Synoptic Weather Patterns and Associated Air Pollution in Taiwan

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Abstract

In this study, the cluster analysis method is applied to the daily averaged wind fields and sea level pressure observed from surface weather stations in Taiwan to classify the synoptic weather pattern and study the corresponding characteristics of air pollutants, including fine particulate matter (PM$_{2.5}$), coarse particulate matter (PM$_{10}$), and ozone (O$_3$), in Taiwan. The study period is from January 2013 to March 2018. The classification identified six weather types: clusters 1, 2 and 3 (C1-C3), which are typical winter weather types and associated with high air pollutant concentrations; C3, which is under the influence of weak synoptic weather, associated with the lowest wind speed and the highest PM$_{2.5}$ and PM$_{10}$ concentrations, and represents the most prevalent weather type that is prone to the occurrence of PM$_{2.5}$ events; C4, which occurs mostly during seasonal transition months and is associated with the highest O$_3$ concentrations; and C5 and C6, which are summer weather types with low air pollutant concentrations.

Further analysis of the local wind flow in the Taiwan area using the 0.3-degree ERA5 reanalysis dataset and surface-observed wind indicates that the land-sea breeze embedded within the synoptic weather forms in western Taiwan in the C3 cluster, which is favorable for air pollutant accumulation. On the other hand, when the prevailing northeasterly wind is obstructed by the Central Mountain Range, the southwestern Taiwan being situated on the leeside of the mountain, often exhibits the worst air pollution problem due to the stagnant wind condition.

Keywords: Synoptic weather classification; Cluster analysis; PM$_{2.5}$; Ozone; Stagnant wind

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INTRODUCTION

Air pollution is an important environmental issue in Taiwan and can be either locally produced or transported long distances from East Asia (Cheng et al., 2012; Chuang et al., 2017). The major domestic anthropogenic emissions are from urban areas, coal-fired power plants, crude oil refinery plants, industrial parks and major highways and are emitted mostly in western Taiwan (Fang and Chen, 1996; Hsu and Cheng, 2016). In addition to emissions, meteorological conditions have been shown to play an important role in affecting air pollution dispersion in Taiwan (Tsai et al., 2008, 2011; Lai, 2014).

Identifying the synoptic weather patterns and large-scale circulation patterns represents a useful method of studying air pollution problems (Rainham et al., 2005; Cheng et al., 2013; Vanos et al., 2015; Hsu and Cheng, 2016). Calvo et al. (2010) characterized the chemical composition of rainwater based on the origin of air masses and found a strong relationship with the origin of air masses and precipitation. The weather classification method can be subjective, such as manual categorizations of weather maps; and it can also be objective, such as the cluster analysis method, which is used to categorize data and has been applied in many studies for classifying weather patterns (Kidson, 2000; Coleman and Roger, 2007; Russo et al., 2015). Ngan and Byun (2011) applied the two-stage cluster analysis method to classify the synoptic weather patterns over eastern Texas using the 850 hPa wind fields for the five-month ozone (O3) season (May to September) in the years 2005 and 2006. The results demonstrate the effectiveness of
Taiwan is an island located on the southeastern fringe of East Asia. The synoptic weather conditions are dominated by the western North Pacific subtropical high-pressure system during summer and the Asian continental anticyclone during winter and spring and further complicated by the land-ocean distribution and high Central Mountain Range (CMR), which runs from north to south across the island. This study was conducted to develop synoptic weather classifications in Taiwan using the cluster analysis method and investigate the role of meteorological conditions in air pollutant concentrations, including fine particulate matter (PM$_{2.5}$), coarse particulate matter (PM$_{10}$) and O$_3$. The objectives of this study are as follows: (1) study the characteristics of synoptic weather patterns and their associated circulation patterns in Taiwan; and (2) examine the role of synoptic weather patterns on PM$_{2.5}$, PM$_{10}$ and O$_3$ concentrations in different areas of western Taiwan.

**METHODOLOGY AND DATA**

Cluster analysis is an objective classification method that establishes relatively uniform groups from the input data, and it separates data into distinctive clusters by minimizing variance within each group and maximizing variance between groups. In this study, a two-stage clustering
method was applied to produce the weather classifications in Taiwan. In the first step, the initial number of clusters and the centroids of the clusters were determined and used as seeds in the second stage for the initiation of the K-means cluster analysis (MacQueen, 1967). The hourly wind speed and wind direction and the sea level pressure (SLP) observed at Central Weather Bureau (CWB) surface stations in Taiwan (refer to Fig. 1 for station location) are used for the cluster analysis. The hourly observed wind data are first decomposed into U and V components, and daily averaged values are estimated. The wind field is selected for the cluster analysis because it provides information on the air pollution dispersion and transport behavior. Moreover, the cluster analysis experiments are applied by including and excluding the SLP variable. The results indicate that the inclusion of the SLP in the cluster analysis can enhance the distinction between the summer and winter classified weather types; therefore, it is included for weather classification in this study.

The study period is from January 2013 to March 2018. To avoid discussions on the tropical depression and typhoon related weather types, the two-stage cluster analysis was applied twice. The first application of the cluster analysis identified a cluster that is associated with the tropical depression and typhoon system (due to the inclusion of the SLP) and includes 35 days (refer to Supplementary Information).
We excluded the 35 days that are affected by typhoons and re-apply the cluster analysis. Moreover, before applying the cluster analysis, the variables are normalized by calculating the standard score of each observed variable based on formula (1):

\[ Z = \frac{X - \mu}{\sigma} \]  

(1)

where \( Z \) is the standard score of meteorological variable; \( X \) is the observed surface \( U, V \), and \( SLP \); and \( \mu \) and \( \sigma \) denote the mean and standard deviation of each meteorological field.

The number of classified clusters is determined according to the silhouette value that measures the similarity within the cluster and the dissimilarity between clusters (Rousseeuw, 1987). In this study, the variation of the silhouette value becomes small when the number of clusters is greater than six; therefore, six clusters are set as the final classified results. For each identified cluster, the mean values of temperature, precipitation, wind speed, and \( PM_{2.5} \), \( PM_{10} \) and \( O_3 \) concentrations acquired from the Taiwan Environmental Protection Agency (EPA) air quality monitoring stations (refer to Fig. 1 for station location) are analyzed. The daily mean SLP and horizontal wind field data from the ERA5 reanalysis data (Hersbach and Dee, 2016) were used to produce the composite surface weather map for each cluster.

Due to the complicated geographical location and topographical conditions in Taiwan, the meteorological conditions can change distinctively from the northern to southern parts of Taiwan. Based on distinct characteristics of the meteorological and emission conditions, the Taiwan EPA
has divided the nation into seven air quality zones (AQZs), namely, northern Taiwan (NT), the Chu-Miao area (CM), central Taiwan (CT), the Yun-Chia-Nan area (YCN), the Kao-Ping area (KP), the Hua-Dong area (HD), and Yilan (YI). The analysis and discussion consider five AQZs (NT, CM, CT, YCN and KP) (Fig. 1) to examine the air pollution problem in different areas of western Taiwan. The HD and YI areas located in eastern Taiwan are not discussed due to the lower impact of local anthropogenic emissions (TEDS-9.0, 2016).

RESULTS AND DISCUSSION

Characterization of the six weather patterns

Based on the cluster analysis results, six weather patterns are identified. Table 1 summarizes the number of days; number of PM$_{2.5}$ event days; daily mean PM$_{2.5}$, PM$_{10}$, and O$_3$ concentrations, wind speed; and daily accumulated precipitation averaged over Taiwan for each cluster during the study period. A PM$_{2.5}$ event day is defined as a day in which there are more than 30 air quality monitoring stations located in western Taiwan with daily mean PM$_{2.5}$ concentrations exceeding 35 μg m$^{-3}$ (the 24-h PM$_{2.5}$ standard in Taiwan). A total of 67 stations are located in western Taiwan, and 30 stations represent approximately half of the total number of stations located in western Taiwan. Overall, the occurrence of days in each cluster is relatively uniform,
with no exceedingly small or large clusters observed and the classification results can represent the general weather patterns in Taiwan.

Fig. 2 shows the composite map of the mean SLP and surface wind fields for each weather type. Fig. 3 shows the number of days and PM$_{2.5}$ event days that occurred in each month for each cluster during the study period.

For cluster 1 (C1), Taiwan is affected by northeasterly monsoonal (NEM) flow due to the intrusion of the Asian continental anticyclone system. C1 occurs for 251 days (13.1%) and appears mostly from November to March during the winter months. Among the six clusters, the mean wind speed is the highest (2.35 m s$^{-1}$) in the C1 cluster due to the prevalence of the NEM flow. Although the strong wind fields can disperse the air pollutants, the mean PM$_{2.5}$ (28.35 μg m$^{-3}$) and PM$_{10}$ (60.19 μg m$^{-3}$) concentrations are the third highest among the six clusters. Due to the influence of the NEM flow, air pollution can be contributed by long-range transported (LRT) air pollutants from East Asia.

Cluster 2 (C2) occurs following the C1 weather type that moves to the east coast of China. With the eastward movement of the anticyclone, the prevailing wind in Taiwan is affected by weak northeasterly to easterly flows due to continental high-pressure peripheral circulation. The monthly occurrence is similar to that of C1, and it mostly appears in the cold season from November to March, although the number of occurrences is 342 days (17.85%), which is higher
than the number of C1 occurrences (Fig. 3). Both C1 and C2 are typical winter weather types. The averaged PM$_{2.5}$ and PM$_{10}$ concentrations in the C2 cluster are the second highest among the clusters.

Cluster 3 (C3) occurs after the eastward passage of the C2 weather type. When the continental anticyclone is located farther from the Asian continent, Taiwan is under the influence of weak synoptic weather and affected by the weak easterly to southeasterly flow. Due to the weak synoptic easterly wind, western Taiwan often exhibits stagnant wind conditions and strong subsidence behavior due to the terrain blocking by the CMR (Hsu and Cheng, 2016). C3 is associated with the lowest wind speed (1.3 m s$^{-1}$) and the highest PM$_{2.5}$ (35.35 μg m$^{-3}$) and PM$_{10}$ (65.48 μg m$^{-3}$) concentrations. C3 typically occurs from October until April, with the highest occurrence frequency appearing in March. The number of PM$_{2.5}$ event days (160 days) is also the highest in the C3 cluster.

C4 mostly occurs in April and May when the winter season is in transition to the summer season and September and October when the summer season is in transition to the winter season. PM$_{2.5}$ event days also occur in the seasonal transition months but are less frequent than in the C1, C2 and C3 weather types. The surface weather map indicates a weak anticyclone over the Asian continent; in addition, the Pacific subtropical high-pressure system does not have an apparent influence in Taiwan. The precipitation observed in the C4 cluster is mainly from the Meiyu
frontal system, which typically occurs in May and June. Notably, C4 is associated with the
highest mean O₃ concentration (34.13 ppb) among the six clusters (Table 1). In Taiwan, during
the summer season, although the photochemical reaction is strong, low concentrations of O₃ are
observed due to the enhanced vertical dispersion (Tsai et al., 2008) and the plentiful precipitation
that is induced by afternoon thunderstorms and mesoscale convective systems (Yen and Chen,
2000). The analysis of the O₃ variation shows that the monthly O₃ concentration is relatively
higher during the seasonal transition months such as in October and April (refer to
Supplementary Information). During the seasonal transition months, when the photochemical
reaction is still strong compared to that of the winter months together with the reduced ventilation
capability, the O₃ concentration can accumulate. The average temperature is also higher in C4
than C1–C3 (Fig 3). As a result, the C4 weather type exhibits the highest mean O₃ concentration.

In cluster 5 (C5), due to the westward stretching of the Pacific subtropical high-pressure
system, the prevailing wind in Taiwan is associated with a weak southeasterly to southerly flow.
C5 mainly appears in the warm season from late spring to early autumn, occurs for 290 days
(15.14%) and is associated with the highest rainfall among the six clusters. In Cluster 6 (C6),
with weaker influence of the subtropical high-pressure system compared to the C5, the prevailing
wind is southwesterly. C6 occurs for 345 days (18.01%), mainly from May to August. Both C5
and C6 are summer weather types and associated with higher rainfall and lower air pollutant
concentrations than the other clusters. A comparison between the C5 and C6 clusters shows that the PM$_{2.5}$, PM$_{10}$ and O$_3$ concentrations are all slightly higher in C6 than C5, which might be related to the higher rainfall in the C5 cluster.

**Backward trajectory for C1 – C4 weather type**

Forty-eight-hour backward trajectories (Fig. 4) were generated for the days within the top 20$^{th}$ percentiles of PM$_{2.5}$ concentrations in the C1 – C4 clusters using the HYSPLIT model (Stein et al., 2015). C5 and C6 are not discussed because they are less associated with air pollution problems. In general, northern Taiwan is more easily affected by the LRT air pollutants from East Asia; however, the emission contributions in central to southern part of western Taiwan are mainly from the locally released emissions. To distinguish the influence of paths of the air masses, we selected two stations located in Taipei (northern Taiwan) and Taichung (central part of western Taiwan) as the trajectory ending points (refer to Fig. 1 for locations).

In the C1 cluster, the majority of the backward trajectories ending at northern station (Fig. 4) are passing over the Beijing-Tianjin-Hebei (BTH) region and Yangtze River Delta (YRD) region, where severe haze problems frequently occur (Cai et al., 2018). The backward trajectories ending at the central station can be from the northern China plains and southern China. The trajectories from the northern China plains can be associated with stronger NEM flows that can penetrate toward the southern region of Taiwan, while the trajectories from southern China can be
associated with the weaker NEM flow and the air mass from southern China, which migrates eastward to the Taiwan area.

In the C2 cluster, for the backward trajectories ending at the northern station, some are from the YRD region and some pass through the East China Sea, which indicates that northern Taiwan can be affected by LRT air pollutants. On the other hand, the backward trajectories ending at the central station are from the East China sea and southern China, which indicates less impact of LRT air pollutants from heavy polluted region in China such as BTH and YRD region.

In the C3 cluster, the backward trajectories ending at the northern station are mostly from the eastern ocean side of Taiwan while the backward trajectories ending at the central station are condensed in the surrounding areas, which indicates that the air pollution problem in the C3 cluster is mainly due to the local release of emissions.

In the C4 cluster, the majority of the backward trajectories are from the northern side. However, unlike the C1 cluster, they do not pass through the heavy polluted areas; rather most of the trajectories pass through the East China Sea.

In general, the trajectory analysis indicated that northern Taiwan can have a significant influence from the LRT air pollutants from China in the C1 cluster. In the C2 cluster, the contribution of emission sources can have a mixed composition. Northern Taiwan can receive LRT air pollutants and locally released emissions; however, central Taiwan is mainly affected by
locally released emissions. In the C3 cluster, air pollution problem is primarily caused by locally
released emissions. In the C4 cluster, although most trajectories are from the northern side; yet,
they do not pass through the heavy polluted areas.

**Diurnal variation of the wind fields and air pollutants in each cluster**

Fig. 5 shows the diurnal variations of the observed wind speed, wind direction, and PM$_{2.5}$,
PM$_{10}$ and O$_3$ concentrations averaged from the surface stations for the days in each cluster. The
wind speed is highest in the C1 cluster and lowest in the C3 cluster. C1, C2 and C4 exhibit
northeasterly wind throughout the day. In the C3 cluster, an apparent land-sea breeze flow occurs
with an onshore northwesterly wind formed during the day and offshore easterly wind during the
night. C5 is affected by the southeasterly wind during the night and southwesterly wind formed
during the day. C6 presents a southerly wind during the night and southwesterly to westerly wind
during the day.

For the PM$_{2.5}$ concentrations, the maximum occurs between 1000 or 1100 local standard time
(LST) in the C2 – C6 clusters; however, the C1 cluster exhibits a different diurnal variation that
can be attributed to LRT air pollutants.

During the winter season, the reduced rainfall results in a significant increase of the exposed
riverbed area (Kuo et al., 2010). With a strong NEM flow, the fugitive dust emissions can be
blown up from the bare land and deteriorate the air quality. Although the mean PM$_{10}$
concentration is the highest in the C3 cluster due to the lowest wind speed, in the C1 cluster, there is an apparent PM$_{10}$ peak appearing in the later afternoon that can be associated with the strong NEM flow and indicates the possible influence from riverbed dust emissions.

The O$_3$ concentration shows a clear diurnal variation. The daily maximum occurs at 1300 LST in the C1 – C4 clusters; however, the daily maximum occurs one hour earlier at 1200 LST in the C5 – C6 clusters. In the C5 and C6 clusters, the formation of the cloud and the afternoon thunderstorm systems may limit photochemical reaction processes and reduce the O$_3$ concentration. Additionally, Table 1 shows the maximum of the mean O$_3$ concentration occurs in the C4 cluster; however, the daily maximum of the O$_3$ concentrations occurs in the C3 cluster (Fig. 5). A comparison between the C3 and C4 clusters shows that the nighttime O$_3$ concentration is generally lower in the C3 than C4 that might be due to the stronger O$_3$ titration reaction in the C3 cluster; as a result, the mean O$_3$ concentration is higher in the C4 than the C3 cluster.

**Spatial analysis of the wind fields in each cluster**

The local air flow embedded within the synoptic weather can have a significant impact on air pollution dispersion. To further investigate the local air flow patterns, the ERA5 reanalysis dataset at a 0.3-degree spatial resolution is used to conduct a wind analysis in the area of Taiwan. In addition, the behavior of the observed surface wind from the air quality monitoring stations is discussed. Figs. 6 and 7 show the spatial distribution of surface wind from the ERA5 reanalysis
dataset layered with the observed surface wind fields at 0200 and 1400 LST, respectively, when the local land and sea breeze is likely to develop in western Taiwan. The analysis is excluded for C5 and C6 clusters due to the reduced issues with air pollution. The NEM flow affects the coastal areas of western Taiwan, and the impact is the strongest in the C1 cluster, followed by the C2 and C4 clusters. C3 exhibits the weakest wind condition with the prevailing easterly wind from east side of Taiwan. The observed surface wind indicates the formation of the onshore sea breeze flow embedded within the synoptic wind flow in western Taiwan at 1400 LST. In the C3 cluster. In C2 and C4 clusters, the observed surface winds also reveal the onshore flow forming from the central to southern parts of western Taiwan, where the influence of the NEM flow becomes weaker than that over northern Taiwan. In fact, the land-sea breeze flow has been reported to lead to air pollutant accumulation in western Taiwan (Cheng et al., 2012).

Moreover, under the influence of the NEM flow, the southwestern Taiwan is located on the leeside of the mountain, where the wind field tends to be stagnant due to the terrain blocking by the CMR. The ERA5 reanalysis data shows a very weak wind field in the nearshore areas of southwestern Taiwan in the C1–C4 weather types.

**Characterization of the air pollutants in each AQZ**

Fig. 8 presents a box plot that summarizes the mean wind speed, mean concentrations of PM$_{2.5}$, PM$_{10}$, and O$_3$ and daily O$_3$ maximum (O$_3$max, defined as the hourly maximum concentration
observed during each day) in five AQZs for each cluster. The average is estimated based on the
data from the air quality stations located within each AQZ. In terms of the wind speed, all five
AQZs all exhibit very weak wind speeds in the C3 cluster. In the C1 – C4 clusters, the KP area
located in southwestern Taiwan always exhibits a weak wind field because it is situated on the
leeside of the mountain, and a stagnant wind condition often forms under the influence of the
NEM flow. The NT and CM areas exhibit relatively higher wind speeds in the C1, C2 and C4
clusters due to the influence of the NEM flow. In the C2, C3 and C4 clusters, the CT, YCN and
KP areas reveal a weaker wind speed compared with the NT and CM areas due to the terrain
blocking by the CMR.

With the weak wind field, all five AQZs exhibit relatively higher PM$_{2.5}$ concentrations in C3
than the other clusters, with the highest concentration occurring in the YCN area. The KP area
generally exhibits higher PM$_{2.5}$ concentrations compared to the other AQZs in the C1 – C4
clusters due to the stagnant wind condition. Moreover, the prevailing NEM flow can bring the
upstream air pollutants toward the KP area. In the C1 cluster, the PM$_{2.5}$ and PM$_{10}$ concentrations
are higher in the NT area than the CM area, which can be attributed to the influence of
transboundary air pollution from East Asia. The central to southern parts of western Taiwan (CT,
YCN and KP areas) are situated on the leeside of the mountains and often experience higher
PM$_{2.5}$ and PM$_{10}$ concentrations than areas in northern Taiwan (NT and CM areas) in the C1–C4
weather types. C5 and C6 are associated with lower PM$_{2.5}$ and PM$_{10}$ concentrations than the other clusters, with the lowest concentration occurring in the KP area. In general, the PM$_{2.5}$ concentrations increase from south to north across Taiwan and PM$_{10}$ variations among the five AQZs are not significant in the C5 and C6 clusters.

The PM$_{10}$ air pollution problem in Taiwan can be caused by river sand dust (Lin and Lin 2012) and is more serious in the YCN and KP areas when under the influence of the strong NEM flow. C1 is associated with the strongest wind among the six clusters, and the YCN and KP areas exhibit higher PM$_{10}$ concentrations because of river sand dust from the Zhuoshui River, which is located along the northern border of the YCN area (Kuo et al., 2010). However, the NT, CM and CT areas exhibit low and even PM$_{10}$ distributions in the C1 cluster.

Compared with the characteristics of PM$_{2.5}$ and PM$_{10}$, the mean O$_3$ concentration in the C1 and C2 clusters is relatively higher in the NT and CM areas than the other AQZs, which can be attributed to the transboundary air pollutants from East Asia. In other words, when C1 and C2 weather types occur, the LRT O$_3$ air pollutants can affect Taiwan due to the Asian continental outflow, and the effect is most significant in northern Taiwan (i.e., the NT and CM areas). However, O$_3$ max exhibits the reverse pattern, with the highest concentration occurring in the KP area and lower concentrations occurring in the NT and CM areas. The impact of the transboundary O$_3$ concentration is typically in the range of 40–60 ppb; however, the domestic
emission contribution to the O$_3$ concentration can exceed 90 ppb, which is more serious than LRT air pollutants (Cheng et al., 2012). The analysis of the O$_{3\text{max}}$ concentration also reflects the importance of the locally released emissions, which contribute to the high O$_3$ concentration problem more so than LRT air pollutants.

In the C1–C4 weather types, the highest O$_{3\text{max}}$ concentrations appear in the KP area. In the CT, YCN and KP areas, the O$_{3\text{max}}$ concentration is relatively higher in the C4 than the C1–C3 weather types. For the C5 and C6 clusters, the mean O$_3$ concentrations are generally lower than that of the other clusters, and the O$_{3\text{max}}$ concentration can reach a higher range in the NT area than the other AQZs.

Moreover, the spatial analysis targeting the PM$_{2.5}$ concentration is conducted using the observed surface datasets. Fig. 9 shows the distributions of the daily mean PM$_{2.5}$ concentrations and wind vector data observed from the EPA surface stations in Taiwan for all clusters. C3 shows an overall higher PM$_{2.5}$ concentration compared with the other clusters, with particularly high concentrations occurring in the stations of the YCN area. The KP area tends to exhibit higher PM$_{2.5}$ concentrations in the C1–C3 clusters, with the highest concentration appearing in the C2 cluster. The daily mean PM$_{2.5}$ concentration is generally lower in the C5 and C6 clusters. In western Taiwan, the observed wind vectors clearly indicate that the NEM flow can reach into the
southern region in the C1 cluster; however, the strength of the NEM flow weakens and is confined in the northern to central part in the C2 and C4 clusters.

CONCLUSIONS

To distinguish the effects of meteorological conditions on the air pollutant concentrations, including PM$_{2.5}$, PM$_{10}$ and O$_3$, in Taiwan, we applied the cluster analysis method to classify the synoptic weather patterns using the observed surface wind fields and SLP in Taiwan. Six weather patterns were identified: C1, which corresponds to the intrusion of the Asian continental anticyclone and affected by the NEM flow; C2, which corresponds to the movement of the anticyclone eastward to the east coast of China and is affected by the continental high-pressure peripheral circulation; C3, which corresponds to a weak synoptic weather pattern and is affected by weak easterly flow; C4, which corresponds to the weather pattern occurring during seasonal transition months and the presence of weak NEM flow; C5, which corresponds to the westward stretching of the subtropical high-pressure system; and C6, which corresponds to the weather pattern associated with southwesterly flow. Among the six clusters, C1, C2 and C3 are winter weather types and associated with higher air pollutant concentrations. C4 mostly appears in the
seasonal transition months. C5 and C6 are summer-related weather types and associated with low air pollutant concentrations.

Due to the NEM flow prevailing in the C1 cluster, the transboundary air pollutants from East Asia affect the air quality in Taiwan, and the impact is apparent in the NT and CM areas. On the other hand, the strong NEM flow also induces high PM$_{10}$ loading in the YCN and KP areas due to the Zhuoshui River sand dust. The C3 weather type exhibits the lowest wind speed, which is favorable for air pollutant accumulation and leads to the highest PM$_{2.5}$ and PM$_{10}$ concentrations, with the highest concentration appearing in the YCN area. C3 is the most prevalent weather type and prone to the occurrence of PM$_{2.5}$ events. Moreover, the mean O$_3$ concentrations are the highest in the C4 cluster than the C1–C3 weather types.

Among the five AQZs, the worst air pollution problem occurs in the KP area, which tends to exhibit higher air pollutant concentrations in the C1–C3 clusters. Under the influence of the NEM flow, the KP area is situated on the leeside of the mountain, where the stagnant wind often traps air pollutants. The reduced dispersion capability and the additional air pollutants from further upstream deteriorate the air quality in the KP area.

The results of the weather classification clearly identify six synoptic weather patterns in the Taiwan area, and each type exhibits a distinct meteorological condition and associated air...
pollution behavior in each AQZ. Such insights are helpful for clarifying the air pollution problem in Taiwan.

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SUPPLEMENTARY MATERIALS

Supplementary data associated with this article can be found in the online version at http://www.aaqr.org.

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Table 1. Occurrence %; number of days; number of PM$_{2.5}$ event days; daily mean PM$_{2.5}$ (µg m$^{-3}$), PM$_{10}$ (µg m$^{-3}$), O$_3$ (ppb) concentrations; wind speed (WS) (ms$^{-1}$); and daily accumulated precipitation (mm) averaged over Taiwan for each cluster.
Table 1. Occurrence %; number of days; number of PM$_{2.5}$ event days; daily mean PM$_{2.5}$ ($\mu$g m$^{-3}$), PM$_{10}$ ($\mu$g m$^{-3}$), O$_3$ (ppb) concentrations; wind speed (WS) (ms$^{-1}$); and daily accumulated precipitation (mm) averaged over Taiwan for each cluster.

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FIGURE CAPTIONS

Fig. 1. Black points identify the locations of EPA surface stations. Blue triangles identify the locations of CWB surface stations. Red triangles identify the forty-eight-hour backward trajectory ending points. The seven AQZs (NT, CM, CT, YCN, KP, YI and HD) are identified by name. The contour line indicates the mountain range (CMR).

Fig. 2. Composite plot of SLP (hPa) (shaded colors) and surface wind vectors (m s\(^{-1}\)) for the C1–C6 clusters.

Fig. 3. The light gray and dark gray colors represent the number of occurrences and PM\(_{2.5}\) event days individually in each month for the C1–C6 clusters. The upper-right corner shows the temperature (°C) averaged from all the air quality surface stations.

Fig. 4. Forty-eight-hour backward trajectories for the days within the top 20\(^{th}\) percentiles of PM\(_{2.5}\) concentrations for C1–C6 clusters. N is the number of backward trajectories in each cluster. The left panel is for the ending location at the northern station. The right panel is for the ending location at the central station in western Taiwan.

Fig. 5. Diurnal variation of the observed wind speed; wind direction; and PM\(_{2.5}\), PM\(_{10}\) and \(O_3\) concentrations averaged from the surface stations for the days in each cluster.

Fig. 6. Spatial distribution of surface wind (m s\(^{-1}\)) from the ERA5 reanalysis dataset and observed surface wind (m s\(^{-1}\)) from the EPA surface stations at 0200 LST for the C1–C4 clusters.
Fig. 7. Similar to Fig. 6 but at 1400 LST.

Fig. 8. From top to the bottom are box plots of the mean wind speed; PM$_{2.5}$, PM$_{10}$, O$_3$ concentrations; and daily O$_3$ maximum concentrations in five AQZs for C1–C6 clusters. The black bar is the median, and the upper and lower boundaries of the box denote the 75$^{th}$ percentile (Q3) and 25$^{th}$ percentile (Q1), respectively. The upper and lower whiskers show the interval between Q3+1.5IQR and Q1-1.5IQR, where IQR is the interquartile range.

Fig. 9. Distributions of the daily mean PM$_{2.5}$ concentrations (µg m$^{-3}$) and wind vector (m s$^{-1}$) from EPA surface stations for the C1–C6 clusters.
Fig. 2.
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