Seasonal variation in surface ozone and its regional characteristics at global atmosphere watch stations in China

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ABSTRACT

We investigated the seasonal and spatial ozone variations in China by using three-year surface ozone observation data from the six Chinese Global Atmosphere Watch (GAW) stations and tropospheric column ozone data from satellite retrieval over the period 2010–2012. It is shown that the seasonal ozone variations at these GAW stations are rather different, particularly between the western and eastern locations. Compared with western China, eastern China has lower background ozone levels. However, the Asian summer monsoon (ASM) can transport photochemical pollutants from the southern to the northern areas in eastern China, leading to a northward gradual enhancement of background ozone levels at the eastern GAW stations. Over China, the tropospheric column ozone densities peak during spring and summer in the areas that are directly and/or indirectly affected by the ASM, and the peak time lags from the south to the north in eastern China. We also investigated the regional representativeness of seasonal variations of ozone at the six Chinese GAW stations using the yearly maximum tropospheric column month as indicator. The results show that the seasonal variation characteristics of ozone revealed by the Chinese GAW stations are typical, with each station having a considerable large surrounding area with the ozone maximum occurring at the same month. Ozone variations at the GAW stations are influenced by many complex factors and their regional representativeness needs to be investigated further in a broader sense.

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Introduction

Tropospheric ozone (\(O_3\)) is an important trace gas involved in the process of atmospheric photochemistry. Ozone has a negative impact on human health and the environment. Furthermore, due to its interactions with both solar and terrestrial radiation, ozone can generate radiative forcings and lead to changes in climate (Heck et al., 1982; Weinstock, 1972; Wofsy et al., 1972; Lee et al., 1996; Shindell et al., 2012; IPCC, 2014). Key factors that influence the seasonal and spatial variations of ozone in a specific region include horizontal inflows and outflows via long-range transport, vertical stratospheric-to-tropospheric transport, photochemical production and destruction, and deposition on the Earth’s surface (Logan, 1985; Ma et al., 2002c). Whereas pollution episodes usually happen in populated and industrialized areas, high concentrations of ozone and its precursors, i.e., nitrogen oxide (\(NO_x\)), carbonic oxide (\(CO\)), and volatile organic compounds (\(VOCs\)), are exported continuously from their emission sources to receptor regions far downwind on regional, intercontinental, and even hemispheric scales (Stohl, 2004; Monks et al., 2009; HTAP, 2010).

In recent decades, several regions of China have experienced high ozone episodes and increasing trends; among these, especially high ozone levels have been linked to elevated regional precursor emissions (Lin et al., 2008; Ding et al., 2013a, 2013b; Xue et al., 2014; Gao et al., 2016; Ma et al., 2016; Wang et al., 2017). Driven by planetary-scale atmospheric circulations, long-range transport of ozone from outside of China contribute to the region’s background ozone levels (Ma et al., 2002c; Wang et al., 2011; Li et al., 2014). More importantly, as a monsoon climate state, China is significantly influenced by the Asian summer monsoon (ASM). Numerous studies have shown that clean marine air masses are transported to mainland China via ASM circulation. This effect is commonly accompanied by clouds and precipitation, in which dilution, clearing, and depletion of ozone and its precursors occur in the directly affected areas. However, this transport process also promotes ozone production in indirectly influenced areas downwind (Ma et al., 2002a; He et al., 2008; Liu et al., 2009; Worden et al., 2009; Zhao et al., 2010; Zhu, 2012; Tang et al., 2013; Zhou et al., 2013; IPCC, 2014; Yang et al., 2014; Safieddine et al., 2016).

To date, network monitoring has been used to obtain the spatial distribution and long-term temporal variation in surface ozone. The Global Atmosphere Watch (GAW) program of the World Meteorological Organization (WMO) has been one of the key international initiatives in long-term monitoring of the atmosphere and its chemical and physical properties. In China, there are six GAW stations, including one global (Waliguan) and five regional (Xianggelila, Akedala, Lin’an, Shangdianzi, and Longfengshan) GAW stations. The surface ozone concentration readings differ considerably among the six stations. For example, the surface ozone concentrations at the Waliguan station, located in the northeastern part of the Tibetan Plateau, show maximum levels in summer and minimum levels in winter (Luo et al., 1996; Ma et al., 2002c; Xu et al., 2016), whereas at the Xianggelilla station, located in the southeastern part of the Tibetan Plateau, maximum and minimum levels are achieved in the spring and summer, respectively (Ma et al., 2014). The Akedala station is located in the northwest China Plain, where surface ozone peaks in spring and reaches its lowest in autumn (Lin et al., 2010). In contrast, the Lin’an, Shangdianzi, and Longfengshan stations are located in the polluted areas of Southeast, mid-eastern, and Northeast China, where the peak ozone concentrations appear in spring, spring/summer, and autumn, respectively (Xu et al., 1998, 2008, 2011; Wang et al., 2001; Lin et al., 2008; Meng et al., 2009; Ma et al., 2016). Long-term observations at these stations show that the variation trends and amplitudes of ozone differ not only among stations but also seasonally at the same station (Xu et al., 2008, 2018).

Ozone data from these stations, especially those with long-term observation, i.e., Waliguan and Lin’an, have been frequently used to evaluate the abilities of atmospheric chemical transport models in simulating seasonal variation characteristics of surface ozone in China (Wang and Mauzerall, 2004; He et al., 2008; Emmons, 2010; Wang et al., 2011; Li et al., 2014). These include both regional and global models, with horizontal resolutions ranging from a few tens to hundreds of kilometers. As for the simulations of monthly ozone variation, each model is biased to degrees against the station observations. While some chemical and physical processes require clarification in the models, the regional representativeness of seasonal ozone variation at these GAW stations are of great concern. This is also important for fully understanding the ozone seasonal–spatial variation characteristics and their major influencing factors over China.

Besides, due to the outstanding advantage in spatial coverage and temporal consistency, satellite remote sensing ozone observation is a widely recognizable method to achieve tropospheric ozone density (Xu and Lin, 2010; Zhao et al., 2010; David and Nair, 2011; Seinfeld and Pandis, 2016; Liu and Ma, 2017).

In this study, three-year (2010–2012) observations of ozone at the six Chinese GAW stations, along with corresponding satellite remote-sensing observation data, are used to analyze seasonal and diurnal ozone variations. Eventually, regional characteristics and representativeness for ozone seasonal variation at each station are revealed via comparisons between surface ozone observations at GAW stations and tropospheric ozone column data from satellite retrieval. Section 1 describes the data and methods adopted in our study. ASM circulation and pollution distribution in China are generally overviewed in Section 2. In Section 3, we analyze the surface ozone variations at each GAW station. In Section 4, we investigate the seasonal variations in tropospheric ozone column over China, and compare them with the variations in surface ozone at the GAW stations. Section 5 evaluates the regional representativeness of ozone seasonal variations at each GAW station using tropospheric ozone columns from satellite retrieval. The conclusions are presented in Section 6.

1. Data and methods

1.1. Surface ozone at GAW stations

In this research, the global GAW station Waliguan is hereafter referred to as WLG, and the five regional GAW stations, Xianggelila, Akedala, Lin’an, Shangdianzi, and Longfengshan,
as XGLL, AKDL, LN, SDZ, and LFS, respectively. WLG, XGLL, and AKDL are in remote areas of western China; more specifically, WLG and XGLL are located in the northeast and southeast Tibetan Plateau, respectively, and AKDL is located in northwestern China. Within 30 km of all the six stations, there are very low population and rarely any villages, and thus insignificant anthropogenic sources of ozone precursors. WLG and LFS are situated on the hill summits, and XGLL is located in the hinterland of mountains, whereas SDZ is situated on the south slope of a hill and north hill side of a valley with a northeast–southwest orientation. AKDL and LN are located in flat ground. LN, SDZ, and LFS are located in eastern China. Geographical locations, latitudes, longitudes, and altitudes of each station are shown in Fig. 1.  

1.2. Tropospheric columns of ozone and CO from satellite observations

Monthly averaged tropospheric ozone column density data were obtained from GSFC/NASA (https://acd-ext.gsfc.nasa.gov/Data_services/cloud_slice/new_data.html). This data set was derived from the total (Ozone Monitoring Instrument (OMI) Level 3 products with 30% cloud filtering) and stratospheric (Microwave Limb Sounder (MLS) Level 2 products) ozone columns and calibrated by the convective cloud difference (CCD) method (Ziemke et al., 2006). Calibration tropospheric ozone column data have a horizontal resolution of 1.25° × 1° and are expressed in Dobson units (DU). OMI and MLS are two of the four sensors onboard the Aura spacecraft, which is flown in a sun-synchronous polar orbit at an altitude of 705 km with 98.2° inclination. The spacecraft has an equatorial crossing time of 1:45 pm (Beijing time) and takes ~98.8 min per orbit (14.6 orbits per day, on average).

As a key precursor for tropospheric ozone, CO has a long lifetime of 30–90 days, and can be taken as tracer for the photochemical production and long-range transport of ozone from pollution sources. The Measurements Of Pollution In The Troposphere (MOPITT) sensor onboard the Terra spacecraft with preferable observation performance for tropospheric CO has a spatial resolution of 22 × 22 km at nadir; its sensitivity appears higher in the daytime and in the thermal infrared radiation (TIR) band (Deeter et al., 2007). As such, the daytime observation (equatorial crossing time: 1:45 pm) Level 3 monthly tropospheric CO data for the TIR band were used in this study (ftp://l5eil01.larc.nasa.gov/MOPITT/MOP03TM.006). The products (with global horizontal resolution of 1° × 1°) undergo 30% cloud filtering before public release; given units of mol/cm², the relationship 1 DU = 2.69 × 10¹⁶ mol/cm² was used to convert the data to DU.

1.3. Meteorology

Six-hour total cloud cover data from ECMWF global reanalysis datasets (horizontal resolution: 0.125° × 0.125°) were used in cloud filtering analysis of surface observation data at each GAW station.

2. General overview of the ASM circulation and columnar CO in China

It is well-known that monsoons are prominent in summer and winter, and transition patterns happen in spring and fall....
over China region. The winter monsoon has higher wind speeds than the summer monsoon does, the latter brings sufficient vapor to the China region (Webster et al., 1998; Wang et al., 2011; Ding, 2013).

Due to its long lifetime and various emission sources including fossil fuel combustion and biomass burning, CO can be taken as an indicator of pollution level for a wide spread area (Lewis et al., 2007; Xu et al., 2011). Owing to the transport of polluted air masses to the downwind directions, positive correlations between \( O_3 \) and CO appear in most time in China, especially in warm seasons (Liu and Ma, 2017). The correlations can reflect the chemical transport process of \( O_3 \), and the positive correlations can reflect the ozone production rates of pollution source area when polluted air masses is mixed with clean background air (Kim et al., 2013). Fig. 2 presents seasonal variations in tropospheric column CO densities over China in 2011. High CO densities were found in eastern China where LN, SDZ, and LFS are located. In contrast, CO densities were much low in western China, where AKDL, WLG, and XGLL are located, especially for WLG and XGLL in the Tibetan Plateau.

3. Variations in surface ozone at GAW stations

3.1. Seasonal variations

Fig. 3 presents monthly variations of surface ozone mixing ratios at each GAW station during 2010–2012. Although both stations are located in the Tibetan Plateau, seasonal variation patterns of ozone at WLG and XGLL are entirely different. Compared with other stations, ozone mixing ratios at WLG kept at higher levels throughout the year with a peak in summer, which is probably due to the abundant ozone transported downward from the upper troposphere and lower stratosphere (Ma et al., 2005). However, there are still many debates on whether anthropogenic pollution or stratospheric intrusion plays a more dominant role (Zhu et al., 2004; Ma et al., 2005; Ding and Wang, 2006; Wang et al., 2006a; Xue et al., 2011; Li et al., 2014). In contrast, XGLL exhibited an ozone mixing ratio trough in summer, as a result of lower ozone air masses and much more cloud cover and precipitation caused by the Indian Ocean monsoon, a part of the Asian monsoon (Ma et al., 2014). Persistent enhanced ozone was observed at AKDL from February to June, owing to strong stratospheric ozone intrusions in spring at a higher latitude (Hsu and Prather, 2009), followed by a decline in July.

There were two peaks at LN during the year: a major peak in May and a minor peak in October, associated with active photochemical production in the spring and autumn over the surrounding region (Xu et al., 2008). Compared with other stations, the summer ozone mixing ratios at LN were lower, mainly due to the influence of clean marine air masses from the northwestern Pacific brought by the ASM (Ma et al., 2002c). Surface ozone at SDZ showed a summer peak in a yearly cycle. Under the control of the ASM, ozone and its precursors are transported continuously from the southwest of North China to the station and accumulate in the SDZ region; the accumulation is accompanied by photochemical production (Wang et al., 2006a; Lin et al., 2008; Xu et al., 2011; Sun et al., 2016; Liu and Ma, 2017). Similarly, LFS exhibited an ozone peak in June due to the influence of transport from North China and the mid-southern region of Northeast China (Xu et al., 2009; Liu and Ma, 2017). The sudden drop of ozone mixing ratios after July at LFS is caused by the stratospheric ozone

Fig. 2 – Seasonal variations in tropospheric column CO densities over China (unit: DU). (a) spring, (b) summer, (c) autumn, and (d) winter.
intrusions associated with western jet streams, which experience springtime maximum and summertime minimum in mid-latitudes (Koch et al., 2006).

In general, the three stations in eastern China uniformly exhibit the patterns of higher ozone in spring and summer and lower ozone in cold season autumn and winter, whereas the three remote stations in western China show different seasonal patterns due to the complex influencing factors.

3.2. Diurnal variations

Fig. 4 shows the seasonal diurnal variations of surface ozone mixing ratio at each station over the three-year period 2010–2012. The diurnal cycles of surface ozone exhibit similar patterns at each station in all the seasons, implying similar factors that influence the variations throughout the year. On the other hand, the diurnal variations have different characteristics among the stations. Ozone mixing ratio consistently attained troughs in the early morning and peaks in the afternoon at LN, SDZ and LFS, reflecting the significant influence of photochemical production (Ma et al., 2002a; Xu et al., 2008); Long-range transport is also responsible for ozone variations over these regions (Xu et al., 1998, 2008; Ma et al., 2002c; Lin et al., 2008, 2010; Xu and Lin, 2010; Ge et al., 2012). In summer, SDZ experiences the highest daytime ozone mixing ratios among all the stations, reflecting the significant photochemical reactions and transport within the North China Plain (Xu et al., 2011). The valley–mountain breeze circulation plays an important role in the diurnal cycle of surface ozone at WLG. At this location, upslope winds dominated by the boundary layer air masses prevail during the daytime, and at night downslope winds bring free tropospheric air masses, resulting in increased ozone during the nighttime (Ma et al., 2002b; Xu et al., 2016). Ozone levels at XGLL and AKDL increased gradually over the course of the morning and reached a peak in the early afternoon. Such diurnal variation pattern is similar to those found for eastern stations (LN, SDZ, and LFS), but the causes are different. Specifically, the diurnal variations of ozone at XGLL and AKDL are influenced dominantly by vertical and horizontal transport (Lin et al., 2010; Ma et al., 2014).

The daily amplitude (i.e., the difference between the maximum and minimum in a diurnal cycle) of ozone mixing ratio is significantly lower for the stations located in western China than for those in eastern China. Surface ozone levels are influenced by both ozone production and transport (Lin et al., 2008). Due to the extremely limited emissions of ozone precursors, photochemistry production rarely affects ozone

Fig. 3 – Monthly variations in surface ozone mixing ratios at each GAW station. (a) WLG, (b) XGLL, (c) AKDL, (d) LN, (e) SDZ, (f) LS.
diurnal variations in western China, especially in the Tibetan Plateau. Conversely, photochemistry plays a key role in ozone diurnal variations in eastern China, where anthropogenic emissions of ozone precursors are very high (Ma et al., 2002c; Wang et al., 2006b). All of the above can explain the difference in the ozone daily amplitude between eastern and western stations in China (Lin et al., 2008).

Nighttime ozone mixing ratios at the two Tibetan Plateau stations (WLG and XGLL) are large among all the stations during most seasons, showing lower free tropospheric ozone levels to some degree. High nighttime ozone can also be found at AKDL during spring and winter, as a result of the low NOx levels at night in the two seasons (figure not shown). Notably, ozone levels from midnight to early morning (0:00–6:00) rank from low to high as follows: LN, SDZ, and LFS during spring and summer, due not only to NO titration for its higher values during nighttime (figure not shown) but also to northward elevation of background ozone in China associated with the transport from the southeastern and mid-eastern China to northeastern China via the ASM. Additionally, stratospheric ozone intrusion has stronger influences on background ozone at higher latitudes than at lower latitudes.

4. Variations in tropospheric ozone column and the comparison with surface ozone at GAW stations

4.1. Seasonal variations in tropospheric ozone column over China

Fig. 5 presents seasonal variations in tropospheric column ozone densities over China in 2011. In summer, most areas in eastern China experienced high-level ozone, above 44 DU. Under the control of the ASM, ozone and its precursors are continuously transported to the mid- to high-latitude areas north of 35°N, where they accumulate and undergo photochemical reactions with intense ultraviolet radiation, leading to severe ozone pollution (Liu and Ma, 2017). However, ozone declines significantly in the mid- to low-latitude areas south of 35°N in summer due not only to dilution by clean marine air masses but also to ozone photochemical depletion with large amounts of water vapor (Ma et al., 2002c). In mid- to low-latitude areas, tropospheric column ozone densities are comparable to those in summer and much lower than those in spring, whereas in mid- to high-latitude areas they are much lower than those in summer. Over all of China, tropospheric column ozone densities in winter are the lowest of the year.

4.2. Comparison in seasonal variation pattern between tropospheric ozone column and surface ozone at GAW stations.

To evaluate if the tropospheric ozone columns can reflect the seasonal variations in surface ozone over China to a certain extent, we compare surface ozone mixing ratios measured at each GAW station with satellite retrieval ozone data. Two data processing steps are necessary. First, the GAW station data around the satellite crossing time were selected at one hour interval. Second, because the satellite products have undergone 30% cloud filtering, total cloud cover data were used to extract the surface data under clear-sky conditions. Subsequently, monthly averages at that time interval were calculated for the sake of comparison with monthly satellite retrieval data.
Fig. 6 presents the comparisons of tropospheric ozone column densities with surface ozone mixing ratios at each station. Generally, the two datasets are in good agreement, with highly significant correlation coefficients ($r$) of 0.597, 0.563, 0.466 and 0.808 at WLG, AKDL, LN, and SDZ, respectively, and a significant correlation of 0.363 at LFS. The lower correlation at LFS might be because ozone column is more frequently affected at higher altitudes than near the ground, e.g. stratospheric ozone intrusions associated with western jet streams. Therefore, the comparisons between surface and satellite-retrieved ozone are more reasonable when the surface influence counts for more. Over all, the tropospheric column ozone densities from satellite retrieval can reflect the seasonal variations in surface ozone at GAW stations.

5. Regional representativeness of ozone seasonal variations at GAW stations

We investigated the appearing months with the maximum tropospheric ozone column density for each grid (with a resolution of $1.25^\circ \times 1^\circ$) in China using monthly satellite retrieval ozone data. The geographical distributions of the 'maximum ozone' months are similar among the years during 2010–2012 and the results for 2011 is shown in Fig. 7. As shown in Fig. 7, the ozone maximum appeared mostly in the spring months over the areas south of 30°N, and in summer in the areas north of 30°N. It is very interesting to see that the same ozone maximum month can be found in a considerable large surrounding area for each station, indicating that all these GAW stations have a regional representativeness of ozone seasonal variation.

The ozone maximum occurred in June in a small narrow area including WLG (Fig. 7). The subsidence of upper tropospheric ozone over a limited area in the northeast Tibetan Plateau seems to be the major cause of this summer ozone peak (Ma et al., 2005). Ozone from Siberia–Mongolia, central Asia, and Europe can be transported upward to the free troposphere via such meteorological mechanisms as the thermal transmission belt, deep convection, and horizontal transport. Ozone from the stratosphere can also make a contribution via stratosphere-to-troposphere exchange over the Tibetan Plateau (Wang et al., 2006b).

XGLL is located at the southeastern edge of the Tibetan Plateau, where tropospheric ozone peaks in May, in accordance with the wide rectangular region to the south of it. In spring, near-surface transboundary transport of polluted air masses, accompanied by photochemical reactions of ozone precursors, can make a dominant contribution to the springtime ozone peak at XGLL. Upper-level long-range transport and the subsequent downward transport of polluted air masses originating from Europe and western Asia may also contribute significantly to tropospheric ozone levels at XGLL (Ma et al., 2014). Vertical transport over XGLL includes the stratosphere-to-troposphere transport and the subtropical jet stream over the Tibetan Plateau, which prevail in all seasons except summer, when the ozone density declines to trough levels due to increased cloud cover and precipitation and the descent of the mixing layer as result of the ASM (Ma et al., 2014; Yin et al., 2017).
AKDL, which is located outside ASM-influenced areas, experiences a tropospheric ozone density peak in April, in line with the northwest-southeast narrow area surrounding it. High-speed northwest winds over AKDL (Lin et al., 2010) transport ozone precursors from the upwind direction, along with polluted air masses.

LN, SDZ, and LFS are three stations in eastern China. LN is located in the northeast corner of southeast China and is directly impacted by the ASM. Ozone in a large area of southeast China including LN peaks in May prior to ASM arrival, when photochemical reactions dominate the contributions to its variation (Xu et al., 2008). Once the ASM begins, ozone is significantly decreased on the entire southeast coast of China including LN due to the marine air masses from the northwest Pacific (Ma et al., 2002a, 2014; Xu et al., 2008; Ding et al., 2013a). The maximum ozone at SDZ appears in July, the same as in a large area to its west. Compared with other seasons, warmer polluted air masses in summer from the North China Plain are transported to SDZ under higher local wind speeds, produces contributing more ozone mainly by direct ozone transport (Lin et al., 2008; Meng et al., 2009; Xu et al., 2011; Ge et al., 2012). LFS experiences an ozone peak in July, in accordance with the small area downwind north of it. In summer, local photochemistry controls the ozone levels at LFS, with air masses at lower wind speeds in the lower altitudes being transported northward from the mid-south of Northeast China and North China (Xu et al., 2009). SDZ and LFS are both located in the areas indirectly influenced by the ASM, which brings southern air masses with ozone precursors, accelerating ozone production at mid- to high latitudes (He et al., 2008; Liu and Ma, 2017).

Fig. 6 – Comparisons of surface ozone and satellite retrieved tropospheric ozone column densities at each station. (a) WLG, (b) XGLL, (c) AKDL, (d) LN, (e) SDZ, (f) LFS.
Fig. 8 presents the wind dependency map of surface ozone mixing ratio at each GAW station in the ‘maximum ozone’ months. Although high ozone is found in each sector from WLG in June, the highest one is in the ENE sector which Xi’ning and Lanzhou located in, conforming with the observations by Wang et al. (2006b). As a result of Indian summer monsoon, surface ozone is significant higher in the W-S sector from XGLL in May. AKDL experiences the highest surface ozone influence from the W-NNW sector in April, reflecting the ozone transport from the upwind directions. As for LN in May, surface ozone is the lowest in the ESE sector that ASM starts founding, whereas ozone is dominantly higher in the S-SW sector with relatively large amount of anthropogenic emission. For SDZ in July, surface ozone is dominantly higher from the SSW-W sector, to which the large area of the North China Plain is located. Surface ozone in July from the SW-SSE sector at LFS is higher, reflecting the significant influence in the southern direction. As a whole, the wind dependency of surface ozone mixing ratio at each GAW station is in line with what has been shown in Fig. 7, conforming the regional representativeness of seasonal ozone variation at these stations.

6. Conclusions

Using 2010–2012 data from surface ozone observations at the six GAW stations in China (WLG, XGLL, AKDL, LN, SDZ, and LFS) and from tropospheric column ozone satellite measurements, seasonal ozone variation at each station and its regional characteristics have been analyzed, and the regional representativeness of seasonal ozone variations have been evaluated.

The influences exerted by the ASM, Tibetan Plateau atmospheric circulation, stratosphere-to-troposphere transport, and long-range transport are different among stations, resulting in differences in the seasonal ozone variation among the three remote stations in western China (WLG, XGLL, and AKDL). On the other hand, seasonal ozone variations at the three stations in eastern China (LN, SDZ, and LFS) are impacted by Asian monsoon circulations and pollution transport from the southern to the northern areas in eastern China, leading to a northward gradual enhancement of background ozone levels at the eastern GAW stations. Moreover, higher surface ozone background levels are found at western stations than at eastern stations due to larger influences of air masses from the upper troposphere and stratosphere in western China.

The monthly averaged surface ozone mixing ratios at each GAW station are shown to have highly significant correlation with the monthly averaged tropospheric column ozone densities from satellite retrieval, indicating that the latter can reflect the seasonal variations in surface ozone in much more extended areas. The tropospheric column ozone densities peak during spring and summer in the areas that are directly and/or indirectly affected by the ASM, and the peak time lags from the south to the north in eastern China. Specifically, the ozone maximums appear mostly in spring in the areas south of 30°N and in summer in the areas north of 30°N. It is found that the seasonal variation characteristics of ozone revealed by the Chinese GAW stations are typical, with each station being included in a considerable
It should be noted that the regional representativeness of ozone seasonal variation at a GAW station mentioned in this study does not mean that ozone observed at the station originates from this area. Instead, it indicates that ozone at the station may be controlled by the same factors as that over its surrounding area. The above research results are significantly instructive in revealing the sources of and variations in surface ozone at GAW stations and in identifying methods to evaluate the performance of various models via GAW station data. It’s also helpful to identify the regional representativeness of the observation data at GAW stations.

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**Fig. 8** - The wind dependency map of surface ozone mixing ratio at each GAW station in the ‘maximum ozone’ months. (a) WLG, (b) XGLL, (c) AKDL, (d) LN, (e) SDZ, (f) LFS.


