Science of the Total Environment 651 (2019) 1892–1902

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

How does El Niño-Southern Oscillation modulate the interannual variability of winter haze days over eastern China?

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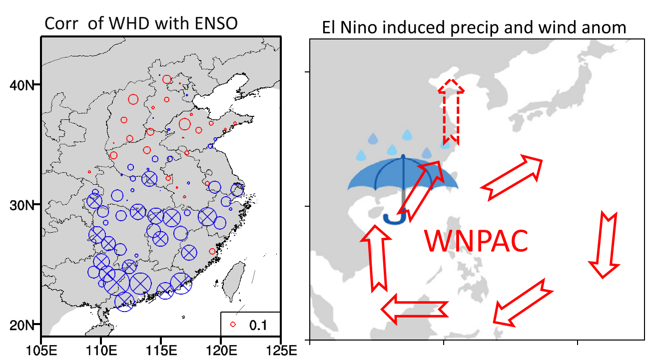
HIGHLIGHTS

- El Niño induces less (more) haze days over southern (North) China in winter.
- Deficient rainfall (southerly wind) anomaly favors haze over southern (North) China.
- WNP anticyclone anomaly links El Niño and interannual haze variability in China.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 15 August 2018
Received in revised form 7 October 2018
Accepted 8 October 2018
Available online 09 October 2018

Editor: Jianmin Chen

Keywords:
Winter haze days
Interannual variability
Meteorological condition
El Niño-Southern Oscillation

ABSTRACT

The haze pollution over eastern China has evident interannual variability. Based on the observed daily visibility at the meteorological stations from 1980 to 2018, the interannual variability of winter haze days (WHD) and its relation to El Niño-Southern Oscillation (ENSO) are investigated. ENSO has a significant negative modulation on the WHD over southern China (south of 30°N) and an insignificant positive modulation on the WHD over North China (north of 35°N). Based on the analyses on the haze-prone weather condition and climate variability conducive to excessive WHD anomaly at interannual time scale, anomalous subsidence with suppressed precipitation plays a dominant role for haze over southern China where wet deposition is the most important, while southerly wind anomaly plays a dominant role for haze over North China. An anomalous anticyclone (cyclone) over western North Pacific is stimulated by El Niño (La Niña) during its peak phase in winter, and the anomalous ascending (descending) motion on the northwestern flank of this anomalous anticyclone (cyclone) induces a significant excessive (deficient) precipitation over southern China, conducive to less (more) WHD over southern China during El Niño (La Niña) winters via wet deposition. The insignificant southerly (northerly) wind anomaly associated with weakened (enhanced) winter monsoon during El Niño (La Niña) is responsible for the slightly more (less) haze days over North China during El Niño (La Niña) winters.

1. Introduction

With the fast economic development of China, air pollution featured by haze has become a serious problem which is harmful for public

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https://doi.org/10.1016/j.scitotenv.2018.10.100
0048-9697/

health (Fu and Chen, 2017; Gao et al., 2017), traffic safety (Liu et al., 2016) and agriculture production (Tie et al., 2016). Eastern China is the most densely populated region in China and suffers from the severest haze pollution. Strong haze pollution usually occurs in winter (Gao and Li, 2015; Wang et al., 2018), such as the long-lasting and widespread haze in the January of 2013 (Wang et al., 2014; Zhang et al., 2014). Haze has a strong variability, in terms of decadal variability (Liao et al., 2015; Zhao et al., 2016; Wang and Chen, 2016), interannual variability (Gao and Li, 2015; Zhao et al., 2018) and intraseasonal variability (Wie and Moon, 2017; Zhou et al., 2017). Increased emission and worsened diffusion condition associated with climate change have both contributed to the decadal trend toward enhanced haze pollution (Wang and Chen, 2016; Xu et al., 2016; Yang et al., 2016; Zhao et al., 2016; Ding et al., 2017). But the pollutant emission is primarily subject to decadal change instead of interannual oscillation (Zhao et al., 2016), and cannot explain the strong interannual variability of haze events. The interannual haze variability probably originates from the meteorological condition modulated by the interannual climate variability, which is driven by the atmospheric internal dynamics (Cheng et al., 2016; Zhang et al., 2016; Gu et al., 2017), and the interaction of the atmosphere with land surface (Xu et al., 2016; Yin and Wang, 2018), sea ice (S. Li et al., 2017; Yin et al., 2017) and the ocean (Yin and Wang, 2016; S. Li et al., 2017; Zhao et al., 2018).

El Niño-Southern Oscillation (ENSO) is the dominant mode of global ocean-atmosphere interaction and the most important signal of interannual climate variability in the tropics. While previous studies confirmed that ENSO has a substantial modulation on the precipitation and temperature over East Asia through atmospheric circulation anomalies (Wang et al., 2000; Zhang et al., 2017; Yang et al., 2018), it is still inconclusive how ENSO modulates the haze pollution in China. There are two major difficulties in the study of the impact of ENSO on haze. First, the interannual climate variability is impacted by a variety of factors as stated above, and it needs a large number of samples (several decades) to extract the impact of ENSO on haze against the other factors. Second, there is no long-term direct observation on the air pollutant concentration or the air quality. The studies using direct observation of particulate matter concentration usually focus on one or two cases (e.g., Chang et al., 2016; Liu et al., 2017), limiting the robustness of the conclusion.

To date back to earlier decades, air pollution needs to be measured by the number of haze days based on the observation of visibility at meteorological stations. Recent studies paid attention to the modulation of ENSO on the air quality in East Asia by using visibility-based haze data (Gao and Li, 2015; S. Li et al., 2017; Zhao et al., 2018), but there are discrepancies among their conclusions. Gao and Li (2015) showed that the regional averaged winter haze days (WHD) over eastern China within about 25°–35°N is positively correlated with ENSO, whereas Zhao et al. (2018) argued that ENSO has a negative modulation on the regional averaged WHD over South China. S. Li et al. (2017) first showed the spatial pattern for the ENSO-WHD relationship, and claimed that the impact of ENSO on haze is limited to southern China. Although ENSO is the leading mode of interannual climate variability in the tropics and an important predictor of climate variability in East Asia (Yang et al., 2018), the mechanism how ENSO modulates haze over eastern China is not well addressed.

The prerequisite to understand the mechanism how ENSO modulates WHD is to find out the haze-prone weather and climate conditions. Based on previous studies, the meteorological factors conducive to haze include the weaker northerly wind of winter monsoon (Chen and Wang, 2015; Cheng et al., 2016; S. Li et al., 2017), higher humidity (Pei et al., 2018; Qian and Huang, 2019), lower boundary layer height (Zhang et al., 2016; Wang et al., 2018), enhanced low-level static stability (Xu et al., 2016, 2017), enhanced subsidence (Xu et al., 2016; P. Wu et al., 2017) and deficient precipitation (S. Li et al., 2017; Wie and Moon, 2017; Zhou et al., 2017). Previous studies explain the impact of ENSO on haze based on the fact that ENSO modulates some of these meteorological factors (e.g., precipitation anomalies or atmospheric circulation anomalies), without strictly examining whether the interannual haze variability is driven by these meteorological factors (S. Li et al., 2017; Zhao et al., 2018). The haze-prone weather condition may differ with the geographical location (Liao et al., 2018; Wang et al., 2018), and the haze-prone weather condition at synoptic scale may not be at work for WHD variability at interannual time scale. In this study, we aim at answering the following two questions: 1) What is the most important meteorological condition conducive to haze at interannual time scale over different parts of eastern China? 2) Through which atmospheric bridge does ENSO modulate the haze anomalies over eastern China?

The remainder of this paper is organized as follows. The data and methods are introduced in Section 2. The interannual variability of WHD and its relation to ENSO are addressed in Section 3. The dominant meteorological conditions responsible for haze and interannual haze variability are documented in Section 4, and the mechanism how ENSO modulates the WHD in eastern China is addressed in Section 5. Finally, the conclusion is summarized in Section 6.

2. Data and method

The following datasets are adopted in this study: 1) Daily observation at the meteorological stations over eastern China to the east of 109°E collected in Global Summary of Day (GSOD) dataset by National Climatic Data Center (NCDC). Totally 119 stations are available over the mainland of eastern China (Fig. 1a). 2) Daily and monthly reanalysis data on atmospheric circulation derived from ERA Interim reanalysis data ranging from 1979 to 2018 (Dee et al., 2011). The vertical resolution of ERA Interim data is 50 hPa in the troposphere, and the horizontal resolution is $2.5° \times 2.5°$ for the daily data and $0.75° \times 0.75°$ for the monthly data. 3) The monthly precipitation from version 2 of global precipitation climatology project (GPCP; Adler et al., 2003). 4) The monthly sea surface temperature (SST) data derived from Extended Reconstructed SST (ERSST) version 5 (Huang et al., 2017). The winters from 1980 to 2018 (actually from December of 1979 to February of 2018) are adopted for analysis, and the winter of a specific year is referred to as the December of the previous year to the February of the current year, for example, the winter for 2018 refers to December of 2017 and January and February of 2018. Bi-linear interpolation is performed to obtain the meteorological condition at the station from the gridded reanalysis and precipitation dataset when necessary. The Niño3.4 index, defined as the regional averaged sea surface temperature (SST) anomaly over 5°S-5°N, 170°-120°W, is adopted to measure the phase and intensity of ENSO.

Following previous studies, a haze day is defined as the daily mean visibility lower than 10 km and daily mean relative humidity lower than 90%, excluding fog, rain and snow as recorded in the GSOD data (Yang et al., 2016). As there are a few missing data at some stations, the number of haze days in winter (WHD) for a station in a year y ($y = 1980, 1981, \ldots, 2018$) is adjusted according to the percentage of the missing data for each station, based on the relationship of $WHD_y = N_y{*}90/M_y$, where M_y is the number of days without missing value from Dec 1 of the previous year to Feb 28 of the year y (M_y is no more than 90), and N_y is the number of days satisfying the criteria of a haze day within these M_y days. The WHD for the winters from 1980 to 2018 is calculated for each station, and the averaged WHD within the 39-year period for all the stations in eastern China is shown in Fig. 1a. The spatial distribution of the WHD climatology is consistent with previous studies based on the GSOD dataset (Yang et al., 2016) and other datasets (Zhao et al., 2018).

A substantial fraction of the stations are less polluted and the WHD in many years are zero, such as Shaoguan and Shenzhen airport station in Guangdong province (Fig. S1 in the Supplementary Information). These stations with any two consecutively zero WHD years are excluded, since the climate variability cannot effectively modulate