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# Applying the anomaly-based weather analysis on Beijing severe haze episodes

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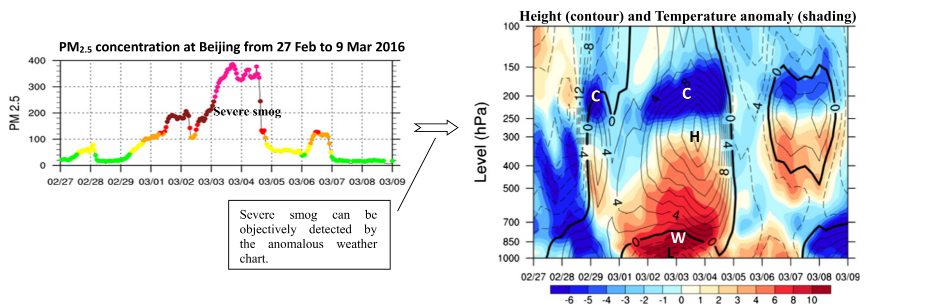
## HIGHLIGHTS

- Severe smog can be objectively detected by the anomalous weather chart.
- $PM_{2.5}$ concentration strengthened following an anomalous temperature inversion.
- Anomalous inversion separates above positive and below negative height anomalies.
- Numerical model is able to predict smog condition for leading about one week.

## GRAPHICAL ABSTRACT

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## ABSTRACT

Smoggiest days like heavy rainfall, tornadic and hail storms are considered as weather extremes. The method of anomaly-based meteorological variable analysis has been recently used to analyze and predict weather extremes. Thus, in this study, the same method was also applied to analyze ten severe haze episodes with $PM_{2.5}$ exceeding 300 micrograms per cubic metre (μg/m$^3$) for >24 h occurred during 2015–2016 in Beijing or North China. The anomalous spatial features of tropospheric meteorological variables show that the haze intensity indicated by $PM_{2.5}$ concentration is strengthened gradually following the five factors of (1) an anomalous temperature inversion in the lower troposphere, (2) negative geopotential anomaly near the surface, (3) positive geopotential anomaly at the upper troposphere, (4) southwesterly wind anomaly and (5) positive anomaly of specific humidity in the lower troposphere. The correlation coefficient between the geopotential anomaly factor at the upper troposphere and $PM_{2.5}$ concentration at Beijing is 0.56 reaching the level of 95% confidence in December 2016. Forecast evaluation analyses reveal that the European Centre for Medium-Range Weather Forecasts (ECMWF) model is able to predict most anomalous temperature-pressure structures related to haze episodes and to indicate haze intensities for leading about one week.



## 1. Introduction

Severe weather extremes such as heavy snow, rain fall, hail and tornadic storms are difficult to be located from the traditional synoptic charts and hard to be predicted directly using the current numerical model products. In the worldwide, the prediction of these severe phenomena is a duty in daily weather forecast. But in China, the intensity of local smog or haze is an additional severe phenomenon, other than the above mentioned weather extremes, that often predicts in daily weather broadcasts in recent years.

Winter weather in eastern China is often influenced by the stronger northwesterly wind so dust storm can cause natural smog in the cold season (Wang et al., 2012). Recent years, however, smoggiest days can occur in any seasons in a year. Outdoor exposure during severe smog hours can cause adverse health effects (Nel, 2005; Peplow, 2014; Yue

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et al., 2015; Chen et al., 2017), especially severe respiratory system related symptoms and deceases (Parrish and Zhu, 2009; Pöschl, 2005; Cao et al., 2014; Yue et al., 2015; Hong et al., 2016; Li et al., 2017; Chen et al., 2017). When the visibility reduces to 100 m, traffic will be disrupted, flight will be cancelled and highway will be closed (Zhou et al., 2012; Zheng et al., 2015; Li et al., 2017). In China, high emissions, particularly from densely distributed megacities (namely city clusters), provide plenty of gas pollutions (Chen et al., 2005; Chan and Yao, 2008; Li et al., 2017; Chen et al., 2017).

These extreme smog events attracted great scientific interest. Beijing is the capital city of China so hundreds of articles concerned Beijing severe smog episodes have been published in recent years. The smog chemical component, formation and impact were described, and regional transport of pollutants was found to contribute considerably to $PM_{2.5}$ concentrations in Beijing (Sun et al., 2006; Liu et al., 2013; Zhang et al., 2014; Liu et al., 2015).

It is commonly known that meteorological conditions under haze weather are usually characterized by high humidity, low wind speed and low irradiation (Li et al., 2017). Therefore, when the air pollutants are constantly and consistently emitted, haze events mainly depend on the prediction of tropospheric circulation systems. In most cases, a severe smog period is shorter than 24 h but the predicted duration is usually longer than 3–4 days. This predicted information can cause additional losses to policy makers. We know that meteorological conditions were significantly different between haze weather and normal weather, but we do not have a definition to describe their differences quantitatively.

The anomaly-based weather analysis, which decomposes a total atmospheric variable into temporal climatology and anomalous component (Qian, 2012), has been recently used in the locating different weather extremes such as heavy rainfall (Jiang et al., 2016; Qian et al., 2016a), heat waves (Chen et al., 2016), cold surges (Qian et al., 2016b), as well as tornadic and hail storms (Qian et al., 2017). In this paper, the same method was applied to analyze and locate severe smog cases with the $PM_{2.5}$ concentration exceeding 300 μg/m$^3$. After this introduction, datasets and the anomaly-based approach are described in Section 2. The climatological feature of $PM_{2.5}$ concentration at Beijing is depicted in Section 3. The tempo-spatial distributions of anomalous variables indicating and predicting synoptic-scale systems for a severe smog case are illustrated in Sections 4. Other cases of severe smog and statistical correlation between geopotential anomaly and $PM_{2.5}$ concentration at Beijing are given in Section 5. Conclusion and discussion are summarized in Section 6.

## 2. Datasets and approach

To identify synoptic-scale systems which may favor the formation of severe weather, three datasets were used in this article. The first was a global atmospheric reanalysis from the European Centre for Medium-Range Weather Forecasts (ECMWF), named 'ERA-Interim' (Dee et al., 2011) with the horizontal resolution of 0.75° × 0.75° and the vertical pressure levels of 37, obtained from the ECMWF's website (http://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/), including variables of geopotential height, air temperature, horizontal wind and specific humidity.

The second was the products of the ensemble prediction systems (EPSs) at the ECMWF, obtained from 'The International Grand Global Ensemble' project (TIGGE, http://apps.ecmwf.int/datasets/data/tigge/levtype=pl/type=cf/). The ECMWF EPS provides 15-day (360-hour) forecasts of geopotential height at 9 vertical levels from 1000 to 50 hPa and temperatures at 8 levels from 1000 to 200 hPa, based on 51 ensemble members.

The third was the hourly observation of $PM_{2.5}$ concentration during 2014–2017 from China National Environmental Monitoring Centre (http://106.37.208.233:20035) with 1497 observational sites. Locations of these sites are depicted in Fig. 5a.

In Qian (2017), daily extreme weather events such as heavy rainfall and severe weather storms were seen as results of anomalous synoptic-scale systems related to temporal climatology. The temporal climatology of a certain location and a certain time is considered as a state under the thermodynamic equilibrium of earth-atmosphere system, which is only forced by the solar radiation (solar declination) and surface conditions rather than daily weather disturbances. Thus, a temporal atmospheric total or full field $F_{\{d,y\}}(\lambda,\varphi,p,t)$ such as geopotential height and air temperature at time $t$ (24 h a day) on a calendar date $d$ in a year $y$ at a spatial point of longitude is $\lambda$ and latitude $\varphi$, and pressure level $p$, is decomposed into a temporal climatic field $\tilde{F}_d(\lambda,\varphi,p,t)$ and an anomalous field $F_{\{d,y\}}'(\lambda,\varphi,p,t)$ following Qian et al. (2014):

$$F_{(d,y)}(\lambda,\phi,p,t) = \tilde{F}_d(\lambda,\phi,p,t) + F'_{(d,y)}(\lambda,\phi,p,t) \qquad (1)$$

The temporal climatic field is estimated by averaging the reanalysis data at time $t$ on calendar date $d$ over $M$ years,

$$\tilde{F}_d(\lambda,\phi,p,t) = \sum_{y=1}^{M} F_{(d,y)}(\lambda,\phi,p,t)/M \qquad (2)$$

where $y$ runs for $M$ years ($M$ > 30 years). It is assumed that the positive and negative anomalies of meteorological variables at a specific grid point and a given calendar time cancel each other during the $M$ years. The climatic state (or temporal climatology) defined by Eq. (2) contains diurnal cycle since it varies temporally from hour to hour. In previous studies (Qian et al., 2014), $y$ runs from 1981 to 2010 for $M = 30$ years. To prove the robustness, the temporal climatology with and without a super typhoon has been tested and found that the difference can be neglected (Qian and Huang, 2018).

## 3. Climatological features of $PM_{2.5}$ concentration

Theoretically, the climatology of $PM_{2.5}$ concentration should be obtained from data of longer than 30 years. However, due to the availability of data, the climatological features of $PM_{2.5}$ are examined only based on the data of the four years 2014–2017 in this study. The hourly-mean climatology at Beijing at 0100 UTC January is averaged by $4 \times 31 = 124$ hourly-mean $PM_{2.5}$ concentrations at 0100 UTC January from 1 to 31 January in 2014, 2015, 2016 and 2017. Fig. 1 shows the hourly-mean climatology of $PM_{2.5}$ concentration for 12 months a year. Seasonally, the maximum and minimum $PM_{2.5}$ concentrations are climatologically apparent in December and August respectively at Beijing. The seasonality of air pollutants may be resulted from both of atmospheric conditions and heating activities. This seasonal variation is consistent with previous studies (Jiang et al., 2009; Zhang et al., 2009; Tang et al., 2017). In Beijing, climatological $PM_{2.5}$ concentration lower than 75 μg/m$^3$ is mainly observed during April, May, June, July, August and September in the summer half year. For the diurnal cycle in the winter half year, the maximum $PM_{2.5}$ concentration is apparent at 1400 UTC or 2200 Beijing Local Time (BLT) while its minimum is found at 0700 to 1000 BLT or 0000 UTC. The climatological $PM_{2.5}$ concentration of November (around 90 μg/m$^3$) and December (100–140 μg/m$^3$) in Beijing, based on the 4-year data, are both higher than the pollution level (75 μg/m$^3$) of National Ambient Air Quality Standards of China. Similar diurnal variation is also detected by other investigators (Lin et al., 2009; Zhao et al., 2009; Gu et al., 2010; Zhang et al., 2012; Alam et al., 2015; Liu et al., 2015; Elorduy et al., 2016; Cao et al., 2018).

The climatological $PM_{2.5}$ concentration may be related to the seasonal differences of both atmospheric conditions and regional emission rates. The largest diurnal variation of climatological $PM_{2.5}$ concentration is observed in December so Fig. 2 shows the vertical distributions of differences between climatological atmospheric variables at 1200 UTC and that at 0000 UTC in December along 39.75°N crossing Beijing. In Fig. 2a, Beijing and regions to its west is climatologically located within a