AGU ADVANCING EARTH AND SPACE SCIENCE

JGR Atmospheres

RESEARCH ARTICLE
10.1029/2022JD037517

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Key Points:

- Several distinct synoptic weather patterns are highly associated with air quality degradation over South Korea during winter and spring
- During winter, weak near-surface northwesterly wind is a potential cause for high particulate matter (PM) under dry moderate (DM) types. On the other hand, during spring, enhanced stability in the lower atmosphere likely results in high PM in both DM and dry tropical types
- Interestingly, the degree of PM concentration depends on the intensity of key weather variables such as wind speed and static stability in case of the same synoptic weather pattern

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:
Lee, D., Kim, H. C., Jeong, J.-H., Kim, B.-M., Lee, D., Choi, J.-Y., et al. (2022). Relationship between synoptic weather pattern and surface particulate matter (PM) concentration during winter and spring seasons over South Korea. *Journal of Geophysical Research: Atmospheres*, *127*, e2022JD037517. https://doi.org/10.1029/2022JD037517

Received 18 JUL 2022
Accepted 9 DEC 2022

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Relationship Between Synoptic Weather Pattern and Surface Particulate Matter (PM) Concentration During Winter and Spring Seasons Over South Korea

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Abstract Regional air quality over East Asia, including South Korea, has recently become a center of public attention because of a few episodes of very high particulate matter (PM) concentrations. Predicting PM variation with lead time of a few hours up to days is one of the key areas that the governments are working on because it can benefit from an early warning system to short-term mitigation effort. In this study, the influence of synoptic weather conditions on regional air quality was investigated with the occurrence frequencies of PM episodes as a function of various synoptic weather patterns during winter and spring. During winter, dry moderate (DM) types occur frequently alongside high PM cases (24 hr mean PM_{10} concentration >100 μgm^{-3}). The composite weather map showed a weak northwesterly wind field as a potential cause. On the contrary, it is interesting to note that dry polar types can be associated with low PM cases (24 hr mean PM_{10} concentration < 100 μgm^{-3}) as well as high PM depending on near-surface wind speed. Furthermore, DM and dry tropical types were found to be highly correlated with high (higher) PM concentrations during spring season, likely because of the enhanced static stability in the lower troposphere. It should be noted that PM concentration depends on the lower atmospheric stability. The close relationship between synoptic weather patterns and PM concentration suggests that synoptic weather can play an important role in regional air quality.

Plain Language Summary East Asia, including South Korea, has become a regional hot spot for the deteriorating air quality in recent years. In spite of the tough regulation policy introduced by the South Korean government, several high particulate matter (PM) episodes have still been reported. In this study, the relationship between the surface PM concentration and synoptic weather patterns over South Korea was investigated. A scientific basis for an early warning system and short-term mitigation strategies was established. The near-surface wind speed was likely a key variable during winter. On the contrary, atmospheric stagnant in the lower troposphere played an important role during spring season. The results indicate a close relationship between the synoptic weather patterns and surface PM concentration.

1. Introduction

Particulate matter (PM), one of the major contributors to air quality degradation, is emitted from both anthropogenic and natural sources such as vehicle, industrial and power generation facilities, and dust. Its adverse impact on environment and human health has led to PM becoming the center of the public attention over East Asian countries (Cakmak et al., 2018; J. Kim, 2019; Kyselý & Huth, 2010), with each country producing its own regulation policies with the aim of reducing PM concentrations. Nevertheless, high PM cases still occur over East Asia (Cai et al., 2017; Callahan et al., 2019; H. C. Kim et al., 2017; G. Lee, Ho, et al., 2020; Seo et al., 2017).

Meteorological conditions including stability and wind speed, play important roles in regional air quality. In Beijing, Cai et al. (2017) found that the shallow East Asia trough prevented pollutants dispersion, which led to stagnant and severe haze. In South Korea, H. C. Kim et al. (2021) suggested that dry tropical (DT) type of

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synoptic weather condition has a strong connection to the increase in surface ozone over the last 30 yr. D. Lee, Wang, et al. (2020) demonstrated that the long-term increasing trend in the static stability and decrease in the near-surface wind speed over East Asia including western Korea, that have resulted from climate change may potentially worsen air quality. Jung et al. (2019) showed that the emissions under stagnant conditions lead to high PM concentrations and favorable conditions for its transport in South Korea.

Various natural climate variabilities that differ over interannual time scales have been referred to as potential causes for severe aerosol episodes over East Asia. Different types of El Niño can impact weather conditions such as wind, precipitation, and planetary boundary layer and eventually the surface $PM_{2.5}$ concentrations over East Asia (J. I. Jeong et al., 2018). El Niño and Southern Oscillation activities affect anomalies of precipitation and wind, as well as high-pressure systems, and lead to higher PM_{10} concentration levels over the Korean Peninsula (Wie & Moon, 2017). The East Atlantic West Russia (EA/WR) and Victoria mode of sea surface temperature anomalies provide particularly favorable weather conditions for high $PM_{2.5}$ concentration days in North China (Li et al., 2022). The regional circulation system that lies over China during winter, which is in response to Arctic-sea ice loss and boreal snowfall increase, is related to severe haze (Zou et al., 2017). In addition, the Siberian high (Siberian high-pressure system) can affect meteorological conditions, and thus, $PM_{2.5}$ concentrations over East Asia (J. I. Jeong et al., 2021). The meteorological variability leads to seasonal dependency in terms of regional air quality (J. I. Jeong & Park, 2013).

Such weather and climate variations are likely to change synoptic weather patterns and thus affect air quality. One recent study suggested that the synoptic weather patterns are associated with atmospheric circulation, implying that air pollutants are transported from China to Korea (H. C. Kim et al., 2016). Another approach is synoptic weather clustering. For example, methods such as *k*-mean clustering (Cheng et al., 2021) and the self-organizing map (Jung et al., 2019) indicate that synoptic weather patterns have strong association with regional air quality. However, these methods are uncertain because the classification variable and cluster number depend on the subjective judgment of the researcher.

Spatial synoptic classification (SSC) is one of the most widely used classification algorithms describing synoptic weather systems. The SSC has been used to investigate how synoptic weather impacts human health through a variety of air pollutants (Cakmak et al., 2018, 2016; J. Kim, 2019; Y. M. Kim et al., 2018). SSC data have also been used directly in researching air quality, ozone concentrations (Davis et al., 2010; Hanna et al., 2011; H. C. Kim et al., 2014, 2021), and $PM_{2.5}$ concentrations (Hawkins & Holland, 2010; Liu et al., 2017). However, no previous study has demonstrated the relationship between synoptic weather system and PM concentration over East Asia using long-term data sets that are based on observations. Decadal changes in the PM concentration-related synoptic weather conditions in South Korea were thus the focus of this study.

This study is an analysis of the co-variability between the synoptic weather pattern based on the SSC and regional PM concentration in South Korea during winter and spring. Detailed information concerning the atmospheric conditions that lead to high PM cases will be revealed. The remainder of the paper is organized as follows: Section 2 describes the data and methodology used to clustering high PM cases under SSC types; Section 3 presents the results both of the dominant weather condition and high PM during winter and spring using SSC, measured PM, and reanalysis data; and Section 4 contains a summary and discussion.

2. Data and Methods

2.1. Particulate Matter Concentration and Atmospheric Reanalysis

Since 1988, daily observations of surface PM concentrations have been provided by Seoul Metropolitan Government (Clean Air). The daily mean PM_{10} concentrations at 25 surface monitoring sites were averaged regardless of location and data length because the stations are distributed across most of the Seoul Metropolitan Area (SMA; a box in Figure S1b in Supporting Information S1). Each case indicating the presence of yellow dust originating from the Mongolian region (41° − 53°N, 87° − 121°E) were removed using Hybrid Single-Particle Lagrangian Integrated Trajectory model (Stein et al., 2015). Data were checked for quality and availability by comparison with the Seoul Research Institute of Public Health and Environment and confirmed data from the National Institute of Environmental Research (Figure S2 in Supporting Information S1), which indicated that the PM_{10} concentration data were statistically significant and that the correlation coefficient between each data set, including cases in which dust was included or removed, were in good agreement ($R > 0.99$). Government regulation has led to a long-term decreasing trend in the measured surface PM_{10} concentrations; however, high concentrations are still sometimes experienced in the region.

Atmospheric variables such as geopotential height, sea-level pressure, near-surface temperature, wind, and lower-tropospheric static stability were derived from the Japanese 55 yr Reanalysis (JRA-55, http://jra.kishou.go.jp/JRA-55) data from 1988 to 2018 with a horizontal resolution of 1.25° × 1.25°, and temporal resolution of 6 hr (Kobayashi et al., 2015). These data were converted into daily mean data by considering the local standard time in Korea.

2.2. Spatial Synoptic Classification (SSC) Data

Typically, synoptic-scale weather covers a horizontal length scale in the order of 100–5,000 km and a time scale in the order of a few days to about 2 weeks. Synoptic weather is directly linked to daily weather conditions, dispersion, and transport of pollutants.

The weather conditions over the Korean peninsula are highly affected by seasonal air masses, The continental origin of the Siberian air masses are dominant during winter and the Yangtze River air masses are prevalent during spring and autumn. The maritime origin of Okhotsk Sea, North Pacific, and Equatorial air masses are dominate during summer. The influence of the different air masses indicates distinct seasonal weather variation in association with the origin. Especially, air masses of continental origin that are transported by westerly winds influence the transport pathway of air pollutants from China to South Korea during winter and spring.

For the study, we obtained daily SSC classifications at the Gimpo International Airport meteorological monitoring site in Seoul directly from SSC homepage (http://sheridan.geog.kent.edu/ssc.html). The available SSC classification could obtain from 17 stations in South Korea and more than 800 stations globally. Four times in a daily ground-based observation of surface temperature, dew point, dew point depression, wind speed, wind direction, cloud cover, and diurnal temperature range from each individual station were incorporated by algorithm into the model to ascertain weather-type characteristics and generate the SSC. The SSC classification scheme on each day was compared to seed days, in which the weather characteristics associated with SSC weather types in different seasons; weather conditions at a particular time and location were then classified as the SSC type most closely resembled (Sheridan, 2002). SSC utilizes synoptic-scale, daily classifications of different types of air mass based on the thermal and moisture characteristics of each type of weather.

The SSC represent nine synoptic weather types, six main categories, one transitional, and two additional categories. The SSC nomenclature is designed to easily identify their weather characteristic through categorical names that are based on thermal and moisture conditions. The first letter indicates moisture conditions; dry (D) and moist (M), while the last letter specifies thermal conditions, from the coldest polar (P), through mild as moderate (M), to the hottest tropical (T). In accordance with nomenclature, SSC types were designated: (a) dry moderate (DM); (b) dry polar (DP); (c) dry tropical (DT); (d) moist moderate (MM); (e) moist polar (MP); (f) moist tropical (MT); (g) transitional (TR); (h) moist tropical plus (MTP); (i) moist tropical double plus (MTDP). DM indicates mild and dry air with zonal wind flow in the mid-latitude. DP points to the coldest temperature alongside dry air. DT indicates the hottest and driest air conditions. MM describes warm and humid air and is associated with frontal activity. MP air is cool and moist, and is the results of inland transport from northern parts of the ocean or frontal overrunning to the far south. MT air is warm and very humid and is associated with warm sectors of mid-latitude cyclones and the western sides of anticyclones. Extreme MT types are separated into MTP or MTDP, which occur during the summer season. We thus define MT groups as MT, MTP, and MTDP because MTP and MTDP are a subset of the MT type; that is, seven synoptic weather types are included in total. TR points to days on which weather is transitioning from one weather type to another.

2.3. Methods

To investigate the relationship between PM_{10} concentration and synoptic weather patterns, the occurrence frequency of specific SSC type at different PM_{10} concentration levels was computed. Four different levels of PM_{10}

are adopted following comprehensive air-quality index (CAI) for PM_{10} concentration in Korea (MOE, 2021). High PM_{10} cases are defined as periods with 24 hr averaged PM_{10} concentration greater than 100 μgm^{-3}, following the environmental standard for ambient air quality in South Korea (MOE, 2021).

Normalization was necessary because the values describing different PM_{10} concentrations differ. Normalization was performed by counting the number of occurrences in each CAI PM_{10} bin for each SSC type. A total of 11,323 data points were used for the analysis and the normalized distribution linking between SSC type with PM_{10} concentration level were utilized. To verify each SSC frequency in accordance with each PM_{10} concentration level, the occurrences of all seven SSC types were combined to ensure a yield of 100%.

The weather pattern indicating each SSC type and its association with high PM_{10}, is examined as the composite spatial weather distribution by daily SSC type. In addition, the time evolution of high PM_{10} with composite was examined in daily intervals from 3 days before and to the onset of each event. The analysis domain was set to East Asia (20° − 50°N, 90° − 160°E in Figure S1a in Supporting Information S1) to verify synoptic-scale weather characteristics for each SSC type. Static stability was composited in a similar manner, and the followed the potential temperature lapse rate suggested in D. Lee, Wang, et al. (2020), allowing focus to be placed on the stagnant condition in the lower troposphere (1, 000 − 975 hPa).

3. Results

3.1. Mean Characteristics of PM According to SSC

The South Korean government has regulated ambient air quality, leading to a clear decreasing trend in the PM_{10} concentrations (MOE, 2021). Nevertheless, episodes of high PM concentration still occur on occasion, probably as a result of meteorological conditions (H. C. Kim et al., 2017). However, neither the extent to which PM concentration are related to different synoptic weather patterns, nor the underlying physical mechanisms that are responsible for such a relationship have been examined, including the ventilation effects that are the result of surface wind and the stagnant conditions in the lower atmosphere.

First, the distribution of mean PM_{10} concentration from December–May (winter and spring) for each SSC is shown in Figure 1. It is clear that certain SSC types are associated with high PM_{10} concentrations and are mostly distributed in western and southeastern Korea. A few important findings were revealed:

1. Conditions associated with DT and the DM types are associated with high PM_{10} concentration, with a mean value of 74 and 71 μgm^{-3} in the SMA (Figures 1a and 1e). The MT and the MM types also show association with high PM_{10}, with a mean value >60 μgm^{-3} in the SMA (Figures 1b and 1f). All these four types are associated with warm and dry air masses that reach the country during northern winter and spring.
2. On the other hand, relatively low PM conditions occur under DP types, which are the most frequent during winter (Table S1 in Supporting Information S1 and Figure 2b), with a mean value of 51 μgm^{-3} in the SMA (Figure 1c). This synoptic pattern is related to cold surge activity (Chen et al., 2004; J. H. Jeong et al., 2006) with strong northerly winds at the near-surface.

In summary, warm and dry conditions, which are often related to DT and DM types, may provide favorable conditions for high PM concentrations. On the contrary, cold and windy conditions, which are often related DP weather, are associated with low PM concentration.

Evidently, the surface PM concentration varied according to the SSC type regardless of seasons. On the contrary, dominant synoptic weather patterns differ during winter and spring (Figure 2b and H. C. Kim et al., 2021). DM type is prevalent in all seasons except in the months of July and August. DP is a common weather type during winter, with well-developed Siberian high-pressure and cold air outbreak over East Asia. Therefore, the relationship between SSC type and PM concentration could be more complex that the simple composite analysis in Figure 1.

The seasonal variation in PM_{10} concentrations for each SSC type was also analyzed, as seen in Figure 2. First, the mean of surface PM_{10} concentration (black line in Figure 2a) shows distinct seasonal patterns, with a peak during the spring. Generally, seasonal variations in PM_{10} for each SSC were as follows: DT (red line in Figure 2a) is associated with the highest level of surface PM during spring, followed by DM (orange line) during winter, and MT (green line in Figure 2a) groups during summer. Polar types (DP and MP) were associ-

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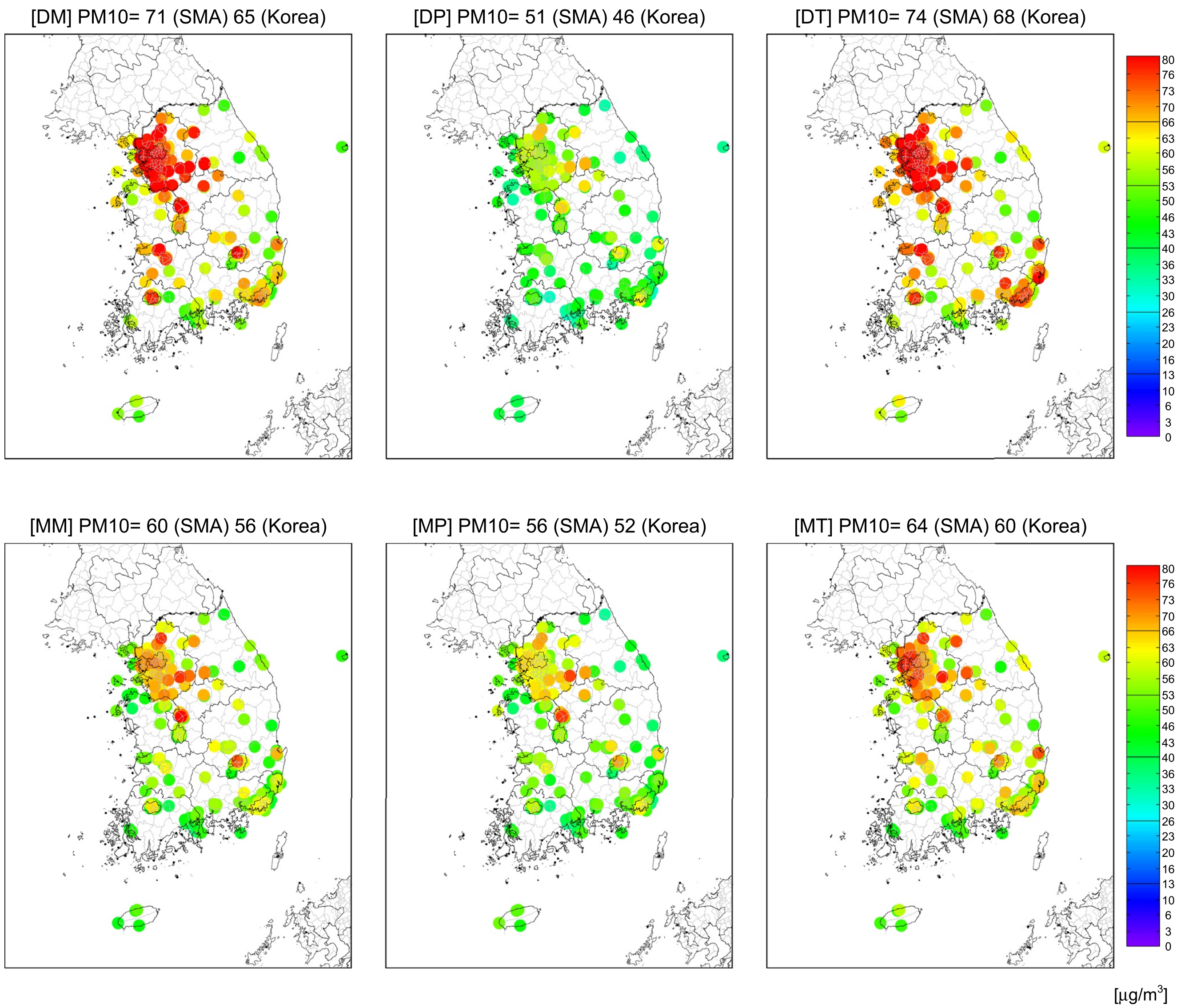

Figure 1. The mean concentrations of PM_{10} distribution for each spatial synoptic classification (SSC) during winter and spring (December–May) in South Korea for (a) the dry moderate (DM), (b) the moist moderate (MM), (c) the dry polar (DP), (d) the moist polar (MP), (e) the dry tropical (DT), and (f) the moist tropical (MT) type. Area averaged value of PM_{10} over Seoul Metropolitan Area (SMA) is shown.

ated with lower PM_{10} concentration in all months except April. Of note, this analysis does not account for the occurrence frequency of different SSCs, which can be critical as shown later, and summer was not included in this study because air pollutants tend to be washed out by the precipitation associated with the summer monsoon.

In general, dry weather types of SSC (DM and DT) were associated with high PM_{10} concentrations. Moist types of SSC (MM, MP, and MT) tend to occur more during summer (H. C. Kim et al., 2021) and are related to lower PM_{10} concentration. Therefore, specific synoptic weather type is highly associated with air quality degradation over South Korea.

3.2. Occurrence Frequency of PM According to SSC

To obtain a more complete picture of co-variability of surface PM_{10} concentration and each SSC type, the occurrences of the four different levels of PM_{10} concentrations, defined and used as CAI for PM_{10} concentration in Korea

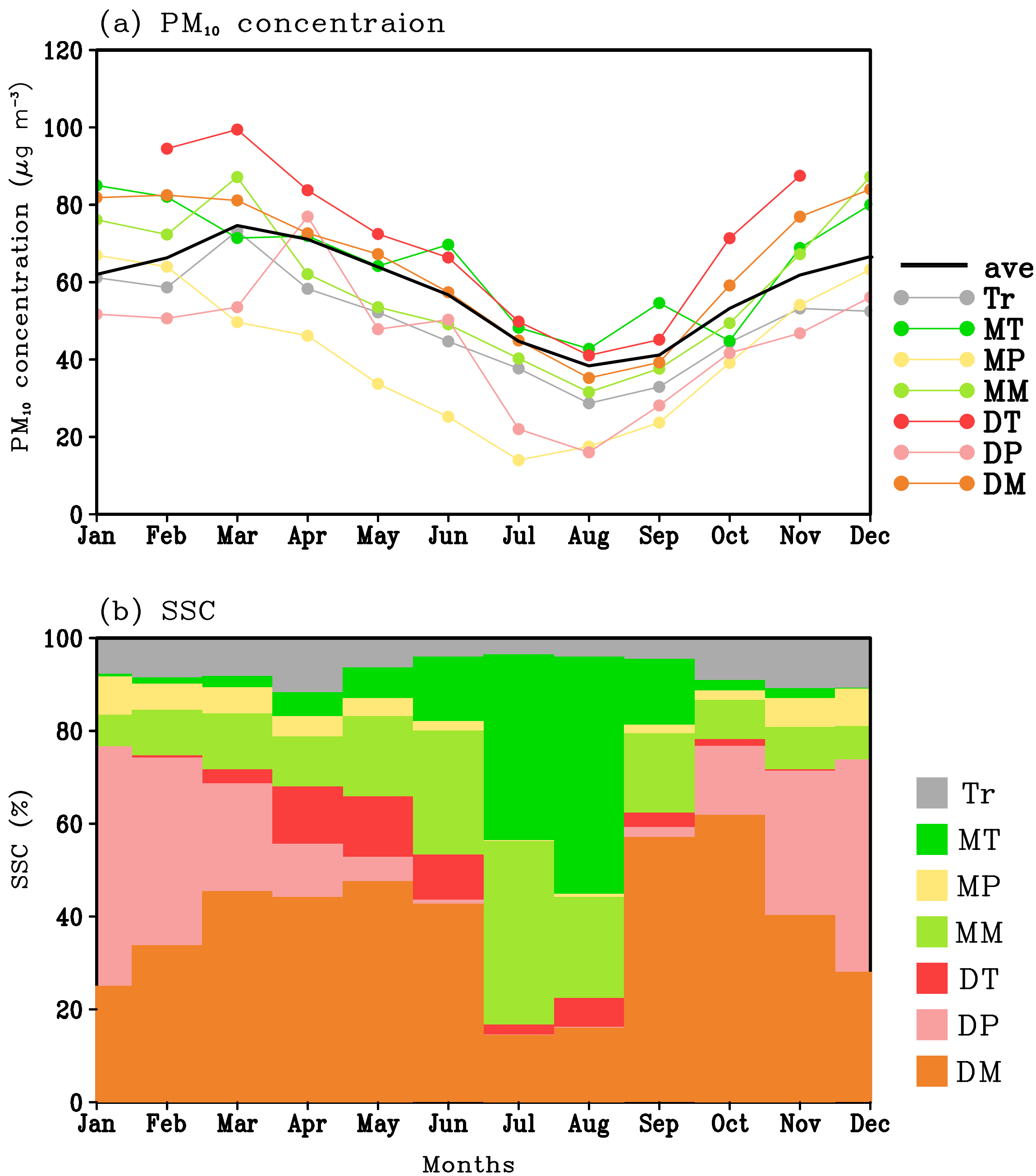

Figure 2. (a) Seasonal climatology of PM_{10} concentration (unit: μgm^{-3}) from 1988 to 2018 averaged over the 25 ground-level observation stations for each spatial synoptic classification (SSC) over Seoul, South Korea. (b) Seasonal variation of the SSC type in Seoul, South Korea from the period 1988–2018.

(MOE, 2021), was counted for each SSC type before normalization. Figures 3a and 3d show the normalized distribution of PM_{10} concentration for each SSC type during winter and spring, showing that the sum of the occurrence frequencies of SSC at each PM_{10} concentration levels yields 100%. The association between certain SSC types and different PM_{10} concentration levels can be used to ascertain which SSC is more closely related to high PM episodes.

The following features stand out during winter (Figure 3a):

1. Good levels ($0\ \mu gm^{-3} < PM_{10} < 31\ \mu gm^{-3}$) are the most frequent under DP types (pink color in Figure 3a) at 52.8% of the total, while the other types comprise less than 15%.

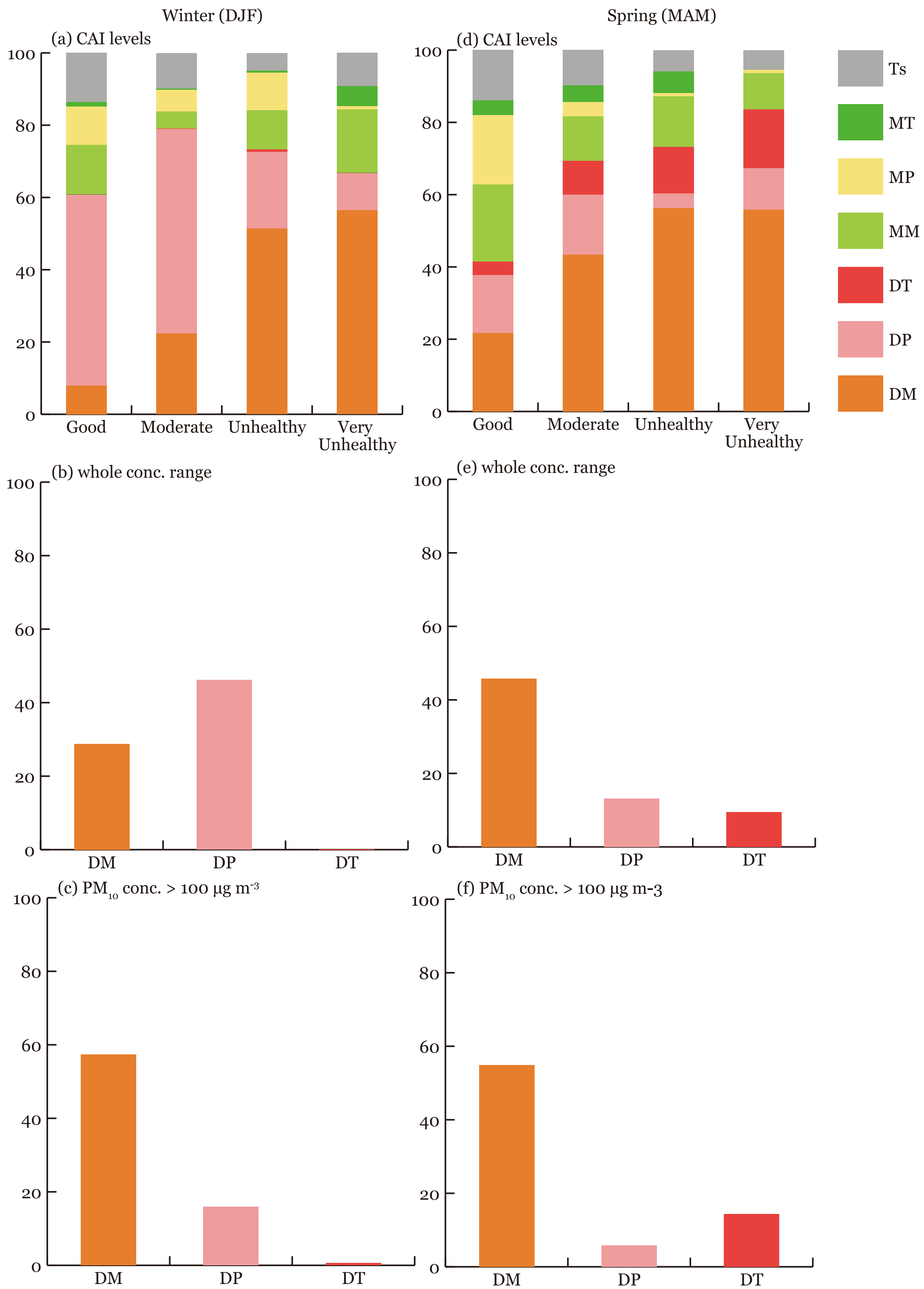

Figure 3. (a and d) Fractional coverage of each spatial synoptic classification (SSC) type in comprehensive air quality index for PM_{10} concentration (unit: μgm^{-3}) bins. *Y*-axis is normalized across all data. (b and e) Frequency of total PM_{10} concentration and (c and f) high PM_{10} concentration by each SSC type during winter and spring.

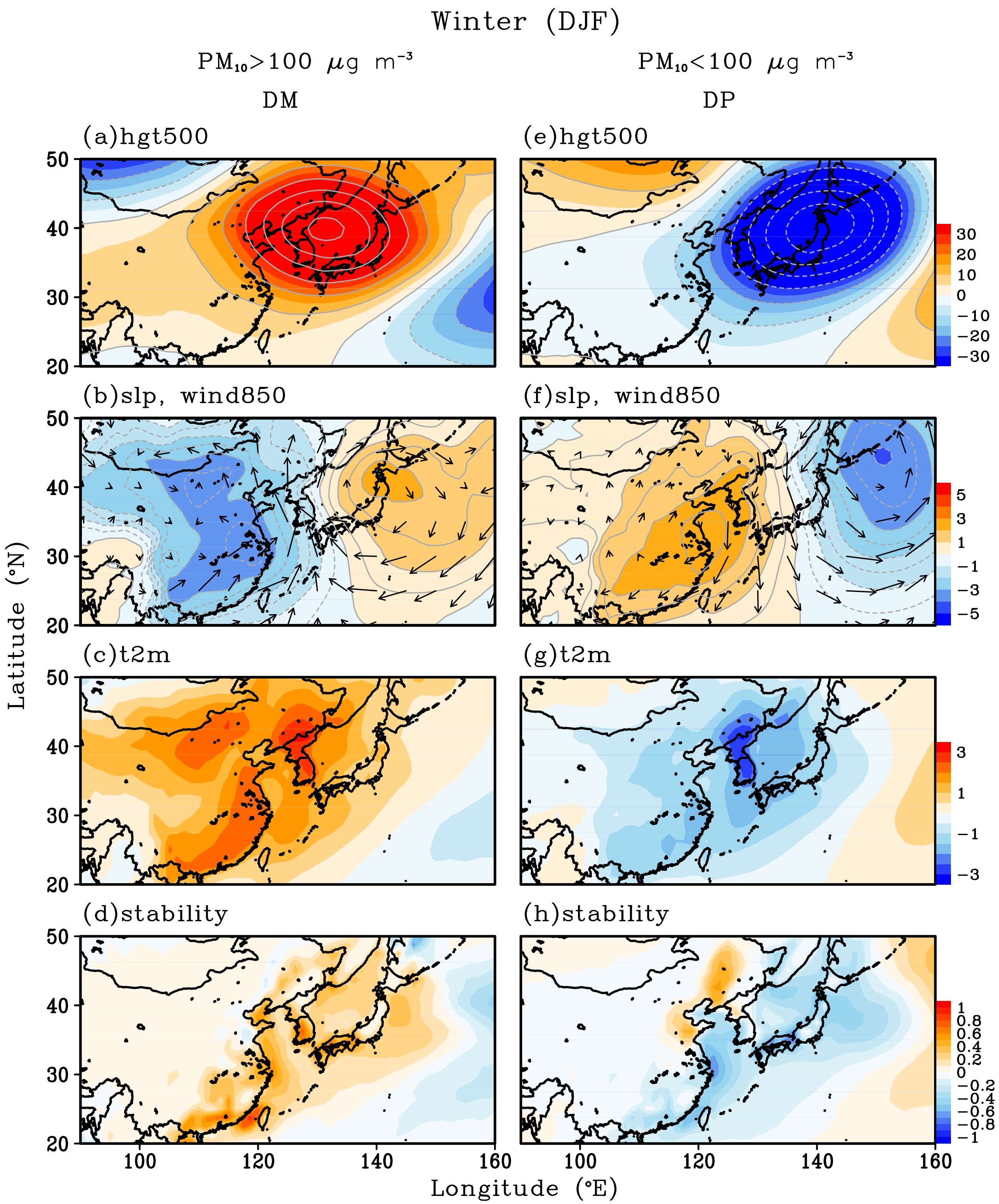

Figure 4. Winter season anomaly composite from 1988 to 2018 in geopotential height at 500 hPa (hgt500), sea level pressure (SLP) with wind vector at 850 hPa (wind850; arrows), 2m temperature (t2m), and static stability based on 1,000–975 hPa (stability) over East Asia. (a–d) high particulate matter (PM) cases under dry moderate (DM) types and (e–h) low PM cases under dry polar (DP) types.

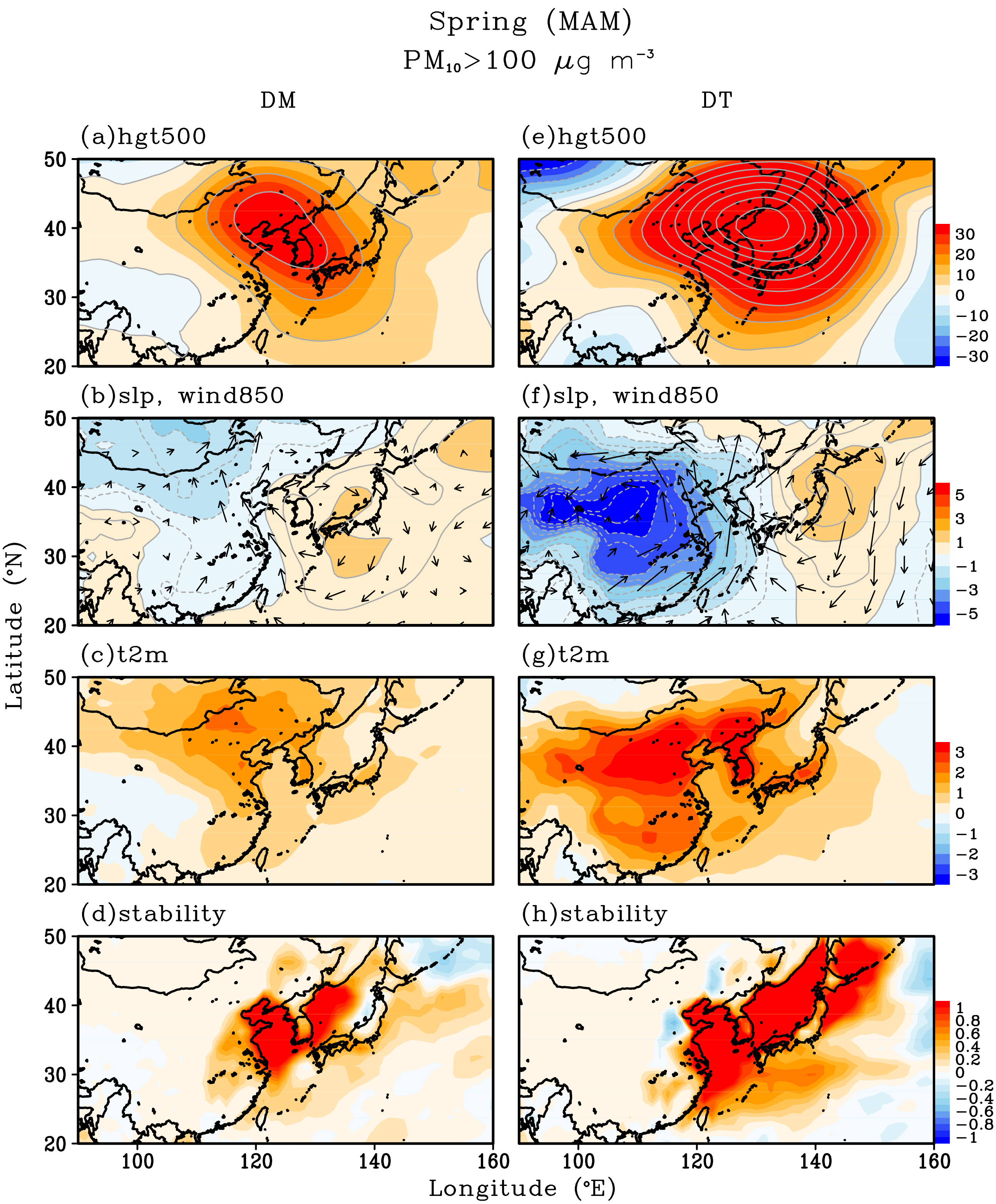

Figure 5. (a–h) Spring season anomaly composite from 1988 to 2018 in geopotential height at 500 hPa (hgt500), sea level pressure (SLP) with wind vector at 850 hPa (wind850; arrows), 2m temperature (t2m), and static stability based on 1,000–975 hPa (stability) over East Asia. (a–d) dry moderate (DM) types and (e–h) dry tropical (DT) types for high particulate matter (PM) cases.

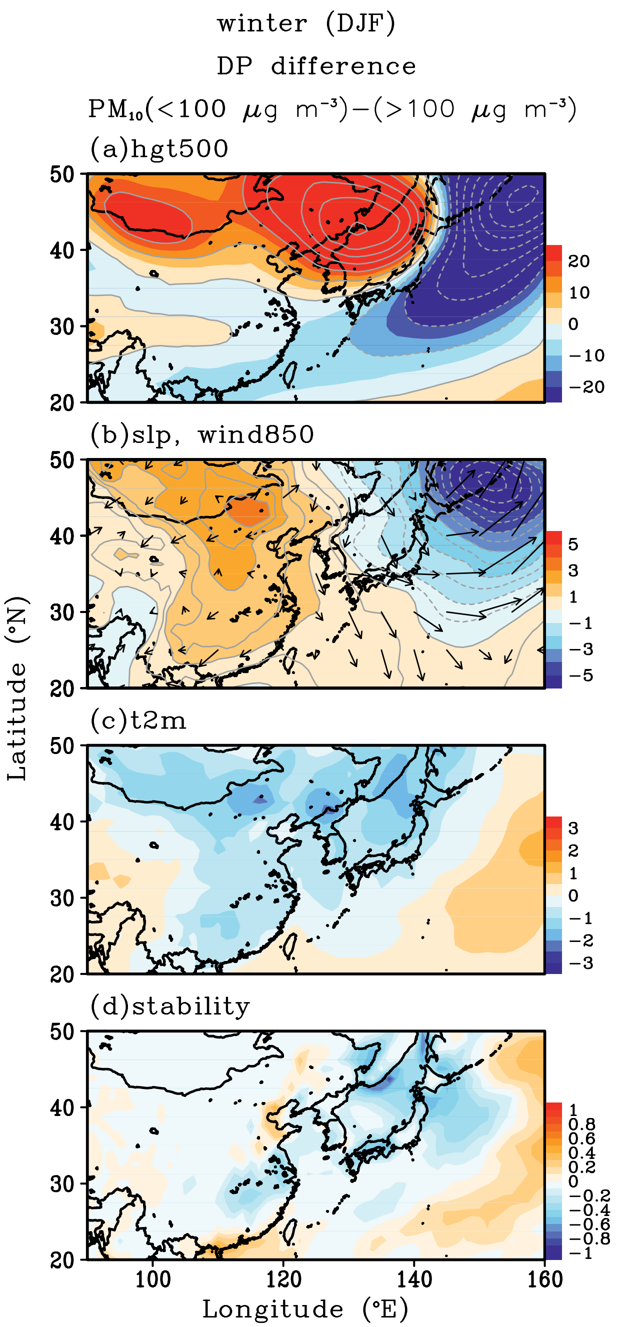

Figure 6. (a–d) Winter season difference under dry polar (DP) types between low particulate matter (PM) and high PM anomaly composite from 1988 to 2018 in geopotential height at 500 hPa (hgt500), sea level pressure (SLP) wind vector at with 850 hPa (wind850; arrows), 2m temperature (t2m), and static stability based on 1,000–975 hPa (stability) over East Asia.

2. Moderate levels (31 μgm^{-3} ≤ PM_{10} < 81 μgm^{-3}) are the most frequent under DP types (56.7%), with a mean concentration of 50.6 μgm^{-3}, followed by DM (22.3%; orange color in Figure 3a).
3. Unhealthy levels (81 μgm^{-3} ≤ PM_{10} < 151 μgm^{-3}) have the highest occurrence in under DM types (51.4%), followed by DP (21.3%). Additionally, very unhealthy levels (PM_{10} conc. ≥ 151 μgm^{-3}), which are relatively the lowest in frequency as compared to other PM_{10} levels, show the highest frequency under DM types (56.4%), with a mean concentration of 80.3 μgm^{-3}.

A large proportion of moderate to very unhealthy levels of PM_{10} concentration events occurred under DP to DM types (Figure 3b). The latter, characterized by warm and dry conditions, was the most dominant synoptic weather pattern associated with unhealthy and very unhealthy conditions (>50%). The former, characterized by cold temperature, was mainly associated with lower PM_{10} concentrations, but was also correlated with moderate PM_{10} conditions. We conclude that DM synoptic type is associated with high PM concentrations while DP synoptic type is associated with relatively low PM concentrations during winter.

During spring, DM becomes more dominant, and DM, DT, and DP become the three dominant weather types (Figure 2b). It is important to note here that DM is associated with all levels of PM_{10} concentrations. Good and moderate levels are the highest occurrence under DM types (21.8% and 43.4%; orange color in Figure 3d). DM and DT (red color in Figure 3d) are dominant in association with unhealthy levels, accounting for more than 68%. DM is also highly correlated with very unhealthy levels (55.8%), followed by DT (16.2%), with a higher mean concentration of 78 μgm^{-3}. DM and DT are thus highly associated with higher PM_{10} concentrations.

To summarize our findings, occurrence frequency of three important weather patterns (DM, DP, and DT) is shown for the all cases and the higher PM_{10} concentration, which is here defined as more than 100 μgm^{-3} (Figures 3b, 3c, 3e, and 3f). During winter season, the high PM (PM_{10} concentrations >100 μgm^{-3}) cases were most frequent under DM types (57.4%), followed by DP (16.0%) (Figure 3c). In contrast, DP types (pink color) accounted for 46.1%, followed by DM (28.8%) (orange color in Figure 3b), implying that low PM (PM_{10} concentrations < 100 μgm^{-3}) cases were most frequent under DP types (50.7%), followed by DM (24.4%) (Figure not shown). During spring, the following features are noted that the highest occurrence of high PM cases were under DM types with the frequency of 54.9%, followed by DT (red color) with the frequency of 14.4%, whereas DP decreased to 5.8% (Figure 3f). In contrast, DM was the dominant type (45.9%) throughout the whole concentration range (Figure 3e). It is noted here that DM type also occurred frequently at 44.4%, followed by DP (14.3%) in the low PM cases (Figure not shown).

3.3. Composite Analysis

3.3.1. Composite Analysis by SSC During Winter and Spring

Next, we explored the physical mechanisms possibly relating each SSC with different PM concentration levels by constructing composite of meteorological variables from the period 1988–2018 using JRA-55. The daily climatology was removed first.

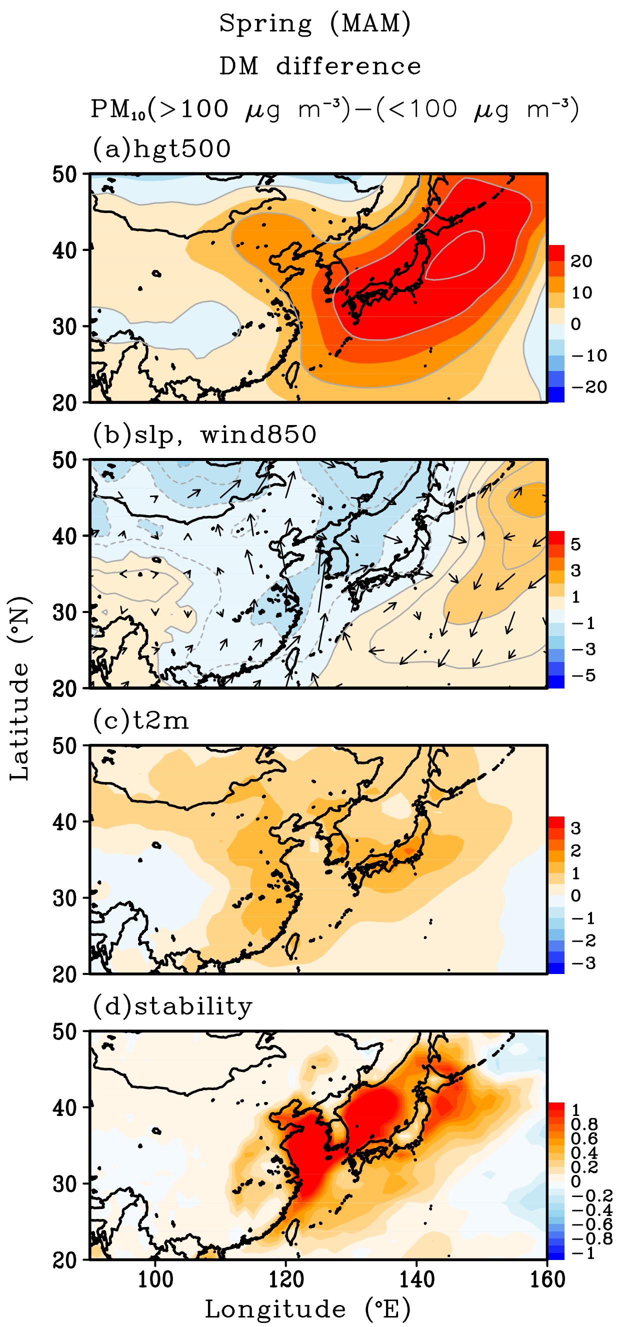

Figure 7. (a–d) Spring season difference under dry moderate (DM) types between high particulate matter (PM) and low PM anomaly composite from 1988 to 2018 in geopotential height at 500 hPa (hgt500), sea level pressure (SLP) with wind vector at 850 hPa (wind850; arrows), 2m temperature (t2m), and static stability based on 1,000–975 hPa (stability) over East Asia.

During winter, composites of atmospheric condition when it is under DM type with high PM cases are presented in Figures 4a–4d. A positive anomaly of geopotential height at 500 hPa over Korea, with the maximum positive anomalies observed in the East Sea (Figure 4a). Corresponding positive sea level pressure anomalies in the lower atmosphere, which are centered on Japan, can be found along with a strong southerly wind anomaly at 850 hPa (Figure 5b), implying the presence of a decreasing climatological northwesterly wind in the lower troposphere over the Korean peninsula. In conjunction with this anomalous high, an anomalous low pressure was located over China, forming a wave-train like pattern, and positive surface temperature anomalies dominate over East Asia, especially in the Korean peninsula (Figure 4c), resulting in increased static stability in the lower troposphere based on $1,000-975$ hPa (Figure 4d). A clear opposite pattern was found when DP types dominated under low PM cases in Figures 4e–4h. A negative anomaly of geopotential height at 500 hPa (Figure 4e) and sea level pressure (Figure 4f) was found enhanced seasonally prevailing northerly flow (Figure 4b; arrows). Additionally, a negative anomaly can be seen in the surface temperature and lower tropospheric stability over Korea (Figures 4g and 4h).

During spring, two dominant SSC types of DM and DT were composited for high PM cases in Figure 5. A positive geopotential anomaly at 500 hPa was found with the maximum positive anomalies around Korea under both types (Figures 5a and 5e). The corresponding positive sea level pressure with southerly wind anomalies at 850 hPa were observed under both DM and DT type (Figures 5b and 5f) alongside positive surface temperature anomalies and enhanced static stability in the lower troposphere (Figures 5c, 5d, 5g, and 5h). Of note, DT types are associated with significantly stronger anomalies in general. Enhanced static stability in the lower troposphere, that is, more stable conditions, are likely to promote higher PM concentrations.

As discussed earlier, DP types do not always guarantee lower PM concentrations. The difference between low and high PM under DP types is shown in Figure 6. In other words, it is clearly shown when PM is lower, negative anomalies in sea level pressure and geopotential height at 500 hPa with stronger northerly wind extended from northern China were observed (Figures 6a and 6b). Negative anomalies in the surface temperature and stability were exhibited over Korea (Figures 6c and 6d). DP type, a typical winter weather pattern that includes features such as cold surge, plays an important role in low PM cases. This is consistent with the results of a previous study (Liu et al., 2017), in which, polar weather types (i.e., the DP) were found to lead to decreased $PM_{2.5}$ levels in the United States because the air temperature is a more critical factor than moisture in determining surface $PM_{2.5}$ concentrations. However, it is cautiously noted here that the contrast in weather variables, such as the wind at 850 hPa, is important but not decisive, with uncertainty existed between one case to another.

A similar analysis was conducted for DM types during spring, which clearly indicated that when PM was higher under DM types, positive anomalies in the geopotential height at 500 hPa extended from Korea to western Pacific (Figure 7a). Consistent patterns of high pressure over the western Pacific were found in sea level pressure, with stronger southerly winds (Figure 7b). Surface temperature and stability in the lower atmosphere exhibited positive anomalies over Korea (Figures 7c and 7d). The enhanced stability was similar to that suggested in a previous study (D. Lee, Wang, et al., 2020), which indicated that static stability strength over northeast Asia in late winter and spring was the most prominent due to climate change. DM, a

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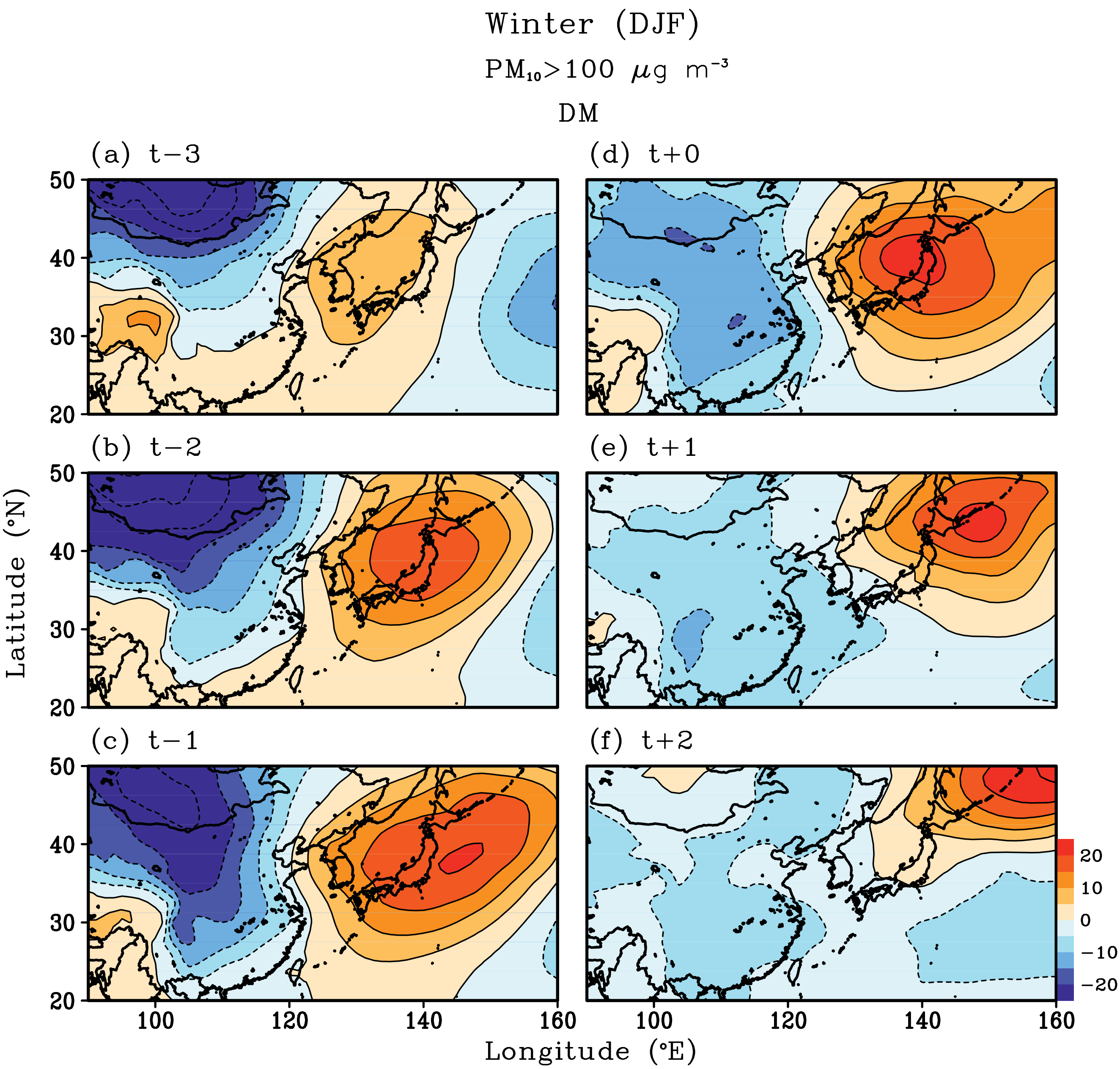

Figure 8. Composite of geopotential at 850 hPa during winter season with high particulate matter (PM) under dry moderate (DM) types with lead (a) 3 days, (b) 2 days, (c) 1 day, and (d) 0 days and lag (e) 1 day, and (f) 2 days.

dominant spring weather pattern, reinforces the atmospheric high-pressure system with stronger stability during spring. Consistent with DP, there were also uncertainty in the relationship between weather variable and PM concentration.

3.3.2. Temporal Evolution of Composite Analysis by SSC

Finally, the temporal evolutions of geopotential at 850 hPa was analyzed for comparison of lead and lag. Figure 8 illustrates the temporal evolution of geopotential height anomaly at 850 hPa from lead 3 days to lag 2 days with high PM under DM types during winter. At lead 3, positive anomalies appeared on the Korean peninsula and further developed over the East Sea and Japan, after which they continued to migrate northeastward over time.

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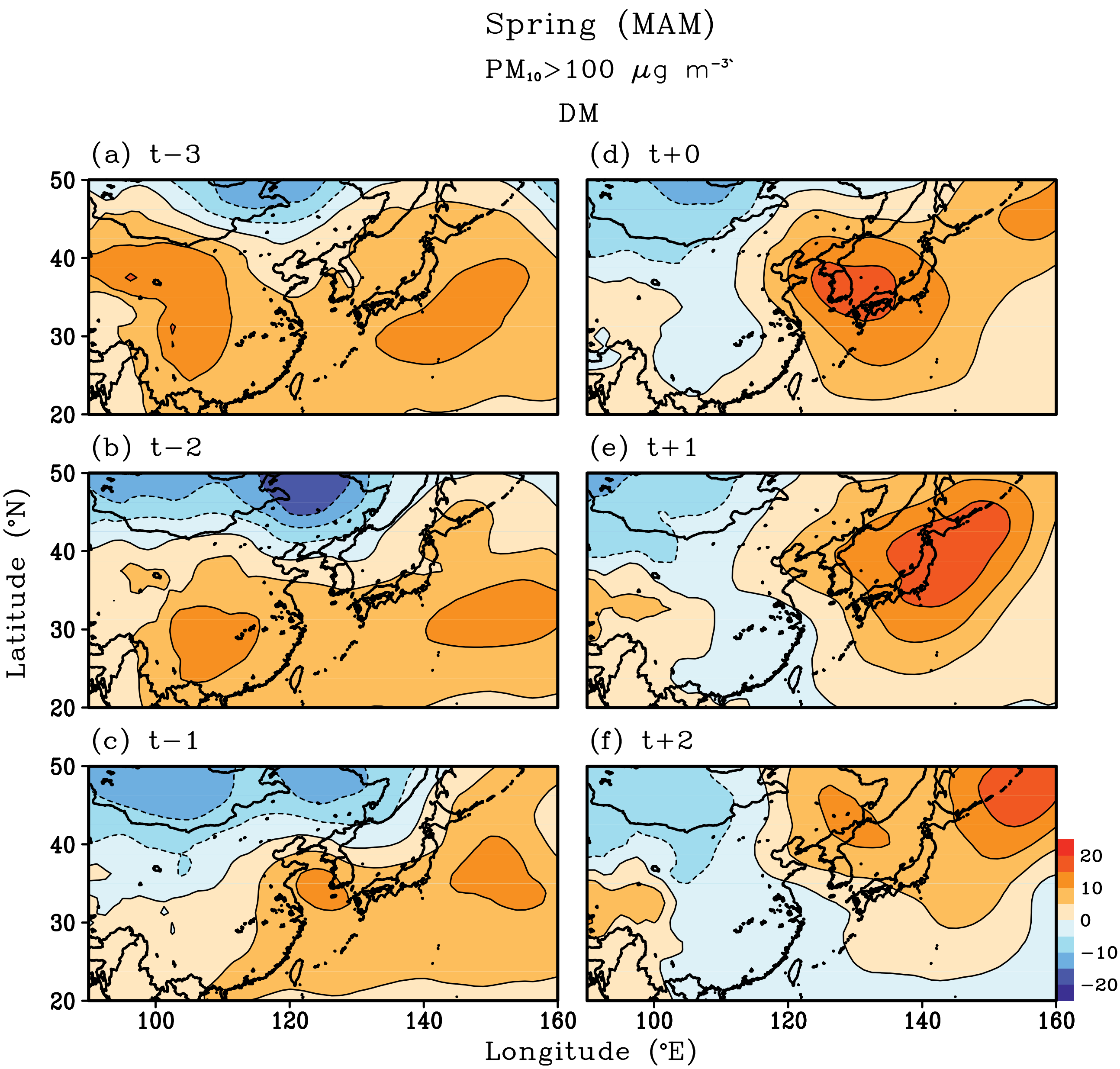

Figure 9. Composite of geopotential at 850 hPa during spring season with high particulate matter (PM) under dry moderate (DM) types with lead (a) 3 days, (b) 2 days, (c) 1 day, and (d) 0 days and lag (e) 1 day, and (f) 2 days.

This system was likely to cause southerly wind and relatively warm anomalies, which could have led to high PM concentration.

On the contrary, the opposite pattern was found under DP cases (Figure S3 in Supporting Information S1). Instead of high-pressure anomalies, negative anomalies of geopotential height at 850 hPa were appeared and continued to develop with northeastward migration. This system generates well organized cold surge patterns over East Asia during winter (J. H. Jeong et al., 2006), with air pollutants flowing out from Korea as a result of the strong northerly wind (J. Lee, Son, et al., 2020).

The temporal evolution under DM types with high PM during spring is shown in Figure 9. A positive anomaly at a geopotential height at 850 hPa covered China and the area east of Japan on lead day 3, after which it moved eastward to reach the Korean peninsula with the strongest positive anomaly at lag 0 before gradually moving northeastward. DT was associated with a stronger circulation system as compared to DM (Figure S4 in Supporting

Information S1). A previous study suggested that the $PM_{2.5}$ concentration over Seoul is strongly associated with a blocking index based on geopotential height anomaly at 500 hPa over the East Sea and Japan (Shin et al., 2021). Moreover, this system shows a wave-train pattern, which is a typical transient synoptic wave pattern over Korea during spring. This migratory high-pressure system may worsen the air quality when its center passes through Korea.

4. Summary and Discussion

Air quality has a profound impact on our daily lives, and is affected by multiple factors including local emissions, long-range transportation, and local weather condition. In this study, a close relationship between synoptic-scale weather patterns and PM concentrations was found over South Korea during winter and spring. In particular, dry weather types of SSC (DM, DP, and DT) were found to be the most dominant and were strongly related to the high/low PM concentrations. The major findings of this analysis can be summarized as follows:

1. During winter season, DM types are the most frequently occurred in association with high PM cases, with well-organized anticyclonic circulation and a weak northwesterly wind flow. On the contrary, DP types are the most frequently occurred in association with low PM cases, with strong prevailing northerly flow.
2. During spring season, DM and DT types are the most frequently occurred patterns in association with high PM cases, with well-developed anticyclonic circulation and strengthened static stability in the lower troposphere. In particular, DT types lead to strongly increased static stability, implying further much high PM concentration as a result of atmospheric stagnancy.
3. Finally, the degree of PM concentration largely varies according to the intensity of key weather variables including wind and stability, in synoptic weather patterns.

Our results indicate that changes in dry types of SSC could largely cause deterioration in the air quality over South Korea through the weak northwesterly wind and enhanced stagnation in the lower troposphere. Neither the impact of emission changes on the current PM_{10} trend nor seasonal variation were considered in this study. Despite this limitation, our results clearly demonstrate that synoptic weather systems play an important role in regional high PM_{10} episodes. This finding will be an indication for regional air quality forecasting based on weather conditions. It is noted that weather condition is one of many factors that contribute to air pollution. Therefore, the findings in this study can likely be used for guidance-like information rather than actual forecasting.

Data Availability Statement

All the data used in this study are publicly available. JRA55 reanalysis (Kobayashi et al., 2015) is from the Japan Meteorological Agency (JMA) at http://jra.kishou.go.jp/JRA-55. The SSC data (Sheridan, 2002) are from http://geog.kent.edu/ssc.html. PM data are originally obtained from the airkorea site and the Seoul Research Institute of Public Health and Environment, which are both in Korean. Processed data is openly available in Zenodo at https://doi.org/10.5281/zenodo.7237301 and https://doi.org/10.5281/zenodo.7237257.

Acknowledgments
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-2021-01-02-066), and a grant from the National Research Found of Korea under NRF-2021R1A2C1011827, NRF-2020M1A5A1110578, and NRF-2021M1A5A1075532. Also it is partially supported by Korea Environment Industry and Technology Institute (KEITI) through "Climate Change R&D Project for New Climate Regime", funded by Korea Ministry of Environment (MOE) (RE2022016655). The authors thank the Seoul Metropolitan government for providing the observed PM_{10} concentration data and Dr. Sheridan for the SSC data.

References

Cai, W., Li, K., Liao, H., Wang, H., & Wu, L. (2017). Weather conditions conducive to Beijing severe haze more frequent under climate change. *Nature Climate Change*, *7*(4), 257–262. https://doi.org/10.1038/nclimate3249

Cakmak, S., Hebbern, C., Pinault, L., Lavigne, E., Vanos, J., Crouse, D. L., & Tjepkema, M. (2018). Associations between long-term $PM_{2.5}$ and ozone exposure and mortality in the Canadian Census Health and Environment Cohort (CANCHEC), by spatial synoptic classification zone. *Environment International*, *111*, 200–211. https://doi.org/10.1016/j.envint.2017.11.030

Cakmak, S., Hebbern, C., Vanos, J., Crouse, D. L., & Burnett, R. (2016). Ozone exposure and cardiovascular-related mortality in the Canadian Census Health and Environment Cohort (CANCHEC) by spatial synoptic classification zone. *Environmental Pollution*, *214*(2), 589–599. https://doi.org/10.1016/j.envpol.2016.04.067

Callahan, C. W., Schnell, J. L., & Horton, D. E. (2019). Multi-index attribution of extreme winter air quality in Beijing, China. *Journal of Geophysical Research: Atmospheres*, *124*(8), 4567–4583. https://doi.org/10.1029/2018JD029738

Chen, T. C., Huang, W. R., & Yoon, J. H. (2004). Interannual variation of the East Asian cold surge activity. *Journal of Climate*, *17*(2), 401–413. https://doi.org/10.1175/1520-0442(2004)017<0401:IVOTEA>2.0.CO;2

Cheng, F. Y., Feng, C. Y., Yang, Z. M., Hsu, C. H., Chan, K. W., Lee, C. Y., & Chang, S. C. (2021). Evaluation of real-time $PM_{2.5}$ forecasts with the WRF-CMAQ modeling system and weather-pattern-dependent bias-adjusted $PM_{2.5}$ forecasts in Taiwan. *Atmospheric Environment*, *244*, 117909. https://doi.org/10.1016/j.atmosenv.2020.117909

Davis, R. E., Normile, C. P., Sitka, L., Hondula, D. M., Knight, D. B., Gawtry, S. P., & Stenger, P. J. (2010). A comparison of trajectory and air mass approaches to examine ozone variability. *Atmospheric Environment*, *44*(1), 64–74. https://doi.org/10.1016/j.atmosenv.2009.09.038

Hanna, A. F., Yeatts, K. B., Xiu, A., Zhu, Z., Smith, R. L., Davis, N. N., et al. (2011). Associations between ozone and morbidity using the spatial synoptic classification system. *Environmental Health: A Global Access Science Source*, *10*(1), 49. https://doi.org/10.1186/1476-069X-10-49

Hawkins, T. W., & Holland, L. A. (2010). Synoptic and local weather conditions associated with $PM_{2.5}$ concentration in Carlisle, Pennsylvania. *Middle States Geographer*, *43*, 72–84.

Jeong, J. H., Kim, B. M., Ho, C. H., Chen, D., & Lim, G. H. (2006). Stratospheric origin of cold surge occurrence in East Asia. *Geophysical Research Letters*, *33*(14), 1–5. https://doi.org/10.1029/2006GL026607

Jeong, J. I., & Park, R. J. (2013). Effects of the meteorological variability on regional air quality in East Asia. *Atmospheric Environment*, *69*(3), 46–55. https://doi.org/10.1016/j.atmosenv.2012.11.061

Jeong, J. I., Park, R. J., & Yeh, S. W. (2018). Dissimilar effects of two El Niño types on $PM_{2.5}$ concentrations in East Asia. *Environmental Pollution*, *242*, 1395–1403. https://doi.org/10.1016/j.envpol.2018.08.031

Jeong, J. I., Park, R. J., Yeh, S. W., & Roh, J. (2021). Science of the total environment statistical predictability of wintertime $PM_{2.5}$ concentrations over East Asia using simple linear regression. *Science of the Total Environment*, *776*, 146059. https://doi.org/10.1016/j.scitotenv.2021.146059

Jung, M. I., Son, S. W., Kim, H. C., Kim, S. W., Park, R. J., & Chen, D. (2019). Contrasting synoptic weather patterns between non-dust high particulate matter events and Asian dust events in Seoul, South Korea. *Atmospheric Environment*, *214*, 116864. https://doi.org/10.1016/j.atmosenv.2019.116864

Kim, H. C., Choi, H., Ngan, F., & Lee, P. (2014). Surface ozone variability in synoptic pattern perspectives. *Air Pollution Modeling and Its Application*, *XXIII*, 551–556. https://doi.org/10.1007/978-3-319-04379-1_91

Kim, H. C., Kim, S., Kim, B. U., Jin, C. S., Hong, S., Park, R., et al. (2017). Recent increase of surface particulate matter concentrations in the Seoul Metropolitan Area, Korea. *Scientific Reports*, *7*(1), 4710. https://doi.org/10.1038/s41598-017-05092-8

Kim, H. C., Kim, S., Son, S.-W., Lee, P., Jin, C.-S., Kim, E., et al. (2016). Synoptic perspectives on pollutant transport patterns observed by satellites over East Asia: Case studies with a conceptual model. *Atmospheric Chemistry and Physics Discussions*, 1–30. https://doi.org/10.5194/acp-2016-673

Kim, H. C., Lee, D., Ngan, F., Kim, B. U., Kim, S., Bae, C., & Yoon, J. H. (2021). Synoptic weather and surface ozone concentration in South Korea. *Atmospheric Environment*, *244*, 117985. https://doi.org/10.1016/j.atmosenv.2020.117985

Kim, J. (2019). Particulate matter mortality rates and their modification by spatial synoptic classification. *International Journal of Environmental Research and Public Health*, *16*(11), 1904. https://doi.org/10.3390/ijerph16111904

Kim, Y. M., Kim, J., Jung, K., Eo, S., & Ahn, K. (2018). The effects of particulate matter on atopic dermatitis symptoms are influenced by weather type: Application of spatial synoptic classification (SSC). *International Journal of Hygiene and Environmental Health*, *221*(5), 823–829. https://doi.org/10.1016/j.ijheh.2018.05.006

Kobayashi, S., Ota, Y., Harada, Y., Ebita, A., Moriya, M., Onoda, H., et al. (2015). The JRA-55 reanalysis: General specifications and basic characteristics. *Journal of the Meteorological Society of Japan*, *93*(1), 5–48. https://doi.org/10.2151/jmsj.2015-001

Kyselý, J., & Huth, R. (2010). Relationships between summer air masses and mortality in Seoul: Comparison of weather-type classifications. *Physics and Chemistry of the Earth*, *35*(9–12), 536–543. https://doi.org/10.1016/j.pce.2009.11.001

Lee, D., Wang, S. Y., Zhao, L., Kim, H. C., Kim, K., & Yoon, J. H. (2020). Long-term increase in atmospheric stagnant conditions over northeast Asia and the role of greenhouse gases-driven warming. *Atmospheric Environment*, *241*, 117772. https://doi.org/10.1016/j.atmosenv.2020.117772

Lee, G., Ho, C. H., Chang, L. S., Kim, J., Kim, M. K., & Kim, S. J. (2020). Dominance of large-scale atmospheric circulations in long-term variations of winter PM_{10} concentrations over East Asia. *Atmospheric Research*, *238*, 104871. https://doi.org/10.1016/j.atmosres.2020.104871

Lee, J., Son, S. W., Cho, H. O., Kim, J., Cha, D. H., Gyakum, J. R., & Chen, D. (2020). Extratropical cyclones over East Asia: Climatology, seasonal cycle, and long-term trend. *Climate Dynamics*, *54*(1–2), 1131–1144. https://doi.org/10.1007/s00382-019-05048-w

Li, J., Hao, X., Liao, H., Wang, Y., Cai, W., Li, K., et al. (2022). Winter particulate pollution severity in North China driven by atmospheric teleconnections. *Nature Geoscience*, *15*(5), 349–355. https://doi.org/10.1038/s41561-022-00933-2

Liu, Y., Zhao, N., Vanos, J. K., & Cao, G. (2017). Effects of synoptic weather on ground-level $PM_{2.5}$ concentrations in the United States. *Atmospheric Environment*, *148*, 297–305. https://doi.org/10.1016/j.atmosenv.2016.10.052

Ministry of Environment (MOE). (2021). Annual report of air quality in Korea, 2020.

Seo, J., Kim, J. Y., Youn, D., Lee, J. Y., Kim, H., Lim, Y. B., et al. (2017). On the multiday haze in the Asian continental outflow: The important role of synoptic conditions combined with regional and local sources. *Atmospheric Chemistry and Physics*, *17*(15), 9311–9332. https://doi.org/10.5194/acp-17-9311-2017

Sheridan, S. C. (2002). The redevelopment of a weather-type classification scheme for North America. *International Journal of Climatology*, *22*(1), 51–68. https://doi.org/10.1002/joc.709

Shin, U., Park, S. H., Park, J. S., Koo, J. H., Yoo, C., Kim, S., & Lee, J.-b.(2021). Predictability of $PM_{2.5}$ in Seoul based on atmospheric blocking forecasts using the NCEP global forecast system. *Atmospheric Environment*, *246*, 118141. https://doi.org/10.1016/j.atmosenv.2020.118141

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. *Bulletin of the American Meteorological Society*, *96*(12), 2059–2077. https://doi.org/10.1175/BAMS-D-14-00110.1

Wie, J., & Moon, B. K. (2017). ENSO-related PM_{10} variability on the Korean Peninsula. *Atmospheric Environment*, *167*, 426–433. https://doi.org/10.1016/j.atmosenv.2017.08.052

Zou, Y., Wang, Y., Zhang, Y., & Koo, J. H. (2017). Arctic sea ice, Eurasia snow, and extreme winter haze in China. *Science Advances*, *3*(3), 1–9. https://doi.org/10.1126/sciadv.1602751