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Factors affecting relative humidity and its relationship with the long-term variation of fog-haze events in the Yangtze River Delta

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ABSTRACT

Relative humidity (*RH*) is one of the most important parameters in the study of fog-haze. This paper first estimates the contributions of the key quantities (temperature, water vapor, air pollutant) and their combinations to the relative change of *RH*, and then investigates the relationships of *RH* with the long-term variation of haze and fog days based on the meteorological data in the Yangtze River Delta over the period 1970–2010. The main conclusions are as follows. (1) Temperature is the foremost factor influencing *RH*, with the effect of specific humidity and direct contribution of air pollutant being second and third. (2) *RH* shows a prominent descending trend in the Yangtze River Delta, due to global warming and the 'analogous heat island effect' (AHIE). (3) Decreasing *RH* was responsible for the reduction of fog days. The AHIE can explain the phenomenon in which fog days in metropolises are less than in small cities. (4) Granger causality analysis of inter-annual variation further shows that increasing aerosol loading Ganger-causes the increasing haze days, rather than meteorological parameters such as RH. High *RH* would enhance hygroscopic growth of particle and then suppress the planet boundary layer height (*PBLH*) and lead to more haze days, lower *PBLH* further increases aerosols and *RH*, this positive feedback mechanism can be established under the condition of aerosol loading being relatively stable and beyond the threshold for haze formation. (5) If aerosol emissions maintain the status quo, climate cooling would result in serious fog-haze events occurring more frequently in Yangtze River Delta. The research provide a scientific basis for understanding the influence of meteorological factors on *RH* and the connection between the variation of long term fog-haze days and *RH* under the background of climate change.

1. Introduction

Under the background of global warming, emissions of anthropogenic aerosols have increased substantially in China over the last two decades due to rapid economic development and urbanization. (Richter et al., 2005; Yoon et al., 2011). Over the same period, an increase in haze days (Che et al., 2009; Zhao et al., 2011; Ding and Liu, 2014; Zhang et al., 2015a,b) and a reduction in fog days (Chen et al., 2006; Ding and Liu, 2014; Yin et al., 2015) have become progressively more common in China, especially in the densely populated economic zones of the Pearl River Delta, Yangtze River Delta, and Beijing-Tianjin-Hebe region. Many studies have been conducted to determine the causes and formation mechanisms of fog and haze, with the results showing that they are closely connected to pollutant concentrations, surface meteorological conditions, and climate change. On one hand, it has been found that fog formation can be enhanced by abundant water vapor (Niu et al., 2010), radiative cooling (Brown and Roach, 1976; Bergot and Guedalia, 1994), temperature inversions and stable weather (Zhang et al., 2005), adequate supply of aerosols as condensation nuclei (Sachweh and Koepke, 1995; Ming and Russell, 2004; Mohan and Payra, 2009), as well as climate change (Chen et al., 2006; Klemm and Lin, 2016). On the other hand, some conditions can lead to the occurrence of haze, such as the increase of primary and secondary aerosols (Li et al., 2010; Guo et al., 2014; Huang et al., 2014), aerosol hygroscopic growth (Kim et al., 2006; Pan et al., 2009; Fu et al., 2014) and gas-particle conversion (Shen et al., 2010; Yue et al., 2015). Climate

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change has also been found to affect haze occurrence (Jacob and Winner, 2009; Wang and Chen, 2016; Cai et al., 2017) including the maintenance of stable weather and atmospheric circulation (Xu et al., 2011; Zhao et al., 2013), and a weakened East Asia monsoon (Cao et al., 2015; Li et al., 2016). Despite the progress in identifying the potential factors affecting fog-haze events, determining the relative contributions of these factors to the development and evolution of fog-haze events remain a challenge.

Relative humidity (*RH*), defined as the ratio of actual vapor pressure to the saturated vapor pressure (Wallace and Hobbs, 2006), is one of the important factors in distinguishing fog and haze. Based on the criterion given by the China Meteorological Administration (CMA, 2003), when visibility is $<$ 10 km and $RH < 80\%$, the air condition is recognized as haze. When the visibility is $<$ 1 km and $RH > 90\%$, the air condition is defined as fog. *RH* is not only a key factor affecting fog and haze process but also plays an important role in the interactive transformation mechanism between them. The increase in anthropogenic aerosol emissions, global warming, urban heat island effect, and the variation of atmospheric water vapor all have an impact on *RH*. However, few studies have quantified the contribution of each factor, and their combinations, to the changes in *RH*. If the theoretical formula for the relationships between *RH* and single or multiple meteorological parameters can be deduced, a variety of sensitivity experiments could be conducted with different parameter combinations, and the results could be applied to investigate actual fog and haze historical trends, it would improve our understanding of the long-term changes in *RH* and fog-haze events.

In this study, we investigate the influences on *RH* of temperature, water vapor, aerosols, and their combinations in terms of their theoretical relationships. Taking the Yangtze River Delta as an example, a long-term dataset on temperature, humidity, fog days, and haze days are used to calculate the contributions of each parameter and their combinations to the relative change of *RH*. We identify the real causes of historical trends of fog and haze days based on the results. On this basis, the relationship between fog-haze events and *RH* under the background of climate change are determined, and possible further developments in climate cooling circumstances are predicted from the perspective of changes in *RH*.

2. Data sources, study area, and methodology

The study focus on the area of Yangtze River Delta during the period of 1970–2010. The dataset of temperature, visibility and *RH* are obtained from the National Meteorological Information Center (http://www.nmic.cn/web/channel-8.htm). The data they provided has been quality controlled to ensure the accuracy and reliability based on the international universal methods (Feng et al., 2004). According to the criterion issued by the CMA (2003) when the visual range is $<$ 10 km and $RH < 80\%$, conditions are recognized as haze, whereas when the visual range is $<$ 1 km and $RH > 90\%$, fog occurs. When *RH* is between 80% and 90%, the deterioration of visibility is caused by the interaction of haze and fog, but the main component is haze (Wu, 2006). Therefore, $RH = 90\%$ is used as the criterion to discriminate between fog and haze. The daily 08:00 sounding data in Nanjing from 1973 to 2010 comes from http://weather.uwyo.edu/upperair/sounding.html, daily maximum planet boundary layer height is estimated by Holzworth (1964) methods. The aerosol optical depth (AOD) data in Yangtze River Region are from Zhang et al. (2017) for the period of 1973–2010.

Granger causality analysis (Granger, 1969) is a statistical hypothesis test for determining whether one time series is useful in forecasting another. A variable X that evolves over time Granger-causes another evolving variable Y if predictions of the value of Y based on its own past values and on the past values of X are better than predictions of Y based only on its own past values. If X and Y are stationary time series after Augmented Dickey-Fuller (ADF) Test examination (Dickey and Fuller, 1979), Granger causality analysis can test whether the high correlation between X and Y has causality, which will help to reveal the interactive connections. Detailed information can be found in relevant literature (Granger, 1969).

The Yangtze River Delta is an economically developed area with a dense population, covering an area of 2. 107 $\times$ 10^5 km^2 including Shanghai, Jiangsu Province, Zhejiang Province, and Anhui Province. According to Guo et al. (2016), the criterion used to distinguish between a metropolis and a small city is based on the urban GDP and population in 2010. A metropolis has GDP over 100 billion RMB or a total population of more than 5 million. Based on these criteria, the cities of Shanghai, Nanjing, Hangzhou, Suzhou, Wuxi, Hefei and other 18 cities in the Yangtze River Delta can be classed as metropolises, the remaining urban areas are classified as small cities.

To calculate the relative change of *RH*, we selected the *RH* of a specific year as a reference and assumed that only one meteorological factor changes, while the others remains constant over the historical period. On the basis of the definition of *RH* (Wallace and Hobbs, 2006), the relative change can be defined as (calculated value-reference value)/reference value × 100%. For example, if *RH* for the reference year is 79%, the calculated *RH* is 80%, then the relative change is (80%–79%)/79% × 100% = 1.3%.

3. Theoretical analysis

Sensitivity experiments are designed to investigate the variation of *RH* with temperature, water vapor, and levels of gaseous pollutants. As shown in Fig. 1, two ideal boxes (Case 1 and Case 2) are considered. Case 1 represents the ideal atmosphere with temperature (T), water vapor mass (m_v) and dry air mass (m_d); Case 2 represents a polluted atmosphere that experienced an increase in temperature ($\triangle T$), water vapor ($\triangle m_v$), and gaseous pollutants ($\triangle m$) compared to the ideal atmosphere in Case 1. The pressure P is assumed to be the same for both cases.

Thus, *RH* in Case 1 (RH_1) is given by

$$RH_1 = \left[\frac{e}{\mathrm{k}e_s(T)}\right]_{p,t} \times 100\% \tag{1}$$

e and $e_s(T)$ are the actual and saturated vapor pressure, respectively. K is an enhancement factor that is used to indicate the deviation of the actual atmosphere from the ideal atmosphere ($\mathrm{k} \approx 1.004$, normal temperature and pressure). The water vapor mixing ratio r defined as the ratio of the water vapor mass (m_v) to dry air mass (m_d) is related to e with

$$r = \frac{m_v}{m_d} \approx \frac{\varepsilon e}{p} \tag{2}$$

where $\varepsilon = 0.622$. Combination of equations (1) and (2) yields

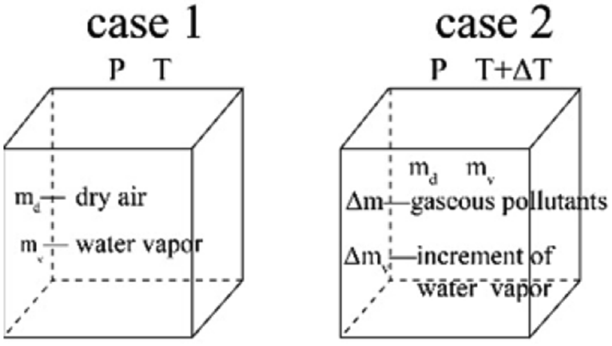

Fig. 1. Illustration of the two cases in the sensitivity experiment.