the world population lives in urban areas and megacities leading to pressure on urban areas due to the increasing of global population. This also promotes steadily ongoing unplanned urbanization trends. Understanding the role of megacities in local to global atmospheric composition is critical to realize air pollution control effectively and climate change effects reduction with the growing trend towards urbanization (Fenger, 1999).

It has been recognized for a long time that air pollution has negative impacts on human health, terrestrial and aquatic ecosystems. Especially, negative impacts of air pollution have not only on human health but also on megacities (like London and New York). They have been attracting attention since the middle of the 20[st] century (Henschel et al., 2012). The adverse effects of poor air quality on ecosystem and urban life, with major financial burdens to society, make air quality as essential challenge of 21st century (Timmermans et al., 2015; Telloli et al., 2018). Additionally, since the last three decades, it has been thought that major contributions to increase anthropogenic gasses originate form megacities. Due to these factors, megacities are considered as the best places for air pollution control and climate change effects reduction. For this purpose, the scientific and engineering knowledge has accumulated with the air pollution and quality control problems in megacities. Unfortunately, currently available demographic and social data about many megacities around the world does not provide a truly comprehensive and integrated assessment for relationship between megacities and air pollution.

The air pollution sources are divided into two basic categories as natural and anthropogenic. Natural sources can be classified as forest fires, volcanos, oceans evaporation and some biological sources. Anthropogenic side includes humankind activities and fossil fuel consumptions, which are be main reason for triggering climate change and global warming. Furthermore, air pollutants are also in rapid increase due to industrial developments. Especially, in industrialized countries national governments have issued several regulations to restrict pollutants emissions (Monforte, 2017). It is clear that anthropogenic

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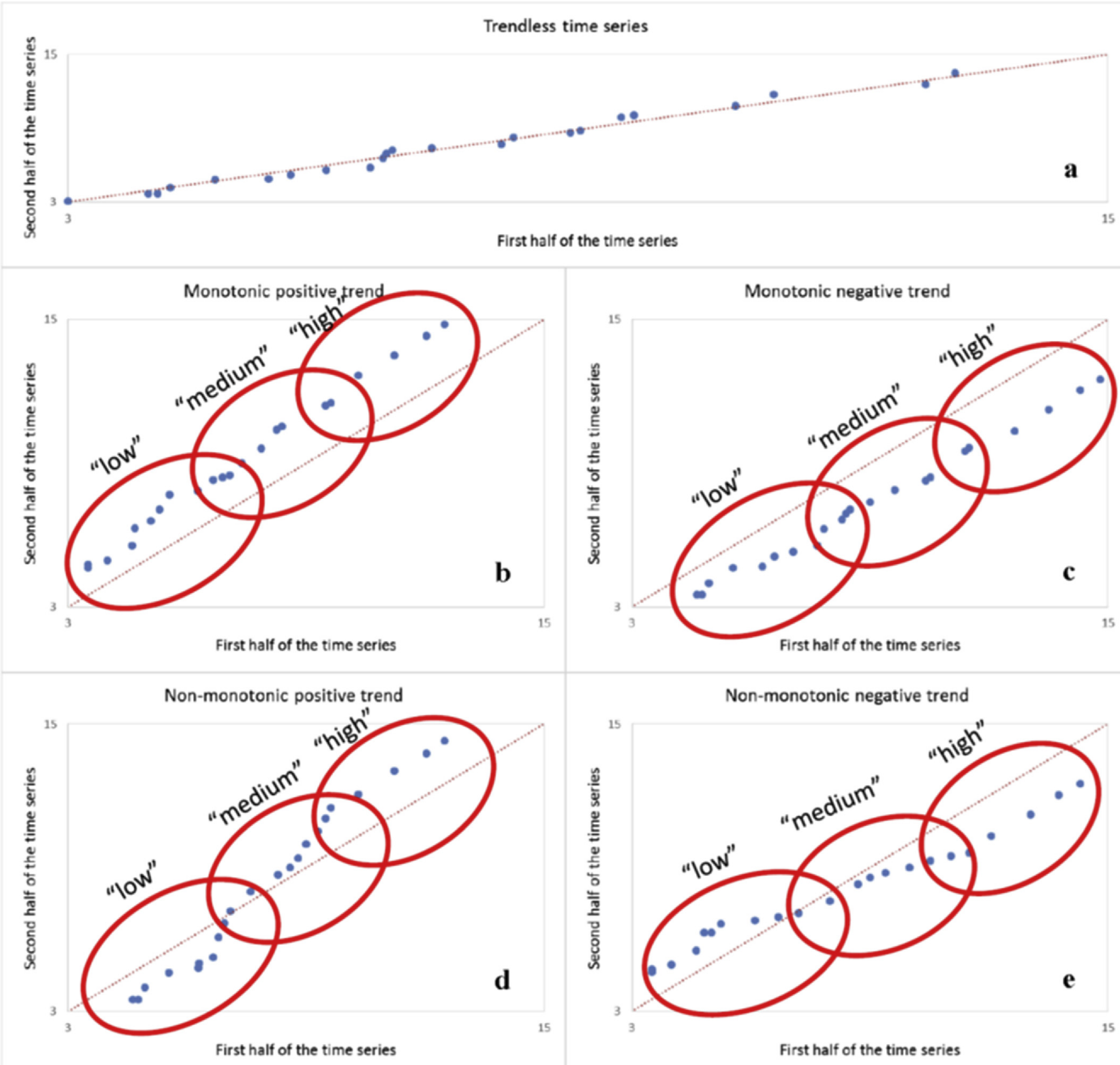

Fig. 1. Possible trend conditions on innovative 1:1 straight-line (Şen, 2012).

emissions limiting and air quality improvements are two of the most important environmental challenges for humankind (Athanasopoulou et al., 2016). It is a fact that still air pollutants contribute to climate change, while many potential measures are in progress to mitigate climate change affect from their emissions (UNEP, 2012; Guldmann, 1988).

The life span of planet Earth depends on air composition in the atmosphere, which includes different rates of nitrogen (N), oxygen (O), carbon dioxide (CO_2), sulfur dioxide (SO_2), carbon monoxide (CO), ammonia (NH_3), nitrogen oxide (NO_x), particulate matter (PM), volatile organic compounds (VOC) and other gases (Stoeckenius et al., 2015; Karim and Ohno, 2000; Hackstadt and Peng, 2014). Air pollution is preceded by the combination of high emissions and unfavorable weather conditions (Papanastasioua et al., 2015). Observation techniques of these gases are relatively different. For instance, PM is generally sampled from an environment by human based activities (Bein and Wexler, 2015). Small sized suspended particulates, (PM10, PM2.5, PM1) are the most important common air quality indicators dealt with many health effects (Lanzafame et al., 2015). Exposure of ambient air to pollution is regarded as an environmental problem threating natural balance (Pope et al., 2002; Şen and Öztopal, 2001). Particle pollution concentrations threat wide range of human health, especially children (Burr et al., 2015). Respiratory and cardiovascular diseases are triggered by air pollution during recent decades (Anil et al., 2014; Titos et al., 2015). Air quality index (AQI) is a dimensionless quantity to show synthetically the overall state of air pollution by concerning PMs. The AQI is calculated from the geometric average of considered pollutants by assessing the air quality rating (AQR) of each pollutant (Chaudhuri, and Chowdhury, 2018). The AQI methodology consists pollutants such as PM10, PM2.5, CO, NO_2, O_3, SO_2 that cause an acute problem on health (Lanzafame et al., 2015). The AQI methodology is widely used for PM analysis. US Environmental Protection Agency

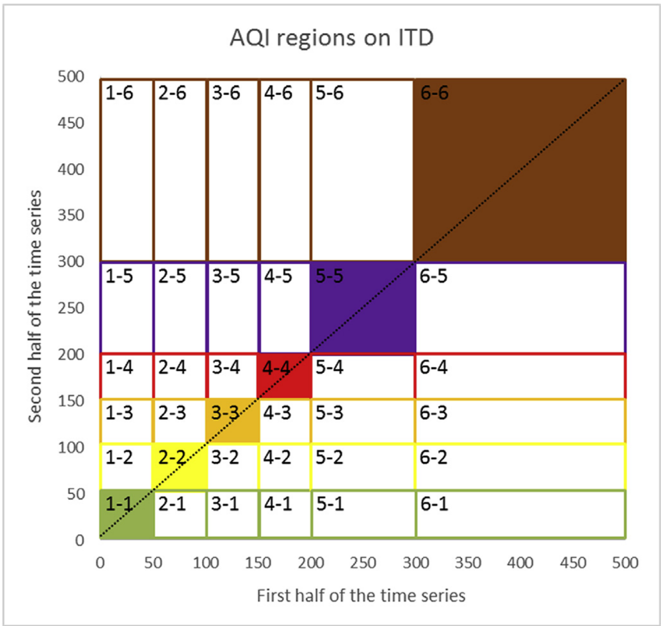

Fig. 2. Air quality index ranges on innovative trend diagram (ITD).

(EPA) developed Air Quality Index (AQI), which consists ground level ozone and PM.

PM transport is essential problem for air quality observed in megacities. Though, it is thought that the PM pollution originated by human as one of the major factors in the deterioration of air quality, Saharan dust effects must also be considered (Cuspilici et al., 2017; Şen, 2018). Small sized PMs can be transported on air on European and Asian latitudes by strong winds (Ansmann et al., 2003). This kind of natural dust pollution is observed especially in the south and north latitudes of Turkey. The brownish colored precipitation including Saharan dust is seen in last days of winter and beginning of spring in particular in Turkey (Tilev-Tanriover and Kahraman, 2015).

Observation and control of air quality is challenging issue for authorities. The most significant point in any kind of air pollution control system is to be able to detect increasing (deterioration) or decreasing (improvement) trends. In literature, methodologies for trend detection vary depending on the purpose. The innovative trend diagram (ITD) as proposed by Şen (2012, 2014) provides additional opportunities for objective and linguistic interpretations. The ITD is based on the 1:1 (45°) straight-line method without any restrictive assumptions. So, it has been used by many researches in the field of time series analyses (Timbadiya et al., 2013; Markus et al., 2014; Saplioglu, 2014; Güçlü, 2016, 2018; Dabanlı et al., 2016; Mohorji et al., 2017; Güçlü et al., 2018; Alashan, 2018). This method also supports the well-known classical tests as Mann-Kendall (MK) approach with trend slope calculation (Sen, 1968). Though, linear regression trend test is improved to make refined comparisons, its application is not possible for all-time series (Haan, 1977). Some researchers have analyzed some time series data using these methods (Qian et al., 2007; Kauffman and Belden, 2010; Kara et al., 2013; Yao and Lu, 2014; Barbara, 2015; Rattigan et al., 2017). Modarres and Dehkordi (2005) performed different time series analysis of daily air pollution for Isfahan city in Iran.

The main purpose of this paper is to apply the ITD-AQI methodology to air pollutant measurements from different locations of Istanbul City, Turkey. Each pollutant is described through the ITD approach coupled with the convenient categorical trend composition on the basis of the EPA health status.

2. Materials and methods

In general, trend analysis is achieved by the classical Mann-Kendall (Mann, 1945; Kendall, 1975) trend test, which is a statistical procedure for detecting increasing and decreasing trend components in a given time series. The differences between each consecutive value are calculated so as to depict positive (+1), negative (−1) and neutral (0) signs, sgn (…) as follows.

$$\mathrm{sgn}\,(x_j - x_k) = \begin{Bmatrix} +1 & if & (x_j - x_k) > 0 \\ 0 & if & (x_j - x_k) = 0 \\ -1 & if & (x_j - x_k) < 0 \end{Bmatrix} \tag{1}$$

where x_j and x_k are time series values at time instances j and k, respectively from a given time series $\{x_1, x_2, \ldots, x_k, \ldots, x_j, \ldots, x_n\}$ with n observations. The Kendall sum statistic, S, is given as,

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \mathrm{sgn}(x_j - x_k) \tag{2}$$

It is obvious that positive (negative) S values, $S > 0$ ($S < 0$) value indicates increasing (decreasing) trend in the time series. This is a statistical test for identifying monotonic trend along all the time series without any comparison within the time series itself.

However, in practical studies, it is better to be able to compare the first part of a given time series with the second half for better understanding whether a trend exists or not. For this purpose, an innovative trend diagram (ITD) analysis has been suggested by Şen (2012, 2014), and it shows even visually the existence of any trend. In the following sequel, 1:1 (45°) straight-line ITD method is combined with AQI classifications based on the EPA health status. The calculation steps of the ITD are as follows.

1) Any given time series, $x_1, x_2, \ldots, x_n$ is divided into two halve series $\{y_{1,n/2}\}$ and $\{y_{2,n/2}\}$ as,

$$\{y_{1,n/2}\} = \{x_1, x_2, \ldots, x_{n/2}\} \tag{3}$$

and

$$\{y_{2,n/2}\} = \{x_{n/2+1}, x_{n/2+2}, \ldots, x_n\} \tag{4}$$

where n/2 is the length of each series.

2) Each half series is ranked according to the time series values in ascending order, hence, there are two ordered series, $\{r_1\}$ and $\{r_2\}$ with the same number of elements,

$$\{r_1\} = \{\min(y_{1,n/2}), \ldots y_i, \ldots, \max(y_{1,n/2})\} \quad (1 < i < n/2) \tag{5}$$

and

$$\{r_2\} = \{\min(y_{2,n/2}), \ldots, y_j, \ldots, \max(y_{2,n/2})\} \quad (1 < j < n/2) \tag{6}$$

3) The values of $\{r_1\}$ series are plotted against the values of $\{r_2\}$ and a scatter diagram is obtained,
4) The scatter diagram will have variation domains between minimum and maximum values of each ordered series,
5) The scatter diagram is put into a form of equal scale sizes on both horizontal and vertical axes depending on the minimum of minimums, min [min $(y_{1,n/2})$, min $(y_{2,n/2})$] and maximum of maximums, max [max $(y_{1,n/2})$, max $(y_{2,n/2})$] values. On the same figure then 1:1 straight-line is put. This is the main structure of the ITD,
6) If all the scatter points fall on the 1:1 straight-line or with insignificantly random deviations from the 1:1 straight-line then there is no significant trend in the basic time series,
7) Otherwise there are significant trends. If the points are below (above) the 1:1 straight-line then there is a significant increasing (decreasing) trend.

Table 1
Trend conditions of air quality index ranges coupled with innovative trend diagram.

Region	Trend condition	First half condition	Second half condition	Result
1 / 1	No trend	Green	Green	Good
1 / 2	Increasing	Green	Yellow	Moderate
1 / 3	Increasing	Green	Orange	Unhealthy (Sens.)
1 / 4	Increasing	Green	Red	Unhealthy
1 / 5	Increasing	Green	Purple	Very Unhealthy
1 / 6	Increasing	Green	Maroon	Hazardous
2 / 1	Decreasing	Yellow	Green	Good
2 / 2	No trend	Yellow	Yellow	Moderate
2 / 3	Increasing	Yellow	Orange	Unhealthy (Sens.)
2 / 4	Increasing	Yellow	Red	Unhealthy
2 / 5	Increasing	Yellow	Purple	Very Unhealthy
2 / 6	Increasing	Yellow	Maroon	Hazardous
3 / 1	Decreasing	Orange	Green	Good
3 / 2	Decreasing	Orange	Yellow	Moderate
3 / 3	No trend	Orange	Orange	Unhealthy (Sens.)
3 / 4	Increasing	Orange	Red	Unhealthy
3 / 5	Increasing	Orange	Purple	Very Unhealthy
3 / 6	Increasing	Orange	Maroon	Hazardous
4 / 1	Decreasing	Red	Green	Good
4 / 2	Decreasing	Red	Yellow	Moderate
4 / 3	Decreasing	Red	Orange	Unhealthy (Sens.)
4 / 4	No trend	Red	Red	Unhealthy
4 / 5	Increasing	Red	Purple	Very Unhealthy
4 / 6	Increasing	Red	Maroon	Hazardous
5 / 1	Decreasing	Purple	Green	Good
5 / 2	Decreasing	Purple	Yellow	Moderate
5 / 3	Decreasing	Purple	Orange	Unhealthy (Sens.)
5 / 4	Decreasing	Purple	Red	Unhealthy
5 / 5	No trend	Purple	Purple	Very Unhealthy
5 / 6	Increasing	Purple	Maroon	Hazardous
6 / 1	Decreasing	Maroon	Green	Good
6 / 2	Decreasing	Maroon	Yellow	Moderate
6 / 3	Decreasing	Maroon	Orange	Unhealthy (Sens.)
6 / 4	Decreasing	Maroon	Red	Unhealthy
6 / 5	Decreasing	Maroon	Purple	Very Unhealthy
6 / 6	No trend	Maroon	Maroon	Hazardous

The trend can be determined first by visual inspection of the data positions relative to 1:1 (45°) straight-line. A set of hypothetical ITDs are presented in Fig. 1.

Under the light of the aforementioned ITD explanations one can make the following interpretations. Fig. 1a implies no trend in the time series. The ITD can be visualized also in terms of a set of classes, and for instance, in Fig. 1 three classes are given as “low”, “medium” and “high” for the sake of discussion. Fig. 1b and c are for monotonically

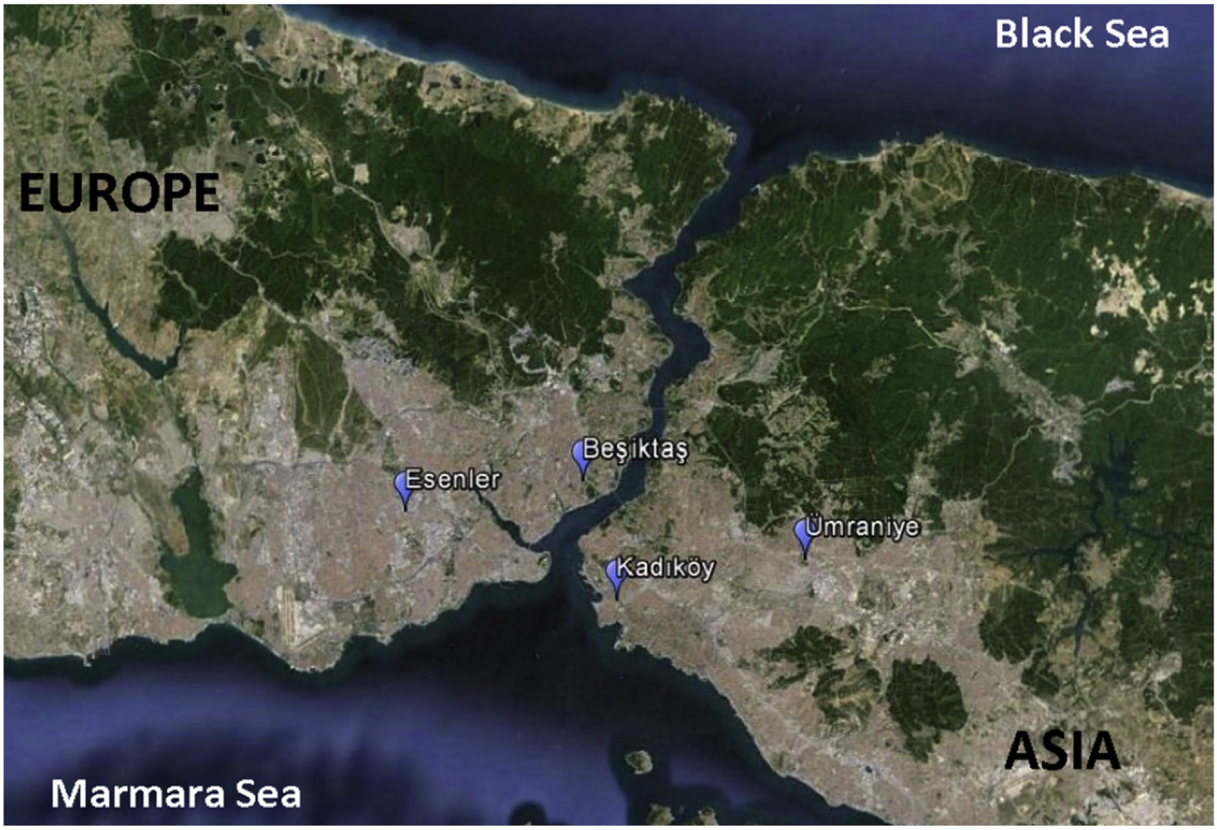

Fig. 3. Air quality measurement stations.

Table 2
Air quality measurement station locations.

Stations	Latitude	Longitude
Esenler	41° 02′ 17″ N	28° 53′ 17″ E
Beşiktaş	41° 03′ 14″ N	29° 00′ 36″ E
Kadıköy	40° 59′ 30″ N	29° 02′ 00″ E
Ümraniye	41° 02′ 17″ N	28° 53′ 17″ E

Table 3
AQI ranges versus SO_2, NO_2, CO, and PM10 measurements (EPA).

Colors	AQI	SO_2	NO_2	CO	PM10
		1 h	1 h	8 h	24 h
Good (Green)	0–50	0–100	0–100	0–5500	0–50
Moderate (Yellow)	51–100	101–250	101–200	5501–10000	51–100
Unhealthy Sens. (Orange)	101–150	251–500	201–500	10001–16000	101–260
Unhealthy (Red)	151–200	501–850	501–1000	16001–24000	261–400
Very Unhealthy (Purple)	201–300	851–1100	1001–2000	24001–32000	401–520
Hazardous (Maroon)	301–500	> 1101	> 2001	> 32001	> 521

increasing and decreasing trends, respectively. In air quality context increasing (decreasing) trend means deterioration (improvement) in air quality. Fig. 1d and e are for non-monotonic increasing and decreasing trend components, respectively.

Furthermore, each diagram can be viewed in a set of classes, and for instance, according to the EPA-AQI classification, there are 6 classes as Good (Green), Moderate (Yellow), Unhealthy Sensitive (Orange), Unhealthy (Red), Very Unhealthy (Purple), and Hazardous (Maroon). These six classes are combined with the innovative trend method leading to 36 different regions (see Fig. 2).

If scatter points are within on 1-1, 2-2, 3-3, 4-4, 5-5 and 6-6 regions, then each one corresponds to a trendless time series case. Other groups of sub-regions are described in Table 1.

3. Study Area and Data

Air pollution measurement stations are considered as Esenler and Beşiktaş on the European, and Kadıköy and Ümraniye on the Asian sides of the Istanbul megacity, where air pollutant records are available for 8 years from the mid-2007 to the mid-2015, inclusively. These records approximately consist of 12,000 daily PM10 measurements at all stations, 140,000 hourly SO_2 measurements at Esenler and Beşiktaş, 17,500 eight-hour CO measurements at Esenler and Beşiktaş, and 140,000 hourly NO_2 measurements at Kadıköy and Ümraniye stations. Measurement station locations are shown in Fig. 3 and their geographical coordinates are available in Table 2.

Three factors were influential in selecting these stations. Firstly to have sufficient and good quality data. Secondly, to accommodate the high population areas. Lastly, to lay on the inner region or coastal zone of İstanbul. While all stations have the first two properties, Esenler and Ümraniye stations are inner parts, but Beºiktaº and Kadıköy are located on coastal zones.

4. Results and discussions

Air pollution and climate impacts are not dependent only on the geographic of megacities but also on the regional meteorology and climatology. Urban centers and megacities are the main concern of air pollution due to economic, social and industrial activities, which give rise to various air pollutants at the lower atmosphere. Especially, PM suspension in the lower atmosphere is dangerous for human health and

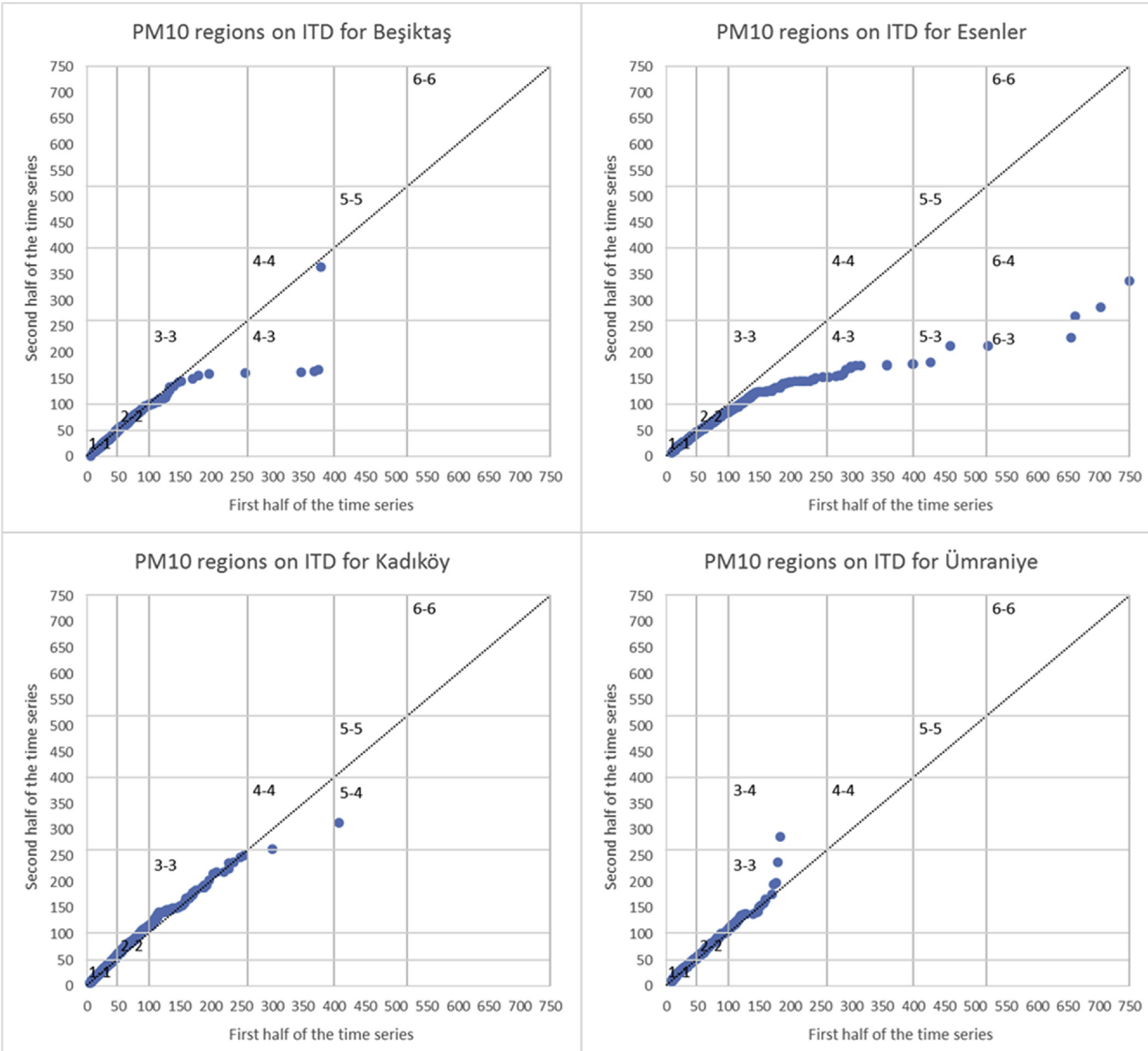

Fig. 4. Trend in PM10 values for all stations.

terrestrial and aquatic ecosystems and environments. It is necessary to monitor, assess and control the air pollutants in urban areas, and especially, in megacities for protecting the ecosystem from undesirable effects. For this purpose, in megacities of the world, there is air pollution monitoring systems. This is the case also in the Istanbul megacity, Turkey, where PM10, CO, SO_2 and NO_2 are monitored from mid-2007 to mid-2015, inclusively.

Although there are some classical methodologies for trend analysis (Mann, 1945; Kendall, 1975; Sen, 1968), but their linguistic interpretations are rather scanty and they do not allow categorical trend identification. Therefore, it is never possible to make categorical trend assessments according to the AQI classification of the EPA using the classical methodologies, but ITD method offers a great opportunity for categorical trend analysis.

Table 3 indicates linguistic and numeric position of each pollutant's averages in μg/m^3 according to the AQI classification of the EPA.

Fig. 4 presents the PM10 ITD-AQI positions at four locations of Istanbul megacity.

Generally, PM10 measurements do not reach to the 5-5 and 6-6 regions in the ITD. The values piled up on the regions 1-1, 2-2 and 3-3 at all stations. When the other regions such as 3–4, 5–4, 4–3 are taken into consideration, it appears that a few data are available, and therefore, there is no significant change in the air quality. However, this is not the case for Esenler data, where a decreasing trend is clearly visible at high PM10 values, indicating improvement in air quality. In summary, most of the PM10 data measured from 2011 to the present (the second half) fall into green, yellow, and orange regions according to AQI linguistic classification.

Fig. 5 shows CO values for Beşiktaş location, where all values remain within the green region. However, the same situation does not occur at Esenler, where measurements concentrate in 1-1 region, but an increasing trend exists as a few high measurement values. While the first-half values fall on the green region, high values in the second-half are shifted towards 1–2 yellow region.

Fig. 6 is for Beşiktaş and Esenler stations' SO_2 scatter diagram, where the scatter points are concentrated usually within the 1-1 and

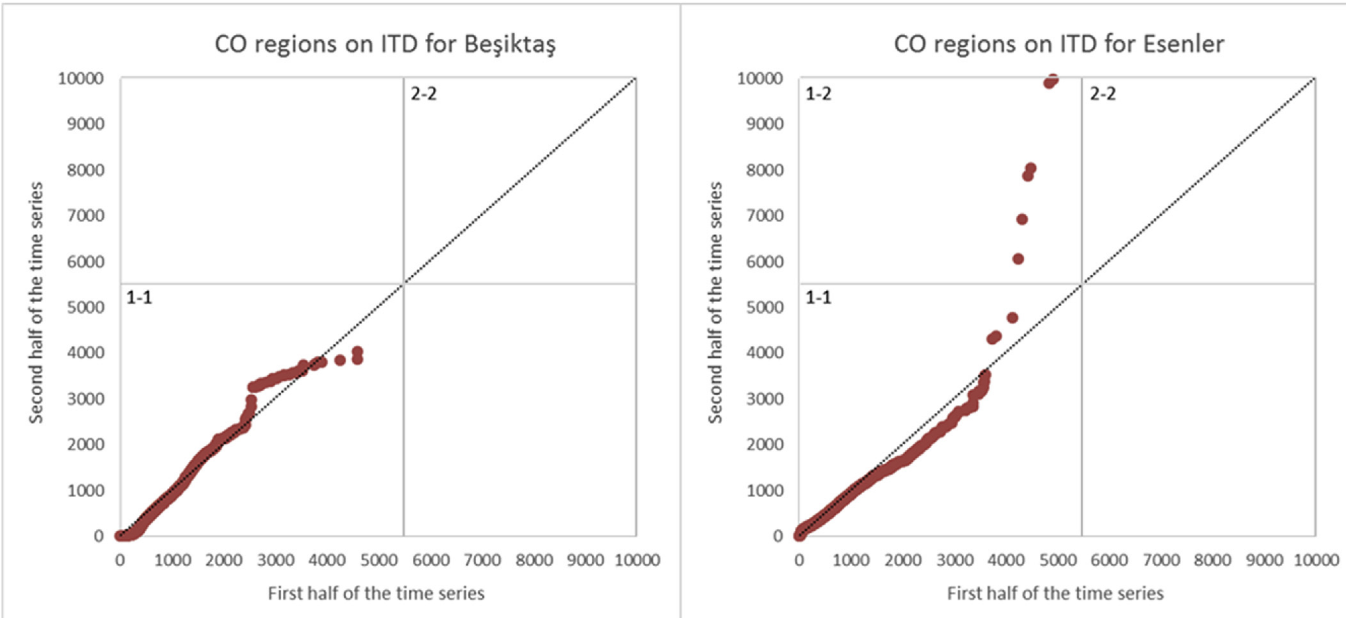

Fig. 5. Trend in CO values for Beşiktaş and Esenler stations.

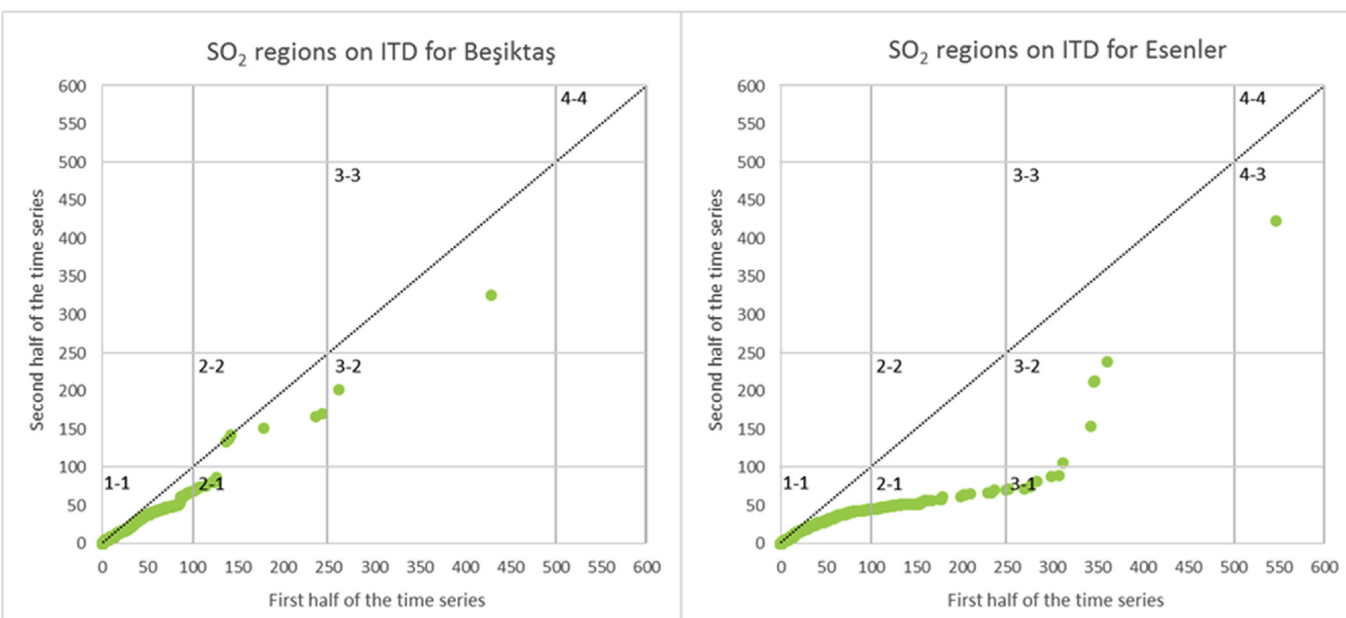

Fig. 6. Trend in SO_2 values for Beşiktaş and Esenler stations.

2–1 regions in slightly decreasing trend form at Beşiktaş station, but some high values are located on 2-2 region.

At Esenler location, SO_2 data fall on the 1-1, 2–1, 3–1 and 3–2 regions indicating a decreasing trend, which implies that there is a significant improvement in terms of SO_2 air quality. At the same location, there is also another decreasing trend at high measurement values. The respective values in Esenler are measured until orange region similar to Beşiktaş.

Finally, Fig. 7 presents trend analysis results for NO_2 data measurements at Kadıköy and Ümraniye stations.

At Ümraniye region, there is no trend within the data until the 3-3 region. However, measurements are seen below the 4-4 region in Kadıköy. NO_2 values from Kadıköy station are scattered usually in the 1-1, 2-2, 3-3, and 4-4 regions with slightly increasing trend, because high values have shifted slightly towards the 3–4 region.

5. Conclusion

Although there are different statistical, quantitative and qualitative approaches for air quality assessments leading to scientific evaluations and assessments towards control activities. In this paper, innovative trend diagram (ITD) is coupled with the air quality index (AQI) classification for better assessment according to Environmental Protection Agency (EPA) health status. This combination provides air pollutants classification in addition to possible trend detections within each class. Increasing (decreasing) trend components correspond to air quality deterioration (improvement). The bases of the ITD have been explained and its combination is presented with EPA health status. The ITD-AQI graphs provided linguistic and objective air quality interpretations. The application of the proposed methodology is presented for four quarters of İstanbul megacity.

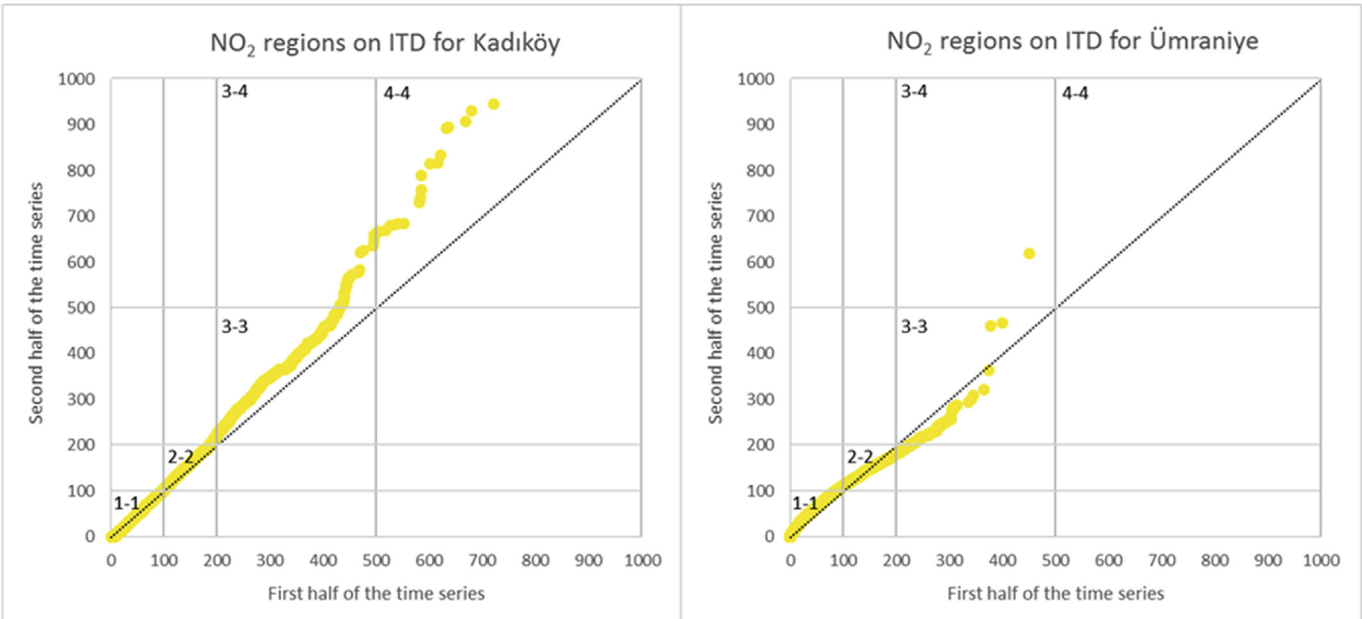

Fig. 7. Trend in NO_2 values for Kadıköy and Ümraniye stations.

It is difficult to improve the air quality for many reasons, such as unorganized and unsystematic urbanization planning, unplanned industrialization, high-density population and poor quality fuel use. However, when the figures are examined, the air quality of Esenler district on the European side of Istanbul megacity with high-population and more industrialization, it is distinctively different from the other stations due to the spread of natural gas services and fuel quality improvements. In addition, the air quality is stable despite high-population in the other stations through the available natural gas system.

As a result, the methodology presented in this paper can be applied successfully in any other part of the world as a supplement to classically existing air quality assessment methodologies.

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