Atmospheric Environment 194 (2018) 14–30

Contents lists available at ScienceDirect

Atmospheric Environment

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

Quantifying impacts of crop residue burning in the North China Plain on summertime tropospheric ozone over East Asia

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ARTICLE INFO

Keywords:
Crop residue burning
Tropospheric ozone
North China Plain (NCP)
Statistical modeling
Ozone pollution

ABSTRACT

Crop residue burning has been proved to have negative impacts on regional atmospheric environment. In this study, an evidence-based statistical modeling framework was established to quantify potential impacts of crop residue burning in the North China Plain (NCP) on summertime tropospheric ozone increase over East Asia during 2004–2016. To assess the intensity of crop residue burning, fire occurrence counts derived from the MODerate-resolution Imaging Spectroradiometer onboard the Terra and Aqua satellites were used as a proxy. Additionally, another six factors were employed as potent explanatory variables. Maximum covariance analysis was first applied to decouple spatiotemporal interactions between tropospheric ozone and each explanatory variable. Based on the decoupled modes, multivariate linear regression (MLR) and artificial neural network (ANN) were used to establish statistical relationships between tropospheric ozone and contributing factors, respectively. The results indicate that the ANN-based modeling scheme enables to approximate the observed tropospheric ozone variations better than MLR. Further investigations reveal that the summertime crop residue burning in the NCP is the predominant factor contributing to the observed additive tropospheric ozone increases over East Asia, yielding extra 8% tropospheric ozone elevation on average in June. Moreover, UV radiation and wind also played critical roles in modulating the observed tropospheric ozone variations therein. In general, the critical role of crop residue burning over the NCP in modulating summertime tropospheric ozone increase over East Asia have been well demonstrated based on the proposed evidenced-based modeling framework.

1. Introduction

Unlike stratospheric ozone present at high altitudes where it protects Earth from the harmful ultraviolet radiation, tropospheric ozone is commonly deemed “bad ozone” due to its adverse impacts on public health (Ebi and McGregor, 2008; Jerrett et al., 2009; Lim et al., 2013), agriculture (Wittig et al., 2009; Ainsworth et al., 2012), ecosystems (Wittig et al., 2009; Ainsworth et al., 2012; Yue and Unger, 2014), and climate (Skeie et al., 2011; Shindell et al., 2012; Myhre et al., 2013; Stevenson et al., 2013). Scientific investigations revealed that concentrations of tropospheric ozone are controlled primarily by photochemical processes associated with ozone production and destruction, as well as deposition and atmospheric diffusion. Specifically, ozone-related photochemical processes are influenced primarily by ozone precursors and meteorological factors such as winds, temperature and humidity (e.g., Jacob et al., 1993; Sillman and Samson, 1995; Neftel et al., 2002; Menut, 2003; Bärtsch-Ritter et al., 2004; McMillan et al., 2005; Dawson et al., 2007; Lou et al., 2015). Atmospheric diffusion alters the distribution of ozone and its precursors at a scale ranging from regional to inter-continental and even hemispheric-scale through long-range transport (e.g., Lin et al., 2014; Derwent et al., 2015), stratosphere–troposphere exchange (Cristofanelli et al., 2010), seasonal transport patterns (Safieddine et al., 2015), and climate variability (Lin et al., 2014). With respect to ozone-related photochemical processes, precursors such as nitrogen oxides (NO_X), volatile organic compounds (VOCs), and carbon monoxide (CO) have been proven to play a critical role as their relative amounts in the atmosphere largely control the production of tropospheric ozone (Sillman, 1999; Sillman and He, 2002). In general, surface anthropogenic emissions from industry and automobiles, emissions from fires, and natural emissions are deemed as three primary sources of these ozone precursors (Turquety et al., 2007; Guenther et al., 2012; Huo et al., 2012; Jaffe and Wigder, 2012; Monks

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https://doi.org/10.1016/j.atmosenv.2018.09.018
Received 20 January 2018; Received in revised form 8 September 2018; Accepted 11 September 2018
Available online 15 September 2018
1352-2310/

et al., 2015).

A variety of studies found that biomass burning could significantly affect tropospheric ozone variations nearby the burning regions and their potential associations have been well investigated around the world, e.g. over Southeast Asia (Liu et al., 1999; Deng et al., 2008; Lin et al., 2009a; Toh et al., 2013; Yadav et al., 2017), especially in Indonesia (Thompson A.M., 2001; Duncan et al., 2003; Chandra et al., 2009; Zhang et al., 2011), tropical Africa (Mauzerall et al., 1998; Martin et al., 2002; Sauvage et al., 2005; Jourdain et al., 2007; Real et al., 2010), India (Kumar et al., 2011; Sarangi et al., 2014; Sinha et al., 2014), Siberia (Jaffe et al., 2004; Verma et al., 2009; Konovalov et al., 2011), South America (Watson et al., 1990; Jonquières et al., 1998; Schultz et al., 1999), North America (Val Martín et al., 2006; Parrington et al., 2012, 2013; Alvarado et al., 2015), and Europe (Amiridis et al., 2012; Cristofanelli et al., 2013). In general, these studies focused primarily on forest fires (Kaufman et al., 1992; Real et al., 2007; Yokelson et al., 2009; Alvarado et al., 2010; Akagi et al., 2012) and savanna fires (Kaufman et al., 1992; Sanhueza et al., 1999; Chandra et al., 2002; Trentmann et al., 2005).

As one distinct type of biomass burning, crop residue burning can also yield large amounts of ozone precursors, which may result in significant tropospheric ozone variations in turn. Nevertheless, the impacts of crop residue burning on regional tropospheric ozone variations have been seldom evaluated relative to forest and savanna fires (Stohl et al., 2007; Li et al., 2008; Yamaji et al., 2010; Ding et al., 2013; Kanaya et al., 2013; Tang et al., 2013; Pan et al., 2015; Stavrakou et al., 2016; Lu et al., 2017), especially in those agricultural dominated economies like China where crop residue burning is salient. As a major wheat production region, the North China Plain (NCP) plays a critical role in wheat yield in China (Huang et al., 2012). However, due to the lack of cost-efficient crop residue recycling technologies, the wheat residue and straw are oftentimes burnt directly in farmland after the wheat harvest from late May to June (Huang et al., 2012; Xue et al., 2014).

By taking advantage of atmospheric chemistry transport models and ground-measured air pollutant emissions from field campaigns, Li et al. (2008) and Yamaji et al. (2010) revealed that crop residue burning over the southern part of the NCP could result in about 37.9% and 26% surface ozone increases at the summit of Mount Tai in June 2006, respectively. Similar results were also evidenced in Kanaya et al. (2013). Likewise, Stavrakou et al. (2016) and Lu et al. (2017) found that crop residue burning could result in 7% increases of the maximum surface ozone in June 2010 over the NCP and accounted for 18% surface ozone formation in the autumn of 2013 in Wuhan, respectively. In addition to model simulated results, associations between crop residue burning and tropospheric ozone variations were also examined by making use of satellite observations (Dufour et al., 2010) and *in situ* measurements (e.g., Li et al., 2007; Ding et al., 2008; He et al., 2008; Lin et al., 2008, 2009b; Meng et al., 2009; Wang et al., 2010; Tang et al., 2013; Pan et al., 2015).

By referring to spatial and temporal variations of tropospheric ozone nearby the NCP and the number of fire occurrence counts (derived from the MODerate-resolution Imaging Spectroradiometer, MODIS) detected in the NCP (Fig. 1), a very tight spatiotemporal coincidence was revealed between the regional tropospheric ozone peaks and the maximum number of fire occurrence counts detected therein. Given the fact that such a vast area of biomass burning could release ample amount of air pollutants like NO_X, VOCs and CO that are often deemed as ozone production precursors (Guo et al., 2004; Yan et al., 2006; Zhang et al., 2008; Suthawaree et al., 2010; Huang et al., 2012; Li et al., 2016; Wu et al., 2016), in conjunction with the observed spatial and temporal coincidence patterns, we may deduce that there is a potential linkage between the observed summertime tropospheric ozone increase and crop residue burning in the NCP.

To demonstrate this hypothesis, impacts of crop residue burning in the NCP on regional tropospheric ozone variations observed nearby should be quantitatively evaluated. Toward such a goal, evidenced-based statistical modeling frameworks were established between the observed tropospheric ozone and a set of potent explanatory variables, including UV radiation, wind speed, air temperature, boundary layer height and relative humidity, in addition to satellite detected fire occurrence counts (as a proxy for the intensity of crop residue burning). Moreover, estimated NO_X emission inventories over China were also employed to examine the associations between crop residue burning and tropospheric ozone variations since NO_X is one important precursor for ozone production besides others like VOCs. The following science questions could be answered by this study: (1) is there any linkage between crop residue burning in the NCP and the summertime tropospheric ozone increase over East Asia? and (2) if so, to what extent can the observed tropospheric ozone increase be explained by crop residue burning? Our hypothesis is that before prominent crop residue burning, the ozone photochemical reaction process over East Asia is primarily limited by NO_X concentrations, and thus the elevated NO_X concentrations resulting from crop residue burning would accelerate ozone photochemical processes and in turn yield regional tropospheric ozone increase.

2. Data sources

2.1. Tropospheric ozone column data

As one conventional algorithm proposed by Fishman et al., in 1990, the tropospheric ozone residual method (TOR) has been widely used to derive tropospheric column ozone (TCO) by subtracting the stratospheric column ozone (SCO) from the total column ozone (Fishman et al., 1990, 2003; Chandra et al., 2003). Although there are several other techniques available for the derivation of TCO from satellite observations, e.g., the modified residual method (Hudson and Thompson, 1998), the UV radiance scan angle method (Kim et al., 2001), the topography differencing method (Newchurch et al., 2001) and the Convective Cloud Differential (CCD) method (Ziemke et al., 2009), TOR provides tropospheric ozone products with better spatial and temporal coverage and is thus widely used (Ziemke et al., 2014).

Compared with total column ozone products, tropospheric column ozone are rarely provided due to instrumental and algorithmic constraints. At present, there are few tropospheric column ozone products available to the public. One data set is a multi-sensor integrated record by combining the CCD method derived tropospheric column ozone from the first Global Ozone Monitoring Experiment (GOME-1) onboard ERS-2 (1995–2011), the Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) onboard ENVISAT (2002–2012) and the second Global Ozone Monitoring Experiment (GOME-2) onboard MetOp-A/MetOp-B (2007-present) over tropics (20°S-20°N) (Leventidou et al., 2016). Another one is derived from the Ozone Monitoring Instrument (OMI) and the Microwave Limb Sounder (MLS) through the TOR method, providing continuous monthly tropospheric ozone over 60°S–60°N from the late August 2004 to present.

In this study, the monthly OMI/MLS tropospheric column ozone product was employed to resemble spatiotemporal variations of tropospheric ozone over East Asia from October 2004 to September 2016 (Table 1). The product is derived by subtracting the SCO (derived from MLS measurements) from the total column ozone (derived from OMI measurements) after adjusting the inter calibration differences between these two instruments through the convective-cloud differential method (Ziemke et al., 2006). OMI and MLS are two critical instruments onboard the Aura satellite. As a nadir-scanning instrument, OMI provides near global coverage total column ozone data at a nadir resolution of 13 km × 24 km, by detecting backscattered solar radiance from visible (350–500 nm) and ultraviolet (UV) wavelength channels (UV-1: 270–314 nm; UV-2: 306–380 nm) (McPeters et al., 2008). The MLS instrument is a thermal-emission microwave limb sounder that measures vertical profiles of mesospheric, stratospheric, and upper tropospheric