ENVIROMENTAL RESEARCH LETTERS

LETTER

Seasonal adjustment of particulate matter pollution in coastal East Asia during the 2020 COVID lockdown

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Keywords: coronavirus lockdown, East Asian seasonality, large-scale control, particulate matter pollution, weather patterns

Abstract
Seasonally, the East Asian particulate matter (PM) level is higher in the winter–spring period than in summer, at which time the level rapidly decreases due to the summer monsoon migration. Attempting to attribute East Asian PM pollution to a source without considering such natural factors is challenging. However, to what degree the effect of season on an attribution bias remains controversial; the bias may even be implicated in PM-related health effects. This study examined seasonal dynamics including the unusual precipitation evolution during 2020—a year in which coronavirus-related lockdowns occurred frequently worldwide—and suggested a large-scale effect from the removal of PM pollutants from most of the coastal cities in East Asia. In winter–spring 2020, compared with that of previous years, a deeper and farther southward intrusion of the East Asian coastal trough and a stronger surface monsoon flow acted jointly to transport air pollutants over the Korea–Japan region. In summer 2020, the strength and migration of the western North Pacific (WNP) high increased precipitation and removed air pollutants in mid-latitude East Asia, whereas it reduced precipitation in the subtropical WNP. Consequently, the reduced PM level in the subtropical region (including Taiwan) may be irrelevant to the anomalous seasonal pattern. Although an artificial effect is conceivable and may be primarily responsible for the marked decrease in 2020 East Asian PM pollutants in some subtropical cities, the modulation of a large-scale and precipitating effect also deserves consideration.

1. Introduction

As a multidisciplinary topic involving a range of considerations, including chemical composition, multispecies interaction, and meteorological parameters, particulate matter (PM) pollution is a topic of increasing focus in environmental and public health research (Miao et al 2015, Dong et al 2019, Lung et al 2020, Salvador et al 2020). However, climatological sensitivity, including seasonal and interannual-scale dynamics, has not been well addressed in relation to PM (or aerosol) pollution (Chen et al 2015, DeWitt et al 2018, Wu et al 2019). Without distinguishing the influence of human versus natural forces on PM pollution, a potential attribution bias cannot be ruled out and may even be implicated in PM-related health effects.

In East Asia, weather patterns are strongly affected by monsoons and interact with disturbances in the westerly mid-latitude (Enomoto 2004, Hirahara et al 2012, Huang et al 2014, Kong et al 2017). The inclusion of the extratropical–tropical interaction makes East Asian seasonality more complex compared with the adjacent monsoon regions. Regarding rainy seasons, in addition to summer precipitation driven by frontal systems and typhoons, spring rain also regularly occurs in East Asia (Linho et al 2008, Chou et al 2011, Wu et al 2017, Chiang et al 2020). In view of dynamic transport and the precipitation-related removal of air pollutants, seasonal variation in East Asian air quality is to be anticipated (Chen et al 2008b, Ding et al 2017). Nevertheless, to what degree monsoons and westerly seasonality relate to PM pollution has been only partially explored (Zhang et al 2016, Wu et al 2019). Specifically, natural variability in the PM distribution across temporal scales (e.g. decadal to interannual variations in seasonal adjustment) has not been well understood.
Although numerical modeling provides valuable information, obtaining insight only through such models remains a challenge (Zhao et al. 2011, Tsai et al. 2016), particularly when unrealistic dynamic patterns and their changes across scale are represented. During 2020, East Asia experienced an overall decrease in the PM pollution level, which could be influenced by the worldwide occurrence of coronavirus-related lockdowns (Shi and Brasseur 2020, Dai et al. 2021) and may provide an opportunity to study human versus natural control of a reduction in PM (Kumar et al. 2020, Benchrif et al. 2021). This study attempted to assess the impact of COVID-19 lockdowns during 2020 on PM pollution across East Asian cities. Whether dynamic patterns during 2020 contributed to this decrease in PM pollution could provide insights into the large-scale seasonal adjustment of PM conditions (Gu et al. 2021). This study aimed to determine whether the effect of seasonal forcing on reduced PM levels during the 2020 virus lockdown was noteworthy. The remainder of this paper is organized as follows: section 2 describes the data and methods; section 3 presents the influence of seasonal dynamics on East Asian PM pollution; section 4 explores the anomalous seasonal effect involved with removing PM pollutants during 2020; section 5 discusses potential limitations of the analysis; and section 6 presents the study’s conclusions.

2. Data and methods

In this study, the daily PM$_{2.5}$ (i.e. particles with a diameter smaller than 2.5 µm) levels observed at stations located in 11 East Asian cities (figure 1(a)) were analyzed. We computed the average PM observations of the participating stations in a city, which ranged from 3 in Jeju, Korea, to 119 in Tokyo, Japan (table 1). The PM data with unit of air quality index (AQI) from 2014 to early 2021 were obtained from the World AQI project. In the current study, a southwest–northeast-oriented area, as marked by a dashed parallelogram in figure 1(a), was specified and is hereafter referred to as the East Asian band; due partly to the diversity in latitudes among the East Asian cities studied, differential seasonal dynamics were considered.

The aerosol optical depth (AOD) obtained from moderate resolution imaging spectroradiometers was also investigated to attain an overview of spatial patterns, although the equivalence of AOD and PM has been contested (Kumar et al. 2007, Guo et al. 2009). The monthly AOD of 0.55 µm over both ocean and land had a latitude–longitude spatial resolution of 1° (Platnick et al. 2015).

We also used data of atmospheric circulation fields obtained from the Japanese 55 year Reanalysis (JRA55) and precipitation obtained from the Global Precipitation Climatology Project (GPCP) and the National Oceanic and Atmospheric Administration’s...
Climate Prediction Center (CPC). The JRA55 data have a six hourly temporal resolution and a 1.25° latitude–longitude spatial resolution (Kobayashi et al 2015); version 1.3 of daily GPCP data has a 1° latitude–longitude spatial resolution (Huffman et al 2001); and the gauge-based daily CPC data (collected from over 30 000 stations) have a 0.5° latitude–longitude spatial resolution (Chen et al 2008a). For timeframe consistency (past 7 years), the PM 2.5 data available from the East Asian cities, namely the AOD, dynamic fields, and precipitation data, were obtained for the period since 2014. Regarding the anomalous characteristics of 2020, a quasi-climatological state in 2014–2019 was compared; a large difference in seasonal contrasts was not anticipated when using a state including more years as a basis. Moreover, because the degree of freedom pertained to only one case season, statistical verification was applied specifically for data pertaining to anomalous seasonal patterns averaged at daily or higher resolution.

To elucidate the seasonal characteristics of PM pollution and to what degree they are affected by precipitation, we explored the probability density function (PDF) distribution of PM$_{2.5}$ and precipitation data of individual cities. We identified 12 ‘mega months’, which were presented as a monthly calendar. In the case of 2020, 1 January to 31 March 2020, was identified as mega-JAN 2020; 1 February to 30 April 2020, was mega-FEB 2020; and 1 December 2020 to 28 February 2021, was mega-DEC 2020. The calendar-like PDF was calculated based on all the days in a mega month; approximately 90 and 540 days were included in a mega month for the periods of 2020 to 28 February 2021, was mega-DEC 2020. The values of East Asian AOD are higher in winter–spring than in summer (figure 1(b)). As though scoured by seasonal advancement of monsoon precipitation corresponding to the Meiyu, Baiu, and Changma seasons (figure 1(c)), the rapid decrease in AOD in subtropical regions (15° N–25° N) occurs earlier during May and later during June–July in the mid-latitude areas north of approximately 30° N. In winter–spring, the East Asian weather phenomenon, which includes cold surges, is influenced by the Siberian high near the surface and the mid-latitude westerly trough; the February–April conditions are represented in figure 1(d).

Atmospheric transport of air pollutants is closely related to the strength of the eastern edge of the surface high and the blocking condition of the coastal trough. By contrast, large-scale dynamics in summer (June–August) are primarily related to the strength and migration of the western North Pacific (WNP) high and mid-latitude westerly jet stream (figure 1(e)). Over the East Asia–WNP region, the seasonal advancement of monsoon precipitation is influenced by a northward shift of the WNP high, a weakening and northward migration of the upper-level westerly jet stream, and the deepening of the WNP monsoon trough. The corresponding weather patterns primarily involve the frontal system in May–June and the later typhoon season. In contrast to the precipitation effect on the removal of air pollutants, the large-scale subsidence surrounding typhoons may cause poor air quality (Ding et al 2013, Wu et al 2019).

The results of PDF distribution further indicate considerable seasonal variations in PM$_{2.5}$ and precipitation (figure 2), and the cities at low latitudes, such as Hong Kong and Kaohsiung, exhibit larger seasonal variations than high-latitude cities. The data for 2014–2019 (as a reference for normal annual cycles), indicate that higher PM levels occur in cold seasons and lower PM levels occur in summer in the various cities surveyed (contours in the right panel). Consistent with the previous inference, less PM$_{2.5}$ corresponds to more precipitation (blue line in the left panel) among the cities; precipitation also exhibits differential timing based on the corresponding city’s latitudes.

The impact of coronavirus-related lockdowns on improving air quality has been noted in recent studies, and the concept of weather-corrected air pollution changes has been emphasized (Venter et al 2020, Hernández-Paniagua et al 2021). In the next section, after discussing seasonal dynamics during 2020, we propose how the changes in East Asian PM levels might be modulated by anomalous seasonal patterns.

### Table 1. Longitudes and latitudes of the selected cities, as marked in figure 1(a). The number of stations where particulate matter observations were included in a city is also recorded.

| City   | Longitude (° E) | Latitude (° N) | Stations |
|--------|-----------------|----------------|----------|
| Qingdao | 120.38          | 36.06          | 18       |
| Shanghai | 121.46          | 31.22          | 37       |
| Hongkong | 114.17          | 22.28          | 15       |
| Seoul   | 126.98          | 37.57          | 95       |
| Busan   | 129.03          | 35.10          | 32       |
| Jeju    | 126.52          | 33.51          | 3        |
| Sendai  | 140.87          | 38.27          | 21       |
| Tokyo   | 139.69          | 35.69          | 119      |
| Fukuoka | 130.42          | 33.60          | 20       |
| Taipei  | 121.53          | 25.05          | 31       |
| Kaohsiung | 120.31         | 22.62          | 20       |

Days in a mega month with precipitation greater than 1 mm d$^{-1}$.
4. Quantifying seasonal PM levels during 2020 COVID lockdown

The decrease in the East Asian AOD was considerable during 2020, particularly in summer in the subtropical region situated at approximately 20° N and during spring through summer in the mid-latitude region of approximately 40° N (large circles, figure 1(b)). A downgraded level of PM pollution was also consistently observed in the target cities (shadings, figure 2). Compared with 2014–2019, a marked weakening of the seasonal PM shape was observed during 2020. With rainy seasons occurring during summer, most East Asian cities experienced increased frequencies of rainy days in 2020 than before; hence, identifying this greater precipitation as the mechanism that removed air pollutants is plausible. However, precipitation may exhibit a secondary effect in other seasons and even in summer in some subtropical cities. For example, despite registering low precipitation in summer 2020, Taipei and Kaohsiung in Taiwan registered a considerable decrease in PM pollutants (compared with during the 2014–2019 period); the decrease in PM may have been inversely related to the strengthened WNP high (to be discussed later) and may imply a limited modulation of the weather pattern.

Figure 3 depicts surface winds and streamfunction circulation at 925 hPa from winter–spring to summer, following the mega month concept. In February–April, corresponding to the east edge of the Siberian high, the flow generally proceeded northwesterly across Korea–Japan and northeasterly across Taiwan near the surface. The large-scale dynamics in relation to atmospheric conditions relate primarily to the vertical interaction between low-level monsoon flow and mid-level westerly fluctuation (mainly involving the blocking of the coastal trough) in the mid-latitudes (figure 3(a)). In 2020, the East Asian mid-level trough traversed further southward than in previous years (figure 3(b)), corresponding to a southeastward extension of the low-level high in southeastern China and Taiwan; the stronger westerly in the south of Korea–Japan and stronger easterly around Taiwan and the Philippines corresponded to weaker trade winds from the central Pacific than in previous years. In winter–spring 2020, a larger monsoon circulation effect on transporting air pollutants over Korea–Japan is conceivable.

In March–May (denoted as spring, figure 3(c)), unaffected by the winter monsoon (e.g., continental surface high, compared with that shown in figure 3(a)), the East Asian mid-level trough intruded further southward in 2020 compared with in 2014–2019 (figure 3(d)). In spring 2020, the anomalous cyclonic circulation over the Korea–Japan region was larger in size than it had been in February–April, which might have affected the decreased PM levels observed in mid-latitude East Asia, despite the low precipitation (figure 2). Closer to summer (figures 3(e)–(j)),
the East Asia–WNP region in 2020 was likely controlled by a strong subtropical high over the ocean. Precipitation along the northern flank of the high may have thus been increased, driving a record-long Meiyu front over the Yangtze–Huai River Valley (Qiao et al. 2021); by contrast, less precipitation occurred adjacent to the high ridge area, including in summer Taiwan. The lower PM levels recorded in the subtropical East Asia–WNP region were, then, unrelated to the anomalous seasonal pattern during 2020.

We further explored meridional connection (figure 4) for a complementary view of atmospheric circulation, with the major focus on the winter–spring and summer periods. In February–April (figure 4(a)), in addition to the vertical coupling of the mid-latitude wavy circulation patterns and the surface monsoon flow, as indicated in figure 3, the East Asian coastal winds can be considered part of the Hadley cell in relation to tropical dynamics. However, the enhanced East Asian coastal northerly flow was likely unrelated to tropical changes in winter–spring 2020. During 2020, tropospheric subsidence was primarily enhanced in the mid-latitudes of approximately 30° N–35° N, corresponding to a deeper divergent northerly from the surface, followed by the stronger northerly over the downstream subtropical region (figure 4(b)).

In summer, strong vertical upward motion connects the eastern extension of the upper tropospheric intercontinental anticyclone (divergent southerly flow, figure 4(c)) and lower tropospheric southerly monsoon winds. During 2020, associated with the stronger and farther westward extension of the WNP high, upward motion was weakened in the lower troposphere south of approximately 27° N, whereas it was strengthened in the north over the Korea–Japan region. A weaker divergent southerly flow was recorded in the upper troposphere (figure 4(d)), corresponding to the shifting pattern of East Asian precipitation. In brief, a notable unnatural effect of removing PM was observed in the subtropical region. However, regarding seasonal dynamics and the precipitation effect, from winter–spring to summer, attributing the marked decrease in PM to seasonal impact remains plausible.

5. Discussion

The COVID-19 lockdowns influenced the air quality worldwide via reduction in concentration of pollutants such as PM, nitrogen dioxide, and ozone (Bauwens et al. 2020, Kondragunta et al. 2021). These findings provide meaningful insights as to the extent to which air pollution can be reduced through policy interventions targeting on-road traffic volume. Notably, studies have also reported insignificant and even opposite change during the virus lockdown; for example, an increase in surface ozone concentration in northern China (Shi and Brasseur 2020). Regarding ozone changes at ground level, in addition to the influence of weather conditions, understanding of other factors including topography and formation reactions provides further details for attribution. Ideally, multidisciplinary efforts have been directed toward understanding the origin and evolution of air pollution, which provides helpful information for policy making to address pollution-related health concerns.

In this study, we considered the seasonal evolution of atmospheric circulation and precipitation to be necessary factors in the modulation of air pollutants. Investigation of a downscale modulation of weather-scale PM-related forcing by climatological dynamics and climate change is a further emphasis of the research. Potential bias in numerical modeling could be reduced when dynamic patterns and their changes across scale can be more realistically represented.
6. Conclusion

In this study, we investigated the seasonal and large-scale regulation of East Asian PM distribution with the aim of evaluating weather-affected changes in air pollution change from the viewpoint of climatological dynamics. In summary, the PM level in winter–spring is higher than that in summer over East Asia. The pollutants rapidly decrease in early summer in subtropical East Asia and in mid-summer farther north in the Korea–Japan region, as though scoured by the seasonal advancement of monsoon precipitation. In the winter–spring period, which involves vertical interaction in the westerly flow, weather patterns in East Asia are primarily influenced by the eastern edge of the Siberian high and the mid-level westerly trough adjacent the coastal regions, which combine to affect air pollutant transportation. In summer, also related to the vertical coupling in the westerly flow, the strength and migration of the WNP high and the upper-level mid-latitude jet stream conjoinly affect East Asian monsoon circulation and precipitation.

Understanding the seasonal adjustment of PM distribution provides insights into the natural variability and numerical modeling of air pollution. Investigation of such natural forcing on PM changes could further reduce the risk of attribution bias. During 2020, an overall decrease in East Asian PM levels was observed and may have been associated with the coronavirus-related lockdown events. However, after exploring the anomalous seasonal and large-scale dynamics during 2020 compared with those in previous years (2014–2019), the effect of seasonal forcing in reducing PM levels cannot be dismissed. In winter–spring 2020, a deeper (with farther southward intrusion) East Asian coastal trough and a stronger surface monsoon flow were evident. A stronger-than-normal dynamic effect on transporting air pollutants over the Korea–Japan region is plausible. In summer, associated with a stronger WNP high, the large increase in precipitation along the northern flank of the high removed air pollutants in the mid-latitude regions of East Asia. However, a stronger WNP high with less precipitation had an inverse effect on the removal of air pollutants over subtropical regions such as Taiwan, implying that a lower PM level in the region than in previous years may be unrelated to the anomalous seasonal patterns observed during 2020.
Data availability statement

All the datasets used in this study are publicly available. The data can be obtained from the World AQI project portal (https://waqi.info/), the Goddard Earth Sciences Data and Information Services Center (https://disc.gsfc.nasa.gov), and the websites of the CPC, GPCP, and JRA55.

All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgments

This work was supported by the Ministry of Science and Technology (MOST), Taiwan, under grants MOST 108–2628–M–001–006–MY4. We are grateful to Ms Pei-Chia Tsai for preparing the PM data, assisting with PDF calculation, and plotting figure 1(a).

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