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Impact of the Western North Pacific Subtropical High on summer surface ozone in the Korean Peninsula

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ABSTRACT

The Western North Pacific Subtropical High (WNPSH) is a crucial circulation system affecting the East Asian summer monsoon region including the Korean Peninsula, but its linkage to surface ozone (O_3) has not been revealed. This study aimed to reveal the relationship between the WNPSH and O_3 levels across the Korean Peninsula. For this purpose, a linear regression analysis was performed to assess WNPSH-related variations in observed O_3 concentrations at 151 air quality monitoring sites during 2001–2015. The results showed that enhanced WNPSH contributed to the observed increase in O_3 levels during summer (June-July-August), with the opposite trend during weakened WNPSH years. We found that anomalous precipitation due to altered circulation patterns mainly contributed to changes in O_3 level. This implies that summer O_3 in Korea is highly sensitive to interannual atmospheric variability. Our results may be useful for revealing the effects of climate variability on air quality in the East Asian region.

1. Introduction

Tropospheric ozone (O_3) is a gaseous air pollutant formed by solar radiation through photochemical reactions involving its precursors, such as methane (CH_4), nitrogen oxides (NO_x), carbon monoxide (CO), and volatile organic compounds (VOCs). O_3 has strong oxidizing power and is a main air pollutant that causes photochemical smog under strong shortwave radiation. High concentrations of O_3 have adverse health effects (Anenberg et al., 2009; Bell et al., 2007), such as irritation of the lungs, skin, and eyes, and detrimental impacts on agricultural crops (Avnery et al., 2010, 2011; Teixeira et al., 2011; Wang and Mauzerall, 2004). With its short-term timescale, O_3 also contributes to global warming as a greenhouse gas and is hence considered one of the short-lived climate pollutants (Akimoto et al., 2015; Scovronick et al., 2015).

The level of O_3 in East Asia has increased over the past decades mainly due to increases in anthropogenic emissions of O_3 precursors (Allen et al., 2012; van der A et al., 2008; Wang et al., 2012). This elevated O_3 over East Asia can affect O_3 concentrations and air quality over adjacent regions (Nagashima et al., 2010), even on a global scale (Akimoto, 2003; Verstraeten et al., 2015). Recently, several studies have focused on the influence of meteorological factors on O_3 concentration (He et al., 2008; Li et al., 2007; Lin et al., 2009), and suggested that the weakening of monsoon circulations would aggravate the pollution problem over China (Zhao et al., 2010). Consequently, weakened monsoon leads to the reductions in the northward penetration of ozone-poor marine air masses, which in turn lead to higher O_3 concentrations.

South Korea, one of the most heavily populated countries, is also experiencing a recent rise in surface O_3 concentrations and the occurrence of severe O_3 episodes during summer (Han et al., 2013), which is associated with the downward transport of O_3 and its precursors (Kim and Chung, 2005; Oh et al., 2010). Similar to other monsoon-affected regions, surface O_3 over South Korea exhibits a spring/autumn maximum followed by a summer minimum (Ghim and Chang, 2000), indicating that summer O_3 concentration in South Korea can be strongly modulated by summer monsoonal flow (Wie and Moon, 2016). Therefore, comprehensive understanding of the impacts of monsoon circulation on interannual variations of summertime O_3 in South Korea is required to guide environmental policies.

The Western North Pacific Subtropical High (WNPSH) is a prime circulation system significantly influencing summer precipitation in East Asia including Korea (Lee et al., 2013; Lee et al., 2006; Wang et al., 2013; Xiang et al., 2013). Therefore, the WNPSH is expected to influence not only meteorological conditions in the Korean Peninsula but also surface O_3 concentrations during summertime. Little attention, however, has been given to this relationship.

Here, we investigated the impact of the WNPSH on summer surface

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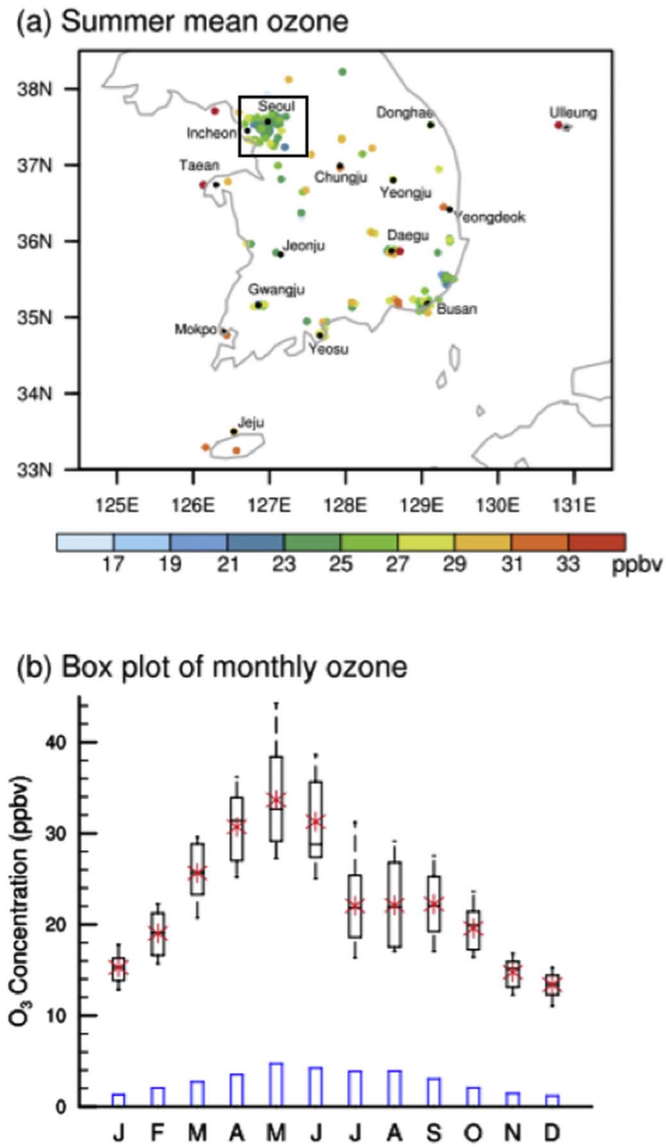

Fig. 1. (a) Distribution of summer (JJA) daily average ozone (p0pbv) observed at 151 sites in the Korean Peninsula during the period 2001–2015. The rectangular box indicates the Seoul Metropolitan Area. Black dots indicate the locations of cities. (b) Boxplots for each month of the monthly average ozone. The heights of the boxes indicate the interquartile range (25–75%) whereas the line and asterisk inside each box show the median and mean, respectively. The vertical whiskers represent the range of the daily mean ozone. The lower bars represent the standard deviation of the monthly mean ozone concentrations.

O_3 in the Korean Peninsula. To quantify the variability of WNPSH, we used the interannual pulse of the WNPSH. Section 2 presents the analysis data and method. Section 3 discusses the analysis results of the observed data on surface O_3 in the Korean Peninsula in summer. Finally, the findings are summarized in Section 4.

2. Data and method

Hourly observations made by the Korea Environment Corporation (KECO, http://airkorea.or.kr) from 2001 to 2015 were used as surface O_3 data. The KECO provides O_3 and nitrogen dioxide (NO_2) mixing ratios in ppbv, measured by the ultraviolet photometric and chemiluminescence methods, respectively. We selected 151 air monitoring sites over South Korea, based on data availability for the period of 2001–2015. These data were first converted into daily mean values, and both the monthly and summer (June-July-August, JJA) means were used depending on the purpose of the analysis. The meteorological data are monthly fields derived from the National Centers for Environmental Prediction–Department of Energy (NCEP-DOE) Reanalysis 2 (NCEP2) with a resolution of 2.5° × 2.5° (Kanamitsu et al., 2002). For precipitation, CPC Merged Analysis of Precipitation (CMAP) data with a resolution of 2.5° × 2.5° were used (Xie and Arkin, 1997). For verification of the results of CMAP data, in-situ precipitation data from 59 weather stations of the Korea Meteorological Administration (KMA) for the same period were used.

According to Wang et al. (2013), the WNPSH index is defined as the normalized summer 850 hPa geopotential height anomalies averaged over the region (115°E–150°E, 15°N–25°N) using the NCEP2 data. This WNPSH index represents a crucial variability of East Asia summer monsoon (He and Zhou, 2014) and is significantly related to the spatial distribution of precipitation in East Asia (Lee et al., 2013). To identify the statistical relationship between the WNPSH index and O_3 concentration, linear regression analysis was performed, which determines whether one variable is associated with another variable (Wilks, 2011).

3. Results

3.1. Surface ozone in the Korean Peninsula

Fig. 1a illustrates the distribution of the summer (JJA) mean surface O_3 concentration in the Korean Peninsula obtained from the values observed at 151 stations. The JJA mean surface O_3 concentration was 25.6 ppbv, and concentrations exceeding 31.0 ppbv appeared in coastal areas such as Incheon, Taean, Mokpo, Jeju, and Ulleung-do. Ozone concentrations were relatively low over metropolitan areas such as Seoul and Busan where relatively high NO_2 concentrations occur due to anthropogenic emission, reflecting NO_x titration effects (Ghim and Chang, 2000). Consistently, a recent observational study in Korea has also suggested that regions with relatively lower O_3 concentrations correspond to those with relatively higher NO_2 concentrations (Seo et al., 2014).

Surface O_3 concentration in the Korean Peninsula peaked in May (Fig. 1b), probably due to the effects of insolation with less cloud cover before the onset of the East Asian summer monsoon (Jeong and Park, 2013). In June and July, O_3 concentrations appear to be summer minimum, a common feature in the East Asian summer monsoon region (He et al., 2008). It should be noted that the strongest interannual variability of O_3 concentration in Korea is found during summertime, implying a strong O_3 sensitivity to WNPSH variations (e.g., Wie and Moon, 2016). Thus, we focus on the effect of WNPSH variability on summer O_3 concentrations in the Korean Peninsula in the following discussion.

3.2. Impact of the WNPSH on summer ozone in Korea

The WNPSH index was defined using the method described by Wang et al. (2013), who argued that WNPSH variability can be used to predict the East Asian summer monsoon and tropical cyclone path. At first, the NCEP2 850 hPa geopotential height anomalies during the period 1979–2015 were obtained and then normalized after calculating the time series of JJA means over the region 115°E–150°E, 15°N–25°N. This region shows the maximum interannual variability in the subtropical Pacific as shown in Fig. 2a, indicating that the position and intensity of monsoonal front vary with changes in the WNPSH (Sui et al., 2007). In

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