




## Analysis of Agglomerate Fog Meteorological Characteristics in Anhui Province Based on Traffic Accident Data

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**Abstract**—Using the data of five agglomerate-fog-related traffic accidents during 2014–2017 and fog-related expressway accidents during 2013–2018 assessed by the Anhui provincial traffic authorities and corresponding meteorological observation data, this article analyzes the spatio-temporal characteristics, geographical environment and weather background of agglomerate-fog-related accidents in detail and identifies the characteristics of changes in terms of visibility, humidity, temperature and wind when agglomerate fog occurs. Furthermore, an agglomerate fog forecast index has been established in Anhui Province to provide a reference basis for the agglomerate fog forecast, early warning and prevention.

**Keywords:** Agglomerate fog, Traffic accident, Meteorological characteristics, Forecast index.

### 1. Introduction

Economic development of any country depends on a safe road traffic system and safe transportation of goods, but road traffic accidents are a serious threat to human's safety and economic development. Almost 1.35 million people die in road accidents every year worldwide (WHO, 2018). In China, 43,000 people died and > 150,000 people were injured because of road traffic accidents in 2019 (NBSC, 2020). Human factors, technology and nature/environment can all contribute to road traffic accidents (Hammad et al., 2019). Weather factors have potential to increase the magnitude and frequency of road accidents (Bergel-Hayat et al., 2013; Theofilatos & Yannis, 2014; Usman et al., 2012),

which can seriously affect traffic safety and operation. In China, agglomerate fog is called “road killer.” The incidence of road traffic accidents caused by agglomerate fog is 30%, which is 2.5 times that of other adverse weather events. The casualties resulting from road traffic accidents caused by agglomerate fog and other adverse weather respectively account for 29.5% and 16% of the total number of casualties (Guo, 2016). Fog not only increases the risk of traffic accidents, but also significantly affects traffic efficiency, resulting in traffic congestion or road blocks (Koetse & Rietveld, 2009; Vajda et al., 2014; Wu et al., 2018). The annual total mileage of highways blocked by fog is roughly 178% of the entire highway mileage in China (Jiang et al., 2020). The total economic losses associated with the impact of the presence of fog on aviation, marine and land transportation are comparable to those of tornadoes or, in some cases, winter storms and hurricanes (Gultepe et al., 2007).

Many scholars have studied the weather background and causes of fog. He et al. (2006) analyzed the cause of a persistent fog process in the North China Plain and found that a warm high ridge in the middle atmosphere with cold high pressure in the surface layer over the plain provided a good background condition. A cooling process produced by net surface radiation fluxes was the trigger and strengthening mechanism for the fog event; subsidence flow at the middle and low tropospheric levels was favorable for the setting-up and maintenance of stable stratification at the boundary layer and weak wind conditions at the ground layer over the fog region. Strong wind brought by cold air was a main dynamic factor in fog dissipation. Jiao et al. (2016) analyzed the causes of a rare persistent heavy fog in

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Table 1  
Information on five agglomerate fog accidents in Anhui Province

Accident ID	Place	Date and time of accidents	Accident situation	Adjacent river	Virtual numbering of traffic weather station	Station altitude and distance from accident site	Observation weather elements
NO.01	Fuyang City, Jman-Guanzhou Expressway, G35	December 6, 2015 05:30 a.m. BJT	5 killed, 1 injured, 11 cars related	Qiuji River in the east; Huai River, Yuwest Lake and Longtan Reservoir in the south	A	54 m, 6 km 40.3 m, 10 km	Visibility Visibility, relative humidity, air temperature, wind speed, wind direction
NO.02	Fuyang City, Chuzhou-Xincai Expressway, S12	October 18, 2014 05:20 a.m. BJT	4 killed, 8 injured, 4 collisions, 13 cars related	Ying River in the north; Huai River in the south	C D E F	35 m, 16 km 33 m, 3 km 30 m, 13 km 26.8 m, 23 km	Visibility Visibility Visibility Visibility, relative humidity, air temperature, wind speed, wind direction
NO.03	Fuyang City, Chuzhou-Xincai Expressway, S12	November 15, 2017 07:30 a.m. BJT	18 killed, 21 injured, 70 cars multiple collision	Huai River, Ying River and Jiaogang Lake in the south; Huajia Lake in the northeast	G	24.5 m, 1 km	Visibility, relative humidity, air temperature, wind speed, wind direction
NO.04	Bengbu City, Nanjing-Luoyang Expressway, G36	March 22, 2015 06:30 a.m. BJT	1 killed, 14 injured, 11 cars multiple collision	Huai River in the south; Diaoyutai Lake in the northwest	I J K	22 m, 3 km 30 m, 10 km 2.8 m, 15 km	Visibility Visibility Visibility, relative humidity, air temperature, wind speed, wind direction
NO.05	Bengbu City, Nanjing-Luoyang Expressway, G36	October 17, 2015 06:00 a.m. – 07:00 a.m. BJT	5 killed, 20 injured, 11 cars multiple collision	Huai River and Tian River in the south; Beifei River and Ci River in the west; Diaoyutai Lake in the east	L K	26 m, 10 km 2.8 m, 10 km	Visibility Visibility, relative humidity, air temperature, wind speed, Wind direction

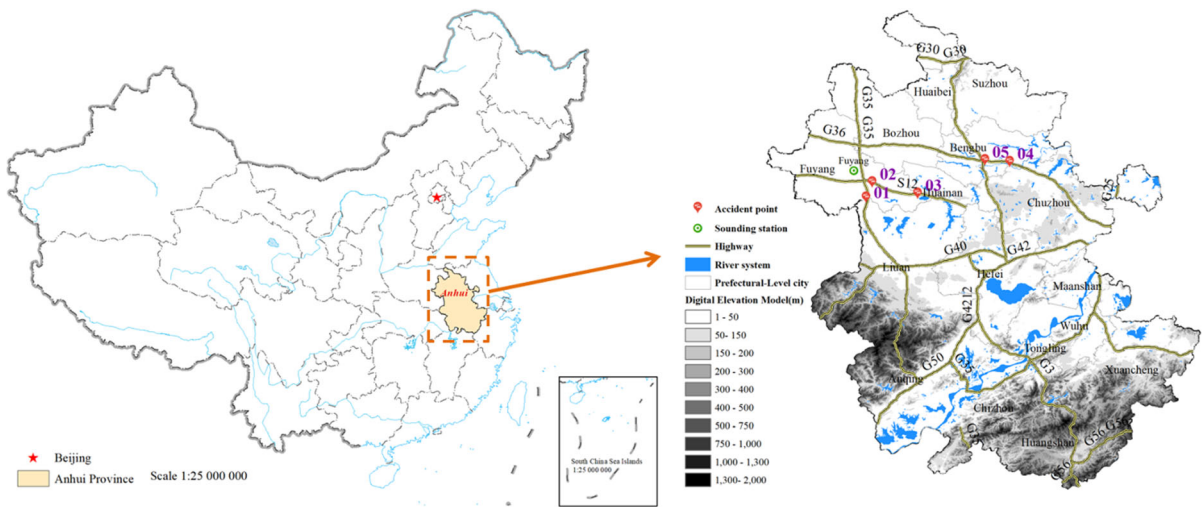


Figure 1  
Research areas

Jiangsu and reached similar conclusions. Jiangsu Province was controlled by persistent continental high pressure. Fog occurred over the uniform and high pressure zone. Apparently, this synoptic pattern provided an important condition for the formation and persistence of fog. Surface layer inversion, low-level downdraft and southeasterly flow of warm and wet air were also main factors in heavy fog formation. An important local thermal condition provided by double deep inversion layers was favorable for heavy fog formation, while the intrusion of a weak cold air mass directly triggered the outbreak and intensification of fog. In addition, the air pollution environment was conducive to fog formation. Air pollutants as condensation nuclei accumulated at low altitude also played an important role in triggering fog (Varotsos et al., 2009; Wang et al., 2005). High ultra-fine particle concentrations at the urban site generally coincided with periods of high NO concentrations and were well correlated with benzene, indicating emissions from motor vehicles (Varotsos et al., 2012). Air pollution research needs to develop a historical perspective based on past measurements to identify ozone changes with time (Varotsos & Cartalis, 1991) and analyze the scaling effect in surface air pollution meteorological parameters, which contribute to the haze and fog forecast (Efstathiou & Varotsos, 2012).

Fog occurs in a wide variety of conditions. These conditions can be described using various fog types. Each type of fog is defined by the main physical processes responsible for their formation as well as circumstances in which these processes occur (Byers, 1959; Gultepe et al., 2007; Willett, 1928). Radiation fog, whose main mechanism is radiation cooling, usually forms near the surface under clear skies in

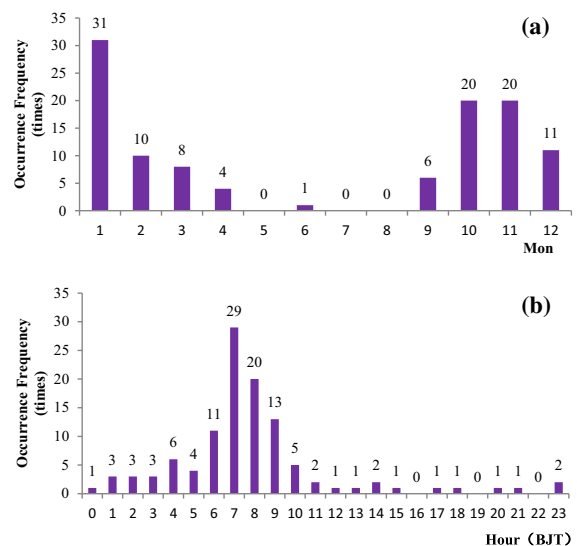


Figure 2  
Temporal distribution of expressway fog accidents in Anhui Province from 2013 to 2018

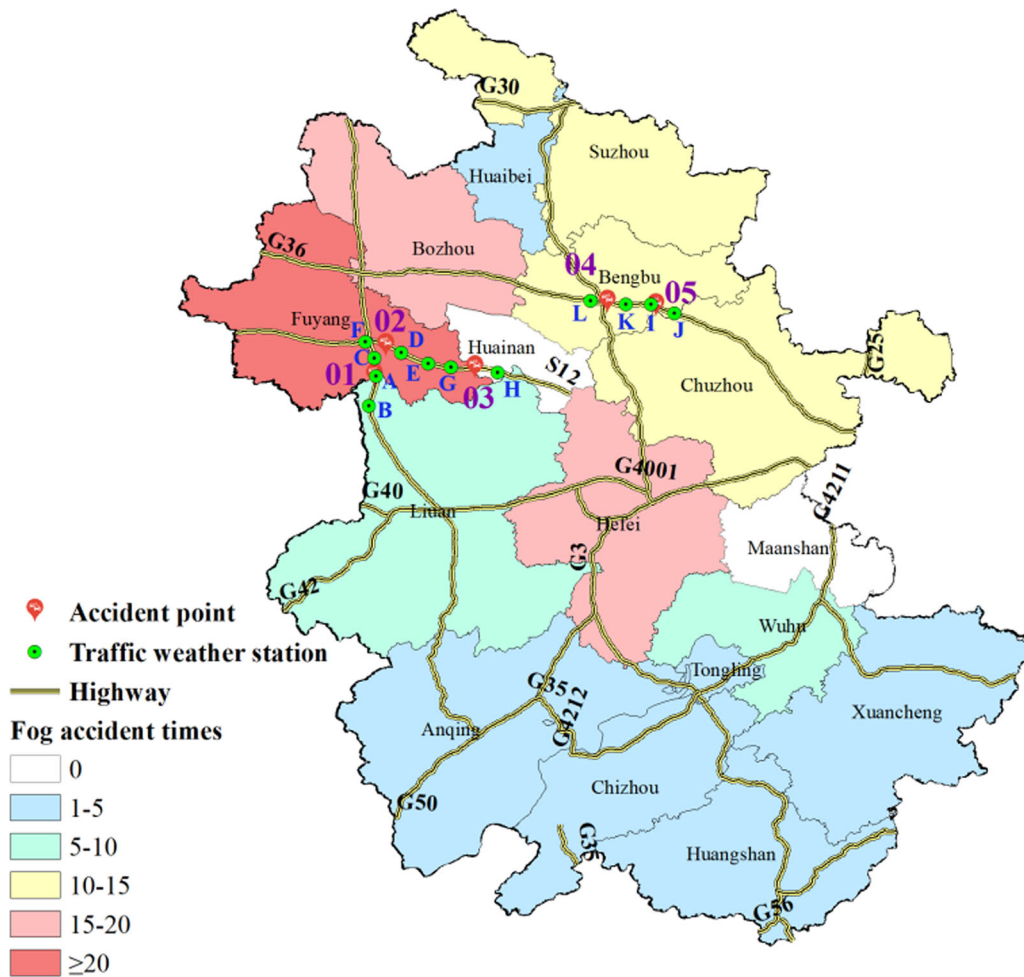


Figure 3  
Regional distribution of fog accidents in Anhui Province from 2013 to 2018

stagnant air in association with an anticyclone (Roach et al., 1976). Advection-radiation fog results from the radiation cooling of moist air that has been advected over land from the ocean or from any large water body during the previous daylight hours (Ryznar, 1977). So-called high-inversion fog usually forms in valleys within a deep moist layer capped by a strong inversion (Holets & Swanson, 1981). In cold regions, due to the extremely low temperature of the surface layer in winter, both super cooling water and ice crystals exist in fog, and those water droplets form ice fog through physical changes such as evaporation, condensation and solidification (Gultepe et al., 2017a). As with any fog, its presence can be a hazard

for ground or airborne traffic because of poor visibility and icing (Gultepe et al., 2011). In China, ice fog only appeared in the northeast of the Daxing'anling and other cold regions in the winter, and the impact area was rather small (Jiang et al., 2019; Lu et al., 2017).

Compared with ice fog, the influence of agglomerate fog on highway traffic in China is more widespread. Most highways in China are susceptible to agglomerate fog, especially in the densely populated areas in the middle eastern part. The formation of agglomerate fog is usually related to local micro-climatic environment. Since the surface albedo of road surfaces is usually lower than other underlying

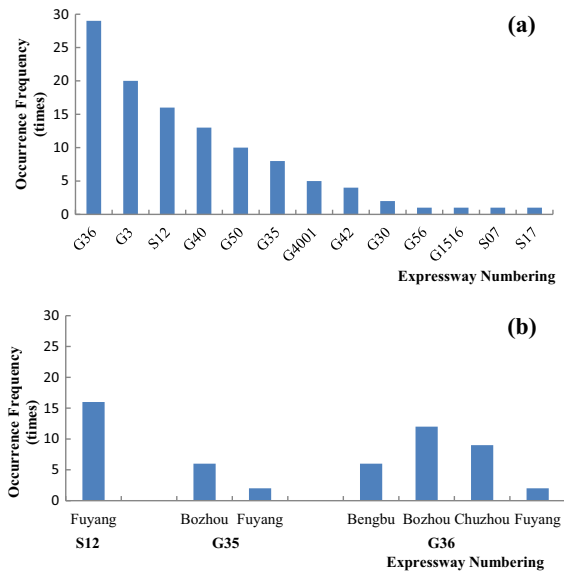


Figure 4

Statistics for fog accident frequency on expressways in Anhui Province from 2013 to 2018. **a** The main expressways in Anhui Province; **b** the fog accident road sections of S12, G35 and G36 expressways

surfaces (vegetation, sand, water, snow, etc.) and the road surface is also impermeable, solar radiation absorbed by road surfaces is about three times higher than in the near-surface atmosphere (Varotsos et al., 2014; Yang et al., 2008). As the radiation cooling effect above the highway surface was obviously greater than the surrounding soil surface or vegetation surface, and the pollution particles caused by exhaust emissions increased, the atmosphere above the highway was more prone to temperature inversion than other places nearby, which was more conducive to the formation of agglomerate fog. Aggregate fog with the local, sudden and small-scale characteristics is difficult to examine by normal meteorological stations. To this end, many scholars simulated and analyzed the occurrence process, characteristics and causes of agglomerate fog. Pagowski et al. (2004) analyzed an agglomerate fog that occurred near Windsor, Ontario, Canada, on 3 September 1999 using the MM5 model and found that the fog was caused by a combination of land-based wind convergence along the lakeshore and the subsequent transport of water vapor over the site of the accident. Yamamoto (2002) examined the climatological features of traffic accidents in Japan on the expressway

with agglomerate fog and found that the accidents mainly occurred in the cooling season and meteorological conditions at the time of the accident were diverse, which was not completely consistent with the general characteristics of the fog in Japan. Yan et al. (2011), using the WRF2.2 model, simulated an agglomerate fog process appearing in the southern part of Jiangsu Province, which covered the Shanghai-Nanjing Expressway on 26 October 2007. They found that the cold advection and ground radiation cooling were the important factors of the formation, development and persistence of the fog. In addition, some scholars analyzed the agglomerate fog characteristics using the observed data from the automatic weather stations on the expressway. Ding et al. (2013) analyzed observed data from the Automatic Weather Monitoring System on Shanghai-Nanjing Expressway and found that the seasonal variations between regional dense fog and agglomerate fog were similar, but the occurrence frequencies and spatial distribution were quite different. The occurrence frequencies of agglomerate fog were generally higher in the western riverside section than in the other sections. Tian et al. (2019) analyzed the variation in meteorological characteristics of agglomerate fog and concluded that the inhomogeneous varied visibilities along the road caused agglomerate fog formation. The formation and dispersion of agglomerate fog were closely related to the wind direction change.

Nowadays, remote sensing is playing an increasing role with a growing array of more accurate sensors, and its measurements are providing more and more information about fog and providing additional data for input to forecasting tools (Andrews & Bright, 2018; Brunner et al., 2016; Cracknell & Varotsos, 2011; Gultepe et al., 2019; Li et al., 2012; Lee et al., 2011). Furthermore, some progresses of fog monitoring and forecasting have been made using microwave radiation data (Martinet et al., 2020; Wang et al., 2018) and image recognition technology (Chaabani et al., 2018; Gao et al., 2019; Kwon 2004; Mandal et al., 2021; You et al., 2018), which can effectively make up for the lack of meteorological traffic observation along the expressway and improve the technical ability of fog monitoring and early warning systems. It is important to analyze the various characteristics of agglomerate fog for low

visibility or agglomerate fog forecasting, especially in China, where different regions have different climate and terrain conditions. Based on the reliable monitoring data along the expressway, research on the meteorological characteristics and reasons for road traffic accidents caused by agglomerate fog is necessary.

In this article, Anhui Province was selected as the analysis area because it has a dense highway network and is prone to fog accidents and blocking events (Jiang et al., 2020; Liu et al., 2017). First, based on the five agglomerate fog accident data during 2014–2017 and the expressway fog accident data during 2013–2018, the temporal and spatial distribution characteristics of agglomerate fog traffic accidents in Anhui Province are analyzed. In the next section, the geographical conditions of agglomerate

Figure 6  
Surface weather map at 02:00 a.m. BJT (left), 05:00 a.m. BJT (middle) and 08:00 a.m. BJT (right) on the days of five agglomerate fog accidents. **a** Accident NO.01 (6 Dec 2015), **b** accident NO.02 (18 Oct 2014), **c** accident NO.03 (15 Nov 2017), **d** accident NO.04 (22 Mar 2015), **e** accident NO.05 (17 Oct 2015)

fog accidents are introduced according to the water network and terrain in Anhui Province. The weather background is analyzed to explore the mechanism of agglomerate fog occurrence. Finally, for finding the main meteorological conditions that contribute to agglomerate fog formation, the variation characteristics in terms of visibility, humidity, temperature and wind for agglomerate fogs are analyzed. This will help in forecasting and providing early warning for

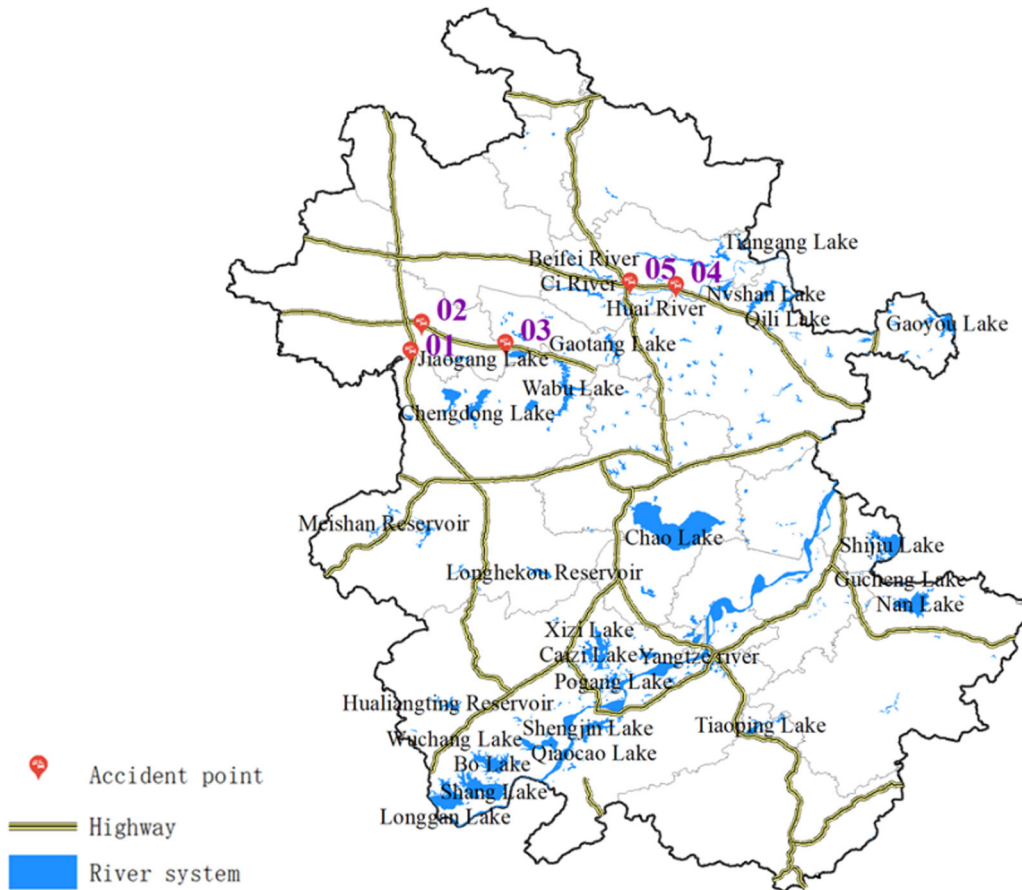
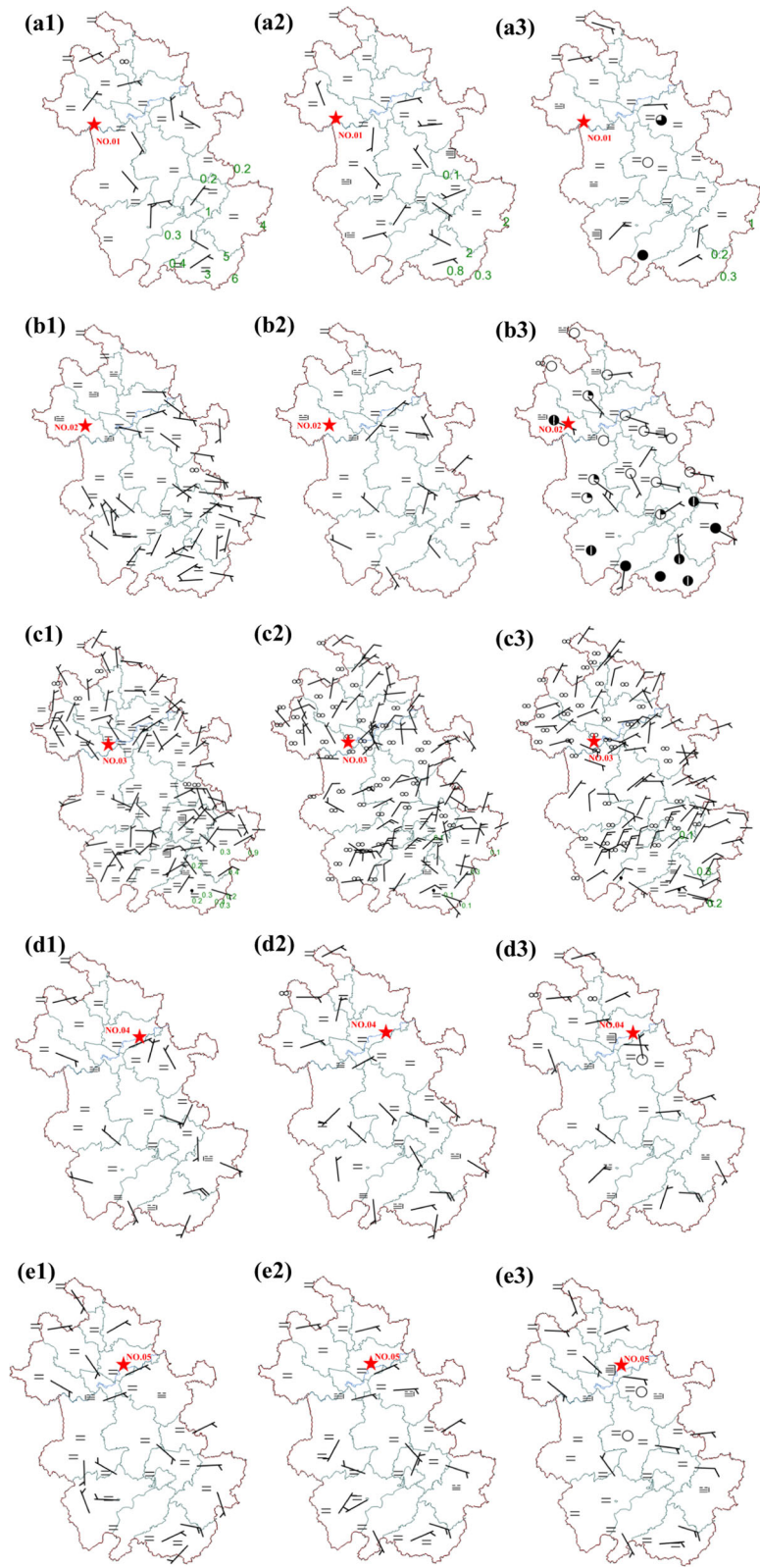


Figure 5  
Regional distribution of the water network in Anhui Province



agglomerate fog and preventing traffic accidents caused by agglomerate fog on the expressway.

## 2. Data

The agglomerate fog accident dataset, containing the time and location of the accidents and other information from the year 2014–2017 in Anhui Province, was obtained from the internet and verified by the traffic control department (Table 1). The fog accident dataset from 2013–2018, obtained from the traffic control department, had the same content as the agglomerate fog accident dataset.

The weather dataset in Anhui Province was obtained from the National Meteorological Information Center (NMIC) of the China Meteorological Administration (CMA). Among them, 3-hourly weather data were measured by meteorological stations, 1-hourly weather data were measured by traffic weather station, and sounding observation data were obtained by L-band radar of Fuyang meteorological station (Fig. 1). Temperature, precipitation, relative humidity, wind direction, wind speed, visibility and other weather factors were included in this dataset. In addition, NCEP reanalysis data ( $1.0^\circ \times 1.0^\circ$ , 6-hourly products) were used in this analysis. The locations of the traffic weather stations around those five agglomerate fog accidents are shown in Fig. 3.

## 3. Space-Time Characteristics of Agglomerate Fog Accidents

### 3.1. Temporal Characteristics

These five agglomerate fog accidents occurred between 05:00 a.m. BJT and 08:00 a.m. BJT in March and October to December. This was consistent with fog accidents in Anhui Province in the recent 6 years (2013–2018). The fog accidents in Anhui Province frequently occurred from autumn to early spring (January to March, September to December), especially in January, October and November. The fog accidents frequently occurred from 04:00 a.m. BJT to 10:00 a.m. BJT, especially from 06:00 a.m. BJT and 09:00 a.m. BJT (Fig. 2).

### 3.2. Spatial Characteristics

These five agglomerate fog accidents occurred in Fuyang City and Bengbu City, which are the fog accident-prone areas in Anhui Province. Figure 3 shows the regional distribution of fog accidents in Anhui Province from 2013 to 2018. Fog accidents frequently occur in the north-central regions and the Huai River basin. There have been 20 fog accidents in Fuyang over 6 years, ranking first in Anhui Province. In addition, there have been 15–20 fog accidents in Bozhou and Hefei that rank second and third, respectively, and 10–15 fog accidents in Chouzhou, Bengbu and Suzhou, ranking fourth, fifth and sixth respectively.

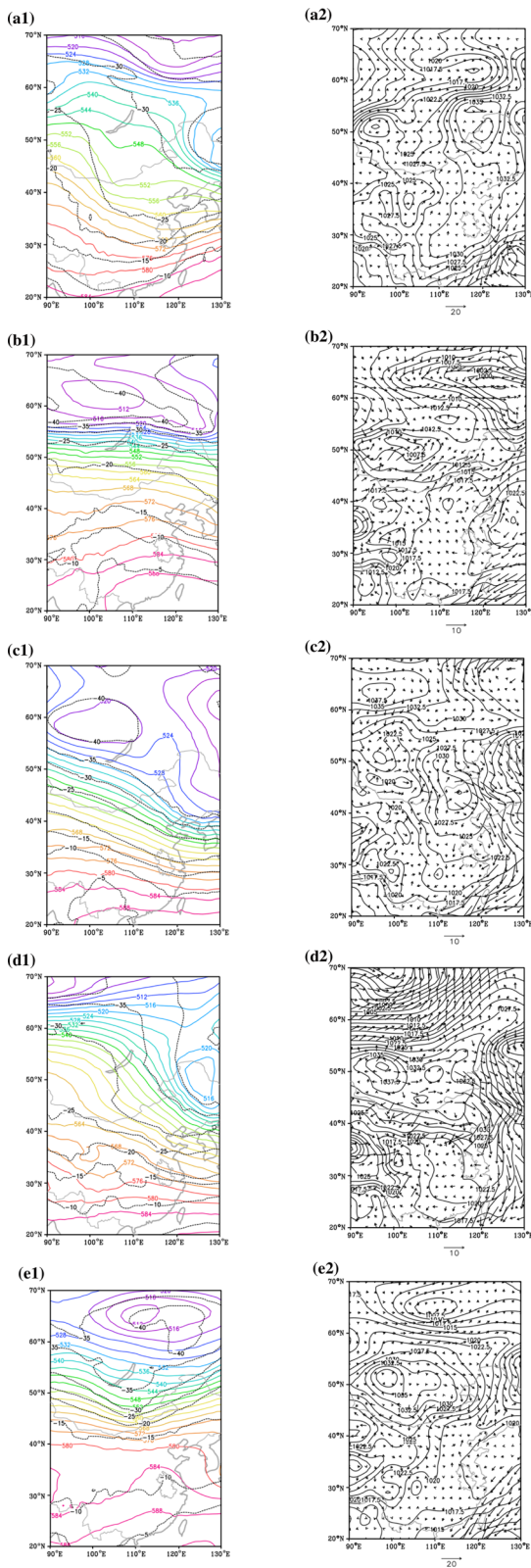
These five agglomerate fog accidents occurred on G36, S12 and G35 expressways, respectively. The number of fog accidents that occurred on the three expressways was very high. Twenty-nine fog accidents occurred on G36, which was significantly more than on other expressways. The number of fog accidents that occurred on S12 was slightly lower than on G3 and ranked third. Eight fog accidents occurred on G35, ranked sixth (Fig. 4a). Fog accidents on the three expressways occurred mainly in Fuyang, Bozhou, Bengbu and Chuzhou sections during the 6 years. Among them, 16 fog accidents occurred in the S12 Fuyang section and 6 in the S36 Bengbu section (Fig. 4b).

## 4. Analysis of the Background of Agglomerate Fog Occurrence

### 4.1. Geographical Environment

Agglomerate fog is a kind of advection-radiation fog, so its occurrence and dissipation are greatly affected by local factors such as underlying surface, local turbulence, aerosol and water vapor conditions. The terrain of Anhui Province is mainly plain and hilly, especially in the north, which is flatter. The altitudes in most of the areas are  $< 50$  m, which is conducive to the transport and accumulation of water vapor. In addition, the water network is dense in Anhui Province where there are  $> 2000$  rivers and 580 lakes. The north of Anhui Province belongs to the Yangtze River Basin and the south to the Huai





◀Figure 7

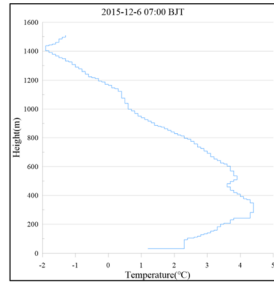
Geopotential height at 500 hPa (left, unit: dagpm) and sea level pressure (right, unit: hPa) with the surface wind (right, unit: m/s) at 08:00 a.m. BJT on the days of five agglomerate fog accidents. **a** Accident NO.01 (6 Dec 2015), **b** accident NO.02 (18 Oct 2014), **c** accident NO.03 (15 Nov 2017), **d** accident NO.04 (22 Mar 2015), **e** accident NO.05 (17 Oct 2015)

River Basin (Fig. 5). A dense water network has an obvious cooling effect on the atmosphere and provides sufficient water vapor, which is very favorable for the formation of fog, especially agglomerate fog.

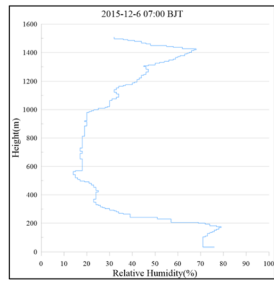
From the perspective of geographical location, accidents NO.01 to NO.03 occurred in Fuyang City, which is located in northwest Anhui Province and is the southernmost tip of the Huaibei Plain. There are no hills in Fuyang City; the terrain is flat, with altitude between 18 and 30 m. There are dense water systems in Fuyang City, such as the Huai River in the south and Ying River in the middle. The S12 expressway runs from southeast to northwest in Fuyang City, and the G35 expressway runs from south to north. Accident NO.01 occurred near the Huai River, and accidents NO.02 to NO.03 occurred north of the Huai River, which is about 10–20 km away. There are also other rivers and lakes near the locations of these accidents. For instance, the Ying River was to the north of accident NO.02. The Ying River and Bali River were southwest of accident NO.03, within 10 km. Jiaogang Lake and Huajia Lake were also east of accident NO.03, within 20 km.

Accidents NO.04 to NO.05 occurred in Bengbu City, which is located north of Anhui Province and belongs to the transition zone of Huang-Huai-Hai Plain and Jianguhai hilly region. In Bengbu City, the area north of Huai River is mainly plain; south of Huai River has scattered hills. There were also dense water systems around accidents NO.04 to NO.05, e.g., the Beifei River in the north, Tian River in the southwest, Ci River and Baligou River in the west, and Longzigou River and Baojiagou River in the east. Accidents NO.04 to NO.05 were < 6 km away from the Huai River, so water vapor around these accidents was sufficient and the terrain was flat, being favorable fog-forming conditions.

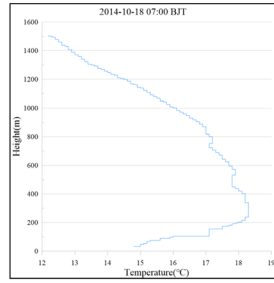
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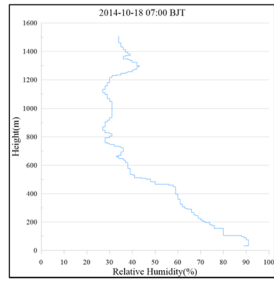
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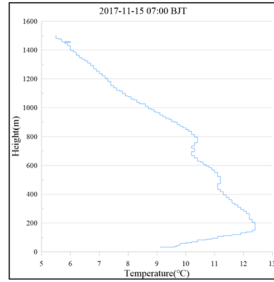
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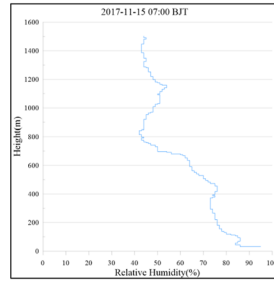
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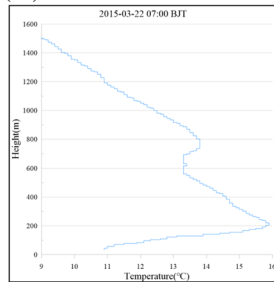
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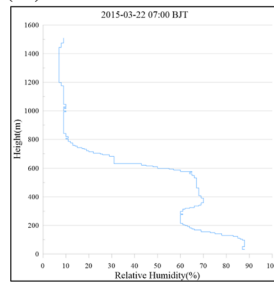
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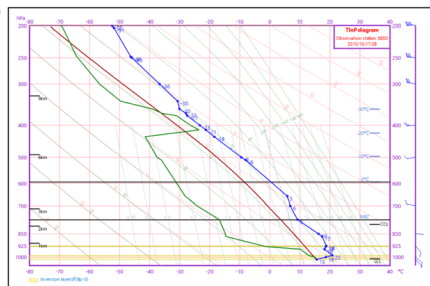
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(d2)



(e)



◀Figure 8

Vertical profiles of temperature (a1–d1) at 07:00 a.m. BJT and relative humidity (a2–d2) at 07:00 a.m. BJT at Fuyang station on the days of agglomerate fog accidents NO.01 to NO.04; the T–lnP figure e at 08:00 a.m. BJT of Fuyang station on the day of agglomerate fog accident NO.05. **a** Accident NO.01 (6 Dec 2015, L-band soundings), **b** accident NO.02 (18 Oct 2014, L-band soundings), **c** accident NO.03 (15 Nov 2017, L-band soundings), **d** accident NO.04 (22 Mar 2015, L-band soundings), **e** accident NO.05 (17 Oct 2015, the blue, green and red solid lines indicate the T–pressure, Td–pressure and state curve, respectively)

#### 4.2. Weather Background

Figure 6 shows the surface weather map on the days when five agglomerate fog accidents occurred. The major weather conditions in Anhui Province were clear or mostly clear when accidents NO.01 and NO.02 and accidents NO.04 and NO.05 occurred. The wind was 1–2 on the Beaufort Scale with light fog in most of the province. All four accidents occurred under foggy conditions. For accident NO.03, the surrounding weather was also clear with Beaufort Scale 2 wind when it occurred. There was light fog at 02:00 a.m. BJT and haze between 05:00 a.m. BJT and 08:00 a.m. BJT. Therefore, accident NO.03 occurred under fog and haze conditions. There was a close relationship between fog and haze (Gautam et al., 2007). Under certain weather conditions, they can transform into each other (Zhang et al., 2013). Many in situ measurements have already been carried out to study the mechanism of haze to fog transformation or atmospheric aerosol microphysics in haze/fog events in China. Results showed that the dominant sequence of the four weather conditions (fog, mist, wet haze and haze) of fog/haze events in Nanjing in November 2007 was haze ← → mist → wet haze → fog → wet haze → mist ←

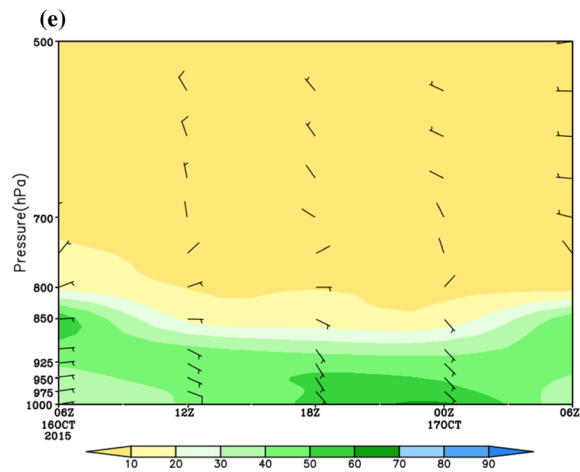
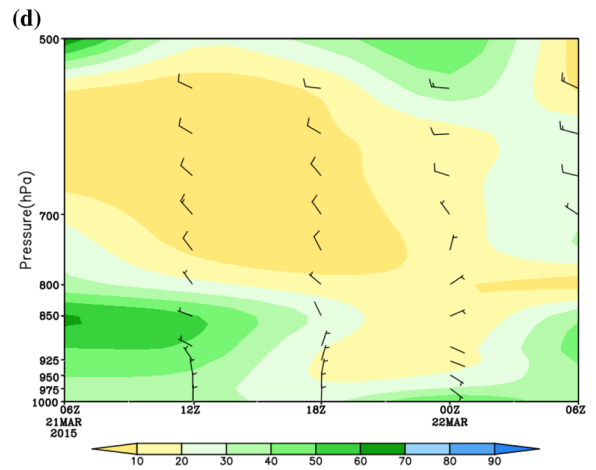
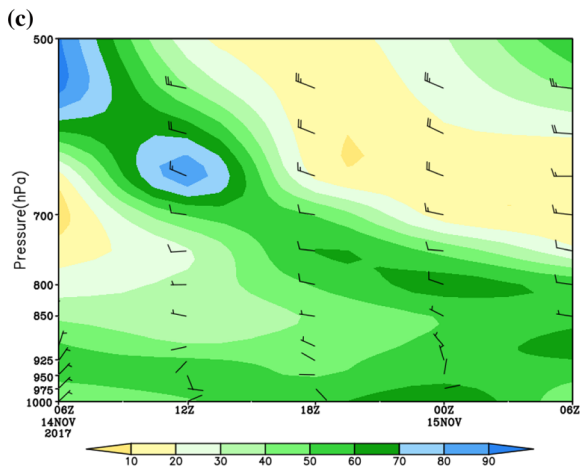
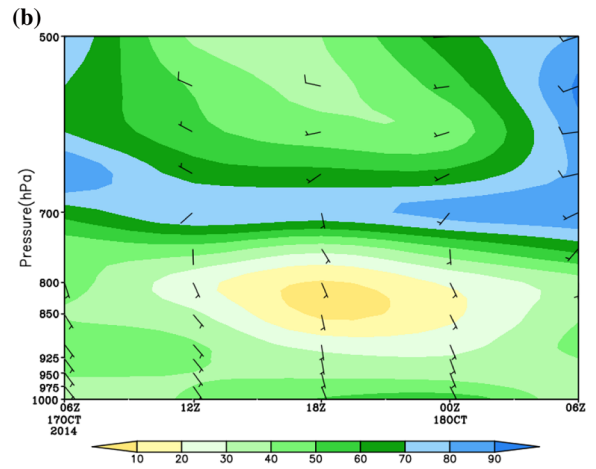
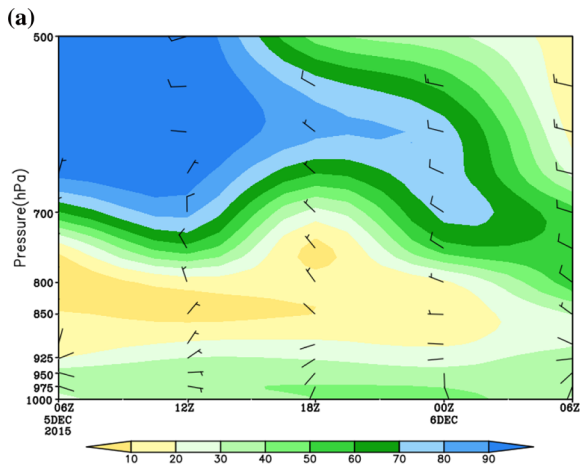
→ haze (Yang et al., 2010). When relative humidity was > 90%, haze aerosols started to transform from haze to fog (Zhang & Niu, 2016). Values of horizontal and vertical turbulent diffusion parameters on fog days were higher than on those without fog under neutral conditions (Wu et al., 2007). The values of turbulence kinetic energy and friction velocity on hazy days were lower than on sunny and foggy days (Li et al., 2015).

As for accident NO.1, there was a shallow trough in 500 hPa geopotential height in the middle eastern part of China during from 08:00 p.m. BJT 5 December 2015 and 08:00 a.m. BJT 6 December 2015 (Fig. 7a). Due to the influence of the short-wave trough moving east, weak precipitation occurred in the south of Anhui Province. The north of Anhui Province had flat westerlies during this period. From the ground map (Fig. 7b), the middle eastern part of China was controlled by a large high-pressure zone, and Anhui Province was located in the homogenizing pressure field of this high-pressure zone. The moving short-wave trough was beneficial to the formation and persistence of fog, and its function was manifested in two aspects. On the one hand, the warm, moist airflow transported in front of the trough was conducive to the air warming of the lower level, while the dry layer in the mid-high level was conducive to radiation cooling of the near ground layer, which easily formed lower level inversion. On the other hand, the warm moist airflow in front of the trough was conducive to the increase of water vapor in the lower level. When accidents NO.02 to NO.05 occurred, the middle eastern part of China was controlled by the high-pressure ridge (Fig. 7b1–e1), and Anhui Province was located in front of or in the high pressure ridge. Anhui Province was also located

Table 2

*The cooling rate in different levels for five agglomerate fogs (unit: °C/h)*

Accident ID	Date	14:00 BJT to 20:00 BJT 1000 hPa; 975 hPa; 950 hPa	20:00 BJT to 02:00 BJT 1000 hPa; 975 hPa; 950 hPa	02:00 BJT to 08:00 BJT 1000 hPa; 975 hPa; 950 hPa
NO.01	20151205	– 0.2; – 0.13; – 0.05	– 0.1; – 0.07; – 0.03	– 0.22; – 0.12; – 0.07
NO.02	20141017	– 0.35; – 0.18; – 0.12	– 0.53; – 0.27; – 0.17	– 0.23; – 0.12; – 0.08
NO.03	20171114	– 0.15; – 0.07; – 0.06	– 0.27; – 0.11; – 0.02	– 0.17; – 0.14; – 0.08
NO.04	20150321	– 0.25; – 0.13; – 0.1	– 0.35; – 0.18; – 0.1	– 0.7; – 0.32; – 0.15
NO.05	20151016	– 0.52; – 0.31; – 0.27	– 0.32; – 0.23; – 0.18	– 0.37; – 0.18; – 0.07



◀Figure 9

Time-height cross-sections of relative humidity (shadow, unit: %), wind field (unit: m/s) near the five agglomerate fog accident sites. **a** Accident NO.01 (6 Dec 2015, 33° N, 116° E), **b** accident NO.02 (18 Oct 2014, 33° N, 116° E), **c** accident NO.03 (15 Nov 2017, 33° N, 117° E), **d** accident NO.04 (22 Mar 2015, 33° N, 118° E), **e** accident NO.05 (17 Oct 2015, 33° N, 117° E)

in the homogenizing pressure field of the high pressure belt (Fig. 7b2–e2). Therefore, the atmospheric condition in Anhui Province was stable under the influence of the westerly airflow, with less cloud in the upper air and strong radiation cooling at night. Moreover, a small surface pressure gradient and weak wind mainly in the southern or eastern direction were conducive to fog formation and persistence.

Figure 8 shows the vertical variation of temperature and relative humidity at Fuyang meteorological station near the accident sites. There were multiple inversion layers in the stratification curves of Fuyang meteorological station in the morning of the five agglomerate fog accidents. The inversion height near the surface was about 100–200 m. The inversion layer inhibited the convective movement of the atmosphere and kept water vapor in the lower level, which was conducive to fog formation and development. In addition, the inversion layer limited vertical dispersion of pollutants, which resulted in pollutants mainly gathering near the surface (Pilie et al., 1975). This is why the haze appeared when the NO.03 accident occurred.

Relative humidity on the night before the occurrence of the five agglomerate fog accidents was relatively low (figure omitted). With radiation cooling, the relative humidity in the ground layer increased rapidly in the morning, staying at about 80–90%. Relative humidity was upper dry and lower wet condition. This condition meant a strong, long wave radiation flux loss near from the ground and large cooling rate near the surface. Referring to the cooling rate expression  $C_c(z) = -(\partial T/\partial t)$  (Zhou & Ferrier, 2008), the cooling rate was calculated from 1000 to 950 hPa (Table 2). It showed that the cooling rate was the largest at 1000 hPa and decreased with the increase of height during the time of fog onset, persistence and dissipation from 20:00 BJT to 08:00

BJT. Large cooling rate near the surface was conducive to water vapor condensation, resulting in the increase of humidity near the surface. The upper-dry and lower-wet condition was conducive to the formation and maintenance of the inversion near the surface layer.

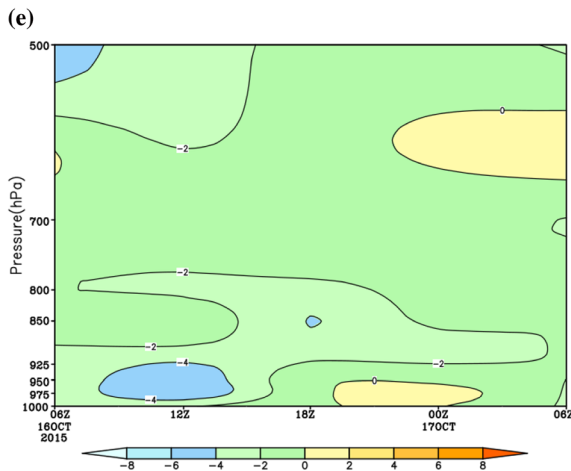
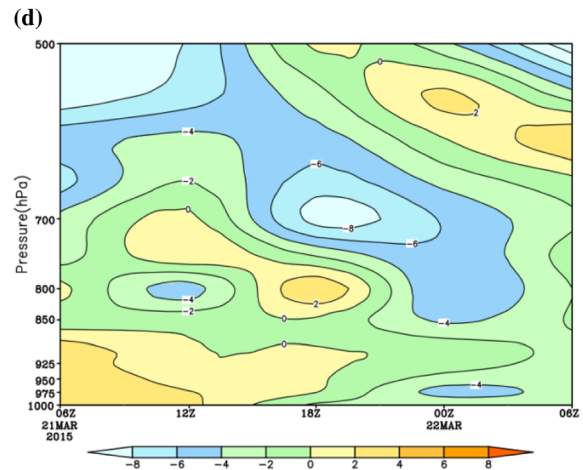
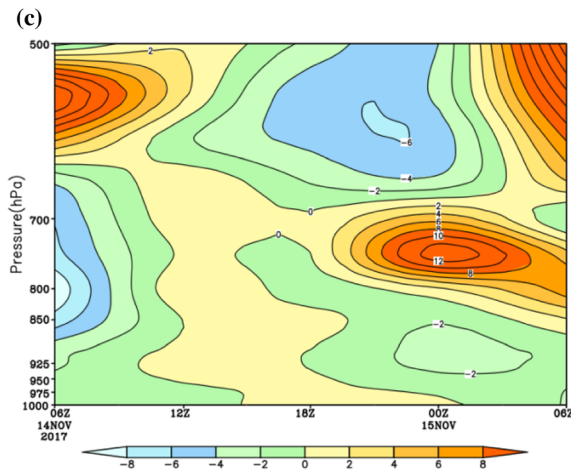
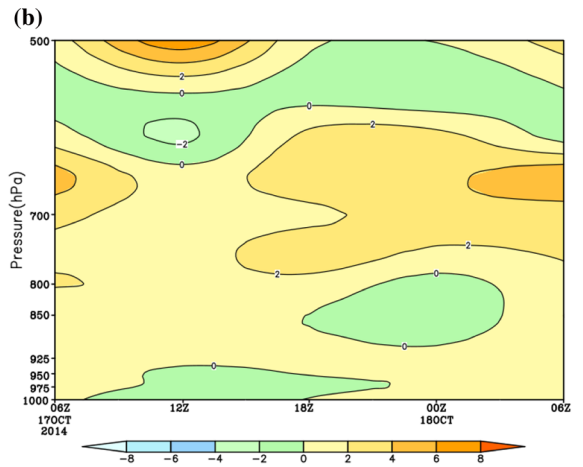
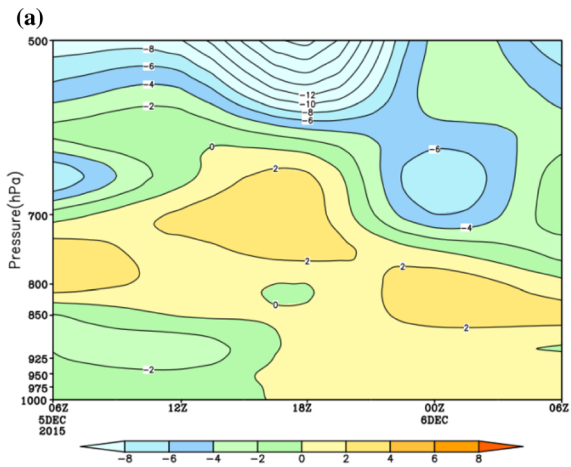
The temporal and spatial profiles of relative humidity near the accident point (Fig. 9) show that before fog formation and during persistence the relative humidity below 800 hPa was in a state of upper dry and lower wet, and the relative humidity from 1000 to 975 hPa increased with the cooling of radiation at night. The relative humidity reached up to the highest level between 1000 to 975 hPa at 08:00 a.m. BJT and then decreased rapidly as the temperature rose. The fog gradually weakened and disappeared. These five agglomerate fog cases all had stratification characteristics of radiation fog that were temperature inversion and “upper dry and lower wet” near the surface layer.

Meanwhile, from the wind field (Fig. 9), the wind speed was weak in the process of the overall fog. During the period of fog formation and persistence, the southeast wind dominated from 1000 to 950 hPa. The warm and moist air from the southeast provided favorable conditions for fog formation and persistence. In addition, as shown in Fig. 9a–c and e, the wind direction below 950 hPa tended to deflect clockwise with height, and so there should be a warm advection. The time-height profile of temperature advection (Fig. 10) also showed that there was weak warm advection below 950 hPa in all four agglomerate fog cases except for accident NO.04 (Fig. 10c) during fog formation and persistence. So all four agglomerate fog cases were advection radiation fog.

## 5. Meteorological Characteristics at the Time of Agglomerate Fog Accidents

### 5.1. Variation Characteristics of Visibility

Figure 11 was the daily minimum visibility along the Anhui Province expressways on the days of five agglomerate fog accidents. The visibility was < 500 m on many highways around the accident



area, and it is significant that the visibility at the location of the accidents was < 100 m. The visibility

was also uneven on the same highway. Therefore, there was a wide range of low visibility around the

◀Figure 10

Time-height cross-sections of temperature advection (unit:  $10^{-5} \text{ } ^\circ\text{C/s}$ ) near the five agglomerate fog sites. **a** Accident NO.01 (6 Dec 2015,  $33^\circ \text{ N}$ ,  $116^\circ \text{ E}$ ), **b** accident NO.02 (18 Oct 2014,  $33^\circ \text{ N}$ ,  $116^\circ \text{ E}$ ), **c** accident NO.03 (15 Nov 2017,  $33^\circ \text{ N}$ ,  $117^\circ \text{ E}$ ), **d** accident NO.04 (22 Mar 2015,  $33^\circ \text{ N}$ ,  $118^\circ \text{ E}$ ), **e** accident NO.05 (17 Oct 2015,  $33^\circ \text{ N}$ ,  $117^\circ \text{ E}$ )

fog incidents, and the distribution of fog concentration was uneven and very local.

Comparing the visibility changes at traffic weather stations near the accidents (Fig. 12) shows that there was low visibility below 500 m monitored by the adjacent traffic weather stations around these five accidents locations, and the visibility showed short-term characteristics of sharp decline and rapid

recovery. In addition, the low visibility appeared and dissipated at different stations and different times on the same expressway, resulting in uneven distribution of visibility intensity along the expressway. When vehicles move through the foggy area quickly on the expressway, drivers will feel that the fog is growing thicker one moment and lighter the next. The change of visibility will easily lead to decreasing driver vigilance, increasing the risk of traffic accidents.

Figure 12 shows that the visibility decreased rapidly to  $< 500 \text{ m}$  within 1 h and then decreased slowly or continued for 3–5 h and finally rose quickly to  $> 1000 \text{ m}$  within 1 h. Taking accident NO.02 as an example, the visibility monitored by the traffic weather station near this accident was between 500 and 1000 m from 00:00 a.m. BJT to 03:00 a.m. BJT

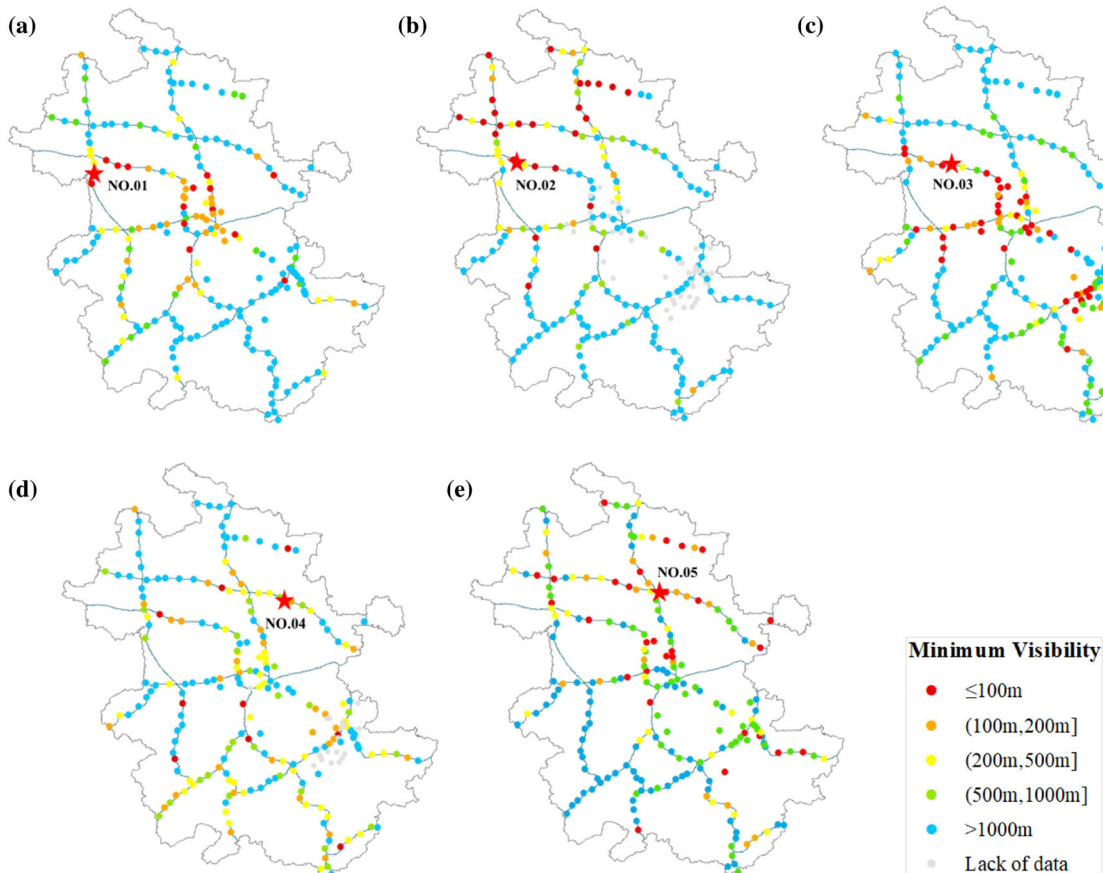


Figure 11

Distribution map of minimum visibility along expressways in Anhui Province on the days of five agglomerate fog accidents. **a** Accident NO.01 (6 Dec 2015), **b** accident NO.02 (18 Oct 2014), **c** accident NO.03 (15 Nov 2017), **d** accident NO.04 (22 Mar 2015), **e** accident NO.05 (17 Oct 2015)

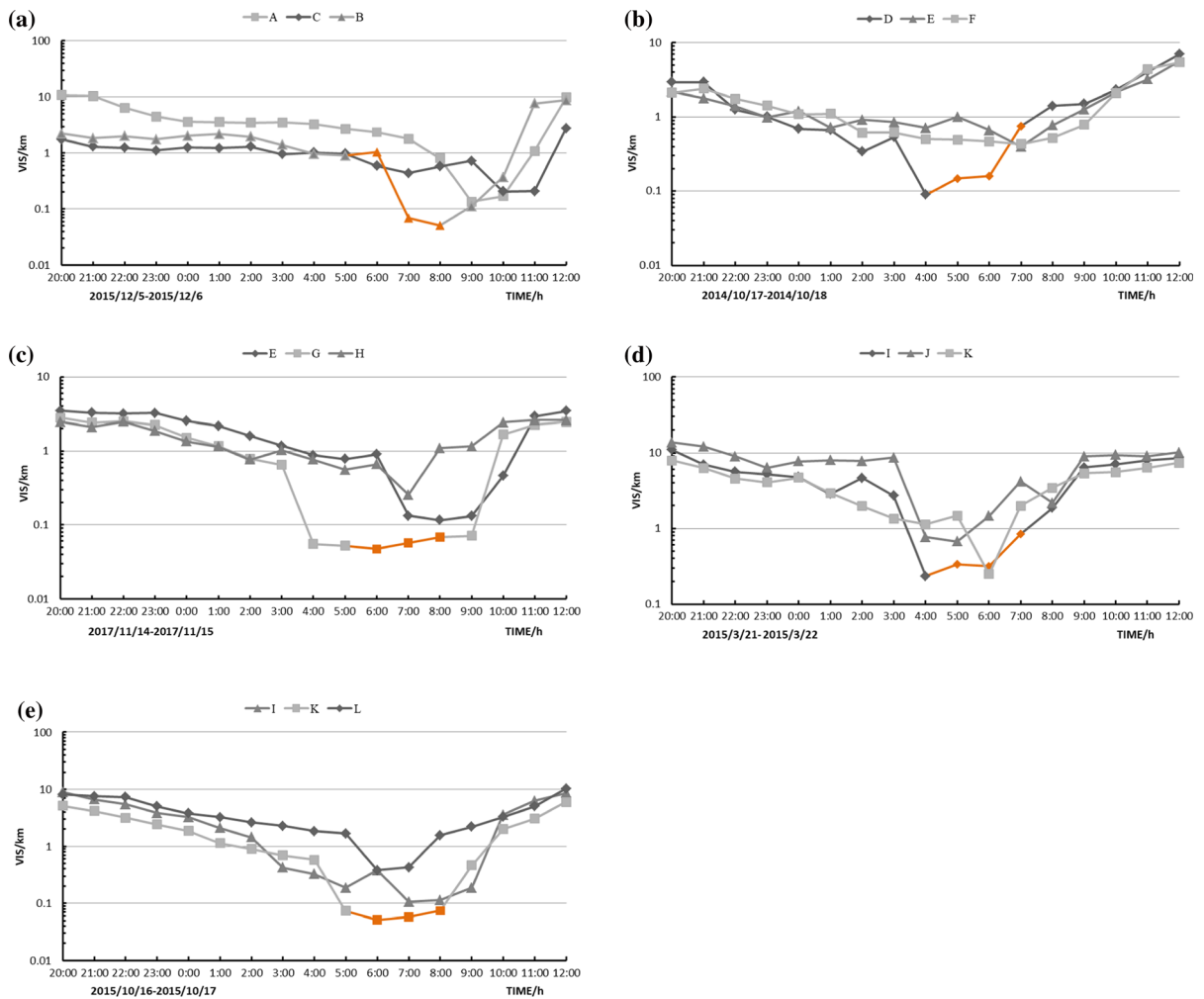


Figure 12

Variation characteristics of visibility monitored by traffic weather stations near the five agglomerate fog accident sites. **a** Accident NO.01 (6 Dec 2015), **b** accident NO.02 (18 Oct 2014), **c** accident NO.03 (15 Nov 2017), **d** accident NO.04 (22 Mar 2015), **e** accident NO.05 (17 Oct 2015)

and then decreased rapidly to 100 m. The visibility gradually recovered after 06:00 a.m. BJT and rose above 1000 m at 08:00 a.m. BJT. It showed that the five agglomerate fogging processes had obvious characteristics of explosive development in the period of low visibility.

In addition, accidents NO.01, NO.02 and NO.04 occurred during the period of sharp visibility change. Among them, one accident occurred in the period of sharp decrease and two accidents in the period of sharp increase. It will make drivers unprepared and block their vision when the visibility suddenly

decreases on an expressway. Furthermore, emergency braking is more likely to lead to a rear-end collision.

### 5.2. Variation Characteristics of Relative Humidity and Temperature

Relative humidity is one meteorological factor that reflects the degree of air moisture and is also one of the most important influencing factors for fog formation. The relative humidity was high when the five accidents occurred. The relative humidity reached 98% when accidents NO.02 and NO.05 took



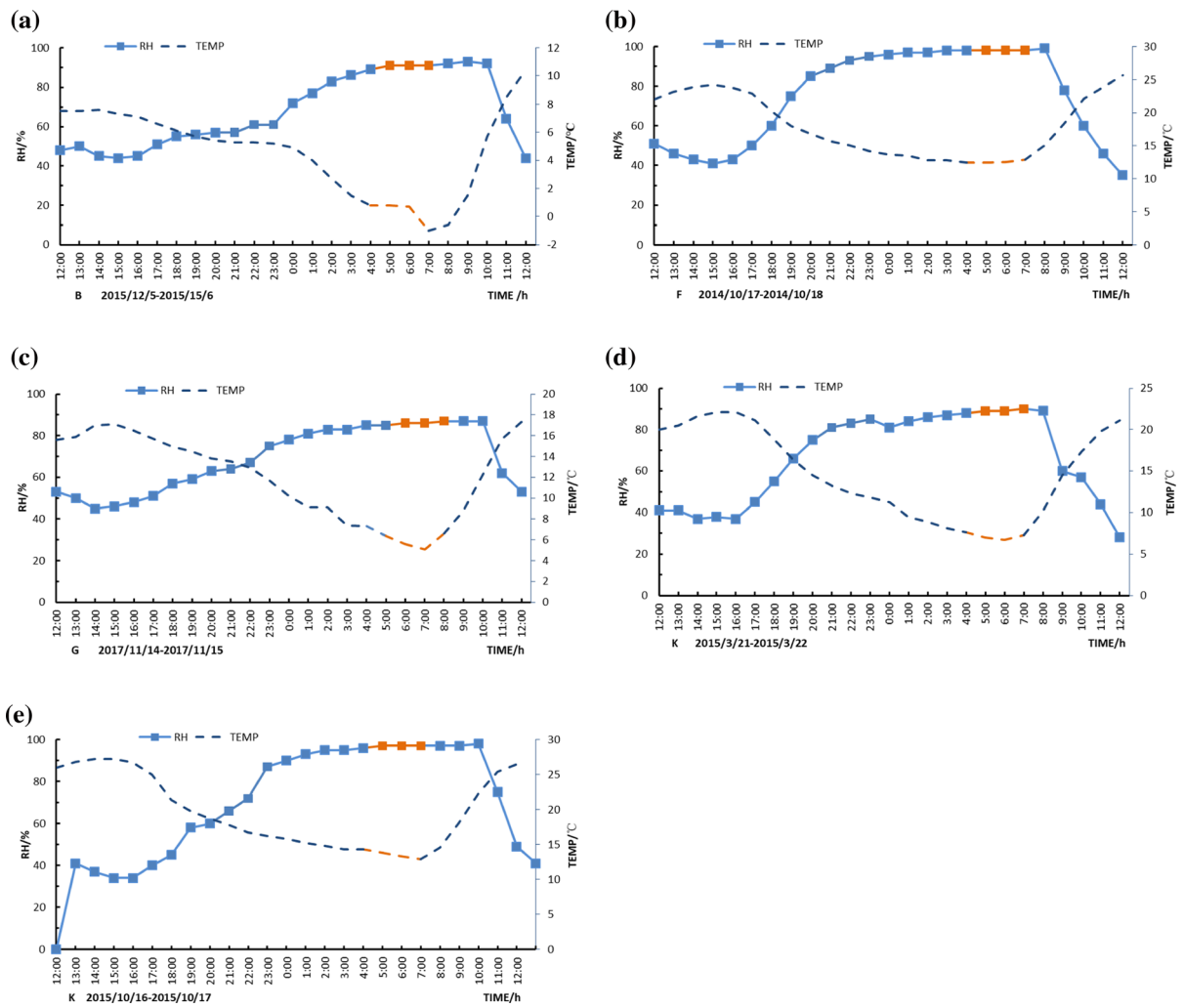


Figure 13

Variation characteristics of relative humidity and temperature monitored by traffic weather stations near the five agglomerate fog accident sites. **a** Accident NO.01 (6 Dec 2015), **b** accident NO.02 (18 Oct 2014), **c** accident NO.03 (15 Nov 2017), **d** accident NO.04 (22 Mar 2015), **e** accident NO.05 (17 Oct 2015)

place. The relative humidity reached 90% when accidents NO.01 and NO.04 occurred. The relative humidity reached 87% when accident NO.03 happened (Fig. 13). The relative humidity decreased obviously as the visibility increased. Among the five accidents, accidents NO.01, NO.02, NO.04 and NO.05 occurred against the background of fog, and accident NO.03 occurred in against combined background of fog and haze. The relative humidity in the pure fog condition was slightly higher than in the situation of combined fog and haze.

The daily variation ranges of temperature during the five agglomerate fog processes were large. The temperature difference between the maximum temperature of the previous day and current temperature was about 8–12 °C when the accidents happened. When the atmospheric water vapor was sufficient and the temperature dropped greatly, it was conducive to the condensation of water vapor and easily produced fog.

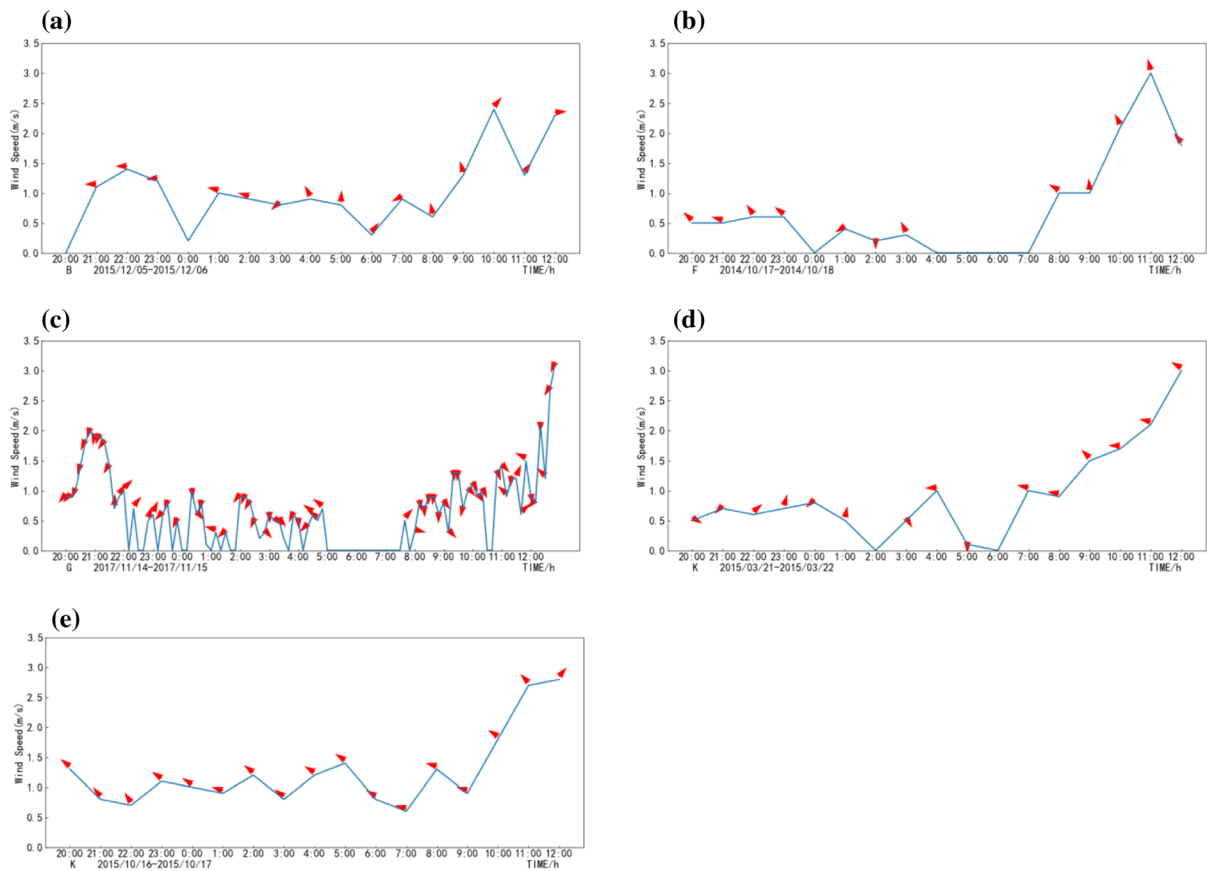


Figure 14

Variation characteristics of wind speed and direction monitored by traffic weather stations near the five agglomerate fog accident sites. **a** Accident NO.01 (6 Dec 2015), **b** accident NO.02 (18 Oct 2014), **c** accident NO.03 (15 Nov 2017), **d** accident NO.04 (22 Mar 2015), **e** accident NO.05 (17 Oct 2015)

### 5.3. Variation Characteristics of Wind Speed and Direction

When the wind speed near the surface is weak or static, the turbulence movement is weak. It easily causes accumulation of water vapor near the ground layer and thus forms fog. The change to low visibility is related to wind direction and water source location. During low visibility and persistence (Fig. 14), the wind speed was basically  $\leq 1.0$  m/s, and there were obvious water sources from the wind direction so that the water vapor was supplemented and strengthened. When the visibility gradually improved, the wind speed increased, the wind direction changed, water vapor transport became weaker and humidity decreased. Considering accident NO.01, there were obvious water sources in the east and south of this

accident location, such as Huai River, Qiujia Lake, Yuwest Lake and Longtan Reservoir (Table 1). The wind direction was easterly from 09:00 p.m. BJT the previous day to 02:00 a.m. BJT that day and then shifted to the south from 04:00 a.m. BJT to 06:00 a.m. BJT when the accident occurred. The easterly and southerly winds brought more moisture, causing the relative humidity to reach 97%. The visibility began to improve after 09:00 a.m. BJT, and the relative humidity decreased to  $< 80\%$ . The wind speed increased to  $> 2.0$  m/s, and the wind direction shifted to the west.

On the whole, the change of low visibility was closely related to wind direction. During the period of agglomerate fog explosive growth, the wind direction was in line with the direction of the water source,

which brought plenty of water vapor. During the dissipation period of agglomerate fog, the wind direction was mostly in the direction of no or fewer water sources, which was conducive to the dissipation of water vapor.

### 6. Conclusions and Discussion

1. The fog-related accidents in Anhui Province had obvious temporal and spatial distribution characteristics. The fog accidents mostly occurred from January to March and September to December, from 04:00 a.m. BJT to 10:00 a.m. BJT during the day and in the north-central part of Anhui Province along the Huai River Basin.
2. There were the stratification characteristics of temperature inversion and “upper-dry and lower-wet” near the surface layer for the five agglomerate fogs. Therefore, they all had the features of radiation fogs. Besides, during fog formation and persistence, there was warm advection below 950 hPa during all four agglomerate fogs except for accident NO.4. Therefore, all four agglomerate fogs were advection radiation fog, and the agglomerate fog in accident NO.4 was radiation fog.
3. Agglomerate fog can occur against the background conditions of fog or the coexistence of fog and haze, and it is more likely to occur when there is fog only. Sufficient water vapor conditions and a geographical environment with flat terrain and dense water network are also important factors in the occurrence of agglomerate fog. The uneven distribution of visibility intensity along the expressway is the major factor explaining why agglomerate fog affects traffic safety.
4. The main conditions that contributed to agglomerate fog formation include: relative humidity > 86%, daily temperature decrease > 8 °C and wind speed < 1 m/s. The formation and dissipation of agglomerate fog are closely related to the wind direction. During the period of explosive agglomerate fog growth, the wind direction is in line with the direction of the water source, while during the dissipation period, the wind mostly

blows from where there are no or fewer water sources.

5. In this article, the meteorological characteristics of agglomerate fog are analyzed based on five agglomerate fog accidents in Anhui Province, and some indicators of agglomerate fog forecast are established, which can provide a reference for agglomerate fog forecast and early warning. However, due to the limited sample data, more agglomerate fog accident data should be collected for further analysis and verification.

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### Data Availability

The fog accidents dataset from the year 2013 to 2018 which was obtained from the traffic control department were used under license for this study. So this dataset are not publicly available due to privacy restrictions. Besides, The agglomerate fog accidents dataset from the year 2014 to 2017, the weather dataset in Anhui Province and NCEP reanalysis data are available from the corresponding author upon reasonable request.

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