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Fine particulate matter events associated with synoptic weather patterns, long-range transport paths and mixing height in the Taipei Basin, Taiwan

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HIGHLIGHTS

- 87.50% of $PM_{2.5}$ events occurred in a north-easterly monsoon period.
- More than 50% of $PM_{2.5}$ events were related to long-range transport across land.
- 81.25% of $PM_{2.5}$ events were related to stagnant conditions.
- Synoptic weather patterns affect the spatial distribution of $PM_{2.5}$ and wind field.
- The worst $PM_{2.5}$ events were attributed to local emissions and long-range transport.

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ABSTRACT

Asian dust storms (ADS) and $PM_{2.5}$ (particle pollution) events have an evident influence on air quality in Taiwan. However, the synoptic weather patterns and atmospheric conditions on ADS days are not entirely similar to those related to $PM_{2.5}$ event days. The aim of this study is to clarify the weather characteristics such as synoptic weather patterns, long-range transport paths, and stagnant conditions that precipitate $PM_{2.5}$ events. Air quality and meteorological data from 2006 to 2013 were obtained from government-owned observation stations, and the mixing height was estimated in relation to the Nozaki planetary boundary layer height. This study used back trajectories as simulated gridded analysis data, which were based on kinematic trajectory analysis using NASA's GMAO (Global Modeling Assimilation Office) and NCEP (National Centers for Environmental Prediction) analyses. For testing the differences between means of two large, independent samples, the confidence interval of a common statistical indicator was employed. The results show that in comparison to low $PM_{2.5}$ level days, weather features such as stagnant conditions, including low mixing height and low wind speed, low rainfall amount, and high solar hours, are favorable for inducing $PM_{2.5}$ events. Eighty percent of the synoptic weather patterns on $PM_{2.5}$ days were associated with either polar continental high pressure, a high-pressure system in mainland China moving from the continent to the sea, or a stationary front stretching from southern China to the East Sea, and moving eastwards. More than 81% of the contributing factors of the causes of $PM_{2.5}$ events were found to be related to stagnant conditions. The pattern of the contributing factors causing the maximum-recorded concentration of $PM_{2.5}$, (73.90 $\mu g/m^3$) was attributed to local emissions, and a long-range transport time that was extended for a longer period over the land than over the sea. The synoptic weather patterns were also found to affect the spatial distribution of $PM_{2.5}$ concentrations in the basin.

1. Introduction

Particulate matter is a common air pollutant in the troposphere. However, fine particulate matter ($PM_{2.5}$) events, in which the particulate matter has an aerodynamic diameter smaller than 2.5 μm, are a cause for concern, as many studies show a definite relationship between high $PM_{2.5}$ concentrations and poor public health (Huttunen et al., 2012; Leiva et al., 2013; Samoli et al., 2014). It is further worrying that the size of regions affected by $PM_{2.5}$ events can extend over several hundred kilometers (Civerolo et al., 2003).

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The occurrence of $PM_{2.5}$ events are related to synoptic weather patterns. These influence regional $PM_{2.5}$ concentrations through long-range transport in winds moving in particular directions. For example, Liu and Cui (2014) indicated that the transport of airflow by a synoptic mid-latitude cycle caused a $PM_{2.5}$ episode in Canada, and it is known that the location of Pacific high-pressure systems, mainland high-pressure systems, low-pressure systems, and the periphery of typhoons affect the long-range transport of fine particulate matter to Japan (Shimadera et al., 2013). In addition, Barmpadimos et al. (2012) suggested that easterly winds can induce high $PM_{2.5}$ episodes in European countries, and Chuang et al. (2008) suggested that 80% of aerosol event days in Taipei were related to the long-range transport of particulates.

In addition to the transport of $PM_{2.5}$ in wind flow dominated by synoptic weather patterns, specific weather conditions also assist the increase of $PM_{2.5}$ concentrations. For example, the mixing height and relative humidity are significantly negatively related to $PM_{2.5}$ concentrations (Tiwari et al., 2014). Beaver et al. (2010) suggested that low surface air-pressure gradients, stable easterly winds, channeled winds, and drainage flows led to a rise in $PM_{2.5}$ concentrations in the San Francisco Bay area. Galindo et al. (2011) indicated that wind speed is negatively related to concentrations of PM_1, $PM_{2.5}$, and $PM_{2.5\text{-}10}$ during winters in the city of Elche in Spain. In addition, Xie et al. (2005) indicated that the occurrence of dust storms caused a concentration of $PM_{2.5}$ that was four times the concentration observed during non-dust weather conditions. Terrain characteristics also play an important role in the increase of PM concentrations. For example, in a basin where terrain blocking occurs, it is difficult for $PM_{2.5}$ to disperse (Chuang et al., 2008), and in coastal regions the tempo-spatial distribution of PM_{10} can be affected by sea–land breezes (Tsai et al., 2011).

In Taiwan, the occurrence of $PM_{2.5}$ events is mainly related to human activities (Lin et al., 2012). In addition, in Asian dust storm (ADS) and non-ADS periods, more than 60% of PM components are related to anthropological activities (Liang et al., 2013). Furthermore, the contribution from the long-range transport of non-dust from anthropological activities is greater for $PM_{2.5}$ than for PM_{10} (Tsai et al., 2014). The long-range transport of $PM_{2.5}$ in Taiwan is partly derived from northern China (Tsai et al., 2014; Tsai and Chen, 2006). In China, emissions of $PM_{2.5}$ are also mainly derived from anthropological activities; for example, 80.6% of the total amount of $PM_{2.5}$ in Chegdu, China, is derived from coal combustion, vehicular emissions, and industrial emissions (Wang et al., 2013).

During the north-easterly monsoon period, ADS have an evident influence on the air quality in Taiwan. However, most ADS events do not induce $PM_{2.5}$ events, and only a few $PM_{2.5}$ events occur with ADS events. As the synoptic weather patterns and weather conditions on $PM_{2.5}$ event days are not entirely similar to those of ADS days, it is therefore important to clarify the cause of $PM_{2.5}$ events. In comparison to ADS, the weather conditions involved in triggering $PM_{2.5}$ events are more complicated, and are associated with specific synoptic weather patterns, long-range transport paths, and stagnation (including mixing height and wind speed). However, some $PM_{2.5}$ events in Taipei occur with a high mixing height but not in stagnant conditions, even though the air pollutants in Taipei, which is in a basin terrain, are much more difficult to disperse when the mixing height is low. The aim of this study therefore, is to clarify the weather characteristics that are associated with $PM_{2.5}$ events, and which characteristics are different from those associated with ADS events.

2. Data sources and methods of analysis

2.1. Study area

Taiwan is situated between the world's largest tectonic plate, the Euro–Asia plate, and the Pacific Ocean. Metropolitan Taipei, which includes New Taipei City and Taipei City, is the largest metropolis on the island. This area has a basin terrain, and is surrounded by the Dadun volcanoes, which have a maximum altitude of 1120 m; the Snowy Mountain Range, with a maximum altitude of 3884 m; and the Linkou Tableland with a maximum altitude of 250 m (Fig. 1). The north-easterly and south-westerly monsoons dominate from October to April and from May to September, respectively. Chuang et al. (2008) suggested that terrain blocking and stagnant weather conditions in the Taipei Basin, associated with specific weather patterns, can induce $PM_{2.5}$ events.

2.2. Data and methods

Hourly concentrations of $PM_{2.5,}$ and wind speed and wind direction recorded from 2006 to 2013 were obtained from the data of 17 monitoring sites in the Taipei metropolis operated by the Taiwan Environmental Protection Administration (EPA). To control the quality of data, if values of nine hours or more were absent, the daily value was omitted.

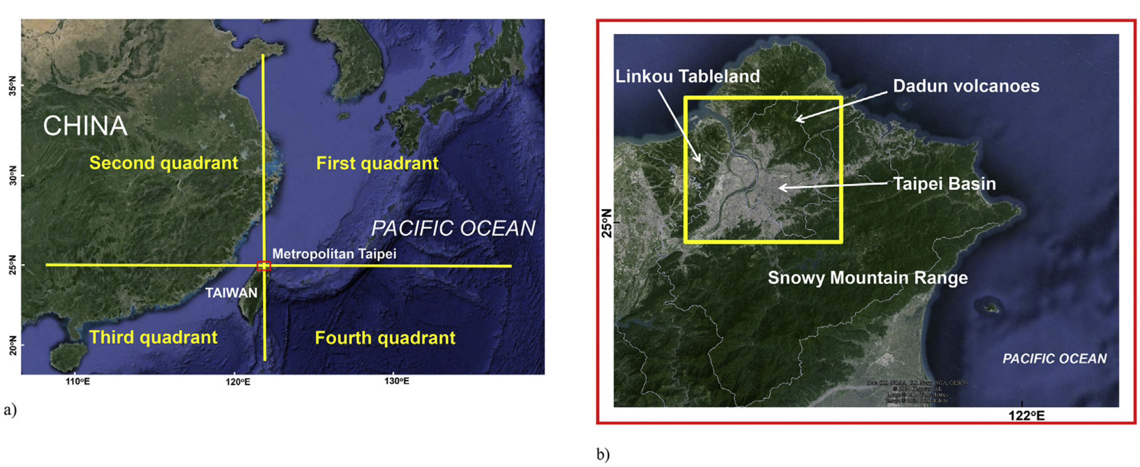

Fig. 1. Geographical location of: a) Taiwan and Metropolitan Taipei; and b) the Taipei Basin. The satellite figures were obtained from http://earth.google.com/download-earth.html (Google Earth). The Cartesian axes divide the plane into four quadrants, and Metropolitan Taipei is located at the intersection of the axes. The first quadrant is between 0° and 90°, the second quadrant is between 90° and 180°, the third quadrant is between 180° and 270°, and the fourth quadrant is between 270° and 360°.