Influence of local circulation on short-term variations in ground-
level PM$_{2.5}$ concentrations

Su Jeong Lee$^1$, Sang-Hyun Lee$^{1,2,*}$, Hyung-Jin Choi$^3$, Joowan Kim$^{1,2}$, Maeng-Ki Kim$^{1,2}$

$^1$Particle pollution Research and Management Center, Kongju National University, Gongju 32588, Gongju-si, Korea

$^2$Department of Atmospheric Sciences, Kongju National University, Gongju 32588, Gongju-si, Korea

$^3$Department of Civil Engineering and Environmental Sciences, Korea Military Academy, 574 Hwarang-ro, Nowon-gu, Seoul, Korea

$^*$ Corresponding author. Tel: 82-41-850-8526
E-mail address: sanghyun@kongju.ac.kr

Abstract

Local air quality is greatly influenced by large- and small-scale weather systems through transport, deposition, and chemical transformation of emissions. Local circulation, in particular, can play a significant role under weak synoptic-scale forcing. To examine the influence of local circulation on daily ground-level PM$_{2.5}$ concentrations, we utilized surface wind features observed at coastal stations in Midwest Korea, which hosts large industrial complexes and is located downwind of the Seoul Metropolitan area. Using K-means clustering, three circulation patterns were identified for the winter of 2021–2022, including one pattern under strong synoptic-scale forcing (Synoptic Cluster) and two local patterns (Sea Breeze Cluster and Stagnation Cluster). Each cluster is characterized by its unique wind patterns and different contributions to local air quality. The Stagnation Cluster, characterized by weak north-easterly circulation with a comparatively short transport distance, was found to be most strongly linked to high PM$_{2.5}$ levels, accounting for 57% of the high PM$_{2.5}$ days (> 35 $\mu$g m$^{-3}$) during the 2021–2022 winter. Additionally, we discovered that the three most extreme PM$_{2.5}$ events were all members of the Stagnation Cluster and that several consecutive stagnant days preceded each of these cases, facilitating local accumulations of nearby anthropogenic emissions. Overall, our findings emphasize that local air quality cannot be fully explained by synoptic-scale analysis, but can be better understood through the analysis of local circulation patterns. The study also highlights the importance of utilizing surface measurements and selecting features that can best describe the local circulation patterns in the region for the classification of local circulation, which contributes
to better capturing both daily and hourly variability in PM$_{2.5}$ concentrations under different weather regimes.

**Keywords:** Local circulation, Particulate Matter, Coastal regions, K-means clustering.
INTRODUCTION

Ever since the International Agency for Research on Cancer of the World Health Organization (WHO) classified particulate matter (PM) as a Group 1 human carcinogen in 2013, there has been a significant increase in public awareness of air quality. Located on the eastern edge of Asia, Korea is dominated by synoptic north-westerly winds during the winter. These winds transport air pollutants from foreign sources into the region, adding to the local emissions and contributing to the degradation of air quality in Korea during the winter season. The concentration of PM with a diameter of less than 2.5 micrometers, or PM$_{2.5}$, in particular, can significantly rise in the boundary layers of metropolitan regions under certain meteorological conditions. Major point sources in Korea are located along the coastlines of the peninsula, but the majority of them are concentrated along the mid-western coastline. South ChungCheong province (Chungnam, hereinafter), in particular, hosts half of the 60 domestic coal-fired power stations (as of May 2023), including the largest site. Apart from large power plants, there are also significant industrial sources that act as point sources of pollution. These domestic point sources are often cited as the main contributors to the degradation of air quality in the region (Lee and Park, 2019).

However, air quality is strongly dependent on the weather system, which determines the transport, dispersion, and accumulation of emissions in an area. Synoptic-scale weather systems, in particular, have been viewed as a quick and useful way to diagnose and predict air quality levels in an area (Kassomenos et al., 2003), and a substantial body of research has been dedicated
to investigating the connection between synoptic weather conditions and PM$_{2.5}$ levels. Applying a classification method to synoptic variables such as sea level pressure, horizontal winds, and geopotential height from a numerical weather prediction model, these studies classified synoptic weather patterns into several clusters and attempted to identify the synoptic cluster that provides favorable conditions for high PM$_{2.5}$ concentrations by exploring the long-term trends and interannual variability (Díaz-Esteban et al., 2022; Gong et al., 2022; He et al., 2018; Luo et al., 2022; Oh et al., 2024), spatial distribution (Liao et al., 2020; Xiang et al., 2022), and regional transport (Hu et al., 2022) of PM$_{2.5}$ in each cluster, or by focusing on high PM$_{2.5}$ episodes (Chae et al., 2020; Chang et al., 2021; Jeong et al., 2023). Most of these studies demonstrated links between synoptic high-pressure systems and high PM$_{2.5}$ concentrations, but the results did not provide clear evidence of a connection between the identified synoptic patterns and PM$_{2.5}$ concentrations, presenting rather insignificant inter-cluster differences in the mean concentration of PM$_{2.5}$. This suggests that the synoptic-scale analysis, which is commonly conducted with coarse-resolution reanalysis data, is not sufficient to characterize the temporal and spatial variations in PM$_{2.5}$ concentrations near the surface. This further suggests that additional information, such as local circulations, is required to fully explain the variations in PM$_{2.5}$ concentrations. This is because local air quality is significantly influenced by local circulations under weak synoptic-scale forcing (Banta et al., 2011; Hsu and Cheng, 2016) by vertically
dispersing air pollutants and carrying them to downstream areas (Clark et al., 2003; Flocas et al., 2009; Miao et al., 2015; Peng et al., 2023). Additionally, local circulation is more closely related to the short-term (diurnal) variability in PM$_{2.5}$ levels, which provides insights to better understand the source apportionment and governing processes of the formation of air pollutants throughout the day (Tanner et al., 2005; Zhang et al., 2022). Since anthropogenic emissions do not vary dramatically on a daily basis, daily fluctuations in PM$_{2.5}$ concentrations can be more correlated with local circulations than the change in emissions or larger-scale weather systems. To investigate the influence of local circulation on air quality, recent studies utilized surface wind measurements from ground stations instead of synoptic variables. For example, Li et al. (2020) demonstrated a clear connection between sea breeze circulation and daily ozone variability in Houston, Texas, by applying K-means clustering to surface wind measurements. Di Bernardino et al. (2023) examined the relationship between local circulation and concentrations of air pollutants, including PM$_{2.5}$ in Rome, Italy, by applying cluster analysis to surface wind measurements, but focus was more on spatial and seasonal variability in air pollutants. To our knowledge, not many researches have been dedicated to local circulations associated with PM$_{2.5}$ concentration variations, and even fewer have considered using surface measurements for the classification of local circulations. In this study, we applied a clustering technique to surface wind measurements to identify local circulation patterns in Chungnam. Despite being one of the most polluted areas
in Korea, Chungnam has received far less research attention. More research is needed to better understand the controlling factors of PM$_{2.5}$ pollution and to improve air quality in the region. Since Chungnam is a coastal area located on the mid-western edge of the Korean Peninsula, local circulations, including sea breezes, can play a particularly important role in the distribution of PM$_{2.5}$ under weak synoptic-scale forcing. Using K-means clustering, this study investigated the relationship between local circulation patterns and ground-level PM$_{2.5}$ concentration in Chungnam for the 2021–2022 winter, i.e., from December 2021 to February 2022 (90 days), during which several high PM$_{2.5}$ episodes were observed. Classifying local circulation patterns in coastal regions can be particularly challenging due to the complex coastal terrain that can give rise to multiple local winds. To capture the main local circulation feature, sea breezes, we utilized surface data measured at coastal surface meteorological stations for the classification.

The rest of this manuscript is structured as follows: Sect. 2 describes the study domain, meteorological and air quality datasets, and the K-means clustering method used to categorize local circulation patterns. Sect. 3 presents the characteristics of the identified local circulation patterns and their relationship to the observed PM$_{2.5}$ concentrations. Finally, the conclusions follow in Sect. 4.

2 METHODS

2.1 Study area and Data
Fig. 1 depicts the geographical location of the study area, characterized by the intricate coastline and complex inland topography, along with the positions of the surface meteorological and air quality measurement stations. Hourly 10-m zonal and meridional surface wind data from the Automated Synoptic Observing System (ASOS) stations, routinely operated by the Korea Meteorological Administration (KMA), were used to analyze the local circulation patterns. All stations are located within 100 km of the north and west coastlines. Among these, five stations within 30 km from the coast, i.e., SeoSan (129), HongSung (177), BoRyeong (235), BuYeo (236), and GunSan (140), were selected to capture the sea breeze circulation features for the K-means clustering algorithm. Data from December 2021 to February 2022, a total of 90 days, were collected for this purpose.

Radiosonde wind profiles were utilized to examine the vertical distribution of winds within the atmospheric boundary layer (ABL). Since no radiosonde stations in Chungnam are routinely operated by KMA, intensive radiosonde observations were performed at Dangjin, located on the north shore of Chungnam, every three hours from 11 to 15 February 2022.

We also utilized the European Centre for Medium-Range Weather Forecasts Reanalysis version 5 (ERA5) (Hersbach et al., 2023) hourly geopotential height and wind data at a horizontal resolution of 0.25° to characterize the upper atmospheric conditions for each local circulation cluster.
The PM$_{2.5}$ concentration data were obtained from the Air Quality Monitoring Station (AQMS) network (https://www.airkorea.or.kr/) operated routinely by the Ministry of Environment of Korea. As of 31 December 2021, there were 885 stations across the nation, with 632 of them managed by local governments (NIER, 2022). For this study, PM$_{2.5}$ concentrations measured at 33 AQMS (Fig. 1) in Chungnam were utilized. During the study period, the Korean government implemented ‘emergency reduction measures’ three times in response to the high PM$_{2.5}$ forecasts for the following days. This measure calls for restrictions on the use of inefficient fuel combustion vehicles, adjustments to working hours at building construction sites, or modifications to the operating hours of facilities that emit air pollutants.

2.2 K-means clustering of local circulation patterns

This study employs the K-means clustering algorithm (Hartigan and Wong, 1979) to classify local circulation patterns. The K-means clustering algorithm is computationally efficient and conceptually simple, making it one of the most popular clustering algorithms for pattern classification problems (Di Bernardino et al., 2022; Li et al., 2020). This method calculates the squared Euclidean distance between the centroid (the center of each cluster) and all points (i.e., given $n$ observations), allowing each observation to be assigned to the cluster with the closest mean. The number of clusters, $k$, is defined by the user. Based on the clustering procedure proposed by Li et al. (2020), surface wind measurements are used to extract seven features of
local circulation. These are the daytime zonal/meridional winds ($U_{\text{day}}$ and $V_{\text{day}}$), nighttime zonal/meridional winds ($U_{\text{night}}$ and $V_{\text{night}}$), the recirculation factor ($R$), and the transport direction ($\cos \theta$, $\sin \theta$), which are fed into the K-means clustering algorithm.

The first four features ($U_{\text{day}}$, $V_{\text{day}}$, $U_{\text{night}}$, and $V_{\text{night}}$) represent the diurnal variation of local circulation in the coastal region. Fig. 2 displays the diurnal cycle of the mean wind speeds and directions measured at 15 ASOS stations, divided into three groups based on their proximity to the coastline: Coastal (< 30 km), Inland (30–90 km), and Far inland (> 90 km). On the Midwest coast of Korea, the sea breeze can advance inland with a wide range of 30–60 km (Park and Chae, 2018; Pokhrel and Lee, 2011), and a mountain range runs approximately 90–100 km from the west coastline, along the eastern border of Chungcheong province. The influence of sea breeze and geography can be found in the wind patterns presented in Fig. 2. The average wind speeds (Fig. 2(a)) display a very similar magnitude and diurnal cycle for the Coastal and Inland stations, whereas in Far-inland stations, winds are much stronger, probably due to the influence of mountain–valley wind. The most dramatic shift in wind directions is observed in the Coastal stations (Fig. 2(b)) due to sea breeze circulation. A counterclockwise shift in the wind direction occurs around 08 LST, from northerly to westerly, and then the second shift occurs at 13 LST, turning from westerly back to northerly. Based on this analysis, we decided to utilize the surface wind measurements from the five coastal stations (Coastal group), which best describe the
important features of local circulation in Chungnam. Daytime horizontal winds ($U_{day}$ and $V_{day}$) were determined by averaging the winds from 13 to 17 LST, and nighttime winds ($U_{night}$ and $V_{night}$) were calculated by averaging the winds from 04 to 08 LST.

In addition to the day/night wind features, the $R$ and $\theta$ factors are introduced to represent the recirculation potential and transport direction that can influence the atmospheric dispersion in coastal regions. The $R$ factor is defined by the ratio of the net transport distance ($L$) to the wind run distance ($S$), expressed as $R = 1 - L/S$ (Allwind and Whiteman, 1994). The $R$ value, which ranges from 0 to 1, serves as an indicator of the level of atmospheric dispersion. A higher $R$ value represents increased recirculation, leading to less atmospheric dispersion. The transport direction $\theta$ represents the wind rotational angle, a clockwise angle from the north. For practical reasons, $\cos \theta$ and $\sin \theta$ are used instead of $\theta$, as the latter is inconvenient for capturing wind directions (e.g., both 1° and 359° indicate northward transport). It is worth noting that the feature selection should be made with caution. It is important to select features that can best describe the local circulation patterns in the region of interest. For example, using daily mean horizontal winds, instead of daytime/nighttime mean winds, may not clearly distinguish sea breezes from other local winds with a similar magnitude of mean winds. Similarly, adding a feature with different properties (e.g., column information such as sea level pressure) may also lead to quite different clustering results.
The seven features described above are calculated for each day over the study period, for a total of 90 days. The clustering algorithm then creates a matrix of 90 days by 7 features by normalizing each feature according to its mean and standard deviation. The optimal number of clusters \(k\) is determined using the elbow method. The method finds the minimum within-cluster sum of squares (WCSS) value as increasing \(k\) \((k = 2, 3, 4, \ldots)\) to determine the optimal \(k\). K-means clustering algorithm is generally very quick to converge, normally within 10 iterations.

3 RESULTS AND DISCUSSION

3.1 Characteristics of the identified local circulation patterns

This section describes the three local circulation patterns identified by the K-means clustering for the winter of 2021–2022 near the surface, at upper atmospheric levels (500 hPa and 850 hPa), and within the ABL. The three clusters include one under strong synoptic forcing (named “Synoptic Cluster”) and two local clusters (named “Sea Breeze Cluster” and “Stagnation Cluster”).

3.1.1 Surface winds

Fig. 3 displays the diurnal variation in surface winds for the three identified clusters. The Synoptic Cluster, the first cluster, is characterized by strong north-westerly winds with minimal variation in the wind direction throughout the day (Fig. 3(a)). This pattern was observed on 16
out of 90 days (17.8%) during the winter of 2021–2022. The Sea Breeze Cluster, the second
cluster, is characterized by light easterlies in the early morning hours, shifting to westerlies at
sunrise, and reaching peak wind speed around 15 LST (Fig. 3(b)). This pattern is typical of the
sea breeze observed on the western coast of Korea during the winter. The Sea Breeze Cluster
takes almost half the study period (45.6%, or 41 out of 90 days). The third cluster, the Stagnation
Cluster, is characterized by winds originating from the northeast during the night and shifting
slightly eastward during the day (Fig. 3(c)). The wind directions of this cluster change in a
counterclockwise direction (from north-easterly to north-westerly) during the daytime,
contrasting with the clockwise movement (from south-easterly to south-westerly) observed in the
Sea Breeze Cluster. This pattern was observed on 33 out of 90 days (36.7%) during the study
period.

On the Synoptic Cluster days, synoptic-scale meteorological forcing dominates in forming
local winds throughout the day. However, on the Sea Breeze and Stagnation Cluster days, local-
scale forcing becomes the primary influence under weak synoptic meteorological forcing
conditions. During the winter period in Chungnam, local circulation patterns of the Sea Breeze
and Stagnation Cluster account for over 80%, significantly surpassing the Synoptic Cluster
conditions.
Fig. 4 illustrates the unique local-transport features of each of the three clusters by comparing $S$, $L$, and the 24-hour transport direction ($\theta$). Daily $S$ and $L$ show similarly long distances exceeding 200 km on the Synoptic Cluster days (Fig. 4(a)), resulting in minimal recirculation ($R = 0.01$).

Throughout the day, $\theta$ stays to the southeast. On the other hand, the Sea Breeze Cluster days show much shorter transport distances ($S = 64$ km and $L = 47$ km) and a higher recirculation value ($R = 0.26$), with the majority of transport occurring eastward during the day (Fig. 4(b)).

With southward transport, the Stagnation Cluster days (Fig. 4(c)) have the shortest wind run distance ($S = 55$ km), which is four times shorter than that of the Synoptic Cluster’s. The prevalence of easterly winds in this cluster results in more stagnant local wind conditions compared to those on the Sea Breeze Cluster days. These results indicate that each cluster exhibits distinct local transport patterns in Chungnam, implying variations in the atmospheric dispersion of local pollutant sources.

### 3.1.2 Upper geopotential heights and winds

Fig. 5 presents the spatial distributions of mean geopotential heights (contours, in m) and horizontal winds (vectors, in m s$^{-1}$) at the 500 hPa and 850 hPa pressure levels, derived from the ERA5 data. In the figures on the left (Figs. 5(a) and 5(e)), the period-mean fields (averages over the 90 days) are shown. The right panels display the deviation of the cluster-mean fields from the period-mean fields at the 500 hPa (Figs. 5(b)-(d)) and 850 hPa (Figs. 5(f)-(h)) levels. The period-
mean wind fields exhibit typical characteristics of large-scale patterns during the winter, with north-westerly winds at 850 hPa and westerly winds at 500 hPa. The change in wind direction, known as *backing*, implies the occurrence of cold advection (Figs. 5(a) and 5(e)). Based on the synoptic patterns observed in the deviation fields of the three clusters (three right panels of Fig. 5), this could be associated with Arctic cold surges that are accompanied by cold advection (Kim and Ahn, 2022). The geopotential height field in the Sea Breeze Cluster (Figs. 5(c) and 5(g)) shows a near-zero difference from the period-mean field at both atmospheric pressure levels, indicating that this cluster is formed under the typical synoptic pattern. In contrast, the Synoptic and Stagnation Clusters show significant differences from the period-mean meteorological fields. The Synoptic Cluster exhibits negative geopotential height differences, with the lowest value of –126 m at 500 hPa and –65 m at 850 hPa levels (Figs. 5(b) and 5(f)), which lead to cyclonic wind deviations over the Korean Peninsula. On the other hand, the Stagnation Cluster exhibits anticyclonic wind deviations resulting from positive deviations in geopotential height, which reach up to 70 m at 500 hPa and 37 m at 850 hPa (Figs. 5(d) and 5(h)). As will be explained in detail in Sect. 3.2, the Stagnation Cluster is strongly correlated with the high PM$_{2.5}$ concentrations, and these positive geopotential height deviations (or anticyclonic conditions) have been reported as a contributing factor to poor air quality in many other previous studies (e.g., Diaz-Esteban et al., 2022; Kim et al., 2023; Seo et al., 2018).
Overall, the magnitude of deviations in the geopotential height fields is not very large, being 2–5% from the mean geopotential height. Even with these small deviations, however, the resulting changes in wind fields play a crucial role in shaping local circulation patterns. For example, on the days of the Stagnation Cluster, the mean enhancement of easterly wind in Chungnam (black rectangles in Fig. 5) is about 5.8 m s$^{-1}$ at 500 hPa (or 3.8 m s$^{-1}$ at 850 hPa). This easterly deviation leads to stagnant atmospheric conditions near the ground, favorable for the accumulation of air pollutants.

### 3.1.3 ABL winds

Radiosonde measurements were conducted at 3-hour intervals from 26 January to 15 February 2022 to explore the diurnal wind characteristics within the ABL. Fig. 6 shows the vertical distribution of wind fields observed at a coastal site in Dangjin (37.04°N, 126.54°E) within the study domain. The shaded contours in the figure represent deviations of wind speeds from the period-mean values, with local circulation patterns overlaid. The first three days (11–13 February) are members of the Stagnation Cluster; the next day is under the Sea Breeze Cluster; and the final day is under the Synoptic Cluster. The period covers the two days (11–12 February) with the highest PM$_{2.5}$ levels. The ABL and the free atmosphere above it are effectively separated by the vertical distribution of wind speed deviations. Specifically, the distribution that spans from near ABL heights (approximately 1–2 km) to roughly 5 km (~500 hPa) supports the results in
Sect. 3.1.2, i.e., the negative deviations on Stagnation Cluster days and the positive deviations on Synoptic Cluster days discussed in Fig. 5. Above the ABL, westerly or north-westerly winds are consistent throughout the entire period, with wind speeds exhibiting distinct variations based on local circulation patterns. In the ABL, wind features are largely determined by local circulations, leading to more noticeable diurnal variations in winds. During the successive Stagnation Cluster days (12–13 February), the ABL winds are continuously weak (light easterly winds), creating stagnant conditions in Chungnam. On the following day (14 February, Sea Breeze Cluster), the wind speeds gradually increase while the wind directions shift from easterly to westerly as sea breezes form. On the last day (15 February, Synoptic Cluster), the ABL winds align with those in the upper atmosphere and become consistent and strong north-westerly winds throughout the day, which can contribute to the dispersion of air pollutants.

Overall, the ABL winds exhibit more pronounced diurnal changes than those in the upper atmosphere, reflecting the characteristics of local circulation patterns. Wind deviations in the ABL display similar patterns to those in the upper atmosphere, i.e., positive deviations for the Synoptic Cluster and negative deviations for the Stagnation and Sea Breeze Clusters, although the magnitudes are significantly smaller in the ABL due to efficient turbulent mixing.
In summary, the radiosonde wind profiles show characteristic features of ABL winds for the three local circulation patterns in Chungnam, consistent with those seen near the surface (as shown in Fig. 3) and in the upper atmosphere (as depicted in Fig. 5).

3.2 Influence of local circulation on ground-level PM$_{2.5}$ concentrations

To explore the influence of local circulation on the ground-level PM$_{2.5}$ concentrations, we compared the observed surface PM$_{2.5}$ concentrations across the three identified clusters. The comparison includes all 33 AQMS in Chungnam to investigate the region-wide influence of local circulation on PM$_{2.5}$ concentrations. Fig. 7 presents the daily all-site mean PM$_{2.5}$ concentrations from 1 December 2021 to 28 February 2022. The color bars indicate the classified local circulation patterns: blue for the Synoptic Cluster, green for the Sea Breeze Cluster, and violet for the Stagnation Cluster. The number marked above the bar indicates the non-attainment day that exceeded the Korea air quality guideline (AQG) 2018 (daily mean PM$_{2.5}$ concentration of 35 µg m$^{-3}$). It was found that the average surface PM$_{2.5}$ concentration in Chungnam was the highest in the Stagnation Cluster, followed by the Sea Breeze Cluster and the Synoptic Cluster in that order. The Synoptic Cluster days have the lowest cluster-mean PM$_{2.5}$ concentration of 14.2 µg m$^{-3}$. Chungnam occasionally meets the WHO AQG 2021 only in this cluster. The Sea Breeze Cluster and the Stagnation Cluster days have higher values of 24.9 µg m$^{-3}$ and 33.6 µg m$^{-3}$, respectively. This indicates that the Synoptic Cluster has a mean PM$_{2.5}$ concentration that is 45.8% lower than
the all-site mean PM$_{2.5}$ concentration of 26.2 µg m$^{-3}$. This is primarily due to the strong north-westerly winds during the Synoptic Cluster days (Figs. 3 and 4), which carry clean marine air inland and rapidly disperse pollutants from Chungnam. On the other hand, the average PM$_{2.5}$ concentration in the Stagnation Cluster is 28.4% greater than the all-site mean concentration. The Sea Breeze Cluster demonstrates a typical concentration level, being 4.9% lower than the all-site mean value. Although the Sea Breeze Cluster and the Stagnation Cluster have similar wind run (S) and transport distance (L) values (Fig. 4), there are noticeable differences in PM$_{2.5}$ concentration levels between the two clusters, and this is presumably attributable to their representative transport directions (θ). Major industrial emission sources, such as coal-fired power plants and petroleum refinery facilities, are situated in the northern coastal region of Chungnam. Moreover, the Seoul metropolitan area, which is a major contributor to the release of PM$_{2.5}$ and its precursors, is located approximately 117 km to the north of Chungnam. The northerly and north-easterly winds in the Stagnation Cluster effectively transport these anthropogenic emissions to the Chungnam region.

The daily variations in the PM$_{2.5}$ concentration averaged over all AQMS (Fig. 7) demonstrate more noticeable changes in accordance with local circulation patterns. During the study period, precisely 23 days (25.6%) exceeded the Korea AQG 2018. Out of these, 13 days (57%) were assigned to the Stagnation Cluster and 10 days (43%) to the Sea Breeze Cluster. Not a single day
was categorized as Synoptic Cluster. In the figure, the three peaks in each month, i.e., 16 December 2021, 9 January 2022, and 12 February 2022, correspond to the highest PM$_{2.5}$ days of each month, for which the Korean government issued the ‘emergency reduction measure’, and the three cases were all classified as Stagnation Cluster. The figure also shows that all the high PM$_{2.5}$ concentration days are preceded by several days of either Sea Breeze Cluster or Stagnation Cluster, suggesting the significant role of local pollutant accumulation on a several-day time scale in elevating PM$_{2.5}$ levels. Another aspect to mention is that, despite emissions control in China during the 2022 Beijing Winter Olympics (5-20 February 2022) (Chu et al., 2022; Wang et al., 2023), the average PM$_{2.5}$ concentrations in Chungnam showed a significant variation by a factor of 8, ranging from 9 µg m$^{-3}$ (on 5 February) to 73 µg m$^{-3}$ (on 12 February). These results underscore the crucial role of local circulations in determining daily PM$_{2.5}$ levels in coastal regions such as Chungnam.

We further examined the diurnal variations of the mean PM$_{2.5}$ concentrations by cluster. Fig. 8 presents the hourly mean PM$_{2.5}$ concentration from 33 AQMS for each local circulation cluster. The solid lines indicate the cluster-mean hourly PM$_{2.5}$ concentrations, and the whisker boxes represent the mean PM$_{2.5}$ concentration distributions from all AQMS, encompassing the lower 10%, lower quartile, median, upper quartile, and upper 10%. The results show that the cluster-mean hourly PM$_{2.5}$ concentration levels strongly correlate with the local circulation patterns.
throughout the day. In contrast to previous studies (Di Bernardino, 2023; Hsu and Cheng, 2019), our results display a quite clear inter-cluster separation by the mean PM$_{2.5}$ concentrations and also by the diurnal cycle. In addition, each cluster exhibits a unique diurnal variation that reflects the interplay between local circulation and the ABL. The highest mean PM$_{2.5}$ concentration is found in the Stagnation Cluster, and the lowest is observed in the Synoptic Cluster. The low PM$_{2.5}$ levels of the Synoptic Cluster are attributed to the inland transport of clean marine air by persistent north-westerly winds. This cluster exhibits the least diurnal variation, and the decrease in the concentration levels between 9 and 12 LST coincides with the rapid formation of the convective ABL. It is worth noting that Chungnam achieves compliance with the WHO AQG of 15 µg m$^{-3}$ on the Synoptic Cluster days only and only in the afternoon. A more pronounced interaction between local winds and the ABL is observed in the Sea Breeze Cluster and the Stagnation Cluster, which are predominantly driven by local-scale forcing. The mean PM$_{2.5}$ concentrations of these two clusters peak at 10 LST and decline to a minimum around 16 LST. This distinct diurnal pattern is particularly noticeable in the Stagnation Cluster, which shows a large amplitude of diurnal variation. The Sea Breeze Cluster exhibits a single peak in the morning, and the PM$_{2.5}$ levels gradually decrease after the onset of the sea breeze (westerly), although the decrease is not significant. The influence of the sea breeze on the dispersion of air pollutants can
vary depending on the direction of the sea breeze (north-westerly vs. south-westerly) and on
whether or not there is inflow from external sources.

The figure also shows that the spatial variation in PM$_{2.5}$ concentrations observed at 33 AQMS,
represented by the vertical lengths of boxes and whiskers in the figure, is the most significant in
the Stagnation Cluster throughout the day, followed by the Sea Breeze Cluster and the Synoptic
Cluster. This could be attributed to the dominant impact of local factors, such as emissions from
local and nearby sources and proximity to the ocean, on the concentration levels at each site,
especially under weak synoptic conditions. Although the PM$_{2.5}$ levels observed at all AQMS are
not perfectly separated by the clusters, their temporal variations within each cluster are in good
agreement with the average concentration variations of the cluster. This indicates that the local
circulation patterns observed in the region concurrently affect the hourly PM$_{2.5}$ concentrations at
all AQMS at spatial scales of roughly 50–100 km. This further supports the significant influence
of local circulation on PM$_{2.5}$ concentration levels.

4 CONCLUSIONS

We investigated the influence of local circulation on wintertime ground-level PM$_{2.5}$
concentrations in Chungnam, a coastal region of mid-western Korea that frequently experiences
high air pollution. To classify local circulation patterns for the third seasonal PM management
period in the winter of 2021–2022, K-means clustering technique was utilized. Using seven local
circulation features derived from surface meteorological stations located near the coastline, three
distinct circulation patterns were identified: one synoptic cluster (Synoptic Cluster) and two local
clusters (Sea Breeze Cluster and Stagnation Cluster).

To characterize the local circulation patterns in the three clusters, winds near the surface, in
the ABL, and at 500 hPa and 850 hPa pressure levels were analyzed together with the upper
geopotential heights. Surface winds distinctly separate the clusters in terms of the distance and
direction of surface transport, displaying the longest (~200 km) southeastward transport for the
Synoptic Cluster and much shorter (50–60 km) net eastward and southward transport for the Sea
Breeze and Stagnation Cluster, respectively. Analysis of the geopotential heights and wind fields
at 500 hPa and 850 hPa of the three clusters also confirmed that the local circulation patterns
observed in Chungnam were affected by different synoptic regimes. The inter-cluster
comparisons suggested that the slight deviations in the upper geopotential height can lead to
significant changes in local winds. These imply that direct analysis of local circulation may more
accurately capture meteorological influence on short-term local air quality. Analyzing the vertical
structure of ABL winds also revealed the features of local circulation patterns. Winds on the
Stagnation Cluster days separated the ABL from the free atmosphere above it by displaying
consistent negative deviations within the ABL, resulting in stagnation conditions. In contrast,
positive wind speed deviations were apparent on the Synoptic Cluster day, showing a relatively weak separation between the ABL and the above atmosphere.

To summarize, the persistent north-westerly winds in the Synoptic Cluster create conditions for the ventilation of local pollutants in Chungnam, resulting in lower PM$_{2.5}$ concentrations, while the weak winds in the two local clusters lead to relatively poor ventilation, resulting in higher PM$_{2.5}$ concentrations. The concentration level is worse in the Stagnation Cluster mainly due to transport direction. The northerly or north-easterly winds in the Stagnation Cluster can transport emissions from local and nearby industries to Chungnam. The extreme air pollution events observed in Chungnam were also caused by the accumulation of those local emissions over several days under successive weak synoptic-scale forcing.

This study demonstrates the essential role of local circulation in explaining both daily and hourly variations in PM$_{2.5}$ levels. In other words, variations in PM$_{2.5}$ concentrations can be better explained through analysis of local circulation than synoptic analysis. The latter can suggest general relationships between synoptic weather patterns and the concentrations of air pollutants (e.g., high pressure systems for the high concentrations), but it cannot fully explain the variations in local pollution concentrations. On the contrary, the PM$_{2.5}$ concentrations are much more clearly separated into three distinct groups by the features of local circulation, suggesting that the concentration of local air pollutants is highly correlated with local circulation. The study also
emphasizes the importance of using surface measurements and selecting features (e.g., daily mean vs. daytime/nighttime mean) that can best describe the local circulations of the region. Missing an important controlling feature or adding redundant or irrelevant features can lead to different clustering results, which in turn could result in a misinterpretation of the relationship between local circulation patterns and concentrations of air pollutants.

ACKNOWLEDGMENTS

The authors declare that they have no competing financial interests or personal relationships that could have influenced the work reported in this paper. This work was supported by a grant from the National Institute of Environment Research (NIER), funded by the Ministry of Environment (MOE) of the Republic of Korea (NIER-2021-03-03-007).

REFERENCES


Gong, S., Liu, Y., He, J., Zhang, L., Lu, S., Zhang, X. (2022). Multi-scale analysis of the impacts of meteorology and emissions on PM$_{2.5}$ and O$_3$ trends at various regions in China from 2013 to


Hsu, C.-H., Cheng, F.-Y. (2016). Classification of weather patterns to study the influence of meteorological characteristics on PM$_{2.5}$ concentrations in Yunlin County, Taiwan. Atmos. Environ. 144, 397–408. http://dx.doi.org/10.1016/j.atmosenv.2016.09.001


https://doi.org/10.5194/acp-18-16121-2018


Fig. 1. (a) Study domain (red box). (b) Locations of the automated synoptic observing system (ASOS) stations, air quality monitoring stations (AQMS), and radiosonde. The five coastal ASOS stations, with their identification number and name, are used to capture sea breeze features.
Fig. 2. Diurnal variations of station-mean (a) wind speed and (b) wind direction at three groups (Coastal, Inland, and Far inland) for the 2021–2022 winter. The 15 ASOS stations were divided into three groups according to the distance from the coastline.
Fig. 3. Three local circulation patterns identified by the K-means clustering in Chungnam for the 2021–2022 winter: (a) Synoptic Cluster, (b) Sea Breeze Cluster, and (c) Stagnation Cluster.
Fig. 4. Local transport features calculated from the surface ASOS measurements for (a) Synoptic Cluster, (b) Sea Breeze Cluster, and (c) Stagnation Cluster. The features include the wind run distance, the net transport distance, the transport direction, and the recirculation factor ($S$, $L$, $\theta$, and $R$, respectively).
Fig. 5. The ERA5 (a, e) period-mean and (b-d, f-h) deviation fields of geopotential height and wind fields at (top) 500 hPa and (bottom) 850 hPa from 1 December 2021 to 28 February 2022. The black rectangle indicates the study domain, Chungnam.
Fig. 6. Radiosonde wind profiles (vectors) and difference from the period-mean wind speed (shaded contour) at Dangjin (37.04°N, 126.54°E) from 11 to 15 February 2022.
Fig. 7. Daily mean PM$_{2.5}$ concentrations observed at 33 AQMS in Chungnam from 1 December 2021 to 28 February 2022. The dash-dot lines represent the daily PM$_{2.5}$ concentration AQG in Korea (NIER) and WHO. The Beijing Winter Olympics were held from 5 to 20 February 2022.
Fig. 8. Boxplots of hourly PM$_{2.5}$ concentrations observed from 33 AQMS in Chungnam for the three clusters. Boxes represent the 25$^{\text{th}}$ and 75$^{\text{th}}$ percentile, central line the median, and bars the 10$^{\text{th}}$ and 90$^{\text{th}}$ percentiles. Thick lines indicate the cluster-mean hourly PM$_{2.5}$ concentrations.