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Determination of Upwind and Downwind Areas of Seoul, Korea Using Trajectory Analysis

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ABSTRACT

To identify the domains that have the greatest impacts on air quality at the surface, both the upwind and downwind areas of Seoul were determined by season using refined wind fields. Four consecutive days were selected as the study period typical of each season. The mesoscale meteorology of the study period was reproduced by using the MM5 prognostic meteorological model (PSU/NCAR Mesoscale Model) with horizontally nested grids. The gridded meteorological field, which was used on the study area of 242 km × 226 km with grid spacing of 2 km, was generated by using the CALMET diagnostic meteorological model. Upwind and downwind areas of Seoul were determined by calculating 24-hour backward and forward air parcel trajectories, respectively, with u, v, and w velocity vectors. The results showed that the upwind and downwind areas were extended far to the northwest and the southeast as a result of high wind speeds in the spring and winter, while they were restricted on the fringe of Seoul in the summer and fall.

Key words: MM5, CALMET, Backward/forward trajectories, Upwind/downwind areas, Seasonal variation

1. INTRODUCTION

The greater Seoul area (GSA), comprising Seoul, Incheon, and Gyeonggi Province, is one of the most populous metropolitan areas in the world with 24 million people and 7.6 million cars in an area of 11,745 km^2 (Land Portal, 2010). The GSA covers about 12% of South Korea's land mass, but its population and number of vehicles account for 50% and 46% of the total population and number of vehicles, respectively. About 40% of the people and cars reside within Seoul proper, an area of 605 km^2 that comprises only 5% of the GSA's land. Emissions of carbon monoxide from the GSA, which have a high proportion of emissions from mobile sources, accounted for about 44% of South Korea's national total, and those from Seoul proper represented about 47% of those from the GSA (Korean Ministry of Environment, 2008). About 30% of the national total of nitrogen oxide (NO_x) emissions are from the GSA, about 28% of which are released from Seoul proper. Air quality in the GSA, including Seoul proper, has significantly improved since the 1980s as a result of continuous efforts to address air pollution; however, the concentration levels of particulate matter and ozone, and the pollution indices (such as for visibility) are still much higher than they are in other areas (Ghim, 2005).

Long-range transport of air pollutants is a frequently discussed topic, along with local emissions, to identify the characteristics of the atmospheric environment in Seoul and the GSA (Ghim, 2005). Located in the northwest of South Korea, the GSA is most directly affected by emissions from the east coast of China, which flow into the GSA along with prevailing northwesterly winds. However, it is still not known how and how much of the upper-level transport of air pollutants from China affects air concentrations at the surface level in Seoul. A large number of aircraft measurement data on SO_2 and NO_x in the Yellow Sea indicate influences of local emissions rather than those of transport, considering high concentrations within the boundary layer, as approaching the coast (Han *et al.*, 2006). SO_2 concentrations measured by a ship crossing the Yellow Sea are high only near the coastal areas but very low on the sea (Kim *et al.*, 2010). Air-quality modeling demonstrates the transport of air pollutants over the continent and the ocean (Uno *et al.*, 2004; Song and Carmichael, 2001), but its impact on the air quality at the surface level cannot be ascertained because of the limitations of the vertical grid resolution.

Variations at the surface might be different between sea and land, and even more different in urban areas with high-rise buildings (Baklanov *et al.*, 2007; Dupont *et al.*, 2004; Kovalets *et al.*, 2004; Kusaka *et al.*, 2001). Several papers mention the contribution of transport to elevated ozone levels in the GSA, but high-ozone episodes since the 1990s occurred under relatively low wind speeds of less than 1.5 m/s (Ghim *et al.*, 2001). This result can be understood in a similar context as pointed out by WHO (2006), suggesting that long-range transport and regional-scale variations contribute to background concentrations in urban areas, while high pollutant episodes result primarily from local emissions.

The "Special Measures for Air Quality Improvement in the Seoul Metropolitan Area" program has been implemented in the GSA since 2005. In the basic plan to support this, maximum allowable emission rates were assigned to each local government, such as Seoul, Incheon, and Gyeonggi Province, which in turn are establishing and administering implementation plans to reduce the emissions. Local governments in the GSA share the airshed, but air pollutants are managed by each local government. Seoul is located downwind of Incheon under prevailing westerly winds and is surrounded by Gyeonggi Province. There is growing attention to exchanges of air pollutants between Seoul and surrounding cities, and additional monitoring stations have been established recently to investigate these further (Seoul Development Institute, 2010).

In this study, upwind and downwind areas of Seoul were determined by estimating backward and forward air parcel trajectories. The backward trajectory identifies upwind sources, which could affect the air quality of Seoul. The forward trajectory identifies downwind areas, whose air quality is affected by sources from Seoul. To determine upwind and downwind areas associated with air quality at the surface level, wind fields were developed on 2-km horizontal resolution grids, and air parcels to track their trajectories were released at a height of 10 m. Identifying the domain that directly affects air quality at the surface level under given meteorological conditions can aid in the design of the monitoring network for air pollutants and the development of air quality management plans by cities and provinces.

2. METHODS

To determine the upwind and downwind areas of Seoul using the backward and forward trajectory analyses by season, study periods that would be representative of each season were selected and then refined wind fields for selected days were developed. These procedures are explained below.

Four consecutive days that represent typical days of each season in terms of wind speed, wind direction, and ambient temperature were selected by reviewing the meteorological data from 1997 in order to investigate seasonal variations, as shown in Table 1. Days on which there was precipitation were excluded to avoid abrupt changes in meteorology. The year 1997 has no special meaning; rather, an attempt was made to select typical days in each season. Nevertheless, a comparison of the values in Table 1 with 30-year averages (Korea Meteorological Administration, 2001) reveals that wind speeds were slightly lower except in spring and the temperatures were generally higher. These differences are probably due to the exclusion of precipitation days and changes in meteorology associated with land use changes in the GSA during the past 30 years. In particular, average wind speeds in Seoul have tended to decrease since the 1970s (Ghim, 2000). Changes in wind patterns are presumably associated with rapid urban development of large-scale apartment complexes and high-rise office buildings in the GSA.

A mesoscale wind field during the study period was reproduced with an MM5 prognostic 3-dimensional meteorological model (PSU/NCAR Mesoscale Model, http://www.mmm.ucar.edu/mm5/) with horizontally nested grids. The grid spacing was reduced from the 108-km value of Grid I to the 36-km, 12-km, and 4-km values of Grids II, III, and IV, respectively. The re-analysis data from the National Center for Environmental Prediction/National Center for Atmospheric Research at 6-hour intervals with grid spacing of $2.5° \times 2.5°$ was used for initial and boundary values. A refined wind field with grid spacing of 2 km for the domain of 242 km × 226 km (Fig. 1) was developed by using the CALMET diagnostic three-dimensional meteorological model, which was provided as a com-

Table 1. Selected meteorological conditions by season at the Seoul weather station in 1997.

Season	Study period (month/day)	Average wind speed (m/s)	Average temperature (°C)	Precipitation (mm)
Spring	4/20-4/23	3.2	14.9	0
Summer	7/26-7/29	1.6	29.4	0
Fall	9/28-10/1	1.3	18.2	0
Winter	1/14-1/17	2.1	−1.8	Negligible

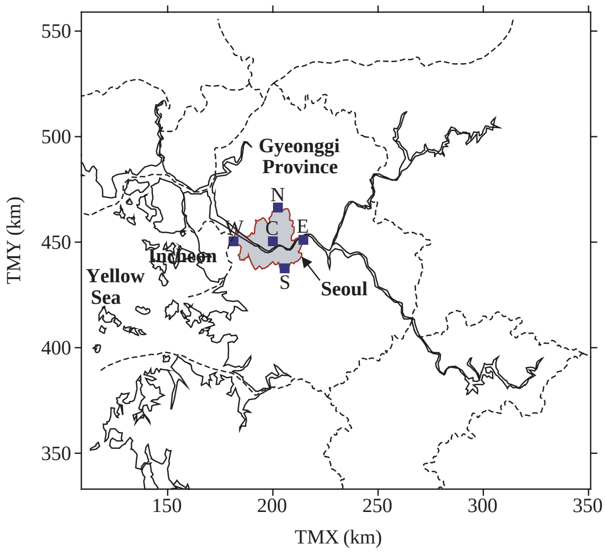

Fig. 1. CALMET modeling domain with origins of the trajectories for determining upwind and downwind areas of Seoul. C, N, E, S, and W denote the center, north, east, south, and west of Seoul, respectively. Dashed lines denote provincial or special administrative region boundaries.

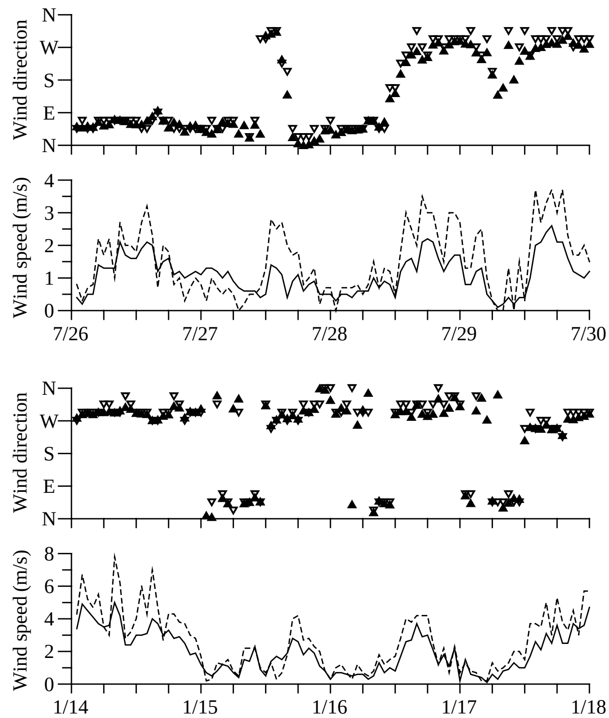

Fig. 2. Comparisons of wind directions and wind speeds between observations at Seoul Weather Station (open symbol and dashed line) and CALMET results (solid symbol and solid line) for the study periods of 7/26-7/29 and 1/14-1/17.

ponent of the CALPUFF modeling system, a non-steady-state meteorological and air quality modeling system (http://www.src.com/calpuff/calpuff1.htm). The output from MM5 on Grid IV was used as an "initial-guess" wind field for CALMET. Observed data from 35 surface weather stations (SWSs) and 172-187 automatic weather stations (AWSs), as well as 2 to 3 upper air stations over the southern half of the Korean Peninsula, were obtained from these observation sites. In the CALMET wind field, six vertical layers were defined up to 1,500 m above ground level (AGL) by placing the cell face at 0, 20, 50, 100 m and so on, while there were 23 layers to 100 hectopascals (hPa) in the MM5 wind field.

Fig. 2 shows comparisons of wind direction and speed between observations at the Seoul Weather Station and CALMET results at its nearest grid cell for summer (7/26-7/29) and winter (1/14-1/17). For both periods, CALMET results capture the general patterns of observed wind direction and speed. However, wind speeds from CALMET are a little lower than those from the observation site. This result might be attributable to the use of observation data obtained from AWSs, which are affected by the local setting and thus have relatively lower wind speeds (Kim and Ghim, 2002).

Isentropic analysis was widely used in the regional-scale trajectory analysis, under the assumption that many atmospheric processes do occur under isentropic (constant entropy) conditions (Kim *et al.*, 2007). However, trajectories were calculated every second with u, v, and w velocity vectors in this study. Air parcels were released twice per day (at 09:00 and 21:00 local standard time [LST]) at the surface level (i.e., at a 10-m height) from five locations (i.e., the center of and the eastern, western, northern, and southern boundaries of Seoul), as shown in Fig. 1. Per season, a total of 30 release scenarios of air parcels (5 locations × twice per day × 3 days) were exercised for each of backward and forward trajectory analysis. The upwind area was determined by identifying the locations of the 24-hour backward trajectory of air parcels for three days. For example, in spring, backward trajectories were started on April 21, 22, and 23, and their locations on April 20, 21, and 22 were identified. The downwind area was similarly determined by identifying the locations of 24-hour forward trajectories, which were started on April 20, 21, and 22 in the spring.

3. RESULTS AND DISCUSSION

Fig. 3 shows selected wind fields at the surface (10-m AGL) by season, as developed by CALMET. By using the wind data from AWSs where local influences

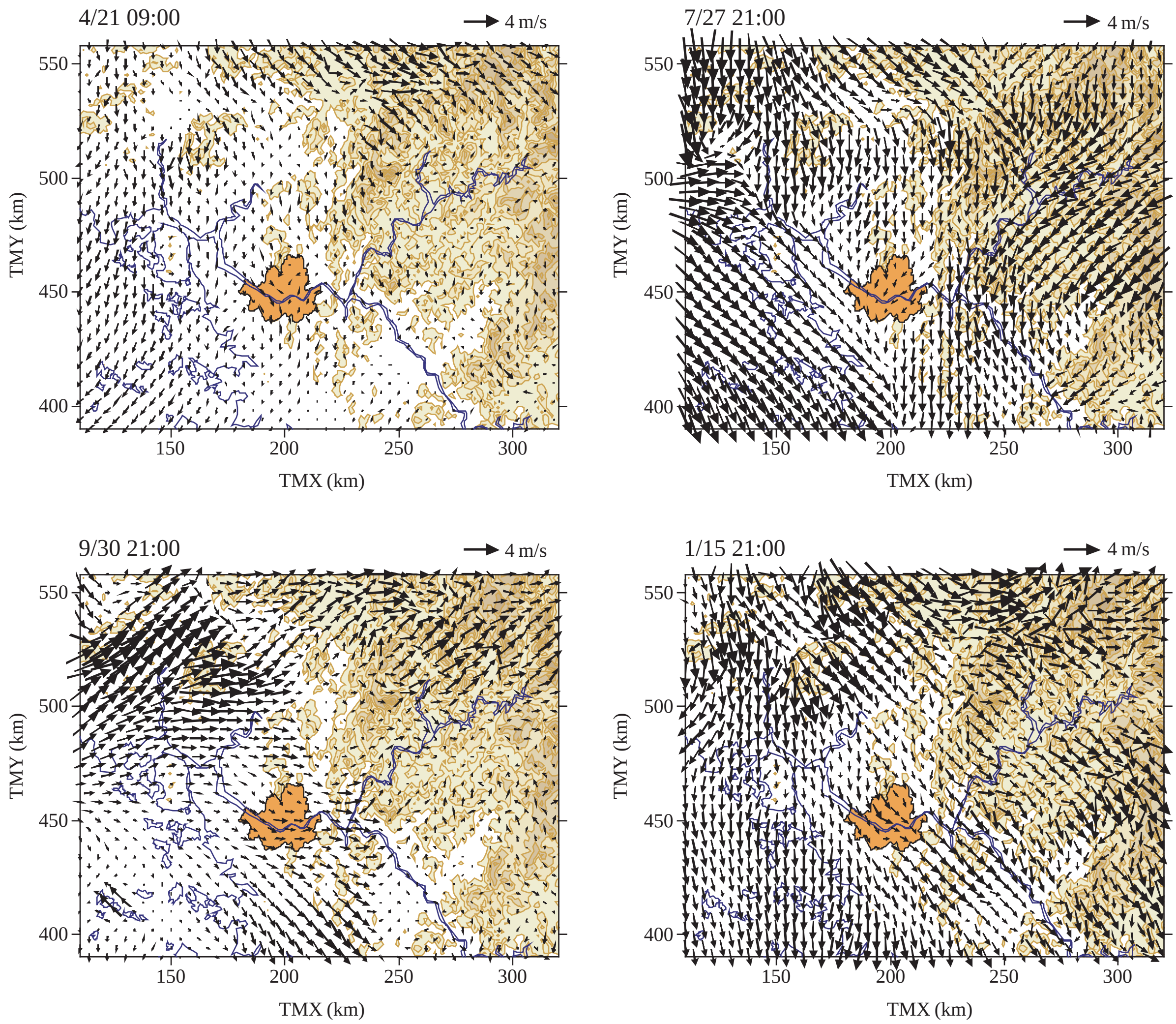

Fig. 3. Selected wind fields at the surface (10-m AGL) by season (top row, spring [left] and summer [right]; bottom row, fall [left] and winter [right]), developed by CALMET. Shaded area in the middle denotes Seoul proper, and filled contours represent topography at 200-m intervals.

were strong (Kim and Ghim, 2002), the terrain effects were distinct on the mountainous area in the east, in contrast to high wind speeds observed over the sea especially at night in the summer (i.e., on 7/27 at 21:00 LST). In addition, since the wind speeds from the AWSs were generally lower than those from the SWSs that are observing the regional-scale variations, wind speeds in Fig. 3 were also lower than MM5-generated wind speeds, which do not explicitly consider observational data.

Fig. 4 shows 24-hour backward trajectories starting from the center of Seoul. Since air parcels released twice per day for three days were tracked, a total of six trajectories are shown. Scattering of the trajectory location at one-hour intervals indicates fast movement of air parcels, along with high wind speeds in spring and winter. In spring, most air parcels arriving at Seoul originate from the southwest-to-north. Some backward trajectories are out of the CALMET modeling domain because of high wind speeds. In winter, most trajectories come from the northwest because of the strong synoptic wind typical of winter.

Clustered trajectories in a small area represent the slow movement of air mass resulting from the low wind speeds that are typical in summer and fall. In summer, the variability of trajectories implies variable wind directions. In fall, when the wind speed is the lowest, backward trajectories originate from the immediate eastern and western areas of Seoul, and some trajectories tend to rotate around Seoul. Accordingly,

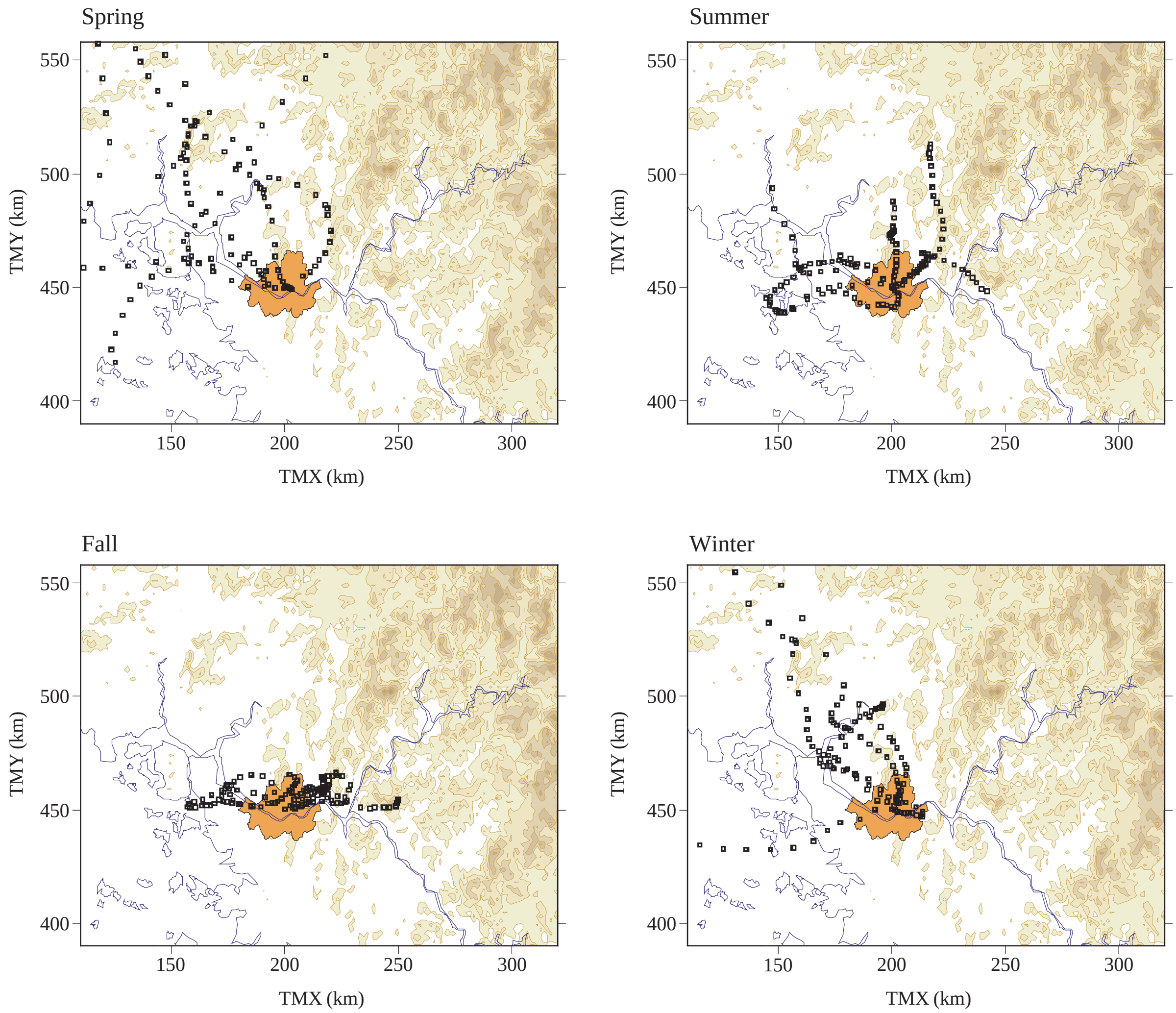

Fig. 4. The 24-hour backward trajectories starting from the center of Seoul, by season. The locations of the trajectories are shown at one-hour intervals.

under favorable meteorological conditions in summer and fall, air pollution episodes could be possible resulting from accumulation and chemical reactions of freshly emitted sources and aged pollutants hovering around Seoul. No backward trajectories originate from the south of Seoul since there are no wind components from the south in Seoul throughout the year. In most cases, travel distances of air parcels for 24 hours are limited to around 120 km in fall. However, travel distances of air parcels exceed more than 200 km in spring and winter, which is outside of the CALMET modeling domain.

Overall features of the forward trajectory were similar to those of the backward trajectory, as shown in Fig. 5. However, since the forward trajectories are generally heading southeastward into the mountainous area, they are more influenced by topography. In spring, forward trajectories are proceeding toward the south and southeast in a more orderly manner, compared with the backward trajectories. The reverse is true for winter. In summer and fall when wind speeds are relatively low, travel distances are short, and trajectories are heading to the east or west, although some tend to rotate around Seoul.

The upwind and downwind areas determined in the current study are given in Fig. 6. Note that the upwind and downwind areas were determined by the final locations of 24-hour backward and forward trajectories, respectively. The backward and forward trajectories released at five locations (see Fig. 1) twice per day for three days were tracked, and thus a total of sixty locations of air parcels (30 backward and 30 forward) are drawn in Fig. 6.

In spring and winter, the upwind and downwind

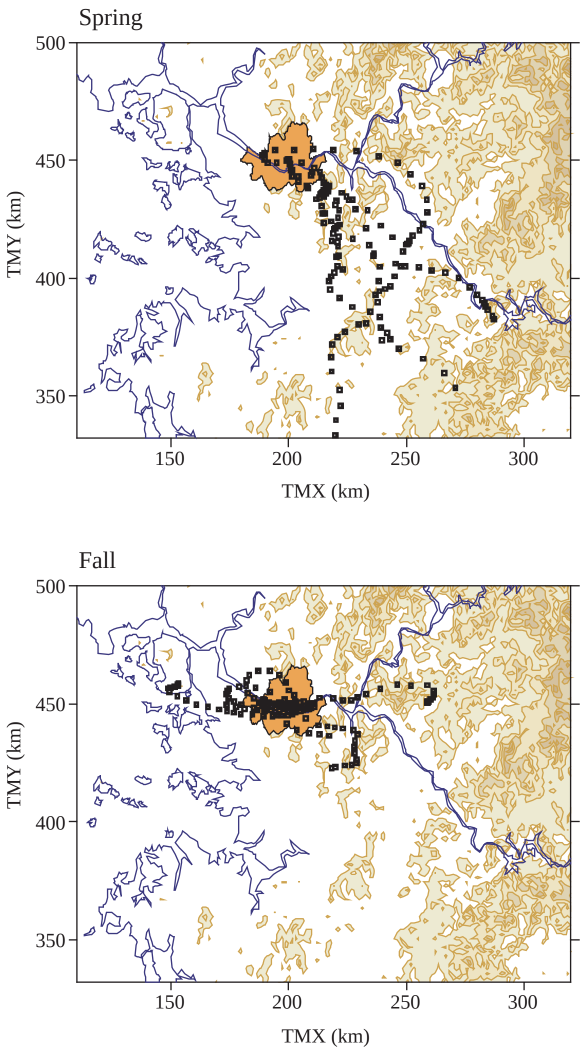

Fig. 5. The 24-hour forward trajectories starting from the center of Seoul, by season. The locations of trajectories are shown at one-hour intervals.

areas are far stretched out in the northwest-southeast direction associated with prevailing northwesterly winds. Their widely elongated shapes of upwind and downwind areas are a slanted parabolic shape because of relatively high wind speeds. In summer, the upwind and downwind areas are situated in the north and south of Seoul, but final locations tend to align in the northeast-southwest direction because of frequent northeasterly winds. In fall, the upwind and downwind areas run in the east-west direction. Upwind and downwind areas in summer and fall have elliptical shapes because of low wind speeds and are limited to a relatively small area. Basically, the shapes and locations of upwind and downwind areas are almost symmetric around Seoul, except for some differences in the locations and shapes. Only the downwind areas to the east of Seoul are limited because of the blocking effect of the complex terrains.

4. SUMMARY

The upwind and downwind areas of Seoul were determined with a refined wind field in order to understand the exchange of atmospheric influences between Seoul and the neighboring cities that directly affects air quality at the surface level. The study periods of 4 days in each season were selected as being representative of the meteorological conditions that would be typical of each season. During these periods, backward and forward trajectories of air parcels starting from five locations within Seoul at the surface level (i.e., a

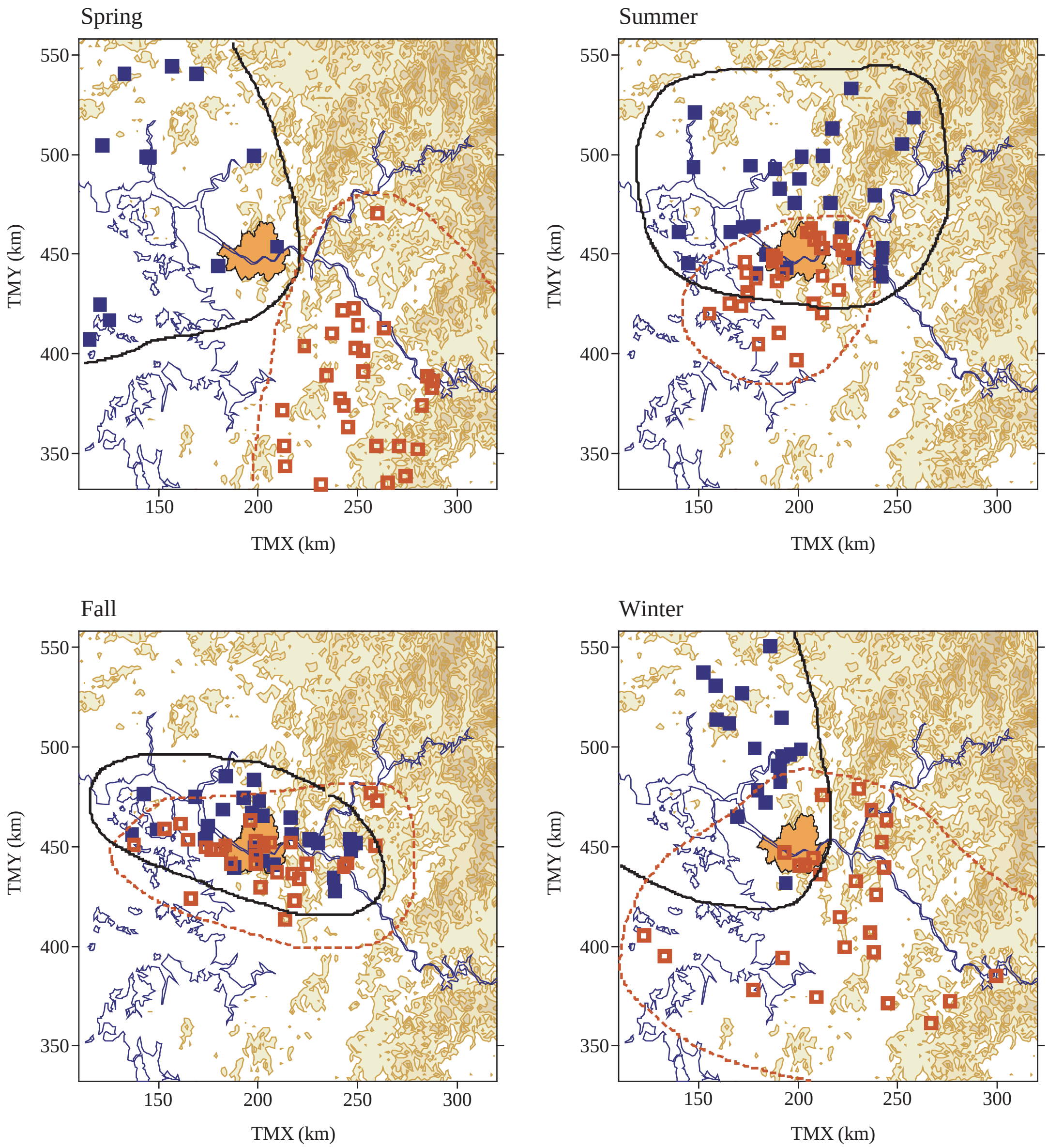

Fig. 6. Upwind and downwind areas of Seoul by season, estimated on the basis of all scenarios. Solid and open symbols denote the locations of 24-hour backward and forward trajectories, respectively. Thin solid lines and dashed lines surrounding the symbols denote the estimated upwind and downwind areas, respectively.

10-m height) were traced for 24 hours.

Backward trajectories originate from the northwest, farther from Seoul in the spring and winter when the wind speeds are relatively higher. This pattern is consistent with the northwesterly synoptic wind that is typical during these seasons. In summer and fall, trajectories flow into Seoul from nearby cities, and some tend to rotate around Seoul. Overall features of forward trajectories are almost symmetrical around Seoul. In spring and winter, upwind and downwind areas are situated in the northwest-southeast direction and have a slanted parabolic shape with vertices around Seoul. In summer, upwind and downwind areas have elliptical shapes and cover the north and south of Seoul, respectively. In fall, upwind and downwind areas are shaped like ellipses, stretching out in the east-west direction.

Upwind/downwind areas, shown in Fig. 6, are much smaller than areas of influence that would be estimated from the trajectory analysis of the widely used HYSPLIT model (Kim *et al.*, 2007), especially in the summer and fall. While using the refined wind field, assimilating the AWS data (which are heavily affected by local effects), and releasing air parcels at the 10 m level, the results in this study faithfully reflect the variation near the surface. However, the influences of high-rise buildings and roads in urban areas are not considered sufficiently. As a result, surface wind fields were mainly determined not based on the detailed land use data but based on the AWS data at a limited number of locations, and this hinders our ability to reproduce the wind variation of the real world.

Recently, concerns for human health risks have generated increased interest in high concentration levels of air pollutants over a short-term period (Seoul Metropolitan Government, 2010) that are more associated with local emissions. More research is needed with regard to integrated data collection amid modeling approaches in order to better reproduce actual wind fields near the surface and to more accurately identify relative contribution of local emissions compared to the long-range transport of air pollutants from the Asian continent.

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