Iranian Journal of Geophysics, Vol 19 No 6, 2026, Page 105 – 123 (Research Article)
DOI: 10.30499/ijg.2025.486036.1647

Effects of meteorological factors and air pollution on the spread and transmission patterns of COVID-19 in Iran

Farahnaz Fazel-Rastgar[1], Sakineh Khansalari[2*] and Venkataraman Sivakumar[1,3]

[1]*Ph.D., Discipline of Physics, School of Chemistry and Physics, University of KwaZulu-Natal, South Africa*
[2] *Assistant Professor, Research Institute of Meteorology and Atmospheric Science, Tehran, Iran*
[3] *Professor, S. V. Raman Researchers Roadmap, Westville, South Africa*

(Received: 29 October 2024, Accepted: 18 January 2025)

Abstract
This study investigates the understanding meteorological and environmental drivers of COVID-19 transmission in Iran. This work examines multiple datasets and models obtained from NASA's Modern-Era Retrospective Analysis for Research and Applications (MERRA) database and ERA5 hourly data from the European Centre for Medium-Range Weather Forecasts (ECMWF). The study underscores the critical role of meteorological factors in the transmission dynamics of COVID-19, emphasizing the interplay of wind patterns, atmospheric levels, and humidity. Wind speeds at 10 meters and 850 hPa show strong positive correlations with transmission risk (correlation coefficients: 0.76 and 0.75). This suggests that stronger surface winds may facilitate the airborne spread of viral particles. Conversely, reduced wind speeds at 700 and 500 hPa show significant negative correlations (-0.53 and -0.70), highlighting how atmospheric stratification affects virus dispersion. Also, this work shows a negative correlation exists between relative humidity and COVID-19 transmission. Higher humidity may suppress the virus's airborne viability or dispersal, emphasizing the need for effective ventilation, especially in low-humidity indoor environments.

The study also observed a notable increase in air pollutants—specifically, NO2, Pm2.5, SO2, and low-level ozone—during the fifth COVID-19 wave. This is in comparison with short pre- and post-events of the peak wave, despite lockdown measures. This caused the pollution accumulation without ventilation due to the specific stable weather. This rise in pollutants highlights the intersection of public health challenges posed by both viruses spread and air quality. The study also noted an expected increase in ozone levels during the summer months of the fifth wave, attributed to high temperatures that generally foster ozone formation. However, the analysis suggests that temperature alone does not significantly influence COVID-19 transmission risk, highlighting the complex role of multiple variables in influencing the spread of virus. Additionally, in the stable atmospheric conditions of the middle and upper levels during hot summer months, both ozone and particulate matter pollution correlated positively with transmission risk. This relationship was especially evident under unusually high temperatures (0.57K above normal) and hazy conditions characterized by increased aerosol optical depth (AOD) in August 2021.

Keywords: Air pollution, COVID-19, Iran, meteorological factors

*Corresponding author: khansalari@yahoo.com

1 Introduction

By the end of 2019, a novel and highly infectious virus (SARS-CoV-2) was detected in Wuhan, China, in December 2019. Coronavirus disease 2019 (COVID-19) has rapidly evolved into a global health crisis since its emergence in late 2019. It can be transmitted via human-to-human contact (Cowling and Leung, 2020; Riou and Althaus, 2020; Burch et al., 2021; World Health Organization, 2021). Later, the rapid spread of different variants of SARS-CoV-2, which was later known as COVID-19, caused extraordinary tension in healthcare systems. By 31 December 2023, it caused significant mortality in approximately 773,449,299 people around the world (https://data.who.int/dashboards/covid19/cases?n=c). The World Health Organization (WHO) confirmed the COVID-19 pandemic on 11 March 2020 (World Health Organization, 2020). Recent studies have shown that heavy mobility limitations, global lockdowns, and limited industrial activity have caused considerable reductions in air pollution (Chen et al., 2020; He et al., 2020; Giani et al., 2021; Ganguly et al., 2021). This was a good point as a natural experiment to discover the consequences of climate change on air quality. Understanding the factors influencing the spread and transmission dynamics of this novel coronavirus is crucial for effective public health management.

Recent research endeavors have sought to shed light on the intricate interplay between weather variables and COVID-19 transmission. Studies have proposed various hypotheses regarding the potential influence of meteorological factors on the stability and transmissibility of the SARS-CoV-2 virus, the causative agent of COVID-19. These hypotheses range from direct effects on viral viability and host susceptibility to indirect impacts on human behavior and societal patterns. However, despite accumulating evidence suggesting possible associations between weather conditions and COVID-19 dynamics, the precise nature of these relationships remains a subject of ongoing investigation and debate. Challenges in data collection, methodological differences, and the complex interdependencies of multiple variables underscore the need for comprehensive and rigorous analyses to discern meaningful patterns.

The relationship between COVID-19 transmission and meteorological factors is a subject of ongoing scientific debate. Numerous studies worldwide have investigated this association, yielding varied and sometimes conflicting results (Nottmeyer et al., 2023); this study underlines the regional heterogeneity of weather-related effects on COVID-19 transmission. Ng et al. (2024) investigated the potential roles of five key meteorological variables (average relative humidity, maximum temperature, average temperature, minimum temperature, and average wind speed) in COVID-19 transmission in Malaysia. Correlations between daily COVID-19 cases and meteorological variables were analyzed using Pearson's and Spearman's correlation tests. The results indicated that average wind speed was positively correlated with COVID-19 incidence, while average relative humidity, maximum temperature, average temperature, and minimum temperature were negatively correlated with COVID-19 incidence. These findings contribute to understanding the relationship between meteorological factors and the spread of COVID-19 in diverse climatic regions and could aid in developing tailored response mechanisms. Examining the relationship between weather conditions and the prevalence of coronavirus disease is highly complex, as changes in human behavior, services, and health regulations at different stages of disease outbreaks are crucial and influential. Also, weather and climate hazards such as extreme temperatures and air pollution like ozone cause human health impacts (Khansalari et al., 2021; Fazel-Rastgar et al., 2024). At the onset of the disease outbreak, due to public unawareness and lack of knowledge about how to combat it through healthcare services and ignorance about its transmission, the rapid spread of the virus occurred within the community. During the COVID-19 outbreak, some hoped that warmer weather would diminish the spread of COVID-19, but widespread disease does not always manifest as a seasonal illness (Lin et al., 2022). As illustrated in Fig. 1a, during the fifth wave of COVID-19 in Iran in August 2021, this phenomenon occurred at the peak of heat and temperature rise. Globally, the results suggest that comparatively low temperatures and low absolute humidity are associated with increased risks of COVID-19 (Lin et al., 2022; Nottmeyer et al., 2023; Ng et al., 2024). However, some research shows that in some areas, the incidence of this disease increases with increasing temperature (Haq et al., 2023). In recent years, studies have increasingly explored the correlation between weather conditions and the incidence of COVID-19 cases, aiming to elucidate the role of meteorological variables such as temperature, humidity, and wind speed in shaping transmission patterns. The influence of weather on COVID-19 has been one of the most studied research topics after the pandemic (Poirier et al., 2020; Paraskevis et al., 2020; Fazel-Rastgar and Sivakumar, 2023). Additionally, many studies have shown a negative correlation between temperature and infectivity (Jahangiri et al., 2020; Kotsiou et al 2020; Lolli et al., 2020; Malki et al., 2020; Prata et al., 2020; Rosario et al., 2020; Shi et al., 2020). However, some research has shown that weather impacts can differ significantly among periods and other weather and climate indicators, such as humidity, wind, and region (Auler et al., 2020; Bashir et al., 2020; Xu et al., 2020; Yao et al., 2020).

A recent study revealed a correlation between air pollution and an 11% increase in deaths from COVID-19 infection for every 1 microgram/cubic meter increase in air pollution (Wu et al., 2020). Additionally, recent research revealed a statistically substantial connection between air pollution and COVID-19 infection and stable weather conditions, with greater accumulation of atmospheric contaminants such as particulate matter, ozone, and NO_2 related to an increased risk of COVID-19 infection (Zhu et al., 2020, Fazel-Rastgar and Sivakumar, 2023). Recent studies that examined the COVID-19 infection based on the satellite and ground base annual air quality in eight countries such as Italy, Spain, Germany, France, the UK, the USA, Iran and China found more viral infections with high levels of PM2.5 (Pansini and Fornacca, 2020).

Iran, as one of the countries significantly impacted by the COVID-19 pandemic, presents a unique context for investigating the relationship between meteorological factors and disease spread. With diverse climatic regions spanning from arid and semiarid to temperate and subtropical regions, Iran offers a rich tapestry for exploring how variations in weather may impact the transmission dynamics of COVID-19.

Fine particulate matter (PM2.5), which is prevalent in many Iranian cities, can lead to greater susceptibility to respiratory viruses. Therefore, in big cities like Tehran, where pollution is consistently high, the risk of COVID-19 transmission and severe outcomes may be compounded by poor air quality. Ultimately, understanding these interactions between climate and transmission dynamics can help improve public health responses in future pandemics. Policy measures should not only account for the medical and social aspects of disease control but also incorporate local climate and environmental factors to optimize interventions and reduce the spread of infectious diseases like COVID-19.

This paper aims to contribute to the growing body of literature on the relationship between meteorological factors and COVID-19 transmission in Iran. Additionally, it examines the impact of weather on the 5^{th} wave of COVID-19, which is the peak in Iran.

2 Materials and methods

2-1 Data and statistical analysis

To investigate the relationship between meteorological factors and the prevalence of COVID-19, we utilized various variables, including wind speed at different levels (surface, 10 meters, and pressure levels of 850, 700, and 500 hPa), relative humidity (at pressure levels of 850 and 700 hPa) and 2-meter temperature, and this meteorological variable at the 850 and 700 hPa pressure levels. Exposure data were obtained from the Copernicus ERA5 dataset (Rienecker et al., 2011) from the European Centre for Medium-Range Weather Forecasts (ECMWF), which provides comprehensive meteorological information with a latitude-longitude grid size of 0.25° × 0.25°.

In order to complement our research, we utilized COVID-19 case time-series data specifically for Iran. These data, with a daily time resolution, were obtained from the publicly available dataset managed by Our World in Data, which can be accessed at the following link: https://github.com/owid/covid-19-data/blob/master/public/data/jhu/full_data.csv. Moreover, this work uses data from Worldometer Info, Jan. 4, 2024 (https://www.worldometers.info/coronavirus/). This approach enabled us to conduct a rigorous analysis of the potential associations between meteorological variables and COVID-19 transmission, leveraging comprehensive and reliable datasets for both meteorological variables and COVID-19 cases in Iran from May 2020 to May 2023. In the methodology of this study, statistical analysis was applied to assess the relationships between the independent variables, which are the three meteorological variables at different levels [relative humidity (RH_{avg}), temperature (T_{avg}), and wind speed (WS_{avg})], and the dependent variable (daily confirmed cases of COVID-19). This data included monthly average meteorological data, encompassing variables such as wind speed, relative humidity, and temperature, along with data about the number of COVID-19 cases. Subsequently, correlations between these datasets were computed to investigate potential associations.

Additionally, in this work, the different atmospheric pollutants obtained from NASA's Modern-Era Retrospective Analysis for Research and Applications (MERRA-2) database, the Atmospheric Infrared Sounder on NASA's Aqua satellite (AIRS), and the Ozone Monitoring Instrument (OMI) onboard NASA's Aura satellite were analyzed and investigated. Also, this study applies the ultraviolet aerosol index to understand the implications for air pollution during the study time.

The ultraviolet aerosol index (UVAI) is a method used to indicate aerosol absorption via satellite measurements. The UVAI is calculated by breaking the radiance spectral contrast due to aerosol effects because of Rayleigh scattering at two wavelengths close to the near-UV region (Herman et al., 1997; Torres et al., 1998; Torres et al., 2007). The numerical models, along with observational data, show that the UV scattering and absorption of particles in the boundary layer can accelerate photochemical responses. It has key implications for air pollution control (Dickerson et al., 1997).

2-2 Study region

The study focuses on Iran, a country that experienced seven waves of COVID-19. The most significant and devastating wave was the fifth wave, which began in the summer of 2021 due to the spread of the Delta variant. This wave led to a sharp increase in daily cases and deaths, overwhelming the healthcare system. For the purpose of this study, COVID-19 time-series data, including daily new cases and deaths, have been used to analyze the spread of the virus across the country.

3 Results and discussion

3-1 COVID-19 waves and impact in Iran

Fig. 1a shows a time series (data obtained from https://www.worldometers.info/coronavirus/) for COVID-19 daily new cases and daily new deaths related to this infection during the pandemic) in Iran. This figure indicates a peak in cases during mid-August 2021, approximately from 11 to 21 August 2021. The highest number of new cases was reported on 18 August 2021, with 50,228 cases. From the beginning of August 2021 to the first day of September of the same year, the daily infection rate reached 38,657 cases, and correspondingly, the hospitalization rate increased by 110%. The highest number of COVID-19-related deaths in Iran exceeded 700 deaths per day. On 24 August 2021, the Ministry of Health of Iran announced the deaths of 702 people due to the coronavirus. On 15 August 2021, 170000 people were infected with COVID-19, which was the highest daily number reported by the WHO (https://covid19.who.int/table). Fig. 1b illustrates the risk of contracting COVID-19 on 7 August 2021, based on the IRNA-INFORAPHIC database. According to this data, almost all regions of Iran were identified as areas with a very high risk of contracting COVID-19.

3-2 Meteorological parameter analysis results

In the quest to understand the phenomenon of COVID-19 incidence, one of the fundamental hypotheses under investigation has been the correlation between temperature and disease transmission. However, the results reported by Haq et al. (2023) demonstrate that there is no significant association between temperature and the spread of the disease. In other words, temperature variations alone may not be a significant contributing factor to the prevalence of COVID-19. Hence, for a more precise understanding of disease transmission dynamics and the provision of effective combat strategies, attention to other factors is necessary. This includes issues such as social behaviors, public health policies, and hygiene conditions, which make the topic of the relationship between meteorological factors and the prevalence of COVID-19 more complex than it may initially appear.

The correlations between meteorological variables and the number of new COVID-19 cases are illustrated in Table 1, with a focus exclusively on 2021. This is because the analysis of the impact of weather conditions on the spread of COVID-19 in 2020 is less accurate due to the public's initial surprise and lack of awareness about virus transmission, as well as insufficient healthcare services. In 2022, widespread vaccination led to a significant decline in the spread of the disease, making the statistical analysis of the impact of meteorological factors on COVID-19 transmission in 2020 and 2022 challenging and prone to errors. This table shows the correlation coefficients and p values for various meteorological variables and their associations with the spread of COVID-19. Positive correlations indicate that higher values of the meteorological variables are associated with increased COVID-19 cases. In contrast, negative correlations suggest that higher values of meteorological variables are associated with a decrease in COVID-19 cases. The statistical significance is denoted by the p values, with values less than 0.05 indicating a significant correlation.

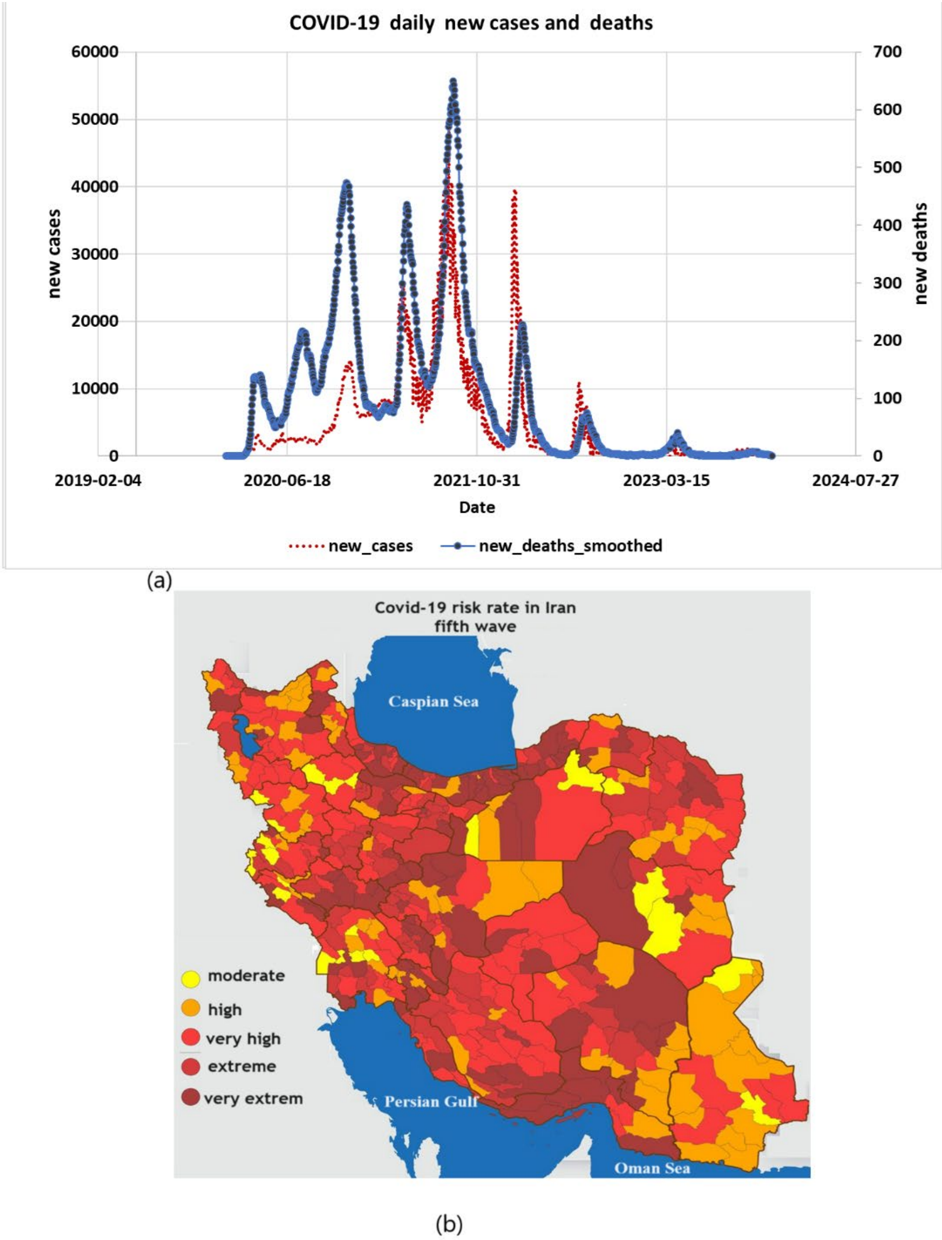
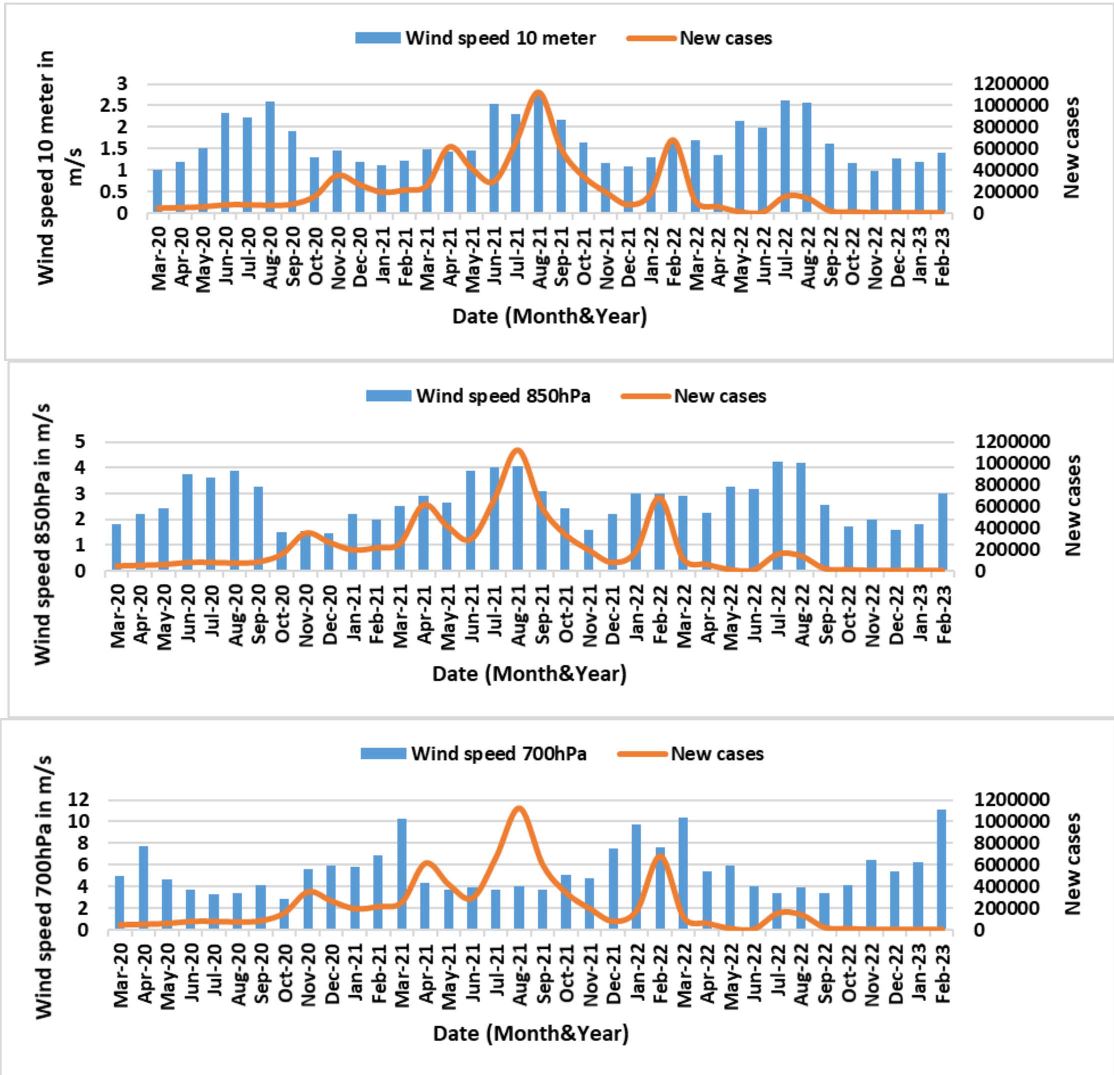


Figure 1. (a) A time series for COVID-19 daily new cases and daily new COVID-19 deaths in Iran during the pandemic. (b) The COVID-19 rate spread risk in Iran reported on 7 August 2021 (data from IRNA-INFORAPHIC).

Table 1. Correlation of meteorological variables with COVID-19 spread.

Meteorological Variable	Correlation Coefficient (r)	p Value
Wind Speed (10 meters)	0.76	< 0.05
Wind Speed (850 hPa)	0.75	< 0.05
Wind Speed (700 hPa)	-0.53	< 0.05
Wind Speed (500 hPa)	-0.70	< 0.05
Temperature (2 meters)	0.54	< 0.05
Temperature (850 hPa)	0.53	< 0.05
Temperature (700 hPa)	0.51	< 0.05
Relative Humidity (850 hPa)	-0.53	< 0.05
Relative Humidity (700 hPa)	-0.65	< 0.05

When the wind speed increases at lower atmospheric levels, the SARS-CoV-2 virus, similar to other aerosols, is more widely dispersed. Conversely, a reduction in wind speed at upper atmospheric levels due to a more stable atmosphere allows these aerosols, along with the virus, to remain longer in the lower levels of the atmosphere. This stability increases the persistence of the virus at these lower levels, thereby accelerating the spread of the disease. Moreover, the stability in the upper levels of the atmosphere likely reduces the vertical mixing of air, thereby decreasing the dilution and removal of viral particles from the lower atmosphere. Consequently, this stable atmospheric condition coupled with higher wind speeds at lower levels creates an environment where viral particles are more likely to remain suspended and be inhaled by individuals, thereby enhancing the transmission of the virus. This dynamic highlights the critical role of wind speed variations at different atmospheric levels in influencing the spread of COVID-19 (Fig. 2), underscoring the need for a nuanced understanding of meteorological impacts on viral transmission.



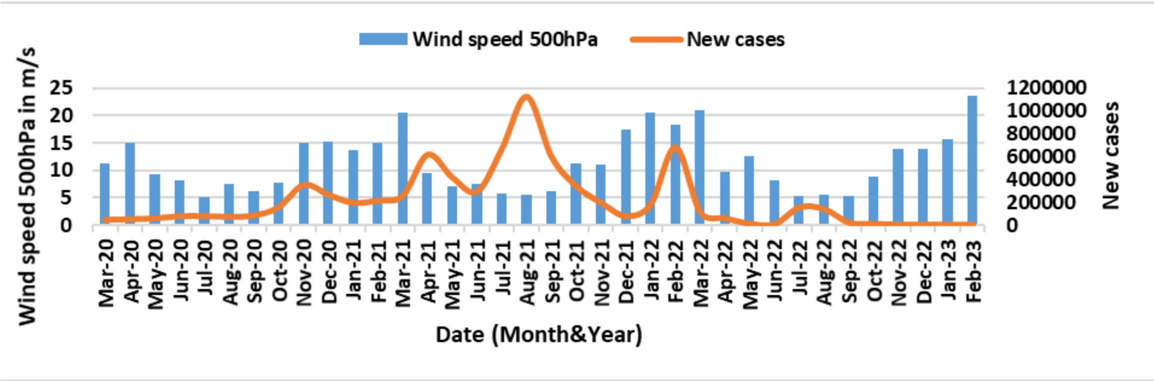


Figure 2. Monthly average wind speed at different levels at 10 m and 850, 700, and 500 hPa (from top to bottom) and the total reported cases per month.

Several studies have investigated the relationship between temperature and the spread of COVID-19 across various countries. In some countries, such as Syria, Yemen, Afghanistan, Nepal, Tajikistan, Uzbekistan, and Malaysia, a decrease in temperature has been associated with an increase in COVID-19 cases. Conversely, in other countries, such as Pakistan, India, Bangladesh, Cambodia, Laos, and Myanmar, the peak of COVID-19 transmission has been observed during periods of extreme heat (Haq et al., 2023; Ng et al., 2024). An extensive analysis by Nottmeyer et al. (2023) revealed 10.5 million confirmed COVID-19 cases across different cities in 20 countries. In most countries in the Northern Hemisphere, two waves of COVID-19 cases observed, occurred in cold seasons. However, there is no scientific evidence to support the hypothesis that COVID-19 transmission is significantly greater at either higher or lower temperatures (Haq et al., 2023). This suggests that the relationship between temperature and COVID-19 spread may be influenced by a multitude of factors beyond just the ambient temperature itself.

In the present study, although the correlation coefficient between temperature and the spread of COVID-19 was positive and approximately 50% over the one-year period of 2021, a review of the three-year trend (March 2020 to February 2023, Fig. 3) revealed no scientific justification for these variations. Peaks in COVID-19 cases were observed during both the maximum and minimum temperature periods. This indicates that temperature alone does not provide a consistent explanation for the fluctuations in COVID-19 transmission. Overall, the analysis indicated that while temperature may have some influence on COVID-19 transmission, it is not the sole determinant. The findings emphasize the importance of considering a broader range of factors, including social behaviors, public health policies, and hygiene practices, in understanding the spread of COVID-19. This multifaceted approach is essential for developing effective strategies to combat the virus across different climatic and geographical regions.

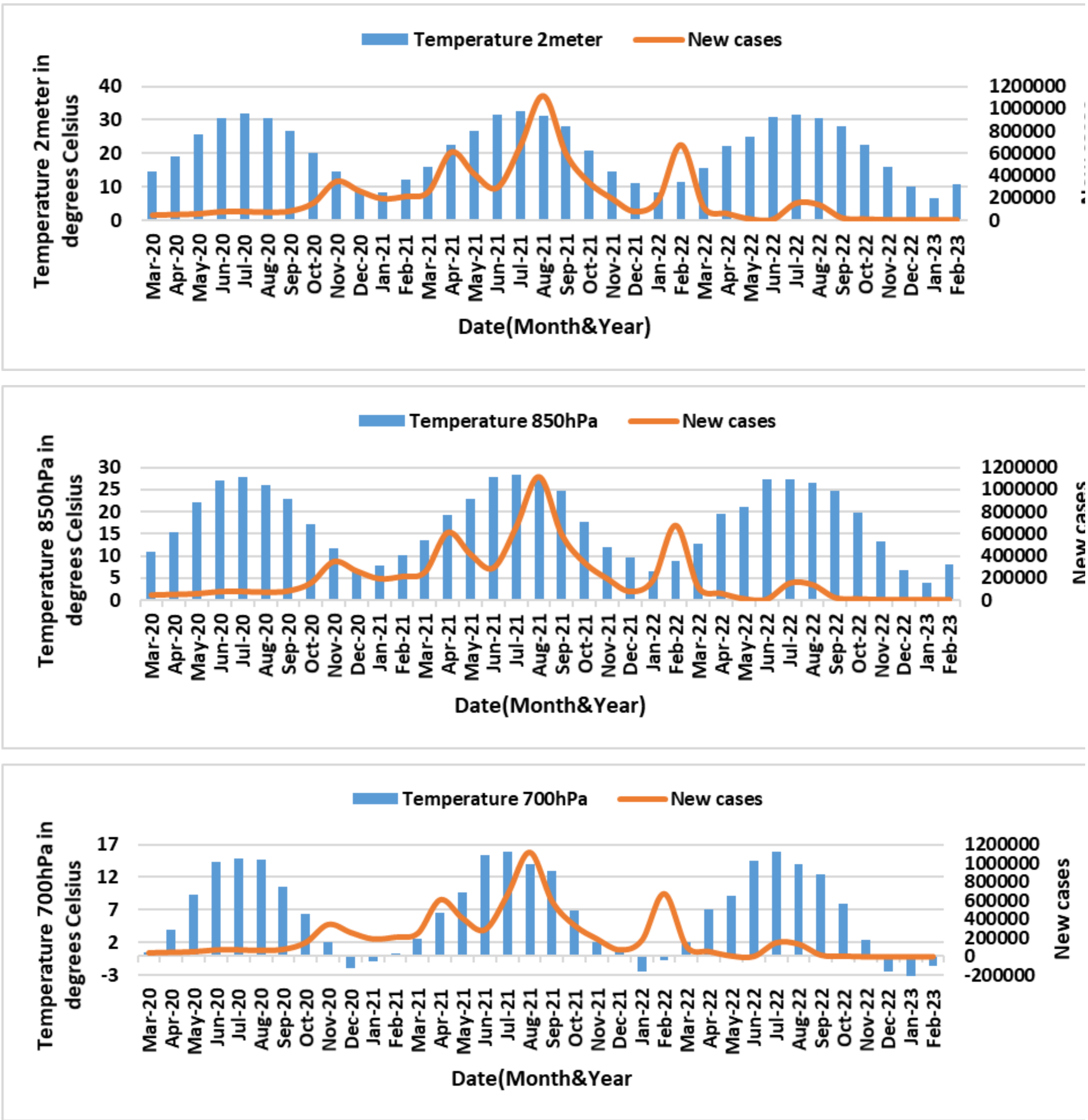


Figure 3. Monthly average temperature at 2 m, 850 hPa, and 700 hPa (from top to bottom) and the total reported cases per month.

The correlation coefficient between relative humidity and the spread of COVID-19 (Table 1), along with the analysis of their variations over a three-year period (Fig. 4), indicates a negative relationship between these two variables. This suggests that higher relative humidity is associated with a decrease in COVID-19 transmission. Lower humidity leads to a reduction in the size of suspended particles, facilitating increased transmission of seasonal viruses such as influenza. This finding underscores the pivotal role of air ventilation as a controlling factor in mitigating the spread of airborne diseases. Efficient air ventilation systems can help minimize the concentration of viral particles in indoor environments, thereby reducing the risk of transmission among individuals. Proper ventilation not only dilutes and removes viral aerosols from enclosed spaces but also helps maintain optimal indoor air quality, which is essential for overall respiratory health. Therefore, enhancing ventilation measures in indoor settings, especially during periods of low humidity, is crucial for reducing the risk of respiratory virus transmission, including that of COVID-19.

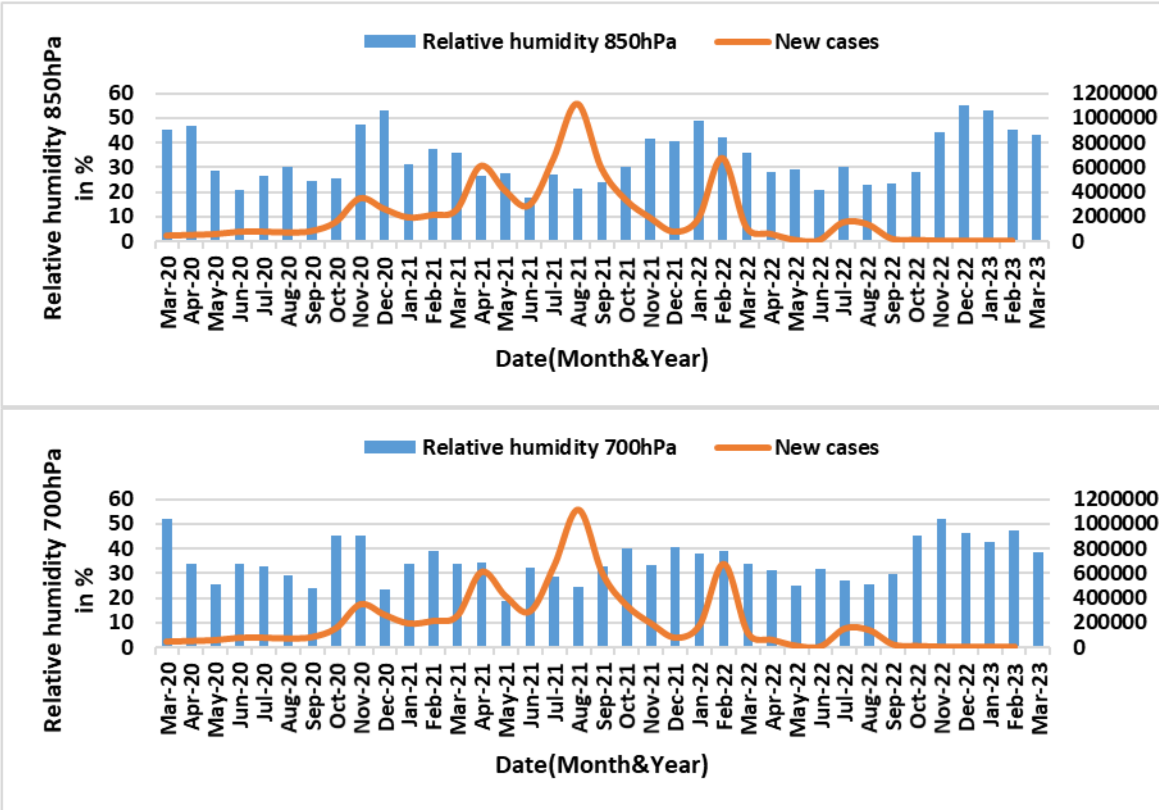


Figure 4. Monthly average relative humidity at 850 hPa (top) and 700 hPa (bottom) and the total number of reported cases per month.

3-3 Air pollution data analysis results

In the previous section, the results demonstrated that the spread of COVID-19 increased with stable atmospheric conditions and reduced wind speeds at the middle and upper levels of the atmosphere. Specifically, wind speeds at 700 and 500 hPa showed significant negative correlations with transmission risk. However, at lower atmospheric levels, such as 10 meters above the surface and 850 hPa, higher wind speeds exhibited a strong positive correlation with the spread of COVID-19.

This dual dynamic can be explained by considering the distinct roles of different atmospheric layers during stable conditions. Stable atmospheric conditions are characterized by limited vertical mixing due to stratification, which acts as a barrier or "ceiling" at the mid-level atmosphere (e.g., 700 and 500 hPa). This stability prevents the upward dispersion of airborne particles, including viral aerosols and pollutants, causing them to remain concentrated closer to the surface. In contrast, higher wind speeds at the surface and lower atmospheric levels facilitate the horizontal dispersion of viral particles, thereby increasing the likelihood of transmission over a wider area.

Fig. 5 shows seasonal changes of an area-averaged low-level ozone mass mixing ratio from 1981 to 2023 over the study area. This figure shows a long-term positive trend for summer with the biggest seasonal changes (in comparison with other seasons) and a remarkable peak during the fifth wave over the study area.

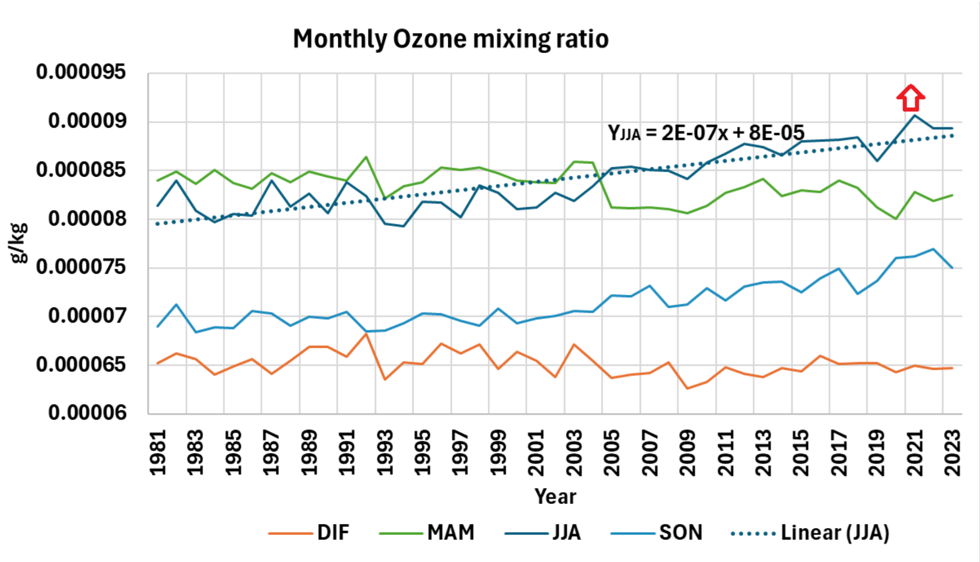


Figure 5. Seasonal changes of an area-averaged low-level ozone mass mixing ratio from 1981 to 2023 over the study area.

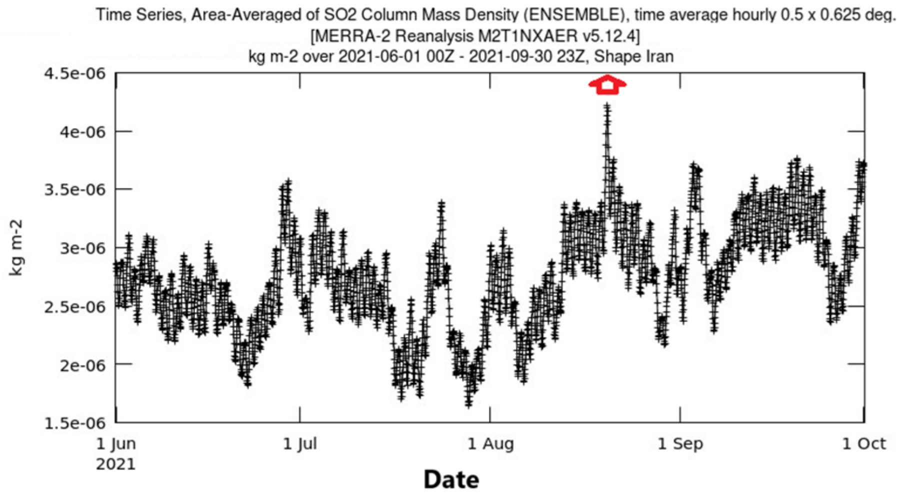


Figure 6. Area-averaged time-averaged hourly SO_2 column mass density from 1 June 2021 to 1 Oct. 2021 over Iran.

Fig. 6 shows a time series of area-averaged time-averaged hourly SO_2 column mass density (0.5 × 0.625 deg.) obtained from the MERRA database from 1 June 2021 to 1 Oct. 2021 over Iran. This figure shows an increasing trend during August peaked at approximately August 2021 over the study area (see the red arrow in the figure).

Fig. 7 shows a time series of the area average of the total column mass density of PM2.5 for the hourly time average (0.5 × 0.625 deg.) obtained from the MERRA database from 1 June 2021 to 1 Oct. 2021 over Iran. This figure shows high values with positive trends on average mostly during July and August 2021 in comparison with June, September, and October 2021. It illustrates a pattern with a significant peak during mid-July (a maximum of ~16 × 10^{-5} kg/m^2). However, this decreases toward the middle of July and again increases and peaks in early August (maximum ~14×10^{-5} kg/m^2). The figure shows another increasing trend during mid-August and peaked at approximately 10×10^{-5} kg/m^2 over the study area.

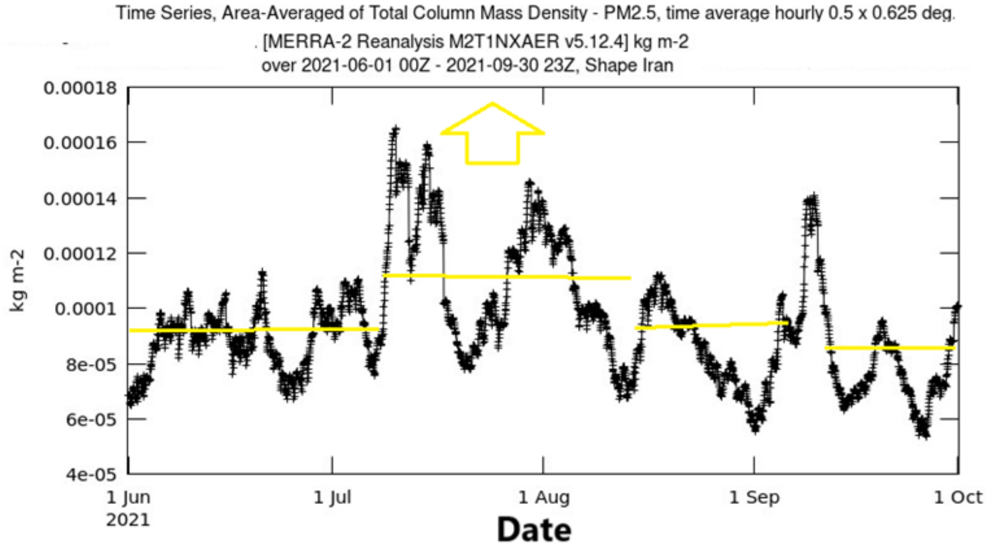


Figure 7. A time series of the area average of the total column mass density of PM2.5 for the hourly time average (0.5 × 0.625 deg.) obtained from the MERRA database from 1 June 2021 to 1 Oct. 2021 over Iran.

Fig. 8 shows a high-resolution (0.25 deg.) daily time series of the area-averaged NO_2 concentration obtained from the MERRA database from 1 May 2021 to 1 November 2021 over Iran. This figure displays a positive trend from May to July 2021 and a considerable decreasing trend from mid-September to November 2021. However, on average, the high values corresponded to sometime between July and September 2021.

Fig. 9 shows a daily time series for the ultraviolet aerosol index (UVAI) during August 2021 averaged over Iran. This figure indicates a significant peak on 14 August 2021.

Fig. 10 shows the high temporal resolution (hourly) of the dust surface mass concentration at the PM2.5 particle size for the area average in Iran during August 2021. This figure clearly shows that the high values of this air contaminant in the study area, mostly in the middle (14th-18th) of August 2021, corresponded to more new COVID-19 cases during the study period.

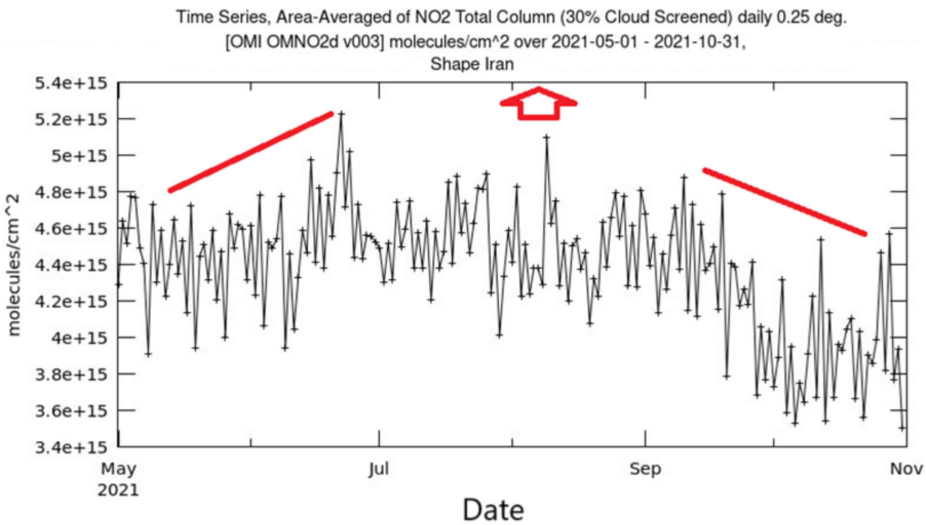


Figure 8. Daily time series of area-averaged NO_2 concentrations obtained from the MERRA database from 1 May 2021 to 1 November 2021 over Iran.

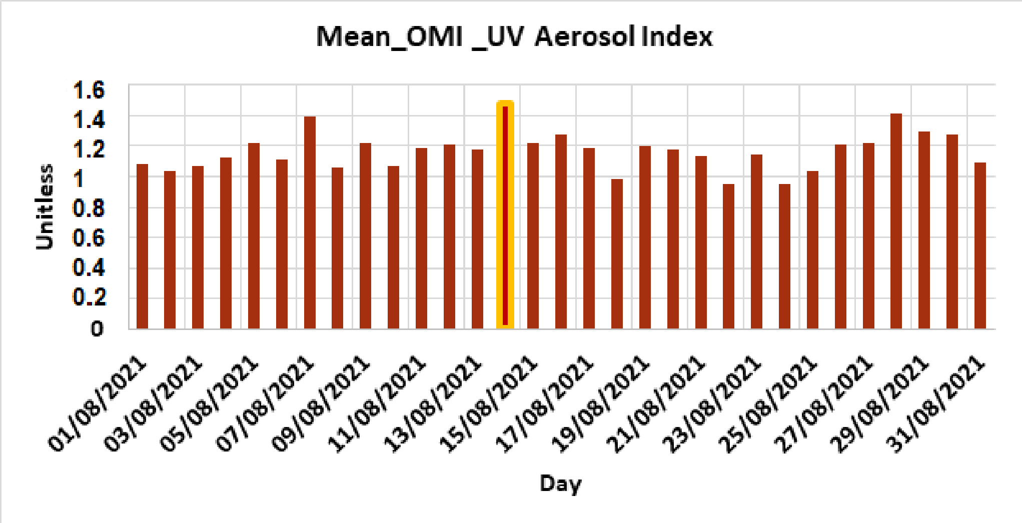


Figure 9. Daily time series for the ultraviolet aerosol index (UVAI) during August 2021 averaged over Iran.

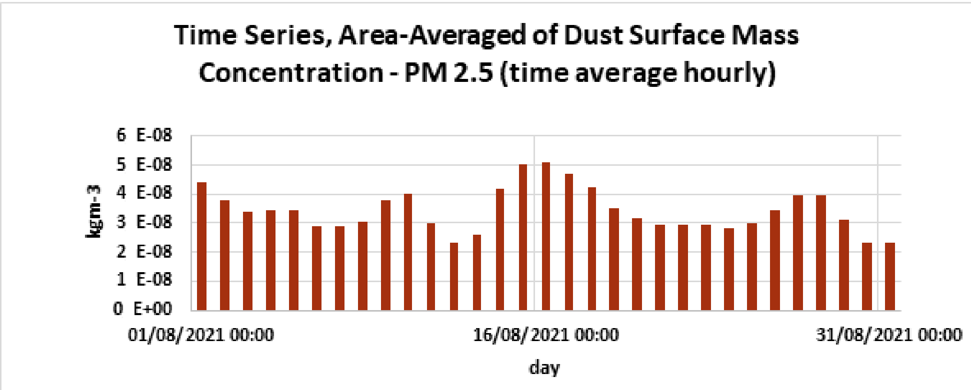


Figure 10. A time series of the average dust mass surface concentration of PM2.5 over Iran during August 2021.

Fig. 11 displays a high-resolution map (0.25 degrees) taken from the MERRA-2 (Rienecker et al., 2011) database for the low-level (800 hPa) time average map of the ozone mass mixing ratio over the study area. This figure presents the values ranging from ~82 over the study area to a maximum value of ~101 ppb, mostly in the southwestern, central, and eastern parts of Iran, on 14 August 2021. The areas with no data are the Zagros and Alborz Mountain regions, where the low levels are above 800 hPa. The figure shows that all parts of the study area have ozone values greater than 80 ppb under unhealthy conditions. Since 1971, the EPA (U.S. Environmental Protection Agency) has expressed national air quality standards for ozone of more than 80 parts per billion (ppb) averaged over 8 hours. Ozone is one of the important pollutants identified under the Clean Air Act by the EPA. Low-level ozone is related to health risk outcomes.

Fig. 12 shows the high values of the Aerosol Optical Depth (AOD), at 500 nm, over the study area during July, August, and September 2021 specifically in July (peaks in late July with 0.63) and early August 2021. Aerosol optical depth (AOD) is the dimensionless measure of extinction of beam (direct) irradiance caused by these aerosols (Ruiz-Arias and Gueymard, 2015). A value of

0.01 relates to an extremely clean atmosphere, and a value of 0.4 would match a very hazy situation.

Fig. 13 shows the long-term deviation of the surface air temperature for August from 2003 to 2022 over the study area. This figure displays a positive (~ 0.57K) anomaly associated with higher temperatures rather than long-term normal values over the study area during August in the 5th COVID-19 wave over the study area.

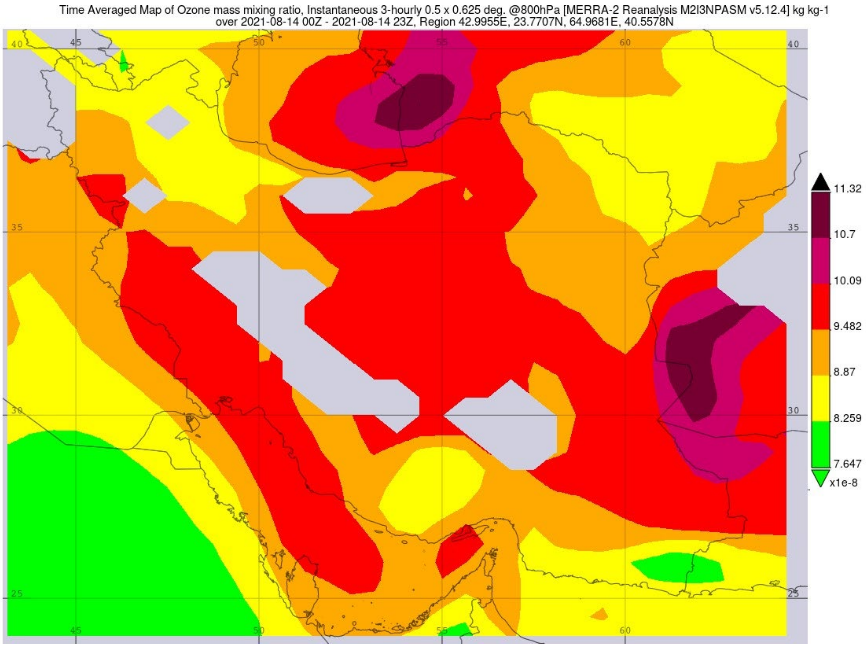


Figure 11. Low-level time average map of the ozone mass mixing ratio over the study area on 14 August 2021.

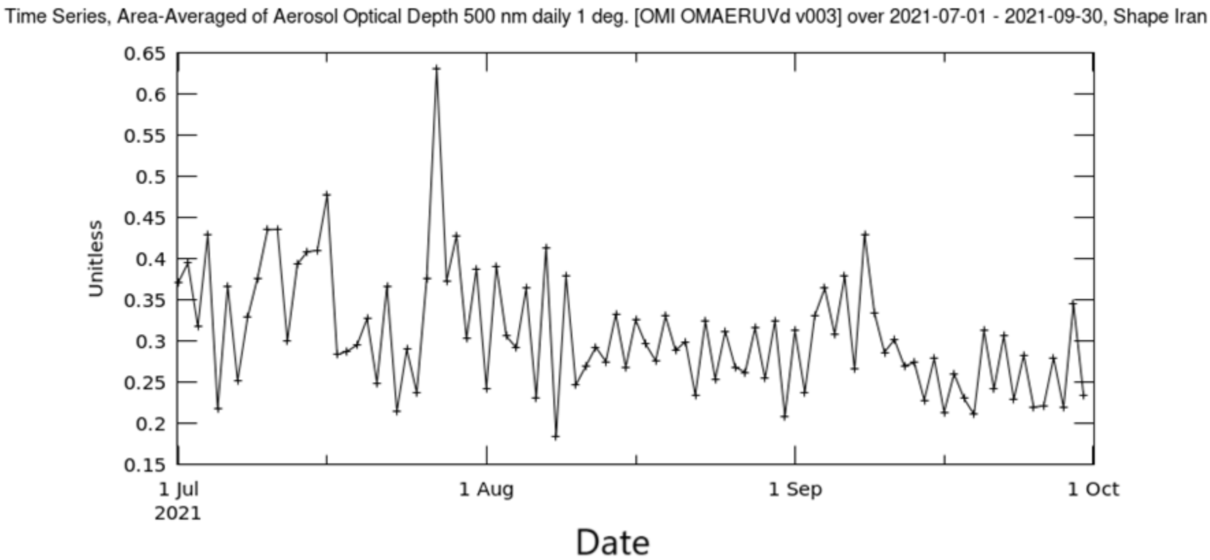


Figure 12. Aerosol optical depth (AOD), at 500 nm, over the study area during July, August, and September 2021.

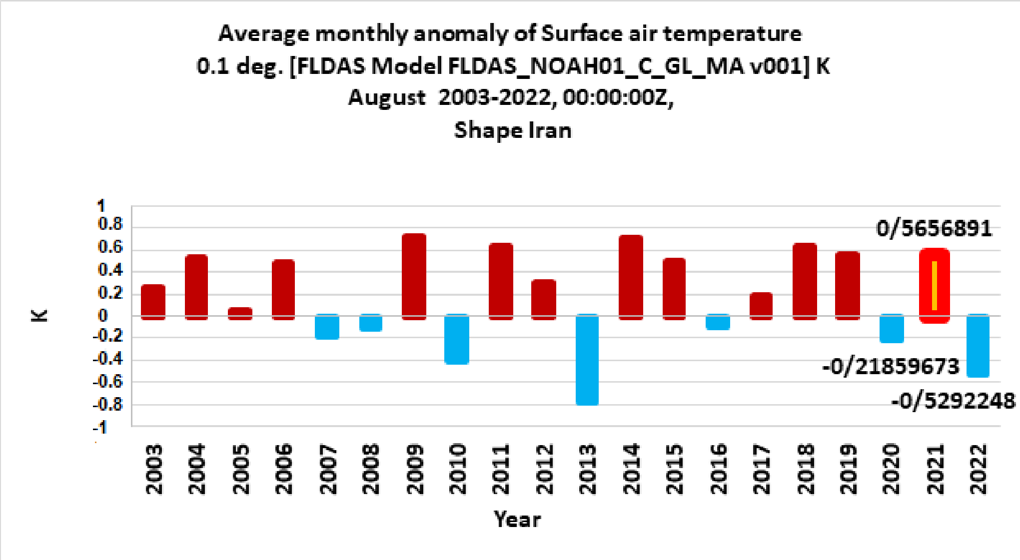


Figure 13. Surface air temperature anomaly for August in Iran from 2003-2022.

4 Discussion and concluding remarks

This study investigated the correlation between meteorological factors and COVID-19 transmission. Our findings indicate that temperature variations alone do not significantly impact the spread of COVID-19. Peaks in cases were observed during both high and low temperatures, suggesting that other factors, such as social behaviors, public health policies, and hygiene practices, play a more critical role.

Wind speed also had significant effects, with increased wind speeds at lower atmospheric levels dispersing the virus more widely, while reduced wind speeds at higher levels allowing the virus to remain in the lower atmosphere longer, increasing transmission risk.

The analysis revealed a negative relationship between relative humidity and COVID-19 transmission, with higher humidity associated with a decrease in cases. This highlights the importance of proper air ventilation in mitigating the spread of the virus, especially in indoor settings with low humidity.

During the fifth wave, air pollution levels, including NO_2, PM2.5, SO_2, and ozone, increased notably. This pollution accumulation was attributed to stable weather conditions that restricted ventilation, particularly during short pre- and post-peak periods, despite lockdown measures. The increase in O_3 levels during the fifth wave was expected due to high-temperature conditions typical of the summer months. However, statistical analysis indicates that temperature variations alone do not significantly or uniquely drive the rise in COVID-19 cases. The study found a notable reduction in overall air quality index (AQI) pollution during COVID-19 lockdowns, except for a consistent increase in O_3 levels, particularly during the fifth wave. In stagnant summer air, with temperatures 0.57 K above the long-term average for August 2021, hazy conditions are reflected by high aerosol optical depth (AOD), along with elevated ozone and particulate pollution. High AOD, along with elevated ozone and particulate pollution, may be associated with increased transmission risk. These conditions suggest that poor air quality, compounded by stagnant weather patterns, could enhance the persistence and spread of viral particles in the atmosphere. Additionally, such pollutants may impair respiratory health, potentially increasing susceptibility to infections,

including COVID-19. This highlights the importance of addressing air quality as part of broader public health strategies to mitigate transmission risks, particularly during periods of stable, warm weather.
Overall, this study emphasizes the need for a multifaceted approach to understanding and combating COVID-19, considering a range of meteorological and non-meteorological factors to develop effective public health strategies. These effects, however, are substantially greater during mealtimes and in periods of high mobility and low containment, suggesting an important role in social behavior.

Also, it can be concluded that several seasonal factors can influence COVID-19 spread, including air quality and pollution such as winter or summer pollution, especially in BIG cities, which can worsen respiratory conditions, making people more susceptible to COVID-19. Furthermore, other factors such as social behavior, sunlight and UV radiation, health conditions, behavioral factors like stress, less physical activity, poor mental health, virus mutations, and seasonal changes may influence mutation rates of the virus, potentially leading to more transmissible variants. Besides, holiday travel increases the risk of spreading the virus between regions.

The connections between the findings of this work and practical public health implications help public health authorities to develop tailored interventions. These include enhanced messaging, monitoring, and policies that address specific risks during different seasons—ranging from improving air quality and encouraging safer social behaviors to promote health measures like vaccination and physical activity.

There are some potential limitations of the study such as the data limitations. The variability in the quality and resolution of meteorological and pollution data may affect accuracy. Also, the unmeasured variables, such as vaccination rates or variant-specific impacts, could influence results. Furthermore, the interactions between pollution, weather, and human behavior are complex and not fully captured. These limitations suggest that while the study provides valuable insights, further research is needed to strengthen the conclusions and explore additional variables.

Acknowledgments
The authors would like to acknowledge the European Centre for Medium-Range Weather Forecasts for the ERA5 and Giovanni online data system, developed and maintained by the NASA GES DISC. Thanks to “Our World in Data", accessible through the following link: https://github.com/owid/covid-19-data/blob/master/public/data/jhu/full_data.csv.

References

Auler, A., Cássaro, F., Da Silva, V., and Pires, L., 2020, Evidence that high temperatures and intermediate relative humidity might favor the spread of COVID-19 in tropical climate: A case study for the most affected Brazilian cities: Science of The Total Environment, **729**, 139090, doi:10.1016/j.scitotenv.2020.139090.

Bashir, M. F., Ma, B., Bilal, Komal, B., Bashir, M. A., Tan, D., and Bashir, M., 2020, Correlation between climate indicators and COVID-19 pandemic in New York, USA: Science of The Total Environment, **728**, 138835, doi:10.1016/j.scitotenv.2020.138835.

Burch, J., Jackson, C., and Bunt, C., 2021, What is the accuracy of World Health Organization (WHO)-specified and related COVID-19 symptoms for diagnosis of COVID-19?: Cochrane Clinical Answers, doi:10.1002/cca.3561.

Chauhan, A. J., and Johnston, S. L., 2003, Air pollution and infection in respiratory illness: British Medical Bulletin, **68**(1), 95-112, doi:10.1093/bmb/ldg022.

Chen, K., Wang, M., Huang, C., Kinney, P. L., and Anastas, P. T., 2020, Air pollution reduction and mortality benefit during the COVID-19 outbreak in China, doi:10.1101/2020.03.23.20039842.

Ciencewicki, J., and Jaspers, I., 2007, Air pollution and respiratory viral infection: Inhalation Toxicology, **19**(14), 1135-1146, doi:10.1080/08958370701665434.

Cowling, B. J., and Leung, G. M., 2020, Epidemiological research priorities for public health control of the ongoing global novel coronavirus (2019-nCoV) outbreak: Eurosurveillance, **25**(6), doi:10.2807/1560-7917.es.2020.25.6.2000110.

Dickerson, R. R., Kondragunta, S., Stenchikov, G., Civerolo, K. L., Doddridge, B. G., and Holben, B. N., 1997, The impact of aerosols on solar ultraviolet radiation and photochemical smog: Science, **278**(5339), 827-830, doi:10.1126/science.278.5339.827.

Fazel-Rastgar, F., Khansalari, S., and Sivakumar, V., 2024, A case study of extreme temperature with air pollution and health risk in Yazd Province during July 2019: *Pollution*, ***10***(1), 550-565, doi: 10.22059/poll.2023.366077.2083.

Fazel-Rastgar, F., and Sivakumar, V., 2023, A case study of weather impact on air pollution during the COVID-19 pandemic in South Africa: Scientific African, **22**, e01914, doi:10.1016/j.sciaf.2023.e01914.

Ganguly, R., Sharma, D., and Kumar, P., 2021, Short-term impacts of air pollutants in three megacities of India during COVID-19 lockdown: Environment, Development and Sustainability, **23**(12), 18204-18231, doi:10.1007/s10668-021-01434-9.

Giani, P., Castruccio, S., Anav, A., Howard, D., Hu, W., and Crippa, P., 2020, Short-term and long-term health impacts of air pollution reductions from COVID-19 lockdowns in China and Europe: A modeling study: The Lancet Planetary Health, **4**(10), e474-e482, doi:10.1016/s2542-5196(20)30224-2.

Haq, F. U., Abduljaleel, Y., and Ahmad, I., 2023, Effect of temperature on fast transmission of COVID-19 in low per capita GDP Asian countries: Scientific Reports, **13**(1), 21165.

He, G., Pan, Y., and Tanaka, T., 2020, The short-term impacts of COVID-19 lockdown on urban air pollution in China: Nature Sustainability, **3**(12), 1005-1011, doi:10.1038/s41893-020-0581-y.

Heger, M., Zens, G., and Meisner, C., 2019, Particulate matter, ambient air pollution, and respiratory disease in Egypt, doi:10.1596/35810.

Herman, J. R., Bhartia, P. K., Torres, O., Hsu, C., Seftor, C., and Celarier, E., 1997, Global distribution of UV-absorbing aerosols from nimbus 7/TOMS data: Journal of Geophysical Research: Atmospheres, **102**(D14), 16911-16922, doi:10.1029/96jd03680.

Khansalari, S., Rastgar, F. F., Mohammadian Mohammadi, L., and Gozalkhoo, M., 2021, Clustering of different atmospheric patterns leading to an increase in different types of atmospheric pollutants in the greater Tehran area during the last 17 years (2004-2020): Journal of Air Pollution and Health, https://doi.org/10.18502/japh.v6i1.7605.

Kotsiou, O. S., Zidros, T., and Gourgoulianis, K. I., 2020, Letter to Editor regarding Prata et al. (2020), Temperature significantly changes COVID-19 transmission in (sub)tropical cities of Brazil. Science of total environment, v729, 138862: Science of The Total Environment, **746**, 141323, doi:10.1016/j.scitotenv.2020.141323.

Kowalska, M., 2012, Short-term effect of changes in fine particulate matter concentrations in ambient air to daily cardio-respiratory mortality in inhabitants of urban-industrial agglomeration (Katowice agglomeration), Poland: Air Quality - New Perspective, doi:10.5772/39235.

Lin, R., Wang, X., and Huang, J., 2022, The influence of weather conditions on the COVID-19 epidemic: Evidence from 279 prefecture-level panel data in China: Environmental Research, **206**, 112272.

Lolli, S., Chen, Y., Wang, S., and Vivone, G., 2020, Impact of meteorological conditions and air pollution on COVID-19 pandemic transmission in Lombardy region, northern Italy, doi:10.21203/rs.3.pex-1045/v1.

Malki, Z., Atlam, E., Hassanien, A. E., Dagnew, G., Elhosseini, M. A., and Gad, I., 2020, Association between weather data and COVID-19 pandemic predicting mortality rate: Machine learning approaches: Chaos, Solitons and Fractals, **138**, 110137, doi:10.1016/j.chaos.2020.110137.

Mehta, S., Shin, H., Burnett, R., North, T., and Cohen, A. J., 2013, Ambient particulate air pollution and acute lower respiratory infections: A systematic review and implications for estimating the global burden of disease: Air Quality, Atmosphere & Health, **6**(1), 69-83, doi:10.1007/s11869-011-0146-3.

Ng, K. Y., Hasan, M. Z., and Rahman, A., 2024, Examining the roles of meteorological variables in COVID-19 spread in Malaysia: Aerobiologia, 1-16.

Nottmeyer, L., Armstrong, B., Lowe, R., et al., 2023, The association of COVID-19 incidence with temperature, humidity, and UV radiation–A global multicity analysis: Science of The Total Environment, **854**, 158636.

Paraskevis, D., Kostaki, E. G., Alygizakis, Thomaidis, N. S., Cartalis, C., Tsiodras, S., and Dimopoulos, M. A., 2021, A review of the impact of weather and climate variables to COVID-19: In the absence of public health measures high temperatures cannot probably mitigate outbreaks: Science of The Total Environment, **768**, 144578, doi:10.1016/j.scitotenv.2020.144578.

Pansini, R., and Fornacca, D., 2020, Higher virulence of COVID-19 in the air-polluted regions of eight severely affected countries: medRxiv, 2020-04.

Park, H. K., Shim, J. Y., Jung, H. L., Shim, J. W., Kim, D. S., Kwak, J. H., and Sol, I. S., 2021, Effect of COVID-19 on air pollution and respiratory viral infection of children in South Korea: Authorea, doi:10.22541/au.161167516.63010319/v1.

Poirier, C., Luo, W., Majumder, M., Liu, D., Mandl, K., Mooring, T., Santillana, M., 2020, The role of environmental factors on transmission rates of the COVID-19 outbreak: An initial assessment in two spatial scales: SSRN Electronic Journal, doi:10.2139/ssrn.3552677.

Prata, D. N., Rodrigues, W., and Bermejo, P. H., 2020, Temperature significantly changes COVID-19 transmission in (sub)tropical cities of Brazil: Science of The Total Environment, **729**, 138862, doi:10.1016/j.scitotenv.2020.138862.

Rienecker, M. M., Suarez, M. J., Gelaro, R., et al., 2011, MERRA: NASA's modern-era retrospective analysis for research and applications: Journal of Climate, **24**(14), 3624-3648, https://doi.org/10.1175/jcli-d-11-00015.1.

Riou, J., and Althaus, C. L., 2020, Pattern of early human-to-human transmission of Wuhan 2019 novel coronavirus (2019-nCoV), December 2019 to January 2020: Eurosurveillance, **25**(4), doi:10.2807/1560-7917.es.2020.25.4.2000058.

Robinson, R., 2012, Even ‘Satisfactory’ levels of air pollution increase stroke risk: Neurology Today, **12**(7), 1, doi:10.1097/01.nt.0000413856.50246.b0.

Rosario, D. K., Mutz, Y. S., Bernardes, P. C., and Conte-Junior, C. A., 2020, Relationship between COVID-19 and weather: Case study in a tropical country: International Journal of Hygiene and Environmental Health, **229**, 113587, doi:10.1016/j.ijheh.2020.113587.

Ruiz-Arias, J. A., and Gueymard, C. A., 2015, Solar resource for high-concentrator photovoltaic applications, Pérez-Higueras, P. J., Fernádez, E. F., eds., in High Concentrator Photovoltaics: Fundamentals, Engineering and Power Plants: Springer, 261-302.

Shi, P., Dong, Y., Yan, H., et al., 2020, Impact of temperature on the dynamics of the COVID-19 outbreak in China: Science of The Total Environment, **728**, 138890, doi:10.1016/j.scitotenv.2020.138890.

Torres, O., Bhartia, P. K., Herman, J. R., Ahmad, Z., and Gleason, J., 1998, Derivation of aerosol properties from satellite measurements of backscattered ultraviolet radiation: Theoretical basis: Journal of Geophysical Research: Atmospheres, **103**(D14), 17099-17110, doi:10.1029/98jd00900.

Torres, O., Tanskanen, A., Veihelmann, B., et al., 2007, Aerosols and surface UV products from ozone monitoring instrument observations: An overview: Journal of Geophysical Research: Atmospheres, **112**(D24), doi:10.1029/2007jd008809.

World Health Organization, 2016, Ambient air pollution: A global assessment of exposure and burden of disease.

Wu, X., Nethery, R. C., Sabath, M. B., Braun, D., and Dominici, F., 2020, Air pollution and COVID-19 mortality in the United States: Strengths and limitations of an ecological regression analysis: Science advances, **6**(45), eabd4049.

Xie, J., Teng, J., Fan, Y., Xie, R., and Shen, A., 2019, The short-term effects of air pollutants on hospitalizations for respiratory disease in Hefei, China: International Journal of Biometeorology, **63**(3), 315-326, doi:10.1007/s00484-018-01665-y.

Yao, Y., Pan, J., Liu, Z., Meng, X., Wang, W., Kan, H., and Wang, W., 2020, No association of COVID-19 transmission with temperature or UV radiation in Chinese cities: European Respiratory Journal, **55**(5), 2000517, doi:10.1183/13993003.00517-2020.