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Variations of Siberian High Position under climate change: Impacts on winter pollution over north China

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ABSTRACT

We examined the correlations between winter aerosol optical depth (AOD) in North China (NC) and three synoptic-scale meteorological indices from 2001 to 2016, including the Siberian High intensity (SHI), East Asian Winter Monsoon intensity (EAWMI), and the Siberian High Position index (SHPI). To separate the influences from meteorology and emissions, NC AOD was detrended by subtracting a linear increasing trend from 2001 to 2013 and a decreasing trend from 2014 to 2016, in correspondence with reported changes in Chinese anthropogenic emissions during the same period. The SHPI explains 37% of the variability in the detrended NC AOD and 83% of the high SHPI winters correspond to high AOD. By contrast, the SHI and EAWMI show little correlation with the observed AOD variability. To project the SHPI in the future climate, we used the ensemble of six global circulation models (GCMs) which were found capable of reproducing the climatic spatial distribution and the longitudinal variability of the Siberian High from 1956 to 2005. The ensemble results show that the frequency of high SHPI winters and consequently more polluted conditions would increase by 29%, 61%, and 100% under RCP2.6, RCP4.5 and RCP8.5 until 2099. There are 11 out of the 25 GCMs examined here that project the possibility of high SHPI conditions to increase under RCP8.5. This indicates changes in the Siberian High position induced by increasing global greenhouse gas (GHG) emissions can lead to more winter pollution in North China in the future.

1. Introduction

High levels of fine particulate matter with aerosol dynamic diameters equal to or less than 2.5 µm ($PM_{2.5}$) are not only associated with increased morbidity and mortality but also affect climate and economic activities (Lelieveld et al., 2015; Chen and Wang, 2015). Extreme haze events in winter have been on the rise during the past decade over the populous North China (NC) region, which can be attributed to the combined effects of increasing anthropogenic emissions and unfavorable weather conditions (Niu et al., 2010; Guo et al., 2011; Gao et al., 2016). Some severe haze events saw levels of $PM_{2.5}$ in many cities exceeded 500 µg/m^3, such as those occurred in January 2013, December 2015 and 2016 (Wang et al., 2014c; Wang et al., 2014a; Xue et al., 2016; Yin and Wang, 2017).

While pollutant emissions from human activities are the underlying cause for high $PM_{2.5}$ levels over NC, meteorological factors also play an important role (Huang et al., 2014; Zhang et al., 2014; Wang et al., 2014b). Many indices characterizing synoptic- or local-scale meteorological patterns have been proposed to explain the variability of winter air quality in NC. On the large scale, the East Asian winter monsoon (EAWM) is the most important circulation pattern over East Asia in winter, influencing the weather and climate in East Asia and even the whole Northern Hemisphere (Gong and Ho, 2002; Chernokulsky et al., 2013; Wang and Chen, 2014). The EAWM is characterized by the northwesterly winds along the coast of East Asia, which is caused by the pressure gradient between the Siberian High (SH) and the Aleutian Low (Chang and Lu, 2012). Wang et al. (2014b) calculated daily SH intensity index (SHI) in January 2013 and found during the haze period, the intensity of the SH is much lower than its climatic average from 1981 to 2010. Gao and Xiang (2015) analyzed winter haze days and the synoptic-scale circulation during 1981–2010 and found circulation patterns with a stronger SH and a stronger Aleutian Low were associated with fewer haze events. Our recent study (Jia et al., 2015) analyzed the anomalous circulation pattern during the severe haze month of January 2013 and established a Siberian High position index (SHPI) which shows good correlations with satellite-

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retrieved aerosol optical depth (AOD) - a good indicator of surface $PM_{2.5}$ - over NC from 2001 to 2013. The SHPI depicts the mean longitudinal position of the SH. High values of SHPI (e.g. the winter of 2003 and January 2013) were found to be associated with extremely high values of winter-mean and monthly-mean AOD over NC due to conditions of low wind speed and high relative humidity over NC. On the local scale, Cai et al. (2017) developed a haze weather index (HWI) using vertical temperature gradient, meridional wind speed on 850 hPa, and zonal wind speed on 500 hPa. They found 70% of the HWI > 1 days in winters from 2009 to 2015 were severe haze days in Beijing. Zou et al. (2017) defined a pollution potential index characterizing both horizontal and vertical ventilation capability, which correlates well with surface PM_{10} (fine particulate matter with aerosol dynamic diameters equal to or less than 10 μm) (r = 0.92) and $PM_{2.5}$ (r = 0.79) in Beijing on the interannual time scale from 1981 to 2015.

Many of the aforementioned indices including the SHPI were developed based on air quality and meteorological data during the period from as early as the 1960s to the early 2010s, during that time emissions of air pollutants in China have increased rapidly. In order to separate the effect of emissions from that of meteorology, our prior study (Jia et al., 2015) assumed that air pollution time series would feature a monotonically increasing trend as a result of increasing emissions. The departure from that trend would then be caused by meteorology-related variability. In that study, a linear trend was subtracted from the time series of AOD between 2001 and 2013 to minimize the influence of increasing emissions on the AOD variability.

However, Chinese anthropogenic emissions have started to decrease recently. The year at which the amount of emissions started to decrease may be different for different pollutants. For example, SO_2 levels were observed to decrease around 2007 due to the implementation of SO_2 emission reduction measures during the 11th Five-Year Plan (2006–2010) (Nickolay et al., 2016), whereas NOx emissions kept increasing during the same period (Wang et al., 2014b). The most recent landmark event is the publication and implementation of the Air Pollution Prevention and Control Action Plan in 2013. Ample evidence has been drawn from *in situ* and satellite data that showed noticeable decreases in SO_2 and NO_2 concentrations together with $PM_{2.5}$ levels after 2013 (Nickolay et al., 2016; Ronald, 2017; Li et al., 2017). Annual mean concentrations of SO_2, NO_2, and $PM_{2.5}$ over China in 2016 were found to be 35%, 12%, and 26% lower from their respective levels in 2014 (Li et al., 2017). Therefore, 2013 may be taken as the emission turning point for many air pollutants in China. As the aforementioned meteorological indices for air pollution were developed under the setting of increasing emissions, it is not clear whether they would still apply after 2013. Therefore, a purpose of this study is to answer this question by examining the record of some synoptic-scale meteorological indices developed previously over a longer time period, covering the most recent years after 2013. The meteorological indices to be examined here are all pertaining to synoptic-scale circulations, including SHI, SHPI, and the East Asian Monsoon intensity index (EAWMI).

These meteorological indices are particularly useful to project future air quality changes associated with different climate scenarios. A typical practice is to apply the observed relationships of air quality and meteorological indices to future projections of those indices from the ensemble of climate models. Cai et al. (2017) projected the future variation of HWI under Representative Concentration Pathway 8.5 (RCP8.5) and found the frequency of HWI will increase during 2050–2099 compared to 1950–1999, indicating the haze frequency in Beijing will become more severe under global warming. Tai et al. (2012) found the variations of annual mean $PM_{2.5}$ in the US is strongly correlated with synoptic periods on the interannual scale. Applying this relationship to the Global circulation model (GCM) ensemble mean results, they projected a weak increase of annual mean $PM_{2.5}$ over the eastern US and a weak decrease over the Pacific Northwest in the 2050s under the A1B scenario (rapid economic growth with a balance across all sources). Shen et al. (2017) quantified the influence of 2000–2050 climate change on $PM_{2.5}$ air quality across the contiguous US. They projected an increase of 0.4–1.4 μg/m^3 in annual mean $PM_{2.5}$ in the eastern US and a decrease of 0.3–1.2 μg/m^3 in the western US by the 2050s. Long-term observational $PM_{2.5}$ data are not available over NC due to the lack of *in situ* surface measurements. Previous studies have shown high temporal and spatial correlations between AOD and *in situ* $PM_{2.5}$ and as such, satellite-derived AOD has been widely used as a good indicator of surface $PM_{2.5}$ (Wang and Christopher, 2003; Ma et al., 2014; Xie et al., 2015; Li et al., 2015). Xie et al. (2015) found moderately high correlations (0.6) between daily AOD from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor and $PM_{2.5}$ at surface monitors in Beijing. Over the North China Plain region, the correlation between MODIS AOD and ground-based $PM_{2.5}$ in winter was reported as 0.59 (Guo et al., 2017). Thus, we used AOD retrieved from MODIS as the proxy data to represent the interannual variations of $PM_{2.5}$. Winters with high AOD (detrended AOD > 0) were defined as polluted winters. This study also projects future changes in NC AOD caused by projected future changes in the synoptic-scale indices following three RCPs (RCP2.6, RCP4.5, and RCP8.5).

The paper is organized as follows. Section 2 describes the data and methods used in the analysis. In section 3, we examine whether SHPI, SHI and EAWMI correlate with winter air quality over NC during the period of 2001–2016 covering both increasing and decreasing emissions. Section 4 evaluates GCMs in simulating the SH and from the evaluation, six GCMs are selected to project the future change of SHPI under RCP2.6, RCP4.5, and RCP8.5. We also examine the variations of SHPI in the historical runs forced by different forcings to discuss the potential reasons for high SHPI conditions.

2. Data

2.1. Aerosol optical depth and in situ $PM_{2.5}$

We used level-3 monthly gridded AOD at 550 nm retrieved from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor aboard both NASA EOS-Terra and Aqua satellite as the proxy data to represent the long-term variations of surface $PM_{2.5}$. The data are from December 2000 to February 2016 with a 1° × 1° resolution. The AOD values over bright surfaces were replaced by the Deep Blue aerosol retrieval (550 nm) at the same grid. MODIS AOD were obtained from NASA website (ftp://ladsweb.nascom.nasa.gov/allData/51).

To verify the variations of AOD in the recent years from 2014 to 2016, during which time AOD over NC shows a large decrease, we also analyzed *in situ* $PM_{2.5}$ over NC. The observational hourly $PM_{2.5}$ data are available at http://www.pm25.in/since November 2013. Similar to our previous study, the NC region is delineated by longitude from 115° E to 123° E, and by latitude from 30° N to 42° N. In situ $PM_{2.5}$ observations from 46 cities in NC were used for the verification of NC AOD. The average $PM_{2.5}$ for a city may contain several monitoring sites. For example, the average of 12 monitoring sites in Beijing is taken as the average $PM_{2.5}$ in Beijing.

2.2. Meteorological data and CMIP5 model results

We obtained meteorological parameters from National Centers for Environmental Prediction (NCEP) reanalysis (Kalnay et al., 1996) to calculate the meteorological indices and test their correlations with winter air quality in recent years. The variables include sea level pressure (SLP) and 850 hPa wind field with a resolution of 2.5° × 2.5°. The NCEP reanalysis data provide a historical record of more than 50 years from 1948 (Kistler et al., 2001), and were obtained from NOAA website (http://www.esrl.noaa.qov/psd/data/gridded/).

We also selected SLP projected by 25 GCMs that participated in the Coupled Model Intercomparison Project Phase 5 (CMIP5) and provided outputs from all three RCPs. Table 1 describes the general information