



A Multidecadal Assessment of Haze Development and Fluctuations in Visibility for Arabian Peninsula

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Abstract

Deteriorating visibility (VR) is an exacerbating problem in the Arabian Peninsula (AP) under the prevailing natural and anthropogenic causes. The main objective of this paper is to analyze the long-term (1975–2023) trends of visibility fluctuations and development of haze for six countries including Kingdom of Saudi Arabia (KSA), Iraq (IRQ), Qatar (QTR), Kuwait (KWT), United Arab Emirates (UAE), and Oman (OMN). To comprehend the time-based patterns of visibility across the ME, we utilized the Mann Kendall (MK) and Modified Mann Kendall (MMK) trend estimators in both space and time. The daily visibility of QTR exhibits significant variations from 1975 to 2023, with the lowest and greatest values representing the dynamic character of visibility in the region. Oman's daily visibility have revealed complex pattern with frequent occurrence of close to zero visibility starting from 1975. Visibility in KWT was 0.5 km in 1994, indicating a period of exceptionally poor visibility whereas the daily mean visibility for KSA was approximately 0.6 km. The UAE data shows strong seasonal spikes in visibility, with peaks of about 2 km. IRQ air quality was severely misty on days when visibility was approximately 0.4 km. Among the six countries, visibility in KWT is improving at 0.06 km/year, while visibility in IRQ is decreasing rapidly at the rate of -0.26 km/year. Keeping in account the overall trends over the decades to assess current visibility conditions, Visibility in KWT and QTR is improving at the fastest trend of +0.15 and +0.05 km/year respectively as compared to OMN, IRQ, UAE and KSA. Policymakers in the region can work on regional environmental policies to further improve the regional atmospheric visibility.

Keywords Air Pollution · Arabian Peninsula · Haze · Mann Kendall · Trend · Visibility

1 Introduction

Atmospheric visibility, often called visual range, is the distance at which objects in the atmosphere may be recognized just by looking at them (Javed et al. 2023, 2024; Shahzad et al. 2012, 2018). Due to its effect on air quality, traffic safety, and other outdoor activities, it is considered as an important

meteorological and aviation feature and sometime hazard due to low values. Climate change assessment and weather prediction also rely on accurate estimates of atmospheric visibility (Aman et al. 2019; Araghi et al. 2019; Fu et al. 2018; Javed et al. 2023). Several causes, both natural and man-made, contribute to the globally prevalent problem of poor visibility. Fog, mist, haze, and dust storms are some of the natural phenomena that drastically diminish visibility (Mezősi 2022; Yair and Yaniv 2023). Moreover, visibility can be severely impaired by heavy precipitation, especially during thunderstorms (Ashrit et al. 2022; Singh et al. 2024). Visibility is reduced due to air pollution caused by human activities, such as emissions from automobiles, industrial processes, and biomass burning (Aldababseh and Temimi 2017; Alhathloul et al. 2021; Javed et al. 2023). Particulate Matter (PM) and pollution levels are typically higher in urban areas, making visibility worse (Aman et al. 2019). The visibility problem is worse in the Middle East (ME)

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because of things like dust storms in the desert, pollution from factories, and cars (Aldababseh and Temimi 2017; Alhathloul et al. 2021; Middleton et al. 2021).

A wide range of ground-based and satellite-based devices are available for visibility measurements, each with its own set of benefits and capacities (Shahzad et al. 2018). One typical application of ground-based sensors is the localized and real-time monitoring of visibility. A Nephelometer measures the amount of light scattered by airborne particles to give information about the visibility conditions (Javed et al. 2023). Transmissometers are another common ground-based instrument for measuring visibility over short to medium distances; they work by measuring the attenuation of a light beam over a defined distance directly. In addition, the Forward Scatter Meter evaluates visibility by analyzing the light scattered by pollutants (Javed et al. 2023; Shahzad et al. 2018). Installing these sensors on the ground at locations like weather stations, roadways, and airports helps with transportation, meteorology, and aviation (Javed et al. 2023).

Since aerosols and other atmospheric components reduce the amount of light reaching the ground, radiometers can indirectly estimate visibility by detecting the amount of radiation emitted or reflected by the Earth's surface and atmosphere (Kiranmai et al., n.d.; Zhang et al. 2020). Vertical profiles of aerosol dispersion and optical properties, including visibility, can be retrieved using Lidar (Light Detection and Ranging) data, which is obtained by emitting pulses of laser light and taking measurements of the reflected light (Wu et al. 2022; Zabukovec et al. 2021; Zhang et al. 2020).

Many factors have contributed to poor visibility in ME from the last five decades where dust storms are the most common in ME and contribute to the low visibility that is common throughout the summer and transitional seasons (Bridhikitti 2023; Mushtaq et al. 2022). The air becomes much less clear and transportation and outdoor activities become more difficult during these dust storms, which typically originate in desert areas and are worsened by dry climate conditions and high winds (Mashat et al. 2020; Xi 2021). Air pollution is also effecting visibility in ME cities due to industrial operations, urbanization, and vehicle emissions. PM in the air has increased due to fast economic expansion and building projects, making visibility worse and affecting public health (Bridhikitti 2023; Mushtaq et al. 2022). Haze and fog sometimes appear from time to time, especially along the shore, which further reduces visibility and makes aviation and maritime navigation more dangerous. Nevertheless, the problems posed by rising urbanization and industrialization highlight the significance of ongoing efforts to reduce air pollution and improve visibility in these areas (Hamidi et al. 2013; Klaus et al. 2016; Lelieveld et al. 2012; Liu et al. 2023).

Tropical cyclones that start in the AP and the ME Several studies have shown that dust storms have become more frequent and intense over the last fifteen years, with an increase in dust Aerosol Optical Depth (AOD) (Middleton et al. 2021; Miller et al. 2008). Dust storms are originated mostly in the Northern Hemisphere where 15–20% of the world's dust emissions come from the ME such as Arabian Peninsula (AP) deserts, the Iraqi planes, and southeast Iran (Klaus et al. 2016; Lelieveld et al. 2012). In contrast, dust activity has decreased across eastern Iran since 2003. Also, there's a good chance that dust activity and AODs in central Iraq and the eastern and southern AP have risen in recent years due to the increased Shamal winds. Variations in the intensity and location of the Siberian High, which affects pressure gradients and wind regimes, as well as the El Niño/La Nina phase and changes in sea surface temperatures in the Indian and Mediterranean seas, are some examples of the large- and small-scale atmospheric dynamics that govern dust activity in the area (Lionello 2012; Mezösi 2022). Soil moisture, soil texture, vegetation cover, and topography are among the many variables that regulate dust emissions (Lionello 2012; Mezösi 2022; Tatishvili and Palavandishvili 2023).

Summertime sees more dust storms associated with the Shamal and Levar winds than wintertime (Lelieveld et al. 2012; Middleton et al. 2021). The summer dust storms that sweep across the area are mostly caused by the Shamal winds are known as "Shamal Dust Storms" (Liu et al. 2023; Meo et al. 2013). Even though they happen rarely, severe dust storms can happen in the winter, usually when cold fronts from higher latitudes make their way into the area (Lelieveld et al. 2012; Rezaazadeh et al. 2013). During the winter season, atmospheric disturbances, mainly connected to lows in the lower hemisphere, help to create dry cyclones and powerful density currents over desert regions, which in turn start frontal dust storms (Lelieveld et al. 2012; Rezaazadeh et al. 2013). Shamal dust storms and frontal dust storms were the two types of dust storms studied by (Hamidi et al. 2013) among 60 dust storms that occurred in the ME between 2003 and 2011.

Less precipitation and higher temperatures led to more severe and frequent droughts in ME. Droughts have become increasingly often and severe in Oman during the past 20 years because of climate change (El Kenawy et al. 2020). As a result of rising temperatures and decreasing precipitation, Iraq experienced severe droughts from 1998 to 2009 (Hameed et al. 2018). From 2003 to 2018, the dust storm intensified, temperatures rose, and precipitation decreased over Iran and Iraq, according to (Javadian et al. 2019). The Palmer Drought Severity Index (PDSI) and other drought indices that take temperature and precipitation data into account correlate better with visibility degradation than the Standardized Precipitation Index (SPI) and other drought

indices that rely solely on precipitation data, according to research by (Mahowald et al. 2007). Variations in local meteorological factors, deficiencies in precipitation, drought conditions, and soil moisture regulate dust emission in dry and semiarid regions, which reduces horizontal visibility (Adamo et al. 2022; Liu et al. 2023; Mezösi 2022).

Multifaceted dynamics of the atmospheric visibility can better be understood by increasing understanding about multidecadal trends in visibility across a unique geographical region, the Arabian Peninsula keeping in view their unique environmental challenges. Hence, given the global interest in understanding visibility and haze, this study is designed to fill such critical research gaps. The main aim of this paper is to analyze the long-term (1975–2023) trends of visibility fluctuations and development of haze for six countries including Kingdom of Saudi Arabia (KSA), Iraq (IRQ), Qatar (QTR), Kuwait (KWT), United Arab Emirates (UAE), and Oman (OMN). The objectives of this research are:

- 1) To analyze the temporal variations (daily, monthly, seasonal, annual & decadal) of visibility and haze over the Arabian Peninsula.
- 2) To analyze the monotonic trends (τ and Sens ‘slope’) of visibility and haze over the Arabian Peninsula.
- 3) To analyze the spatial variations of visibility and haze over the study region.

Prior research on visibility trends in ME, particularly in the AP, is rare. An increase in events of low visibility is a direct outcome of the fast growth of major cities in this region. Visibility variability in the AP including Saudi Arabia (KSA), Iraq (IRQ), Qatar (QTR), Oman (OMN), Kuwait (KWT), and United Arab Emirates (UAE) has not been studied before. We compiled and evaluated the unexplored visibility trends in these six countries, considering their terrain, climate, economic development, population growth, urbanization, and present air quality. This new contribution will help evaluate the AP climate dynamics, and more specifically, the air pollution status of these countries, separately. The topographical map of the AP provides an extensive picture of the varied physical aspects of the region, including countries of IRQ, KWT, KSA, QTR, UAE, and OMN (Fig. 1). The map shows elevation levels and landforms such as IRQ with its varied topography, KWT with its mostly flat terrain, and KSA with its mountainous sections. Even though much of the ME is hot and dry, there are a few important exceptions to the Mediterranean and the hilly areas, which become very cold during winter. The region is also known to face frequent episodes of extreme weather events like heat waves, droughts, floods, and air pollution events in addition to usual

dust storms from May to September impacting visibility and regional air quality.

2 Materials and methods

2.1 Data

Daily visibility observations (~1.17 Million) from 219 NOAA ground stations in KSA, OMN, QTR, UAE, IRQ, and KWT have been collected from 1975 to 2023 (Table 1). Consistent data collection has made it possible to fully analyze and comprehend meteorological trends and patterns over the given time, with daily observations.

2.2 Methodology

To assess the changes in visibility measures over the study area from 1975 to 2023, the dataset was divided into average daily, monthly, seasonal, annual, and decadal time series to estimate spatiotemporal trends for the region (Fig. 2) (Aldababseh and Temimi 2017; Alhathloul et al. 2021; Javed et al. 2022).

A Men Kendall (MK) trend estimator was employed to comprehend the temporal patterns of visibility over the study region from 1975 to 2023 for time series data ranging from daily to monthly, seasonal, and decadal. After its utilization for the first time by (Mann 1945) and its development by (Farlie and Kendall 1971), the World Meteorological Organization has advocated for the use of the MK test (Alhathloul et al. 2021). The Mann-Kendall trend estimator is widely recommended for analyzing meteorological and environmental data trends due to its non-parametric nature, robustness, and ability to handle non-normally distributed datasets cars (Aldababseh and Temimi 2017; Alhathloul et al. 2021; Middleton et al. 2021).

Gaps in data are expected for large diverse regional ground stations. MK has proven effective to analyze such data as it works well for nonparametric data even in the presence of outliers (Alhathloul et al. 2021a; Iqbal and Athar 2018). If the alternative hypothesis is accepted, it means that the data series does in fact exhibit a trend, while the null hypothesis states that the trend is random. MK first determines the parameter S by calculating the difference between the data and applying the sign function for a time series x_i ($i = 1, n$) using Eq. (1).

$$S = \sum_{i=1}^{N-1} \sum_{j=i+1}^N \text{sign}(x_j - x_i) \quad (1)$$

Where

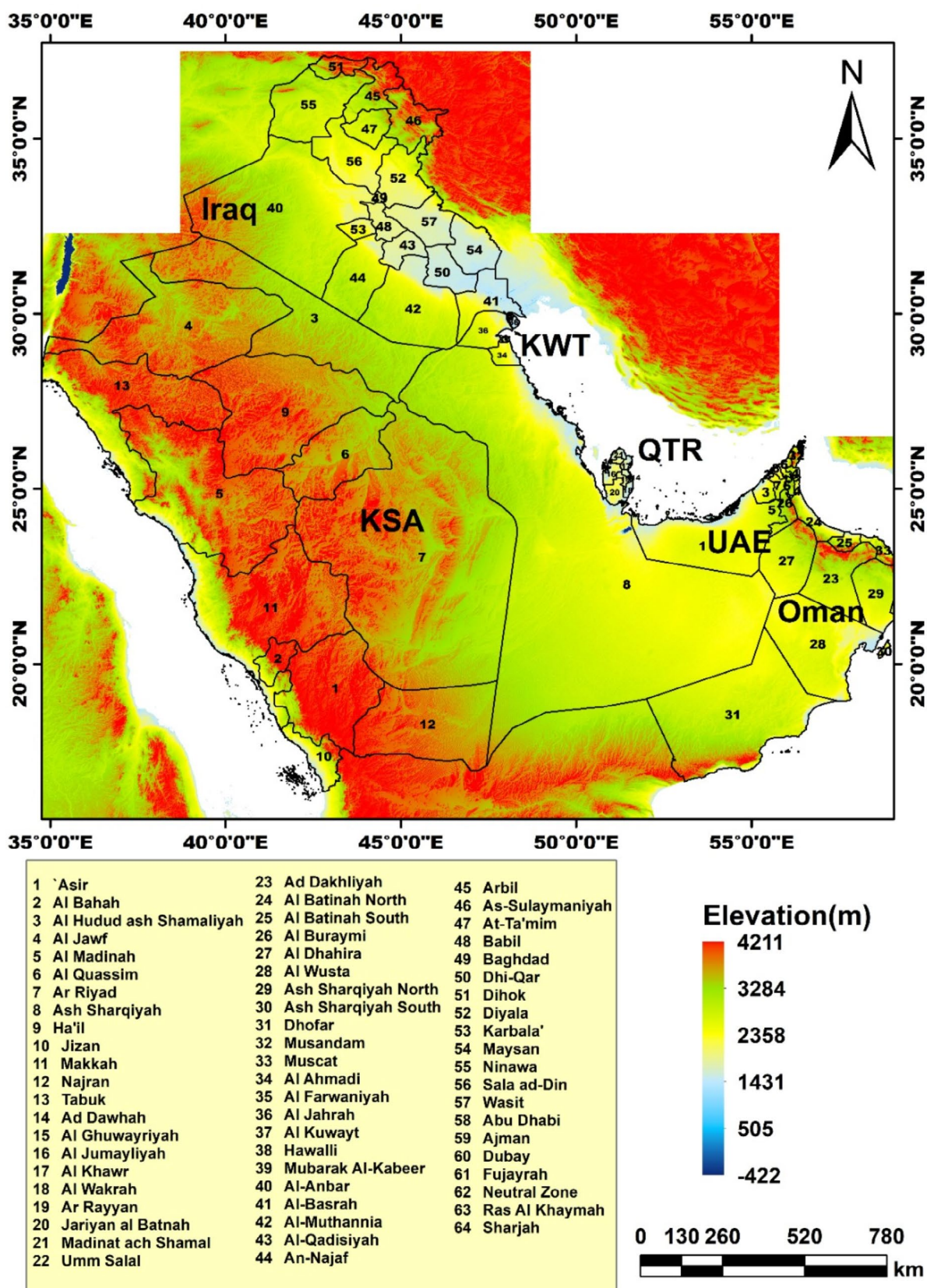


Fig. 1 The study area map with the elevation in meters and locations of the visibility monitoring stations for 06 ME countries: Kingdom of Saudi Arabia (KSA), Iraq (IRQ), Qatar (QTR), Kuwait (KWT), United Arab Emirates (UAE), and Oman (OMN)

Table 1 Number of observations recorded from available number of NOAA visibility monitoring stations in AP: Kingdom of Saudi Arabia (KSA), Iraq (IRQ), Qatar (QTR), Kuwait (KWT), United Arab Emirates (UAE), and Oman (OMN)

Sr. No.	Country	Number of Observations	Number of NOAA Stations
1	KSA	486,130	56
2	OMN	117,118	27
3	QTR	38,198	13
4	UAE	108,927	16
5	IRQ	208,726	81
6	KWT	58,035	26
Total		1,017,134	219

$$sign(x_j - x_i) = \begin{cases} +1 & \text{if } x_j - x_i > 0 \\ 0 & \text{if } x_j - x_i = 0 \\ -1 & \text{if } x_j - x_i < 0 \end{cases} \quad (2)$$

Here N is the number of data points, x_i and x_j are the data values in time series i and j (where $j > i$), respectively. Since all stations have over a decade of data hence presence of potential variance is also computed (Eq. 3) (Iqbal and Athar 2018; Javed et al. 2022, 2023).

$$Var(S) = \frac{N(N-1)(2N+5) - \sum_{i=1}^m (t_i-1)(2t_i+5)}{18} \quad (3)$$

Here m denotes the count of series containing duplicate data, and t is the frequency of data that has identical values. At last, the Z-score is computed, and then the standardized MK test statistics (Z_{mk}) are determined (Eq. 4) (Javed et al. 2023).

$$Z_{mk} = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & \text{if } S < 0 \end{cases} \quad (4)$$

The null hypothesis is accepted in a two-tailed test to determine the trend of a data series if the following conditions are

met: the significance level is α , the normal standard distribution at the level α , and the absolute value of Z is less than or equal to 2. We utilized $\alpha/2$ because the test was two-tailed. With a confidence level of 0.95, this study utilized the MK test. A positive Z-score indicates an upward trend in the data series, while a negative Z-score indicates a downward trend (τ) (Eq. 5) (Bevan and Kendall 1971).

$$\tau = \frac{S}{\frac{n(n-1)}{2}} \quad (5)$$

Equation (6) can be used to determine the P-value, or significance value, for any trend where the cumulative distribution function of a standard normal variate is represented by ϕ .

$$P = 0.5 - \phi(|Z_{mk}|) \quad (6)$$

When time series data is autocorrelated, the MK test's variance increases. One option is to pre-whiten the data (Aldababseh and Temimi 2017; Alhathloul et al. 2021) or utilize the modified MK tests (Hamed and Ramachandra Rao 1998). To assess autocorrelation effects, this study also used the Hamed and Rao-modified MK test (MMK). All significant lags are used to modify the variance (Eqs. 3, 7 and 8) (Asadi and Karami 2022).

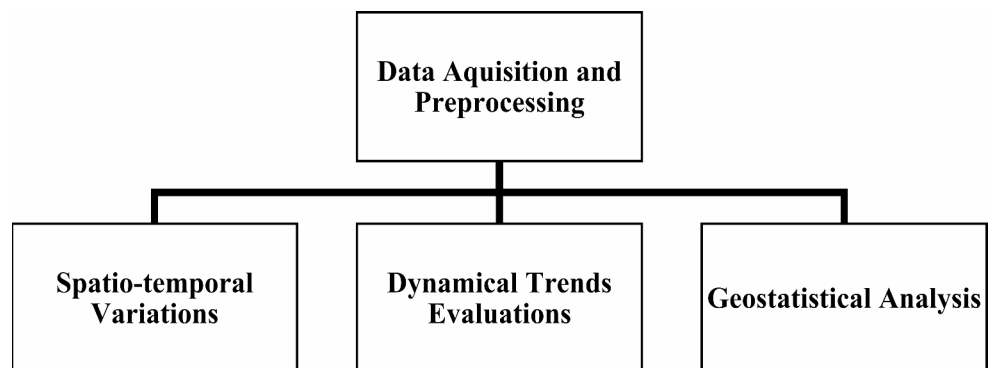
$$Var(S)^* = \frac{n}{n_s} Var(S) \quad (7)$$

$$\frac{n}{n_s} = 1 + \frac{2}{n(n-1)(n-2)} \sum_{k=1}^{n-1} (n-k)(n-k-1)r_k \quad (8)$$

Here n stands for the real number of observations, n_s^* for the effective number of observations, n/n_s^* for the variance correction factor, and r_k for the autocorrelation function of rank k of the observations at a 95% confidence interval.

To determine the trends' magnitude, the median slope estimator proposed by Theil and Sen is used (Sen 1968).

Fig. 2 Methodological workflow adopted in the study



Due to its immunity to outliers, this technique improves upon previous trend estimation methods (Eq. 9) (Alhathloul et al. 2021; Asadi and Karami 2022).

$$\beta = \text{Median} \left(\frac{Y_i - Y_j}{i - j} \right) \text{ for } i = 1, \dots, n \tag{9}$$

The data values at time i are represented by Y_i , and at time j , the values are Y_j , where $i > j$.

To observe spatiotemporal distributions of visibility over AP, the Inverse Distance Weighted interpolation method (IDW) was used. Here, points closer to the target position are given more weight (Alhathloul et al. 2021a; Javed et al. 2023). $Z(S_o)$, the value at point S_o that is unknown (Eq. 10):

$$Z(S_o) = \sum_{i=1}^n W_i Z(S_i) \tag{10}$$

In this case, $Z(S_i)$ represents the value at the sampled locations, and n stands for the monitoring station. S_i , where W_i is the weight of S_i (Eq. 11)

$$W_i = \frac{\frac{1}{d_i^k}}{\left(\sum_{i=1}^n \frac{1}{d_i^k} \right)} \quad i = 1, 2, \dots, n \tag{11}$$

where k is the power of the distance and d_i is the horizontal distance between the points observed and the points used for interpolation.

3 Results

3.1 Temporal Variations in Average Visibility

3.1.1 Average Daily Visibility

Starting in 1975 and continuing until 2023, the time series plots offer a comprehensive view of the daily visibility range in six countries (Fig. 3). There are distinct variations in the daily visibility of QTR from 1975 to 2004 where VR remained most of the time near 1.0 km. However, improvement in VR is witnessed onwards until 2023 where VR kept fluctuating with magnitude of 1.5 km. While the lowest visibility values, of about 0.5 km, do occur sometimes across the whole period, they are more common in the early years, specifically from 1975 to the mid-1980s (Fig. 4). Dust storms and other natural phenomena can cause temporary, severe reductions in visibility, which is why these low visibility events are likely to have occurred (Abulibdeh 2022; Al Midani and Fadli 2023; Al-Thani et al. 2020a, b; Reinolsmann et al. 2021). At the other end of the scale,

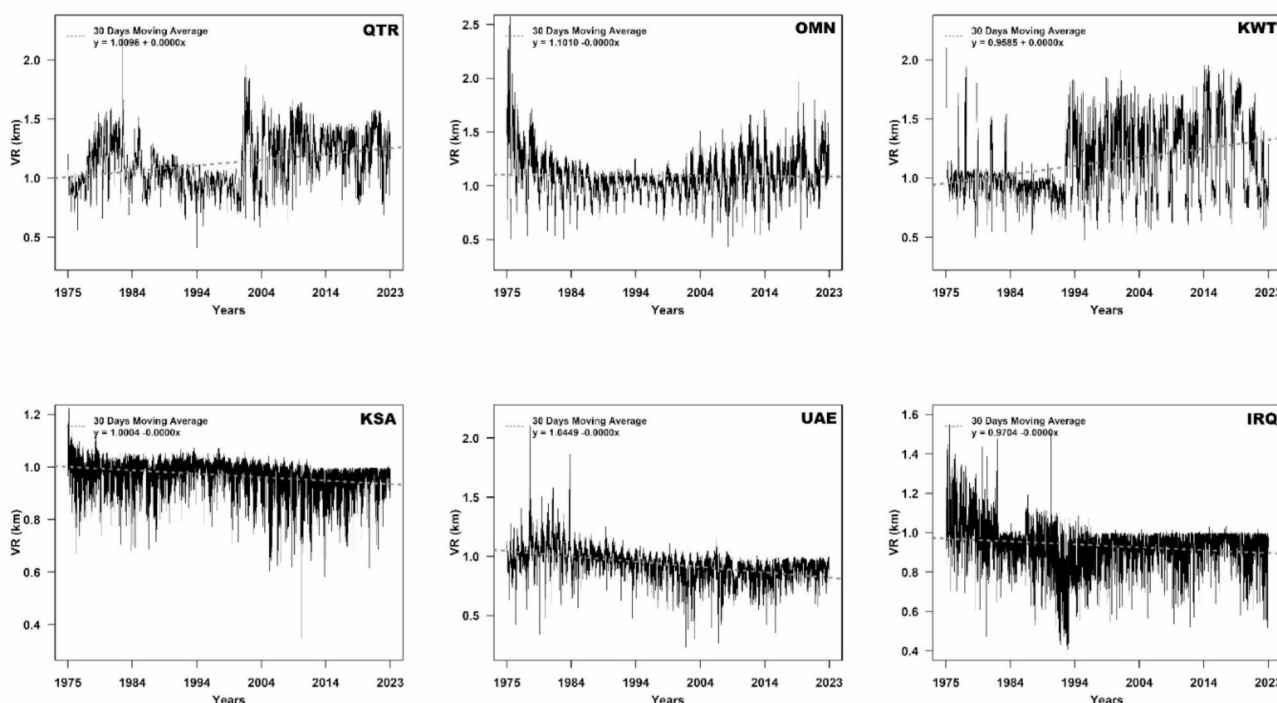


Fig. 3 Daily variations in the VR superimposed by 30 days moving average to reveal the trend (red dotted line) for KSA, IRQ, QTR, KWT, UAE, and OMN

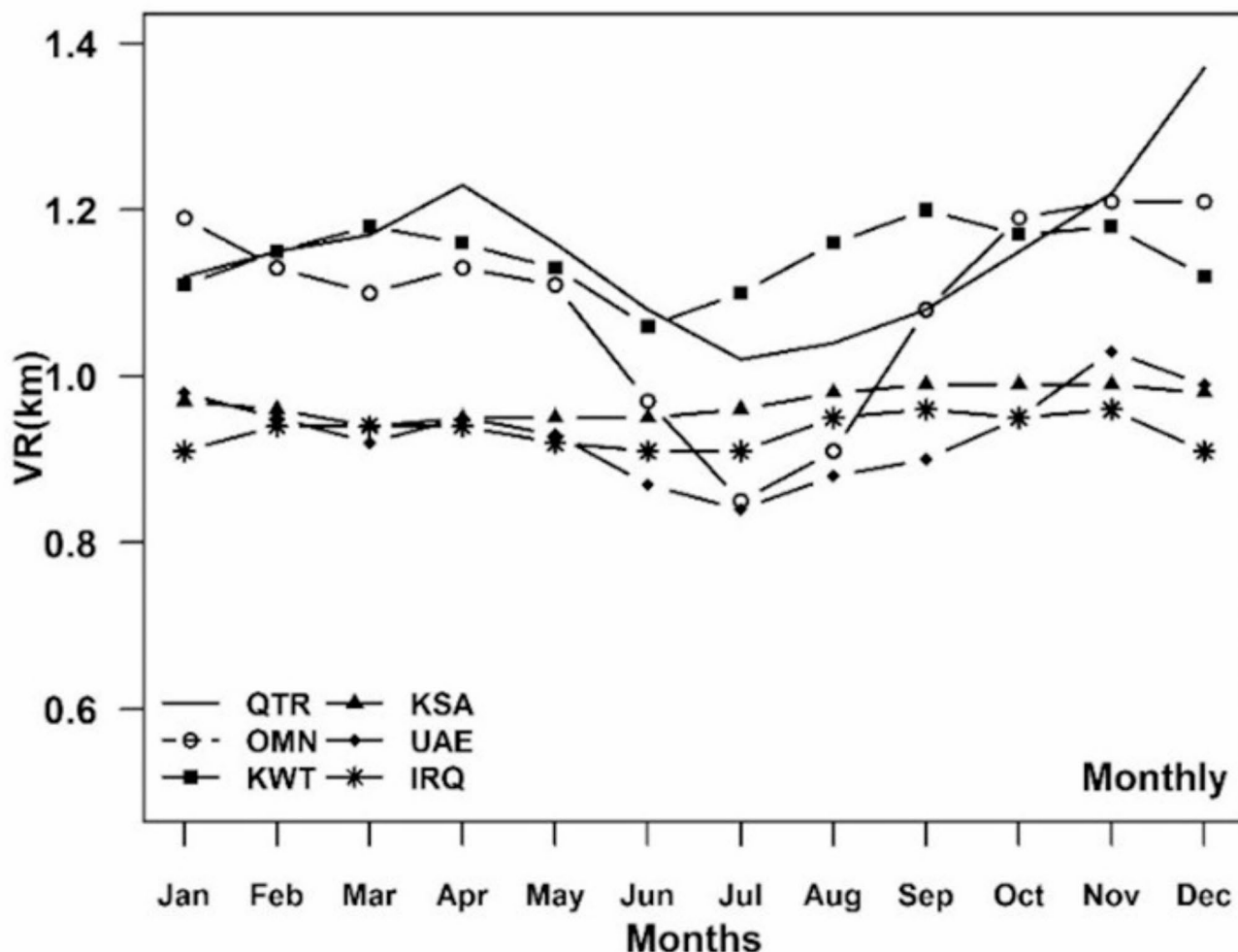


Fig. 4 Comparison of variations in the monthly average VR for KSA, IRQ, QTR, KWT, UAE, and OMN

visibility values can reach up to about 2 km. There are frequent episodes of high visibility about 1.5 km noticeable after the year 2000. Enhanced air quality management and a decline in the frequency of severe weather occurrences are two reasons for the observed increase in visibility (Abulibdeh 2022; Al Midani and Fadli 2023; Al-Thani et al. 2020a; Javed and Guo 2021; Reinolsmann et al. 2021). There is no distinct seasonality or cyclicity in the visibility variability for QTR. The amplitude of variations in visibility, however, increases after 2000. Maximum visibility of 2.1 km was observed in 1983 followed by 1.8 km in 2003. There may have been a correlation between these stretches of unusually clear weather and certain weather trends or anomalies (Al-Thani et al. 2020a). The 30-day moving average line has been very stable at 1 km before 2000, but it has risen since then, indicating that visibility has improved over the past few years in QTR. Reasons for this could include the government’s initiatives to protect the environment and lower air pollution levels (Abulibdeh 2022; Adamo et al. 2022).

Observations of Oman’s daily visibility show a complicated pattern in air clarity throughout the years. At the beginning in 1975, the minimum visibility value is near to 0.5 km, indicating quite limited visibility. This could be attributed to severe weather or other environmental causes like dust storms (Al-Kindi and Hird 2020; Al-Shidi et al. 2021). Midway through the 1980s and into the 1990s, visibility fluctuates around 1.0 km followed by an increasing tendency in 2000s. From this high point onward, the values display a pattern of fluctuations until around 2014, when a clear trend becomes apparent. Beginning in 2014 and continuing onwards, the variations take on a more noticeable form, with wildly fluctuating visibility. The visibility value peaks around 2.0 km by 2020, signifying relatively clear days. A 30-day moving average stays around 1.1 km throughout the course of the period. Nevertheless, it does show small ups and downs, reflecting broader tendencies during certain times.

The lowest visibility value at KWT was recorded in 1994, a little over 0.5 km, indicating a time when visibility was drastically low. It may be due to atmospheric conditions like dust storms (Al-Hurban et al., 2021; Alahmad et al. 2021; Alsaber et al. 2021; Hamoda et al. 2022; Yuan et al. 2020). By mid-2004, the maximum visibility has reached nearly 2 km, a sign of clear days. Variability in atmospheric conditions, impacted by both natural and human-made variables, is reflected in these visibility extremes (Alahmad et al. 2021; Al-Hurban et al. 2021a). Somewhat like QTR visibility in KWT improved after 1994 with marked difference in amplitude of the variations in visibility. Prior to 1994 daily visibility fluctuated very close to 1.0 km on average, which later remained between 0.5 and 1.7 km with increased frequency in maximum values of visibility above 1.5 km. More erratic weather patterns or other environmental variables reducing visibility could be the cause of this (Alahmad et al. 2021; Al-Hurban et al. 2021a).

The daily visibility for KSA remained consistently low close to 1.0 km unlike other countries in AP with minimum visibility of approximately 0.3 km in 2010. Maximum value was about 1.2 km in 1975 which later reduced drastically little above 1.0 km. Interestingly unlike QTR, OMN and KWT, there is an increased frequency of lowest visibility episodes in KSA over time. This has given rise to a decreasing average regional visibility. This may also be a result of more turbid air caused by growing urbanization and industrialization (Aldababseh and Temimi 2017; Fattahi Masrouf and Rezazadeh 2022; Middleton et al. 2021). The occurrence of sandstorms, among other possible causes, is common in the area (Fattahi Masrouf and Rezazadeh 2022; Hassan et al. 2023; Maghrabi 2021). Overall, the 1.0 km mark is maintained by the moving average line showing general visibility in KSA has not changed much over the years, despite daily fluctuations.

UAE observed visibility close to 2.0 km between 1975 and 1984 with frequent occurrence of visibility close to 1.5 km prior to 1984. This trend is absent after 1984 reducing maximum visibility close to 1.0 km in subsequent years up to around 2023. Like KSA, UAE also experience reduced magnitude of minimum visibility 1984 onwards owing to rapid urbanization (Aldababseh and Temimi 2017; Fattahi Masrouf and Rezazadeh 2022; Middleton et al. 2021).

Interestingly, average daily visibility over IRQ also was close to 1.5 km more frequently before 1980 somewhat like KSA and UAE. Minimum visibility observed was around 0.4 km in abundance for early 1990s. A cluster of higher peaks appears in the years 1975–1980, suggesting that clear days occurred more often during that time. These days of great prominence, however, become less common as the values progress through the late 1980s and into the early 2000s. After 2000, there is an increase in frequent episodes

of low visibility of 0.5 km till 2023. There is a consistent decreasing trend in the average visibility owing to increase in frequency and magnitude of minimum visibility.

3.1.2 Average Monthly Visibility

OMN, KWT and QTR have visibility greater than 1.0 km whereas the rest of the countries have visibility less than 1.0 km. QTR has observed the highest value of visibility of 1.4 km among all in the month of December whereas least monthly visibility observed is 0.9 km in OMN and KSA during July (Fig. 4). All countries have shown a dip in the visibility during July with a relative peak in December. It is surfaced that there are two groups of countries with relatively high visibility (OMN, KWT and QTR) and low visibility (KSA, UAE and IRQ). OMN, KWT and QTR have marked mutual deviations in visibility compared to visibility in KSA, UAE and IRQ. Interestingly monthly average visibility during February, March and April for KSA, UAE and IRQ is very close to each other around 0.95 km. OMN has shown extreme variation in visibility range from minimum of 0.9 km in Jul to maximum of 1.2 km in December. Similarly, there are marked variations in the monthly visibility for OMN, QTR and KWT whereas countries with relatively low visibility (KSA, UAE and IRQ) have minor variations in monthly visibility. Hence KSA, UAE and IRQ have observed a smaller number of clear days and more consistent hazy days than OMN, QTR and KWT. Possibly because dust settles and humidity levels drop in December, visibility is at its peak. Seasonal sandstorms or increasing temperatures that stir up dust particles may contribute to the decrease in visibility that happens in May (Al-Thani et al., 2020; Al Midani and Fadli 2023; Fattahi Masrouf and Rezazadeh 2022). Similarly, winter weather is likely to blame for the dramatic improvement in visibility over KSA from January to March, when it reaches a height of about 1.2 km. After that, visibility drops down until August, when it eventually levels out for the year (maybe because summer sandstorms have arrived) (Al-Thani et al., 2020; Fattahi Masrouf and Rezazadeh 2022; Javed and Guo 2021; Mashat et al. 2020). Visibility in OMN drops in June to slightly more than 0.8 km, which is a notable decrease. This decrease might be because of the summer monsoon season, which impacts visibility with its increased humidity and, potentially, dust from the Arabian Peninsula (Al-Kindi and Hird 2020; Al-Shidi et al. 2021).

Visibility trends in the UAE are comparable to those in OMN, albeit with fewer extreme swings. Over the course of the year, visibility stays over 1 km, only to slightly decrease about mid-year. The same weather patterns that are impacting OMN, such the summer monsoon, could really be

responsible for this (Aldababseh and Temimi 2017; Middleton et al. 2021).

The visibility in KWT varies from season to season, with big spikes and dips occurring at various times of the year. March has the best visibility, at around 1.2 km, while June and July have the worst, at about 0.8 km. These variations could be associated with localized severe weather occurrences, including summer dust storms (Al-Hemoud et al. 2021; Al-Hurban et al., 2021; Alahmad et al. 2021; Alsaber et al. 2021; Hamoda et al. 2022; Yuan et al. 2020).

The visibility of Iraq has been steadily rising since January, reaching a maximum of more than 1.3 km in December. Potentially better weather conditions, including lower temperatures and less dust storm activity, towards the year’s end might be responsible for this gradual improvement (Attiya and Jones 2020; Hameed et al. 2018; Khayoon and Al-Taai 2022).

Changes in the seasons, pollution, and natural occurrences like sandstorms are some of the reasons that cause variations in visibility across these countries. Weather

conditions, including wind patterns and humidity levels, can change throughout the year, which can have a major effect on visibility (Klaus et al. 2016; Rocha-Lima et al. 2024). The presence of Particulate Matter (PM) into the air can also diminish visibility, because of environmental pollution caused by industrial activity and vehicle emissions. Circumstantial factors, such as sandstorms, which are more prevalent in these areas, can lead to abrupt and significant degradation (Hamidi et al. 2013; Klaus et al. 2016; Rocha-Lima et al. 2024).

3.1.3 Average Seasonal Visibility

KWT, KSA and IRQ experience high monthly average visibility in autumn whereas OMN, QTR and UAE observe maximum visibility in winter (Fig. 5). Highest seasonal visibility (1.20 km) is in OMN during winter and lowest (0.9 km) is in UAE during summer. Hence, autumn and winter are appropriate seasons for sightseeing and outdoor tourism in Arabian peninsula where summer being

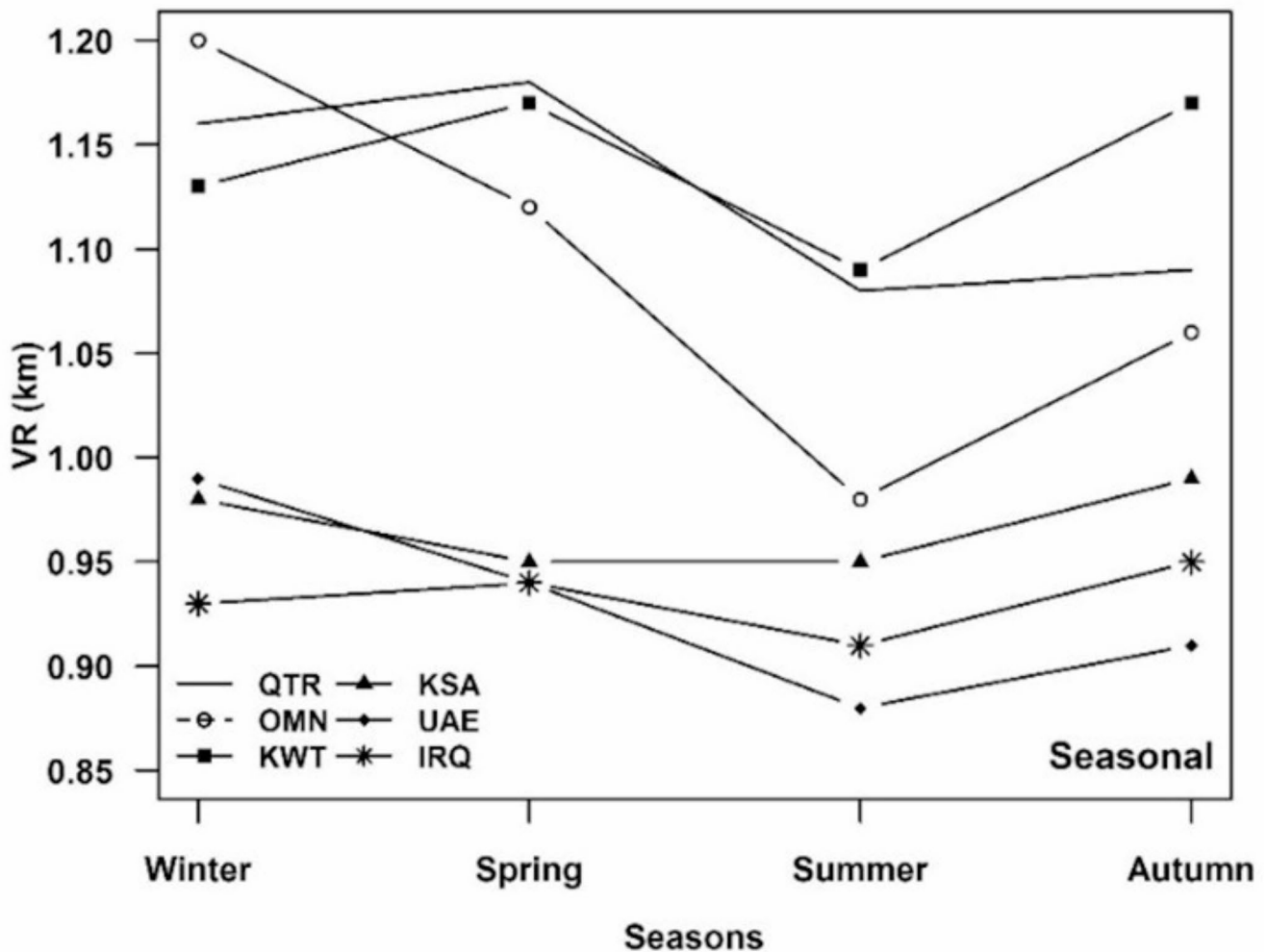


Fig. 5 Comparison of variations in the seasonal average VR for Kingdom of KSA, IRQ, QTR, KWT, UAE, and OMN

least appropriate. This is probably because the weather is cooler and steadier in winter. Spring sandstorms, which are prevalent during this season, may be due to the precipitous decline in visibility, which descends to slightly more than 0.9 km (Abulibdeh 2022; Middleton et al. 2021).

Beginning in winter and reaching a height of almost 1.15 km, KSA visibility gradually decreases until summer. Autumn is when visibility in KSA is at its best, reaching 1.2 km, which may be because dust settles, and heat haze decreases as temperatures start to fall (Alhathloul et al. 2021; Hasanean and Almazroui 2015; Mashat et al. 2020). Except for summer, the visibility in OMN is consistently around 1 km throughout the year. In the fall, when the monsoon season ends and the skies are brighter, visibility peaks at around 1.15 km (Al-Shidi et al. 2021; Amoatey et al. 2020; El Kenawy et al. 2020). As a result of rising humidity and dust, visibility in the UAE drops to a minimum of approximately 0.9 km during the summer. Visibility stays above 1 km throughout the year, which is indicative of consistent weather (Aldababseh and Temimi 2017; Fattahi Masrou and Rezazadeh 2022; Middleton et al. 2021).

Visibility in KWT peaks at over 1.05 km in the spring and drops to about 0.8 km in the summer, with more noticeable changes than in other seasons. One possible reason for these shifts is the increased frequency of dust storms and scorching temperatures in the area throughout the summer (Al-Hemoud et al. 2021; Al-Hurban et al., 2021; Alahmad et al. 2021; Hamoda et al. 2022; Yuan et al. 2020). Visibility in IRQ increases from season to season, peaking in winter at over 1.3 km. Reasons for this could include the season's generally lower temperatures and the less frequent occurrence of dust storms (Awadh 2023; Khayoon and Al-Taai 2022).

3.1.4 Average Annual and Decadal Visibility

Annual and decadal variations in visibility give a comprehensive overview of the historic and probable future conditions of visibility in AP (Fig. 6). Historically OMN has been the country with the cleanest sky in the AP with maximum average annual visibility of 1.9 km followed by KWT (1.4 km) and so on with minor difference in the value of average annual visibility for the rest of AP countries under study. Minimum visibility has been observed in IRQ during 2000 about 0.6 km followed by KWT (0.8 km). OMN starting from 1975 has high visibility which later dropped close to visibility observed in other countries from 1984 to 2009. Beyond 2009, visibility in OMN improved over the years along with KWT, and QTR. Seemingly, visibility in OMN, QTR and KWT improved over the years with a marked increase in the last two decades. However, there is no or minimum change in the prevailing visibility for KSA,

UAE and IRQ. There are pronounced variations in the visibility of QTR, OMN and KWT as well indicating transient atmospheric conditions cyclic episodes.

Plausible causes of the variations include industrialization, urbanization, and natural occurrences like dust storms. Because of its strong environmental policies and lower industrial emissions than its neighbors, OMN has been able to maintain stable visibility. In QTR KWT, industrialization and urban sprawl may have begun about that time, which would explain the first poor visibility. There were little but steady changes in KSA's visibility over the years, which remained about 1 km. KSA may have taken steps to regulate air pollution, as the visibility has remained consistent, even if the country's industrial output has increased.

With a starting point of about 1 km in 1975, the UAE had more dramatic oscillations, falling dramatically in the mid-1980s, recovering in the 1990s, and then recovering again after 2010. The fast rate of urbanization and economic development in the UAE could be reflected in these variations, which influence visibility and air quality. Data from IRQ, which dates to the mid-1990s, indicates that the country is stable around the 1 km mark. Probable causes for the apparent lack of change in visibility include regional efforts to curb air pollution or a slowdown in industrialization. According to (Sabetghadam et al. 2021), natural and man-made sources of gases and aerosols contribute to deteriorating visibility when dry conditions predominate because they absorb and scatter light.

Around 75% of the air pollution in KSA's capital city of Riyadh is caused by dust (H. et al., 2014). Meshari et al. (2017) examined dust storm patterns in the AP for 38 sites between 1983 and 2013. They confirmed that there are notable favorable tendencies in the northeastern region's increasing dust storm activities over the past 20 years (Mashat et al. 2020). Most dust storms in KSA occur when fronts formed by cyclones in the Mediterranean or blowing in from the northwest arrive over the spring, summer, and winter (Mashat et al. 2020). According to Al-Dabbagh (2020b) the east and northeastern portions of KSA receive dust from the Tigris and Euphrates basins, which is the second main source of dust in the country. One of the most significant primary dust sources in KSA and IRQ. The most significant sources in Iraq are found in the alluvial plain, and they have an impact not only on Iraq but also on the countries surrounding it, which may also be impacted by dust sources in the Syrian Desert (Al-Dabbagh 2020b).

Socioeconomic and infrastructure development in KWT has been booming in recent decades. Air pollution in KWT has been exacerbated by the country's ever-increasing population, industrial output, transportation network, and energy consumption (Al-Hurban et al. 2021b; Ghorani-Azam et al. 2016; Shen and Mickley 2017).

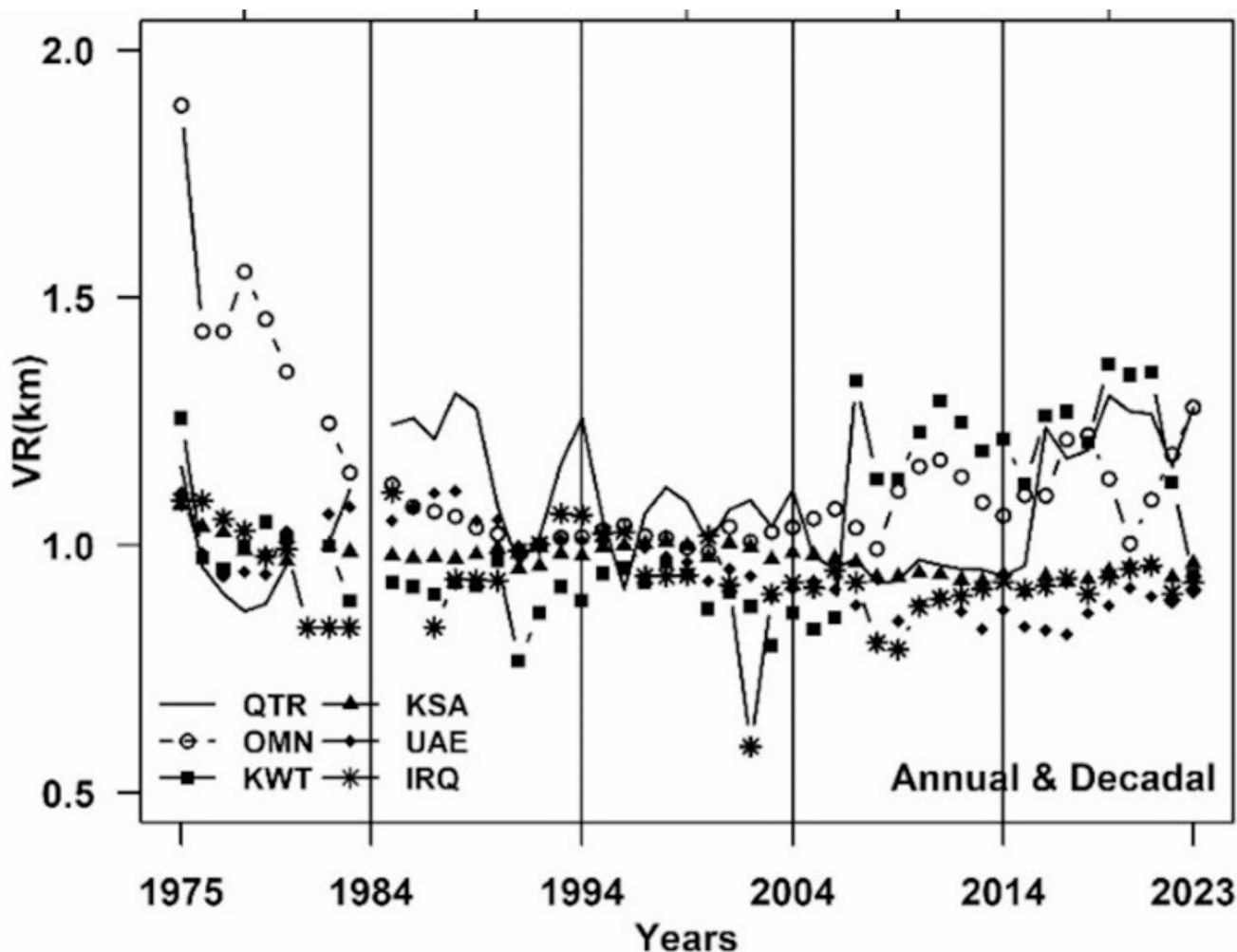


Fig. 6 Comparison of variations in the annual cum decadal average VR for KSA, IRQ, QTR, KWT, UAE, and OMN

Concerns about public health, food security, and the availability of desalinated water are just a few ways in which QTR’s economy has been hit hard by climate change caused by carbon dioxide emissions (Al-Maamary et al. 2017).

3.2 Monotonic Trend Evaluations

Daily average visibility in KWT and QTR is improving at the fastest trend of +0.15 and +0.05 km/year respectively among 06 countries of AP under study (Fig. 7). The detailed trend statistics (MK, MMK and SS) for decadal timescales visibility over Arabian Peninsula countries is listed in Table 2 and tables S1 and S2. Visibility in UAE is rapidly declining at maximum negative trend of -0.28 km/year KSA (-0.20 km/year) followed by IRQ (-0.10 km/year) and OMN (-0.06 km/year). Monthly average visibility has an overall decreasing trend for all AP countries except Jun, July and August. Monthly average visibility has dominated declining trends during January to May and September to November with maximum negative trend of -0.94 km/year

during November. Monthly average visibility is increasing dominantly from Jun to August with +0.4 km/year during July. Like trends of average daily visibility, monthly average visibility in QTR and KWT for all months is increasing with maximum magnitude in July. However, OMN has shown an increasing trend in average monthly visibility only during November and December whereas for the rest of the monthly average visibility is decreasing in OMN. Unlike QTR, KWT and OMN, IRQ, UAE and KSA have persistent declining trends in monthly average visibility. KSA has approximately uniform declining trend in monthly average visibility for all months ranging between -0.14 to -0.26 km/year. IRQ and UAE have negatives by varying trend for monthly average visibility.

During the winter and autumn seasons, KWT shows an upward trend in seasonal average visibility, with MK values around 0.6 km/year and 0.7 km/year, respectively. Visibility has improved significantly this season, with a maximum positive trend value of 0.7 km/year in SON. The visibility trend in IRQ in the winter season is negative, with an MK

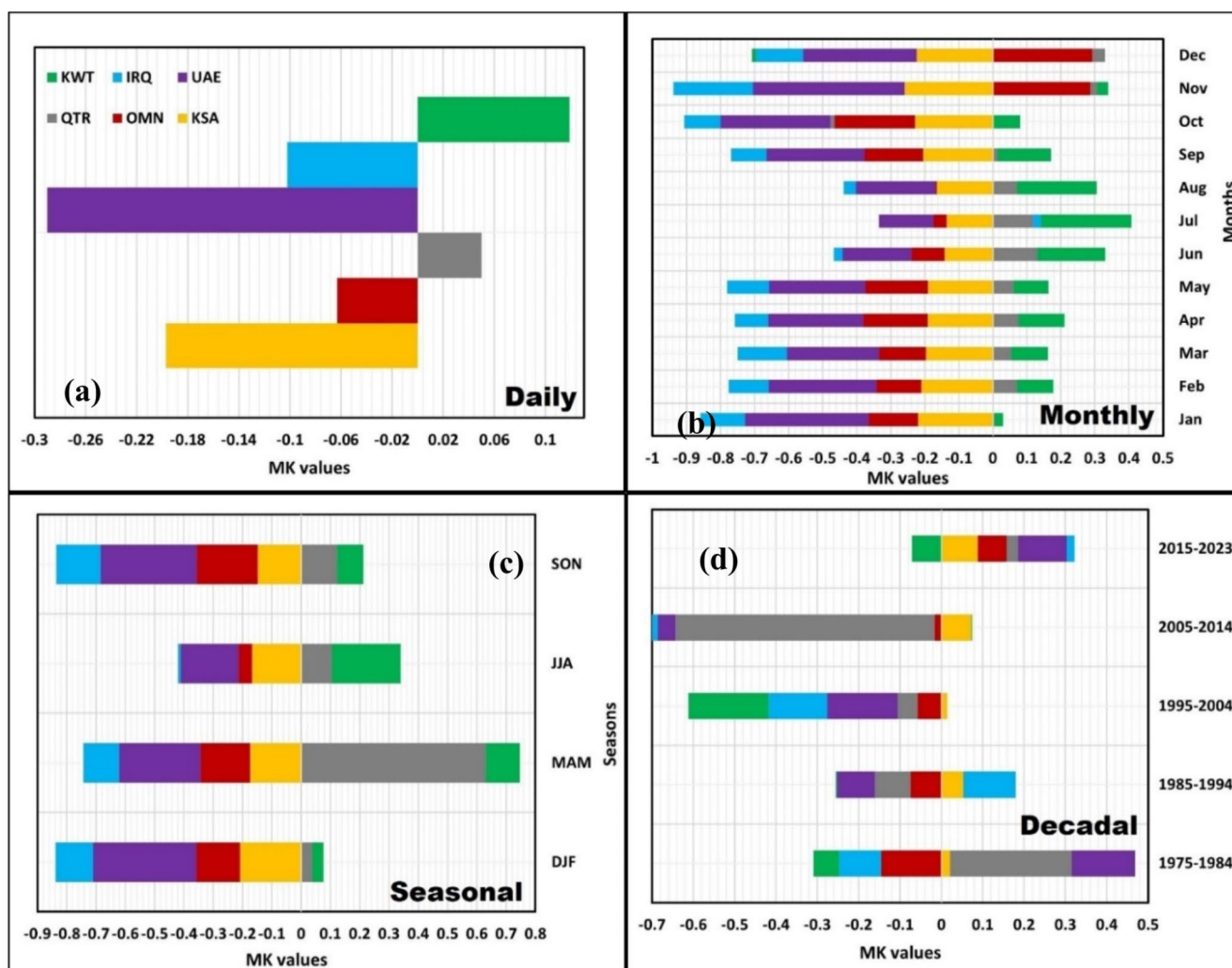


Fig. 7 Trends in km/year computed from MK, MMK, and Sen's slope (SS) variations for (a) daily, (b) monthly, (c) seasonal, and (d) annual mean VR for KSA, IRQ, QTR, KWT, UAE, and OMN. DJF (Decem-

ber, January, February), MAM (March, April, May), JJA (June, July, August), SON (September, October, November)

value of -0.3 km/year, indicating that visibility is poorer in the winter months. But in the summer season, the trend becomes positive with an MK value of 0.3 km/year, suggesting that visibility is better throughout the summer. While summer has a maximum trend value of 0.3 km/year and winter a minimum of -0.3 km/year. The UAE's visibility trend remains consistent throughout the year, with little discernible change between the winter and summer seasons. The visibility in the UAE does not change significantly across the seasons, based on this consistency. The visibility trend in QTR is clearly negative during the winter season, with an MK value of -0.7 km/year, suggesting a considerable drop in visibility over the winter months. During the autumn season, the tendency improves, but it is still negative overall. The most significant decline in visibility is reflected by the lowest trend value of -0.7 km/year in winter. During the winter season, OMN shows an upward trend in visibility,

with an MK value of 0.4 km/year, indicating that visibility is better in the winter. A modest decline in summertime visibility is indicated by a trend that is marginally negative during the summer season, with an MK value of -0.1 km/year. For winter, 0.4 km/year is the highest possible positive trend value. Among the 06 countries studied for the winter season KSA exhibited the most pronounced decline in visibility, with an MK value of -0.8 km/year, during the winter season. Having said that, the summer season does not show any discernible trend. With a trend score of -0.8 km/year in winter, the most significant decline in visibility is indicated.

The average decadal visibility of KWT has fluctuated significantly throughout the decades, with MK values ranging from -0.9 to 0.5 km/year. The visibility trend in IRQ has been lowest in the past few decades. The MK values in this region range from -0.8 to 0.4 km/year. With values between -0.6 and 0.4 km/year, the UAE has consistent MK. Rapid

Table 2 Trends in km/year for decadal variations in VR over AP region: KSA, IRQ, QTR, KWT, UAE, and OMN

	Test	1975–1984	1985–1994	1995–2004	2005–2014	2015–2023
KSA	MK	0.021	0.053	0.014	0.072	0.088
	SS	0.000	0.000	0.000	0.000	0.000
	MMK	0.020	0.051	0.012	0.070	0.085
	SS	0.000	0.000	0.000	0.000	0.000
OMN	MK	-0.146	<i>-0.075</i>	<i>-0.057</i>	<i>-0.016</i>	0.069
	SS	-0.000	<i>-0.000</i>	0.000	0.000	0.000
	MMK	-0.145	<i>-0.073</i>	<i>-0.054</i>	-0.015	0.065
	SS	-0.000	<i>-0.000</i>	0.000	0.000	0.000
QTR	MK	0.294	<i>-0.086</i>	<i>-0.049</i>	<i>-0.627</i>	0.029
	SS	0.000	<i>-0.000</i>	<i>-0.000</i>	<i>-0.000</i>	0.000
	MMK	0.293	<i>-0.085</i>	-0.048	<i>-0.061</i>	0.029
	SS	0.000	<i>-0.000</i>	-0.000	<i>-0.000</i>	0.000
UAE	MK	0.1534	<i>-0.0912</i>	<i>-0.1700</i>	<i>-0.0431</i>	0.1172
	SS	0.0000	<i>-0.0001</i>	<i>-0.0001</i>	0.0000	0.0000
	MMK	0.1502	<i>-0.0893</i>	<i>-0.1646</i>	<i>-0.420</i>	0.1115
	SS	0.0000	<i>-0.0001</i>	<i>-0.0001</i>	0.0000	0.0000
IRQ	MK	<i>-0.101</i>	0.127	<i>-0.142</i>	<i>-0.023</i>	0.019
	SS	<i>-0.000</i>	0.000	<i>-0.000</i>	0.000	0.000
	MMK	<i>-0.098</i>	0.111	<i>-0.138</i>	-0.021	0.015
	SS	<i>-0.000</i>	0.000	<i>-0.000</i>	0.000	0.000
KWT	MK	-0.063	-0.003	<i>-0.194</i>	0.002	<i>-0.072</i>
	SS	0.000	0.000	<i>-0.000</i>	0.000	<i>-0.000</i>
	MMK	-0.061	-0.002	<i>-0.185</i>	0.002	<i>-0.072</i>
	SS	0.000	0.000	<i>-0.000</i>	0.000	<i>-0.000</i>

Significant increasing trend is shown in **bold**, significant decreasing trend is shown in *Italic* and rest of the values show no trend. However, values for insignificant trends are underlined. Here MK = Mann-Kendall, MMK = Modified Mann-Kendall, SS = Sen’s slope

urbanization and industrialization may have caused times of decreased visibility, as indicated by the minimum visibility trend. With MK values ranging from -1 to 0.5 km/year, QTR displays extremely variable visibility trends. The visibility of OMN has improved over the decades, as seen by its MK values, which vary from -0.7 to 0.4 km/year. KSA demonstrates the most consistent patterns, with MK values varying marginally from -0.6 to 0.3 km/year.

KSA shows a consistent positive trend in visibility over the years with all values being positive, which is increasing every decade. UAE has a mix of increasing and decreasing trends but shows a significant increasing trend in the latest decade (2015–2023). IRQ also shows a mixed trend with some decades having a positive trend and others a negative one. However, the positive trend in the latest decade (2015–2023) is noted. OMN initially shows a negative trend but changes to a positive trend in the latest decade (2015–2023). QTR has significant variability with a large negative trend in the 2005–2014 decade, and a small positive trend in the latest decade (2015–2023). KWT mostly shows a negative trend across the decades with no significant improvement in visibility trends in recent years. Keeping in account the overall trends over the decades, giving weight to the most recent decade (2015–2023) to assess current visibility

conditions, KSA has shown maximum visibility trend followed by UAE, IRQ, OMN, QTR and KWT.

3.3 Spatial Distribution of Visibility

Spatial variation in daily, and seasonal average visibility are not very different (Fig. 8). There is a decrease in the visibility from west to east of the study area decreasing visibility from 1.77 km to almost zero (0.02) km. KSA has significantly clear sky than rest of the countries in the region. Extreme east (UAE and OMN) and north (IRQ) of the study has some pockets of high visibility like Asir, Al Quassim, Ar Riyadh, and Ash Sharqiyah near UAE and Jarlyan al Batnah in OMN. Similarly, in the north of the study area Al Anbar, Al Muthannia and Dlyala of IRQ. Areas with the most frequent minimum visibility experience are mostly in OMN in east and few in IRQ in north of the study area. Hence there are two countries KSA with large number of areas having visibility more than 1.7 km and OMN having large number of areas with minimum visibility near to 0.02 km. Rest of the countries in AP has a blend of low and high visibility areas.

Northern regions of IRQ, like Mosul and Erbil, typically have better daily visibility than southern regions because of

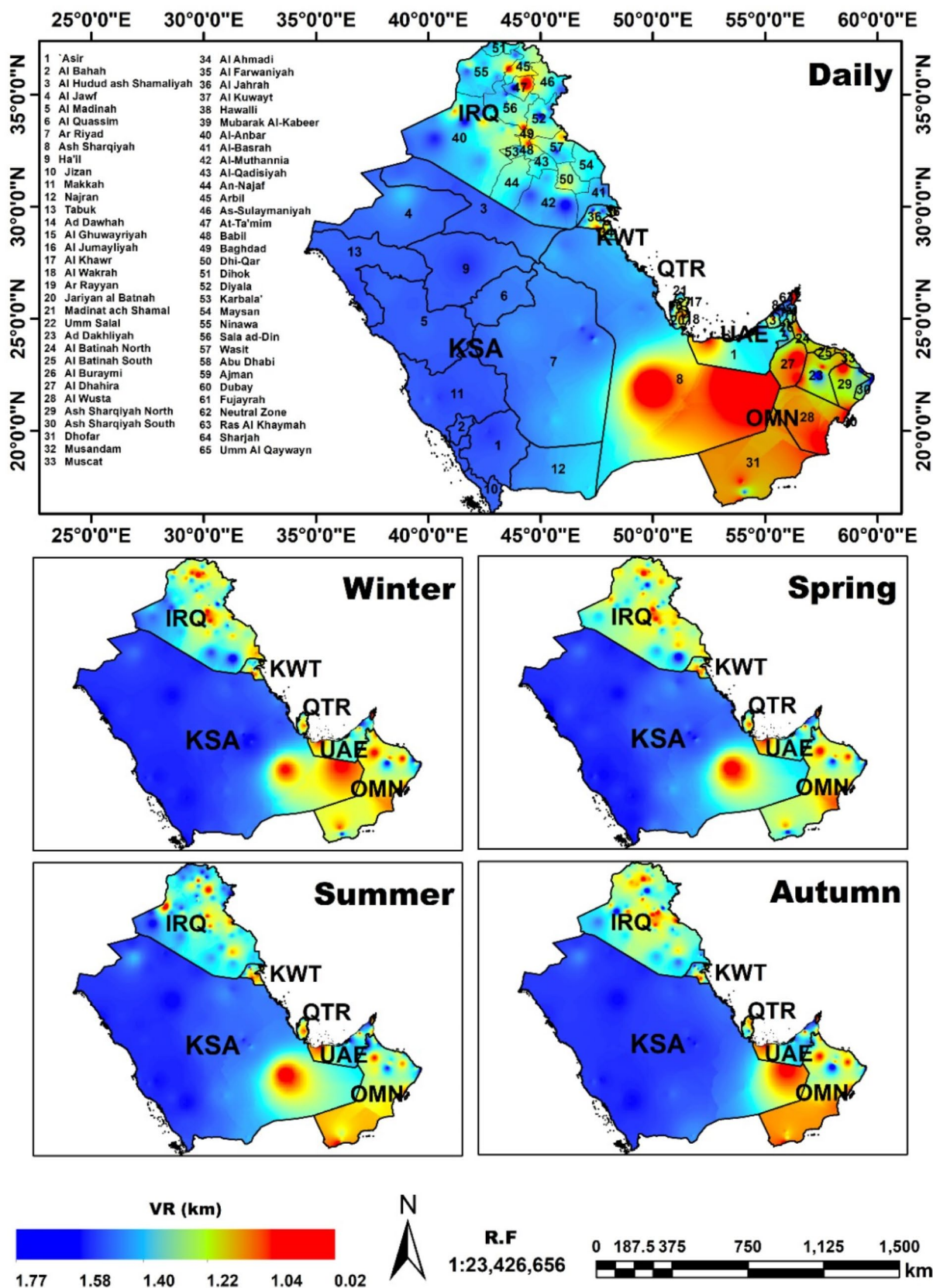


Fig. 8 Spatiotemporal variations in VR for (a) daily, (b) winter, (c) spring, (d) summer, and (e) autumn

their height and distance from desert dust sources (Fig. 7). The southern regions, which include Basra, are prone to dust storms, which reduce visibility, particularly during the summer. Wintertime see-through conditions are more common, while seasonal winds in the spring reduce visibility. Higher visibility levels return in the autumn.

Visibility in KWT varies; coastal locations, such as KWT City, benefit from the marine climate's ability to clear the air, leading to better visibility overall. When temperatures rise and dust storms become more common in the summer, visibility decreases in inland regions like Jahra.

Northwestern QTR, especially Al Khor, enjoys better daily visibility than the rest of the country owing to its closer proximity to the sea and less industrialization. Hot and muggy summers make visibility even worse in the southern region, where Al Wakrah is located. Spring and autumn have moderate visibility, while winter has the maximum. Visibility is reduced in the UAE's most densely populated cities, such as Abu Dhabi and Dubai, because of pollution and airborne particles. There is more visibility in the inner locations, such as Al Ain. Winter has better visibility across the nation, followed by spring and fall, with summer having the worst.

There is a clear trend in OMN, with higher daily visibility in coastal locations like Muscat caused by the sea wind that disperses pollution. However, during the summer, visibility reduces dramatically, especially in southern regions impacted by the monsoon, such as Salalah. Spring and autumn feature moderate amounts of visibility, while winter has higher levels.

KSA has modest visibility, however the western districts, such as Jeddah, see increased visibility every day because of the effect of the Red Sea. In the summer, when temperatures and dust levels are highest, visibility is reduced in the main area, which includes Riyadh. In winter, visibility is at its finest, whereas dust is only marginally an issue in spring and fall. In the summer, visibility drops to its lowest point of the year, with certain parts of OMN and the UAE seeing visibility as low as 0.02 km, which is completely obscured. In the winter, when the air is clearer due to lower temperatures and more precipitation, the northern parts of Iraq experience the highest visibility levels, up to 1.77 km.

4 Discussion

In the driest areas of ME, there are more than 300 dry days per year, and in the desert areas of KSA and southern IRQ, there can be up to a year of dry days. The average precipitation ranges from 50 mm yr⁻¹ in the driest regions to 700 mm yr⁻¹ in the wettest regions around Lebanon. The climate is hot and dry on average. Seasonal dust cycles in

the ME vary among regions (Adamo et al. 2022; Awadh 2023; Hamidi et al. 2013). Dryer months, such as March through September, usually have greater aerosol levels.

Haboobs, which produce walls of blowing sand and dust that are carried to higher elevations, or thunderstorm cells are the culprits behind intense dust storms in the ME (Klingmüller et al. 2016; Middleton 2017). Furthermore, dust is a known disease vector because it carries pollutants, viruses, and bacteria into the air (Morris et al. 2011). In a study conducted by the World Bank in 2019, it was shown that around 25% of the total dust emissions come from human activities, while the remaining 75% comes from natural sources. The study also highlighted that the locations of the dust sources are not always clearly identified. Nearly a third of the world's yearly atmospheric dust burden originates in central Asia and the ME (Kok et al. 2021). Many factors contributed to the escalation of dust activities in the years leading up to 2013, as reported by (Hamidi et al. 2013). Dam building projects on the Tigris and Euphrates rivers reduced the water content of soil downstream, urbanization in areas that were once agricultural, and a lack of power prevented proper irrigation of farmlands. Despite these tendencies, little is known about the underlying climatic causes (Albugami et al. 2019). In their study, Michael et al. (2015) established a connection between the AP's dust activity fluctuation and the long-term drought in the Fertile Crescent region. This region encompasses the area between the Nile River in Egypt and the Euphrates and Tigris rivers. Using data collected from satellites, Nabavi et al. (2016) found that dust was increasing in frequency in an area to the east of Syria and northwest of Iraq. According to Xia et al. (2022) the increase of irrigated areas is a contributing factor to the reversal of the ME AOD trend in subsequent years. The main meteorological elements that drive AOD changes over the ME, according to Che et al. (2019) are sea level pressure and wind speed. The correlation between ME dust storms and climatic decadal oscillations has been the subject of more recent science. El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) were linked by Xi (2021) to the AOD patterns in the ME. As an example, when the El Niño and La Niña phases coincide, the effects on the winds and sea surface temperature are magnified, leading to a region in the ME characterized by high surface pressure, increased heat, and decreased precipitation. Researchers believe that La Niña and negative PDO phases are linked to the dryness in the Tigris-Euphrates Basin. This, in turn, can impact agriculture and cause vegetation loss in the Fertile Crescent. Furthermore, Liu et al. (2023) connected the change in the northern tropical Atlantic (NTA) sea surface temperature (SST) to the positive-to-negative AOD trend in the ME about 2010. Lastly, deforestation and droughts have been connected to the recent rise in AOD in

the ME, while the precise origins of this phenomenon are still unclear (Klaus et al. 2016; Middleton et al. 2021).

5 Conclusions

This research primarily aims to analyze visibility patterns over a lengthy period (1975–2023) in six ME countries: KSA, IRQ, QTR, KWT, UAE, and OMN. Using average time series plots, partition of the dataset was done into daily, monthly, seasonal, annual, and decadal time series. This allowed us to examine the variations in visibility measurements across the research area from 1975 to 2023. To understand the patterns of visibility over time in the research region, the MK and MMK trend estimators were used. Finally, the IDW was employed to ascertain the visibility's spatiotemporal distribution over the area. The time series plots provide detail on this range. Our 30-day moving average gives a more consistent picture of trends, and our daily visibility readings are on the other side.

- The daily visibility of QTR shows significant improvement from 1975 to 2023, this variation is reflecting the changing nature of visibility in the area. Daily visibility observations in OMN reveal a complex pattern in air clarity over the years.
- Starting in 1975, the lowest possible visibility value is close to zero. In 1994, the visibility value at KWT was slightly over half a km, which indicates a period of extremely low visibility. There are days with significantly reduced visibility, as seen by the daily visibility statistics for KSA, which shows a minimal visibility of about 0.6 km.
- The daily visibility is shown by a time series plot, which provides a detailed look at the atmospheric clarity of the UAE over the last fifty years. In the beginning, around 1975, the data reveals extremely high visibility peaks, reaching up to around 2 km. Despite experiencing occasional variations, the moving average remains flat within the visibility range of 1 to 1.5 km.
- There was a lot of fog on days when the visibility was about 0.4 km, according to the daily visibility above IRQ. At about 0.06, KWT has the highest positive trend value among the six nations. This indicates that air quality has improved over time, since visibility has grown.
- The country with the least negative trend score, IRQ, shows a decrease in visibility over time, with a value of about -0.26 . Due to their elevation and distance from desert dust sources, northern IRQ regions, such as Erbil and Mosul, usually enjoy better visibility daily than southern ones. Coastal areas, like KWT City, have it good because the marine climate helps to clear the air.

- More than 300 days of dryness occur annually in the driest parts of the ME, and as much as a year can pass without rain in the deserts of KSA and southern Iran. The exact causes of the current upsurge in AOD in the ME remain unknown, however deforestation and droughts have been linked to it.
- It is possible to think of this comprehensive data-driven study as a baseline visibility study for these six nations. Policymakers can use this information to reduce air pollution and the causes of it.

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