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Peculiar weather patterns effects on air pollution and COVID-19 spread in Tokyo metropolis

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ABSTRACT

As a pandemic hotspot in Japan, between March 1, 2020–October 1, 2022, Tokyo metropolis experienced seven COVID-19 waves. Motivated by the high rate of COVID-19 incidence and mortality during the seventh wave, and environmental/health challenges we conducted a time-series analysis to investigate the long-term interaction of air quality and climate variability with viral pandemic in Tokyo. Through daily time series geospatial and observational air pollution/climate data, and COVID-19 incidence and death cases, this study compared the environmental conditions during COVID-19 multiwaves. In spite of five State of Emergency (SOEs) restrictions associated with COVID-19 pandemic, during (2020–2022) period air quality recorded low improvements relative to (2015–2019) average annual values, namely: Aerosol Optical Depth increased by 9.13% in 2020 year, and declined by 6.64% in 2021, and 12.03% in 2022; particulate matter PM2.5 and PM10 decreased during 2020, 2021, and 2022 years by 10.22%, 62.26%, 0.39%, and respectively by 4.42%, 3.95%, 5.76%. For (2021–2022) period the average ratio of PM2.5/PM10 was (0.319 ± 0.1640), showing a higher contribution to aerosol loading of traffic-related coarse particles in comparison with fine particles. The highest rates of the daily recorded COVID-19 incidence and death cases in Tokyo during the seventh COVID-19 wave (1 July 2022–1 October 2022) may be attributed to accumulation near the ground of high levels of air pollutants and viral pathogens due to: 1) peculiar persistent atmospheric anticyclonic circulation with strong positive anomalies of geopotential height at 500 hPa; 2) lower levels of Planetary Boundary Layer (PBL) heights; 3) high daily maximum air temperature and land surface temperature due to the prolonged heat waves (HWs) in summer 2022; 4) no imposed restrictions. Such findings can guide public decision-makers to design proper strategies to curb pandemics under persistent stable anticyclonic weather conditions and summer HWs in large metropolitan areas.

1. Introduction

The ongoing COVID-19 global pandemic of the last three years changed human behavior, and the governments' responses to crises, placing healthcare systems in an emergency state. The COVID-19 pandemic crisis amplified sustainability issues through its adverse impacts on Sustainable Development Goals (Elsamadony et al., 2022). The global in progress pandemic COVID-19 disease produced by Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) and its variants exceeded 679, 352, 152 cases nowadays (February 24, 2023) and more than 6,796,188 fatalities in 231 countries (Johns Hopkins Coronavirus, 2023; Worldometer Info, 2023). On February 24, 2023 Japan recorded 33, 151, 209 COVID-19 cases representing 4.88% of global cases, and 72,051 deaths representing 1.06% of global deaths.

According to the number of confirmed COVID-19 positive cases in Tokyo, seven waves of coronavirus infection were observed between February 2020 and October 1, 2022, presently is ongoing is the 8th wave. The analyzed waves in this study peaked around mid-April 2020, from the end of July to the beginning of August 2020, at the beginning of January 2021, in mid-May 2021, in mid-August 2021, in mid-March 2022, and mid-August 2022. While the number of daily new positive cases in the 6th and 7th waves was much higher than in the previous waves, the number of COVID-19 deaths remained at a low level in comparison with other countries. However, Japan had the lowest number of COVID-19 cumulative deaths per million people (377.28) among the 38 OECD (Organisation for Economic Co-operation and Development) countries (Botta and Yamasaki, 2020), and Tokyo had 435.67 cumulative deaths per million people during the pandemic period till October 31, 2022 (TMG, 2022). Japan's adopted policy for COVID-19 was to limit the outbreak of infection, maintain the medical

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system, and focus on dealing with the severely ill (Yamauchi and Takeuchi, 2022; Inoue, 2020). Function of the epidemic situation in each region, Tokyo Government implemented various restrictions, including declaring five times a state of emergency.

Although multiple epidemic waves of COVID-19 have occurred in Japan, with different clinical characteristics, and the novel coronavirus infection (COVID-19) has become a public health threat worldwide, the epidemiological characteristics of patients differ significantly between European and Western countries and Asia (Hayakawa, 2022). During the first five COVID-19 waves periods in Tokyo have been identified many variants of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) (including B.1.1.284, B.1.1.214, R.1, AY.29, and AY.29.1) with the corresponding mutations in S, N, and NSPs associated with the increase of transmissibility and/or severity (Tsuchiya et al., 2022; Karako et al., 2022). The 6th COVID-19 wave was triggered by the Omicron variant (B.1.1.529 lineage), which started in early January 2022 (Itoh et al., 2022; Tallei et al., 2022), while the next 7th and the 8th were triggered by the Omicron BA.5, BA.2.75 BQ.1.1, BF.7, BQ.1, and XBB variants.

Due to the increased urbanization and climate changes, the main air pollutants with high oxidative toxicity, particulate matter-PM (PM2.5 μm, and PM10 μm), ozone (O_3), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and carbon monoxide (CO) may have an important impact on COVID-19 disease spreading (Domingo et al., 2020; Rovira et al., 2020; Marquès and Domingo, 2021, 2022; Zoran et al., 2020a, 2020b; López-Feldman et al., 2021; Shao et al., 2022). Was demonstrated that air pollution is a major environmental risk factor for human health, being responsible of 4.2 million deaths per each year globally, primarily attributed to cardiorespiratory diseases, like as chronic obstructive pulmonary disorder (COPD), lung cancer and acute respiratory infections (WHO, 2021). Acute and chronic exposure (Wang Y et al., 2022) to high levels of outdoor air pollutants concentrations above WHO guidelines (WHO, 2023) implemented by the Directive 2008/50/EU and the US-EPA in large urban areas, have been associated with increased viral infections and COVID-19 cardiorespiratory morbidity and mortality rates (WHO, 2023; Beloconi, Vounatsou, 2023; Domingo and Rovira, 2020; Leirião et al., 2022; Prinz and Richter, 2022; Hvidtfeldt et al., 2021; Travaglio et al., 2021; Marquès et al., 2022; Chong et al., 2022). Several epidemiologic and toxicologic studies have linked air pollution exposure to incidence, morbidity and mortality of coronavirus disease 2019 (COVID-19), which seriously challenging healthcare systems since 2020 (Hyman et al., 2023; Heald et al., 2022; Kolluru et al., 2023; Isphording and Pestel, 2021; Kirwan et al., 2022; Lavigne et al., 2022; Veronesi et al., 2022; Ma et al., 2023). It seems that also urban high traffic, especially the primary pollutants emitted from diesel and gasoline-powered engines and road dust may be involved in the spread and pathogenicity of different viruses (Frimpong et al., 2023; Fayyazbakhsh et al., 2022).

Based on the relevant scientific literature results, is considered that particulate matter play a double role in COVID-19 outcomes (a chronic one linked the possible impacts of long-term and short-term exposure to high PM concentrations in developing severe forms of COVID-19, and an acute one related to the possible carrier function of PM in SARS-CoV-2) (Collivignarelli et al., 2023; Woodby et al., 2021).

Is well recognized that atmospheric PM is an important issue in air quality monitoring, and bioaerosol forms a crucial component of PM. A possible mechanism of attachment of viruses on PM surface is considered adsorption/absorption of organic molecules and viruses on the aqueous atmospheric aerosols (Manoj et al., 2020; Anand et al., 2021). The aqueous atmospheric aerosols offer a favorable surface for the adsorption/absorption of organic molecules and viruses on them, offering a route for a higher diffusion rate of viruses under proper environmental conditions (Luisetto et al., 2020; Chennakesavulu and Reddy, 2020). The distribution and composition of microbial diversity (viruses, bacteria, and fungi) in bioaerosol exhibit distinct signatures in different regions and under different environmental and seasonal conditions (Coccia, 2022; Du et al., 2018; Ma et al., 2023; Gong et al., 2020; Xiao et al., 2021; Yang et al., 2023). Meteorological significant factors such as air temperature, pressure, humidity, precipitations, sunlight, wind speed intensity and direction, have a greater effect on microorganisms influencing the persistence of infectious SARS-CoV-2 in aerosols (Dabisch et al., 2021; Aboura, 2022; Manik et al., 2022). Due to its toxicity O_3, has a negative correlation with most microorganisms. Also, experimentally was shown that the mean total airborne microbe concentration was higher on haze days, exhibiting a bimodal distribution with two peaks coinciding with traffic rush hours (Yan et al., 2022). Besides indoor airborne transmission of viruses, outdoor airborne transmission could play an important role in determining the differences observed in the spread rate. SARS-CoV-2 virus responsible for the Coronavirus disease 2019 (COVID-19), which is affecting the world since the end of 2019 was detected not only in indoor healthcare settings (Ahlawat et al., 2020; Baboli et al., 2021; Barbieri et al., 2021), but also among other viruses in the outdoor airborne PM2.5 samples collected in urban areas like as Bern, Lugano, and Zurich in Switzerland (Tao et al., 2022) and virus-laden aerosol PM10 samples in Veneto and Apulia regions (Chirizzi et al., 2021) or Venice (Pivato et al., 2022) of Italy.

Fine particulate matter PM2.5 is one of the main contributors to air pollution and is considered the fourth leading risk factor for death and disability in the world (GBD C, 2020; WHO, 2016; Xu et al., 2020). Besides, long-term and short-term exposure to air pollutants was demonstrated that cumulative smoking and chronic obstructive pulmonary disease (COPD) are additional factors for severe COVID-19 infections (Watase et al., 2023). As one modulating factor of COVID-19 disease clinical outcomes, control of air pollution and short- and long-term exposure to toxic air pollutants are essential for improving public health measures, especially to protect the vulnerable population in urban dense areas (Clerbaux et al., 2022). In addition is well known that coinfection with the influenza A virus and other viral infections enhances SARS-CoV-2 infectivity in lower immunity human systems (Bai et al., 2021; Chrysanthopoulou et al., 2023). However, outdoor and indoor environmental exposures (Yang et al., 2023) are interlinked with social, demographic, and evolutionary factors (Destoumieux-Garzon et al., 2022).

In the frame of global warming and increased frequency of heat waves (HWs), several studies have shown that COVID-19 may potentially exacerbate the air pollutants and temperature effects on human health during heat waves (Bhatt et al., 2020). Also, the cumulative effects of climate parameters seasonal variability, at urban and regional scales may have significant impacts on viral infections spreading. Tokyo metropolis in Japan represents a typical urban environment where diesel vehicular emissions are responsible of the main atmospheric aerosol loading PM and BC (Black Carbon) (Mori et al., 2020; Nishikawa et al., 2023). Tokyo experienced the most rapid economic and urban development processes, where air pollution that threatened the public health led to improved technology and one of the most efficient and intensive air pollution control strategies. Japan considered of high importance the issue of climate change and air quality improvement, especially in Greater Tokyo metropolitan area, and addressed climate change as a major national strategy for economic and social development (Zhang et al., 2022; Azuma et al., 2020). The Tokyo Metropolitan Government implemented several measures toward the transition to net zero greenhouse gas (GHG), especially in the densely urban areas of Greater Tokyo, and established more ambitious targets for the concentration of PM2.5 and photochemical oxidants reduction and the improvement of air quality, aiming to have no days with photochemical smog advisory alerts (Botta and Yamasaki, 2020; Ito et al., 2021a). Like in several countries worldwide (Andreoni, 2022; Hu et al., 2021), the COVID-19 crisis in Tokyo and the related lockdown restrictions have forced a reduction of traffic and industrial activities and a consequent energy consumption drop, especially during weekend periods (Hu et al., 2021).

Due to the increased protection measures against the COVID-19 pandemic, the incidence of non-COVID-19 viral infections decreased significantly in the Tokyo metropolitan area (Yan et al., 2022; Kanda et al., 2023; Yamamoto et al., 2023). Considering that the main factors which may favour increase and suppress COVID-19 disease are: strength of immunity system, epidemic variant, climate and seasonal variability and synergy response to SARS-CoV-2 pathogens and seasonal influenza. In order to assess the linkage of future COVID-19 waves is an urgent need to understand the COVID-19 shape pandemic risk related to environmental factors (Jana et al., 2023; Rayan, 2021; Bontempi, 2021; Bakhshandeh et al., 2021; Chen J.H. et al., 2021; Baay et al., 2020; Bontempi et al., 2020; Luo et al., 2020; Wang et al., 2020; Mu et al., 2020). This study explores the impact of outdoor air pollutants on the incidence and severity of COVID-19 pandemic in Tokyo metropolis, focusing on inhalable fine particulate matter PM with size diameter ≤2.5 μm (PM2. 5) and ≤10 μm (PM10) coarse particles, ozone (O3), and nitrogen dioxide (NO2), with typical oxidative toxicity that does not comply with air quality standards in Tokyo metropolis.

The main analysis in this study is related to the impact of air pollutants, climate variables, and the number of daily new COVID-19 cases (DNC) and daily new COVID-19 deaths (DND) during the seven COVID-19 waves recorded in Tokyo between 1 January 2020–1 October 2022. In optical terms, aerosol-related air pollution is described by total Aerosol Optical Depth (AOD) at 550 nm. Also are examined PM2. 5/PM10 ratios, which could provide useful information on PM emissions contributions. In order to assess the cause of the increase of DNC and DND cases during the 6th and especially the 7th epidemic COVID-19 waves in Tokyo, a comparative per-waves analysis of the cumulative environmental factors (climate and air pollutants) effects on the COVID-19 daily incidence and mortality is achieved. The main investigated climate parameters (daily air temperature, maximum air temperature, relative humidity, pressure, wind intensity and direction, rainfall rate, global horizontal surface solar irradiance, Planetary Boundary Layer height - PBL, synoptic meteorological circulation, and eight days land surface temperature- LST) are quantitatively analyzed, in order to provide information to further improve air pollution and prevent the spreading of pathogens for future pandemic infections. In spite of scientifically debated, associations between SARS-CoV-2 viral infection transmission and environmental factors, this study aims to reveal the role of air pollution, synoptic atmospheric circulation and Planetary Boundary Layer height variability and urban heat waves impacts on COVID-19 incidence and severity in Tokyo. Also, the findings of this study are expected to make a significant contribution to the existing literature in the field of environment-epidemiology interaction for Tokyo, Japan's Greater Metropolitan Area, and to provide comprehensive information to decision-makers' authorities for future preventive strategies design and sustainable planning of air quality management and urban heat improvement in Tokyo, and other megacities for the epidemic controls.

2. Data & methods

2.1. Study area description

If Japan extends from 20° to 45° N Latitude (Okinotorishima to Benten-Jima) and from 122° to 153° E Longitude (Yonaguni to Minami Torishima), Tokyo, the largest metropolis in the world, and the capital city of Japan is located in the Northern part of Tokyo Bay in Tokyo prefecture, and in the Southern coastal area of Honshu Island at 35°41ˋ23ˋˋ N Latitude and 139°41ˋ32″ E Longitude. In the upper part Fig. 1 presents the location of Tokyo on the Japan map, and in the lower part Tokyo metropolis urban structure with residential, commercial and industrial components. Tokyo metropolis has an area of 2194 km^2, and an elevation of 40 m, and 13.96 million people in 2021 year. Also, Tokyo includes five towns, 26 more cities, and eight villages, each of which with a local government. Greater Tokyo Metropolitan Area, one of the largest urbanized areas in the world, is placed in the Kanto Plain of the

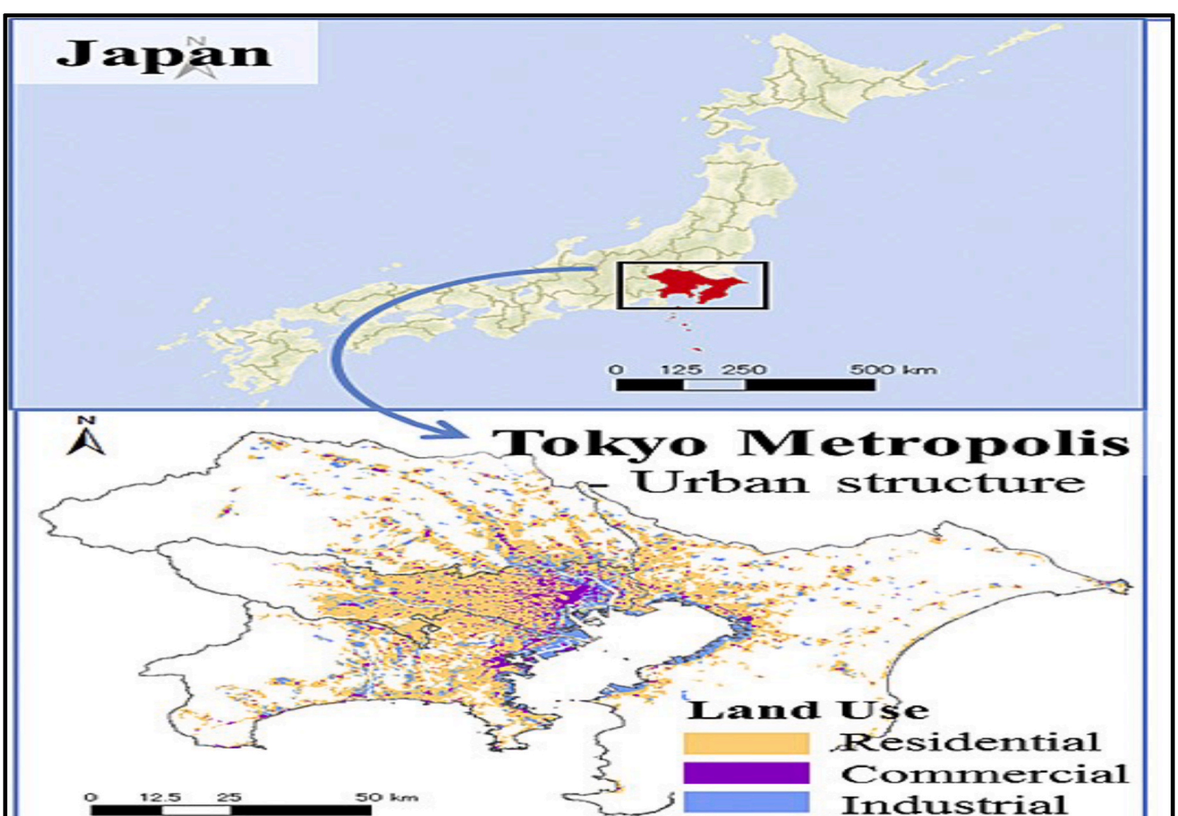

Fig. 1. Study test site Tokyo metropolis, capital of Japan.

main island of Japan and includes Tokyo metropolis, Kanagawa Prefecture, Saitama Prefecture, and Chiba Prefecture with a total area of 13,562 km^2 and its population of more than 38 million (UN, 2019). Tokyo metropolis has a peculiar humid subtropical climate with hot, humid summers and mild to cool winters with occasional cold spells.

The region, experiences the warmest month August, which averages 26.4 °C, and the coolest month January, averaging 5.2 °C. Yearly average rainfall is about 1530 mm, with a drier winter and a wetter summer. Spatiotemporal variations in precipitation levels depend predominantly on the activities and tracks of mid-latitude disturbances and tropical cyclones, which means that an urban effect is not easily detected in long-term observational data (Kim et al., 2022). Tokyo also often experienced large-scale circulation anomalies associated with extreme climate events like Heat Waves (HWs) and typhoons every year, though few are strong (Noh et al., 2021; Xu et al., 2019; Seino et al., 2018).

Tokyo is located in a polluted background with various significant PM2.5, PM10, O3, and NO2 sources surrounding it within about a 100 km radius (Damiani et al., 2022). While urbanization has accelerated the conversion of vegetated land covers to built-up areas, the effects of green vegetation as biofilters for particulate matter have been reduced (Lee et al., 2022), urban green and blue spaces being inversely associated with pandemic COVID-19 incidence and mortality (Peng et al., 2022; Ciupa, 2023; Falco et al., 2023). Also, as a consequence, the urban land surface temperature increased (Zaitunah et al., 2022) in annual mean at the rate of 3.0 °C/century during the 1901–2015 period (Matsumoto et al., 2017).

2.2. Data sets

The daily time series analysis of climate and air pollutants seasonality in relation to COVID-19 incidence and mortality in the Tokyo metropolitan region used a large global dataset built by collecting information from various freely available sources from January 2020 up to the end of the 2022 year. We applied an integrated approach that exploits various independent datasets retrieved from observational in-situ networks and satellite platforms.

2.2.1. COVID-19 data

This study uses the COVID-19 incidence and lethality data cases recorded in Japan and Tokyo (Total cumulative, Daily New Cases-DNC, Daily New Deaths-DND and Total Deaths) provided by COVID-19 information websites (Worldometer Info, 2022; Johns Hopkins Coronavirus, 2022; and Statista, 2022; WHO, 2022; Japan COVID-19, 2023; Tokyo, 2023; MHLW, 2022).

2.2.2. Satellite and reanalysis data

Synoptic meteorological conditions over the Tokyo metropolitan area during the entire analyzed COVID-19 pandemic period was provided by NCEP/NCAR Reanalysis Intercomparison Tool/NOAA/ESRL Physical Sciences Laboratory, Boulder Colorado, USA (NOAA, ESRL, 2022) by composite anomaly surface charts of 500 hPa geopotential heights, representing airflow at a height of approximately 5500 m height above the ground for monitoring of atmospheric circulation variability elements. According to meteorological information of daily geopotential height charts at 500 hPa anomalies, positive anomalies are associated with anticyclones stability, blocking systems with proper conditions for air pollutants and bioaerosols accumulation near the ground, while negative anomalies are specific for cyclones conditions and dissipation of air pollutants and bioaerosols (Sofiev et al., 2022; Danko et al., 2021). Such information is useful for the analysis of lower atmospheric circulation conditions associated with people's exposure to air pollutants and COVID-19 viral disease spreading in Tokyo during 1 January 2020–October 1, 2022.

Also, this study used time-averaged charts of monthly PBL heights 0.5 × 0.625 deg. [MERRA-2 Model M2TMNXFLXv5.12.4] m provided by National Aeronautics and Space Administration (NASA) Geospatial Interactive Online Visualization and Analysis Infrastructure (Beaudoing, H. and M. Rodell, NASA/GSFC/HSL, 2020; Giovanni, 2022) GIOVANNI portal. MERRA-2 (Modern-Era Retrospective Analysis for Research and Applications) is the latest reanalysis NASA's (Buchard et al., 2017; Randles et al., 2017) that provides an aerosol product with resolution 0.625 × 0.5° and 72 vertical layers from the surface to approximately 80 km. The monthly MODIS-AOD data were acquired through the National Aeronautics and Space Administration (NASA) Geospatial Interactive Online Visualization and Analysis Infrastructure (Giovanni, 2023) portal. The retrieved MODIS Terra/Aqua AOD data are a level-3 gridded atmosphere joint product with a resolution of 1° × 1° grid average values of atmospheric parameters (Acker and Leptoukh, 2007). Also, this paper used (MERRA-2) derived at 3 h AOD at 550 nm product provided by NASA and Copernicus Atmosphere Monitoring Service (CAMS) (MERRA, 2022; CAMS, 2022). In the following analysis, we employed daily time series of climate data, including air average temperature (T) at 2 m height, maximum temperature (Tmax), air relative humidity (RH), air pressure (p), average wind speed intensity (w), and wind direction and Planetary Boundary Layer height (PBL) for Tokyo metropolitan region from MERRA-2Version 2 (MERRA, 2022).

The NASA MODIS (Moderate Resolution Imaging Spectroradiometer) Terra/Aqua satellites collects remotely sensed diurnal and nocturnal land surface temperatures LST. While MODIS Terra's orbit around the Earth passes from North to South across the equator in the morning, MODIS Aqua passes South to North over the equator in the afternoon. Land surface temperature (LST) data for the Tokyo metropolis located centered Latitude 35.683 N and Longitude 139.759 E have been provided by Terra MODIS/VIIRS Land Products Global Subsetting Tool at the ORNL DAAC, MOD11A2 LST_Day_1 km and MOD11A2 LST_Night_1 km (ORNL, 2018; Hulley and Hook, 2021).

2.2.3. Air pollutants and meteorological observational data

Daily average time series data of air pollutants concentrations PM2.5, PM10, O_3, and NO_2, for Tokyo metropolitan selected stations have been collected from AQICN (AQICN, 2022). Daily time series of meteorological data, including average air temperature (T) at 2 m height, maximum air temperature (Tmax), air relative humidity (RH), air pressure (p), average wind speed intensity (w) and direction have been collected from both Weather Wunderground (Weather Wunderground, 2022), Copernicus Climate Change Service (C3S) datasets (Copernicus, 2022) and weather stations operated by Japan Meteorological Agency (JMA, 2022).

2.3. Methods

Data on air pollutants, meteorological and epidemiological variables were processed in the time series analyses to provide useful insights for decision-making concerning the COVID-19 pandemic. In order to establish the particulate matter emission sources' contribution at total air pollution, PM2.5/PM10 ratios have been evaluated. For lower contributions of fine particles (PM2.5) as compared to coarse particles PM10, PM2.5/PM10 ratios are less than 0.5. While PM2.5 particles are considered a proxy of exhaust emissions, PM10 particles describe non-exhaust contributions. Identifying the synoptic weather and large-scale circulation patterns represents a useful method of studying air pollution problems. The synoptic weather conditions are sometimes associated with periods of high PM2.5 and PM10 concentrations.

2.3.1. Statistical analysis

This study analyzed the daily and monthly time-series environmental variables (main air pollutants and climate) drivers' impact on the incidence and mortality of the COVID-19 pandemic in Tokyo metropolis during COVID-19 multiwaves evolution. The comparative analysis of the daily, monthly, and annual average concentrations of the main air pollutants (PM2.5, PM10, O_3, NO_2) during COVID-19 multiwaves was done related to available average concentrations recorded during the same time windows of pre-pandemic years (2015–2019). For transient correlations was used descriptive statistical analysis, that identify similar variations in the daily average time series climate parameters and exposure to air pollutants (considered independent variables) data, together daily COVID-19 incidence and mortality data (considered dependent variables) over the seven COVID-19 waves during March 1, 2020 and October 1, 2022. To evaluate the similarity between two-time series data, and to explore the relationship between combined daily air pollutants concentrations (PM2.5, PM10, O_3, NO_2), AOD and the main climate parameters with the daily of daily new COVID-19 cases (DNC) and daily new COVID-19 deaths (DND) was used cross-correlation analysis. Also, the normality of data was evaluated through Kolmogorov-Smirnov Tests for daily time-series data sets.

Because the DNC shows a non-normal distribution, Spearman rank correlation was adopted to identify the existing correlations with selected independent variables. The sign orientation and the strength of the interactions between pairs of variables is measured by *r*, Spearman rank correlation index expressed by equation (1):

$$r = 1 - \frac{6 \times \sum d_i^2}{n(n^2 - 1)} \quad (1)$$

where d_i is the difference between the two parameter ranks, n is the number of alternatives, and the values r = +1 and −1 show perfect positive, and respectively negative correlations, while 0 shows no correlation. The corresponding „p-value" parameter shows the statistical significance the result. P values of <0.01 and < 0.05 are considered statistical significant. Though correlation and p-value provide us with the existing relationship between the two variables, care should be taken to interpret them correctly. Our performed analysis adopted non-parametric statistical tests, that are more suitable compared with parametric statistical tests for non-normally distributed data, which are present in our daily time series air pollutants and meteorological parameters data. All statistical analyses in this study were processed with ORIGIN 10.0 software, version 2021 for Microsoft windows.

2.3.2. Change detection analysis

The annual mean percentage difference among the analyzed air pollutants concentrations (PM2.5, PM10, O_3 and NO_2) and total AOD at 550 nm between 2015 and 2019 averaged and the annual mean values for 2020, 2021 and 2022 years were computed using Eq. (2) (Hu et al., 2021):

$$Percentage\ Change(\%) = \frac{Annual\ Mean\ Value - Mean\ Value\ (2015 - 2019)}{Mean\ Value\ (2015 - 2019)} x100(\%) \quad (2)$$

where Annual Mean Value coresponds to annual mean monthly value of each considered air pollutant concentration or annual monthy average of total aerosol optical depth at 550 nm for respectively 2020, 2021 and 2022 years. Mean Value (2015–2019) represent the average value for air pollutants concentrations or AOD values during five previous years period. We compared concentrations of the main atmospheric constituents to measure the effects and significance of the pandemic, of the previous five years and during the lockdown.

3. Results and discussion

3.1. Infection status of COVID-19 pandemic in tokyo

As a pandemic hotspot in Japan, between March 1, 2020 and October 1, 2022 Tokyo metropolitan region in Japan experienced seven COVID-19 waves with increased incidence rates during the 6th and 7th waves. From November 2022 until February 2023 Tokyo is experiencing the 8th wave of infection with high transmissibility of new Omicron variants XBB and BQ.1 of SARS-CoV-2. Fig. 2 presents the pandemic shape of COVID-19 in Tokyo metropolis until February 2023. As is seen in

Table 1
Declared state of emergency (SoE) periods in Tokyo during COVID-19 pandemic.

SoEs	Starting Dates	Ending Dates
1st SoE	April 7, 2020	May 25, 2020
2nd SoE	January 8, 2021	March 21, 2021
3rd SoE	April 25, 2021	June 20, 2021
4th SoE	July 12, 2021	September 30, 2021
5th SoE	Jan 2022	March 21, 2022

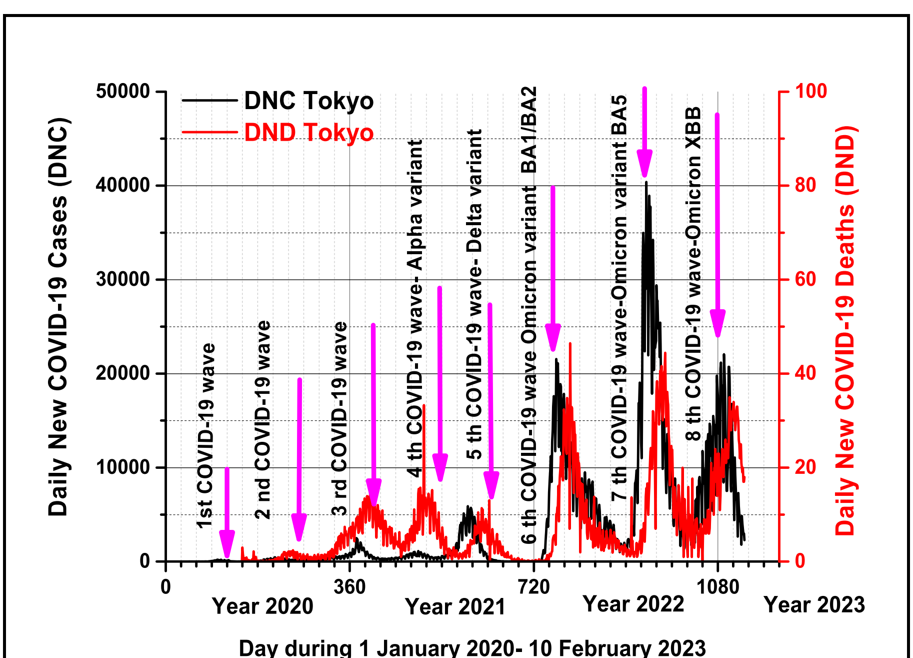

Fig. 2. Temporal evolution of COVID-19 multiwaves in Tokyo metropolis during January 2020–10 February 2023.

Table 1, between 2020 and 2022, during the COVID-19 pandemic in Japan, the Japanese Government imposed five states of emergency declarations (SoE) in each of its 47 prefectures (Ghaznavi et al., 2023). However, the public health interventions for the COVID-19 pandemic may have effectively prevented the transmission of most droplet-transmitted diseases and those transmitted through other routes (Hibiya et al., 2022). During the 2022 year, 'the quasi-States of Emergency have been adopted. However, due to increased protection measures against the COVID-19 pandemic including physical distancing, hygiene measures, and lifestyles, the synergic incidence of non-COVID-19 infections significantly decreased in Japan prefectures including in Tokyo metropolitan area (Yan et al., 2022; Kanda et al., 2023).

Before the implementation of the massive coronavirus disease vaccination campaign in 2021 year, Japan experienced three COVID-19 epidemic waves (Matsunaga et al., 2022). During Tokyo Olympic Games held in Tokyo, Japan from 23 July to August 8, 2021, the 5th COVID-19 wave, the new Delta viral variant (B.1.617.2) was active. It seems that the effect of the Olympic Games on the spread and decay of the pandemic wave was neither dominant nor negligible due to the shifting of the national holiday dates to coincide with the Olympic Games (Hirata et al., 2022; Hester et al., 2021; Ito K.et al., 2021; Jung et al., 2022). Summer 2022 was the first summer in three years in which Japan has not implemented a COVID-19 state of emergency, or restrictions to curb the spread of the virus. As the heat wave from late June 2022 subsided, an unprecedented "7th wave" of COVID-19 was raising concerns about the healthcare system and emergency services in parts of the country. It seems that the factors involved in the summer 2022 with high transmission rates of BA.5 and BA.2 subvariants of the Omicron variant of the virus may be attributed also to an increase in public gatherings, and waning immunity.

3.2. Air pollutants impacts on COVID-19 multiwaves in Tokyo

In Greater Tokyo Area, the change in people's mobility was smaller and more gradual compared to other worldwide countries because of avoidance of adopted strict legal restrictions, showing the largest mobility drop during the weekends, with decreases about 10% larger than on weekdays. (Sugawara et al., 2021; Damiani et al., 2022). However, the implemented COVID-19 pandemic lockdowns during States of Emergency (SOEs) in Tokyo (Table 1) led to a sharp drop in socio-economic activities, including reductions in fossil fuel use, industry productions, and traffic volumes. For the entire COVID-19 analyzed period in Tokyo this study found positive Spearman rank correlation between exposure to high concentrations of daily average PM2.5 and the daily new COVID-19 cases (DNC) ($r = 0.42$, $p \leq 0.05$), but non-significant correlation with daily COVID-19 deaths (DND). This result may support the hypothesis that air pollutants especially particulate matter are dominant carriers of infectious pathogens, and chronic exposure under proper climate conditions might lead to more severe and lethal forms of COVID-19, playing a critical role in the spread of disease. The finding is similarly with results reported by other epidemiological studies, air pollution especially with PM2.5 particles in large urban areas may be associated with worse COVID-19 outcomes (Ali and Islam, 2020). A possible explanation may consider that both short-term and long-term exposure to high concentrations of ambient fine and coarse particles may enhance virus-induced lung inflammation and damage, and their contribution to COVI-19 pathogenesis (Leirião et al., 2022; Feng et al., 2022; Domingo et al., 2020; Marquès et al., 2021; Huang et al., 2020).

Using the observational data across the Tokyo metropolis from January 1, 2020 to October 1, 2022 the present study found an average ratio PM2.5/PM10 of (0.319 ± 0.164), less than 0.5, that suggest the dominance of coarse particulate matter fraction in Tokyo metropolis attributed to non-exhaust contributions. According to a previous study in Tokyo and Japan over the past 30 years was established that in spite of the decreasing trends of surface PM2.5 concentrations, the highest reduction was found in elemental carbon component of PM2.5, while organic carbon was not changed significantly compared to other components, suggesting that especially VOCs species in traffic and heavy industries related emissions, need to be reduced in both urban and periurban sites of Tokyo metropolis (Ito et al., 2021a; Hsi-Hsien et al., 2020; Fukusaki et al., 2021). Like other studies (Kaneyasu et al., 2020), our results show that PM2.5 concentrations are high in winter to spring (often caused by transboundary air pollution besides urban pollution) and low in summer, while PM10 concentrations are high in winter and spring, and low during summer and autumn seasons (Fig. 3) (Nakata and Deng, 2020; Ito et al., 2021b). Differently, the assessed PM2.5/PM10 ratios are the highest in winter and the lowest in spring. Because PM2.5/PM10 ratios show strong independence on PM2.5 and PM10, it can provide extra useful information about the type of aerosol pollution, findings that are in good accordance with the existing literature in the field (Nakata and Deng, 2020; Panko et al., 2019). The findings in Table 2 present the annual means of the surface levels of air pollutants PM2.5, PM10, O3, and NO2 in the Tokyo metropolitan area in the pre-pandemic period 2015–2019 and during the 2020–2022 pandemic period with COVID-19 restrictions. For the 2020–2022 pandemic period in Tokyo metropolis (considering the urban and surrounding domains) the percentages of annual concentrations of PM2.5, PM10, O3, and NO2 relative to the 2015–2019 period are presented in Table 3 showing a clear decrease pattern of PM2.5 for the 2021 year (−62.26%), (−10.22%) for the 2020 year and only (−00.39%) for the 2022 year, while the annual percentage changes for PM10 show a lower decrease trend for 2020, 2021 and 2022 years respectively of (−4.42%, −3.95% and −5.76%). These decreased trends of PM2.5 and PM10 at the ground level concentrations recorded during 2020–2022 period have been associated with adopted COVID-19 restrictions in Tokyo metropolis. Also, our results highlight the increasing trend of the ozone ground levels during the pandemic period from 10.01% in the 2020 year with the spring lockdown, to 13.74% in 2021 year, and 27.09% in 2022 year. An inverse relationship was found in the case of nitrogen dioxide which has a decreasing trend of (15.30%, 17.58%, and 28.57%) respectively for the years 2020, 2021, and 2022, results that are concordant with other findings in the literature (Ghasempour et al., 2021; Anbari et al., 2022; Zoran et al., 2020a; Cooper et al., 2022).

In spite of the reduced fossil fuel use, industry productions, and traffic volumes during COVID-19 restrictions periods in Tokyo, due to unfavourable meteorologic conditions percentage changes of air quality variables were not so high like in other worldwide metropolitan cities (Fu et al., 2023; Wen et al., 2022; Zoran et al., 2020b, 2021; Xiang et al., 2020; Pal et al., 2021; Ravina et al., 2021).

A detailed cumulative statistics analysis of the total daily new COVID-19 incidence and deaths cases per waves periods, and the daily average of AOD and the main air pollutants concentrations, recorded during 1 March 2020–October 1, 2022 in Tokyo metropolitan city is illustrated in Table 4.

A significant result of this study confirms the strong COVID-19 viral disease response to high daily average PM2.5 concentrations (16.95 ± 7.94) $\mu g/m^3$ and high value of PM2.5/PM10 ratio (0.40), associated with the highest numbers of total DNC (1,584,940) cases and total DND (1,728) deaths recorded in Tokyo during the 7th COVID-19 wave period. Besides coexistance of persistent heat waves, this finding may be partially explained through contribution of PM2.5 particles as a main potential airborne transmitter of SARS-CoV-2 and its new variants pathogens, hypothesis sustained by several experimental works (Setti et al., 2020a, 2020b).

Nitrogen dioxide (NO_2) related to fossil fuel combustion due to urban traffic and thermal power plants is among the main drivers of air quality degradation. Several epidemiological studies have shown that nitrogen dioxide (NO_2) exposure is often associated with adverse health effects such as lung cancer, asthma, and cardiopulmonary mortality (Wang et al., 2020; Berg et al., 2021). Based on the average of in-situ

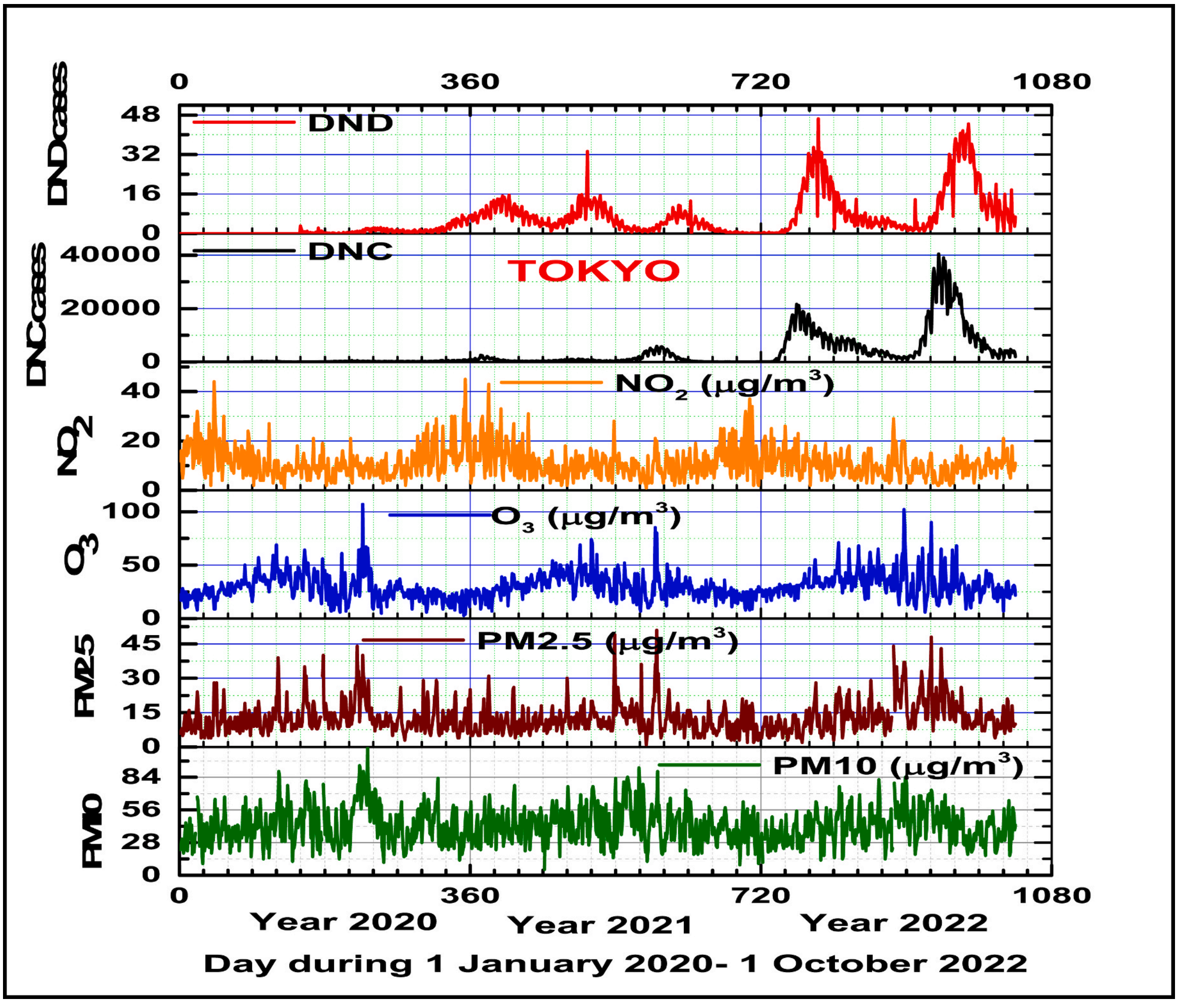

Fig. 3. Temporal patterns of the daily average surface levels of PM2.5, PM10, NO_2 and O_3 concentrations in relation with the daily new confirmed COVID-19 cases (DNC) and daily new COVID-19 deaths (DND) during the entire analyzed COVID-19 pandemic period in Tokyo metropolis.

Table 2
The annual means of the ground level air pollutants in Tokyo metropolitan area during pre-pandemic period (2015–2019) and during pandemic (2020–2022) period with COVID-19 restrictions.

Ground level air pollutants in Tokyo Year	Annual Mean AOD 550 nm	Annual Mean concentration PM2.5 (µg/m^3)	Annual Mean concentration PM10 (µg/m^3)	Annual Mean concentration O_3 (µg/m^3)	Annual Mean concentration NO_2 (µg/m^3)
2015	0.229	29.52	91.42	54.9	26.8
2016	0.258	25.14	88.84	51.16	27.46
2017	0.244	28.04	84.42	50.57	29.12
2018	0.223	30.87	92.01	51.9	28.23
2019	0.251	28.83	87.18	52.8	27.19
Average 2015–2019	0.241	28.48	88.774	52.266	27.76
2020	0.263	25.57	84.85	57.5	23.52
2021	0.225	23.20	85.26	59.45	22.88
2022	0.212	28.37	83.66	66.43	19.83

Table 3
The percentage changes of AOD, PM2.5, PM10, O_3 and NO_2 during 2020–2022 pandemic period in Tokyo metropolis.

Year	Percentage Change AOD 550 nm (%)	Percentage Change PM2.5 (%)	Percentage Change PM10 (%)	Percentage Change O_3 (%)	Percentage Change NO_2 (%)
2020	**9.13**	**−10.22**	**−4.42**	**10.01**	**−15.30**
2021	**−6.64**	**−62.26**	**−3.95**	**13.74**	**−17.58**
2022	**−12.03**	**−00.39**	**−5.76**	**27.09**	**−28.57**

observational data at air pollution network stations in Tokyo metropolis, during the lockdown from April–May 2020, NO_2 experienced a decrease of 15.30% compared to the previous year, similar to other studies from satellite data found for Tokyo a value of 19% decrease (Ghahremanloo et al., 2021; Damiani et al., 2022).

In order to interpret the results in this study, we consider that during the COVID-19 pandemic, the outdoor and indoor inhalation of virus-laden particles PM2.5 and PM10 are irritant factors of human airways modifying different immune defense responses against bacterial and viral infections (Kayalar et al., 2021; Tao et al., 2022; Sidell et al., 2022).

Table 4
Cumulative statistics of the total daily new COVID-19 incidence and deaths cases per waves periods, and the daily average of main air pollutants concentrations, recorded during March 1, 2020–1 October 2022 in Tokyo metropolitan city.

Time period	Daily New COVID cases (DNC)	Daily New COVID Deaths (DND)	Daily average ± SD PM2.5 (μg/m^3)	Daily average ± SD PM10 (μg/m^3)	PM2.5/PM10	Daily average ± SD O_3 (μg/m^3)	Daily average ± SD NO_2 (μg/m^3)	Daily average ± SD PBL height (m)
First COVID wave 1 March 2020–1 June 2020	5207	5	11.78 ± 5.15	41.97 ± 14.63	0.28	35.86 ± 9.29	9.87 ± 4.72	824.6 ± 62.03
Second COVID wave 1 July 2020–1 October 2020	19,741	76	15.22 ± 7.45	48.2 ± 20.16	0.32	28.18 ± 16.28	8.73 ± 3.59	652.58 ± 105.07
Third COVID wave 1 December 2020–1 March 2021	70,854	739	11.02 ± 5.97	40.18 ± 13.15	0.27	23.05 ± 8.35	16.53 ± 8.48	890.17 ± 16.63
Fourth COVID wave 1 April 2021–1 July 2021	52,923	721	13.5 ± 6.2	45.42 ± 15.28	0.30	38.3 ± 11.6	9.68 ± 4.34	792.41 ± 65.09
Fifth COVID-19 wave 1 July 2021–1 October 2021	205,766	373	13.45 ± 7.69	47.71 ± 18.18	0.28	29.23 ± 12.82	8.76 ± 4.36	650.08 ± 49.29
Sixth COVID-19 wave 1 January 2022–April 1, 2022	875,450	1252	10.66 ± 5.63	37.99 ± 13.29	0.28	32.32 ± 8.24	11.69 ± 4.92	894.61 ± 91.18
Seventh COVID-19 wave 1 July 2022–October 1, 2022	1,584,940	1728	16.95 ± 7.94	42.87 ± 14.15	0.40	32.06 ± 15.0	8.35 ± 8.64	657.40 ± 26.1

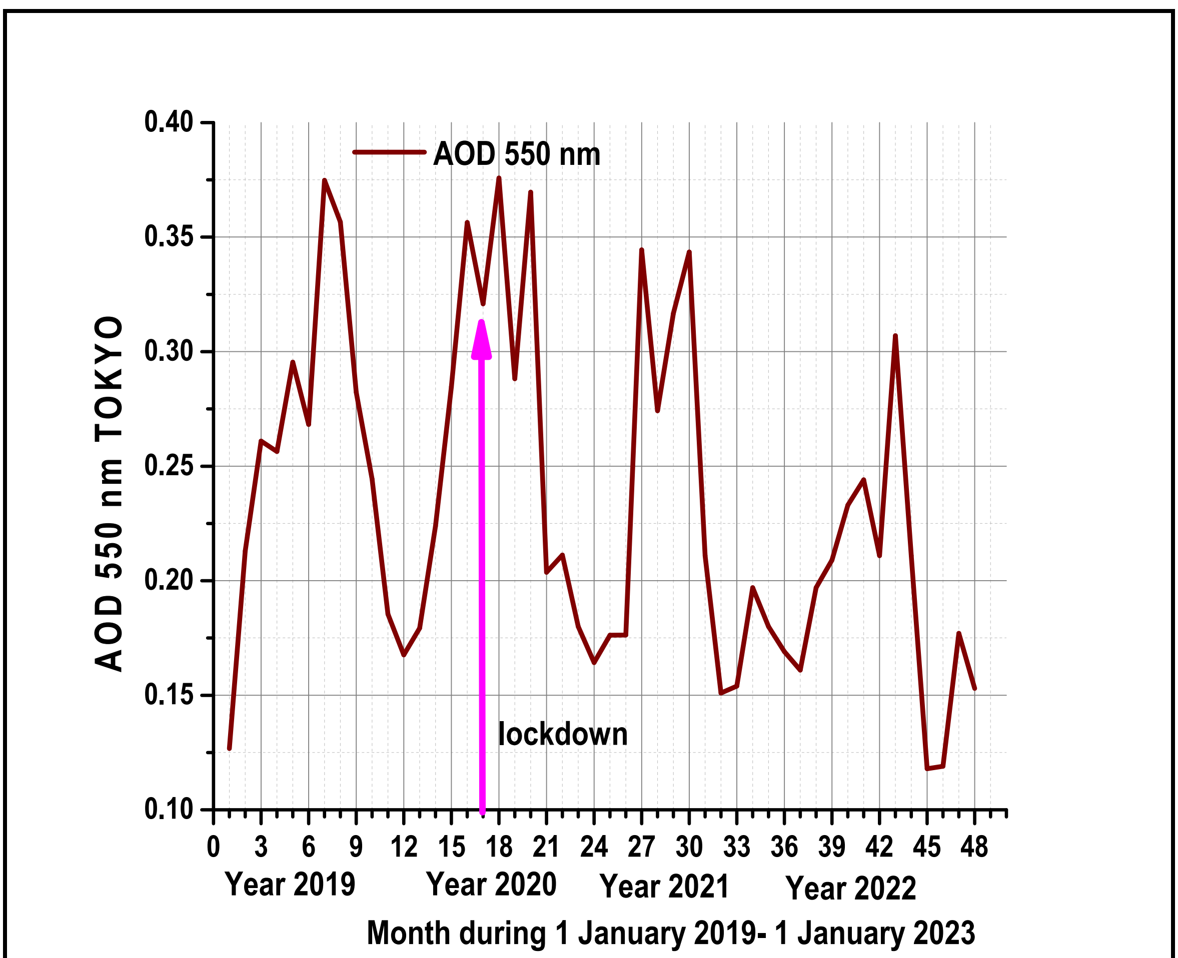

Fig. 4. Temporal pattern of mean monthly Total Aerosol Optical Depth at 550 nm over Tokyo metropolis during 2019–2022 years.

Association with the increased permeability in the respiratory tract by reducing tight junction proteins results in a higher penetration of SARS-CoV-2 in the different regions of the cardiorespiratory system (Baker, 2000; Shahbaz et al., 2021). It is considered that the human immune response to SARS-CoV-2 pathogens determines different degrees of COVID-19 infection severity, while genes related to the initial stages of infection, regarding the binding to the cell receptors and entry into the respiratory system, determine different susceptibilities to SARS-CoV-2 (Anastassopoulou et al., 2020).

3.3. *Aerosol Optical Depth analysis during COVID-19 pandemic multiwaves in Tokyo*

Under imposed restriction periods during the State of Emergency (SOEs), insignificant or worsened air quality conditions were observed from AOD at 550 nm monitoring in Tokyo (Table 2). The annual percentage of AOD change were increased during 2020 b y 9.13%, while in 2021 and 2022 years decreased by 6.64% and 12.03% respectively relative to annual average (2015–2019).Similar results have been reported by other studies for Tokyo (Ghahremanloo et al., 2021; Papachristopoulou et al., 2022).

Over the entire analyzed pandemic period in Tokyo the daily new COVID-19 new cases and deaths were low positively correlated with daily PM2.5/AOD and PM10/AOD ratios (rDNC = 0.21, $p \leq 0.05$; and rDNC = 0.19, $p \leq 0.05$), and respectively DND cases with daily PM2.5/AOD and PM10/AOD ratios (rDND = 0.18, $p \leq 0.05$; rDND = 0.24, $p \leq 0.05$).

However, the trends of AOD interannual and intraannual (seasonal) variability declined during COVID-19 pandemic relative to the previous pre-pandemic period in Tokyo. As can be seen in Fig. 4, total AOD at 550 nm exhibits strong seasonal and interannual variability in Tokyo megacity, higher values of the monthly mean AOD can been seen during spring-summer seasons, with respect to the surrounding area, and lower values during autumn-winter periods. As urban traffic in Tokyo metropolis is one of the main sources of outdoor air pollutants at the surface level, adopted lockdown in the 1st COVID-19 wave between 7

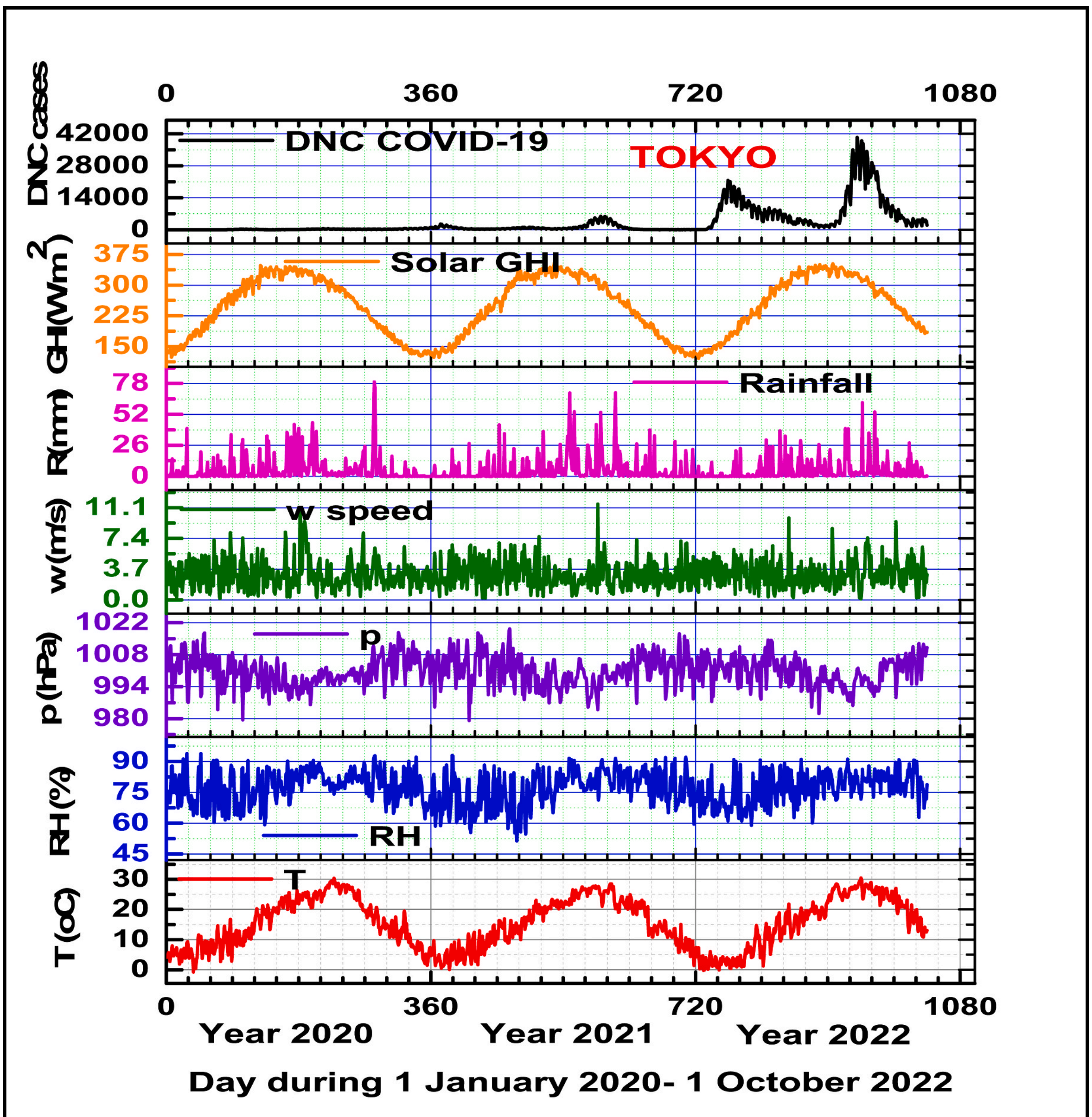

Fig. 5. Temporal patterns of the daily average air temperature at 2 m height, relative humidity, atmospheric pressure, wind speed intensity, rainfall, and surface solar irradiance in relation with daily new COVID-19 positive cases (DNC) during the seven COVID-19 pandemic waves in Tokyo metropolis.

April 2020–25 May 2020 did not significantly change AOD levels. However, in Japan, the transboundary transportation of high-concentration PM2.5 was widely reported (Mori et al., 2020).

Local and regional climate seasonal variability and desert dust transport have a high impact on aerosol load of the atmospheric column (Che et al., 2019; Gupta et al., 2022; Logothetis et al., 2021; Xiao et al., 2023). Our results are in a good agreement with other studies, which based on satellite-derived AOD at 550 nm trends against those obtained from groundbased AERONET data found for the megacity of Tokyo a spatiotemporal, intraannual and interannual AOD variability with a decreasing trend of averaged AOD for the broader area of Tokyo during the long-term (2003–2020) annual averaged period (Papachristopoulou et al., 2022).

3.4. Effects of climate parameters variability on COVID-19 multiwaves pattern

Local and regional topography and meteorological factors influence the evolution of Planetary Boundary Layer heights profiles and the associated peculiar atmospheric stability conditions in Tokyo metropolis. Selected available daily average of meteorological parameters, such as air surface temperature at 2m height (T), relative humidity (RH), pressure (p), wind speed (w) and wind direction, rainfall (R), surface solar irradiance (GHI) and Planetary Boundary Layer height (PBL) were selected to study their effects on COVID-19 waves pattern in Tokyo metropolitan region. The daily time series of selected meteorological parameters were plotted against the corresponding COVID-19 waves. The obtained results are presented in Fig. 5. Analysis of the time-series meteorological data during 1 January 2020–October 1, 2022 in relation with DNC and DND cases in Tokyo may provide useful infrmation on the role of climate varibility and true seasonal signatures on SARS-CoV-2 pathogens.

Low significant positive Spearman rank correlations between the (DNC) COVID-19 cases and air temperature at 2 m height ($r = 0.57$; $p \leq 0.05$), and respectively air pressure ($r = 0.26$; $p \leq 0.05$), have been found in this study. Atmospheric pressure is inversely correlated with air temperaure ($r = -0.46$; $p \leq 0.05$). In spite of being a debated issue, contrarly to other studies (Xiao et al., 2021; Tian et al., 2021; Srivastava, 2021; Jiang et al., 2021; Sanchez-Lorenzo et al., 2021; Li et al., 2020; Benedetti et al., 2020; Bolaño-Ortiz et al., 2020), and similary to other works (Menebo, 2020; Li H. et al., 2020; Zhu and Xin, 2020; Bashir et al., 2020; Xie and Zhu, 2020; Pani et al., 2020; Islam et al., 2021; Xia et al., 2022), this study found for the entire COVID-19 pandemic in Tokyo a positive relationship between air temperature and incidence of COVID19 cases.

Due to the reduction of anthropogenic heat release, a recorded negative anomaly of the mean daily air temperature of (0.5 °C), and (0.7 °C) in the nighttime, larger than in the daytime, and extended for several tens of kilometers (Fujibe, 2020) was registered during the first SoE and COVID-19 lockdown in Tokyo in the spring of 2020. This information, together with cyclonic atmospheric conditions may explain our finding related to the lower COVID-19 incidence and mortality in Tokyo during the 1st wave.

Also, similar to some paper's results (Nottmeyer et al., 2023), and contrary to other papers (Zoran et al., 2021) this study found a positive Spearman rank correlation association ($r = 0.38$; $p \leq 0.05$) between the DNC COVID-19 cases and surface global horizontal solar irradiance (GHI). This finding was unexpected because UV solar radiation is considered to be a virus inactivation factor (Herman et al., 2020; Heβling et al., 2020; Schuit et al., 2020; Biasin et al., 2021) and solar radiation is increasing vitamin D and immunity system. However, as can be seen from Fig. 5, COVID-19 and climate-driving factors have mutual seasonality patterns in Tokyo.

The wind rose diagram (Fig. 6), that illustrates the frequency of winds blowing from particular directions over the entire COVID-19 multiwaves pandemic and multiseasons analyzed period in Tokyo, shows that was a mixture of wind patterns. The length of each colored bar represents the percent of time the wind blows from that direction. Each bar is subdivided with colors to show wind speed ranges associated with each direction. The highest COVID-19 cases fit in with wind

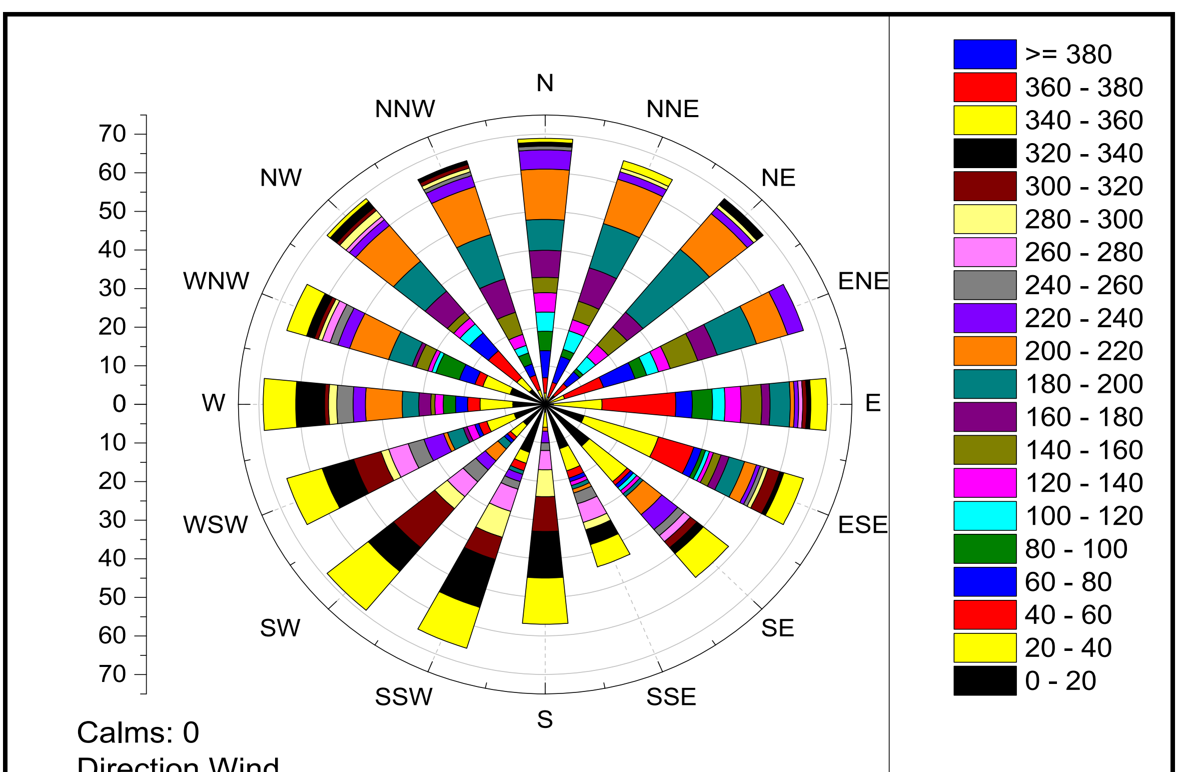

Fig. 6. Wind direction rose distribution and daily frequency over Tokyo metropolis during the analyzed pandemic period 1 January 2020–October 1, 2022.

direction blows, the dominant wind direction in Tokyo blows to the West-SouthWest and North parts of the metropolitan area with a daily average wind speed of (3.08 ± 0.41) m/s in the range of (0.13–11.54) m/s. Function of the concentration and size distribution of virus-laden particles, strong winds may be responsible for spreading and transport over long distances of SARS-CoV-2 pathogens carried by ambient Particulate Matter (PM) of chemical or biogenic compounds, adversely affecting the COVID-19 disease incidence and severity (Dinoi et al., 2022; Kayalar et al., 2021; Asif et al., 2022). Different climate factors can affect the viability of SARS-CoV-2 and its distribution in the urban environment. Under the influence of local and regional climate parameters (air temperature, relative humidity, pressure, wind speed intensity, and direction, Planetary Boundary Layer heights - PBL, surface global horizontal solar irradiance GHI) interannual and interannual variability of the urban lower atmospheric system can be a significant transport vector for airborne microbiome (bacterial, fungal, viral) communities and their seasonal variability in both the concentration and biodiversity (Xia X.et al., 2022; Tignat-Perrier et al., 2020).

Under different synoptic-scale weather patterns, seasonal climate variability at Tokyo metropolitan level is reflected by micro and macro-scale-scale circulation, which modulate regional air quality and mutual interaction with viral infections like COVID-19. Subsequent evolution of Planetary Boundary Layer heights is associated with changes of air pollutants concentrations in the lower atmospheric system, that have a strong impact on viral infections seasonality (Rayan, 2021; Liu et al., 2021; Yuan et al., 2021; Du et al., 2018; Zoran et al., 2021, 2022a; Uetake et al., 2019). This study provides a clear evidence to support the role of air pollution and climate variability factors in the spread of COVID-19 in Tokyo metropolis.

3.5. Heat waves impacts on COVID-19 incidence and severity

Several long term pre-pandemic studies revealed that elevated levels of air pollution are related to heat stress mortality due to cardiovascular and respiratory diseases and associated morbidity (Williams et al., 2018; Gasparrini and Armstrong, 2011; Scortichini et al., 2018). Especially in large metropolitan areas during summer periods and long term human exposure to heat waves (HWs) may be increased the effects of air pollutants high concentrations at the ground levels (Li et al., 2017; Breitner et al., 2014). Also the associated formation of ground-level O_3 in the atmosphere due to high solar irradiance and high temperature may result in the increased risks of cardiorespiratory diseases.

Synergy of COVID-19 pandemic disease with HWs and Urban Heat Islands (UHIs) can amplify the impacts of thermal stress on human body and associated comorbidity and mortality risks. High temperatures and air pollutants may cause synergistic effects through airway irritation and inflammation processes, and decreasing of pulmonary function. Urban large regional differences in heat exposure due to high air temperature and HWs and interactive effects with key ambient air pollutants (PM2.5, PM10, NO_2 and O_3) were observed in countries like Portugal, Spain, the UK, Japan, Germany, Thailand, Kuwait, and Switzerland (Rai et al., 2023; Roye et al., 2021; Pascal et al., 2021; Konstantinoudis et al., 2022). As a key parameter of urban thermal environment, urban heat described by maximum air temperature at 2m height and land surface temperature, represents the combined effect of HWs and UHIs, due to climate change and urbanization. Due to the cumulative effects of climate warming and the increased urbanization, during the summer period of 2022 Tokyo metropolis experienced the co-occurrence of urban heat increase due to strong heat waves (Harmay and Choi, 2022; Wang and He, 2023; Kearl and Vogel, 2023), which function of local climate zones (O'Malley and Kikumoto, 2022; Hatakeyama. , Seposo, 2022) enhanced the UHI in the central part of Tokyo and its surrounding areas, and enhanced impacts of COVID-19 viral infectious disease. The Japan Meteorological Agency (JMA) issued a report based on data from June to August 2022, noting that the average temperature was 0.91 °C warmer than usual, which marked the second highest hot summer after 2010 since record-keeping began in 1898. With nine consecutive days above 35 °C, in June 2022, Tokyo recorded its most severe heat wave (JMA, 2022).

During the 7th COVID -19 wave in Tokyo metropolis, in comparison with the daily mean values recorded for the same periods of time in Tokyo during 2015–2019, this study found for 1 July-1 October 2022 period, that the average daily maximum air temperature at 2m height (Tmax) value was very high (30.85 ± 2.56) ^{o}C in the range of (25–36.11) ^{o}C (Fig. 7), the average daily relative humidity (RH) value was also very high (81.03 ± 4.22) % in the range of (71.7–91.1) %, the average daily air pressure (p) value was very low (994.84 ± 4.05) hPa in the range of (985.77–1004.38) hPa, and the average daily wind speed intensity was also low (3.39 ± 1.73) m/s in the range of (3.05–7.47) m/s, values which may explain favorable conditions for higher heat stress impact on human health and associated decreased human immunity system. However, these findings may explain the interrelationship between urban heat during summer HWs and higher COVID-19 incidence and mortality cases recorded in the 7th wave in Tokyo. Also, as can be seen in Fig. 7 this study found for 1 July-1 October 2022 period the highest 8 Days land surface temperatures (LST) registered by MODIS11A2 Terra LST_Day_1 km satellites products with an average 8 days LST of (40.19 ± 2.71) oC in the range of (35.09–44.73) oC, while from MODIS11A2 Terra LST_Night_1 km satellites products 8 days the average LST was (25.74 ± 2.06) ^{o}C in the range of (21.13–29.07), values associated with the 7th COVID -19 wave in Tokyo metropolis. From Land Surface Temperature (LST) MODIS Terra data for summer 2022, this study found also the highest maximum temperatures (LST_Day_1 km of 42 °C) ever recorded from 2002 year in Tokyo.

In order to explain the highest rates of the 7th COVID-19 DNC and DND cases, this study

analyzed for the entire pandemic period the Spearman rank correlations between air Tmax and LST max with the main air pollutants (PM2.5, PM10, O_3, and NO_2) together with the main climate parameters and DNC and DND COVID-19 cases in Tokyo metropolis (Table 5). Have been underlined the significant positive correlations of Tmax and LSTday max with T (at 2 m), GHI, RH, AOD, PM2.5 and PM10, and negative correlations with NO_2, w, p.

The results in Table 5 show high positive correlations between maximum air temperature at 2 m height (Tmax) and DNC ($r = 0.79$; $p \leq 0.05$) and respectively DND ($r = 0.37$; $p \leq 0.05$). Like other studies (Roshan et al., 2022), the results in this study may suggest that an increase in the air temperature especially during summer heat wave (HWs) events allows an increase in viral infection viability, stability, and survival of SARS-CoV-2 pathogens and transmission of COVID-19.

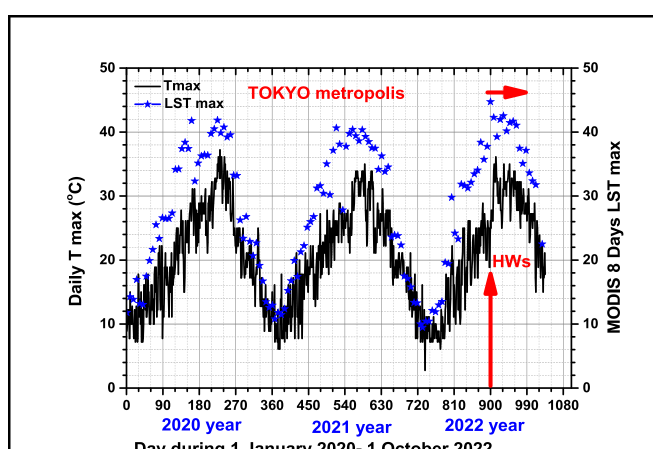

Fig. 7. Temporal patterns of the daily maximum air temperature and 8 days MODIS maximum land surface temperature over Tokyo metropolis during 1 January 2020–October 1, 2022 pandemic period.

Table 5
Spearman rank correlation coefficients and p values, between daily average air Tmax at 2m height, and 8-days maxiumum MODIS LST Day, with the main daily average air pollutants and climate drivers, as well as with DNC and DND COVID-19 cases, for Tokyo metropolis during the entire analyzed pandemic period, 1 January 2020–October 1, 2022.

Tokyo metropolis	PM2.5	PM10	AOD	O3	NO2	T	RH	w	p	GHI	DNC	DND
Tmax	**0.36***	**0.29***	**0.47***	**0.19***	**−0.36***	**0.93***	**0.45***	**−0.28***	**−0.42***	**0.72***	**0.79***	**0.29***
MODIS LST Day max	**0.57***	**0.37***	**0.59***	**0.37***	**−0.39***	**0.91***	**0.49***	**−0.27***	**−0.43***	**0.89***	**0.37***	**0.11****

Note: PM2.5 (Particulate Matter of 2.5 μm size), PM10 (Particulate Matter of 10 μm size), O_3 (ozone), NO_2 (nitrogen dioxide), T air temperature at 2 m height, RH relative humidity, w wind speed intensity, p air pressure, GHI solar global horizontal irradiance, DNC daily new COVID-19 cases, and DND daily new COVID-19 deaths, * indicate $p \leq 0.05$, ** indicate $p \geq 0.05$.

Also, present study clearly evidenced the negative effects of summer high air and urban land cover temperatures in synergy with air pollution on human health, which may exhibit immediate effects on COVID-19 viral infection disease through cardiorespiratory disease severity.

A recent global climate projection for Japan and East Asia forecasted for the next years an increase in heat-related mortality (Madaniyazi et al., 2021, 2022). This hypothesis supports our results, and may explain the hot summer 2022 temperatures' impacts on the highest numbers of daily new cases and deaths DNC and DND recorded in the Tokyo metropolis during the 7th COVID-19 wave. Also, this research suggests that urban heat stress during summer persistent heat waves has a significant impact on COVID-19 viral infection related incidence and mortality, which demands decision makers interventions to improve air quality and pandemic disease control, especially in highly vulnerable population groups.

3.6. Effects of Planetary Bounday Layer heights variability on COVID-19 multiwaves

As Table 6 presents, this study found significant anticorrelations between daily average Planetary Boundary Layer heights over Tokyo metropolitan city and daily new COVID-19 confirmed cases and non-significant correlations with DND cases. Also, PBL heights over Tokyo during the entire investigated COVID-19 period have been anti-correlated with daily average PM2.5, PM10 and total AOD at 550 nm, and positive correlated with daily average at surface level NO_2 concentrations. No significant correlations have been associated with daily O_3 concentrations.

Tables 4 and 5 show clear evidence that during the 7th COVID-19 wave lower PBL heights (657.40 ± 26.21) m associated with higher PM2.5 concentrations (16.95 ± 7.94) μg/m^3 may be associated with high concentrations of SARS-CoV-2 viral pathogens at the near surface, and higher transmission rates, explaining the highest rates of COVID-19 DNC cases (1,584,940) and DND deaths (1,728) registered in Tokyo metropolis.

Inversely, high levels of daily PBL heights of (824 ± 62.03) m and lower levels of PM2.5 concentrations (11.78 ± 5.15) μg/m^3 recorded during the 1st COVID-19 wave in Tokyo may explain the low severity of the 1st COVID-19 wave, with COVID-19 DNC cases (5,207) and DND deaths (5). Our findings confirm that being the lowest part of the troposphere, PBL, which is related to the vertical mixing dynamics and accumulation or dilution of air pollutants and bioaerosols (viruses, bacteria, and fungi) near the ground is directly involved in COVID-19 viral infection spreading, especially in large metropolitan areas (Zoran et al., 2022a; Tang et al., 2016). If the lower levels of PBL heights may be associated with increased viral pathogens concentrations at the near surface, and higher transmission rates, higher levels of PBL heights are responsible for pathogens dilution and lower rates of viral diseases spreading. Seasonal variability of climate parameters and PBL heights are mutually interlinked with SARS-CoV-2 and its new variants' seasonal patterns (Byun et al., 2021; Zoran et al., 2021).

As a marker for urban air quality in Tokyo, especially during cloudy and lower PBL heights PM2.5 and PM10 particles at the surface level, together with other pollutants can increase human vulnerability to viruses reduction of the immune system, and associated risk of pulmonary infections by impairing the function of alveolar macrophages and epithelial cells in the lung (Jerrett et al., 2023; Neupane et al., 2010). Several epidemiological and toxicological studies linked urban air pollution to the risk of cardiorespiratory COVID-19 viral infections, increased morbidities, and mortality (Rebuli et al., 2021; Nobile et al., 2022). Urban PM2.5 particulate matter pollution can be associated with a greater sensitivity of people to airborne viruses, and a greater severity of the pathologies.

3.7. Synoptic atmospheric circulation patterns related to COVID-19 multiwaves in tokyo

During specific local and regional climate conditions, the probability of outdoor airborne diffusion of bioaerosols is the function of virus, bacteria and fungi-laden aerosol concentrations, their viability and lifetime, and the minimum dose to transmit the infectious diseases. During stagnant air and atmospheric inversions over several days with weak horizontal and vertical ventilation over large metropolitan areas are recorded high levels of air pollutants (Chang et al., 2021; Cho et al., 2021; Garrido-Perez et al., 2018; Lu et al., 2021). For this study we used composite anomalies geopotential charts at 500 hPa because these capture atmospheric circulation features associated with high PM concentration days better than surface level measurements (Chang et al., 2021; Jeong et al., 2022).

For the investigated COVID-19 pandemic period (1 January 2020–1 October 2022), have been analyzed synoptic meteorological conditions during each of the COVID-19 multiwaves in Tokyo metropolis (Fig. 8a, 8b, 8c, 8d, 8e, 8f, 8g). The epidemiologic trend of the COVID-19 pandemic disease transmission in Tokyo during the entire investigated period can be uniquely categorized according to the seven different periods, and seven waves and associated or not implemented restrictions (TMG, 2022). Before widespread of coronavirus disease (COVID-19) vaccinations, Tokyo experienced three COVID-19 epidemic waves.

1) A first COVID-19 wave (1 March 2020–1 June 2020)

Table 6
Spearman rank correlation coefficients and p values between daily mean PBL heights and the daily mean of AOD, PM2.5, PM10, O_3 and NO_2 during analyzed period (1 January 2020–October 1, 2022) in Tokyo metropolis.

TOKYO	DNC COVID-19	AOD	PM2.5	PM10	NO_2	O_3
PBL heights	**−0.37***	**−0.52***	**−0.59***	**−0.30.2***	**0.51***	**−0.09****

Note: PM2.5 (Particulate Matter of 2.5 μm size), PM10 (Particulate Matter of 10 μm size), O_3 (ozone), NO_2 (nitrogen dioxide), PBL (Planetary Boundary Layer height), * indicate $p < 0.05$, and ** indicates $p > 0.05$.

2) The second COVID-19 wave (1 July 2020–1 October 2020)
3) The third COVID-19 wave (1 December 2020–1 March 2021)
4) The fourth COVID-19 wave (1 April 2021–1 July 2021)
5) The fifth COVID-19 wave (1 July 2021–1 October 2021)
6) The sixth COVID-19 wave (1 January 2022–April 1, 2022)
7) The seventh COVID-19 wave (1 July 2022–October 1, 2022)

Presently (February 2023) Tokyo experiences the eighth COVID-19 wave, which started on November 1, 2022.

During the first COVID-19 wave in the 500-hPa height field, negative anomalies were seen over Tokyo metropolis with upwards airflows in the upper troposphere, associated with cyclonic meteorological patterns in the mid-troposphere, and instability conditions that are not favorable for COVID-19 disease fast spreading (Fig. 8a). A similar finding was reported by other studies in Europe (Zoran et al., 2022b). These meteorologic specific conditions may explain the low rate of COVID-19 incidence and mortality in Tokyo (Table 4).

During the second (Fig. 8b), the third (Fig. 8c), the fourth (Fig. 8d), the fifth (Fig. 8e), the sixth (Fig. 8f), the seventh (Fig. 8g), COVID-19 waves, NCEP/NCAR Reanalysis Intercomparison Tool provided positive composite anomalous synoptic anticyclonic conditions, with downwards airflows in the upper troposphere of 500 mb geopotential height (m), that suggests proper conditions for air pollutants and SARS-CoV-2 viral pathogens accumulation near the ground, with associated severity of COVID-19 incidence and mortality.

Was found that holding the Tokyo Olympics in the summer 2021 significantly increased the new confirmed COVID-19 positive cases (DNC) during the fifth wave in Tokyo metropolitan region (Esaka and Fujii, 2022).

Also, a clear finding of this study highlights the lack of adopted lockdown or other traffic and travel restrictions for air pollution control during the 7th COVID-19 in Tokyo, which possible could limited viral disease spreading (Wong et al., 2022; Chen et al., 2021; Chinazzi et al., 2020).

Synoptic atmospheric circulation significantly affects particulate matter PM 2.5. PM10 and microbial community concentration variability by modulating wind speed and Planetary boundary Layer height (Lu et al., 2021) on different time scales like as daily, intra-seasonal, and interannual (Chang et al., 2021; Chauhan, Singh, 2020; Cho et al., 2021). Also is well known that stable synoptic conditions, and the contribution of polluted air masses and long-range transported dust are responsible to the occurrence of high COVID-19 microbial episodes in Tokyo. The influence of atmospheric bioaerosols can extend over a wide area, because biological material can be long distances transported by dust particles from the emission source (Xie et al., 2018; Whitehead et al., 2016).

Our results suggest that under stagnant cyclonic atmospheric conditions recorded during the second, third, fourth, and fifth but mostly in the sixth and seventh COVID-19 waves, the aerosolized virus SARS-CoV-2 could remain infectious for extended periods of time in the Tokyo metropolis, explaining the recorded high rates of Daily New COVID-19 positive cases, and higher mortality rates compared with the previous waves. Outdoor short-term and long-term human exposure to air pollutants can increase the susceptibility to morbidity and lethality from respiratory viral infections including COVID-19 disease (Wang Y. et al., 2022; Wang T. et al., 2021; Mu G. et al., 2021; Zhou L et al., 2021; Manoj et al., 2020; Romano et al., 2020; Cohen and Kupferschmidt, 2020; Coccia, 2020). Outdoor exposure to high levels of fine and ultra-fine particulate matter can explain the links with recorded severe pathologies (Bourdrel et al., 2021; Miller M.R., 2020; Baron, 2022; Zang et al., 2022), playing an essential role in increasing the risk of the COVID-19 infection during air pollution episodes in Tokyo due to associated cardiopulmonary and metabolic as comorbidities of COVID-19. As the principal mode by which people are infected with COVID-19 is through airborne transmission not only indoors but likely also outdoors, may explain the COVID-19 mortality increase during high air pollution events and the time-delay of the order of a few days only. Also, the results in this study are consistent with previous studies on the existing

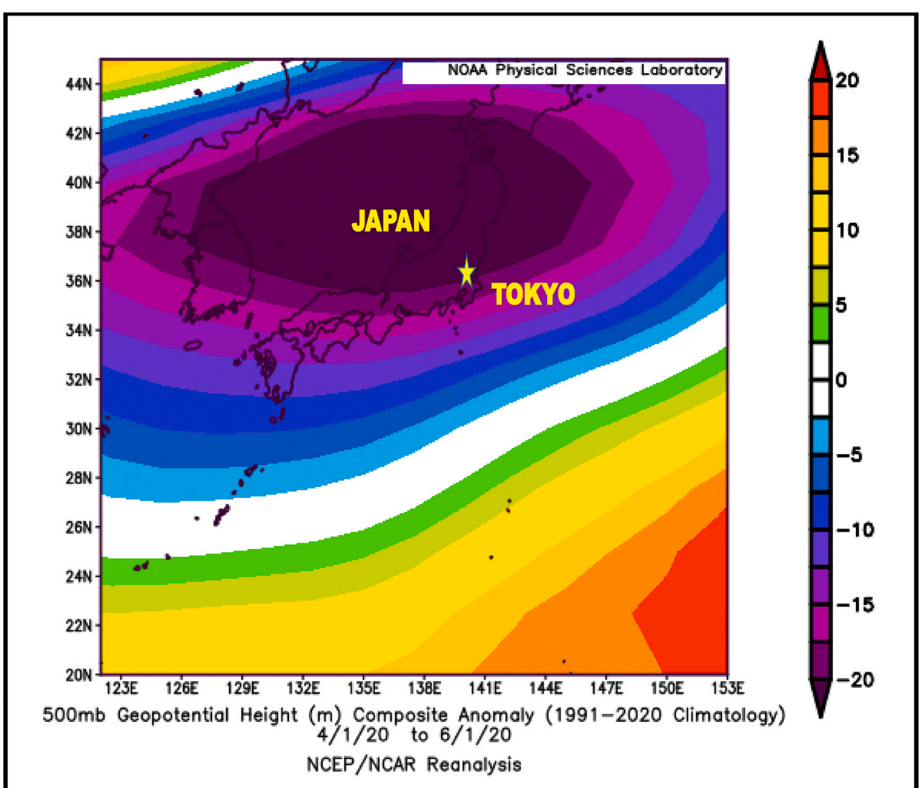

Fig. 8a. Composite anomaly chart of 500 mb geopotential.

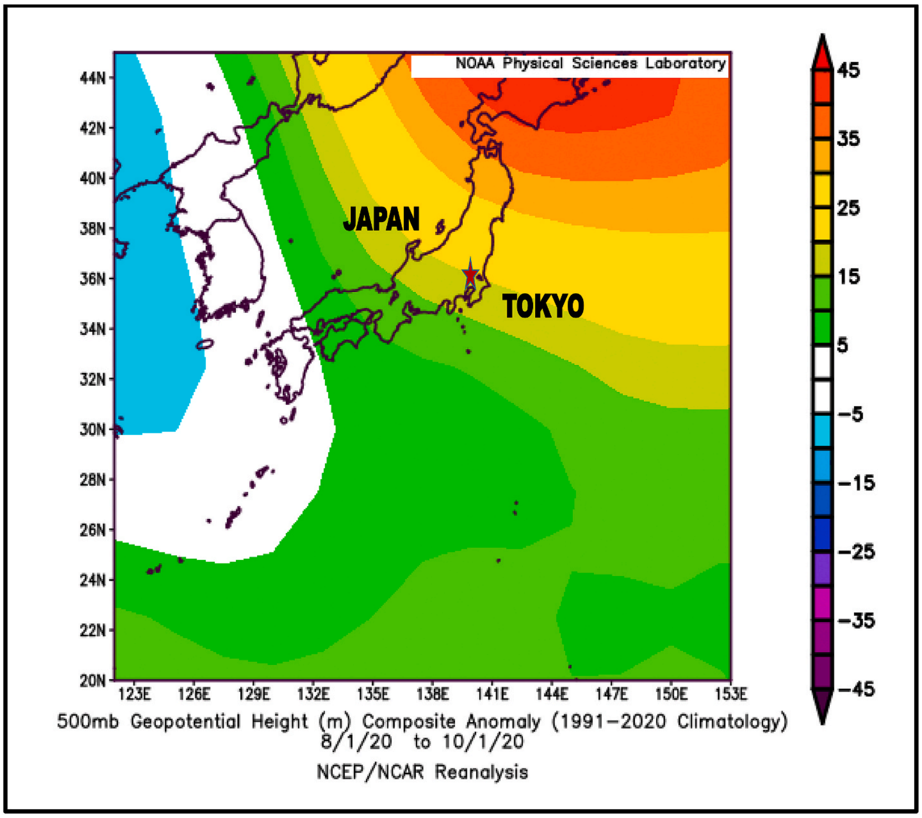

Fig. 8b. Composite anomaly chart of 500 mb geopotential height over Japan and Tokyo during the first COVID-19 wave over Japan and Tokyo during the second COVID-19 wave.

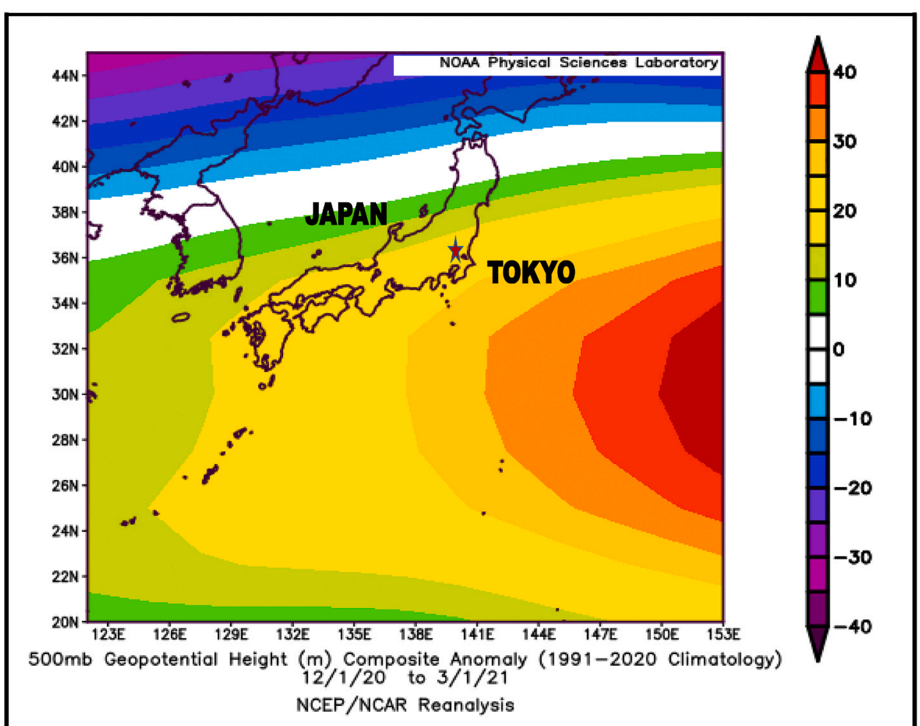

Fig. 8c. Composite anomaly chart of 500 mb geopotential.

associated anticyclonic conditions with COVID-19 waves in some hot-spot worldwide countries (Baron, 2022; Ma et al., 2023).

Experimentally was demonstrated that in urban areas air pollution and climate parameters variability alter the bacterial and viral species distribution in PM2.5., structure and composition of the atmospheric microbial community related to diurnal and seasonal changes (Long

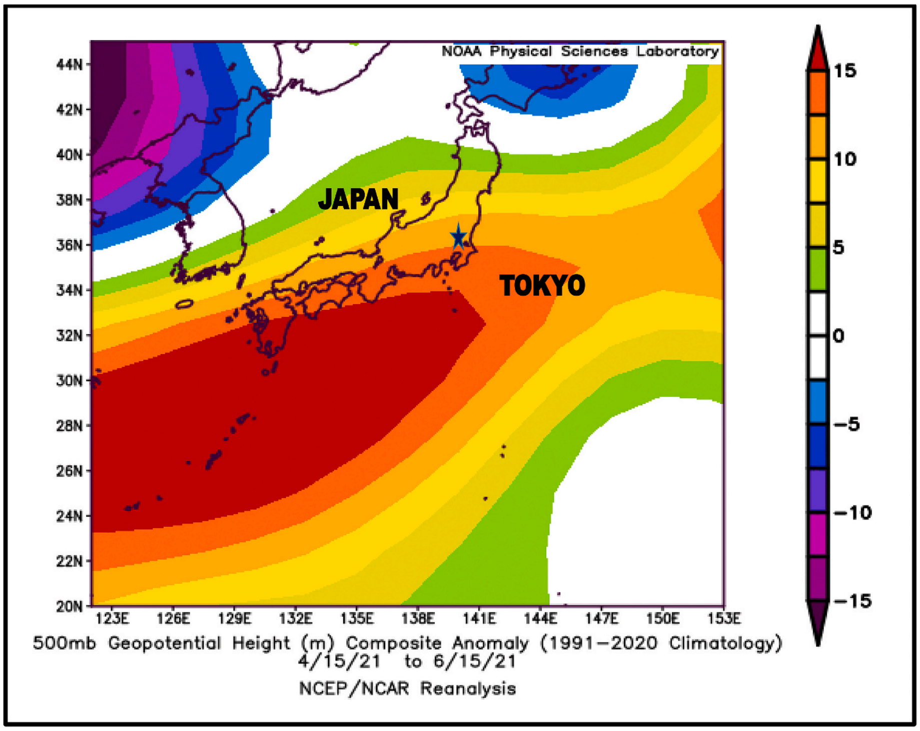

Fig. 8d. Composite anomaly chart of 500 mb geopotential height over Japan and Tokyo during the third COVID-19 wave height over Japan and Tokyo during the forth COVID-19 wave.

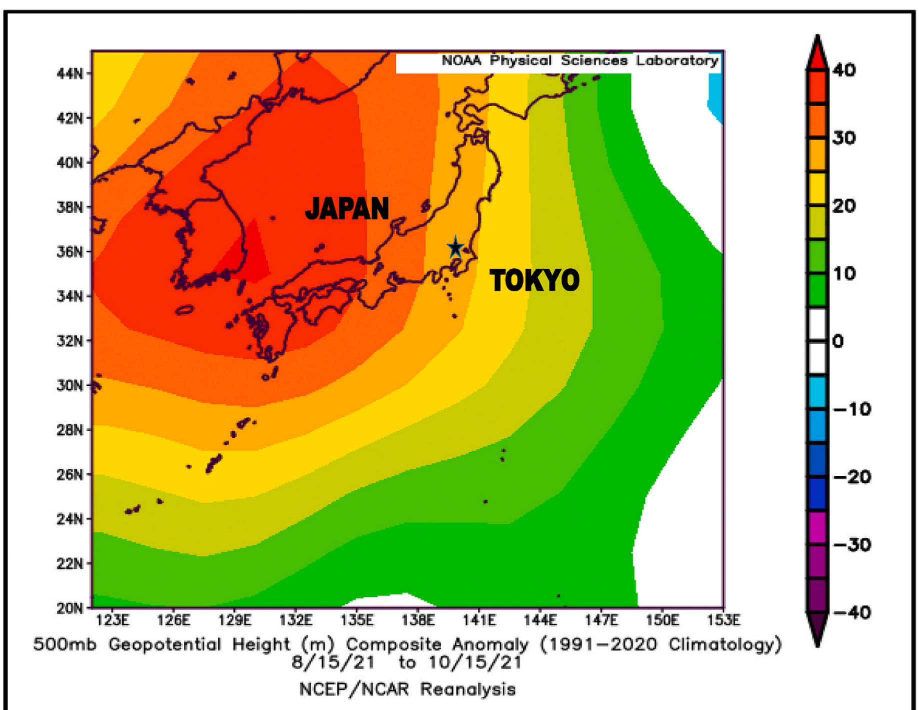

Fig. 8e. Composite anomaly chart of 500 mb geopotential height.

et al., 2022). For the both short term and long term exposures, the findings of this study confirm previous works' results on the link between PM2.5 and PM10 urban air pollution and COVID-19 incidence and mortality (Juarez et al., 2022) and the influence of direct links with synoptic meteorological conditions (Ju et al., 2021).

Seasonal variability of air pollutants and climate parameters are closely related to several strains of microorganisms with similar seasonal cycles, which have been detected in both indoor and outdoor air viable and dead airborne biological particles linked with various health issues, including viral infectious diseases, such as COVID-19, influenza, etc. (Liang et al., 2022; Cai et al., 2022; Marcovecchio and Perrino, 2021; Xie et al., 2018).

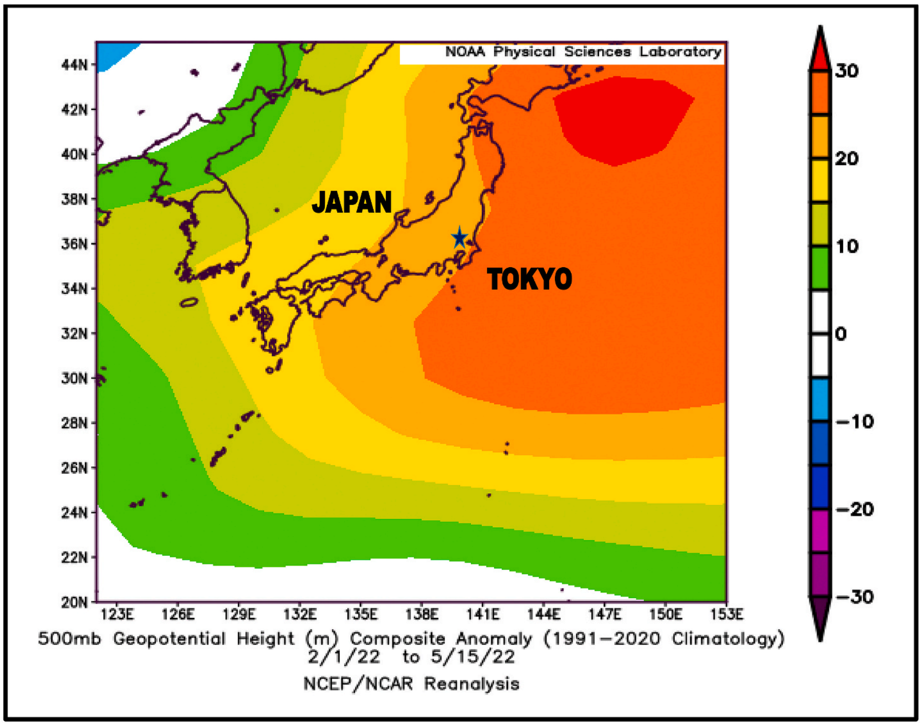

Fig. 8f. Composite anomaly chart of 500 mb geopotential height over Japan and Tokyo during the fifth COVID-19 wave. over Japan and Tokyo during the sixth COVID-19 wave.

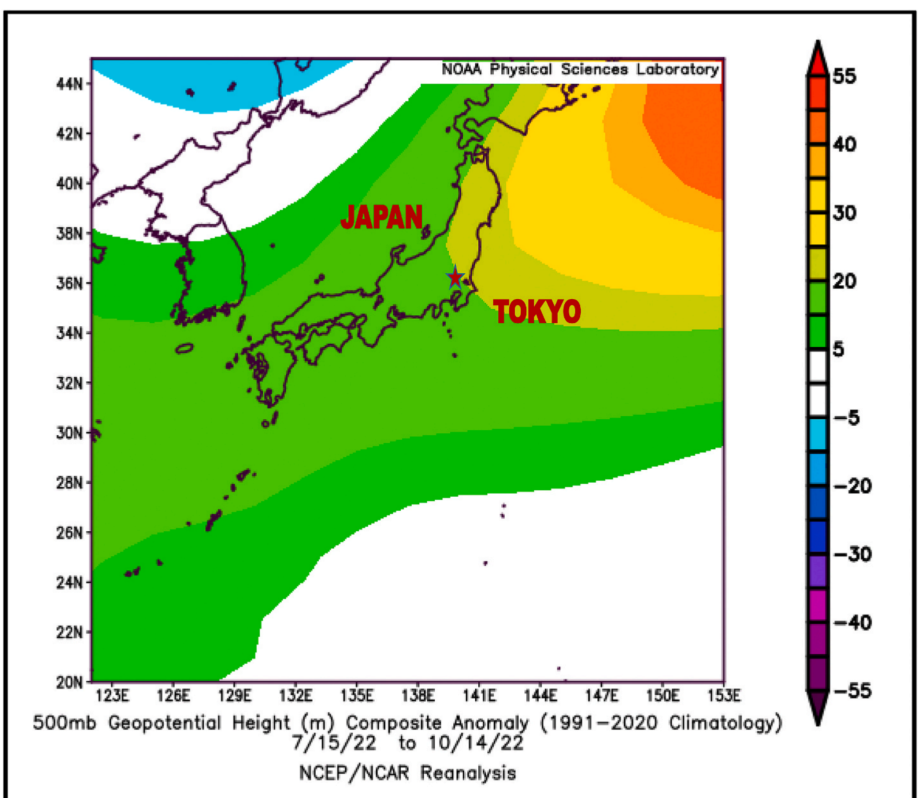

Fig. 8g. Composite anomaly chart of 500 mb geopotential height over Japan and Tokyo during the seventh COVID-19 wave.

The findings of this study show that ambient pollution in Tokyo metropolis and the COVID-19 pandemic disease are interconnected: higher levels of air pollutants at local and regional scales under synoptic atmospheric stagnant conditions and lower heights of Planetary Boundary Layer increase COVID-19 incidence of new cases and deaths, leading to a much more severe course of the pandemic during mostly 7th

COVID-19 wave. A plausible mechanism linking urban air pollution to the spread and course of COVID-19 viral infection is attributed to both short-term and long-term exposure to high concentrations of at the surface level of particulate matter especially PM2.5 or PM10, and pollutant gases (O_3, NO_2, SO_2, CO, VOCs), linked to medical pre-conditions of the respiratory and immune systems that can exacerbate the course of the COVID-19 (Wang T. et al., 2021; Chakrabarty et al., 2021; Gkatzelis et al., 2021). The high incidence of COVID-19 incidence at the end of heat season in August–September 2022 can be explained not only by the environment but also through factors related to people's immunity decrease (Carlson et al., 2020).

Besides the different concentrations of air pollutants and especially PM2.5 particles, the existing differences in the response to the COVID-19 pandemic waves periods in Tokyo metropolis may be attributed to local and regional seasonality of Planetary Boundary Layer heights and of climate parameters, infectivity rates of several SARS-CoV-2 variants, as well as to adopted prevention and interventions strategies both at the metropolitan and at the prefectures levels. The lack of implemented restrictions during the seventh wave may justify the higher rates of COVID-19 incidence and mortality recorded during summer-autum 2022 in Tokyo.

4. Strengths and limitations

As an added value of this study, to the best of our knowledge, this is the largest study to date describing the changes in air pollution and environmental conditions in relation to epidemiological patterns of COVID-19 during the seven epidemic waves in Tokyo metropolis in Japan. Implications of all available evidence we present important local and regional climate impact information on viral infection transmission during anomalous stagnant atmospheric circulation resulted in an increase of aerosols and airborne microbes concentration near the ground, especially during the 6th and the 7th COVID-19 waves. However, air pollution and COVID-19 exposure in Tokyo metropolis vary significantly by local topography and community. A main supposition considers that the chemodynamics of SARS-CoV-2 pathogens and particulate matter in different size fractions interactions may be responsible for the viral disease spreading during several seasons and COVID-19 multiwaves, and explains the existing correlations between urban air pollution, and climate variability during the seven COVID-19 waves analyzed in this study.

We identified several strengths: a long time observation period (almost three years) of environmental factors related to COVID-19 epidemiology in the Tokyo metropolis, that spanned several seasons from January 1, 2020 till October 1, 2022, allowing us to examine a big range of time series climate and air quality data; combined use of time-series satellite and in-situ at the ground level observations to study the impact of environmental factors-COVID-19 disease transmission; according to our findings, long-term high-resolution spaceborne AOD, PBL, meteorological parameters retrievals from MERRA-2 data and Giovanni platform, as well as land surface temperature (LST) MODIS data can be utilized for detecting spatial and temporal aerosol, Planetary Boundary Layer height and LST variability at a metropolitan large scale, helping towards the current and future research of air quality and related impacts on pandemic periods, which can serve as the basis for health-related and other forecasting services.

As a limitation, this study did not consider spatial and mobility distribution of people of no-infected and infected people. When the number of infections is low, it is expected that many infected people in so-called clusters have a known contact history. Also, another limitation consists in undertesting and underreporting throughout the course of the pandemic that may produce uncertainties of COVID-19 cases, limiting this study's capability to capture all COVID-19 cases. Additional limitation linked to epidemiologic data collection is related to asymptomatically infected cases which are contagious (Kronbichler et al., 2020) and therefore, estimations of the relationship between air pollutants and COVID-19 may be biased by the unknown metropolitan distribution of asymptomatic cases.

5. Conclusions and policy implications

This study investigated the impact of the main air pollutants and climate variability on COVID-19 multiwave incidence and severity in Tokyo metropolis, in Japan. Through a systematic analysis of the daily time-series data of the main air pollutants, Aerosol Optical Depth, meteorological and synoptic atmospheric conditions, the land surface temperature during summer 2022 heat waves, and COVID-19 incidence and mortality, this paper found the existing cross-correlations between environmental variables and the transmission of SARS-CoV-2 pathogens during the entire pandemic period in such datasets. However, although the molecular mechanisms explaining the interaction between air pollution and urban heat exposure, and the pathogenesis of SARS-CoV-2 is still debated, this research supports the hypothesis that the synergy interaction of peculiar characteristics of atmospheric circulation associated with periodic low-pressure systems and summer heat waves passing over Tokyo with PM viral vectors increases the risk of COVID-19 incidence and mortality. As a conclusion, weak horizontal and vertical ventilation conditions under anticyclonic circulation days with the daily 500 hPa geopotential height positive anomalies, stable atmospheric stratification and temperature inversions and persistent summer HWs recorded in Tokyo metropolis during the 7th COVID-19 wave may be responsible of high concentrations of particulate matter and gaseous pollutants accumulation in the lower atmosphere, and the associated increase of airborne pathogens like as SARS-CoV-2 and other bioaerosols.

Interestingly, our results suggest that the magnitude of the contribution to COVID-19 or other viral infections transmission and severity during stagnant synoptic air circulation conditions associated with low levels of PBL heights and high levels of particulate matter, especially PM2.5 that have the capacity to act as viral vectors, may be controlled by decision makers through drastic reduction of mobile and fixed air pollutant emissions.

The air pollution in Tokyo metropolis was improved mainly through measures to limit vehicle emissions during SoEs. Without restrictions, due to the peculiar climate characteristics of Tokyo, and the high infectivity rates of new Omicron SARS-CoV-2 variants, the seventh COVID-19 wave resulted in the highest numbers of COVID-19 DNC and DND cases. However, despite of strict mobility restrictions adopted for Tokyo metropolis during the COVID-19 pandemic, widespread adherence to the foreseen recommendations designed to limit the SARS-CoV-2 pathogens transmission resulted in unique air quality small improvements. In order to controll COVID-19 pandemic the environmental drivers of it spreading and viability must be considered epidemiological factors, knowing that both indoor and outdoor aerosol particles' interaction with respiratory droplets is crucial vector for the airborne transmission and transport of novel SARS-CoV-2 pathogens, the causal agent of COVID-19 viral infection. The findings along with the pandemic shape are suggestive that the warm season and the strong heat waves might have real impacts on the pandemic during the study period in the Tokyo region. In the frame of global warming and increasing the frequency of extreme climate events, to address the issue of the evolution of the pandemic in the metropolitan environment of Tokyo, it is necessary to continuously monitor and survey air pollution, under different synoptic meteorological conditions, considering negative impacts of urbanization on health and environment. Besides traffic related air pollution, further improvement of air quality during severe epidemic events in Tokyo and Japan, must consider also the impact of non-vehicle emission sources and transboundary transportation. However, while climate and air pollution conditions may increase or limit SARS-CoV-2 pathogens transmission, mitigation policies (e.g., public health measures) and behaviors are likely to play a sugnificant role in determining the degree of transmission.

Credit author statement

Maria Zoran: Conceptualization; Methodology, Supervision, Writing - review & editing. Roxana Savastru: Methodology, Validation, Review., Dan Savastru: Methodology, Validation, Review. Marina Tautan: Methodology, Validation.

Consent for publication

All the co-authors consent the publication of this work.

Consent to participate

Not applicable.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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ABBREVIATION

SARS-CoV-2	Severe Outdoor Respiratory Syndrome Coronavirus 2
COVID-19	Coronavirus Disease 2019
SARS-CoV	Severe Outdoor Respiratory Syndrome Coronavirus
MERS-CoV	Middle East respiratory syndrome coronavirus
DNC	Daily New COVID-19 positive cases
DND	Daily New COVID-19 Deaths
PM	Particulate Matter: PM1(1 μm), PM2.5 (2.5 μm) and PM10 (10.0 μm) diameter
O3	Ozone
NO_2	Nitrogen dioxide
SO_2	Sulfur dioxide
CO	Carbon monoxide
PBL	Planetary Boundary Layer height
T	Air temperature
p	air pressure
RH	Air relative humidity
w	Wind speed intensity
SI	Surface solar global irradiance
UHI	Urban Heat Island
HWs	Heat Waves
OECD	(Organisation for Economic Co-operation and Development)
NOAA	National Oceanic and Atmospheric Administration U.S.A.

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