

## Research Article

# Fog Formation in Cold Season in Ji'nan, China: Case Analyses with Application of HYSPLIT Model

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Fog events almost happened every year in cold season in North China Plain. In this study, hybrid single-particle Lagrangian integrated trajectory (HYSPLIT) model was applied to analyze the formation of four fog events occurring in Ji'nan, China, during the period from March 2012 to February 2014. Three types of fog have been distinguished, including radiation fog, advection fog, and frontal fog. When fog events happened, the average surface temperature ranged from near zero to 10°C and the relative humidity was around 90%. Fog events often happened immediately after haze episodes (i.e., fog-haze) and sometimes after light rain. Back trajectory analyses show that the air masses during the fog events mostly came from the local Shandong areas and moved in very slow speed (4–24 km h<sup>-1</sup>). During the fog events, the humidity along the air trajectories always gradually increased to saturation. The mixed layer depth was small, generally below 400 m at noon and around 100 m at midnight. However, the air temperature exhibited complex variations—sometimes decreased and sometimes kept stable or even increased.

## 1. Introduction

Fog is featured with high humidity, very low visibility, and possibly high pollutant contents (e.g., fog-haze and acid fog). Dense fogs are dangerous for high-way driving and aircraft landing and take-off and have adverse impacts on people's life, agricultural production, and socioeconomic activities [1–3]. In addition, fog can accumulate air pollutants and promote the formation of secondary aerosols in a certain extent, leading to deteriorated air quality and doing harms to human health [4, 5]. Due to the serious impacts on air quality, environment, and anthropogenic activities, fog and fog-haze have received close attention from both researchers and the public in past decades.

Generally, fog can be divided into two sorts, air-mass fog and frontal fog [6]. Air-mass fog is primarily caused by radiation or/and advection and often appears in North China Plain [2, 7–9], while frontal fog is mainly caused by the evaporation of precipitation into the stable cold air [10]. Reduced air temperature, high humidity, and weak diffusion are necessary for fog formation. Besides, air-mass transport

is also an important factor influencing formation of fog. Moisture transport always promotes the occurrence of fog, while air pollutants (in particular aerosols) can have positive or negative effect on fog formation [2]. Recent studies also showed that the temperature increase and humidity decrease due to urban heat island effect and urban land use can inhibit fog occurrence [11–13], while the impacts of increased aerosol concentration on fog formation are dualistic and uncertain [2, 14, 15]. The complexity of fog and the interaction with atmospheric environment puts forward the urgent need to further investigate the fog formation, especially in the densely populated and seriously polluted region. As severe haze episodes often occur in China [16–18], fog chemical composition shows a plenty of secondary species sulfate, nitrate, ammonium, and OC/EC [19–22]. The meteorological formation of haze episodes calls for close attention [23–25]. However, only limited investigation of fog formation has been done under heavy air pollution in China [23].

Hybrid single-particle Lagrangian integrated trajectory (HYSPLIT) model is a complete system for computing simple air parcel trajectories as well as complex dispersion and

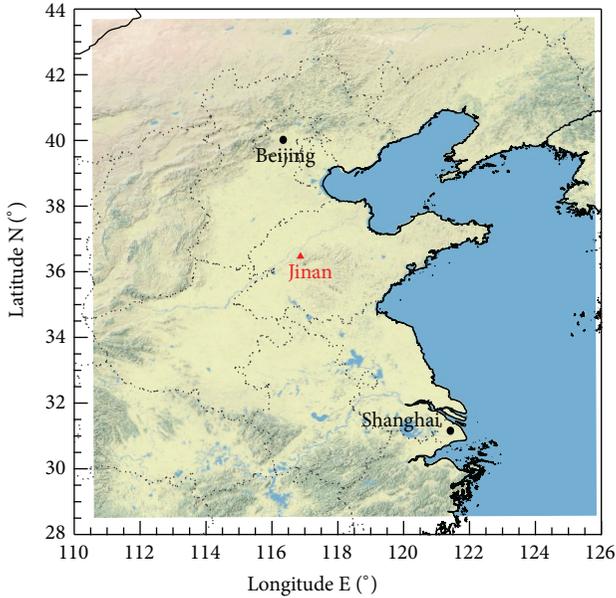


FIGURE 1: Topographic map of North China which shows the study area of Jinan.

deposition simulations [26]. The air-mass back trajectory analysis by using HYSPLIT model provides a useful method to examine the history of air-mass transport, though uncertainty exists due to a lot of factors such as phase change. It has been extensively used in researches on atmospheric pollution to track the source regions and the transport pathways [27–30]. The HYSPLIT model not only presents three-dimensional air trajectories arriving to the selected location but also provides many meteorological data along the air trajectories, including temperature, humidity, pressure, mixed layer depth, and solar flux, which are important factors for fog formation.

In this study, four fog events occurring in Jinan, China, in cold season were identified and analyzed by using HYSPLIT model. We first present the weather conditions before, during, and after the fog events. Then, air-mass back trajectories and the corresponding meteorological parameters including temperature, humidity, and mixed layer depth are compared and discussed to explore the formation processes of the fog events.

## 2. Methods

**2.1. Identification of Fog Events.** In this study, the fog events occurring during the period from March 1, 2012, to February 28, 2014, were examined. Meteorological data in Jinan (36.6°N, 117.1°E, 169 m a.s.l., no. of 54823, shown in Figure 1) reported by the Weather Underground (<http://www.wunderground.com/weather-forecast/Shandong/Jinan.html>) were used to identify the fog events. If the relative humidity was above 90% for more than six hours and the weather was marked as fog but not rain or snow, the period was selected as a fog event. Note that the weather

records in the Centre Campus of Shandong University were also used to further verify the fog event.

**2.2. Air-Mass Back Trajectory Analyses.** Air-mass backward trajectories for each fog event were calculated every six hours using HYSPLIT model with GDAS data online [26]. For each fog event, eight to twelve 72 h backward trajectories were calculated at 50 m AGL. The trajectory data including latitude, longitude, and height together with the meteorological parameters including air pressure, temperature, relative humidity (RH), mixed layer depth, and solar flux for air masses were collected for further analyses.

**2.3. Calculation of Air-Mass Transport Speed.** The average horizontal transport speeds of the air masses (without consideration of the vertical transport) were calculated based on the cumulative transport distance and the transport duration of 72 hours. The transport distance between the two points of the air trajectory with time interval of one hour was calculated by using the following equations:

$$C = \sin(\text{LatA}) * \sin(\text{LatB}) + \cos(\text{LatA}) * \cos(\text{LatB}) * \cos(\text{LonA} - \text{LonB}), \quad (1)$$

$$\text{Distance} = R * \text{Arccos}(C) * \frac{\pi}{180}.$$

Here,  $C$  is an angle,  $\text{LatA}$  and  $\text{LonA}$  represent the latitude (N) and longitude (E) of point A,  $\text{LatB}$  and  $\text{LonB}$  stand for the latitude (N) and longitude (E) of point B,  $R$  is the radius of the earth (6371 km), and  $\pi$  is the circumference ratio (3.14).

## 3. Results and Discussions

**3.1. Fog Events Occurring in Jinan.** From March 2012 to February 2014, four dense fog events have been identified and are listed in Table 1. They all happened in cold season, especially in wintertime. The duration of these fog events ranged from 30 to 81 hours, all longer than 24 hours. Note that there was an interrupt for ~15 hours in daytime during the fog event beginning at 23:00 on January 13, 2013, and interrupts for several hours in daytime during the fog events beginning at 23:00 on January 28, 2013, and at 23:00 on November 2, 2013. During the four fog events, the average surface temperatures were mostly above 0°C and below 10°C and sometimes slightly lower than 0°C. The average surface RH varied from 90.2% to 95.5%. Before the fog appeared, the weather was usually haze, which means the fog happened as fog-haze. Sometimes, fog appeared immediately after light rain, which is called frontal fog and is caused by the evaporation of precipitation [10]. However, once fog disappeared, it was still haze or changed to clear. The cases of weather remaining haze after fog scavenging on air pollutants suggest that in some conditions fog could not cleanse the fine aerosol pollution.

**3.2. Trajectory and Transport of Air Mass during Fog Events.** The air-mass back trajectories during the four fog events are shown in Figure 2. In the past 72 hours, most of the air masses

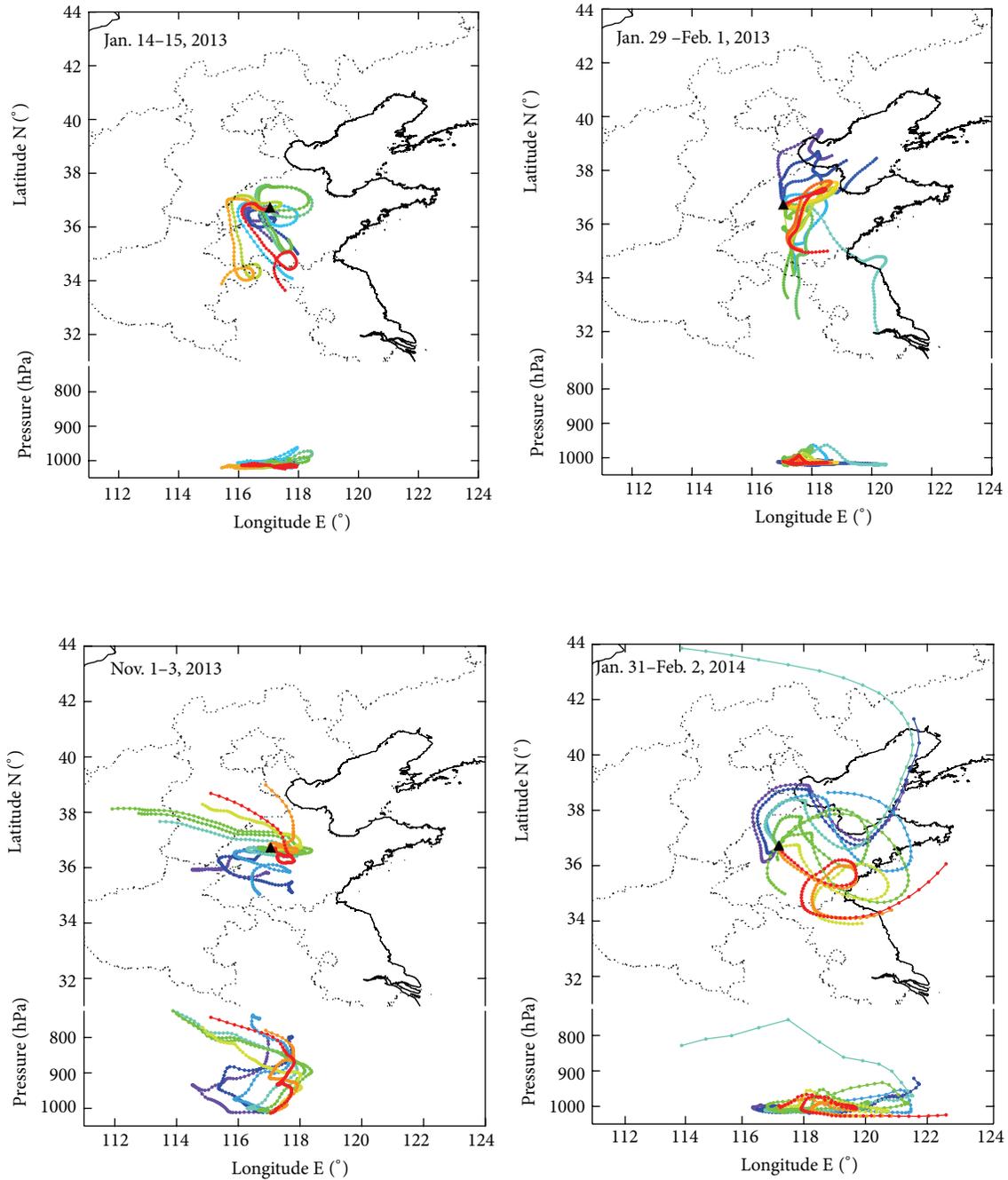


FIGURE 2: Air-mass back trajectories and the changes in height indicated by pressure for the four fog events occurring in Ji'nan during the period from March 2012 to February 2014.

arrived in urban Ji'nan from local Shandong area, especially from south, north, and west Shandong. The air masses did not move along straight lines. They went with clockwise twirling or first twirled clockwise and then twirled counterclockwise, indicating that the flow field in Ji'nan during fog events was controlled by weak low pressure or that weak low and high pressures appeared in turn in this region.

Back trajectory analyses also showed that the air masses transported to Ji'nan in low altitude and in slow speed when the fog events appeared. The pressures of the air masses were

mostly higher than 900 hPa, corresponding to altitudes below ~1000 m. The average transport speeds (without consideration of the height) of the air masses were mostly between 4 and 10 km h<sup>-1</sup> and were a little faster (11–24 km h<sup>-1</sup>) for the fog event starting at 5:00 on February 1, 2014. The air masses moved so close to the ground surface that the large amounts of air pollutants emitted from urban city would transfer into fog. In addition, the weak diffusion condition in atmosphere also caused air pollutants accumulation and secondary aerosol formation in mixed layer.

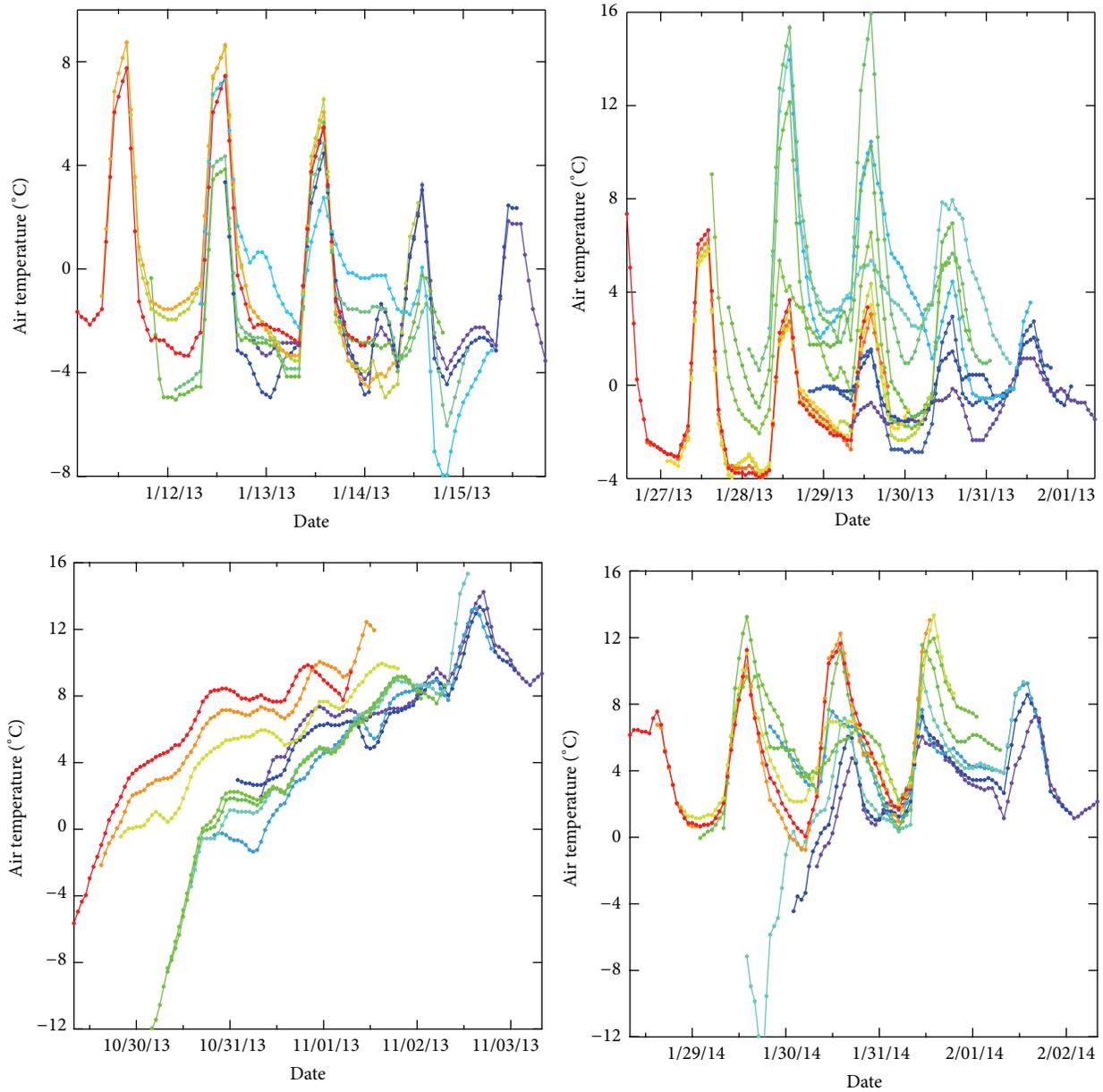


FIGURE 3: Changes in temperature along the air-mass back trajectories for the four fog events occurring in Ji'nan during the period from March 2012 to February 2014.

TABLE 1: Start time, duration, average surface air temperature, relative humidity, and weather conditions before and after fog for the four fog events occurring in Ji'nan during the period from March 2012 to February 2014.

Start time	Duration (h)	Surface temp. (°C)	Surface RH (%)	Weather before fog	Weather after fog	Note
Jan. 13, 2013 23:00	42	-2.5	90.2	Haze	Haze	Interrupt for ~15 hours in daytime
Jan. 28, 2013 23:00	81	0.5	95.5	Haze	Clear	Interrupt for several hours in daytime
Nov. 02, 2013 23:00	33	9.9	91.9	Light rain	Clear	Interrupt for several hours in daytime
Feb. 01, 2014 05:00	30	2.5	94.5	Haze	Haze	

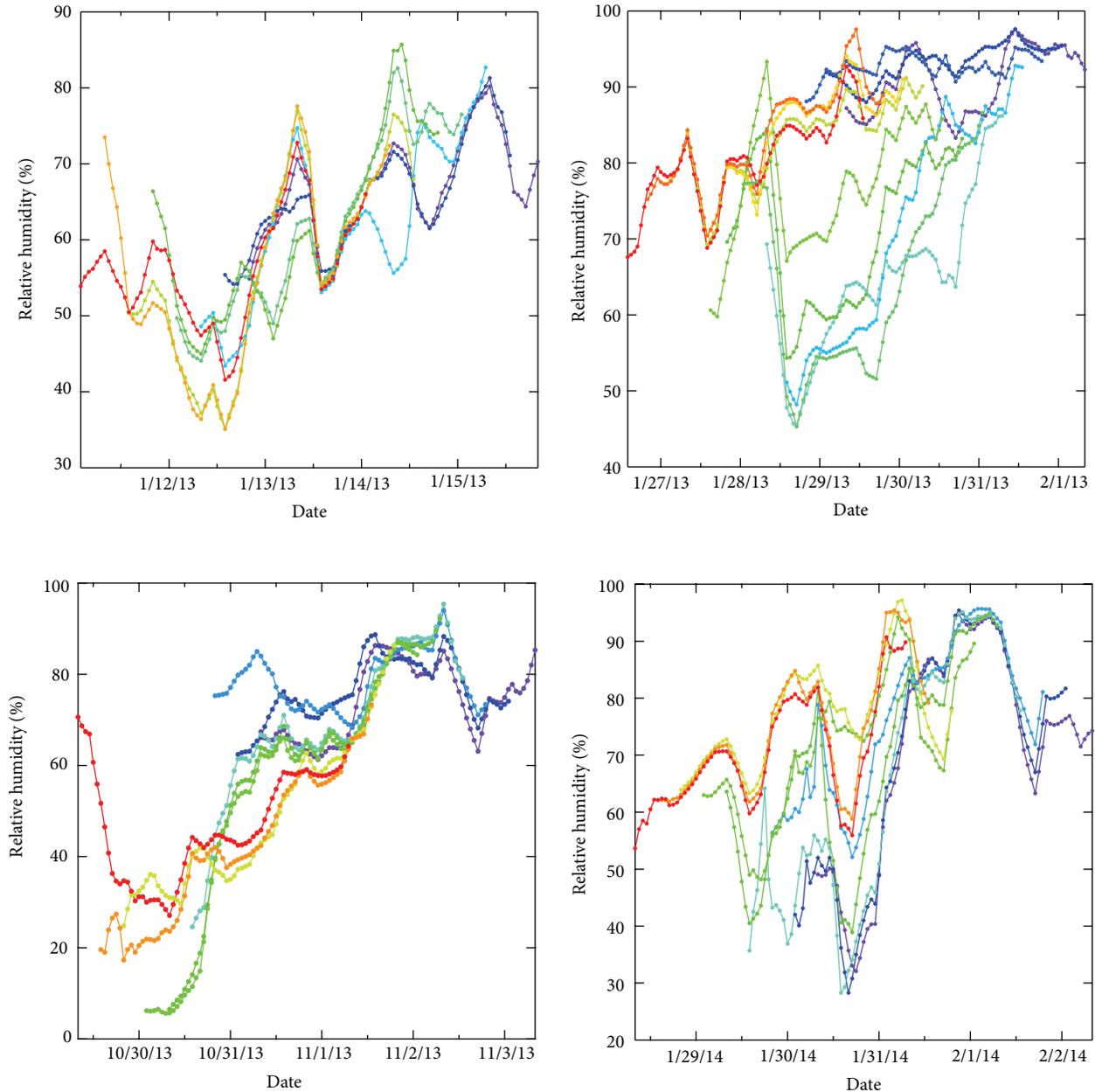


FIGURE 4: Changes in relative humidity along the air-mass back trajectories for the four fog events occurring in Jīnan during the period from March 2012 to February 2014.

*3.3. Impacts of Air Temperature, Humidity, and Mix on Fog Formation.* The temperature, humidity of the air masses, and the mixed layer depth are important for fog formation. Generally, high humidity and decreased temperature and mixed layer depth are favorable for the occurrence of fog. In this study, the changes in temperature and humidity of the air mass along the air trajectories and in the mix layer depth during the four fog events were analyzed to investigate the impacts of these meteorological parameters on fog formation.

Temperature changes along the air trajectories are found rather complex (see Figure 3). For the two fog events occurring in January, 2013, the air temperature exhibited gradual decrease and the diurnal temperature difference turned lower

and lower. In the nighttime of January 13 and 14, 2013, the radiation cooling led to the formation of fog in late night and early morning. In the next daytime, the temperature increased and the fog weakened or disappeared. There was no significant reduction in the solar radiation at noon during the fog event from January 13 to 15, 2013 (the figure is not shown here). The observed surface temperature also dropped by a large degree from 3°C at 11:00 to -4°C at 23:00 on January 14. The above results suggest that this fog event is radiation fog. Although the surface temperature was always below 0°C in this fog event, it was mostly above -4°C, meaning that it was difficult to form ice fog [31]. From the night of January 28 to the morning of February 1, the temperatures

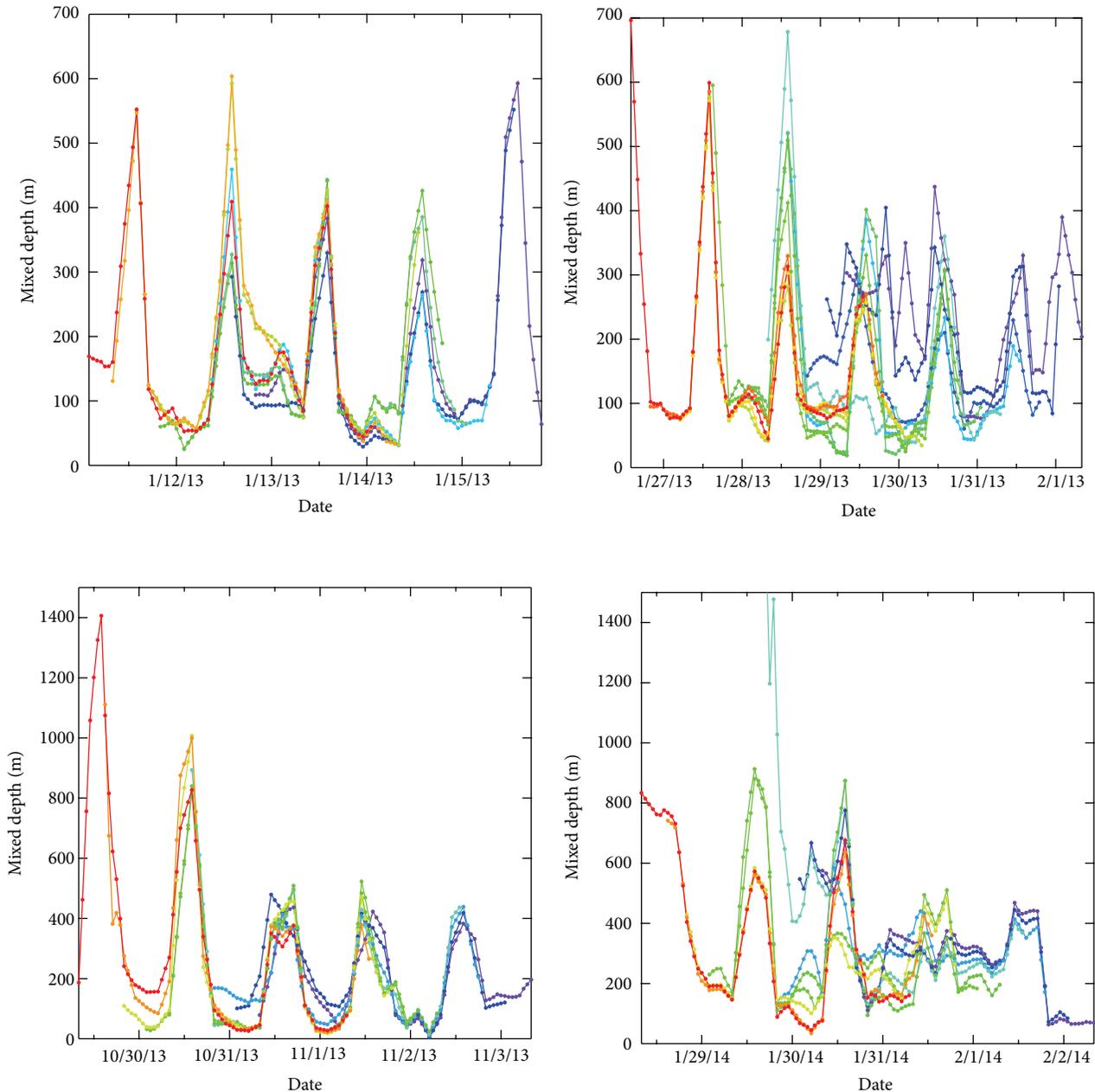


FIGURE 5: Changes in mixed layer depth along the air-mass back trajectories for the four fog events occurring in Ji'nan during the period from March 2012 to February 2014.

of surface air masses were relatively low (equal to or slightly above  $0^{\circ}\text{C}$ ) and the diurnal temperature differences were much smaller than normal days, causing a long duration of fog for more than three days. However, as to the two fog events appearing in November 2013 and February 2014, the temperature increased to certain degrees along the air trajectories, partly due to the decreases in height of the air masses. In the afternoon and evening of November 1, light rain happened following the sharp decline of the air masses. Then, fog occurred when the air masses were close to the earth surface and the air temperature tended to be steady. There was little change in surface air temperature ( $\sim 9^{\circ}\text{C}$ ) during the fog event from February 1 to 2, 2014.

Saturated humidity is the necessary condition for fog formation. With inspection of Figure 4, relative humidity all exhibited apparent gradual rise along the air trajectories, usually increasing from  $\sim 40\%$  to  $\sim 90\%$ . When the humidity was close to saturation, the fog appeared. The relative humidity in high altitude with low pressure was usually much lower than that at earth surface. Note that from January 28 to 30, 2013, the humidity of the southerly air masses was high and exhibits little diurnal variation, indicating that this fog event was partly/mainly caused by advection of moist air and belonged to advection fog.

The mixed layer depth, to a certain degree, reflects the stability of the mixed layer and also the air masses. Decreased

mixed layer depth is necessary to maintain the fog event. During these four fog events, the mixed layer depth at noon was generally lower than 400 m and that at midnight was mostly around 100 m (shown in Figure 5). For the fog event starting at February 1, 2014, the mixed layer depth at nighttime was substantially higher than other foggy days, which is probably the reason why the air masses transported faster than others.

#### 4. Summary and Conclusions

Fog formation in Ji'nan, China, was analyzed by deploying a HYSPLIT model. During the period from March 2012 to February 2014, total of four fog events were identified and they all appeared in cold season—from November to February in next year. We have distinguished three types of fog, that is, radiation fog, advection fog, and frontal fog. When fog occurred, the surface temperature was relatively low, averagely from zero to 10°C. The relative humidity was saturated. The fog events often appeared as fog-haze and sometimes happened after light rain. According to the back trajectories, during the fog events, air masses mostly came from the local Shandong Province and transported very slowly—below 24 km h<sup>-1</sup>. Along the air trajectories, the relative humidity always gradually increased to approximate 90%. The mixed layer depth at noon was usually below 400 m and was around 100 m at nighttime. Nevertheless, the air temperature presents complex characteristics. The temperature decreased in some fog events and kept stable or rose in some other fog events. Overall, the HYSPLIT model is a useful tool for fog research.

#### Conflict of Interests

The authors declare that there is no conflict of interests regarding to the publication of this paper.

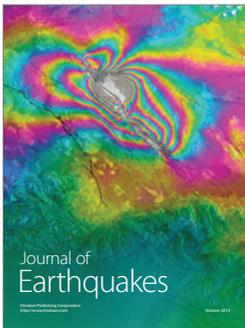
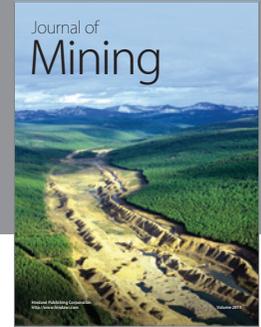
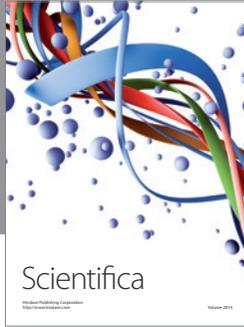
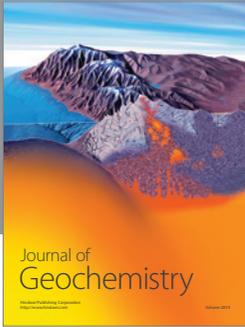
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