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Back-trajectory analyses for evaluating the transboundary transport effect to the aerosol pollution in South Korea☆

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ABSTRACT

This study performed a back-trajectory analysis to determine the influence of transboundary transport on the extent of aerosol pollution in South Korea, based on 5-year $PM_{2.5}$ measurements (2015–2019) in five cities covering South Korea. A transboundary transport case was selected if a back trajectory passed over a dedicated region (BOX 1 and BOX 2) in the Yellow Sea. First, we found that the frequency of transboundary transport largely increases in the high pollution case, and this pattern is almost consistent for all months and all five cities, indicating the importance of investigating the horizontal direction of air mass movement associated with $PM_{2.5}$, which has been discussed extensively in previous studies. In this study, we also examined the altitude change and straight moving distance (defined as travel distance) of back trajectories regarding the extent of local $PM_{2.5}$. Consequently, we found that back trajectories in high aerosol pollution showed much lower altitudes and shorter travel differences, implying a significant contribution of surface emissions and stagnant air conditions to severe aerosol pollution. As a result, the local $PM_{2.5}$ level was not significantly enhanced when the air mass passed over the Yellow Sea if transboundary transport occurred at high altitudes with rapid movement (i.e., high altitude and long travel distance back-trajectory). Based on these results, we suggest utilizing the combined information of the horizontal direction, altitude variation, and length of back trajectories to better evaluate transboundary transport.

1. Introduction

The Korean Peninsula is located in East Asia, where the most severe aerosol pollution occurs globally, and the situation is improving (Lee T. et al., 2022; Yeo and Kim, 2022). Public interest in domestic aerosol pollution is relatively high; therefore, an advanced understanding of the properties of airborne aerosols in South Korea is required. Because local emissions contribute to domestic aerosol pollution, improving air quality should begin with accurately detecting emission sources and preparing policies to reduce local emissions. Another significant factor influencing the induction of severe aerosol pollution in South Korea is the contribution of transboundary transport. Haze occurrence in the Korean Peninsula is associated with aerosol or precursor species transported from the outside, supported by many data analyses and public experiences. Both emissions and transboundary transport influence are comparable in South Korea (Bae et al., 2021; de Foy et al., 2021). Nonetheless, our knowledge of the role of transboundary transport remains simple and limited, resulting in deficient quantification and less accurate forecasting of its effects.

Several studies have assessed the pattern of transboundary transport and how it relates to aerosol load in the Korean Peninsula. Initially, a weather chart analysis was conducted to determine the relationship between regional meteorological patterns and the transport of air pollutants into the Korean Peninsula (e.g., Choi and Choi, 2008; Lee et al., 2011; Jeon et al., 2015). Although this approach is useful, the direct chase of air mass movement is limited. This restriction can be resolved using a backward trajectory (hereafter referred to as a back-trajectory analysis). Thus, there have been many studies to perform back-trajectory simulations to investigate aerosol pollution cases, enabling the direct detection of the air mass moving track from the

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source to the receptor region. Despite the modeling uncertainty (Su et al., 2015), the calculated back-trajectories describe the aerosol plume movement well, as confirmed by comparison with surface and satellite measurements (Lee S. et al., 2019; Schade and Gregg, 2022). Thus, back-trajectory analysis is still valid for reliable diagnosis, although some advanced techniques, such as adjoint modeling (Lee et al., 2017; Choi et al., 2019) and modeling to determine sensitivity to the emission source (Kim et al., 2017; Bae et al., 2019) have been recently utilized for the evaluation of the transboundary transport effect. Simulated back-trajectories have been analyzed for specific cases (Lee et al., 2013; Oh et al., 2020; Jung et al., 2021), but general long-term back-trajectory patterns have also often been investigated by applying statistical techniques, such as the potential source contribution function (PSCF) (Heo et al., 2009; Jeong et al., 2011; Choi and Ghim, 2021), suggesting some ideas about the potential source regions associated with severe aerosol pollution in South Korea.

Although there have been many meaningful studies on aerosol pollution in South Korea using back-trajectory datasets, some limitations remain.

(1) The temporal variation of back trajectories has not been extensively discussed. General patterns of back trajectories related to serious haze events or specific campaign periods have been discussed (Lee et al., 2018; Cho et al., 2022), but seasonal and even annual variations in back trajectories have not been thoroughly investigated. Because both the extent of aerosol pollution and meteorological patterns have significant temporal variations in the Korean Peninsula (Koo et al., 2021), it is necessary to inspect the various temporal variations in back-trajectories to better assess the transboundary transport effect.

(2) Even in very recent studies, back-trajectory analyses were only targeted to the Seoul metropolitan area (Lee D. et al., 2019; Kim D. et al., 2022; Kim Y. et al., 2022) or the west of the Korean Peninsula (Lee S. et al., 2019; Oh et al., 2020), and not the whole area of the Korean Peninsula. The implications of these results may not be adequate for analyzing the transport effect on haze occurring east of the Korean Peninsula, where some large cities are located (Busan and Gangneung).

(3) Previous studies focused on the back-trajectory pattern based on the variation of aerosol concentration's 'mean' pattern. This approach is useful but does not explain how transboundary transport differs between strong and weak haze cases and how vital the transboundary transport effect is with severe aerosol pollution in South Korea. For this reason, the range of transboundary transport contributions has not yet converged among relevant studies: moderate (Kim et al., 2016; Lee S. et al., 2021) to large effects (Kim et al., 2009; Lee S. et al., 2019). It is necessary to observe the back-trajectory patterns separately under the level of aerosol pollution.

(4) The moving track (related to wind direction) is usually assessed when the transboundary transport effect is evaluated. However, other influential factors, such as air mass movement's speed or altitude variation, have not been examined in detail. A simple interpretation based on the moving track can only provide a biased idea; for example, westerlies with moderate wind speeds can bring air pollutants from the source region in China to the receptor region in South Korea, but the transported aerosols do not accumulate in the Korean Peninsula if the wind is too fast, owing to the intensified ventilation effect. This feature was partially confirmed by Lee S. et al. (2019) for a limited period in 2016.

Thus, we performed another investigation of back-trajectories to better understand the influence of transboundary transport on Korean aerosol pollution based on a simulation over multiple years (5 years) in multiple regions (five cities) covering South Korea uniformly. This study compares air mass moving tracks between low and high aerosol concentrations, examines transport altitude, and investigates transport speed. By conducting these analyses, we can improve previous findings on the transboundary transport patterns of air pollutants and provide new features that were not significantly recognized in the analysis of aerosol pollution in South Korea.

2. Site and data description

As mentioned, we can determine whether the transboundary transport effect is consistent or different following the location of aerosol pollution. Thus, this study compared aerosol pollution in five cities in South Korea: Seoul (northwestern region), Gwangju (southwestern region), Gangneung (northeastern region), Busan (southeastern region), and Daejeon (central South Korea). The exact locations of these cities are shown in Fig. 1. We used the particulate matter (PM) with an aerodynamic diameter less than or equal to a nominal 2.5 μm ($PM_{2.5}$) for the determination of aerosol pollution. There are other parameters showing the aerosol pollution, such as PM_{10} with an aerodynamic diameter less than or equal to a nominal 10 μm (PM_{10}) or aerosol optical depth (AOD). Since PM_{10} value in Korea largely reflects the property of natural aerosols such as mineral dust (gon Ryou et al., 2018), and AOD is often attributed to the dense aerosol plumes in the free troposphere (Zhai et al., 2021), is the representative used in the environmental studies focusing on the surface air pollution.

Since 2015, there have been several urban air quality monitoring stations operated by local governments or the Ministry of Environment, Republic of Korea: 25 stations in Seoul, seven stations in Gwangju, one station in Gangneung, 19 stations in Busan, and eight stations in Daejeon. The $PM_{2.5}$ has been continuously measured since 2015 based on the β-ray absorption method. Measurement information was obtained from the AIRKOREA web data archive (https://www.airkorea.or.kr/eng/). This $PM_{2.5}$ dataset had been evaluated by the rigorous quality assurance and control processes at multiple stages following the guidelines of NIER and KMOE (2022), and was publicly released as the 'quality-confirmed' data. This 'quality-confirmed' dataset is now the most qualified data in Korea and has been widely utilized for most of PM-related studies in Korea. The $PM_{2.5}$ monitoring stations have been installed with consideration for the surrounding environment and weather conditions, with sampling heights ranging from above 1.5 m to below 10 m above ground level for the sampling of surface air masses (NIER and KMOE, 2022).

To obtain closer general characteristics, we used 5-year measurements (2015–2019) at each site (city) and prepared a representative value by averaging the measured data at all stations in each city. Because of the unique air quality patterns after the coronavirus disease 2019 (COVID-19) outbreak in South Korea and China (Kang et al., 2020; Koo et al., 2020), we did not include observations after 2020 in this analysis.

When the extent of aerosol pollution is diagnosed, specific criteria of the absolute $PM_{2.5}$ value have generally been used. Several previous studies decided the bad haze occurrence in South Korea if the measured $PM_{2.5}$ is higher than the warning criteria (Ghim et al., 2019; Park et al., 2021), which is 35 μg m^{-3}. This approach works well in a fixed location but is challenging to apply to comparisons among multiple locations because the range of $PM_{2.5}$ variation is regionally different. Therefore, using absolute $PM_{2.5}$ criteria is inappropriate for detecting high aerosol pollution in weakly polluted regions. Since this study examines the $PM_{2.5}$ pattern for South Korea, where aerosol pollution in the western area is usually higher than that in the eastern area (Lee J. et al., 2021; Bae et al., 2022), the use of relative $PM_{2.5}$ criteria seems better for assorting cases of low and high aerosol pollution in each region. Therefore, we classified the three levels of aerosol pollution based on the percentile $PM_{2.5}$ values at each city by month: low aerosol pollution for the 5th to 15th percentiles, middle aerosol pollution for the 45th to 55th percentiles, and high aerosol pollution for the 85th to 95th percentiles of

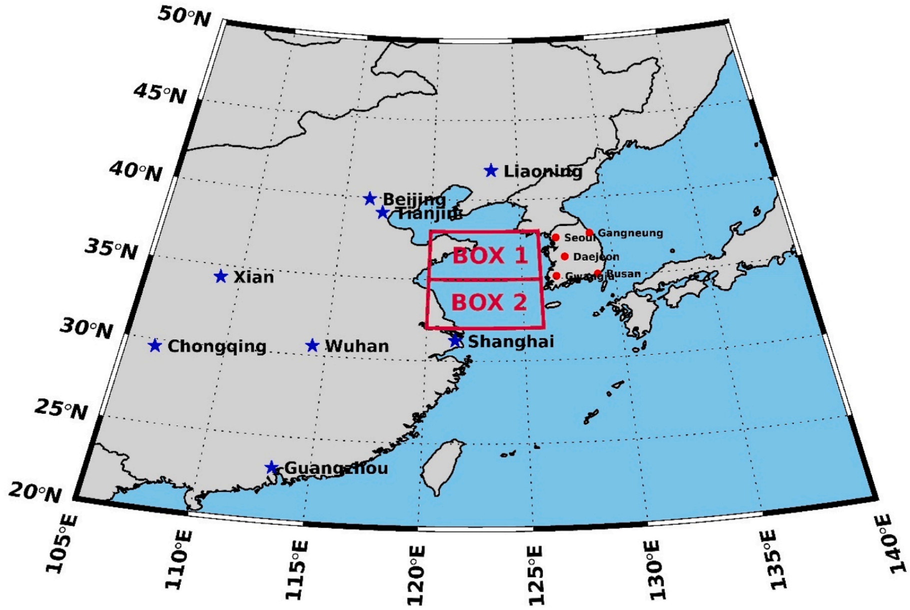

Fig. 1. Locations of 5 cities in South Korea (Seoul, Gwangju, Gangneung, Busan, and Daejeon, red dot) and some cities in China (blue star) are shown. The exact location of 5 cities in South Korea is as next: 37.55°N, 126.99°E (Seoul), 35.16°N, 126.84°E (Gwangju), 37.71°N, 128.83°E (Gangnueng), 35.21°N, 129.07°E (Busan), 36.34°N, 127.39°E (Daejeon). Seoul and Gwangju is remotely located ~20–30 km from the coast, but Gangneung and Busan includes the coast. Daejeon is almost in the middle of South Korea. Also, two rectangular regions in the Yellow Sea (BOX 1 and BOX 2, red line) are depicted, which are used for the decision of transboundary transport (BOX 1: 35 to 38°N and 120 to 126 °E, BOX 2: 32 to 35°N and 120 to 126 °E).

hourly $PM_{2.5}$. The selected data for each case - high, middle, and low – comprises over 300 cases per month, as shown in Table S1.

The patterns of the back trajectories were examined for these three levels of aerosol pollution. The back-trajectory calculation uses the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model developed by the National Oceanic and Atmospheric Administration (Stein et al., 2015). This model calculates the trajectory based on hybrid between the Lagrangian (i.e., moving frame of air-mass location) and Eulerian (i.e., fixed three dimensional grid) approaches. Trajectories are basically calculated by considering the advection components and dispersion process (Draxler and Hess, 1998), and the HYSPLIT model considers the matching of advection and dispersion in backward direction for the back-trajectory calculations. For the proper usage of this modeling, the well-mixed air condition and reversible movement (i.e., without the contact to the surface) is guaranteed (Stein et al., 2015), meaning that the application to the local scale atmosphere results to large uncertainty.

A meteorological field in the calculation was obtained from the Global Data Assimilation System (GDAS) with a $1 \times 1°$ spatial resolution. While the GDAS dataset also provides a higher resolution ($0.5 \times 0.5°$), generally, it is known that the quality of back-trajectory calculation is better with the GDAS $1 \times 1°$ dataset for the PM analysis. Su et al. (2015) compared the information of calculated back-trajectories to the wind velocity measurement, and confirmed the back-trajectories based on the GDAS with $0.5 \times 0.5°$ resolution do not well reflect the observed wind pattern in upper altitudes, resulted in a little difference of vertical movement. In contrast, horizontal moving patterns between back-trajectories from the GDAS $1 \times 1°$ and $0.5 \times 0.5°$ resolution is not much different, probably because the back-trajectory moving velocity is close to the observation (Su et al., 2015).

Our own comparison of calculated back-trajectories showed same lesson: similarity for the horizontal pattern but discrepancy for the vertical movement between back-trajectories from $1 \times 1°$ and $0.5 \times 0.5°$ spatial resolution (Figs. S1, S2, S3, and S4). Difference of vertical movement becomes larger when the higher arrival height is considered (1000 m vs. 50 m), similar to the lesson from Su et al. (2015). In spite of the quantity difference, qualitatively the variation of vertical altitude of back-trajectory depicts similar pattern (Figs. S3 and S4), implying the spatial resolution difference of the utilized meteorology may not alter the main lessons founded from our analyses. Considering all these examination, we decided to use the back-trajectories calculated based on the GDAS $1 \times 1°$ resolution in this study. The analysis of 48- to 72-h back-trajectories has been regarded as an appropriate time range for diagnosing the transboundary transport effect (Kim et al., 2014; Park et al., 2014). Therefore, in this study, 48-h back-trajectories were calculated for five cities every hour from January 1, 2015, to December 31, 2019. We also considered two arrival heights, 50 and 1000 m, to see if there was a significant difference in the transboundary transport pattern between the surface and the top of the boundary layer.

3. Results and discussion

First, back-trajectories in the low, middle, and high aerosol pollution levels were sorted for each city and season (Fig. 2, S5, S6, S7, S8, and S9). Based only on this simple separation, we found a clear difference in the back trajectories regarding $PM_{2.5}$. For example, HYSPLIT model outputs in Seoul (Fig. 2) show that most of the back trajectories indicate northwesterly winds in winter and spring, but the proportion of westerlies passing over eastern China and the Yellow Sea increases with high aerosol pollution. In addition, the travel distance under high aerosol pollution was much shorter than that under low aerosol pollution. The shorter travel distance with more frequent westerlies in Seoul, which has high aerosol pollution, indicates a larger contribution of anthropogenic emissions from eastern China.

The contrast of the back trajectories is evident in summer. HYSPLIT model outputs show that the easterly wind pattern occurs predominantly at low aerosol pollution, typical of advection from oceanic to continental regions during the summer monsoon period. However, the dominant contribution of the westerlies passing over the Yellow Sea was observed at high aerosol pollution levels. Because summertime westerly occurrences are rare in Korea (Koo et al., 2007), the connection between strong westerly (easterly) and high (low) aerosol pollution in Seoul is crucial evidence showing the large impact of transboundary transport on the extent of Korean aerosol pollution. We obtained the same result

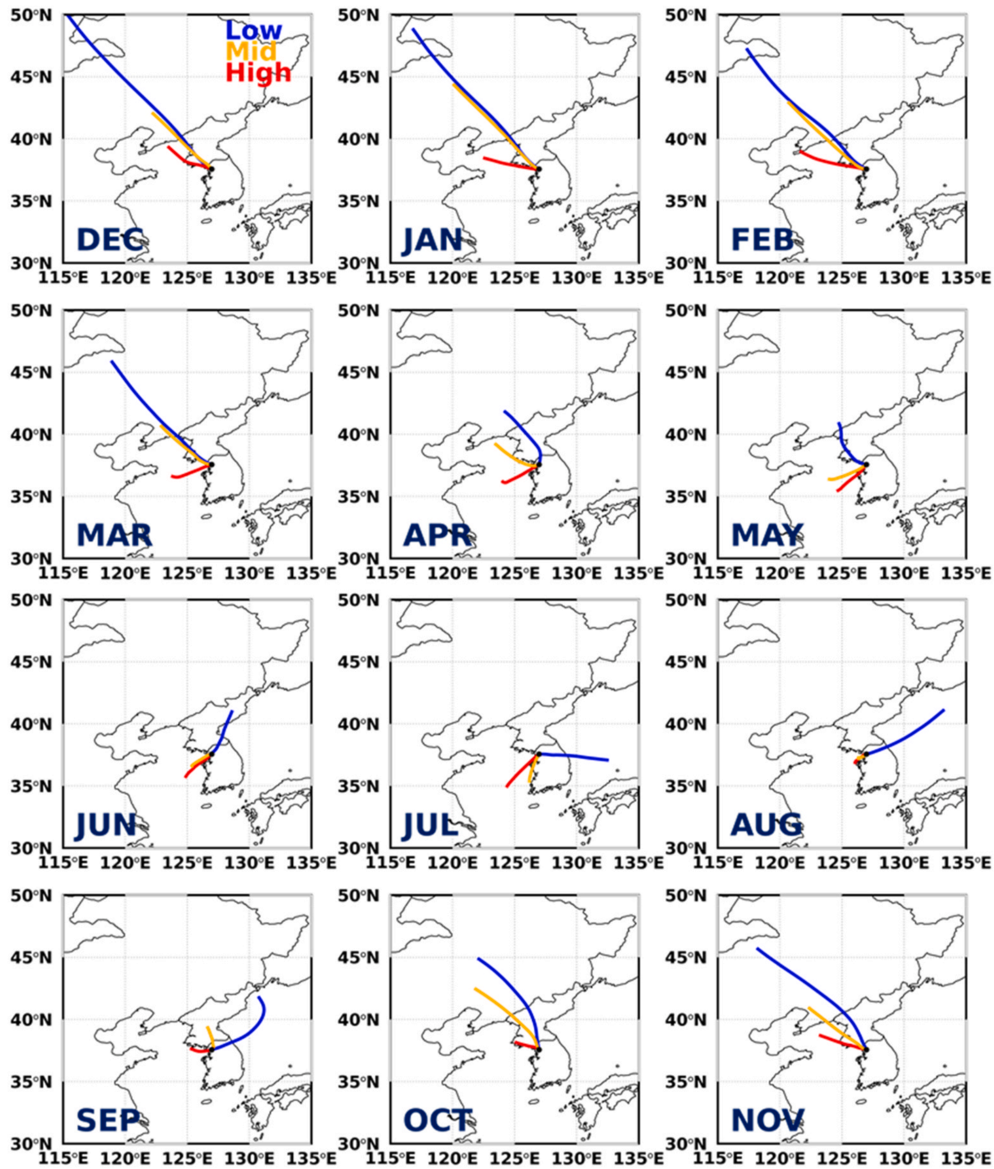

Fig. 2. Mean monthly 48-h back-trajectories for the cases of low (blue), middle (orange), and high (red) aerosol pollution in Seoul are compared for each month from December to November. The arrival height of the back-trajectory was 50 m.

when we expanded this analysis to other cities (Figs. S6, S7, S8, and S9).

For a better expression, we define the transboundary transport frequency (TTF), which represents the portion of transboundary transport cases compared to all cases. A transboundary transport case was considered if a back trajectory ontained from the HYSPLIT modeling passed over the designated region over the Yellow Sea. Considering the back-trajectory pattern (Fig. 2, S5, S6, S7, S8, and S9), we designated two regions: BOX 1 and BOX 2, as shown in Fig. 1. BOX 1 includes the Shandong Peninsula and the nearby Yellow Sea area. BOX 2 is located to the south and has the same longitudinal range as BOX 1. Using BOX 1 and BOX 2 regions, we separately estimated the TTF for each month's low, middle, and high aerosol pollution for all five cities (Fig. 3).

Considering BOX 1 region for detecting transboundary transport, the TTF pattern differs slightly according to the target city. In Seoul and Gangneung, we can find a large enhancement of TTF in high aerosol pollution for all months; for example, TTF was ~10–40 % in low aerosol pollution but ~30–80% in high aerosol pollution in Seoul (Fig. 3). In Daejeon and Busan, mostly we can see the same enhancement of TTF in high aerosol pollution was observed; however, irregular patterns (i.e., high TTF in low aerosol pollution) were partially observed in some winter months. The TTF pattern was significantly different at Gwangju; The TTF pattern did not show consistent variation according to the level of aerosol pollution. In summary, the influence of air mass transport over the Yellow Sea area between the Shandong Peninsula and the Seoul metropolitan area (SMA) (i.e., BOX 1) is strongly connected to high aerosol pollution in the north of South Korea, as in the case of Seoul and Gangneung (Fig. 1). However, it is not associated with aerosol pollution in other cities located in the southern part of South Korea.

We examined the reason for this regional difference when BOX 1 was considered. Fig. 4 is an example case from January, showing all back-trajectories in low aerosol pollution in Seoul (Fig. 4a) and Gwangju (Fig. 4b). Both cases illustrate the same transport pattern with a fast northwesterly movement from northern China. Gwangju is located south of Seoul; however, most of these back trajectories for low aerosol pollution at Gwangju pass over BOX 1 region. As a result, we cannot distinguish the difference in back-trajectory patterns between low and high aerosol pollution in Gwangju using only BOX 1 region. In contrast, considering BOX 1 region has the benefit of splitting the back-trajectory pattern between low and high aerosol in northern South Korea (Seoul and Gangneung).

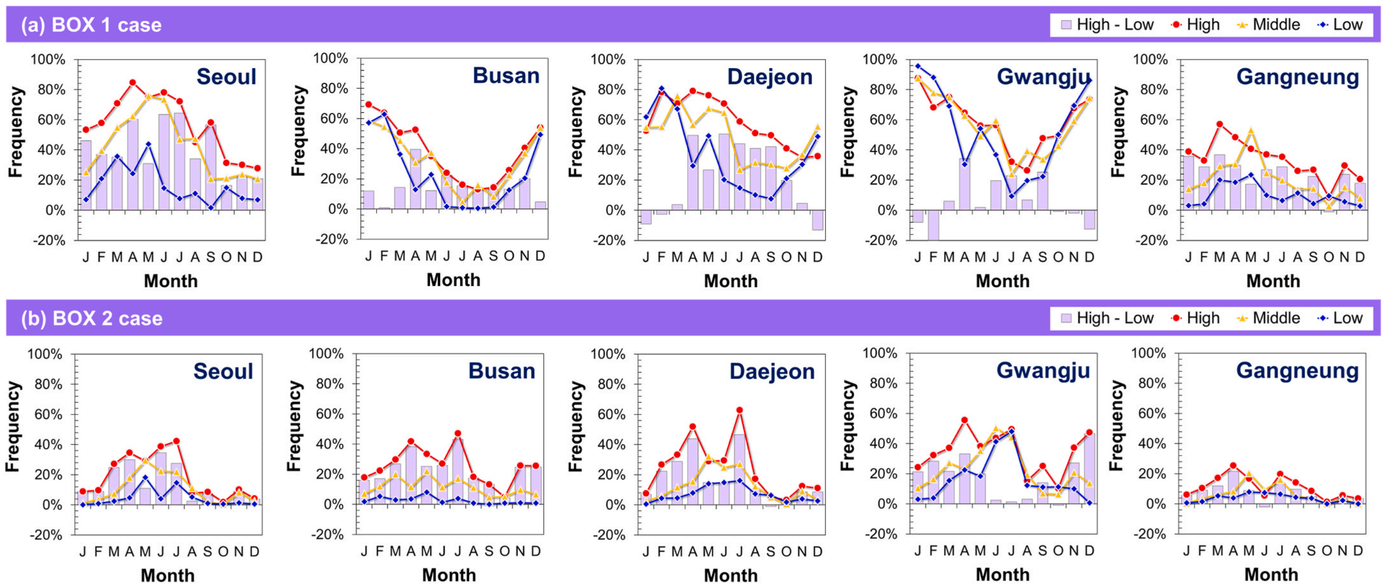

Fig. 3. Monthly variation of the transboundary transport frequency for the low (blue), middle (yellow), and high (red), aerosol pollution at five cities (Seoul, Busan, Daejeon, Gwangju, and Gangneung), based on the consideration of BOX 1 (top) and BOX 2 (bottom) region in the Yellow Sea. Monthly difference of the transboundary transport frequency between high and low (high – low) is also shown (purple bar).

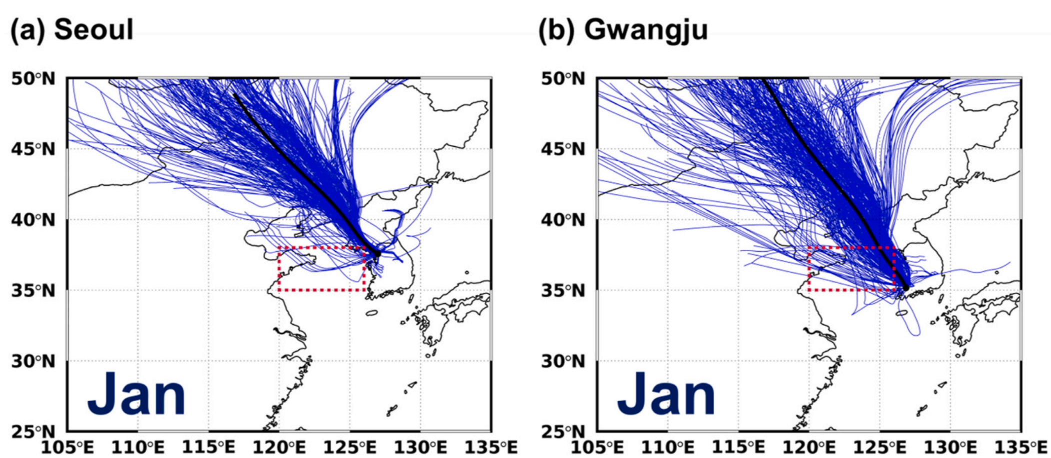

Fig. 4. Comparison of all 48-h back-trajectories in low aerosol pollution at (a) Seoul and (b) Gwangju for January cases only. BOX 1 region is also depicted (red dash).

Alternatively, we repeated the TTF estimation considering BOX 2 region, located southwest of the Korean peninsula (Fig. 1). As a result, the estimated TTF was consistently higher under high aerosol pollution for all five cities and seasons (Fig. 3b), describing the large connection between the air mass in southern China and the air quality of South Korea. Compared to the TTF estimation by considering BOX 1 region (mostly related to transport from eastern China, where the North China Plain is located), the total TTF diminishes significantly, meaning that the inflow of air mass transport from the south of China has a relatively smaller contribution to aerosol pollution in South Korea. In addition, the estimated TTF with BOX 2 consideration is generally higher in summer because the wind pattern from the ocean to land is more intense in summer due to the general pattern of the East Asian summer monsoon system.

Based on these analyses, we recognize that considering the Yellow Sea area (i.e., BOX 1 and 2 regions) is a good approach for depicting the transboundary transport effect on high aerosol pollution in South Korea, which supports the findings of previous studies (Bhardwaj et al., 2019). Consideration of BOX 1 region seems influential in determining the influence of air pollution in the North China Plain, and the Jing-Jin-Ji area (Li et al., 2021), and that of BOX 2 region seems to connect to air pollution in the Yangtze River Delta (Wang and Wang, 2021). In this context, we conducted an additional analysis to determine the difference in mean $PM_{2.5}$ between cases with and without transboundary transport, as summarized in Table 1. All five cities clearly show a large $PM_{2.5}$ enhancement (i.e., mean $PM_{2.5}$ for cases with transboundary transport is higher than mean $PM_{2.5}$ for cases without transboundary transport) when transboundary transport occurs, regardless of BOX 1 and BOX 2 regions. In particular, the $PM_{2.5}$ enhancement in Seoul was the largest due to the influence of transboundary transport.

In addition to horizontal variation, we investigated the altitude change of the back-trajectories in terms of the level of aerosol pollution. Fig. 5 illustrates the mean altitude variation of 48-h back-trajectories during each season for the cases of high, middle, and low aerosol pollution. In general, HYSPLIT model outputs obviously show that the back-trajectory movement in the high-pollution case occurs at a lower altitude range, that is, in the boundary layer with an average of 1–1.5 km as a typical daily maximum boundary layer height in South Korea (Lee J.

Table 1
Summary of $PM_{2.5}$ enhancements by the transboundary transport for considering either BOX 1 or BOX 2 region ($PM_{2.5}$ for the case with transboundary transport/$PM_{2.5}$ for the case without transboundary transport).

Month	BOX 1					BOX 2				
	Seoul	Busan	Daejeon	Gwangju	Gangneung	Seoul	Busan	Daejeon	Gwangju	Gangneung
Jan	171%	111%	91%	85%	168%	180%	146%	154%	151%	166%
Feb	141%	102%	104%	74%	142%	142%	131%	158%	156%	142%
Mar	139%	113%	102%	106%	149%	164%	139%	162%	131%	139%
Apr	178%	144%	167%	136%	133%	150%	159%	171%	145%	147%
May	135%	112%	131%	104%	115%	112%	131%	117%	124%	116%
Jun	175%	140%	160%	119%	135%	148%	153%	119%	101%	93%
Jul	198%	157%	172%	135%	146%	146%	168%	180%	102%	128%
Aug	141%	121%	155%	105%	123%	108%	149%	124%	104%	130%
Sep	203%	142%	172%	132%	148%	154%	163%	101%	136%	138%
Oct	126%	115%	130%	102%	97%	151%	123%	121%	102%	164%
Nov	133%	119%	104%	100%	142%	134%	149%	125%	142%	121%
Dec	132%	103%	86%	85%	161%	133%	159%	146%	190%	216%

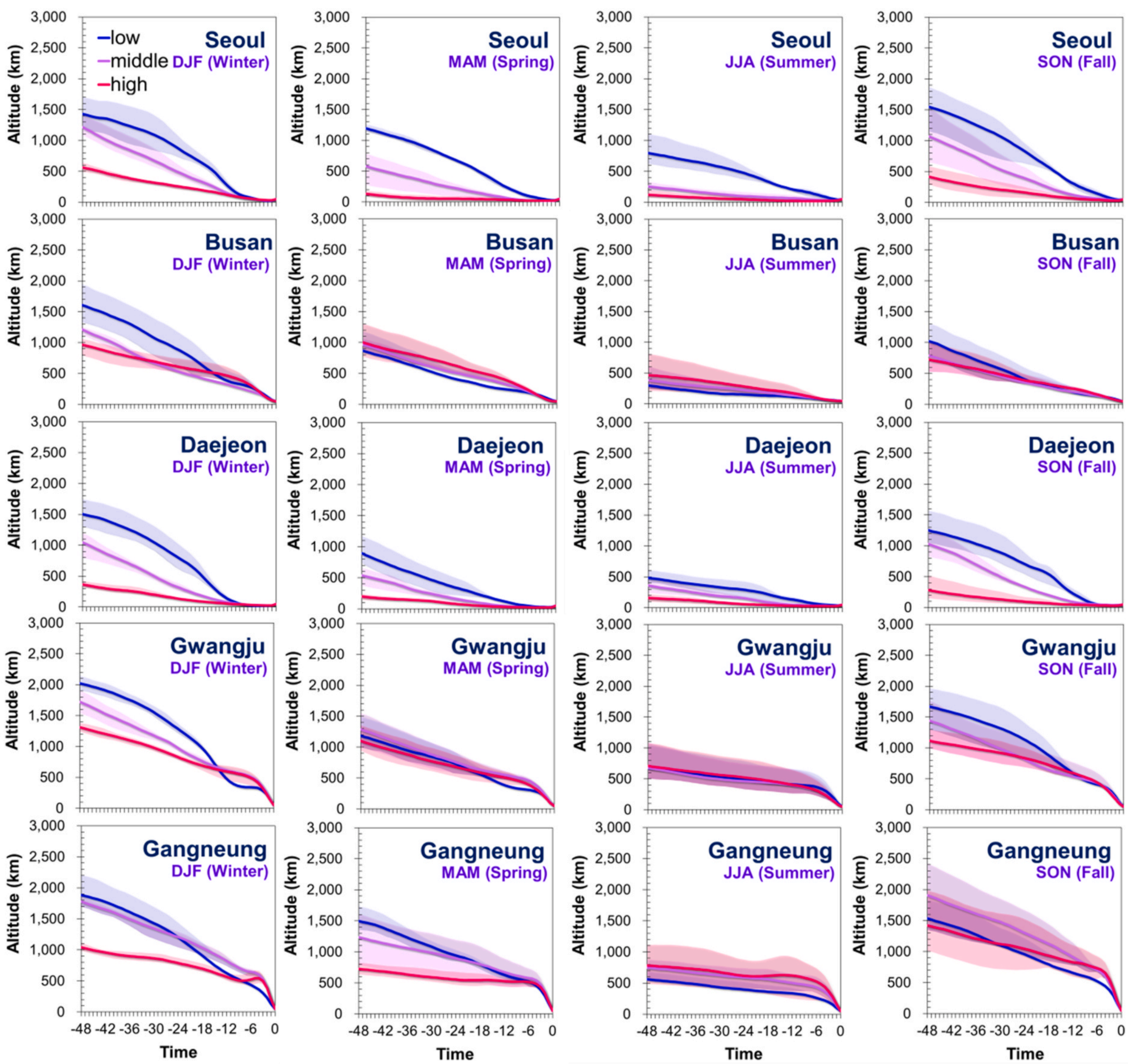

Fig. 5. Mean hourly change of altitude in 48-h back-trajectories in high (red), middle (purple), and low (blue) aerosol pollution cases for all seasons (winter, spring, summer, and fall) at five cities (Seoul, Busan, Daejeon, Gwangju, and Gangneung). Back-trajectories are calculated from 2015 to 2019, and the arrival height is 50 m. The shaded area describes each aerosol pollution case's maximum and minimum monthly mean.

et al., 2019; Min et al., 2020). This feature indicates that the larger contribution of surface emissions during transboundary transport results in high $PM_{2.5}$ levels in South Korea. The altitude difference between low and high aerosol pollution is relatively weaker in summer when the wind intensity decreases around the Korean Peninsula (Koo et al., 2007). In addition, HYSPLIT model outputs obviously show that the altitude difference was the smallest in Busan, probably because it was the farthest location from the emission source. If we repeat the comparison of the altitude differences among low, medium, and high aerosol pollution using only back-trajectories passing over BOX 1 or BOX 2 regions (Figs. S10 and S11), the addressed altitude change is also well found (BOX 1 cases are slightly more distinctly), meaning that the larger the free-tropospheric air mass transport is added, the lower the aerosol pollution occurs despite the air mass passing over the Yellow Sea.

Finally, we examined whether there was a relationship between the extent of local aerosol pollution and the moving distance of the back-trajectory (implying the speed of transboundary transport). Here, the ’travel distance’ is defined as the straight distance between the location of each back-trajectory at 0 and 48 h before the arrival. All travel distance values estimated using the HYSPLIT model outputs were averaged for the high, middle, and low aerosol pollution cases and compared for the five cities (Fig. 6). Surprisingly, the mean travel distance was much shorter in high aerosol pollution, even with a 1000-km difference during two days (48 h) in winter between low and high pollution cases. This pattern indicates the importance of ventilation in improving the air quality. Slow transboundary transport significantly worsens aerosol pollution in South Korea due to air pollutant accumulation.

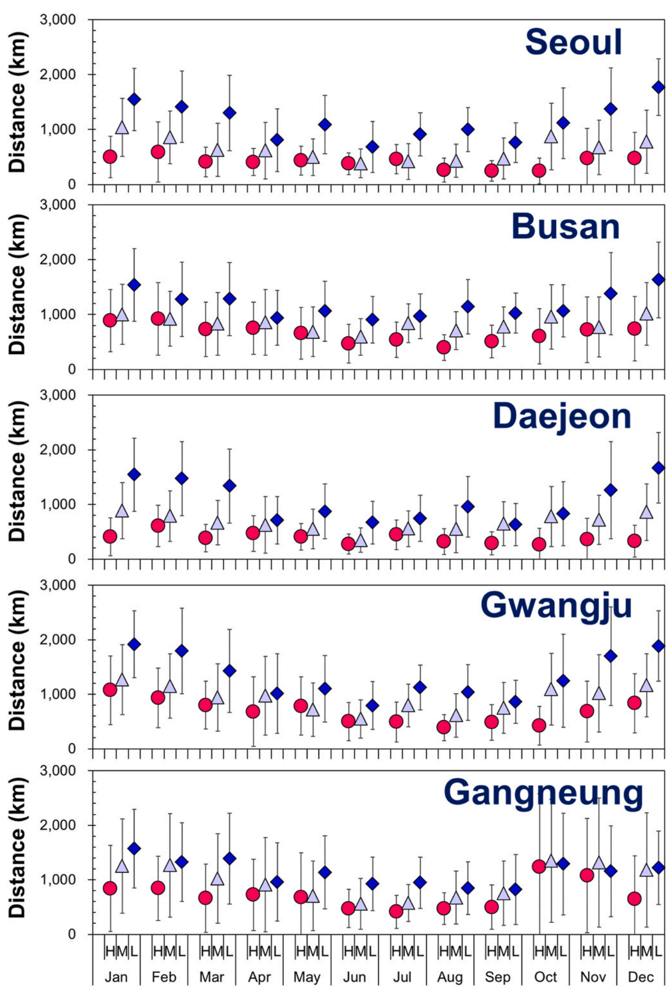

Fig. 6. Travel distance of all 48-h back-trajectories in high (H, red dot), middle (M, gray dot), and low (L, blue dot) aerosol pollution cases at five cities (Seoul, Busan, Daejeon, Gwangju, and Gangneung). Back-trajectories are calculated from 2015 to 2019, and the arrival height is 50 m. Vertical bars describe the range of 1-sigma standard deviation for each mean pattern

If we combine this ’travel distance’ information with the horizontal direction of the back trajectory obtained from the HYSPLIT model outputs, the evaluation of transboundary transport becomes clearer. Table 2 shows that the enhancement of $PM_{2.5}$ by the air mass transport passing over BOX 1 and BOX 2 regions in the Yellow Sea is the largest when the travel distance is from 500 to 1500 km (Table 2). This characteristic was pronounced when BOX 1 region. Because the straight distance between Gangneung (i.e., the east coast) and Incheon (i.e., the west coast at the same latitude as Gangneung) is only approximately 200 km, the high enhancement of $PM_{2.5}$ in Gangneung with a travel distance from 500 to 1500 km, implies that severe aerosol pollution is significantly affected by the inflow of external air pollutants emitted from outside of the Korean peninsula (North China Plain).

Some significant emission sources are located in the domestic area, such as the Daesan industrial complex in Seosan (located on the west coast of South Korea), which is a representative example (Duncan et al., 2016). If the emissions here are significant to aerosol pollution in South Korea, the largest enhancement of $PM_{2.5}$, should be found with a shorter travel distance (e.g., less than 500 km in Table 2). While the domestic emission effect also relates to the $PM_{2.5}$ enhancement, we can say that transboundary transport outside South Korea is strongly connected to severe aerosol pollution in South Korea, limited to the west coast and the whole country. If the travel distance was higher than 2000 km, PM in all five cities was not significantly enhanced, despite the consideration of air mass transport across BOX 1 and BOX 2 regions, except for some cases in cities located far from China (Table 2), owing to the strong ventilation effect. It shows that the analysis of the transboundary transport effect is insufficient only regarding wind direction. We would underline the necessity of analyzing the travel distance of air mass transport (i.e., the length of the back-trajectory) to avoid under or overestimation in the evaluation of the transboundary transport effect.

Thus far, our analyses have used back trajectories obtained from the HYSPLIT model outputs arriving at an altitude of 50 m in the five cities. If we repeat the same analyses using back-trajectories arriving at an altitude of 1000 m, we do not observe a large difference in the horizontal back-trajectory patterns between the 50-m and 1000-m arrival cases (Figs. S5, S6, S7, S8, and S9). The differences in altitude and travel distance of 1000-m arrival back-trajectories between high and low aerosol pollution (Fig. S13) are not as drastic as in the 50-m arrival cases, but the key lessons of our findings do not change in general. These properties suggest that the transboundary transport effect occurs near the surface but is valid at the top of the boundary layer in South Korea, which is consistent with the findings of previous studies (Lee H. et al., 2019; 2022).

4. Summary and conclusion

In this study, we investigated the mean characteristic of 5-year (2015–2019) back-trajectories in five cities in South Korea to determine the extent to which transboundary transport affects local aerosol pollution. We found that the westerlies across the Yellow Sea are mostly related to high aerosol pollution. Considering a single region in the Yellow Sea does not perfectly describe the transboundary transport effect for all five cities; therefore, designating multiple regions seems to be a better approach. We also examined the altitude change and travel distance of back trajectories between low and high aerosol pollution and detected a significant difference: a strong influence of transboundary transport at lower altitudes with shorter travel to high pollution. In terms of the evaluation of transboundary transport, many previous back-trajectory studies have placed a large weight on the horizontal direction (i.e., east, west, south, or north) only; however, here, we would suggest the importance of utilizing the information of the altitude (i.e., above or below the boundary layer) and distance (i.e., fast or slow) of the air mass

Table 2
Comparison of $PM_{2.5}$ enhancements by the transboundary transport for considering either BOX 1 or BOX 2 region ($PM_{2.5}$ for the case with transboundary transport/ $PM_{2.5}$ for the case without transboundary transport) following the travel distance.

Distance (D)	BOX 1					BOX 2				
	Seoul	Busan	Daejeon	Gwangju	Gangneung	Seoul	Busan	Daejeon	Gwangju	Gangneung
D < 500 km	119%	116%	121%	107%	120%	112%	107%	114%	112%	104%
500 km ≤ D < 1000 km	188%	160%	200%	151%	172%	156%	164%	156%	129%	144%
1000 km ≤ D < 1500 km	131%	173%	144%	178%	147%	135%	193%	96%	98%	170%
1500 km ≤ D < 2000 km	98%	149%	110%	140%	110%	117%	192%	71%	115%	105%
D ≥ 2000	105%	126%	112%	113%	108%	0%	196%	0%	161%	158%

movement together.

Based on this study, we recognized that a combined analysis of the direction, altitude, and travel distance of back trajectories can better describe the characteristics of the transboundary transport effect, contributing to the enhanced quality of the $PM_{2.5}$ forecasting system in South Korea (Jeong et al., 2022; Koo et al., 2023) and the application of Geostationary Environment Monitoring Spectrometer (GEMS) measurements for the hourly monitoring of East Asian air pollutants by 2020 (Kim et al., 2020) will enable the advanced evaluation of transboundary transport. As Chinese air quality is rapidly improving now (Ma et al., 2019; Zhang et al., 2021), updated results in the future will provide new and different discussion points.

The 'long-range transport (LRT)' terminology is discussed in the conclusion. In several studies on air quality in South Korea, the word 'LRT' is often used to examine the influence of anthropogenic emission sources in overseas countries (e.g., the Jing-Jin-Ji area). However, some LRT analyses are also related to transporting Asian dust from deserts in northern China and Mongolia (Choo et al., 2021; Park et al., 2021), which are natural emission sources. This dust event is crucial for Korean air quality, but it is significantly different because the dust particles largely contribute to coarse-mode aerosols, not fine-mode aerosols ($PM_{2.5}$). In addition, LRT is often very rapid; therefore, it may not affect surface air quality. Without a clear definition of LRT in a specific study, it is challenging to determine the meaning of the main findings and apply them in real-world situations. In this context, we recommend using or including the term 'transboundary' to evaluate the transport effect from the outside country to the domestic region.

CRediT authorship contribution statement

Ja-Ho Koo: Conceptualization, Formal analysis, Methodology, Writing – original draft. **Donghee Lee:** Methodology, Software, Visualization. **Hyejin Bae:** Methodology, Software, Visualization. **Taegyung Lee:** Software, Visualization. **Seong Gyun Na:** Software, Visualization. **Sang-Wook Yeh:** Formal analysis, Writing – review & editing. **Jinsoo Park:** Methodology, Writing – review & editing. **Minju Yeo:** Conceptualization, Supervision, Writing – review & editing.

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

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2024.124031.

References

Bae, C., Kim, B.-U., Kim, H.C., Yoo, C., Kim, S., 2019. Long-range transport influence on key chemical components of $PM_{2.5}$ in the Seoul Metropolitan Area, South Korea, during the Years 2012–2016. Atmosphere 11 (1), 48. https://doi.org/10.3390/atmos11010048.

Bae, M., Kim, B.-U., Kim, H.C., Kim, J., Kim, S., 2021. Role of emissions and meteorology in the recent $PM_{2.5}$ changes in China and South Korea from 2015 to 2018. Environ. Pollut. 270, 116233 https://doi.org/10.1016/j.envpol.2020.116233.

Bae, M., Kim, B.-U., Kim, H.C., Woo, J.-H., Kim, S., 2022. An observation-based adjustment method of regional contribution estimation from upwind emissions to downwind $PM_{2.5}$ concentrations. Environ. Int. 163, 107214 https://doi.org/10.1016/j.envint.2022.107214.

Bhardwaj, P., Ki, S.J., Kim, Y.H., Woo, J.H., Song, C.K., Park, S.Y., Song, C.H., 2019. Recent changes of trans-boundary air pollution over the Yellow Sea: implications for future air quality in South Korea. Environ. Pollut. 247, 401–409. https://doi.org/10.1016/j.envpol.2019.01.048.

Cho, J.-H., Kim, H.-S., Yoon, M.-B., 2022. The influence of atmospheric blocking on regional PM_{10} aerosol transport to South Korea during February–March of 2019. Atmos. Environ. 277, 119056 https://doi.org/10.1016/j.atmosenv.2022.119056.

Choi, H., Choi, D.S., 2008. Concentrations of PM_{10}, $PM_{2.5}$, and PM_1 influenced by atmospheric circulation and atmospheric boundary layer in the Korean mountainous coast during a duststorm. Atmos. Res. 89 (4), 330–337. https://doi.org/10.1016/j.atmosres.2008.03.018.

Choi, J., Park, R.J., Lee, H.-M., Lee, S., Jo, D.S., Jeong, J.I., Henze, D.K., Woo, J.-H., Ban, S.-J., Lee, M.-D., Lim, C.-S., Park, M.-K., Shin, H.J., Cho, S., Peterson, D., Song, C.-K., 2019. Impacts of local vs. trans-boundary emissions from different sectors on $PM_{2.5}$ exposure in South Korea during the KORUS-AQ campaign. Atmos. Environ. 203, 196–205. https://doi.org/10.1016/j.atmosenv.2019.02.008.

Choi, Y., Ghim, Y.S., 2021. Variations in major aerosol components from long-term measurement of columnar aerosol optical properties at a SKYNET site downwind of Seoul, Korea. Atmos. Environ. 245, 117991 https://doi.org/10.1016/j.atmosenv.2020.117991.

Choo, G.-H., Lee, K., Seo, J., Kim, S.-Y., Lee, D.-W., Shin, H.-J., 2021. Optical and chemical properties of long-range transported aerosols using satellite and ground-based observations over Seoul, South Korea. Atmos. Environ. 246, 118024 https://doi.org/10.1016/j.atmosenv.2020.118024.

de Foy, B., Heo, J., Kang, J.-Y., Kim, H., Schauer, J.J., 2021. Source attribution of air pollution using a generalized additive model and particle trajectory clusters. Sci. Total Environ. 780, 146458 https://doi.org/10.1016/j.scitotenv.2021.146458.

Draxler, R.R., Hess, G.D., 1998. An overview of the HYSPLIT_4 modeling system for trajectories, dispersion, and deposition. Aust. Meteorol. Mag. 47, 295–308.

Duncan, B.N., Lamsal, L.N., Thompson, A.M., Yoshida, Y., Lu, Z., Streets, D.G., Hurwitz, M.M., Pickering, K.E., 2016. A space-based, high-resolution view of notable changes in urban NOx pollution around the world (2005–2014). J. Geophys. Res. Atmos. 121 (2), 976–996. https://doi.org/10.1002/2015JD024121.

Ghim, Y.S., Choi, Y., Park, J., Kim, S., Bae, C.H., Seo, J., Shin, H.J., Lim, Y.J., Lyu, Y.S., Lee, Y.J., 2019. Overall characteristics of nationwide high $PM_{2.5}$ episodes during 2013~ 2016. Journal of Korean Society for Atmospheric Environment 35 (5), 609–624. https://doi.org/10.5572/KOSAE.2019.35.5.60 (in Korean with English abstract).

gon Ryou, H., Heo, J., Kim, S.-Y., 2018. Source apportionment of PM_{10} and $PM_{2.5}$ air pollution, and possible impacts of study characteristics in South Korea. Environ. Pollut. 240, 963–972. https://doi.org/10.1016/j.envpol.2018.03.066.

Heo, J.-B., Hopke, P.K., Yi, S.-M., 2009. Source apportionment of $PM_{2.5}$ in seoul, Korea. Atmos. Chem. Phys. 9 (14), 4957–4971. https://doi.org/10.5194/acp-9-4957-2009.

Jeon, W., Choi, Y., Lee, H.W., Lee, S.-H., Yoo, J.-W., Park, J., Lee, H.-J., 2015. A quantitative analysis of grid nudging effect on each process of $PM_{2.5}$ production in the Korean Peninsula. Atmos. Environ. 122, 763–774. https://doi.org/10.1016/j.atmosenv.2015.10.050.

Jeong, D., Yoo, C., Yeh, S.-W., Yoon, J.-H., Lee, D., Lee, J.-B., Choi, J.-Y., 2022. Statistical seasonal forecasting of winter and spring $PM_{2.5}$ concentrations over the Korean Peninsula. Asia-Pacific Journal of Atmospheric Sciences 58 (4), 549–561. https://doi.org/10.1007/s13143-022-00275-4.

Jeong, U., Kim, J., Lee, H., Jung, J., Kim, Y.J., Song, C.H., Koo, J.-H., 2011. Estimation of the contributions of long range transported aerosol in East Asia to carbonaceous aerosol and PM concentrations in Seoul, Korea using highly time resolved measurements: a PSCF model approach. J. Environ. Monit. 13 (7), 1905–1918. https://doi.org/10.1039/C0EM00659A.

Jung, E., Seo, S., Chang, K.-H., Yum, S.-S., Heo, B.-H., 2021. Aerosol properties within and above the planetary boundary layer across the Korean peninsula during December 2016. Atmosphere 12 (10), 1299. https://doi.org/10.3390/atmos12101299.

Kang, Y.-H., You, S., Bae, M., Kim, E., Son, K., Bae, C., Kim, Y., Kim, B.-U., Kim, H.C., Kim, S., 2020. The impacts of COVID-19, meteorology, and emission control policies on $PM_{2.5}$ drops in Northeast Asia. Sci. Rep. 10 (1), 1–8. https://doi.org/10.1038/s41598-020-79088-2.

Kim, B.M., Seo, J., Kim, J.Y., Lee, J.Y., Kim, Y., 2016. Transported vs. local contributions from secondary and biomass burning sources to $PM_{2.5}$. Atmos. Environ. 144, 24–36. https://doi.org/10.1016/j.atmosenv.2016.08.072.

Kim, D.-Y., de Foy, B., Kim, H., 2022. The investigations on organic sources and inorganic formation processes and their implications on haze during late winter in Seoul, Korea. Environ. Res. 212, 113174 https://doi.org/10.1016/j.envres.2022.113174.

Kim, H.C., Kim, E., Bae, C., Cho, J.H., Kim, B.-U., Kim, S., 2017. Regional contributions to particulate matter concentration in the Seoul metropolitan area, South Korea: seasonal variation and sensitivity to meteorology and emissions inventory. Atmos. Chem. Phys. 17, 10315–10332. https://doi.org/10.5194/acp-17-10315-2017.

Kim, J., Jeong, U., Ahn, M.-H., Kim, J.H., Park, R.J., Lee, H., Song, C.H., Choi, Y.-S., Lee, K.-H., Yoo, J.-M., Jeong, M.-J., Park, S.K., Lee, K.-M., Song, C.-K., Kim, S.-W., Kim, Y.J., Kim, S.-W., Kim, M., Go, S., Liu, X., Chance, K., Miller, C.C., Al-Saadi, J., Veihelmann, B., Bhartia, P.K., Torres, O., Abad, G.G., Haffner, D.P., Ko, D.H., Lee, S. H., Woo, J.-H., Chong, H., Park, S.S., Nicks, D., Choi, W.J., Moon, K.-J., Cho, A., Yoon, J., Kim, S.-k., Hong, H., Lee, K., Lee, H., Lee, S., Choi, M., Veefkind, P., Levelt, P.F., Edwards, D.P., Kang, M., Eo, M., Bak, J., Baek, K., Kwon, H.-A., Yang, J., Park, J., Han, K.M., Kim, B.-R., Shin, H.-W., Choi, H., Lee, E., Chong, J., Cha, Y., Koo, J.-H., Irie, H., Hayashida, S., Kasai, Y., Kanaya, Y., Liu, C., Lin, J., Crawford, J. H., Carmichael, G.R., Newchurch, M.J., Lefer, B.L., Herman, J.R., Swap, R.J., Lau, A. K.H., Kurosu, T.P., Jaross, G., Ahlers, B., Dobber, M., Thomas McElroy, C., Choi, Y., 2020. New era of air quality monitoring from space: geostationary Environment Monitoring Spectrometer (GEMS). Bull. Am. Meteorol. Soc. 101 (1), E1–E22. https://doi.org/10.1175/BAMS-D-18-0013.1.

Kim, Y., Kim, S.-W., Yoon, S.-C., Kim, M.-H., Park, K.-H., 2014. Aerosol properties and associated regional meteorology during winter pollution event at Gosan climate observatory, Korea. Atmos. Environ. 85, 9–17. https://doi.org/10.1016/j.atmosenv.2013.11.041.

Kim, Y.J., Woo, J.-H., Ma, Y.-I., Kim, S., Nam, J.S., Sung, H., Choi, K.-C., Seo, J., Kim, J. S., Kang, C.-H., Lee, G., Ro, C.-U., Chang, D., Sunwoo, Y., 2009. Chemical characteristics of long-range transport aerosol at background sites in Korea. Atmos. Environ. 43 (34), 5556–5566. https://doi.org/10.1016/j.atmosenv.2009.03.062.

Koo, J.-H., Kim, J., Kim, M.-J., Cho, H.K., Aoki, K., Yamano, M., 2007. Analysis of aerosol optical properties in seoul using skyradiometer observation. Atmosphere 17 (4), 407–420 (in Korean with English abstract).

Koo, J.-H., Lee, J., Kim, J., Eck, T.F., Giles, D.M., Holben, B.N., Park, S.S., Choi, M., Kim, N., Yoon, J., Lee, Y.G., 2021. Investigation of the relationship between the fine mode fraction and Ångström exponent: cases in Korea. Atmos. Res. 248, 105217 https://doi.org/10.1016/j.atmosres.2020.105217.

Koo, J.-H., Kim, J., Lee, Y.G., Park, S.S., Lee, S., Chong, H., Cho, Y., Kim, J., Choi, K., Lee, T., 2020. The implication of the air quality pattern in South Korea after the COVID-19 outbreak. Sci. Rep. 10 (1), 1–11. https://doi.org/10.1038/s41598-020-80429-4.

Koo, Y.-S., Kwon, H.-Y., Bae, H., Yun, H.-Y., Choi, D.-R., Yu, S., Wang, K.-H., Koo, J.-S., Lee, J.-B., Choi, M.-H., Lee, J.-B., 2023. A development of $PM_{2.5}$ forecasting system in South Korea using chemical transport modeling and machine learning. Asia-Pacific Journal of Atmospheric Sciences 1–19. https://doi.org/10.1007/s13143-023-00314-8.

Korea Ministry of Environment (KMOE), National Institute of Environmental Research (NIER), 2022. Guidelines for Installation and Operation of Air Quality Monitoring Networks. NIER-GP2022-001, Incheon. (in Korean).

Lee, D., Choi, J.-Y., Myoung, J., Kim, O., Park, J., Shin, H.-J., Ban, S.-J., Park, H.-J., Nam, K.P., 2019. Analysis of a severe $PM_{2.5}$ episode in the Seoul Metropolitan area in South Korea from 27 February to 7 March 2019: focused on estimation of domestic and foreign contribution. Atmosphere 10 (12), 756. https://doi.org/10.3390/atmos10120756.

Lee, H.-J., Jo, Y.-J., Kim, S., Kim, D., Kim, J.-M., Choi, D., Jo, H.-Y., Bak, J., Park, S.-Y., Jeon, W., Kim, C.-H., 2022. Transboundary aerosol transport process and its impact on aerosol-radiation-cloud feedbacks in springtime over Northeast Asia. Sci. Rep. 12 (1), 4870. https://doi.org/10.1038/s41598-022-08854-1.

Lee, H.-J., Jo, H.-Y., Kim, S.-W., Park, M.-S., Kim, C.-H., 2019. Impacts of atmospheric vertical structures on transboundary aerosol transport from China to South Korea. Sci. Rep. 9 (1), 13040 https://doi.org/10.1038/s41598-019-49691-z.

Lee, H.-M., Park, R.J., Henze, D.K., Lee, S., Shim, C., Shin, H.-J., Moon, K.-J., Woo, J.-H., 2017. $PM_{2.5}$ source attribution for Seoul in May from 2009 to 2013 using GEOS-Chem and its adjoint model. Environ. Pollut. 221, 377–384. https://doi.org/10.1016/j.envpol.2016.11.088.

Lee, J., Hong, J.-W., Lee, K., Hong, J., Velasco, E., Lim, Y.J., Lee, J.B., Nam, K., Park, J., 2019. Ceilometer monitoring of boundary-layer height and its application in evaluating the dilution effect on air pollution. Boundary-Layer Meteorol. 172, 435–455. https://doi.org/10.1007/s10546-019-00452-5.

Lee, J., Koo, J.-H., Kim, S.-M., Lee, T., Lee, Y.G., 2021. Comparison of aerosol properties in the Korean peninsula between AERONET version 2 and 3 data set. Asia-Pacific Journal of Atmospheric Sciences 57 (3), 629–643. https://doi.org/10.1007/s13143-020-00221-2.

Lee, S., Ho, C.-H., Choi, Y.-S., 2011. High-PM_{10} concentration episodes in Seoul, Korea: background sources and related meteorological conditions. Atmos. Environ. 45 (39), 7240–7247. https://doi.org/10.1016/j.atmosenv.2011.08.071.

Lee, S., Ho, C.-H., Lee, Y.G., Choi, H.-J., Song, C.-K., 2013. Influence of transboundary air pollutants from China on the high-PM_{10} episode in Seoul, Korea for the period October 16–20, 2008. Atmos. Environ. 77, 430–439. https://doi.org/10.1016/j.atmosenv.2013.05.006.

Lee, S., Hong, J., Cho, Y., Choi, M., Kim, J., Park, S.S., Ahn, J.-Y., Kim, S.-K., Moon, K.-J., Eck, T.F., Holben, B.N., Koo, J.-H., 2018. Characteristics of classified aerosol types in South Korea during the maps-seoul campaign. Aerosol Air Qual. Res. 18 (9), 2195–2206. https://aaqr.org/articles/aaqr-17-11-maps-0474.

Lee, S., Kim, J., Choi, M., Hong, J., Lim, H., Eck, T.F., Holben, B.N., Ahn, J.-Y., Kim, J., Koo, J.-H., 2019. Analysis of long-range transboundary transport (LRTT) effect on Korean aerosol pollution during the KORUS-AQ campaign. Atmos. Environ. 204, 53–67. https://doi.org/10.1016/j.atmosenv.2019.02.020.

Li, Z., Yang, X., Zhao, C., Fan, T., 2021. Ratio of $PM_{2.5}$ to PM_{10} mass concentrations in Beijing and relationships with pollution from the North China plain. Asia-Pacific Journal of Atmospheric Sciences 57, 421–434. https://doi.org/10.1007/s13143-020-00203-4.

Ma, Z., Liu, R., Liu, Y., Bi, J., 2019. Effects of air pollution control policies on $PM_{2.5}$ pollution improvement in China from 2005 to 2017: a satellite-based perspective. Atmos. Chem. Phys. 19 (10), 6861–6877. https://doi.org/10.5194/acp-19-6861-2019.

Min, J.-S., Park, M.-S., Chae, J.-H., Kang, M., 2020. Integrated system for atmospheric boundary layer height estimation (ISABLE) using a ceilometer and microwave radiometer. Atmos. Meas. Tech. 13 (12), 6965–6987. https://doi.org/10.5194/amt-13-6965-2020.

Oh, H.-R., Ho, C.-H., Koo, Y.-S., Baek, K.-G., Yun, H.-Y., Hur, S.-K., Choi, D.-R., Jhun, J.-G., Shim, J.-S., 2020. Impact of Chinese air pollutants on a record-breaking PMs episode in the Republic of Korea for 11–15 January 2019. Atmos. Environ. 223, 117262 https://doi.org/10.1016/j.atmosenv.2020.117262.

Park, D.-H., Kim, S.-W., Kim, M.-H., Yeo, H., Park, S.S., Nishizawa, T., Shimizu, A., Kim, C.H., 2021. Impacts of local versus long-range transported aerosols on PM_{10} concentrations in Seoul, Korea: an estimate based on 11-year PM_{10} and lidar observations. Sci. Total Environ. 750, 141739 https://doi.org/10.1016/j.scitotenv.2020.141739.

Park, M.E., Song, C.H., Park, R.S., Lee, J., Kim, J., Lee, S., Woo, J.-H., Carmichael, G.R., Eck, T.F., Holben, B.N., Lee, S.-S., Song, C.K., Hong, Y.D., 2014. New approach to monitor transboundary particulate pollution over Northeast Asia. Atmos. Chem. Phys. 14 (2), 659–674. https://doi.org/10.5194/acp-14-659-2014.

Schade, G.W., Gregg, M.L., 2022. Testing HYSPLIT plume dispersion model performance using regional hydrocarbon monitoring data during a gas well blowout. Atmosphere 13 (3), 486. https://doi.org/10.3390/atmos13030486.

Stein, A.F., Draxler, R.R., Rolph, G.D., Stunder, B.J.B., Cohen, M.D., Ngan, F., 2015. NOAA's HYSPLIT atmospheric transport and dispersion modeling system. Bull. Am. Meteorol. Soc. 96, 2059–2077. https://doi.org/10.1175/BAMS-D-14-00110.1.

Su, L., Yuan, Z., Fung, J.C.H., Lau, A.K.H., 2015. A comparison of HYSPLIT backward trajectories generated from two GDAS datasets. Sci. Total Environ. 506, 527–537. https://doi.org/10.1016/j.scitotenv.2014.11.072.

Wang, M., Wang, H., 2021. Spatial distribution patterns and influencing factors of $PM_{2.5}$ pollution in the Yangtze River delta: empirical analysis based on a GWR model. Asia-Pacific Journal of Atmospheric Sciences 57, 63–75. https://doi.org/10.1007/s13143-019-00153-6.

Yeo, M.J., Kim, Y.P., 2022. Long-term trends and affecting factors in the concentrations of criteria air pollutants in South Korea. J. Environ. Manag. 317, 115458 https://doi.org/10.1016/j.jenvman.2022.115458.

Zhai, S., Jacob, D.J., Brewer, J.F., Li, K., Moch, J.M., Kim, J., Lee, S., Lim, H., Lee, H.C., Kuk, S.K., Park, R.J., Jeong, J.I., Wang, X., Liu, P., Luo, G., Yu, F., Meng, J., Martin, R.V., Travis, K.R., Hair, J.W., Anderson, B.E., Dibb, J.E., Jimenez, J.L., Campuzano-Jost, P., Nault, B.A., Woo, J.-H., Kim, Y., Zhang, Q., Liao, H., 2021. Relating geostationary satellite measurements of aerosol optical depth (AOD) over East Asia to fine particulate matter ($PM_{2.5}$): insights from the KORUS-AQ aircraft campaign and GEOS-Chem model simulations. Atmos. Chem. Phys. 21, 16775–16791. https://doi.org/10.5194/acp-21-16775-2021.

Zhang, Q., Pan, Y., He, Y., Walters, W.W., Ni, Q., Liu, X., Xu, G., Shao, J., Jiang, C., 2021. Substantial nitrogen oxides emission reduction from China due to COVID-19 and its impact on surface ozone and aerosol pollution. Sci. Total Environ. 753, 142238 https://doi.org/10.1016/j.scitotenv.2020.142238.