Possible Relationship of Weakened Aleutian Low with Air Quality Improvement in Seoul, South Korea[✉]

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ABSTRACT

Cold-season air quality in Seoul, South Korea, has been improved noticeably between 2001 and 2015 with a near-50% decrease in the mean concentration of particulate matter with aerodynamic diameters $\leq 10 \mu\text{m}$ (PM_{10}). Like the change in mean concentration, the occurrence frequency and intensity of the extreme-high- PM_{10} episodes exceeding $100 \mu\text{g m}^{-3}$ has significantly decreased as well. In addition to the multilateral efforts of the South Korean government to reduce air pollutant emissions, this study proposes that large-scale circulation changes also could have contributed to the air quality improvements. Specifically, the recent weakening of the Aleutian low may have intensified the tropospheric westerlies around the Korean Peninsula, resulting in a shorter residence time of particulate matter over South Korea. Thus, despite constant governmental effort to reduce pollutant emissions, the improvement in air quality over South Korea may be delayed if the Aleutian low recovers its past strength in the future. This study emphasizes the importance of the meteorological field in determining the air quality over South Korea.

1. Introduction

Air pollution is known to cause numerous adverse social and economic issues, such as reduction of visibility, mechanical failure in facilities, and deterioration of plant growth (Harrison and Yin 2000; Hong et al. 2002; Lau

et al. 2008; Hyslop 2009). The adverse effects of air pollution on human health are among the most serious concerns (Pope and Dockery 2006). Worldwide, approximately 800 000 premature deaths occur each year due to particulate matter (PM) air pollution, making it the thirteenth leading cause of mortality (Anderson et al. 2012). Several epidemiological studies have shown a consistent increase in cardiac and respiratory morbidity and mortality from exposure to PM (Pope and Dockery 2006): a $10 \mu\text{g m}^{-3}$ increase in the average 24-h PM with aerodynamic diameters $\leq 10 \mu\text{m}$ (PM_{10}) concentration is associated with an increase in daily mortality of

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approximately 0.6% (Samoli et al. 2008). Therefore, the World Health Organization (WHO) has set guidelines for PM₁₀, urging that its annual and 24-h average concentrations should be less than 20 $\mu\text{g m}^{-3}$ and 50 $\mu\text{g m}^{-3}$, respectively (WHO 2006, 174–175).

Accordingly, developed countries have attempted to control pollutant emissions by promoting public transportation, clean burning, renewable fuels, and energy efficient plants and buildings (WHO 2006, 174–175). For example, in the states of the European Union (EU), the number of high-PM₁₀ days, that is, a 24-h average PM₁₀ concentration larger than 50 $\mu\text{g m}^{-3}$, is not supposed to exceed a frequency of 35 days yr^{-1} (Ştefan and Roman 2015). In case a member state exceeds the limit, it has to report and explain the exceedance frequency. In 2005, the South Korean government began to implement the 10-Year Act, including a series of strict policies to reduce the local emission of air pollutants in major cities (e.g., Seoul, Pusan, Daegu, Daejeon, and Gwangju), where more than half of the population of South Korea resides (Baek and Koo 2008; Gyeonggi Research Institute 2011). The government invested approximately 4 trillion South Korean won¹ in the act for the first 10 years. The second phase of the 10-Year Act commenced in 2015 (<http://eng.me.go.kr/eng/web/index.do?menuId=238>). It includes various air quality control strategies, such as enforcing the installation of particulate filters in diesel engines, encouraging the use of eco-friendly (i.e., hybrid and electric) cars, and increasing air pollutant monitoring (Gyeonggi Research Institute 2011; Kamal-Chaoui et al. 2011; Kim and Shon 2011).

Previous studies have reported that PM₁₀ concentrations in Seoul have steadily decreased over the past few years because of the various policies implemented to improve air quality (e.g., Lee et al. 2011; Ahmed et al. 2015). However, ambient PM₁₀ concentration levels can also be significantly influenced by the tropospheric circulation (Zhang et al. 2009; Gao et al. 2011; Titos et al. 2014). For example, the presence of a strong anticyclonic pattern leads to a stable meteorological condition, typically characterized by warmer temperature, stagnant winds, and lower mixing depth, which tends to increase the local PM₁₀ levels (Pun and Seigneur 1999; Grambsch 2009). A nearly stationary large-scale meteorological pattern, known as blocking, can cause high-PM₁₀-concentration episodes by preventing the dispersion of air pollutants (Lee et al. 2013; Seo et al. 2017). The PM₁₀ concentration in South Korea has also been found to be highly

influenced by the tropospheric wind speed over the country (Kim et al. 2017).

Because of the importance of the meteorological circulation of air quality, this study aims to investigate if there is any evidence to suggest that changes in tropospheric circulation could have contributed to the recent improvements in air quality in South Korea, along with the government's actions on emission control.

2. Data and methods

We utilized the hourly PM₁₀ mass concentration, measured at 27 air quality monitoring sites in Seoul, during the cold season (October–March) of 2001–15. Since 2 of the sites were closed in 2009, the data from the remaining 25 sites were utilized for 2009–15. Considering that Seoul has the longest and the most qualified PM₁₀ concentration data, we utilized the PM₁₀ concentration of Seoul as a representative value for South Korea (<http://www.airkorea.or.kr/detailViewDown>). For comparison, the PM₁₀ concentration data of six other major cities (i.e., Pusan, Daejeon, Daegu, Gwangju, Incheon, and Ulsan) were examined. The number of monitoring sites in the 6 cities is less than that in Seoul (<http://www.airkorea.or.kr/detailViewDown>): 10 in Pusan, 4 in Daejeon, 7 in Daegu, 5 in Gwangju, 11 in Incheon, and 13 in Ulsan. The PM₁₀ concentration data were measured using the beta-ray absorption method, which determines the concentration by detecting the attenuation that occurs when beta rays irradiate particulate matter collected on a filter (Shin et al. 2011). The measurement error, mainly due to particle-containing moisture, is known to be 10% (Chang and Tsai 2003).

In this study, the collected hourly data were converted into daily average values. We analyzed high-PM₁₀ episodes to explain the overall change in PM₁₀ air quality in Seoul. High-PM₁₀ episodes are defined as events in which the daily mean PM₁₀ concentration exceeds 100 $\mu\text{g m}^{-3}$, in accordance with Lee et al. (2011) and Oh et al. (2015). Since high-PM₁₀ episodes over South Korea can occur because of both anthropogenic sources and yellow dust events (Koo et al. 2010; Lee et al. 2011), it is necessary to classify each episode based on its cause (Shin et al. 2007). Here, we focus only on anthropogenic high-PM₁₀ episodes. Therefore, 62 yellow dust days issued by the Korea Meteorological Administration (KMA; <http://web.kma.go.kr/eng/weather/asiandust/intro.jsp>) were excluded from the overlapping high-PM₁₀ episodes. A total of 108 episodes (217 days) during the analysis period were selected as the anthropogenic high-PM₁₀ episodes. To determine whether the high-PM₁₀ days in Seoul are representative of the nationwide air quality, we used the

¹ In July 2018, \$1 corresponded to 1,115 KRW.

ratio of small mode aerosol optical depth (AOD) to the total AOD at $0.55\ \mu\text{m}$, which is called the fine mode fraction (FMF), obtained from Moderate Resolution Imaging Spectroradiometer (MODIS)/Terra (Levy et al. 2013; <https://adsweb.modaps.eosdis.nasa.gov/search/order>). This was because the anthropogenic AOD is dominated by small mode aerosols. Because of cloud contamination, some of the high-PM₁₀ days could not be checked. Therefore, we were able to examine 173 days out of a total of 217 high-PM₁₀ days.

To evaluate meteorological contributions to the recent improvements in the PM₁₀ air quality, daily meteorological data, including geopotential height and zonal and meridional wind at the 500-hPa level, were obtained from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) Reanalysis 2, with a longitude–latitude resolution of $2.5^\circ \times 2.5^\circ$ (Kalnay et al. 1996). We used anomalies against the daily climatology for 2001–15 to exclude seasonality while identifying the meteorological characteristics on high-PM₁₀ days. The daily precipitation and wind speed, observed at the weather stations of Seoul, were obtained from the KMA (<http://www.kma.go.kr>). All meteorological data were analyzed for the same period as that of the PM₁₀ concentration data used.

We further used the total amount of emissions for 2001–14 to examine the relative contributions from large-scale circulations, precipitation frequency, and local emissions to the PM₁₀ level over South Korea using data from the National Air Pollutants Emission Service (<http://airemiss.nier.go.kr/mbshome/mbs/airemiss/index.do>).

3. Results

Figure 1a displays the time series of the number of the mean PM₁₀ concentration (black filled circles), high-PM₁₀ days (gray filled circles), and the intensity of high-PM₁₀ episodes (gray open circles) during the cold seasons of 2001–14. There is a notable downward trend in both the cold-season-mean PM₁₀ concentration and high-PM₁₀ days. During the analysis period, the number of the cold-season-mean PM₁₀ level and high-PM₁₀ days decreased by $22\ \mu\text{g m}^{-3}\text{decade}^{-1}$ and 19 days decade^{-1} , respectively. Both the trends are statistically significant at the 99% confidence level. The intensity of high-PM₁₀ episodes, defined as the PM₁₀ concentration on the day of the onset of high-PM₁₀ episodes, also declined significantly by $9.8\ \mu\text{g m}^{-3}\text{decade}^{-1}$. Figure 1b shows the trend of probability distribution functions of daily mean PM₁₀ concentrations during the analysis period. The trend is positive for low PM₁₀ concentration ($\leq 50\ \mu\text{g m}^{-3}$), while it is negative for most

FIG. 1. (a) Average PM₁₀ concentration (black filled circles), high-PM₁₀ days ($>100\ \mu\text{g m}^{-3}\text{day}^{-1}$; gray filled circles), and intensity of high-PM₁₀ episodes (gray open circles) during the cold season in Seoul; (b) the trend of probability distribution functions of daily mean PM₁₀ concentrations; and (c) average PM₁₀ concentration (black circles) in the six major cities (Pusan, Daejeon, Daegu, Gwangju, Incheon, and Ulsan) of South Korea. The years along the x axis represent the starting year of each cold season (e.g., the year 2014 means October 2014–March 2015).

moderate and high PM₁₀ concentrations. The result indicates that low-concentration days have become more frequent in recent years, and vice versa.

Here, to see if the PM₁₀ concentration of Seoul is representative of the air quality of South Korea as a whole, we examined the PM₁₀ concentration in six major cities in South Korea (i.e., Pusan, Daejeon, Daegu, Gwangju, Incheon, and Ulsan). Figure 1c shows the cold-season-mean PM₁₀ concentrations (black circles) of the

FIG. 2. Composites of anomalous FMF for the high- PM_{10} day in Seoul from MODIS/Terra. FMF is the ratio of small mode AOD to the total AOD at $0.55\ \mu\text{m}$. Gray and black dots denote the regions significant at the 90% and 95% confidence levels based on the t test, respectively.

six cities. In accordance with the trend for Seoul (Fig. 1a), the long-term trends were downward. The number of cold-season-mean PM_{10} levels decreased by $8\ \mu\text{g m}^{-3}\ \text{decade}^{-1}$ during the analysis period. Although the trend is smaller than those in Seoul, a notable trend is observed in the five other cities (not shown). There are significant correlations in the PM_{10} concentrations of Seoul with those of the other cities (correlation coefficient r within the range of 0.60–0.91, being 0.73 on average) as well, which means that the PM_{10} concentration of Seoul can represent general air quality in South Korea. This is also consistent with the satellite data analysis results (Fig. 2): positive FMF anomalies in South Korea and northeastern China for high- PM_{10} days in Seoul. This indicates that small-sized particles increased across a vast area, including northeastern China and South Korea, during the high- PM_{10} days in Seoul. These results suggest that PM_{10} concentration in Seoul adequately reflects the PM_{10} level across the entire country. Hence, hereafter, we will utilize only Seoul's PM_{10} concentration data, which are of good quality with regard to the observation in the country, as mentioned in the data and methods section.

To understand the causes of the change in air quality over the large area of South Korea from the perspective of large-scale circulation, we first analyzed the time evolution of geopotential heights for high- PM_{10} episodes. The geopotential heights are plotted from lag day -3 to lag day $+3$ from the onset day of the high PM_{10} episodes (Fig. 3). The typical synoptic weather

pattern to cause high- PM_{10} episodes is the stagnant high pressure system over the Korean Peninsula. During the high- PM_{10} episodes, weather systems move slowly during the entire lag-day period. There is the dominant pattern that a strong anomalous high is located over South Korea, accompanied by an anomalously deep low over the Bering Sea. Considering that the typical geopotential height pattern over East Asia and the North Pacific that is characterized by the west high (Siberian high) and east low (Aleutian low) pressure during the cold season (Rodionov et al. 2005), the large-scale circulation for high- PM_{10} episodes indicates a strong wavy pattern of the annual-mean geopotential height. The synoptic weather systems generally move slowly, because the quasi-stationary large and deep structures, such as the Aleutian low, can slow down the weather systems moving to its east, and vice versa. The negative pressure anomaly over the Bering Sea could obstruct the eastward movement of the anomalous high over South Korea. The low over the Bering Sea deepens further through lag days -3 to -1 , so that it can effectively inhibit the eastward propagation of the high over the north of South Korea, as shown as in lag day -3 (Fig. 3). In fact, from lag day -3 to lag day 0, the high moved slowly southeastward instead of eastward. Consequently, the stagnant high could lead to more stable, less windy, and dry tropospheric conditions, all of which are favorable for the occurrence of high PM_{10} (Lee et al. 2011). After lag day 0, the deepened low over the Bering Sea begins to decay (Figs. 3d–f). At the same time, the high over

FIG. 3. Composite of anomalous geopotential height at 500 hPa from lag day -3 to lag day $+3$ from the day of onset of the high- PM_{10} episodes. Gray and black dots denote the regions significant at the 90% and 95% confidence levels based on the Student's t test, respectively.

South Korea moves rapidly toward the east, finally dissipating on lag day +3. Thus, the standing low over the Bering Sea can be considered as the main trigger for the high-PM₁₀ episodes, while its intensity can be an important precursor for the persistence of the high-PM₁₀ episodes.

Figure 3 suggests that the tropospheric large-scale circulation may have affected high PM₁₀ episodes. To examine the relationship between high-PM₁₀ episodes and large-scale circulations, we identified the days that have an atmospheric circulation pattern identical to the high-PM₁₀ episodes, while not considering the PM₁₀ concentrations. The days are defined as “similar-pattern days with high-PM₁₀ days,” when correlations in their patterns of 500-hPa geopotential heights with the day-0 geopotential height (i.e., the anomalous anticyclonic circulation over East Asia and cyclonic circulation over the Northwest Pacific), as shown in Fig. 3d, are higher than 0.4 over East Asia and the Northwest Pacific (30°–55°N, 100°–175°E). Note that the threshold value, 0.4, is not only statistically significant at the 99% confidence level but also the highest to get a sufficient number of similar-pattern days (i.e., about 40 days). If we apply a higher threshold value, the number of similar-pattern days decreases. Conversely, if we apply a lower one, the statistical significance becomes worse. The similar-pattern days have significantly decreased by 15 days decade⁻¹ (Fig. 4a), indicating less favorable large-scale conditions for the occurrence of high-PM₁₀ episodes. This further implies that the changes in large-scale circulation may have contributed to the recent reduction in the PM₁₀ concentration over South Korea (Fig. 1a). The correlation coefficient between similar-pattern days and the cold-season-mean PM₁₀ concentration is 0.56, which is statistically significant at the 95% confidence level. It is noted that the similar-pattern days are not always related to high-PM₁₀ episodes; the number of picked similar-pattern days is larger (approximately 40 days) than that of the high-PM₁₀ days (approximately 20 days). This indicates other factors also play important roles in determining air quality.

The very well-known primary factors to determine the ambient PM₁₀ level are the amount of emission and precipitation (Gao et al. 2011). Emission is the main source of tropospheric PM₁₀, while rainfall is the major sink because of its wet scavenging effect (Loosmore and Cederwall 2004; Choi et al. 2008; Kim et al. 2014). Therefore, we investigated these two key factors, that is, emission amount of PM₁₀ in Seoul (Fig. 4b) and frequency of light and moderate-to-heavy rainfall (Fig. 4c) in addition to the similar-pattern days.

It should be noted that the method for estimating emissions in South Korea has been changed almost

FIG. 4. (a) Time series of similar-pattern days with high-PM₁₀ episodes when the pattern correlation coefficient of anomalous geopotential height at 500 hPa vs Fig. 3d is higher than 0.4 over the region of 30°–55°N, 100°–175°E; (b) annual-average emission amount of PM₁₀ and emission amount for 2008–14 adjusted to have average difference from 2001 to 2007 with exactly 90% and 99% significance; and (c) frequency of total (black circles), moderate-to-heavy (dark gray circles), and light (gray circles) precipitation during the cold season in Seoul. The emission data are available from the National Air Pollutants Emission Service (<http://airemiss.nier.go.kr/mbshome/mbshome/airemiss/index.do>).

every year. In particular, an abrupt drop of emissions in Seoul occurred in 2008 (Fig. 4b), which would be due to the alteration in the classification system of road-movement pollution sources and the method for estimating them (D. Kim et al. 2010). This change especially contaminates emissions data for megacities like Seoul that cope with heavy vehicular traffic. The big drop shown in Seoul is not observed in other small cities and rural areas (not shown). Therefore, we attempted to adjust the emissions data across the years 2007 and 2008. Let μ_1 and μ_2 (black dotted lines) stand for the mean emissions for two periods 2001–07 and 2008–14, respectively, from the original emissions record (black line in Fig. 4b). We reproduced two new time series (dark and light gray lines in Fig. 4b) by letting the difference between μ_1 and μ_2 become statistically significant at the 90% (90%-drop time series) and 99% (99%-drop time series) confidence levels, respectively. In other words, we left only significant changes at the 90% and 99% confidence levels. On the other hand, there was a major change in the estimation method on emission in 2007; that is to say, the fugitive dust and anthracite are additionally taken into account. As a result, the estimated emission largely increased between 2007 and 2008, particularly in nonurban areas in which many power plants are located (not shown). Our analysis, however, can be regarded as investigations on pure urban areas, since we examined the PM₁₀ levels of Seoul, which is a megacity with about 10 million people. In addition, the urban PM₁₀ levels can be less influenced by nonurban sources. Considering these two points, we could ignore this inconsistency problem between 2007 and 2008. Actually, there was little change in Seoul's emission data between the years (see Fig. 4b).

There are strong negative trends in the original emission data ($-298.5 \mu\text{g m}^{-3} \text{yr}^{-1}$), as well as in the revised data at the 90% ($-88.3 \mu\text{g m}^{-3} \text{yr}^{-1}$) and the 99% ($-135.8 \mu\text{g m}^{-3} \text{yr}^{-1}$) confidence level. Despite the uncertainty in the emission data, the correlation coefficient between the cold-season-mean PM₁₀ level (intensity of high-PM₁₀ episode) and the emissions profiles is in the range of approximately 0.76–0.88 (0.52–0.64). This indicates that a significant portion of the decreased PM₁₀ level in Seoul is affected by the reduced local emissions due to the successful government policy (e.g., a wide use of natural gas busses and introduction of the tenth-day-no-driving system) for controlling air quality in the metropolitan areas, as previously demonstrated (K.-H. Kim et al. 2010; Kim and Shon 2011).

For rainfall (Fig. 4c), there is a slight positive trend, 0.64yr^{-1} , in the frequency of total precipitation. Particularly, the increasing trend, 0.77yr^{-1} , is dominant in the light rain category below 5mm day^{-1} even if light

TABLE 1. Adjusted coefficients of determination for averaged PM₁₀ concentration during the cold season in Seoul with explanatory variables as PM₁₀ emission amount, adjusted emission with 90%- and 99%-significant decrease from the year 2008, similar-pattern days, and precipitation frequency.

	Adjusted coefficients of determination
Emission, similar-pattern days, precipitation frequency	0.72
Adjusted emission (90%), similar-pattern days, precipitation frequency	0.73
Adjusted emission (99%), similar-pattern days, precipitation frequency	0.77
Emission, similar-pattern days	0.74
Adjusted emission (90%), similar-pattern days	0.69
Adjusted emission (99%), similar-pattern days	0.76
Emission, precipitation frequency	0.73
Adjusted emission (90%), precipitation frequency	0.55
Adjusted emission (99%), precipitation frequency	0.71
Similar-pattern days, precipitation frequency	0.34
Emission	0.75
Adjusted emission (90%)	0.55
Adjusted emission (99%)	0.72
Similar-pattern days	0.26
Precipitation frequency	0.05

rainfall is not a good scavenger of PM₁₀ (Choi et al. 2008). The frequency of moderate-to-heavy rainfalls that efficiently remove tropospheric PM₁₀ has decreased by -0.13yr^{-1} .

To explain the relative contributions of each factor (i.e., the similar-pattern days, emission, and precipitation frequency) on reducing the PM₁₀ level over South Korea, multiple linear regression analysis was applied. We used similar-pattern days, the total precipitation frequency, and emission as independent variables. We performed the multiple linear regression in various combinations. Table 1 summarizes the adjusted r^2 value for the mean PM₁₀ concentration during the cold season in Seoul. The result of the multilinear regression using all these variables explains the greatest portion of the change in the cold-season PM₁₀ concentration. Interestingly, the revised emissions profile (Table 1) yields higher r^2 than the original emissions profile (Table 1), indicating that the revised emissions profile better accounts for the changes in the PM₁₀ concentration. Table 2 shows the regression coefficient and corresponding p values for each predictand. The regression coefficients for the emissions profile and the similar-pattern days are positive, but that for precipitation is negative. This indicates that

TABLE 2. Multiple-regression result for averaged PM₁₀ concentration during the cold season in Seoul with explanatory variables as PM₁₀ emission amount, adjusted emission with 90%- and 99%-significant decreases from the year 2008, similar-pattern days, and precipitation frequency.

	Regression coefficients	<i>p</i> value
Intercept	43.08	0.00
Emission	0.01	0.00
Similar-pattern days	0.12	0.41
Precipitation frequency	−0.13	0.47
Intercept	2.79	0.88
Adjusted emission (90%)	0.01	0.00
Similar-pattern days	0.33	0.02
Precipitation frequency	−0.26	0.15
Intercept	16.03	0.26
Adjusted emission (99%)	0.01	0.00
Similar-pattern days	0.23	0.08
Precipitation frequency	−0.18	0.26

our results are reasonable, since more emissions and similar-pattern days increase PM₁₀ level, while more precipitation decreases PM₁₀ level. The similar-pattern days solely explain about 26% of the variance of the PM₁₀ concentrations, while the emissions profile and precipitation explain about 67% and 5% of the variance, respectively.

To find the relationship between change in similar-pattern days and large-scale circulation, Fig. 5 depicts the regression map of 500-hPa geopotential height against the time series of similar-pattern days (Fig. 5a) and the trend of 500-hPa geopotential height over the analysis period (Fig. 5b). Figures 5a and 5b represent nearly the same features with opposite signs. This indicates that the large-scale circulation associated with similar-pattern days has a significant relevance to the intensified Aleutian low, while the Aleutian low has recently become weak. The low pressure anomaly over the Bering Sea turned into a high pressure anomaly (Fig. 5b). This change indicates that the trough became relatively shallower, suggesting that the low pressure system was weaker. Particularly, the fact that the significant decrease in 500-hPa geopotential height is only shown over the Aleutian implies that the weakened Aleutian low is considerably related to the recent decrease of synoptic weather patterns of similar-pattern days over South Korea. The correlation coefficient between the similar-pattern days and the geopotential height over the Aleutian low area is 0.69, implying that the Aleutian low does not account for 100% of the variation of the similar-pattern days although the correlation coefficient is statistically significant at the 99% confidence level. In fact, Zhang et al. (2008) and Giotfelty et al. (2014) implied a possible role of the Aleutian low in transporting the Asian pollution plume from East Asia to North America across

the Pacific by westerly winds. However, the role was just examined as a climatological-mean perspective.

As discussed above, the similar-pattern days can be described as the stagnant high system, hence it may allow air quality to become bad by reducing local wind speed and so vertical mixing. Actually, wind speed in Seoul has become significantly stronger in the recent decades at the 99% confidence level (Fig. S1 in the online supplementary material). The similar-pattern days and the wind speed are significantly correlated with each other ($r = -0.58$) as well. Hence, it can be considered that the decreased frequency of occurrence of similar-pattern days, accelerating the tropospheric flows over South Korea, plays a role in improving the air quality in South Korea.

4. Summary and discussion

This study shows a sharp decline in the PM₁₀ concentration over South Korea in recent years. Through the multilinear regression analysis, we found that a significant variance (approximately 26%) with regard to the improved air quality is explained by the changes in the large-scale tropospheric circulations, although a large portion of the air quality improvement is attributable to reduced emission. Particularly, the recent weakening of the Aleutian low could make the tropospheric flow over South Korea more zonal, which can increase the wind speed across the country, consequently reducing the residence time of air pollutants. Hence, we can say that the change in large-scale tropospheric circulation could have contributed to the recent improvements in air quality in South Korea, along with the decreased emission amount due to the government's emissions control measures.

Another interesting research topic would be to investigate the possible cause of the recently weakened Aleutian low. The weakening of the Aleutian low has become evident after 2001 (not shown). Although this is beyond the scope of the present study, it may be valuable to discuss the possible mechanisms in a future study. Various factors may account for the recent changes in the Aleutian low. The Aleutian low is generally linked to a teleconnection pattern that is strongly affected by the variation in sea surface temperature over the Pacific, such as El Niño–Southern Oscillation (ENSO) and the Pacific decadal oscillation (PDO; Wang et al. 2000; Rodionov et al. 2005; Wang et al. 2012). The relationship between ENSO events and the Aleutian low has been known since the mid-1960s (Bjerknes 1966). In particular, the Pacific–North America (PNA) pattern, which is the downstream effect of ENSO, determines both the strength and the central position of the Aleutian low (Wang et al. 2012). A positive (negative) PNA indicates an intensified (weakened) Aleutian

FIG. 5. Regression map of 500-hPa geopotential height against the (a) similar-pattern days and (b) trend of average anomalous geopotential height at 500 hPa during the cold season. Gray and black dots denote the regions significant at the 90% and 95% confidence levels based on the Student's t test, respectively.

low (Rodionov et al. 2005). Mantua et al. (1997) suggested that the Aleutian low is significantly correlated with the PDO, with the warm (cold) phase of the PDO corresponding to a strong (weak) Aleutian low. Kao et al. (2016) reported that the Aleutian low affected by the negative PDO phase plays a role in the weakening of the East Asian winter monsoon circulation, which is further related to the changes in air quality in East Asia (Li et al. 2016; Yang et al. 2016). The Arctic Oscillation (AO) also can affect the Aleutian low (Overland et al. 1999; Sun and Wang 2006), with a strong AO potentially resulting in the deepening of the Aleutian low. Based on these previous studies, we examine several indices (i.e., PNA, East Asian winter monsoon, PDO, and AO) to account for the recent changes in the Aleutian low. However, we cannot find a significant relationship between the indices and the change in the Aleutian low.

The PDO is more likely to be a factor than others. In fact, the cold phase of the PDO was under way from 2002/03 to 2013/14 (<http://research.jisao.washington.edu/pdo>; Fig. S1). However, some strong peaks during the cold seasons of 2001/02, 2009/10, and 2014/15 could not account for the relatively steady reduction of high-PM₁₀ and similar-pattern days (Figs. 1, 4a; Fig. S2). Presumably, the recently weakened Aleutian low cannot be fully explained by one index. It may be a combined effect such as various large-scale variations and/or global warming. More in-depth investigation on the mechanisms of weakened Aleutian low is necessary, which can be a topic for further study.

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