Space-borne and ground observations of the characteristics of CO pollution in Beijing, 2000–2010

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ABSTRACT

Both the long-term and short-term variability of carbon monoxide (CO) pollution in Beijing metropolitan area, China are studied with 11 years of MOPITT observations and 10 years of ground measurements. The impact of the 2008 Beijing Olympic Games on regional air quality is also examined. MOPITT CO columns exhibit different temporal patterns from ground CO concentration measurements. MOPITT CO column in August has gradually increased from 2000 to 2007, even though ground level CO concentrations have significantly decreased due to continued local air pollution control effort. Both CO columns and ground CO concentrations were reduced due to strict albeit temporary emissions control measures from July to September 2008 to support the Beijing Olympic Games. However, the reduction of total CO columns (∼13%) was less pronounced than ground CO concentration (∼44%), indicating that local emission control effort was partially offset by the continuously deteriorating regional air quality. In addition, MOPITT CO mixing ratio profiles indicate a significant regional pattern at higher altitudes. CO total columns after 2008 show an overall increasing trend, in contrast to the decreasing trend observed in ground measurements.

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1. Introduction

Carbon monoxide (CO) is a toxic gas produced as a by-product of combustion. Inhaling even relatively small amounts of the gas can lead to hypoxic injury, neurological damage, and even death. On average, exposures at 100 ppm or greater is dangerous to human health (Prockop and Chichkova, 2007). The heart is one of the most sensitive organs to hypoxia caused by carbon monoxide. Carbon monoxide exposure may lead to a significantly shorter life span due to heart damage (Henry et al., 2006). In addition, CO plays a central role in atmospheric chemistry by acting as the largest sink of hydroxyl radicals and through its role in the production of ozone. Therefore, it has a major influence on the oxidizing power of the atmosphere and the global composition of air pollutants.

CO is one of the criterion ambient air pollutants in China. The Beijing municipality has made significant efforts to improve air quality during the 2008 Summer Olympic Games and Paralympic Games. From July 20 to September 20, multiple control measures were enforced including removing approximately one-half of the on-road vehicles (∼1.5 million) off the road on alternate days

under an even-odd license plate system, temporarily closing or limiting the production of major polluting industries, temporarily shutting down construction activities and coal-burning boilers, and enhancing street cleaning. In addition, emission control measures were implemented in neighboring Tianjin municipality, Hebei, Shanxi, Shandong provinces, and Inner Mongolia Autonomous Region during this period (Fig. 1).

Major anthropogenic sources of CO emissions in China include industry, residential heating, and transportation (Zhang et al., 2009b). As of September 2010, there are over 4.5 million on-road vehicles and over 22 million permanent residents in Beijing (http://gs.people.com.cn/GB/183355/12754795.html, http://www.chinadaily.com.cn/china/2010-02/26/content_9511839.htm, accessed on October 31, 2010). In addition, combustion of approximately 30 million tons of coal for power and heating supply (2007 value) in Beijing (http://www.bjstats.gov.cn/tjnj/2009-tjnj/content/mV69_0404.htm, accessed on October 31, 2010) also contributes to the CO pollution in Beijing. CO is considered as an important indicator of overall air quality of Beijing. To date, the variability of ground level CO in Beijing has been studied using one-year worth of measurements (Xue et al., 2006), but the interannual variability of CO total column and its relationship with ground level CO as well as CO vertical distribution have not been reported. We characterized the spatial and temporal distribution of column CO concentrations over Beijing retrieved by the
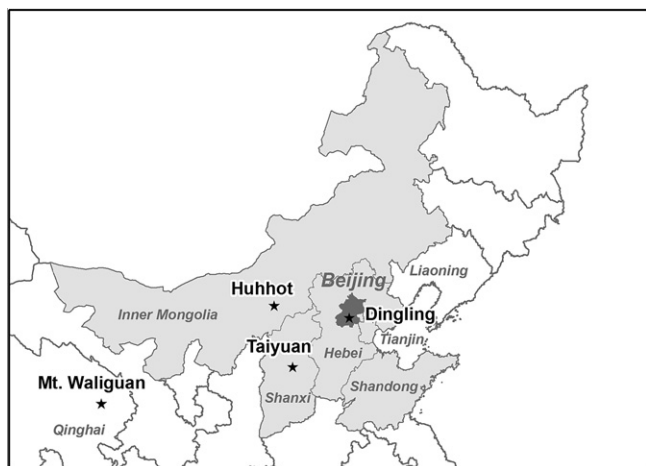
Fig. 1. Locations of the study sites (Dingling as the Beijing background, Huhhot near major coal-burning power plants, Taiyuan in major coal production region, and Mt. Waliguan as the continental background). Temporary emissions control measures during the 2008 Summer Olympic Games were taken in Beijing (dark grey region) and the surrounding provinces (light gray regions).

Measurement of Pollution in the Troposphere (MOPITT) instrument between 2000 and 2010, and compared with ground measurements. In addition, we also compared the CO trend in Beijing with other sites in northern China in order to evaluate the impact of emission control measures on the air quality of Beijing and surrounding regions.

2. Data and method

The MOPITT instrument was launched aboard the NASA Earth Observing System Terra spacecraft in 1999 to a Sun-synchronous orbit with a 10:30 local equator crossing time. MOPITT was designed to operate by sensing infrared (IR) radiation from either thermal IR emission/absorption at 4.7 μm for CO profiles, or reflected solar radiation in the near-IR at 2.2–2.4 μm for CO and methane column measurements during daytime. MOPITT is equipped with gas correlation radiometers incorporating both length modulation and pressure modulation cells operating in two distinct spectral bands: the near-infrared (NIR) CO overtone band near 2.3 μm and the thermal infrared (TIR) fundamental band near 4.7 μm. The NIR radiances provide information with respect to the CO total column with very weak sensitivity to the vertical distribution of CO whereas the TIR radiances are sensitive to differences in CO concentrations over broad layers in the troposphere (Deeter et al., 2009). MOPITT CO measurements have been used in air quality monitoring in a few case studies. For example, Clerbaux et al. demonstrated that the CO pollution arising from large cities and urban areas can be distinguished from background transported pollution by selecting and averaging MOPITT data over long time periods (Clerbaux et al., 2008). Dayside MOPITT retrievals in the lower troposphere have been shown to provide useful information on surface sources of atmospheric CO over the Indian subcontinent (Kar et al., 2008). In addition, using CO data from MOPITT together with a chemistry transport model, Pfister et al. estimated the wildfire emissions in Alaska and Canada in the summer of 2004 (Pfister et al., 2005). It has also been reported that the trans-Pacific transport of CO patterns are well captured with the global chemistry and transport model LMDz-INCA based on the complementary pictures provided by the satellite measurements from MOPITT, SCIAMACHY and ACEFTS (Turquety et al., 2008). In the current analysis, we collected Version 4 MOPITT level 2 daily (MOP02.004, 22 km × 22 km) CO total column and mixing ratios as well as level 3 gridded monthly mean

(MOP03 M.004, $1° × 1°$) CO total column (ftp://l4ftl01.larc.nasa.gov/MOPITT) over Beijing, China between 2000 and 2010. To compare the temporal pattern of CO regional pollution in Beijing with other regions in northern China, we also collected CO column data over Huhhot (capital city of Inner Mongolia near multiple major coal-burning power plants), Taiyuan (capital city of Shanxi Province, major coal production region in China), and Mt. Waliguan (in Qinghai Province, continental background; Zhou et al., 2004) (Fig. 1). MOPITT level 3 data were selected by matching city or site centroids to nearest $1° × 1°$ pixel center. Level 2 data were selected to cover Beijing and its surrounding provinces (36–43 N, 113–123 E). Retrieval bias drift in Version 4 MOPITT CO data is typically about 1 ppbv yr^{-1} for levels in the mid troposphere, and about 2 ppbv yr^{-1} in the upper troposphere (Deeter et al., 2010).

Ground level CO concentrations in Beijing were collected by the Beijing Municipal Environmental Monitoring Center. CO was measured with commercial, non-dispersive, infrared gas filter correlation analyzers (Thermo Fisher Scientific Inc., Waltham MA, USA). Hourly CO concentrations from 2000 to 2009 were collected from eight urban sites, and averaged to represent Beijing local conditions. Data from the Dingling site (50 km north of city center, surrounded by forest and pastures, distant from highways or major point sources) were used as Beijing's urban background. Unfortunately, ground-level CO measurements are not accessible for the other sites because local environmental protection agencies in China are only required to publish the daily levels of the dominant air pollutant among sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and inhalable particulate matter (PM_{10}).

3. Results and discussion

3.1. Seasonal variations of CO in northern China

3.1.1. Seasonal trend of MOPITT CO columns

To smooth out the inter-annual variability in CO concentrations, we calculated monthly mean MOPITT CO column using 2000–2009 data in Beijing and three other sites in northern China. As shown in Fig. 2, the CO columns are highest in Beijing and lowest in Mt. Waliguan, and Taiyuan and Huhhot stay in between. Because CO is the primary air pollutant related to fossil fuel combustion and biomass burning and MOPITT CO columns are more sensitive to free
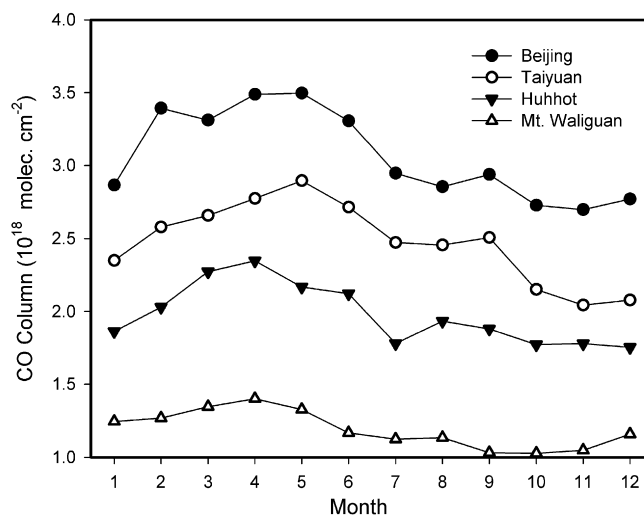

Fig. 2. Monthly trend of CO average column concentrations in northern China (2000–2009). Note that MOP03M.004 data is available since March 2000, and data in June and July of 2001 and August and September of 2009 are missing.

tropospheric CO (Deeter et al., 2007). Fig. 2 suggests that Beijing has the highest regional air pollution levels as it is surrounded by highly industrialized and heavily populated regions. Taiyuan as the capital city of China's primary coal production province has the second worst regional air pollution. Huhhot is located in a less populated area on the Mongolian plateau but there are several large coal-fire power plants nearby (Zhang et al., 2009b). As the continental background site, CO level at Mt. Waliguan is much lower than any of these urban sites. MOPITT CO columns at all four sites show similar seasonal trends, with the highest CO level in late spring (April and May), and lowest in late fall (October and November). Studies also showed that the remote background sites in northeast Asia including eastern Siberia as well as Japan, South Korea, and Mongolia observed the highest surface CO level in the spring (Pochanart et al., 2004). The trend of MOPITT CO column is consistent with these reported findings.

3.1.2. Seasonal variations of ground-level CO concentrations in Beijing

Fig. 3 shows monthly mean surface CO concentrations in Beijing calculated using 2000–2009 data. The urban sites (i.e., average concentration of eight monitors in Beijing urban area) demonstrate a significant "U" shape, with substantially higher CO concentrations during heating season (from November to March) as compared to non-heating season (from April to October). The background site (i.e., Dingling site) shows a similar trend although the difference is smaller.

3.1.3. Differences between ground-level and column CO trends

Because CO concentrations in the mid-troposphere are often heavily weighted by the MOPITT retrieval averaging kernels, the total MOPITT CO column is more representative of regional CO pollution patterns than local emissions which greatly influence ground level CO concentrations (Deeter et al., 2010). As a result, it is not surprising to see the difference between Figs. 2 and 3. The regional characteristics of CO column are masked out in Beijing area because CO emissions during the heating season as well as weaker dispersion caused by increased atmospheric stability in winter have much greater impacts on ground level CO concentrations. The seasonal variation shown in the background sites may be attributed to the following reasons. First, northeast Asia experiences distinctive seasonal land-ocean air exchange, with the air mass over land moving towards the ocean in winter and spring, and vice versa in the summer and fall. Over 50% of atmospheric CO comes from anthropogenic emissions (Khalil and Rasmussen, 1988) and the air
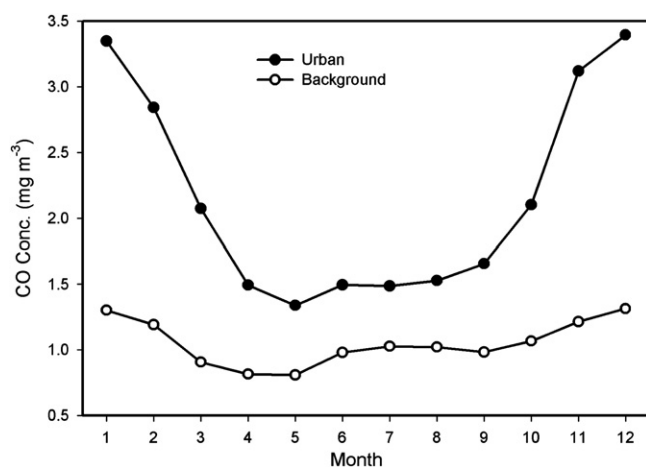
mass over ocean is less affected by human activities. As a result, background CO concentrations tend to be higher in winter and spring. Second, CO emissions are significantly higher in winter due to residential heating in the region. As CO is removed from the atmosphere by being oxidized by OH which has a lower concentration in winter, CO concentration reaches its peak level in spring, then gradually decreases. On the other hand, surface level CO concentrations in densely populated urban centers are dominated by local emissions. The seasonal cycle shown in Fig. 3 reflects the increased emissions from residential heating in winter which is the largest CO contributor in China (Zhang et al., 2009a).

3.2. Diurnal variation of ground-level CO concentrations in August

As shown in Fig. 4, the diurnal variation of mean surface level CO concentrations in August in Beijing urban area exhibits two peaks at 9 am during rush hour and between 22 pm and midnight due to weak dispersion caused by shallow and stable nighttime boundary layer. CO concentration is lower in early morning and late afternoon. On average, lower CO concentration in late afternoon lasts slightly longer than in the morning. Background CO concentrations measured at Dingling Site show a different pattern, with generally higher concentrations during daytime and lower concentration at night. The summertime wind field in Beijing has the typical pattern of mountain-valley breeze. As Beijing is surrounded by mountains from the north and east, northerly mountain breeze blows at night reducing CO levels in the urban area with cleaner air. Southerly valley breeze dominates during daytime transporting polluted air from industrial regions south of Beijing into the city (Hu et al., 2005; Xue et al., 2006).

3.3. Impact of emission control measures during the Olympic Games on CO concentrations in Beijing

3.3.1. Inter-annual variability of August CO levels in northern China between 2000 and 2007

Fig. 5 shows MOPITT CO columns in August from 2000 to 2010 in four sites in northern China. Between 2000 and 2007, CO columns have been slowly but steadily rising in Beijing from 2.6×10^{18} molec. cm^{-2} in 2000 to 3.1×10^{18} molec. cm^{-2} in 2007, suggesting a 20% increase of regional CO levels. The sudden decrease in 2004 could be attributed to the severe power shortage which caused many highly polluting small-to-medium size factories to operate below their full production capacity. CO columns
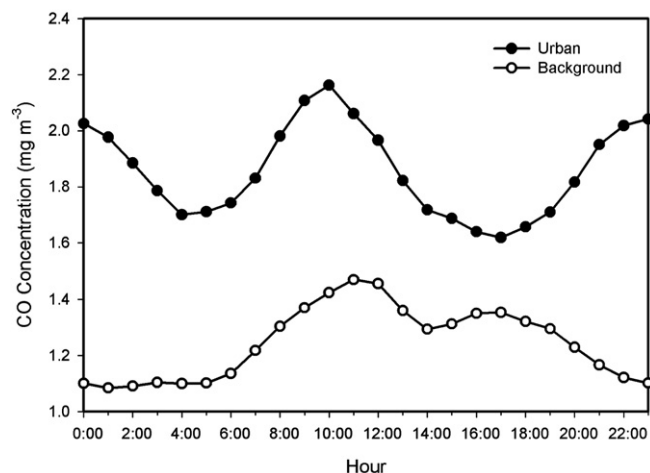

Fig. 3. Seasonal cycles of CO average mass concentration in Beijing (2000–2009).

Fig. 4. Mean daily variations of CO average mass concentration in August in Beijing, calculated using 2004–2006 data.
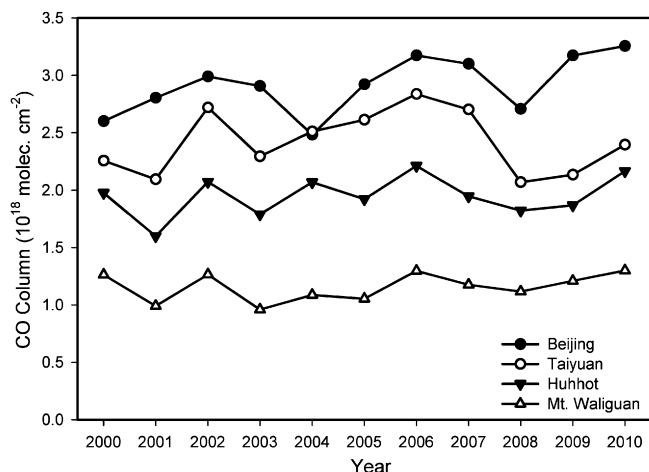
Fig. 5. MOPITT CO columns at four cities in Northern China, August 2000–2010. Note that MOP03M.004 data in August 2009 is missing, the value presented here is calculated by multiplying the July 2010 MOPITT column by the mean ratio of August to July CO columns between 2006 and 2010.

Fig. 6. Inter-annual trend of CO mass concentrations in Beijing urban area, 2000–2009.

also increased by 20% in Taiyuan while remained relatively unchanged in Huhhot and Mt. Waliguan.

The eastern and central region of China including Shandong, Shanxi (capital city: Taiyuan), Hebei and Liaoning Provinces (Fig. 1) have the highest annual CO emissions in the nation (Streets et al., 2006). Zhang et al. reported that CO emissions in China changed from 142 Tg yr^{-1} in 2001 to 167 Tg yr^{-1} in 2006, a 18% increase (Zhang et al., 2009a). The increasing CO levels observed by MOPITT appear to support their estimated emissions changes. The trends of CO columns in Beijing and Taiyuan after 2007 are related to the Beijing Olympic Games as well as the worldwide economic recession, which are discussed in the following sections.

3.3.2. Impact of emission control measures during the Beijing Olympic Games

Despite the steady increase of CO column, both annual average and August surface level CO concentrations have been decreasing in Beijing between 2000 and 2008. Particularly, the August average CO concentrations in 2008 is ~44% lower than that in 2007 (Fig. 6). The dramatic decrease in 2008 directly reflected the aggressive emission control measures taken during the Olympic Games. The emission reduction from July to September also caused the annual mean CO concentrations to decrease by ~21%.

On one hand, ground CO measurements support that limiting on-road vehicle traffic and closing or limiting industrial activities can effectively lower local CO pollution levels despite the large negative impact on regional economy. On the other hand, regional CO loadings measured by MOPITT CO columns indicate that sustained regional collaboration on emission control is necessary to fundamentally improve air quality in northern China. The Beijing–Tianjin–Tanggu region is an important base for coal, iron and steel, and petrochemical industries in China. Rapid economic development in recent years has caused continued increase in regional CO emissions. Fig. 5 shows that in 2008, the August average MOPITT CO columns in Beijing are ~ 13% lower than 2007 levels. This smaller reduction than that shown by ground level measurements is likely caused by regional transport from surrounding regions which had implemented less stringent emission control measures.

3.3.3. Vertical distribution of CO

Fig. 7 shows CO total column (a), mixing ratios at 900 hPa, 700 hPa, and 400 hPa on August 3, 2008 in northern China. This date
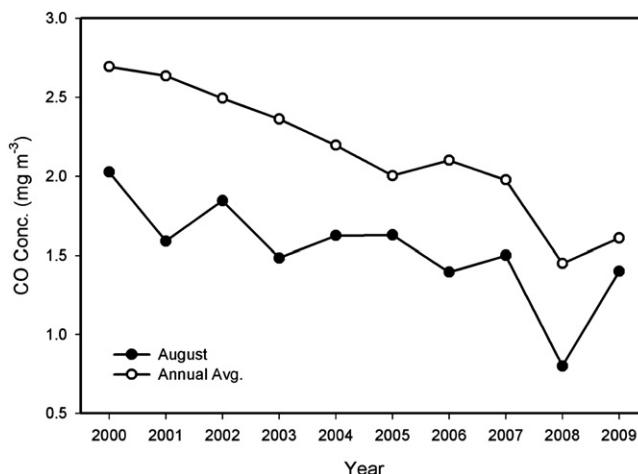
is selected because MOPITT had a comprehensive spatial coverage and the emission control measures had already been in effect in Beijing. According to the official air pollution index (API) published by Beijing Environmental Protection Bureau (http://www.bjepb.gov.cn, accessed on October 31, 2010), the 24-h average air quality was class I (good) on August 3, 2008, and class II (moderate) on August 4, 2008 (note that the API on August 3 is calculated from the mean air pollution levels from noon August 2 to noon August 3, and so on). MOPITT CO columns clearly show a high CO level southwest-northeast belt corresponding to the Beijing–Tianjin–Tanggu industrial region. This pattern has also been reported in satellite retrieved aerosol optical depth (AOD) spatial distributions (Li et al., 2009). The CO mixing ratios at 900 hPa has a similar spatial pattern except the low mixing ratios in Shandong province. CO mixing ratios at higher elevations tend to be more uniform and extend southward. At 400 hPa, the high CO regions in northern China and northeast China are connected to include Liaoning and Shandong provinces. Shandong contributes to ~15% of China's crude oil production from its coastal platforms and is an important producer of cement and steel (http://www.stats-sd.gov.cn/disp/tjgb.asp?aa=1100200800, accessed October 31, 2010). This is reflected by the high CO total columns and mixing ratio at 400 hPa in this area. Despite the temporary but aggressive emission reduction, both CO column and mixing ratios at different altitudes show higher pollution levels in the heavily industrialized northern China than the relatively under-developed Inner Mongolia at higher elevations.

3.3.4. Post-Olympic CO trends

After the Olympic Games, industries resumed full-capacity production and vehicle traffic restrictions were lifted. Fig. 6 clearly shows that mean surface CO concentration in August 2009 in Beijing is substantially higher than that in 2008 although it is still lower than pre-Games years probably due to both the worldwide economic recession and the gradual recovery of industrial activities in 2009. Fig. 5 shows that MOPITT CO column continued to increase after 2008 and reached the highest level in Beijing in 2010. CO columns at the other sites are also rising, which suggests that overall CO emissions in northern China bounced back substantially. Shanxi province is the primary coal production area in China. Its energy, coal production, and manufacturing sectors were severely damaged during the economic recession. After a 13–22% drop in coal production and export in 2008, Shanxi has been slowly recovering in 2009 and 2010 (http://www.stats-sx.gov.cn/html/2009-4/200941131743119960649.html, accessed October 31, 2010).
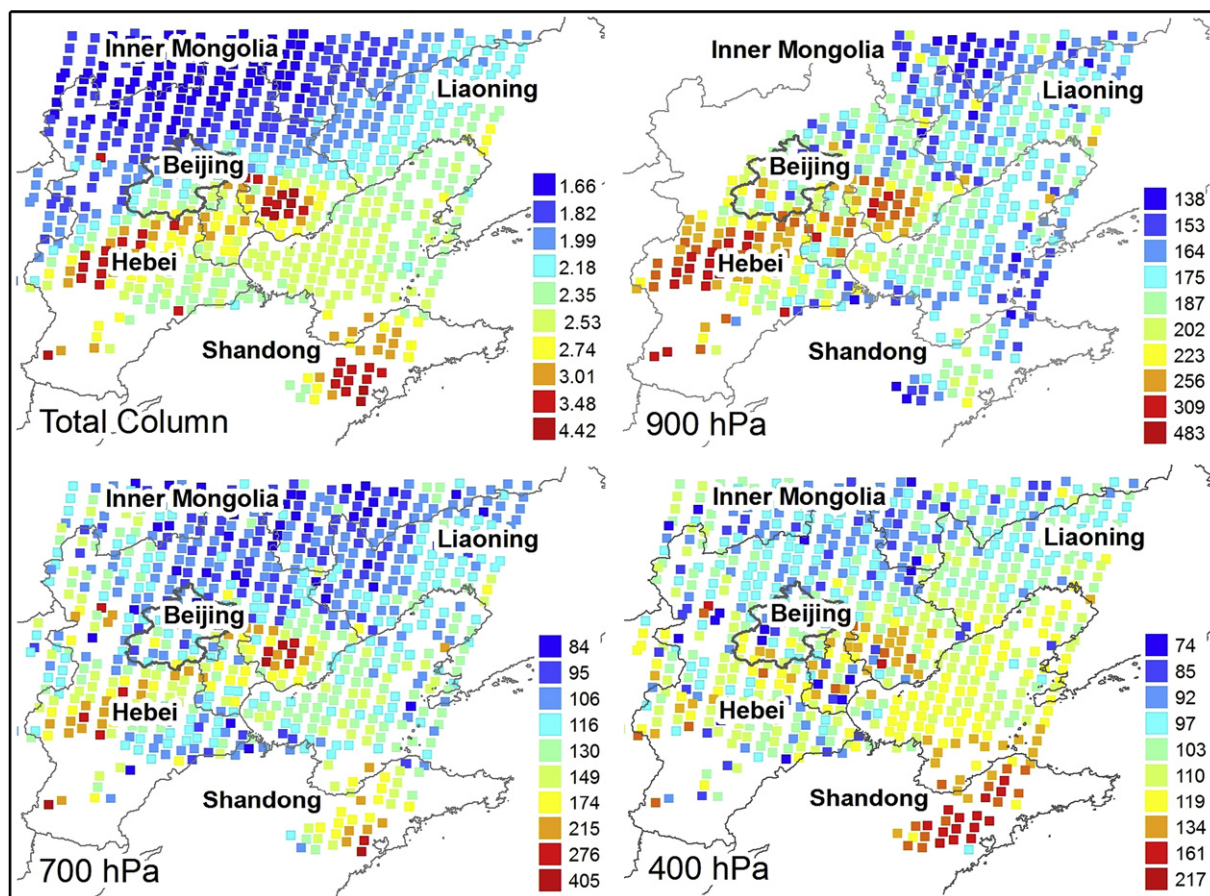
Fig. 7. MOPITT CO total column (unit: 10^{18} molec cm^{-2}), and mixing ratios (unit: ppbv) at 900 hPa, 700 hPa and 400 hPa over Beijing and surrounding provinces on August 3, 2008.

4. Conclusions

We studied the temporal variation of CO levels between 2000 and 2010 in Beijing and how the air pollution control measures during the Beijing Olympic Games affected ground-level CO concentration and total CO column in Beijing and surrounding regions. We found that MOPITT CO columns are more representative of regional air pollution, while ground-level CO concentrations measured at urban-area air quality monitoring stations are determined by local emissions and meteorological conditions. MOPITT CO columns show similar seasonal patterns due to lack of local emissions at all four sites, whereas ground-level CO concentration in Beijing shows significant contrasts between heating and non-heating seasons.

During the 2008 Olympic Games, the percentage decrease of ground-level CO concentration ($\sim$44%) is much greater than that of the CO column ($\sim$13%). This shows that although the temporary emission control measures substantially lowered ground-level CO concentrations during the Games, the severe regional air pollution in the region was not changed. In 2009, ground CO concentrations bounced back although it was still lower than 2008 level possibly due to the economic recession. Increasing CO emissions are also reflected in the upward trend in MOPITT CO columns after 2008 at all four sites in our study. Nationwide emission control policies must be designed, such as converting coal to natural gas for heating, tightening vehicle exhaust standards, and relocating polluting industries, in order to fundamentally improve air quality in northern China.

Acknowledgement

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