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Influence of the West Pacific subtropical high on surface ozone daily variability in summertime over eastern China

Zijian Zhao [a], Yuxuan Wang [a, b, *]

[a] Department of Earth System Science, Tsinghua University, Beijing, China
[b] Department of Earth and Atmospheric Sciences, University of Houston, Houston, TX, United States

HIGHLIGHTS

- EOF analysis reveals the dominant component of ozone variability in eastern China is a marked north-south contrast.
- A stronger WPSH is associated with lower ozone in South China but with higher ozone in North China.
- This south-north difference can be explained by changing moisture transport associated with the WPSH variability.

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ABSTRACT

The West Pacific subtropical high (WPSH), as one of the most important components of the East Asian summer monsoon (EASM), is the key synoptic-scale circulation pattern influencing summertime precipitation and atmospheric conditions in China. Here we investigate the impacts of the WPSH on surface ozone daily variability over eastern China, using observations from recently established network of ozone monitors and meteorology reanalysis data during summer (June, July, August; JJA) 2014–2016 with a focus on 2014. An empirical orthogonal function (EOF) analysis of daily ozone variations reveals that the dominating eigenvector (EOF1), which contributes a quarter (25.2%) to the total variances, is a marked north-south contrast. This pattern is temporally well correlated ($r = -0.66$, $p < 0.01$) with daily anomalies of a normalized WPSH intensity index (WPSH-I). Spatially, the WPSH-I and ozone correlation is positive in North China (NC) but negative in South China (SC), which well correlates with the ozone EOF1 pattern showing the same north-south contrast ($r = -0.86$, $p < 0.01$). These associations suggest the dominant component of surface ozone daily variability in eastern China is linked with the variability of the WPSH intensity in that a stronger WPSH leads to a decrease of surface ozone over SC but an increase over NC and vice versa. This is because a stronger WPSH enhances southwesterly transport of moisture into SC, creating such conditions not conducive for ozone formation as higher RH, more cloudiness and precipitation, less UV radiation, and lower temperature. Meanwhile, as most of the rainfall due to the enhanced southwesterly transport of moisture occurs in SC, water vapor is largely depleted in the air masses transported towards NC, creating dry and sunny conditions over NC under a strong WPSH, thereby promoting ozone formation.

1. Introduction

Ozone is an important air pollutant and poses health and ecology problems on the ground level (Jacob and Winner, 2009; Kinney, 2008). Surface ozone concentrations depend on both emissions and meteorological conditions. Meteorological factors such as UV radiation, temperature, relative humidity (RH), and winds can influence ozone photochemical formation and dispersion processes (Bloomfield et al., 1996; Camalier et al., 2007; Leibensperger et al., 2008). High temperatures, typically associated with stagnant and sunny conditions, usually lead to high ozone events (Davis and Speckman, 1999; Steiner et al., 2010). As an indicator of atmospheric moisture, RH often shows a negative correlation with surface ozone (Elminir, 2005). Since the meteorological factors are not independent to each other but rather interconnected at certain spatiotemporal scales, the occurrence of high surface ozone

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* Corresponding author. Department of Earth System Science, Tsinghua University, Beijing, China.
E-mail address: ywang246@central.uh.edu (Y. Wang).

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concentrations cannot be attributed to one or few meteorological factors individually. For example, the synoptic-scale circulation patterns such as cold fronts, jet winds, and high-pressure systems have been identified as meteorological drivers affecting surface ozone variability (Chen et al., 2008; Shen et al., 2015; Zhu and Liang, 2013; Wang et al., 2016).

Previous studies have suggested that air quality over a large portion of East China in summer is subject to influences from the East Asian summer monsoon (EASM hereafter), and that these influences depend on the strength and tempo-spatial extension of the monsoon (Ding et al., 2013; Sun et al., 2016; Worden et al., 2009; Yamaji et al., 2006). On interannual scales, Yang et al. (2014) found a strong positive correlation between the EASM index and summer mean ozone over China during the period of 1986–2006 when the effects of changing anthropogenic emissions were removed. Wang et al. (2009) and Zhou et al. (2013) revealed that ozone enhancements in the free troposphere over coastal South China were associated with monsoon-induced transport of pollutants that originated from continental anthropogenic and biomass burning sources. At the surface, ozone exhibits a bi-modal seasonality in regions with strong EASM influences: monthly mean ozone peaks first in late spring (Apr or May), followed by a drop in the middle of summer (July and August) and the second peak in the fall (Sep or Oct). Such a summertime trough has been attributed to the influence of the EASM circulation (Li et al., 2007; Luo et al., 2000; Xu et al., 2008; Wang et al., 2008; Zheng et al., 2010). Through modeling analysis, Wang et al. (2011) suggested that the summer trough was resulted from a reduction in background ozone brought by the inflow of clean maritime air mass associated with the southeasterly monsoonal winds. While these studies clearly demonstrate the linkage of tropospheric ozone with the EASM on the interannual and seasonal scales, the extent to which the EASM impacts the daily ozone variability has yet to be characterized.

The West Pacific subtropical high (WPSH hereafter), as one of the most important components of the EASM, is the key synoptic pattern controlling daily weather conditions in east China during the monsoon season (Wang et al., 2006). The EASM begins to establish in late May and migrates to its most northern position by mid August. The northward migration of the EASM occurs in a stepwise fashion, characterized by two northward jumps of the WPSH and the related rain belt in mid-June and late-July (Su et al., 2014). This intraseasonal variability of the WPSH is related to the heat-induced unstable Rossby waves and the convective activities in the warm pool region (Chen et al., 1993; Lau and Peng, 2010; Su et al., 2014). The WPSH has thus been suggested as a key factor controlling the general areas of rain production in summer over east China (Gao et al., 2015; Liu et al., 2008). Liu et al. (2008) and Wang et al. (2006) demonstrated that the WPSH anomaly was responsible for the daily to sub-monthly regional weather anomalies linked with the extreme rainfall events over the Yangtze River Delta (YRD) region during the 1998 great flood in the Yangtze River basin. Since the position and intensity variations of the WPSH can change the regional temperature, precipitation, and wind conditions, they are expected to exert significant influences on ozone levels in east China. As a case study, He et al. (2012) found that ozone mixing ratios in a summer month at a surface site near Shanghai were often higher during the days when the center of the WPSH was located to the southeast of that site with a weaker intensity. Except for few cases, the daily-scale linkage of surface ozone with the WPSH variability in east China has not been systematically examined over the course of a summer season. In this study we will establish that such a linkage is significant on a daily scale, using ozone observations from the recently-established, extensive surface network in China. A mechanistic understanding of the factors responsible for the WPSH-ozone association will then be developed.

The rest of the paper is organized as follows. Section 2 describes the data source and methodology. Here daily variables of surface ozone and meteorological conditions during June, July, and August (JJA) are used to analyze the connection between the WPSH and ozone from 2014 to 2016, with a focus on 2014. Several indices for the WPSH are evaluated in order to characterize its variations. Section 3 summarizes summertime surface ozone distributions over east China and presents the spatial pattern of ozone daily variability using the empirical orthogonal functions (EOFs). Section 4 investigates the WPSH relationships with surface ozone on the daily scale. In Section 5, we analyze the mechanisms of the WPSH-ozone relationship. Section 6 discusses the drawbacks and potential implications.

2. Data and methodology

2.1. Ozone and meteorological observations

Hourly surface ozone concentrations were obtained from the China Ministry of Environment Protection (MEP, http://datacenter.mep.gov.cn/index). This data became available as an open dataset since 2013. The original unit of the MEP ozone observations is μg/m^3, which we converted to mixing ratios (unit: ppbv) using a constant temperature of 25 °C and pressure of 1013.25 hPa. There are 191 cities in China with ozone monitors in the dataset. If a city has more than one ozone monitors, they are averaged to represent mean ozone concentration of that city. Maximum daily 8-hour average (MDA8) ozone was calculated using hourly surface ozone mixing ratios. The following analysis uses MDA8 ozone of 191 cities in China during JJA (92 days) from 2014 to 2016, with a focus on 2014.

The meteorological data from 2014 to 2016 were obtained from the National Centers for Environmental Prediction (NCEP) Reanalysis dataset (Kalnay et al., 1996) and the European Center for Medium-Range Weather Forecasts (ECMWF) Reanalysis Interim (ERA-Interim) (Simmons et al., 2007). The NCEP and ERA-Interim Reanalysis data have a horizontal resolution of 2.5° × 2.5° and 0.5° × 0.5°, respectively, including mean daily geopotential height, meridional and zonal wind, RH, total cloud cover, downward UV radiation at the surface, 24-hour mean air temperature, and total precipitation amount per day.

2.2. WPSH index

Fig. 1 presents the climatological (1986–2005 mean) isolines and wind fields over the western Pacific in summer at 500 hPa. The

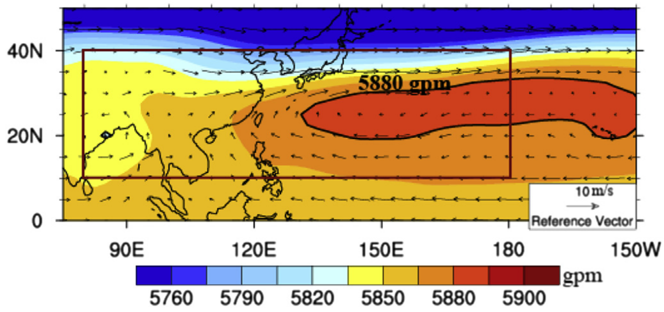

Fig. 1. The climatological position of the characteristic WPSH isoline and wind fields in summer at 500 hPa (measured by contour line for 5880 gpm). The red rectangle outlines the region used in the definition of WPSH-I. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)