Uplifting of carbon monoxide from biomass burning and anthropogenic sources to the free troposphere in East Asia

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To: Atmospheric Chemistry and Physics

January 2015

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Abstract

East Asia has experienced rapid development with increasing CO emission in the past decades. Therefore, uplifting CO from the boundary layer to the free troposphere in East Asia can have great implications on regional air quality around the world. It can also influence global climate due to the longer lifetime of CO at higher altitudes. In this study, three cases of high CO episodes in the East China Sea and the Sea of Japan from 2003 to 2005 are examined with spaceborne Measurements Of Pollution In The Troposphere (MOPITT) data, in combination with aircraft measurements from the Measurement of Ozone and Water Vapor by Airbus In-Service Aircraft (MOZAIC) program. High CO abundances of 300-550 ppbv are observed in MOZAIC data in the free troposphere during these episodes. These are among the highest CO abundances documented at these altitudes, likely occurring 2-4% in time in the respective altitudes over the region. Correspondingly, elevated CO is shown in MOPITT daytime data in the middle to upper troposphere in the 2003 case, mostly in the lower to middle troposphere in the 2004 case, and in the upper troposphere in the 2005 case. Through analyses of the simulations from a chemical transport model GEOS-Chem and a trajectory dispersion model FLEXPART, we found different CO signatures in the elevated CO and distinct transport pathways and mechanisms for these cases. In the 2003 case, CO from large forest fires near Lake Baikal dominated the elevated CO, which had been rapidly transported upward by a frontal system from the fire plumes. In the 2004 case, anthropogenic CO from the North China Plain experienced frontal lifting and mostly reached ~700 hPa near the East China Sea, while CO from biomass burning from Indochina experienced orographic lifting,

leeside-trough induced convection, and frontal lifting through two separate transport pathways, leading to two distinct CO enhancements around 700 hPa and 300 hPa. In the 2005 case, high CO of ~300 ppbv, observed in the MOZAIC data around 350 hPa, originated from the anthropogenic source over the vicinity of the Sichuan basin and biomass burning from Indochina, after convection and strong frontal lifting. These cases show that topography affects vertical transport of CO in East Asia via different ways, including orographic uplifting over the Hengduan Mountains, assisting frontal lifting in the North China Plain, and facilitating convection in the Sichuan basin. In particular, topography-induced leeside troughs over Indochina lead to strong convection that assisted CO uplifting to the upper troposphere. This study shows that the new daytime MOPITT near-infrared (NIR) and thermal-infrared (TIR) data (version 5 or above) have enhanced vertical sensitivity in the free troposphere and may help qualitative diagnosis of vertical transport processes in East Asia.

1 Introduction

Carbon monoxide (CO) plays several important roles in the atmosphere. The oxidizing capability, an ability of the atmosphere to cleanse itself, is strongly influenced by the CO level in the troposphere. CO near the surface is a major pollutant. Under high NO_x conditions, CO is a precursor of ozone, while in low NO_x airmasses, CO helps ozone destruction (Jacob, 1999; Holloway et al., 2000). As carbon dioxide (CO_2) is produced in both ozone production and destruction processes (Holloway et al., 2000), CO is linked to the global carbon cycle (Suntharalingam et al., 2004; Yurganov et al., 2008; Nassar et al., 2010) affecting climate change. With a lifetime of weeks to months, CO is a good tracer

47 tracking transport of pollution. In the purview of these roles, it is important to understand
48 processes influencing the CO distribution and variability in the atmosphere.
49 Although the main sources of atmospheric CO and its mean status are generally
50 understood (Novelli et al., 1998; Jacob, 1999; Holloway et al., 2000), many processes
51 influencing CO variations at different time scales are not well known. Uplifting CO from
52 the boundary layer to the free troposphere (FT) is such a process, which usually occurs on
53 the synoptic scale that spans hundreds to thousands of kilometers in space and lasts hours
54 to days in time (Daley, 1991). Uplifted CO usually has a longer lifetime and can be
55 transported fast by the upper layer winds over long distances through continents and
56 between hemispheres in the troposphere (Stohl, 2001; Stohl et al., 2002; Damoah et al.,
57 2004). Uplifting airmass from the surface to FT generally takes place by three processes
58 (1) frontal lifting, (2) orographic lifting, and (3) deep convection (Brown et al., 1984;
59 Banic et al., 1986; Dickerson et al., 1987; Bethan et al., 1998; Pickering et al., 1998;
60 Chung et al., 1999; Donnell et al., 2001; Kowol-Santen et al., 2001;Cooper et al., 2002;
61 Liu et al., 2003; Miyazaki et al., 2003; Chan et al.; 2004; Mari et al., 2004; Li et al., 2005;
62 Liu et al., 2006; Kar et al., 2008; Zhao et al., 2008; Ding et al., 2009; Randel et al., 2010;
63 Chen et al., 2012).
64 East Asia has experienced rapid development with increasing CO emission in the
65 past decades (Duncan et al., 2007). In addition to impacts on local air quality (Wang et al.,
66 2010), continuing increase in CO emissions will lead to great impacts on regional air
67 quality (Jaffe et al., 1999; Bertschi et al., 2004) and climate (Berntsen et al., 1999) of the
68 world because of an expected upward trend in pollution outflow from the region. East
69 Asia is characterized by its unique and complex meteorology, topography, and land

covers. Vertical transport of CO can be modulated by one or more of these conditions or by their interactions. For example, the likelihood of when and where extratropical cyclones are active is closely linked to the locations and frequency of frontal uplifting. Wet and dry convections prevail in different seasons in northern China because of the distinct climatological pattern in precipitation there (Dickerson et al., 2007). The topography there also plays an important role in uplifting of CO alone and/or interplaying with frontal systems, aiding convection in mountainous regions (Liu et al., 2003; Ding et al. 2009). Recently, Lin et al. (2009) proposed a new mechanism that emphasizes the impact of topography-induced leeside troughs over Indochina on strong convection. A variety of land cover types in East Asia make CO sources there diversified. In highly populated urban areas, such as those in the North China Plain, anthropogenic emissions are high. Large biomass burning, occurring in areas with abundant vegetation, can generate great amounts of CO for vertical transport when meteorological conditions become favorable. Two such areas are Southeast Asia and the boreal forested area in Russia (Wotawa et al., 2001; Schultz, 2002; Duncan et al., 2003). So far, our understanding of the impacts of these processes and their interactions on CO uplifting is still rather limited (Dickerson et al., 2007). The objectives of studying vertical transport of CO in East Asia are to better understand the vertical distribution of CO in the region, to advance the assessment of impacts of long-range transport of Asian CO on regions downwind, and to help improve simulating this process in atmospheric models on the synoptic scale, eventually leading to more realistic chemical weather forecast in the future (Lawrence et al., 2003).

Due to lack of continuous measurements, most studies on CO in East Asia are based

on observations from periodic field campaigns (Jacob et al., 2003; Tsutsumi et al., 2003; Li et al., 2007; Ding et al., 2009) or simulations by chemical transport models (Berntsen et al., 1999; Bey et al., 2001) or both (Liu et al., 2003). CO measurements from satellites provide unprecedented data revealing CO variations over East Asia. One of the instruments is the Measurements Of Pollution In The Troposphere (MOPITT) (Drummond, 1992; Drummond and Mond, 1996). MOPITT provides data of CO total column and CO vertical profiles at several altitude levels, which are retrieved using a nonlinear optimal estimation method theoretically based on the observed radiances and their weighting functions, the a priori information, and the retrieval averaging kernels (Rogers, 2000; Deeter et al., 2003). As a result, the MOPITT retrieval at one level can be influenced by CO at other levels and thus MOPITT vertical resolution is coarse, generally having only 2-3 pieces of independent information vertically in the troposphere. MOPITT's vertical sensitivity was an issue in earlier applications of MOPITT data (Jacob et al., 2003). Nevertheless, a few studies (Deeter et al., 2004; Kar et al., 2004, 2006, 2008; Liu et al., 2006) demonstrated MOPITT's vertical sensitivity to some extent. Kar et al. (2004) found Asian summer monsoon plumes in MOPITT CO data as a strong enhancement of CO in the upper troposphere over India and southern China. Deeter et al. (2004) illustrated similar distributions of the rain rate and the ratio of MOPITT CO at 350 hPa to at 850 hPa in the Tropical Eastern Pacific Ocean. Liu et al. (2006) observed large differences (20-40 ppbv) in MOPITT CO at 250 hPa between two cases of vertical transport of CO and attributed the differences to the respective weather systems. Furthermore, the MOPITT data in new versions that use both thermal infrared and near infrared radiances have offered enhanced vertical sensitivity (Worden et al., 2010; Deeter

et al., 2012; 2013). Therefore, a detailed examination of MOPITT's vertical sensitivity in East Asia, especially for its ability in detecting vertical transport of high CO episodes, is desirable.

In this study, three cases of high CO episodes in East Asia from 2003 to 2005 are examined with MOPITT satellite data, in combination with aircraft measurements from the Measurement of Ozone and Water Vapor by Airbus In-Service Aircraft (MOZAIC) program (Marenco et al.,1998) (see Sects.2 and 4). The vertical transport mechanisms are analyzed with simulations from a trajectory dispersion model FLEXPART (Stohl et al., 2005) and a chemical transport model GEOS-Chem (Bey et al.,2001), along with other meteorology data and satellite fire data (see Sects.2 and 4). MOPITT data are analyzed in two ways. First, the vertical sensitivity of MOPITT is evaluated with the coincident MOZAIC data (see Sect.3) and further illustrated with the three high CO episodes in comparison with the MOZAIC data (see Sect.4). Second, the vertical variation in CO captured by MOPITT is used to diagnose vertical transport of CO (see Sect. 4). Discussion on the three cases is synthesized in Sect.5 and the major conclusions are provided in Sect.6.

2 Model and data

2.1 Satellite MOPITT CO data

MOPITT is the first space instrument that targets continuous measurements of tropospheric CO. MOPITT has been onboard of the Terra satellite launched in 1999, making scientific measurements since March 2000.Terra is flying in a sun synchronous polar orbit with an altitude of 705 km, crossing the equator at ~10:45 and 22:45 LT and

making 14-15 daytime and nighttime overpasses each day. MOPITT uses a cross-track scanning method with a swath of 29 pixels (4 pixels in a row), each pixel being 22 km × 22 km. Therefore, with a swath of ~600 km, only about one third of the global area is covered in a day. Additionally, clouds can cause even more gaps in MOPITT daily data. This makes it challenging to use MOPITT data for synoptic studies. It takes 3 days to achieve a near-complete global coverage (Edwards et al., 1999) if assuming no blocks from clouds.

MOPITT measures upwelling radiation in two narrow infrared spectral regions for CO retrieval: (1) a thermal-infrared (TIR) band near 4.7 μm that has strong carbon monoxide absorption and (2) a near-infrared (NIR) band near 2.3 μm that has weak CO absorption. MOPITT Version 5 retrieval products are significantly different from earlier products and offer three distinct products depending on application requirements. One of them is a TIR/NIR "multispectral" product, which has enhanced sensitivity to CO in the lower-most troposphere (Worden et al., 2010; Deeter et al., 2012; 2013). Validations and evaluations of MOPITT data in various versions are documented in Emmons et al. (2004), Worden et al. (2010), and Deeter et al. (2012, 2013).

We first examined the MOPITT vertical sensitivity through comparison between coincident MOPITT and MOZAIC CO profiles. Advances of Version 5 (V5, a TIR/NIR "multispectral" product) from Version 4 (V4, a TIR-only product) data were assessed with the level 2 data. Then, V5 level 2 data were used throughout the case studies, in which MOPITT data were gridded horizontally into 0.25 °latitude × 0.25 °longitude and at the MOPITT vertical resolution of 100 hPa from the surface to 100 hPa.

2.2 Aircraft MOZAIC CO data

The Measurement of Ozone and Water Vapor by Airbus In-Service Aircraft (MOZAIC) program was initiated in 1993 by European scientists, aircraft manufacturers, and airlines to collect experimental data (Marenco et al., 1998). MOZAIC consists of automatic and regular measurements of ozone, CO, and water vapor by several long range passenger airliners flying all over the world. The aim is to build a large database of measurements to allow studies of chemical and physical processes in the atmosphere.

In comparing MOPITT with MOZAIC CO data, coincident MOPITT and MOZAIC data from 2003 to 2005 were screened within a radius of 1.5 °and within a 4 h period. The radius of 1.5 °was applied to selected MOZAIC profiles at 500 hPa and the MOZAIC slant path was included in the radius. MOZAIC profile was smoothed by applying the MOPITT averaging kernels and the a priori profile for the co-located retrieved MOPITT profile to account for the bias introduced by the averaging kernels and the a priori. Therefore, the smoothed MOZAIC CO profile $\hat{\mathbf{x}}^{MOZAIC}$ is derived by (Rogers, 2000)

$$\hat{\mathbf{x}}^{MOZAIC} = \mathbf{x}_{\mathbf{a}}^{MOPITT} + \mathbf{A}\left(\mathbf{x}^{MOZAIC} - \mathbf{x}_{\mathbf{a}}^{MOPITT}\right) \quad (1)$$

where $\mathbf{A} = \partial\hat{\mathbf{x}}/\partial\mathbf{x}$ is the MOPITT averaging kernel matrix which describes the sensitivity of the MOPITT CO estimate to the true profile of CO, $\mathbf{x}^{MOZAIC}$ is the MOZAIC CO profile, which has been mapped to the MOPITT pressure grid. The quantity $\mathbf{x}_{\mathbf{a}}^{MOPITT}$ is the MOPITT a priori, which is based on CO simulations from the MOZART model (Emmons et al., 2004).

The MOZAIC measurements usually extend from the surface to ~ 250 hPa. When validating MOPITT data using Eq.(1), CO mixing ratios above 300 hPa was

supplemented with CO from the GEOS-Chem chemical transport model (see Sect.2.6) on the same location and day, similar to the treatments by Worden et al.(2010), who used the MOZART climatology simulations. Because CO above 250 hPa is lower than that in the middle and lower troposphere, the bias due to this treatment is expected to be low.

2.3 MODIS fire count data

The Moderate-resolution Imaging Spectroradiometer (MODIS) is a type of instruments which have been onboard of the Terra (EOS AM) satellite since 1999 and on the Aqua (EOS PM) satellite since 2002. The MODIS fire products include a validated daily global active fire product (MOD14 Terra and MYD14 Aqua) (Justice et al., 2002), generated using a global active fire detection algorithm that uses a multispectral contextual approach to exploit the strong emission of midinfrared radiation from fires allowing subpixel fire detection (Giglio et al., 2003). The horizontal resolution is 1 km. The fire data are acquired from the Fire Information for Resource Management System (FIRMS) (Davies et al., 2009).

2.4 NCEP FNL meteorological data

The NCEP Final (FNL) global tropospheric analyses are on 1 °by 1 °grids every 6h (http://rda.ucar.edu/datasets/ds083.2/). Parameters in FNL include surface pressure, sea level pressure, geopotential height, temperature, sea surface temperature, potential temperature, relative humidity, precipitable water, u and v winds, and vertical motion, available on the surface, at 26 levels from 1000 to 10 hPa, the tropopause, the boundary layer, and a few others. In addition to driving FLEXPART (see Sect. 2.5), the FNL data

209 are used to analyze the meteorological conditions including the surface pressure, wind
210 fields, and development of a cyclone. The data are generated from the Global Data
211 Assimilation System (GDAS).
212

213 ## 2.5 The FLEXPART trajectory model

214 To diagnose the transport processes and trace CO sources, we used the FLEXPART
215 model (Stohl et al., 2005), which is a Lagrangian Particle Dispersion Model developed at
216 the Norwegian Institute for Air Research in the Department of Atmospheric and Climate
217 Research. FLEXPART can be driven by meteorological input data generated from a
218 variety of global and regional models. In this study, the simulations were driven by the
219 NCEP FNL data. This model has been extensively validated (Stohl et al., 1998;
220 Cristofanelli et al., 2003) and widely used in studies of the influence of various
221 meteorological processes on pollution transport (Cooper et al., 2004, 2005, 2006;
222 Hocking et al., 2007; Ding et al., 2009; Barret et al., 2011; He et al., 2011; Chen et al.,
223 2012). In running FLEXPART, a large number of particles are released from defined
224 locations (latitude, longitude, and altitude) at a time. Backward or forward trajectories of
225 the particles are recorded in latitude ( ), longitude ( ), and altitude (km) every hour.
226

227 ## 2.6 The GEOS-Chem chemical transport model

228 GEOS-Chem is a global three dimensional chemical transport model
229 (http://geos-chem.org). The model contains detailed description of tropospheric
230 O3-NOx-hydrocarbon chemistry, including the radiative and heterogeneous effects of
231 aerosols. It is driven by assimilated meteorological observations from the National

Aeronautics and Space Administration (NASA) Goddard Earth Observing System (GEOS) from the Global Modeling and Assimilation Office (GMAO). In this study, GEOS-Chem version v9-1-3 was employed and executed in the full chemistry mode, which is driven by GEOS meteorology with temporal resolution of 6h (3h for surface meteorological variables), with a horizontal resolution of 2 °latitude by 2.5 °longitude and 47 vertical levels, including ~35 levels in the troposphere from 1000 to 100 hPa.

GEOS-Chem uses anthropogenic emissions from the Emissions Database for Global Atmospheric Research (EDGAR) global inventory (Olivier and Berdowski, 2001), which are updated with regional inventories, including the emission inventory in Asia (Streets et al., 2006; Zhang et al., 2009). The biomass burning emissions are from the Global Fire Emissions Data (GFEDv3) monthly inventories (van der Werf et al., 2010) and biogenic VOC emissions are taken from the Model of Emissions of Gases and Aerosols from Nature (MEGAN) global inventory. Emissions from other natural sources (e.g., lightning, volcanoes) are also included.

The model has been extensively evaluated and used in studies of atmospheric chemistry and pollution transport (Bey et al., 2001; Heald et al., 2003; Liu et al., 2003; Liu et al., 2006; Zhang et al., 2006; Jones et al., 2009; Nassar et al., 2009; Kopacz et al., 2010; Jiang et al., 2011). GEOS-Chem can generally describe CO variability in the troposphere but somewhat underestimate the observations in the northern mid-latitudes possibly due to biases in the CO inventory or numerical diffusion in the model or both (Heald et al., 2003; Duncan et al., 2007; Nassar et al., 2009; Kopacz et al., 2010).

3 Comparison between MOPITT and MOZAIC CO profiles

MOPITT's vertical sensitivity can be described in terms of the averaging kernels (see Eq.1) and the Degree of Freedom for Signal (DFS). The averaging kernel matrix indicates the sensitivity of the MOPITT CO estimate to the true CO profile, with I (identity matrix) being the best, when true CO profiles are retrieved, and 0 being the worst, when MOPITT retrievals just take the a priori. In reality, the average kernel matrix is less than I, implying some contribution of CO from other levels to the retrieved level so that the CO vertical structure cannot be fully resolved. DFS gives the number of independent pieces of information available vertically in the measurements and it is the sum of the diagonal elements of the averaging kernel matrix (Rogers, 2000). Figure 1 shows a yearly mean of DFS for daytime and nighttime, respectively, in East Asia for the V5 TIR/NIR data, indicating substantial increases in DFS compared to earlier MOPITT versions (Worden et al., 2010; Deeter et al., 2012). The daytime DFS in East Asia (Fig.1a) ranges from 0.5 to 2.7, usually decreasing with latitude, similar to its distribution in other regions and on the global scale (Deeter et al., 2004; Worden et al., 2010). In the same latitudinal zones, the DFS is higher over land than over ocean. The daytime annual DFS is high in the Sichuan basin, the eastern part of mainland China, the Indochina peninsula, and the Indian subcontinent. Over the mountain or valley regions, DFS is low, such as above the Tibetan Plateau. The stars indicate the cities where MOZAIC vertical measurements are available for validation of MOPITT data. The annual mean DFS is 1.65, 1.51, 1.60, and 1.64, respectively, in an area of 1°x1° around Beijing, Narita, Shanghai, and Hong Kong, with a maximum of 1.98, 1.64, 1.81, and 1.74 for the cities, respectively. The nighttime DFS values (Fig. 1b) are lower (from 0.5 to 1.5) than the daytime values, similar to that in Deeter et al. (2004) for an earlier MOPITT version.

Spatially, nighttime DFS is high over regions where the daytime DFS is also high.

The general patterns of MOPITT averaging kernels have been documented (Pan et al., 1998; Emmons et al., 2004; Deeter et al., 2003, 2004, 2012; Kar et al., 2008; Worden et al., 2010). For V5 MOPITT data, the averaging kernels at the four cities are similar to these in Worden et al. (2010, in their Fig. 7). The difference in the averaging kernels between V4 and V5 can be as large as 0.14 in the surface and lower troposphere and as 0.10 in the upper troposphere (not shown).

Figure 2 shows the relative bias between MOPITT and the smoothed MOZAIC ($\hat{\mathbf{x}}^{MOZAIC}$) profiles (see Eq. 1), which is also referred as "MOPITT estimate of in situ" in Worden et al. (2010) and "transferred profile" in Emmons et al. (2004). For V5 data (in red), the mean bias is within ±20% for all the cities. In all the altitude levels, the bias is smallest (close to zero) around 500-400 hPa and increases upward and downward. The bias is mostly positive above 500-400 hPa, while below 500-400 hPa, it is positive at Beijing, Narita but negative at Shanghai and Hong Kong. Whether the sign change is related to the change in the geographic location (Shanghai and Hong Kong are both coast cities) can be a subject for further study. The V4 data (in green) also show the smallest bias in the middle troposphere. In the lower troposphere, the bias in V5 is reduced by 5-10% at Beijing and Narita. At Shanghai and Hong Kong, the bias changes from positive in V4 to negative in V5, with a smaller (at Shanghai) or larger (at Hong Kong) magnitude. In the upper troposphere above 500-400 hPa, the bias in V5 at Beijing, Narita, and Shanghai changes to positive, with a magnitude as the same as or larger than in that in V4. At Hong Kong, the bias in V5 remains positive but the magnitude is enlarged. Deeter et al. (2013) compared MOPITT data with the NOAA aircraft measurements over

North America and data from the HIAPER Pole to Pole Observations (HIPPO) field campaign data (Wofsy et al., 2011). They found a positive bias in MOPITT V5 TIR/NIR data at 400 hPa (4%) and 200 hPa (14%). They also showed a latitude-dependent positive bias in the northern hemispherical upper troposphere in MOPITT V3 and V4 data. This study suggests an overall positive bias, agreeing with Deeter et al. (2013) in magnitude and sign, in MOPITT V5 data for the upper troposphere. As a comparison, we also validated MOPITT data in other cities in the globe and found that the mean bias in Europe or the United States is lower than in East Asia, especially in the surface layer (not shown).

The correlation between MOPITT and smoothed MOZAIC data is shown in Fig. 3. From 500 to 100 hPa, the correlation coefficient between the two data sets is 0.92, 0.86, 0.83, 0.68 at Beijing, Narita, Shanghai, and Hong Kong, respectively (Fig.3a), while from the surface to 600 hPa, the correlation becomes closer, being 0.90,0.92, 0.92, 0.94 at Beijing, Narita, Shanghai, and Hong Kong, respectively (Fig. 3b). The correlation coefficient between the two data is the best in the middle troposphere (500-400 hPa, not shown).

4 Uplifting of CO to the free troposphere

Daily MOPITT and MOZAIC data from 2003-2005 were screened to find cases of high CO episodes observed by both MOPITT and MOZAIC at the same location and time. We found three cases of high CO in MOPITT data with close-by MOZAIC measurements, while it was hard to find such high CO episodes with exact coincident MOPITT and MOZAIC observations because of large gaps in MOPITT data and limited

aircraft sampling coverages. In the three cases, high CO concentrations up to 300-500 ppbv are observed by MOZAIC in the free troposphere from 750 to 350 hPa.

In the following, we provide detailed analyses of each case, ordered by year of occurrence in Table 1. The cases occurred over the East China Sea or the Sea of Japan or both. High CO was shown in MOPITT daytime data in the middle to upper troposphere in case 2003, mostly in the lower to middle troposphere in case 2004, and in the upper troposphere in case 2005. For comparison, MOPITT and MOZAIC observations for the three cases are shown in Figs. 4-6, followed by analyses for each case with FLEXPART and GEOS-Chem simulations, in combination with MODIS fire data and NCEP FNL meteorological data. Table 1 provides a brief summary for all the cases. The cases occurred in spring and summer when cyclone activities are strong in East Asia (Chen et al., 1991; Yue and Wang, 2008). The CO sources are identified as biomass burning or a combination of biomass burning and anthropogenic origins. The outflow of the high CO episodes finally reached the boundary layer at the west coast of the United States and Canada.

4.1 Case study I: 6 June 2003

On 6 June 2003, a large area (~ 400 km × 1500 km) of high CO up to 350 ppbv appeared in the MOPITT image over the Sea of Japan and the nearby continent in the middle to high troposphere (Fig. 4a). In Fig. 5a, the MOPITT CO profile averaged over the boxed area in Fig. 4a shows a broad enhancement from the monthly profile between 650-300 hPa, with peak CO abundances of ~300 ppbv appearing around 550 hPa. The large difference between the MOPITT a priori and the measurements over these altitudes

indicates MOPITT's capability of capturing pollution episodes with some degree of vertical sensitivity. The vertical sensitivity is demonstrated through (1) the strongest CO source among the three cases was captured by the largest magnitude of CO enhancement of 200-250 ppbv from the a priori, (2) the altitude of the maximum CO enhancement was detected around the middle troposphere, in contrast to the other two cases which show the maximum in the lower-middle and upper troposphere, respectively, and (3) the elevated CO was over a broad range of altitudes as the vertical resolution of MOPITT is rather coarse, i.e., the maximum DFS is about 2.5 (Figure 1). This CO peak was not shown in the MOPITT monthly mean profile, reflecting the episodic nature of this event. The high CO episode was also captured by a near-by MOZAIC measurement (Fig. 5b). A layer of elevated CO is apparent between 500-350 hPa, with a CO peak up to ~ 550 ppbv around 400 hPa. In addition, the MOZAIC relative humidity (RH) and ozone profiles are shown in Fig. 5b. Around the altitudes of CO buildup, elevated humidity followed the CO profile, while ozone also showed some enhancement.

A latitude-altitude cross section from MOPITT is shown in Fig. 6a. It is the average between two blue dashed lines in Fig. 4a. The arrows represent the winds in the meridional and vertical directions and the contour represents the zonal wind speed. Consistent with Fig. 4a, high CO up to 350 ppbv appears in the middle to upper troposphere between 35-50 ºN.

To trace down the CO source, backward trajectories of the air particles were simulated using FLEXPART after releasing 30 000 and 7000 particles, respectively, from the locations of the large and small boxed areas in Fig. 6a (the same as the blue bars in Fig. 4a) on 6 June 2003 when CO was high in the MOPITT data. Because CO has a

relatively long lifetime (weeks to month), it is assumed that CO is not removed in the backward trajectories. Figure 7 shows the distribution of particle concentration between 6.25-10.25 km (~ 500-250 hPa, Fig. 7a) and between 0-3.25 km (~ 1000-650 hPa, Fig.7b). The contour lines indicate the geopotential height at 850 hPa at 12:00 UTC on 3 June 2003 (Fig. 7a) and at 0 UTC on 2 June 2003 (Fig. 7b), respectively. The stars, diamonds, and circles in Fig. 7b show the location of large forest fires near Lake Baikal from MODIS fire data. The circles, diamonds, and stars denote daily mean fire counts of 20-100, 100-300, and 300-500 per 2.5 °× 2.5 °grid area, respectively, from 31 May to 6 June. The high particle counts between 0-3 km in the vicinity of Lake Baikal match well with the location of fire counts (Fig. 7b). On 3 June 2013, there was a cyclone with a cold frontal system (Fig. 7a) that rapidly lifted the CO originated from the fires along the warm conveyer belt (WCB) to the upper level. The particle distribution in the upper troposphere shows the transport pathway of the particles to the Sea of Japan. To further illustrate this, particles were released from the fire region near Lake Baikal (93-115 °E, 50-60 °N, 0-3 km, following Lavoué et al. (2000), who found an average injection height of Siberian fires of ~ 3 km). Forward trajectories were simulated and the resultant vertical distribution of the particles varying with time during 1-15 June 2003 is shown in Fig. 8. It is found that the released particles from the fires traveled along the isobars to northeast of Lake Baikal from 1 June to 3 June 2003 and then the particles were lifted to the upper layers (3-8 km) on 3 June at 12 a.m. (in 60-70 h) (Fig. 8). Then, the particles were transported to the east along these altitudes. On 6 June (in 120-140 h), a large amount of particles appeared in a layer of 3-8 km (Figs. 8 and 4a). The altitudes with high particle concentrations agree well the MOPITT data between 650-350 hPa (Figs. 4a and 6a).

393 It is the cyclone with a front northeast of Lake Baikal that transported the CO up
394 along the WCB (Figs. 7a and 8). Figure 5b shows that the relative humidity reached about
395 65 % in MOZAIC measurement, suggesting the air mass indeed came from a WCB
396 (Cooper et al., 2002). The MOZAIC ozone profile also shows elevated ozone at the same
397 altitudes but the shape does not follow exactly the ones of CO and humidity, implying
398 complexity of chemical processes involved. The polluted air reached as high as 9 km
399 although most particles remained at heights of about 3-8 km (Fig. 8). After being lifted to
400 higher altitudes, the polluted air was transported by strong westerlies over long distances.
401 Figure 8 shows that the particles were further transported to the east and sink slowly after
402 7 June. Around 14 June 2003, the particles reached the east coast of Canada (0-5 km).
403 The satellite MODIS data show a large number of hot spots near Lake Baikal in May and
404 June 2003. Earlier studies have shown that forest fires in Asia can impact air quality in
405 North America (Jaffe et al., 2004; Liang et al., 2004; Oltmans et al., 2010). This case
406 illustrates again the role that WCBs played in the intercontinental transport of pollution
407 for such high CO. It should be noted that the FLEXPART simulation was made by using
408 the FNL meteorological data, which may have not considered the buoyancy force due to
409 fires. Such buoyancy force can lift CO plumes even faster and higher.
410 Our analyses are consistent with Nédélec et al. (2005), who analyzed 320 MOZAIC
411 flight routes from Europe to Asia in 2003 and reported the observations of high CO up to
412 800 ppbv above 8 km (~ 350 hPa) on 3 and 4 June 2003 around 57 °N (northeast of Lake
413 Baikal). This matches well with the time and location of frontal lifting of CO in this
414 FLEXPART simulation. With analyses of different data sets, i.e., Along Track Scanning
415 Radiometer (ATSR) fire data, the Total Ozone Mapping Spectrometer (TOMS) aerosols

data and the MODIS cloud data, Nédélec et al. (2005) also attribute the high CO at these altitudes to front lifting of CO from large forest fires near Lake Baikal. Furthermore, this analysis provides a detailed description on the CO transport pathways (Figs. 7 and 8). We found that this case, caused by the strongest CO source among the three cases, show the largest horizontal area with CO plumes (Fig. 5), the widest vertical CO buildup with strongest abundances (Fig. 7), and the biggest enhancement of 200-250 ppbv from the a priori (Fig. 6).

4.2 Case study II: 18 March 2004

This case occurred on 18 March 2004 when high CO appeared in the MOPITT data in the lower and middle troposphere over the East China Sea (Fig. 4b). The elevated CO of 200-250 ppbv is observed between 750 and 550 hPa vertically in MOPITT data (Fig. 5c). The departure of the MOPITT CO profile from its a priori reflects the MOPITT's vertical sensitivity (Fig. 5c). The MOPITT monthly mean, like for the other two cases, follows a typical CO profile pattern with CO concentrations being the highest near the surface and decreasing gradually with altitude. The CO on 18 March 2004 was 50 ppbv higher than the monthly mean above 800 hPa. A layer of large elevated CO appeared in the MOZAIC profile between 750-550 hPa with a peak of 500 ppbv around 650 hPa (Fig. 5d). The high RH (~ 90-100 %) below 600 hPa in the MOZAIC data suggests that the air mass experienced some uplifting process that enhanced its humidity, likely from a WCB. The MOZAIC ozone peaked (~ 70 ppbv) around the same altitudes as CO, implying that ozone may be produced in the air mass carrying high CO during the transport process. Figure 6b shows a latitude-altitude cross section averaged between the

two blue dashed lines in Fig. 4b. Around 30 °N, elevated CO levels (~ 200 ppbv) are evident around 700 hPa. The corresponding winds (blue lines and arrows) show that there were strong descents north of the elevated CO and moderate ascents in the south of the region (Fig. 6b), indicating the formation of a frontal system with downward and upward flows, south and north of the front, respectively.

This case was simulated with GEOS-Chem to identify the sources of CO and to explore the transport mechanisms. The MODIS fire data suggest biomass burning over northern Indochina peninsula to be a source for the observed high CO (Fig. 9). The time series of fire counts over area of 20-25 °N and 92-105 °E peaked on 12 March 2004. Correspondingly, high CO of ~ 300 ppbv appeared in the MOPITT composite of 11-18 March 2004 at 700 hPa over northern Indochina peninsula (Fig. 9). In the GEOS-Chem simulation (Fig. 10b), this source is also recognized. In addition, the anthropogenic source concentrated over the North China Plain (NCP) (approximately 30-40 °N, 110-125 °E) is identified as another source of high CO (Fig. 10c). Figure 11 shows the latitude-altitude cross sections of the GEOS-Chem simulations of CO, fire-induced CO, and anthropogenic CO, respectively, along 130 °E on 18 March 2004. The CO from biomass burning was more widely spread to the south than the anthropogenic CO. CO abundances from both sources were high around 700 hPa (Fig. 11b and c) between 25-35 °N across 130 °E where MOPITT observed high CO (Fig. 6b).

The different CO distributions for the two sources in three dimensions (Figs. 10 and 11) reflect rather different transport pathways and uplifting mechanisms. The transport of the fire-induced CO can be divided into the following four processes. First, the CO was orographically lifted along the Hengduan Mountains from the surface to ~ 750 hPa. The

462 lifted CO is shown in Fig. 12 around 100 °E on a longitude-altitude cross section along
463 22 °N. Then, the CO experienced two separate transport pathways. In the second process,
464 part of the lifted CO was further transported upward to 400-300 hPa, shown as a bulb in
465 Fig. 12 around 105 °E. This is due to strong convection, possibly caused by a frontal
466 system developed on March 17, 2004 (Fig. 9), interplayed with the leeside troughs east of
467 the Hengduan Mountains. The vertical velocity reached 0.2 m s^{-1} in FNL data around this
468 level (not shown). The ECMWF (European Centre for Medium-Range Weather Forecasts)
469 data also show northeastward airflow from Indochina peninsula with high potential
470 energy (warm and wet) available for strong convection. All of these suggest that the
471 strong convection over the leeside troughs rapidly lifted CO up to ~350 hPa. In fact, the
472 orographic lifting and topography-induced convection are quite common in this region so
473 high CO often appears at these two altitudinal levels in March as simulated by
474 GEOS-Chem (not shown). On 17 March, the lifted CO was with even higher
475 concentrations (~ 500 ppbv) around 400 hPa than the monthly mean because of the high
476 CO source from large forest fires. In the third process, the uplifted CO around 400-300
477 hPa (near 105 °E in Fig. 12) was transported northeastward by strong winds along the
478 front in the upper troposphere, reaching the East China Sea (near 30 °N, 130 °E) on 18
479 March (Figs. 10b and 11b). This transport enables high CO from forest fires in southern
480 Asia in low latitudes to rapidly reach the upper troposphere in the mid-latitudes. In the
481 fourth process, paralleling to the second and third, part of the orographically lifted CO
482 stayed around ~700 hPa because of leeside-trough induced convection. This CO was
483 transported eastward along the isobars of the low pressure system around 700 hPa (Figs.
484 10 and 12). This process occurred at lower altitudes than processes two and three. The

transport was slower and it took longer time (from 15 to 18 March) for the CO to reach the East China Sea. Processes two and three brought CO to the upper troposphere, while process four increased CO in the lower to middle troposphere (Fig. 11b). For the anthropogenic CO in the North China Plain, the vertical transport was mainly carried out by frontal lifting. Horizontally, anthropogenic CO was transported eastward along 30 °N (Fig. 10c). Consequently, the total CO shows a buildup centered near 700 hPa around 30 ° N and 130 °E, mostly coming from the two CO sources (Fig. 11a-c).

The Hengduan Mountains run mainly north to south, with elevations ranging from 1300 to 6000 metres. This topography provides a favorable condition for the formation of the leeside troughs if meteorology is satisfied. Such troughs promote vertical transport of CO on the west flank of the Mountain (in the second and fourth processes), while the orographic lifting occurred on the east flank of the Mountains (in the first process).

Comparison of the simulated vertical structure of CO (Fig. 11a) with the MOPITT observation (Fig. 6b) shows that MOPITT can generally capture vertical transport of CO from forest fires and anthropogenic sources, although the magnitude of CO in MOPITT data was lower and there were also substantial gaps in the MOPITT images due to convective clouds. In the MOPITT data, high CO of ~ 200 ppbv reached up to 200 hPa. In the lower to middle troposphere, elevated CO (~ 200 ppbv) was centered around 650-700 hPa. These features are similar to the GEOS-Chem simulations. Note that the CO buildup around 300 hPa in the GEOS-Chem simulation (Fig. 11a and b) was reflected in the MOPITT data (Fig. 6b), but not as obvious as in the simulation since the MOPITT retrievals are smoothed with the averaging kernels. This CO is also shown as a little bump around 300 hPa in MOPITT vertical profile in Fig. 5c. This buildup is missing in

the MOZAIC profile (Fig. 5d) because the aircraft flew towards the north and outside the region with high CO.

As the backward trajectories starting from the boxed area in Figure 4b indicated the most particles came from the large fire regions starting from 11 March 2004, air particles were released in FLEXPART over the regions from the surface to 1 km on 11 March 2004, and forward trajectories were simulated to track down the air parcels until 18 May 2004 at 2 a.m. Taking the same zonal means as for Fig. 6b, it is found that the vertical distribution of particle concentrations is similar to that in Fig. 6b with highest particle concentrations between 4-5 km (not show). As simulated by FLEXPART, the outflow of the high CO finally reached the west coast of the United States with particles mainly distributed around 5 km in altitude. High CO observed in East Asia in this case appeared the most southerly among the three, leading to a most southerly outflow.

The transport mechanism of biomass burning by the fourth processes was first proposed by Lin et al. (2009) who found that the leeside troughs above the Indochina peninsula play a significant role in uplifting of ozone there as there is lack of tropical deep convection to explain such strong convection. In this study, we even found these leeside troughs promote vertical transport of CO to the upper troposphere (the second process, Fig. 12). It is the interplay of the leeside troughs and the cyclone in the northeast of China which formed a front system that transported CO from the Indochina peninsula upward.

4.3 Case study III: 10 April 2005

In this case, MOPITT observed high CO of ~ 250 ppbv at 300 hPa near the east coast

of Japan on 10 April 2005 (Fig. 4c). To compare MOPITT and MOZAIC data, the mean MOPITT profile was taken over a boxed area (in Fig. 4c) upwind of the MOZAIC measurement. The MOPITT vertical profile clearly shows a CO peak around 300 hPa, where it departs from the MOPITT monthly mean (Fig. 5e). Comparing with cases 2003 and 2004, MOPITT CO peaked at higher altitudes, illustrating some MOPITT vertical sensitivity even at these altitudes. In Fig. 5f, a sharp peak of 300 ppbv in MOZAIC CO is shown around 350 hPa. The profile of relative humidity follows closely that of CO, with values up to 90-100 % around 350 hPa, implying that the elevated CO was lifted to this level from the lower troposphere by a cyclone system along its WCB. However, the MOZAIC ozone profile varies differently from the CO and relative humidity profiles. This is found due to a strong stratospheric intrusion introduced by the cyclone. HYSPLIT simulations suggest that a large amount of air mass plunged around 4 April from 9 to 3-4 km over northwest of China, bringing high ozone to the lower troposphere (not shown). Miyazaki et al. (2003) also observed downwelling of stratospheric air on the back side of cyclones. Figure 6c shows an altitude-latitude cross section averaged between 120-150 °E (between two dashed lines in Fig. 4c). High CO of 200-250 ppbv appeared between 300-200 hPa around 35 °N. This is a rare case in which MOPITT reports such high CO (200-250 ppbv) at these high altitudes (around 300 hPa). Documented CO abundances observed by MOPITT at these altitudes were ~130 ppbv over Indian summer monsoon seasons (Kar et al., 2004), 110-150 ppbv in the North America from the forest fires, chemical, and anthropogenic sources (Liu et al., 2005; 2006), and ~150 ppbv in spring at Hong Kong (Zhou et al., 2013).

The MODIS fire data show that there were indeed large fires over Indochina

554 peninsula in 3-10 April 2005, shown as stars in Fig. 13. Using GEOS-Chem, CO from
555 fire and anthropogenic sources was simulated to identify their respective contributions
556 and transport pathways.

557 The entire process of vertical transport of CO is well reproduced by GEOS-Chem
558 (Fig. 14). Figure 14a provides the CO distribution in the lower troposphere on 8 April
559 2005, while Figs. 14b and 14c show the CO distribution on the next day and the day after
560 in the middle and upper troposphere, respectively. The geopotential heights at 750, 450,
561 and 250 hPa are overlaid with the CO images for each layer accordingly. On 8 April 2005,
562 there was a cyclone developing in the east of Lake Baikal between 110-120 °E, 45-55 °N.
563 The surface CO was transported upward and northeastward along the WCB (Fig. 14a).
564 On 9 April, the cyclone moved to the east (Figs. 13 and 14b). The high CO shows a
565 "comma" shape along WCB at the mid-troposphere; this shape is typical for a mature
566 cyclone system with a WCB (Cooper et al., 2002). The cyclone further moved eastward
567 and reached the Sea of Japan on 10 April (Fig. 14c). The GEOS-Chem simulation shows
568 accumulation of high CO over the ridge of high pressure and along the front at the upper
569 troposphere. The GEOS-Chem simulations suggest that the outflow of the high CO
570 reached Canada on 16 April.

571 The combined effects of cyclone activities, topography, and CO from different
572 sources and locations are reflected in distinct CO signatures along the WCB. Figure 15
573 shows the CO from the fires (Figs. 15a and 15c) and from the anthropogenic source (Figs.
574 15b and 15d) in the middle and upper troposphere, respectively, overlaid with the
575 geopotential height at 450 hPa (Figs. 15a and 15b) and 250 hPa (Figs. 15c and 15d),
576 respectively. In the middle troposphere (500-400 hPa), a large amount of CO from the

fires in Indochina peninsula was uplifted to this level along the middle part of the WCB on 9 April 2005 and was transported eastward on 10 April, 2005 (Fig. 15a). One source of the anthropogenic CO was concentrated around the North China Plain (Ding et al., 2009) where high CO was evident in MOPITT data (Fig. 13, 35-45 °N, 100-120 °E) (Fig. 15b). On 8 April, this CO was uplifted along the WCB and further transported to the middle troposphere, coming across sudden elevated terrains on the way and forming the head of the "comma" in the cyclone system (Figs. 14b and 15b). The topography's role was noticed by Liu et al. (2003), who found a ring of convergence around the North China Plain associated with elevated terrain, and by Ding et al. (2009), who speculated possible topography lifting in North China Plain. In the southern end of the WCB (near 30 °N, 120 °E in Fig. 15b), the CO came from the anthropogenic source in the vicinity of the Sichuan basin (~ 26-34 °N, 102-110 °E). This CO was transported vertically to 500 hPa on 8 April at 18:00 UTC to 9 April at 00:00 UTC. Air pollution often accumulates in the Sichuan basin because of its special topography. The development of small scale cyclones there is well known as the southwest vortex or Sichuan low (Tao and Ding, 1981). Accumulated pollutants there usually are transported to the free troposphere by such convection. The strong convection can last more than 6 h and peak at the midnight (Yu et al., 2007). As this anthropogenic source is quite stable, its contribution should not be understated.

Interestingly, Lin et al. (2009) reported an observed ozone enhancement from ozonesonde data at 4 km in Taiwan on 11 April 2005. They proposed a new transport mechanism from their study as discussed in Sect. 4.2, in which they attributed the elevated ozone to the biomass burning in Indochina. Similarly, CO from biomass burning

600 is also apparent over Taiwan at the middle troposphere in the GEOS-Chem simulation
601 (Fig. 15a), although the maximum CO enhancement was north of Taiwan at this altitude.
602 The white dot in Fig. 15 indicates the location where MOZAIC passed over. It is clear
603 that MOZAIC measurement was within the WCB at 200-300 hPa, while it was at a
604 distance from the WCB at 500-400 hPa. This is consistent with the MOZAIC CO profiles
605 shown in Fig. 5f, suggesting that MOZAIC in fact measured air from the stratosphere at
606 these altitudes. As the wind was stronger in the upper than in the lower troposphere, the
607 WCB-transported CO reached further east in the upper levels (Fig. 15). The simulations
608 suggest that over the boxed area in the MOPITT image in Fig. 4c at 300 hPa, the fire and
609 anthropogenic sources each contributed about ~ 20 % of the observed CO. Comparing the
610 GEOS-Chem simulation (Fig. 14c) with the MOPITT observation (Fig. 4c), we noticed
611 that there were large gaps in MOPITT data north of 35 °N where CO abundances were
612 even higher than the MOPITT measurements south of 35 °N. These gaps were caused by
613 clouds associated with the cyclone system. The complication due to clouds is a problem
614 with an optical instrument like MOPITT, which explains why it is hard to find cases like
615 this in which high CO can be observed by both MOPITT and MOZAIC under a frontal
616 condition.
617 In this case, the strong part of the front (close to the centre of the cyclones) swept
618 southern China, where CO was high (Fig. 13). Along the front (30-40 °N, 100-120 °E),
619 the temperature gradient at 925 hPa was as high as 4.9 C per degree. Strong ascents
620 occurred ahead of the front, with vertical velocity being ~ 0.05 m s^{-1} at 900 hPa and ~
621 0.20 m s^{-1} at 750 hPa, and increasing with altitude until 300-250 hPa where the maximum
622 vertical velocity was 0.26 m s^{-1}. Consequently, the high CO can be rapidly lifted to the

623 upper troposphere in this case.

624 FLEXPART was also used to trace down high CO in the MOPITT image by releasing
625 air particles in the boxed area in Fig. 6c (indicated by a bar in Fig. 4c). We found that the
626 most CO came from the southwest part of China (boxed area in Fig. 13) where MOPITT
627 CO composite of 3-10 April 2005 shows high CO of 250-300 ppbv. This CO was lifted
628 along the WCB described above. This agrees with the GEOS-Chem simulation which
629 shows the major contribution of the anthropogenic source to CO in the upper troposphere,
630 likely from the Sichuan Basin (Fig. 15d).

631

632 # 5 Discussion

633 New insights gained from this study and suggestions for future work are discussed as
634 follows.

635 ## 5.1 Observations of high CO episodes

636 In the three CO episodes, high CO abundances 300-550 ppbv were observed by
637 MOZAIC in the free troposphere (Fig 5). The elevated CO abundances are among the
638 highest documented at these altitudes in East Asia. Ding et al. (2009) observed high CO
639 episode of ~1185 ppbv at 2.6 km (850-700 hPa) over the North China Plain in summer
640 2007. Nédélec et al. (2005) found CO up to 800 ppbv above 8 km (~400 hPa) near the fire
641 region of Lake Baikal on 3 and 4 June 2003. Highest CO concentrations during
642 TRACE-P were between 250-300 ppbv from 2-12 km (Heald et al., 2003; Liu et al., 2003;
643 Miyazaki et al., 2003). Occurrences of such high CO episodes are not by chance. They
644 reflect the uniqueness and complexity of meteorology, orography, vegetation covers, and
645 CO sources in East Asia. For example, in all the cases, biomass burning occurred from

regions with dense vegetation covers and with most active forest fires in East Asia (Schultz, 2002; Duncan et al., 2003). These fires are usually most active in summer in boreal forest in Russia, like in case 2003, and in spring in the southern East Asia, like cases 2004 and 2005, enhancing chances of high CO episodes in these seasons.

The frequency of occurrences of such high CO is illustrated in Table 2. As the three cases occurred near Japan, MOZAIC data around the vicinity of Narita from 2001 to 2006 are summarized, showing occurrences of various CO abundance ranges in the boundary layer (the surface-850 hPa), the lower (850-600 hPa), middle (600-400 hPa), and upper (400-200 hPa) troposphere. Among all the data in the upper troposphere, CO abundances occurred 93 times (17%) between 200-300 ppbv, 19 times (4%) between 300-400 ppbv, and 6 times (1%) over 400 ppbv. In the middle troposphere, the fraction of occurrences of CO within 200-300, 300-400, and over 400 ppbv was 14%, 3%, and 2%, respectively. In the boundary layer, the highest occurrences of CO abundances (38% of all the data in the layer) were within 200-300 ppbv, while the range was within 100-200 ppbv in the lower (47%), middle (74%), and upper troposphere (66%). Seasonally, there were more high CO occurrences in the higher altitudes in spring and summer than in fall and winter.

The frequency of such high CO episodes is also examined in the GEOS-Chem simulations and MOPITT observations in the vicinity of Narita (126-140 °E 30-40 °N) in 2005 (Table 3). For the GEOS-Chem simulations, a count is added to a CO range if the daily maximum CO in the area at a layer falling into that CO range. Thus, the total counts for all the CO ranges at a given layer are 365, while the counts are 281 for MOPITT due to missing data. To minimize noise in daily MOPITT data, only when there were at least

669 10 data with the maximum CO values falling into a given CO range, a count is added.
670 GEOS-Chem can simulate CO up to 400 ppbv in the upper troposphere, while the
671 maximum CO in MOPITT data is lower so that different CO ranges are used in Table 3.
672 Overall, MOZAIC, MOPITT and GEOS-Chem all show a high frequency of high CO
673 (larger than 200 ppbv) at the surface, gradually shifting to a high frequency of low CO
674 (less than 200 ppbv) at the upper troposphere. Between 400-200 hPa, CO episodes with
675 200-300 ppbv occurred 1.2 times every 10 days in GEOS-Chem, slightly lower than in
676 MOPITT (1.8 times) and MOZAIC (1.7 times). Overall, MOZAIC observes 2-5% more
677 transport of high CO to the upper troposphere than GEOS-Chem, while the latter
678 simulates 10-20% more transport of CO (with lower abundances) to the middle and lower
679 troposphere.

680 It is likely that on average, the extremely high CO episodes like the three cases (Fig.
681 5) occurred 2-4 times per 100 days in their respective altitudes over the East China Sea
682 and the Sea of Japan (Tables 2 and 3). As stated, air mass with lower CO abundances of
683 200-300 ppbv can be transported to 400-200 hPa in a frequency of 1-2 times per 10 days
684 (Tables 2 and 3). The frequency can be even higher in spring and summer (Table 2),
685 approximately once a week. Significant impacts of such transport can be expected on the
686 air quality downwind and on the global climate. The transport mechanisms and CO
687 source contributions revealed in this study can also be applicable for these CO episodes,
688 even with lower CO abundances or at lower altitudes.
689

690 ## 5.2 The role of topography

691 East Asia's topography varies significantly across its vast width, increasing from east

to west, with a variety of terrains. This study found that topography there affected the three cases in different ways. In addition to its general function in orograpic lifting (in case 2004), topography also interplay with frontal systems and enhance the uplifting substantially in the North China Plain (in cases 2004 and 2005). Under the influence of the Tibetan Plateau, the southwest vortex (or the Sichuan low) is formed (Tao and Ding, 1981) and can facilitate strong convection in the Sichuan basin (in case 2005).

In particular, topography-induced convection due to the leeside troughs east of the Hengduan Mountains, proposed by Lin et al. (2009), offers a new mechanism for vertical transport of pollutions from the region (in case 2004). Lin et al. (2009) mainly aimed at vertical transport of pollutions to the lower and middle troposphere. Extending from Lin et al. (2009), this study found it possible to explain pollution transport to the upper troposphere using such a mechanism.

5.3 The implications of WCB trends on uplifting of CO

Extratropical cyclones and associated frontal activities are important in lifting CO from the boundary layer to the free troposphere. This also applies to other air pollution. Zhao et al. (2008) found that the influence of Asian dust storms on North American ambient particulate matter levels is highly related to the height to which the frontal cyclones in East Asia can lift dust. Although the functions and characteristics of WCBs have been recognized by earlier studies, this study provides some details unique for the three cases. In case 2004, we found that it is the interplay of the leeside troughs and the cyclone in the northeast of China which formed a front system that transported CO from the Indochina peninsula upward. This case also appeared the most southerly among the

three, leading to a most southerly outflow. In case 2005, we found downwelling of stratospheric clean air on the back side of cyclones. We also found that anthropogenic CO from two regions and CO from biomass burning dominated different parts of a WCB. The source allocation was sensitive to the location of the front. Comparing cases 2004 and 2005, we found that when large CO source coincided with the strongest part of a WCB, uplifting of CO to the upper troposphere became more possible.

In East Asia, cyclones occur most frequently in two regions in spring and summer: one over the lee sides of the Altai-Sayan and the other in the East China Sea and the Sea of Japan (Chen et al., 1991; Yue and Wang, 2008). These are the locations and seasons where and when we can expect similar events to happen in the future. Chen et al. (1991) suggested a decline in cyclonic events in East Asia from 1957 to 1977 and no such decline from 1977 to 1987. Recently, an analysis for a longer term from 1951 to 2010 based on ensembles of Twentieth Century Reanalysis (20CR) showed a decreasing trend in the northern part of the Sea of Japan and an increasing trend over the southern part of the Sea of Japan and the leeside of the Altai-Sayan in summer (Wang et al., 2013). The implications of these trends on uplifting of CO deserve further investigation. It would be helpful to conduct statistical analysis of the CO source distribution along WCBs in East Asia in the future.

5.4 Comparison between observations from aircraft and satellite and model simulations

Pollution transport can be tracked computationally with Euler and Lagrangian approaches, as represented by GEOS-Chem and FLEXPART models, respectively.

738 GEOS-Chem can not only track transport of CO (a physical process) but also consider
739 chemical reactions during the transport while FLEXPART can visualize transport
740 pathways and pin down source regions effectively, without considering chemical
741 functions in the meantime. GEOS-Chem can also fill the gaps in MOPITT satellite data
742 (Figs. 10, 11, and 14). This study found that GEOS-Chem simulated the observed aircraft
743 and satellite CO well in cases 2004 and 2005 but cannot fully reproduce the elevated CO
744 in MOZAIC data in case 2003. The CO plume is simulated in lower mixing ratios at
745 lower altitudes than in the MOZAIC data. The plume also appeared further north. This is
746 possibly due to an underestimated fire inventory or conservative parameterizations in
747 simulating large forest fires or both in GEOS-Chem. Nassar et al. (2009) reported
748 underestimates of CO by GEOS-Chem over the 2006 Indonesia fire region, in
749 comparison with the Tropospheric Emission Spectrometer (TES) observations.
750 FLEXPART can generally simulate the three cases, strikingly well sometimes in
751 agreement with observed details in space and time, although discrepancies between
752 FLEXPART and satellite and aircraft observations can be found in various places on
753 small scales. FLEXPART is good at simulating strong sources, while weak sources
754 sometimes are ignored.
755

756 ## 5.5 Applications of MOPITT data

757 We analyzed MOPITT data from two aspects: vertical sensitivity on the synoptic
758 scale. Both are challenging and have not been studied adequately.
759 Large gaps due to clouds and the limited MOPITT swath make application of
760 MOPITT on the synoptic scale difficult. Thus application of MOPITT data over East

761 Asia were mostly focused on monthly or seasonal scales (Tanimoto et al., 2008; Zhao et
762 al., 2010; Hao et al., 2011; Liu et al., 2011; Zhou et al., 2013; Su et al., 2014). This study
763 shows that even with large gaps, daily MOPITT data can capture vertical disturbances of
764 CO on the synoptic scale, which are usually diluted on longer time scales. This study also
765 suggests the importance of filling the gaps with other satellite data or in designing new
766 satellite instruments, for the purpose of detecting such variation over large area on the
767 regional and global scales.

768 Typically for satellite remote sensing products, the MOPITT retrieval at a specific
769 pressure level is influenced by CO from other levels and thus its retrieval at that pressure
770 level can be bias. However, MOPITT can more accurately measure average CO mixing
771 ratio over a thick layer. This results in a coarse vertical resolution and the vertical
772 variation in CO seemed not to be fully resolved in earlier applications of MOPITT data
773 (Jacob et al., 2003). This study addressed the MOPITT vertical sensitivity with newly
774 MOPITT V5 data and found enhanced vertical sensitivity in V5 data in the free
775 troposphere, even the upper troposphere, in addition to in the boundary layer emphasized
776 by Worden et al. (2010) and Deeter et al. (2012). The enhanced DFSs and the averaging
777 kernels in V5 illustrated by Worden et al., (2010) and Deeter et al. (2012) are supported
778 (Fig. 3 and Sect.3).

779 In Fig. 5, the smoothed MOZAIC profiles were calculated using the averaging
780 kernels and the a priori in an area upwind of the MOZAIC measurement within 0-5 °
781 distance for each case as there were no MOPITT data available at the locations of the
782 MOZAIC measurements. Although this may introduce some bias, the averaging kernel
783 smoothed MOZAIC profiles in V5 show more vertical structure in CO than an earlier

784 version of MOPITT data in Jacob et al. (2003). The detection of high CO in the upper
785 troposphere in case 2005 makes MOPITT data promising in studying vertical transport of
786 CO or the vertical distribution of CO qualitatively up to that level. Overall, this study
787 found: (1) MOPITT can differentiate the magnitude of different CO plumes (Figs. 5 and
788 6), (2) MOPITT can distinguish elevated CO in the lower, middle, and upper troposphere
789 (Figs. 5 and 6), (3) the shape of CO plumes in vertical direction matches with simulations
790 of GEOS-Chem and FLEXPART, sometimes remarkably well (Fig.6), and (4) there is
791 more vertical structure in CO in new V5 than in earlier versions of MOPITT data (Fig. 5).
792 It is the relative variations in MOPITT CO data that help diagnose of CO transport
793 vertically or horizontally. This study suggests using MOPITT data quantitatively with
794 caution, especially at altitudes with high CO plumes, as illustrated that the magnitude of
795 elevated CO in MOPITT retrievals can be lower than in the MOZAIC data at altitudes
796 where CO peaked (Fig. 5). Therefore, the vertical variation of CO, even enhanced in V5,
797 is still much smoothed in MOPITT data. MOPITT can distinguish elevated CO in
798 different layers of the free troposphere, yet sometimes cannot specify the exact altitude of
799 elevated CO shown in the MOZAIC measurements (Fig. 5). One limitation for MOPITT's
800 application of vertical transport is the complication of clouds, which often accompany
801 frontal systems. As shown in cases 2004 and 2005, CO is usually high in cloudy areas.
802 Therefore, the magnitude of CO abundances can be underestimated by MOPITT in these
803 areas.
804

805 6 Conclusions

806 East Asia is characterized by its unique and complex meteorology, topography,

807 vegetation covers, and CO sources. The characteristics are reflected in uplifting of CO
808 illustrated in three high CO episodes during 2003-2005 in this study. Through integrated
809 analyses of observations from the airborne MOZAIC and spaceborne MOPITT
810 instruments and simulations from a trajectory dispersion model FLEXPART (Stohl et al.,
811 2005) and a chemical transport model GEOS-Chem (Bey et al., 2001), this study draws
812 the following conclusions.

813 1. In the three CO episodes, high CO abundances of 300-550 ppbv are observed in
814 aircraft MOZAIC data in the free troposphere over the East China Sea and the Sea
815 of Japan. These are among the highest CO abundances ever documented at these
816 altitudes. The three cases occurred in the seasons and at locations where
817 meteorological and CO source conditions are favorable for such episodes. It is
818 likely that on average, such high episodes occur 2-4 times per 100 days at the
819 respective altitudes in the region. CO episodes in lower altitudes and with lower
820 abundance occur more frequently in the region, about 1-4 times every 10 days with
821 200-300 ppbv in 600-400 hPa.
822 2. GEOS-Chem and FLEXPART simulations reveal different CO signatures from
823 biomass burning and anthropogenic sources in the CO enhancement in the three
824 cases, reflecting different transport pathways and mechanisms and locations of both
825 sources. In case 2003, CO from large forest fires near Lake Baikal dominated the
826 elevated CO. In case 2004, anthropogenic CO came from the North China Plain
827 and mostly reached ~ 700 hPa near the East China Sea, while CO from biomass
828 burning in Indochina was transported through two separate pathways, leading to
829 two distinct CO enhancements around 700 hPa and 300 hPa. In case 2005, along a

WCB over the East China Sea and the Sea of Japan, anthropogenic CO from the North China Plain and from the Sichuan basin prevailed in the northern and southern part of the WCB, while CO from biomass burning in Indochina was mostly distributed in the middle part of the WCB.

3. Topography in East Asia influences vertical transport of CO in different ways. In particular, topography-induced leeside troughs east of the Hengduan Mountains over Indochina lead to strong convection. This new mechanism proposed by Lin et al. (2009) is supported by this study in explaining CO transport to the middle troposphere and further extended for CO transport to the upper troposphere. Strong convection from the Sichuan basin also plays an important role in vertically transporting anthropogenic CO. The topography interacting with frontal activities can enhance the vertical transport of CO substantially in North China Plain.
4. Extratropical cyclones and associated frontal activities are important mechanism in lifting CO from the boundary layer to the free troposphere, as illustrated by the three cases and earlier studies. East Asia is one of two regions between 25-45 °N with most frequent WCB events (Eckhardt et al., 2004). Inside East Asia, there are two regions where cyclones occur most frequently: one over the lee sides of the Altai-Sayan and the other in the East China Sea and the Sea of Japan, occurring mostly in spring and summer over both regions (Chen et al., 1991). The seasons and locations of the three high CO episodes just match well with these two areas and active cyclone seasons, which may not happen by chance.
5. Biomass burning is identified as an important source for all three episodes, suggesting that CO from sporadic fire activities can provide additional CO to less

varying anthropogenic emission and enhance chances of high CO episodes. The fire regions shown in this study are the places with dense vegetation covers and with most active forest fires in East Asia.

6. The MOPITT's vertical sensitivity is found to be enhanced in its new V5 NIR/TIR data in the free troposphere, even in the upper troposphere. The daytime V5 data can detect synoptic disturbances of weather systems on horizontal variation of CO. The data also show more vertical structure than earlier versions and can distinguish CO enhancements at different layers of the troposphere, although the detected high CO is over a broad range in altitudes and lacks detailed vertical structure in comparison with the aircraft observations. Because the CO retrieval at a certain pressure level is often smoothed by CO from other levels, the MOPITT retrievals usually underestimate elevated CO peaks at altitudes with high CO plumes. The complication of clouds within frontal systems can generate large gaps in MOPITT data and cause underestimation of CO statistically in these regions. Nevertheless, MOPITT data may be used to qualitatively help diagnose vertical transport processes, with caution on their absolute CO values. On average, MOPITT slightly overestimates the background CO in the upper troposphere.

Acknowledgements.

The authors gratefully acknowledge the following data and modeling tools. The satellite CO data are provided by the MOPITT team and acquired from the NASA Langley Research Center Atmospheric Science Data Center. The MOZAIC CO data are from the European Commission, Airbus, and the Airlines (Lufthansa, Austrian, Air

France) who carry free of charge the MOZAIC equipment and perform the maintenance since 1994. The Final Analysis Data (FNL) were obtained from NOAA CDC. The GEOE-Chem model is developed and managed by the Atmospheric Chemistry Modeling Group at Harvard University with support from the NASA Atmospheric Chemistry Modeling and Analysis Program (ACMAP). The FLEXPART model development team consists of Andreas Stohl, Sabine Eckhardt, Harald Sodemann, and John Burkhart at the Norwegian Institute for Air Research (NILU). Insights and critiques from two anonymous reviewers are highly appreciated. Financial support is provided by an open fund from the Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences (OFSLRSS201107), the Key Basic Research Program (2010CB950704, 2014CB441203), and the Natural Science Foundation of China (41375140).

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Figure caption

Fig. 1. The Degree of Freedom for Signal (DFS) of the MOPITT V5 TIR/NIR data over East Asia, averaged for 2005 during (a) daytime and (b) nighttime. Locations of four cities with MOZAIC CO measurements are indicated as stars. Note that the MOZAIC CO data from Narita also include a small portion of measurements from its surrounding cities at Osaka and Nagoya.

Fig. 2. Relative bias of CO profiles (in %) between MOPITT and MOZAIC data (smoothed with the MOPITT averaging kernels, see Equation 1) from 2003 to 2005 at

Beijing, Narita, Shanghai, and Hong Kong for MOPITT V4 and V5 data. The number of profiles for the comparison is 18, 23, 11, and 15, respectively, at Beijing, Narita, Shanghai, and Hong Kong. The error bars indicate the interquartile range of the mean.

Fig. 3. Correlation between MOPITT and MOZAIC data (smoothed with the MOPITT averaging kernels, see Equation 1) from 2003 to 2005 at Beijing, Narita, Shanghai, and Hong Kong (a) from the middle to upper troposphere and (b) from the surface to the middle troposphere.

Fig. 4. MOPITT CO mixing ratio (ppbv, in color) (a) on 6 June 2003 at 500 hPa, (b) on 18 March 2004 at 700 hPa, and (c) on April 10, 2005 at 300 hPa. All are overlaid with horizontal winds (in arrows) at the same altitude. In each subfigure, the geographic locations of MOZAIC data at 900, 600, and 300 hPa are indicated as red, blue and pink dots, respectively. The box indicates an area over which mean MOPITT CO profile are taken and displayed in Fig.5. The box is selected to ensure over 30 MOPITT samplings at the closest upwind direction of MOZAIC measurements. The two blue dashed lines define the longitudinal zone, over which the CO abundances were averaged and shown in Fig 6. The solid blue bars in Figs. 4a and 4c indicate the locations where particles were released and backward trajectories were simulated using FLEXPART (see text for detail).

Fig. 5. Profiles of MOPITT CO and the a priori, averaged over the corresponding boxed area in Fig. 4 on (a) 6 June 2003, (c) 18 March 2004, and (e) 10 April 2005, respectively, along with their monthly mean MOPITT CO profile over the same area. The corresponding MOZAIC CO profiles (along the dots in Fig. 4) on the same day are shown in (b), (d), and (f), respectively. The corresponding MOZAIC ozone and relative humidity profiles are also shown in (b), (d), and (f). Note that the smoothed MOZAIC CO profiles (MOZAIC CO(s)) were calculated using the averaging kernels and the a priori in the boxed area in each case (see Sect. 5 for discussion).

Fig. 6. A latitude-altitude cross section of MOPITT CO averaged between the two blue dashed lines in Fig.4 on (a) June 6, 2003, (b) March 18, 2004, and (c) April 10, 2005. The contour lines indicate U wind speed (m s^{-1}). Vectors are for wind directions in V and W. For a better illustration, W is enlarged by a factor of 100. The pink box(es) in (a) and (c) indicate the locations where particles were released and backward trajectories were simulated using FLEXPART (see text for detail).

Fig. 7. (a) Particle distribution between 6.25-10.25 km (~550-250 hPa) during June 1-6, 2003. The particles were released from two locations (in pink lines) around 400 hPa (also see Figs. 4a and 6a) on June 6, 2003 and backward trajectories were calculated. The contour lines are the geopotential heights at 850 hPa on June 3, 2003. A cold front and a warm front are indicated by green and red lines, respectively. (b) The same as (a), but between 0-3.5 km. The contour lines are the geopotential heights at 850 hPa on 2 June 2003. The circles, diamonds, and stars denote daily mean fire counts of 20-100, 100-300, and 300-500 per 2.5×2.5 °grid area, respectively, from May 31 to June 6.

Fig. 8. Vertical distribution of particles, varying with time from 1 June 2003 at 0 UTC to

16 June 2003 at 0 UTC. The particles were released from fire regions in Fig. 7b from the surface to 3 km on 1 June 2003 and forward trajectories were calculated (15 days). The forward time (in hour) and date (in June) are indicated in the x-axis on the bottom and the top, respectively.

Fig. 9. MOPITT CO mixing ratio at 700 hPa from 11-19 March 2004, overlaid with the geopotential height at 850 hPa on 17 March 2004 in blue contour and with a front shown by brown solid line. The large and small stars denote daily mean fire counts of 100-200 and over 200 per 2.5×2.5 °grid area during the period, respectively. "L" and "H" indicate a low and high pressure system, respectively.

Fig. 10. (a) CO, (b) CO from biomass burning, and (c) CO from the anthropogenic source on March 18, 2004 at 0 UTC, simulated by GEOS-Chem. The geopotential height at 700 hPa is indicated with white lines. "L" indicates a low pressure system.

Fig. 11. Latitude-altitude cross sections along 130°E of (a) CO, (b) CO from biomass burning, and (c) anthropogenic CO on March 17, 2004 at 6 UTC, simulated by GEOS-Chem. The contour lines indicate U wind speed (m s^{-1}). Vectors are for wind directions in V and W. For a better illustration, W is enlarged by a factor of 100.

Fig. 12. A longitude-altitude cross section of CO along 22°N on March 17, 2004 at 6 UTC, simulated by GEOS-Chem. The topography of the Hengduan Mountains is indicated in white.

Fig. 13. MOPITT CO mixing ratio at 800 hPa from April 3-10, 2005, overlaid with the geopotential height at 850 hPa on April 9, 2005 at 0 UTC in blue contour and with a front in brown solid line. The large and small stars denote daily mean fire counts of 100-200 and over 200 per 2.5×2.5 °grid area during the period, respectively. The boxed area was identified as a major CO source region from the FLEXPART simulation (see text for detail).

Fig. 14. The GEOS-Chem simulated CO (a) on April 8, 2005 in the lower troposphere (800-700 hPa), (b) on April 9 in the middle troposphere (500-400 hPa), and (c) on April 10 in the upper troposphere (300-200 hPa). The contours are the geopotential height at 850, 450, and 250 hPa, respectively.

Fig. 15. The GEOS-Chem simulated fractional CO (a) from biomass burning and (b) from the anthropogenic source on April 10, 2005 at 00 UTC in the middle troposphere (500-400 hPa). (c) and (d) are the same as for (a) and (b), respectively, but in the upper troposphere (300-200 hPa). The geopotential height at 450 and 250 hPa is overlaid with the CO images in the middle and upper troposphere, respectively. White dots indicate the location of MOZAIC measurements.

Table caption

Table 1. Characterization of the three cases.

1462 **Table 2.** Occurrences of various CO ranges at different altitudes in the MOZAIC
1463 measurements in the vicinity of Narita from 2001 to 2006.
1464
1465 **Table 3.** Occurrences of various CO ranges at different altitudes in GEOS-Chem
1466 simulations and MOPITT observations in the vicinity of Narita (126-140 °E 30-40 °N) in
1467 2005.
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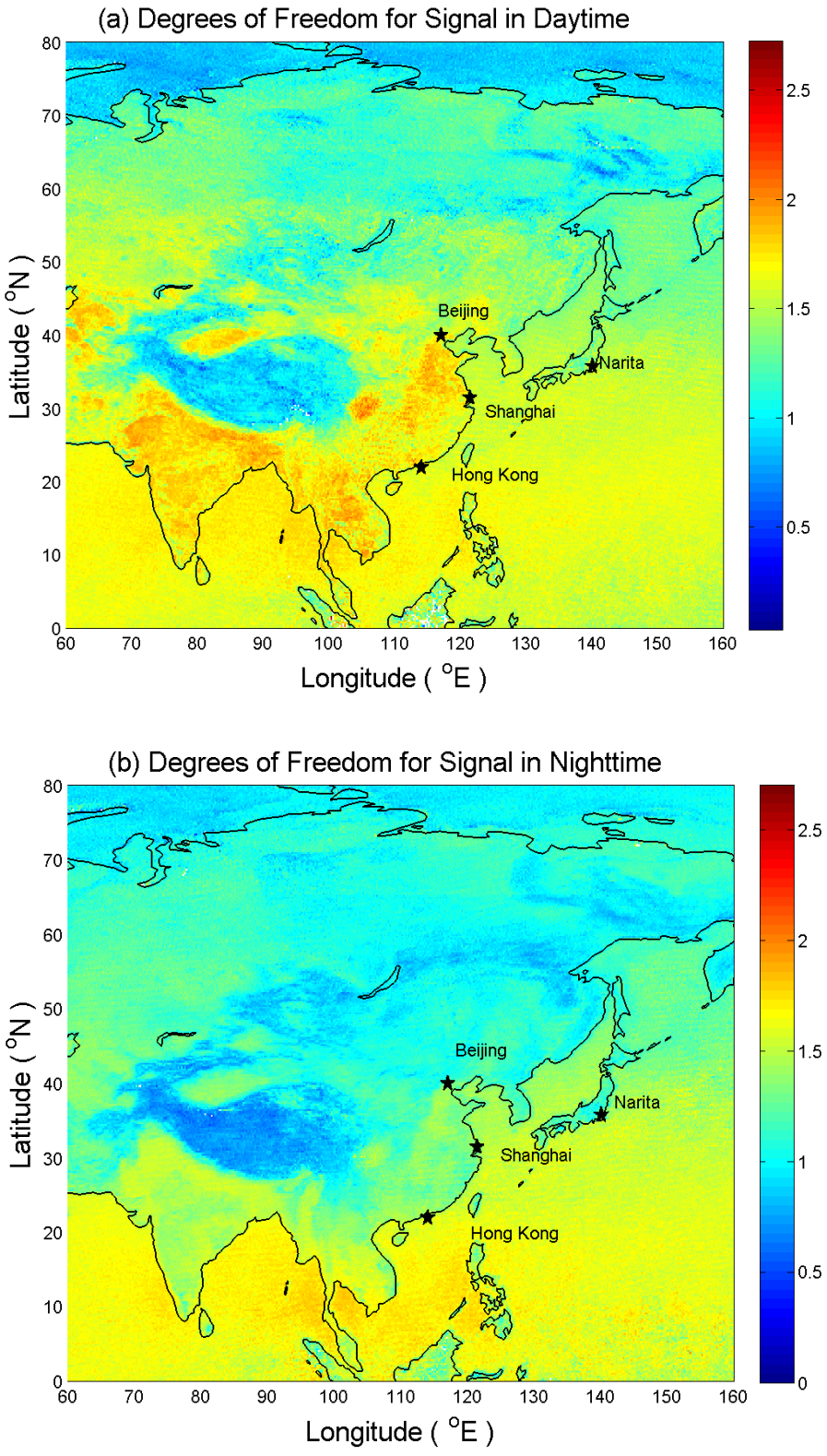

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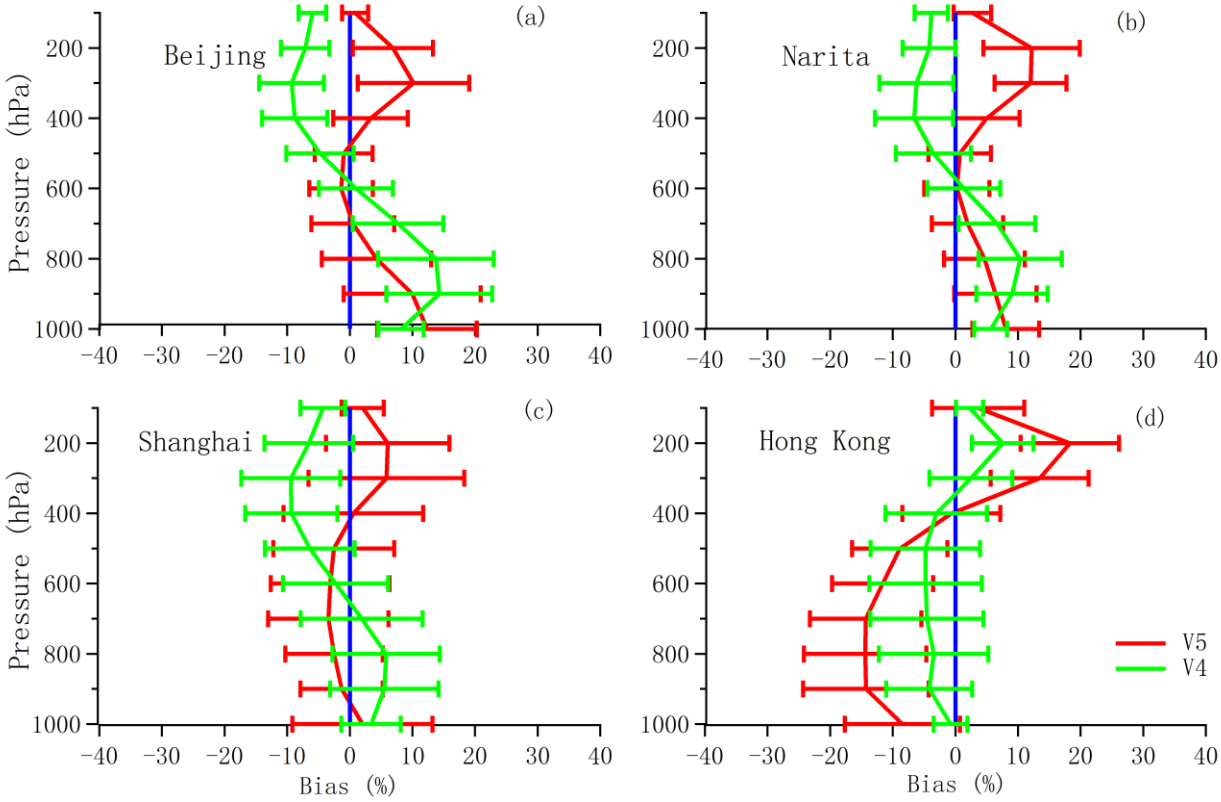

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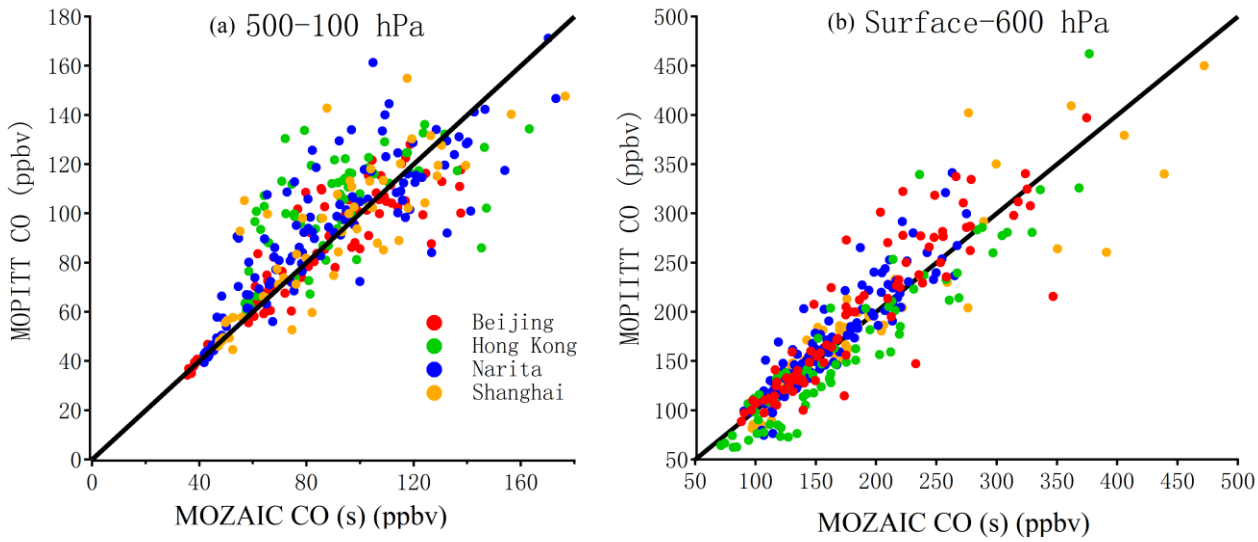

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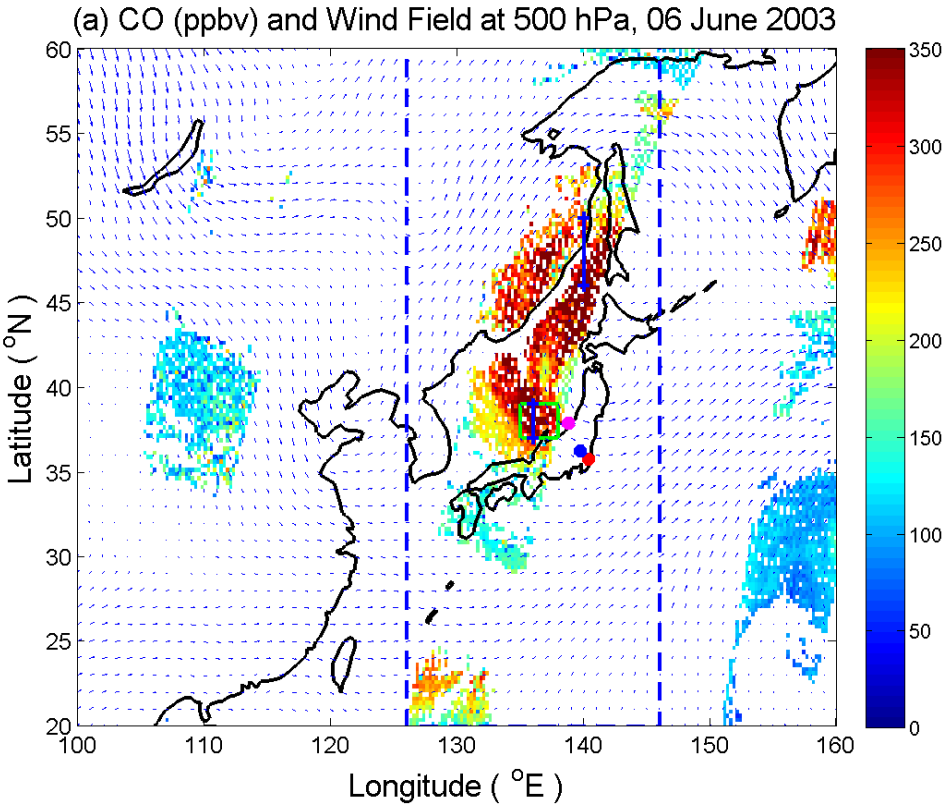
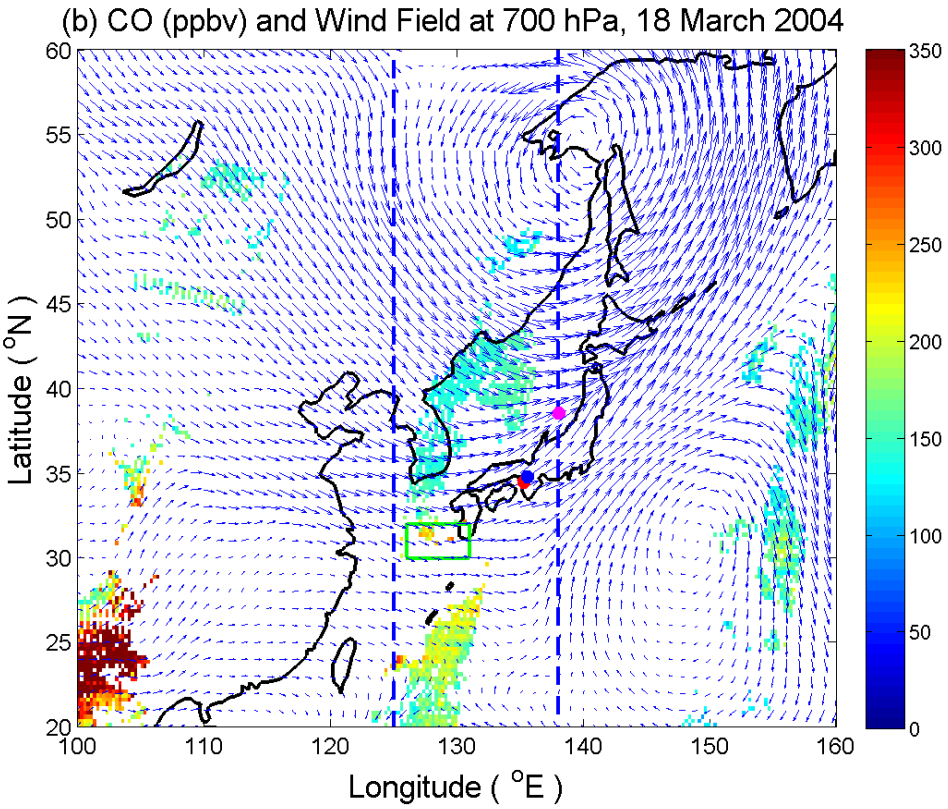

(a) CO (ppbv) and Wind Field at 500 hPa, 06 June 2003
Latitude (°N)
Longitude (°E)
60
55
50
45
40
35
30
25
20
100
110
120
130
140
150
160
350
300
250
200
150
100
50
0


(b) CO (ppbv) and Wind Field at 700 hPa, 18 March 2004
Latitude (°N)
Longitude (°E)
60
55
50
45
40
35
30
25
20
100
110
120
130
140
150
160
350
300
250
200
150
100
50
0

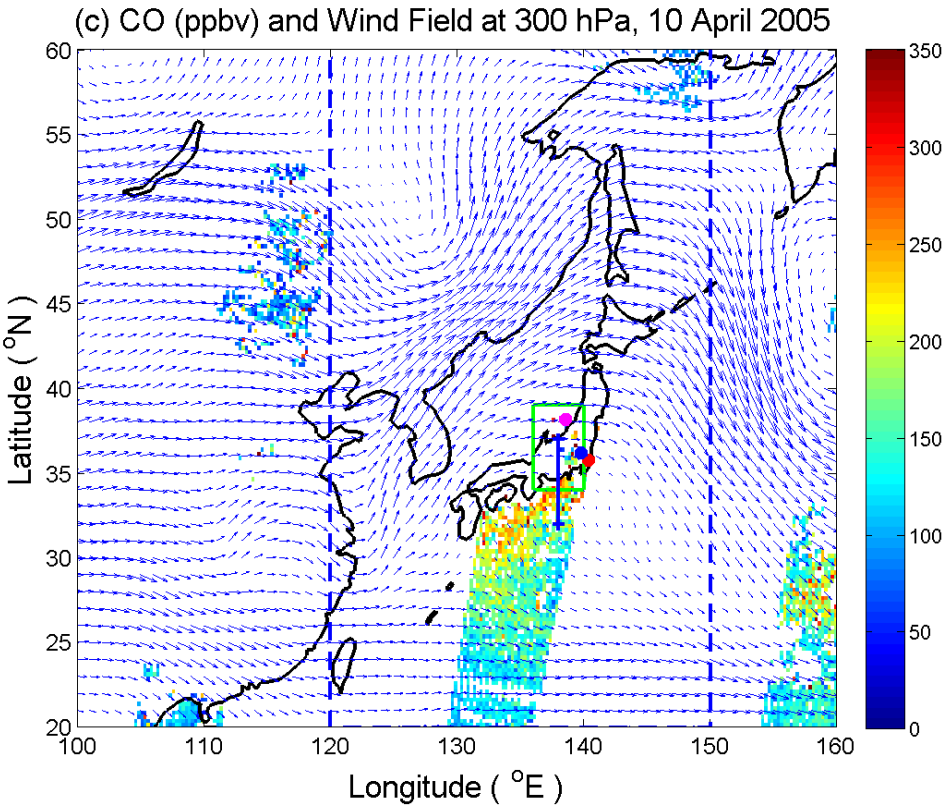
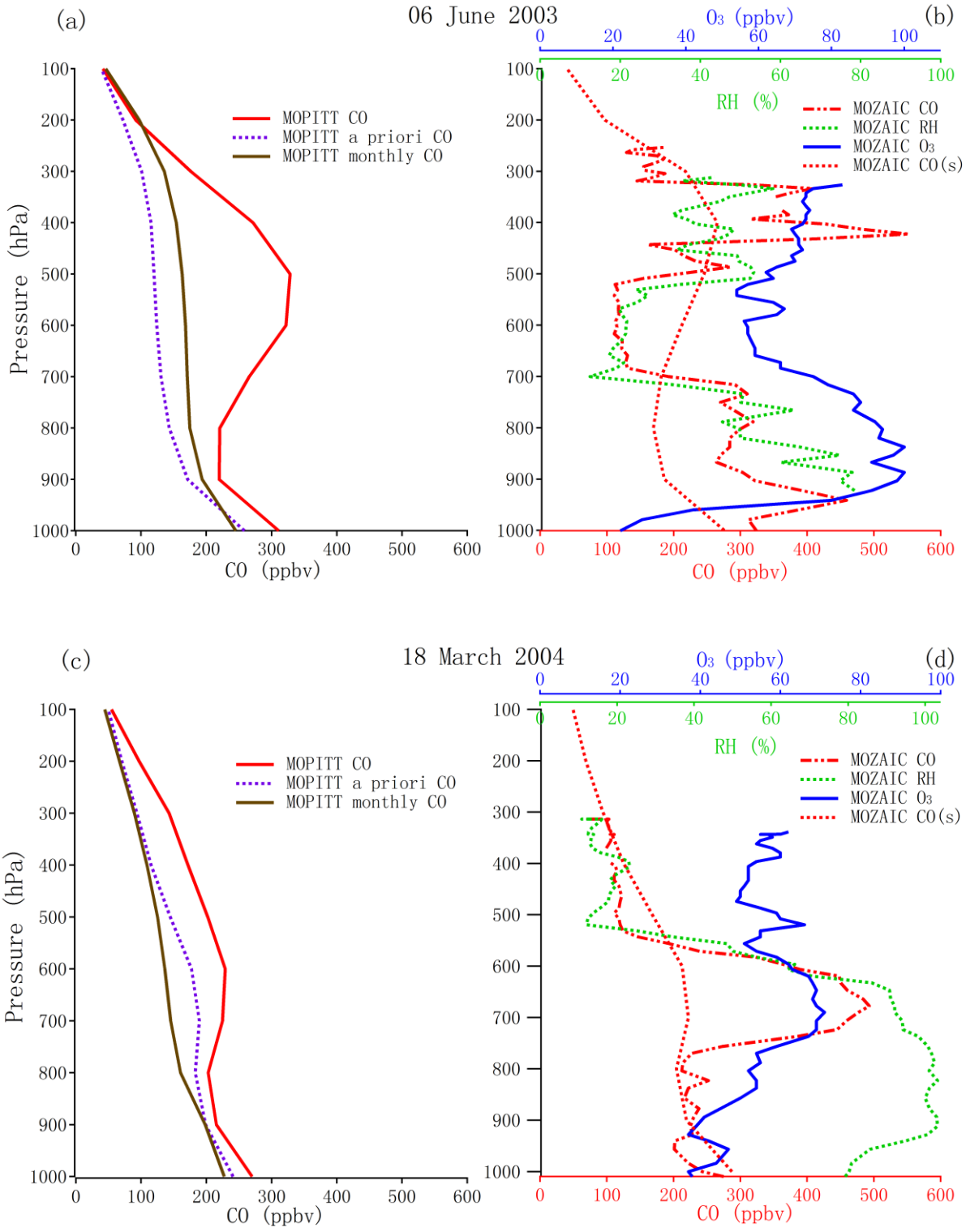


Fig. 4. MOPITT CO mixing ratio (ppbv, in color) (a) on 6 June 2003 at 500 hPa, (b) on 18 March 2004 at 700 hPa, and (c) on April 10, 2005 at 300 hPa. All are overlaid with horizontal winds (in arrows) at the same altitude. In each subfigure, the geographic locations of MOZAIC data at 900, 600, and 300 hPa are indicated as red, blue and pink dots, respectively. The box indicates an area over which mean MOPITT CO profile are taken and displayed in Fig.5. The box is selected to ensure over 30 MOPITT samplings at the closest upwind direction of MOZAIC measurements. The two blue dashed lines define the longitudinal zone, over which the CO abundances were averaged and shown in Fig 6. The solid blue bars in Figs. 4a and 4c indicate the locations where particles were released and backward trajectories were simulated using FLEXPART (see text for detail).


(a)
06 June 2003
(b)
(c)
18 March 2004
(d)
Pressure (hPa)
CO (ppbv)
MOPITT CO
MOPITT a priori CO
MOPITT monthly CO
O3 (ppbv)
RH (%)
MOZAIC CO
MOZAIC RH
MOZAIC O3
MOZAIC CO(s)

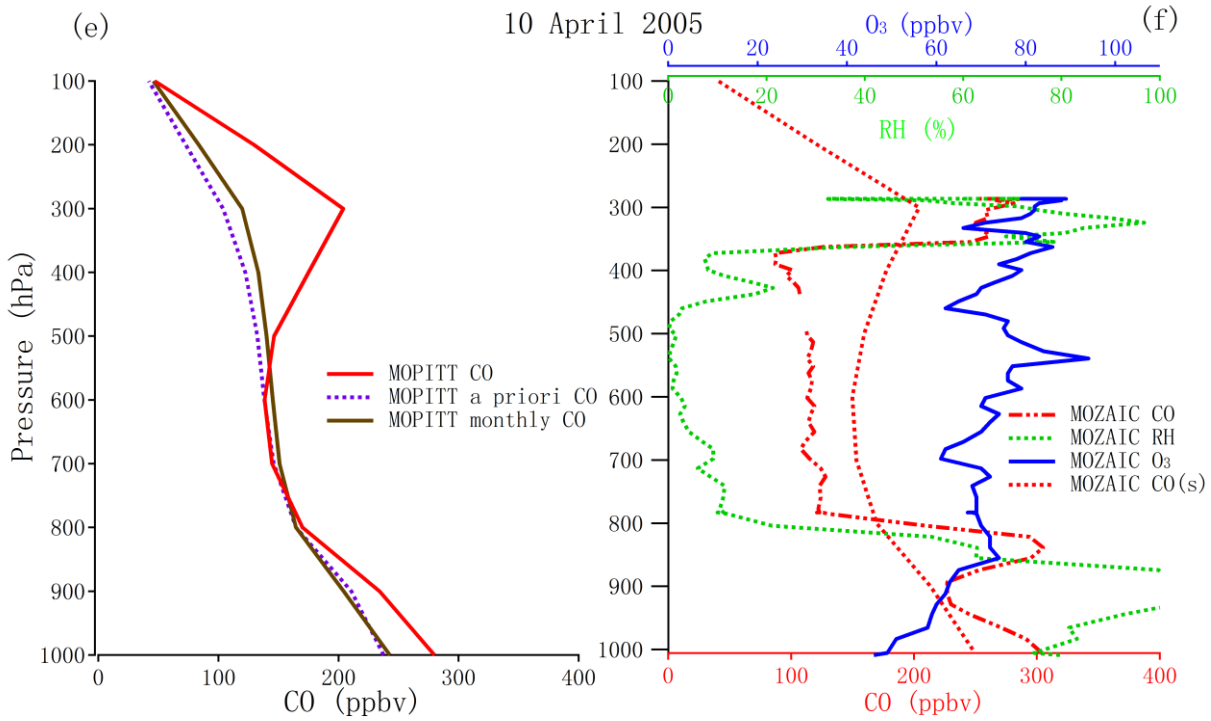
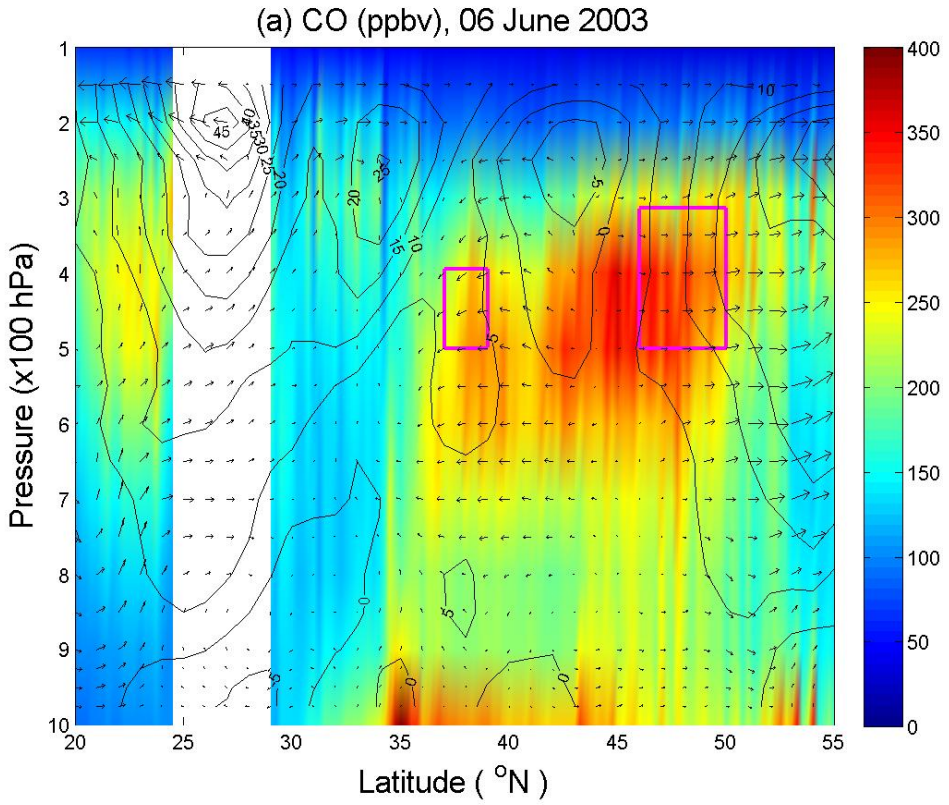
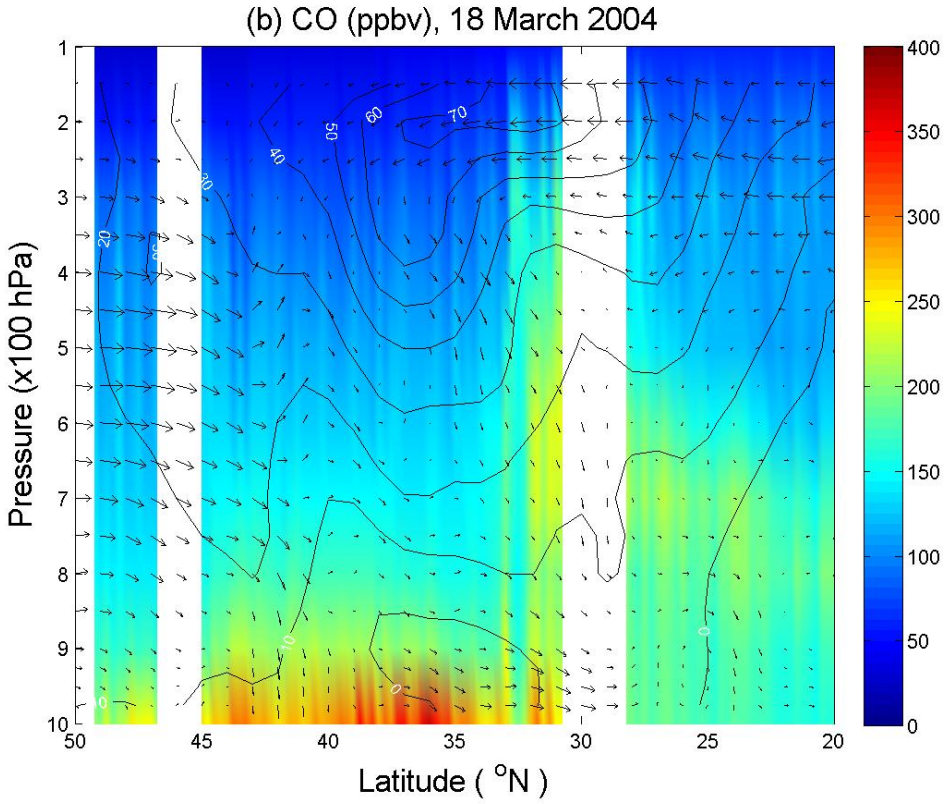


Fig. 5. Profiles of MOPITT CO and the a priori, averaged over the corresponding boxed area in Fig. 4 on (a) 6 June 2003, (c) 18 March 2004, and (e) 10 April 2005, respectively, along with their monthly mean MOPITT CO profile over the same area. The corresponding MOZAIC CO profiles (along the dots in Fig. 4) on the same day are shown in (b), (d), and (f), respectively. The corresponding MOZAIC ozone and relative humidity profiles are also shown in (b), (d), and (f). Note that the smoothed MOZAIC CO profiles (MOZAIC CO(s)) were calculated using the averaging kernels and the a priori in the boxed area in each case (see Sect. 5 for discussion).


(a) CO (ppbv), 06 June 2003
Pressure (x100 hPa)
Latitude (°N)
1
2
3
4
5
6
7
8
9
10
20
25
30
35
40
45
50
55
400
350
300
250
200
150
100
50
0


(b) CO (ppbv), 18 March 2004
Pressure (x100 hPa)
Latitude (°N)
1
2
3
4
5
6
7
8
9
10
50
45
40
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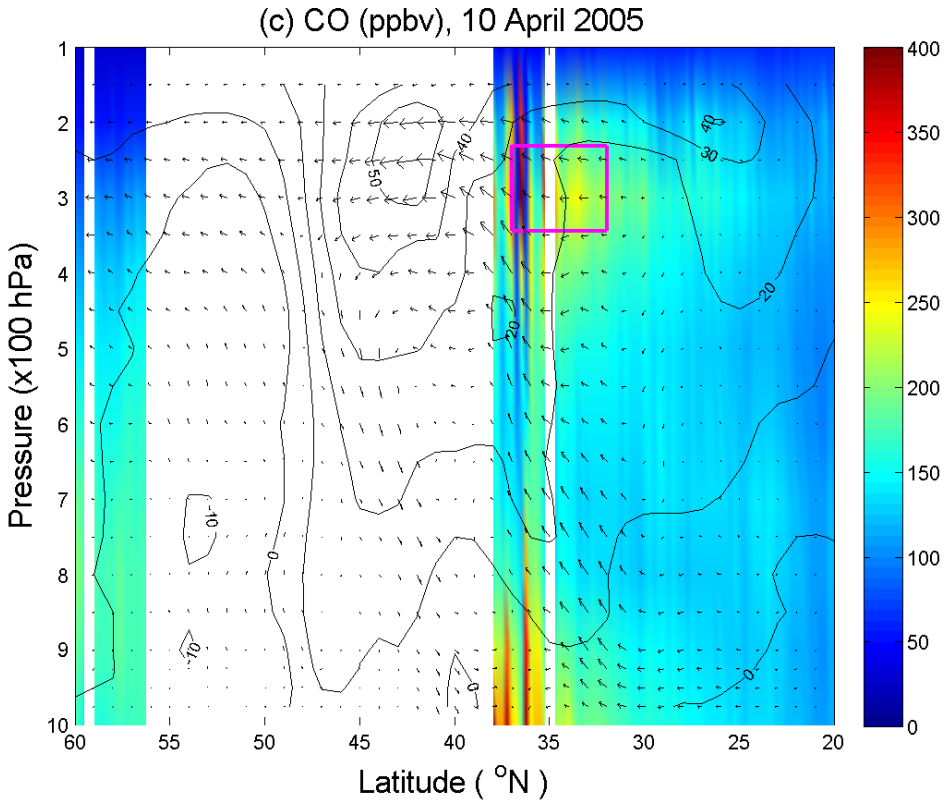
30
25
20
400
350
300
250
200
150
100
50
0



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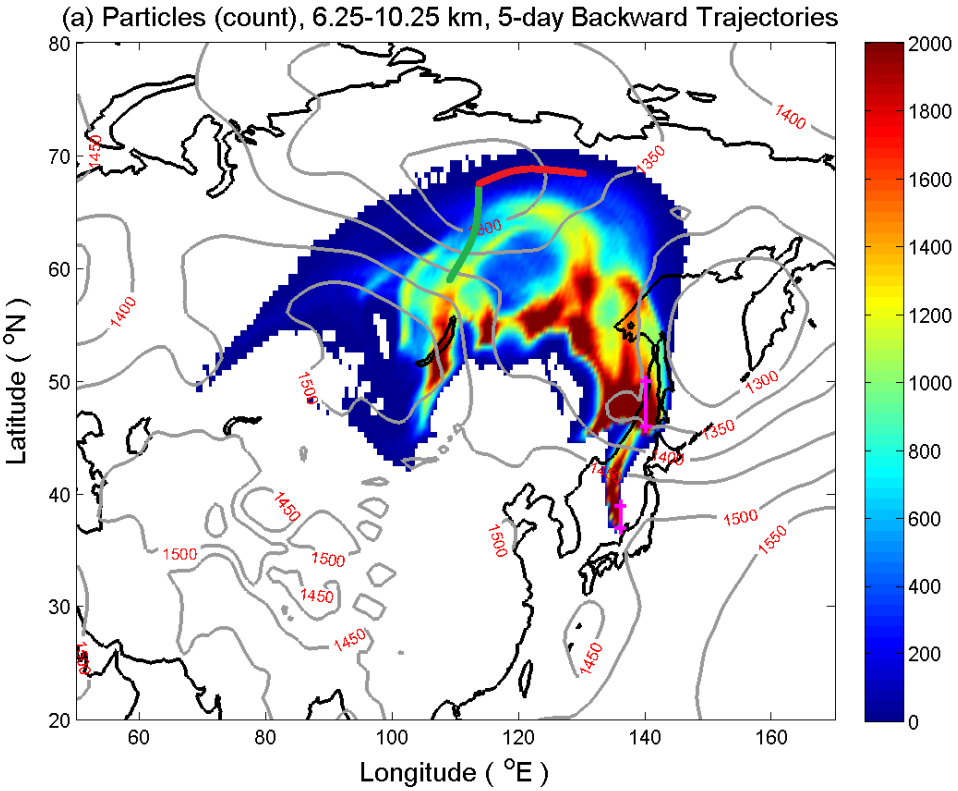

(a) Particles (count), 6.25-10.25 km, 5-day Backward Trajectories
Latitude (°N)
Longitude (°E)
80
70
60
50
40
30
20
60
80
100
120
140
160
2000
1800
1600
1400
1200
1000
800
600
400
200
0
1400
1350
1300
1450
1500
1550

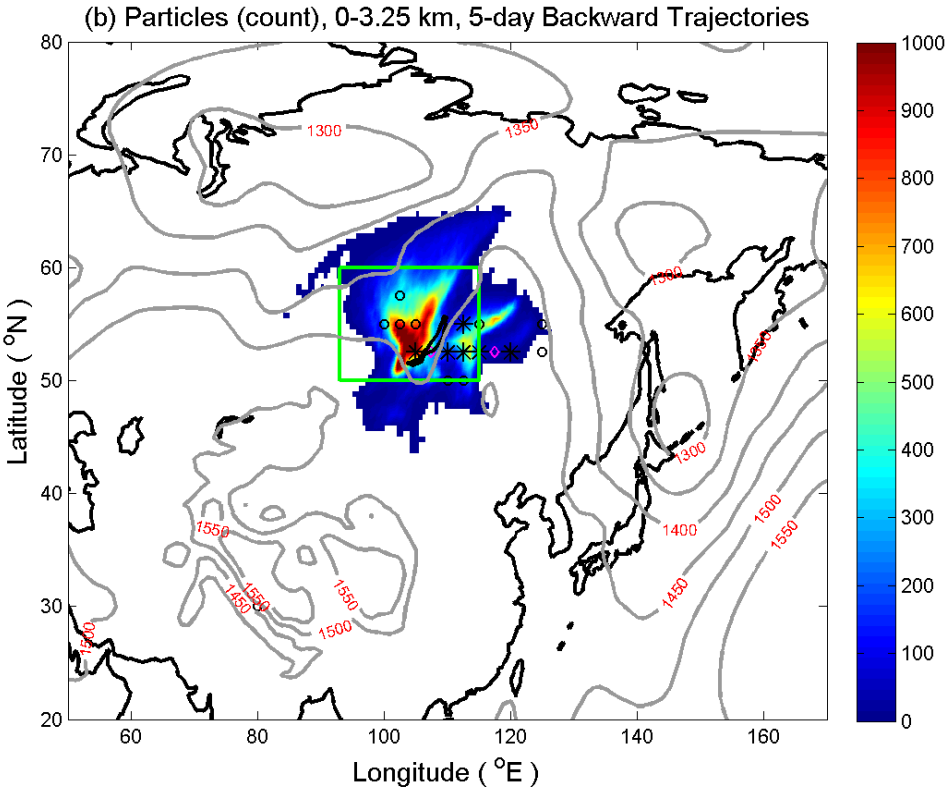

(b) Particles (count), 0-3.25 km, 5-day Backward Trajectories
Latitude (°N)
Longitude (°E)
80
70
60
50
40
30
20
60
80
100
120
140
160
1000
900
800
700
600
500
400
300
200
100
0
1300
1350
1400
1450
1500
1550

Fig. 7. (a) Particle distribution between 6.25-10.25 km (~550-250 hPa) during June 1-6, 2003. The particles were released from two locations (in pink lines) around 400 hPa (also see Figs. 4a and 6a) on June 6, 2003 and backward trajectories were calculated. The contour lines are the geopotential heights at 850 hPa on June 3, 2003. A cold front and a warm front are indicated by green and red lines, respectively. (b) The same as (a), but between 0-3.5 km. The contour lines are the geopotential heights at 850 hPa on 2 June 2003. The circles, diamonds, and stars denote daily mean fire counts of 20-100, 100-300, and 300-500 per 2.5×2.5 °grid area, respectively, from May 31 to June 6.

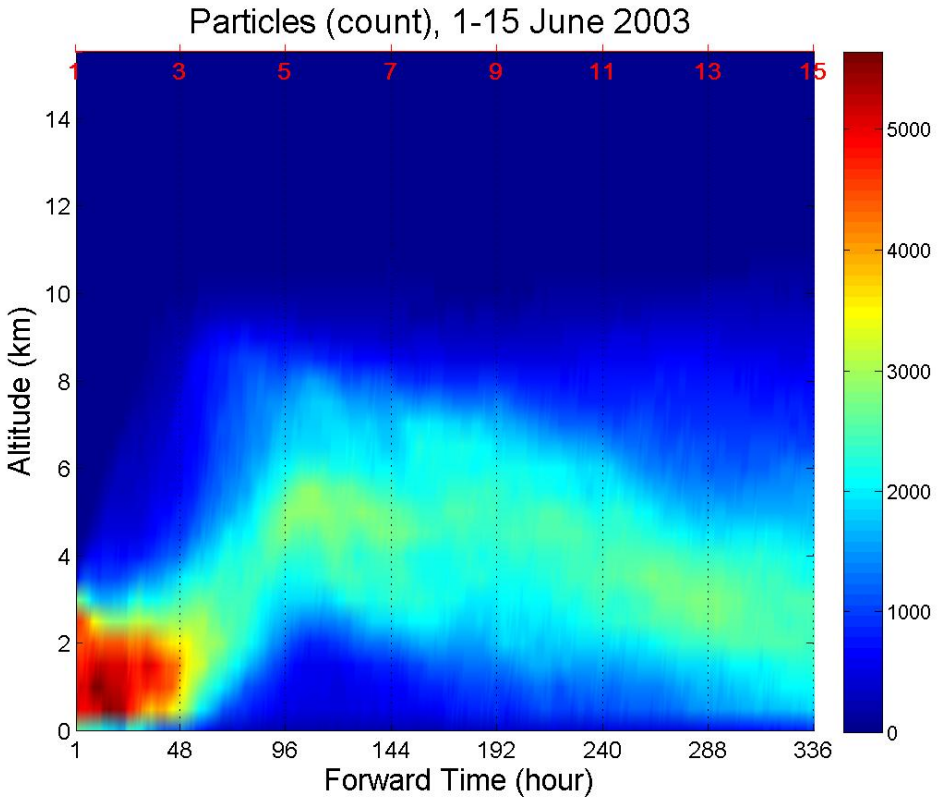


Fig. 8. Vertical distribution of particles, varying with time from 1 June 2003 at 0 UTC to 16 June 2003 at 0 UTC. The particles were released from fire regions in Fig. 7b from the surface to 3 km on 1 June 2003 and forward trajectories were calculated (15 days). The forward time (in hour) and date (in June) are indicated in the x-axis on the bottom and the top, respectively.

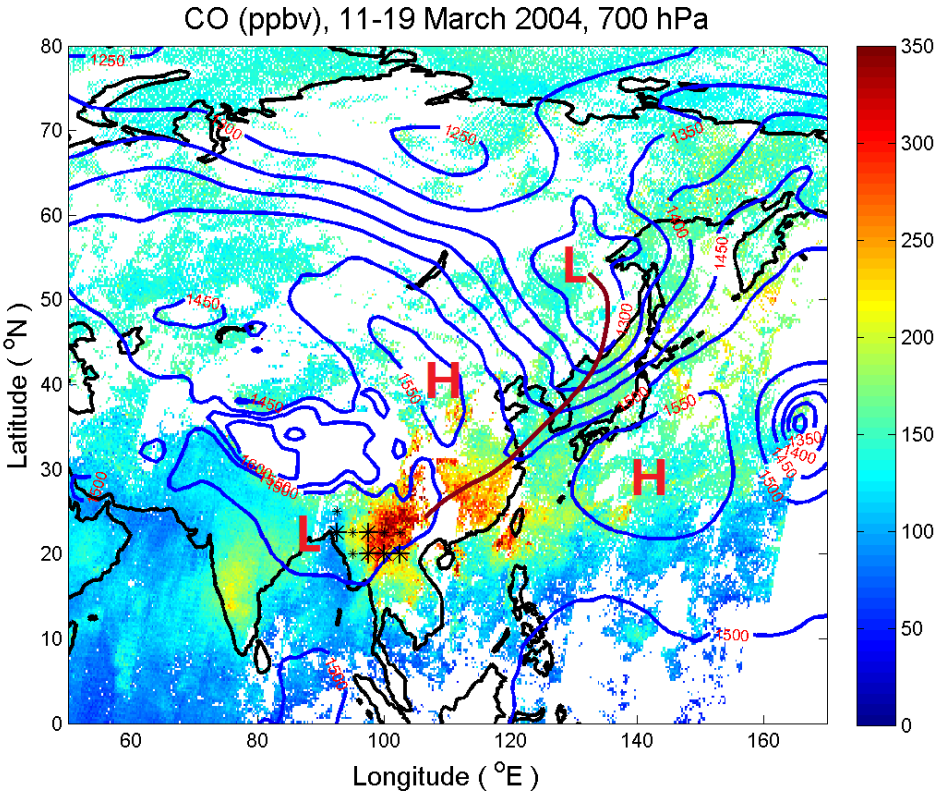
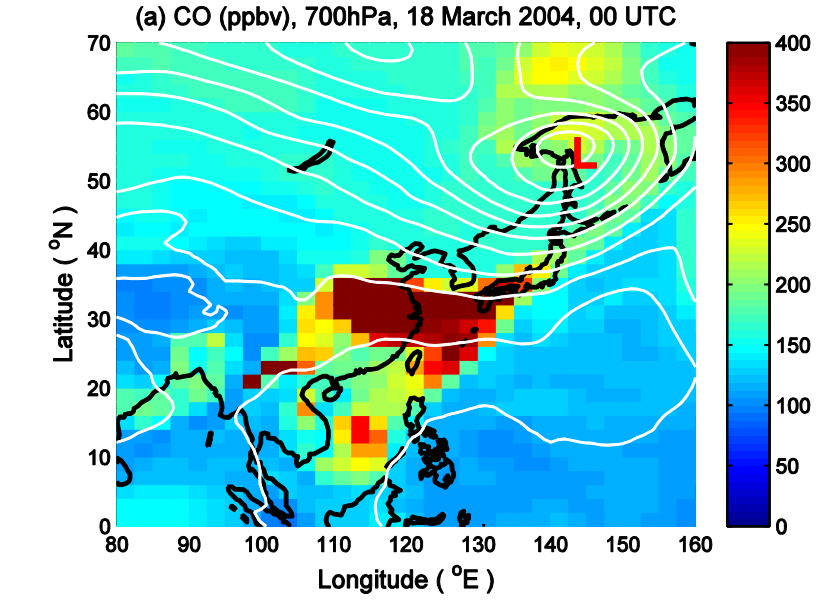
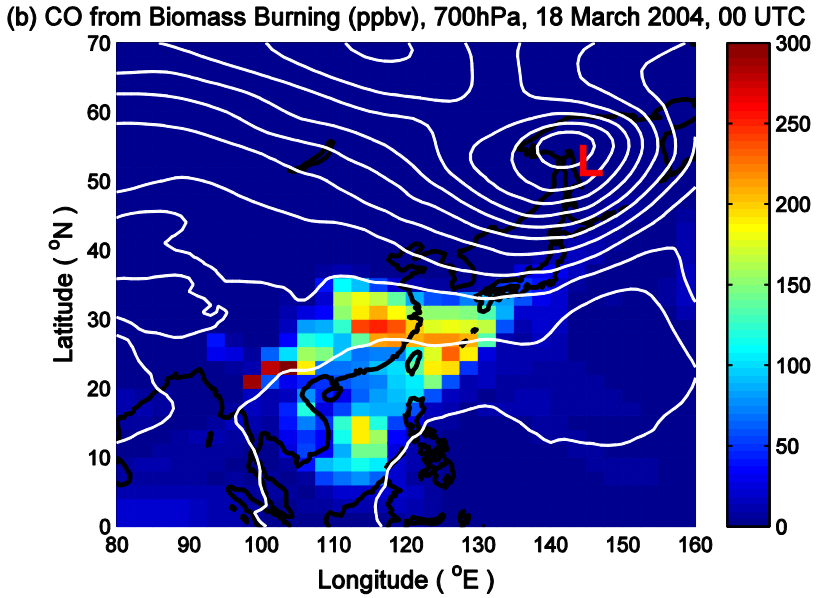


Fig. 9. MOPITT CO mixing ratio at 700 hPa from 11-19 March 2004, overlaid with the geopotential height at 850 hPa on 17 March 2004 in blue contour and with a front shown by brown solid line. The large and small stars denote daily mean fire counts of 100-200 and over 200 per 2.5×2.5 °grid area during the period, respectively. “L” and “H” indicate a low and high pressure system, respectively.


(a) CO (ppbv), 700hPa, 18 March 2004, 00 UTC
Latitude (°N)
Longitude (°E)
L


(b) CO from Biomass Burning (ppbv), 700hPa, 18 March 2004, 00 UTC
Latitude (°N)
Longitude (°E)
L

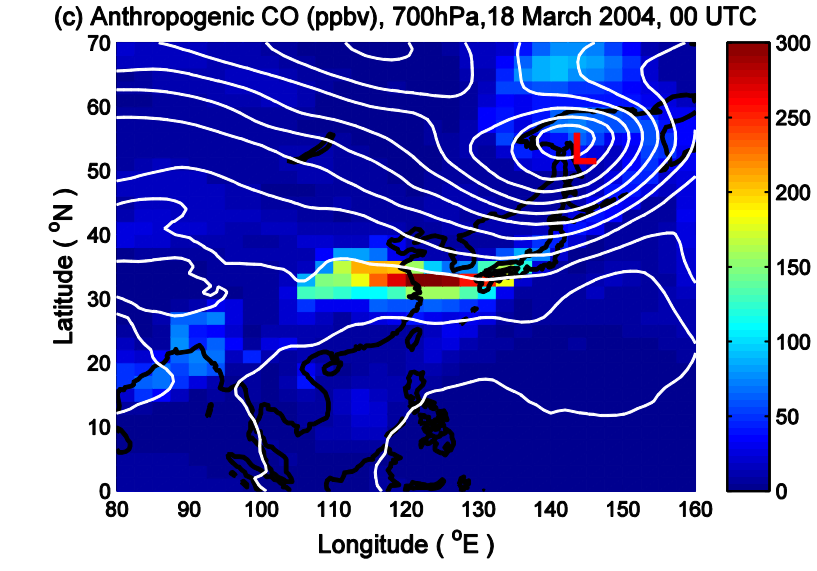
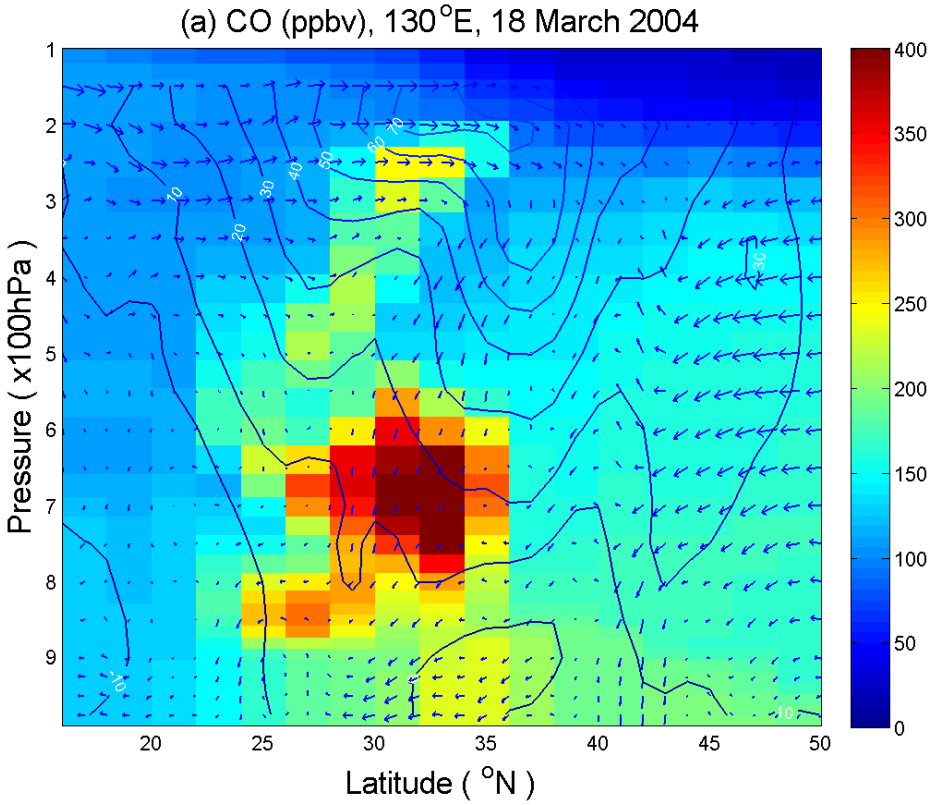
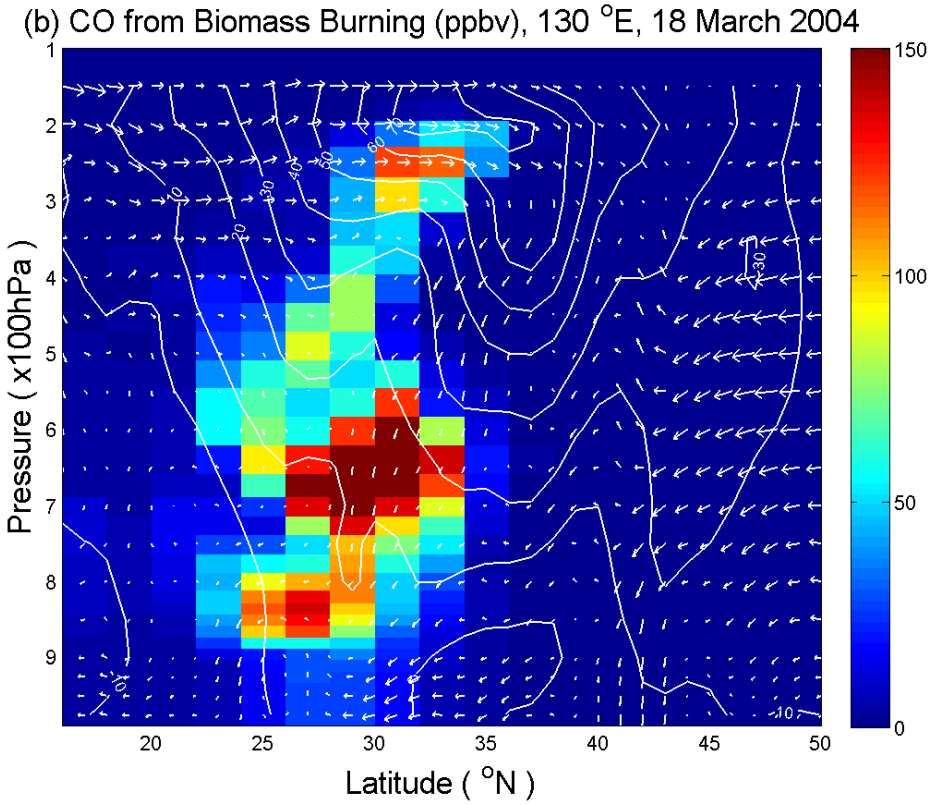

(c) Anthropogenic CO (ppbv), 700hPa,18 March 2004, 00 UTC
Latitude (°N)
Longitude (°E)
L

Fig. 10. (a) CO, (b) CO from biomass burning, and (c) CO from the anthropogenic source on March 18, 2004 at 0 UTC, simulated by GEOS-Chem. The geopotential height at 700 hPa is indicated with white lines. “L” indicates a low pressure system.


(a) CO (ppbv), 130°E, 18 March 2004
Pressure (x100hPa)
Latitude (°N)
1
2
3
4
5
6
7
8
9
20
25
30
35
40
45
50
400
350
300
250
200
150
100
50
0


(b) CO from Biomass Burning (ppbv), 130 °E, 18 March 2004
Pressure (x100hPa)
Latitude (°N)
1
2
3
4
5
6
7
8
9
20
25
30
35
40
45
50
150
100
50
0

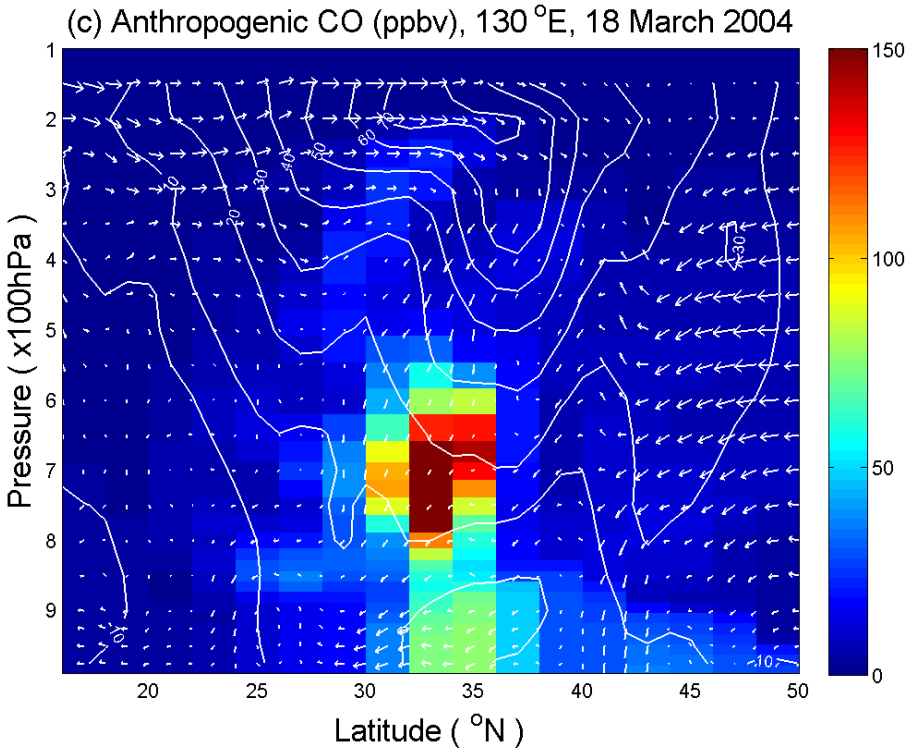


Fig. 11. Latitude-altitude cross sections along 130°E of (a) CO, (b) CO from biomass burning, and (c) anthropogenic CO on March 17, 2004 at 6 UTC, simulated by GEOS-Chem. The contour lines indicate U wind speed (m s^{-1}). Vectors are for wind directions in V and W. For a better illustration, W is enlarged by a factor of 100.

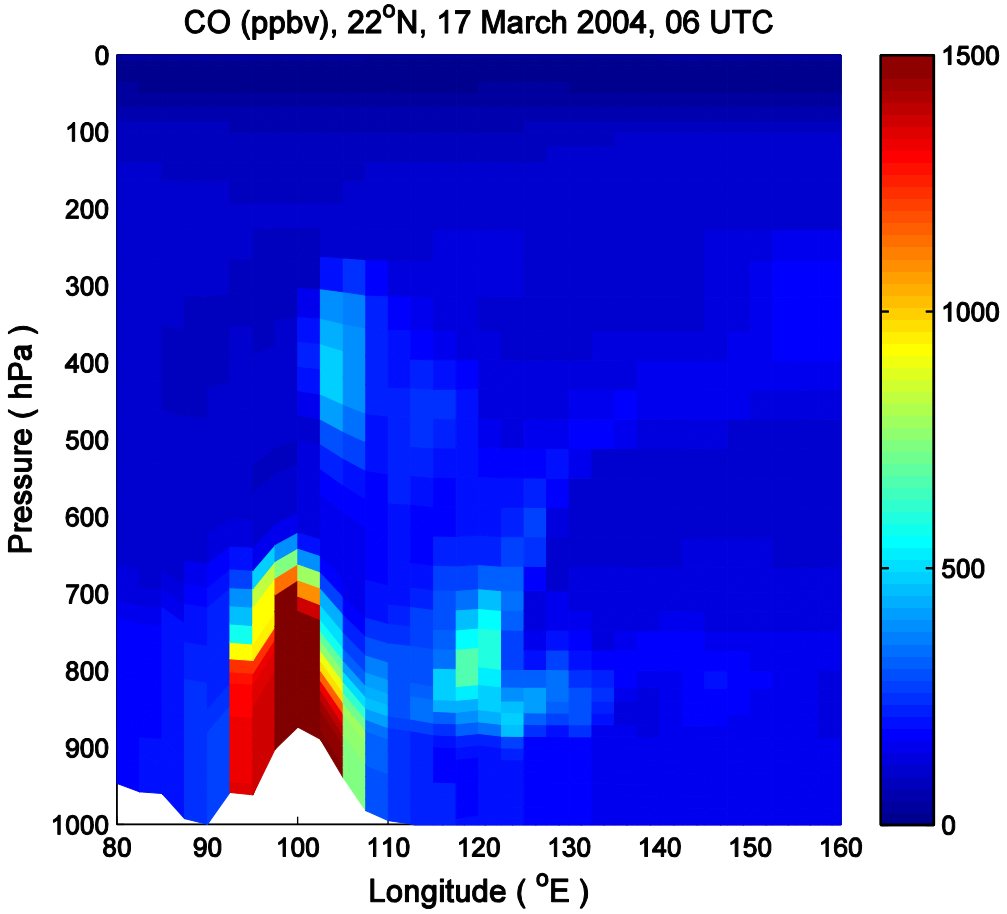


Fig. 12. A longitude-altitude cross section of CO along 22°N on March 17, 2004 at 6 UTC, simulated by GEOS-Chem. The topography of the Hengduan Mountains is indicated in white.

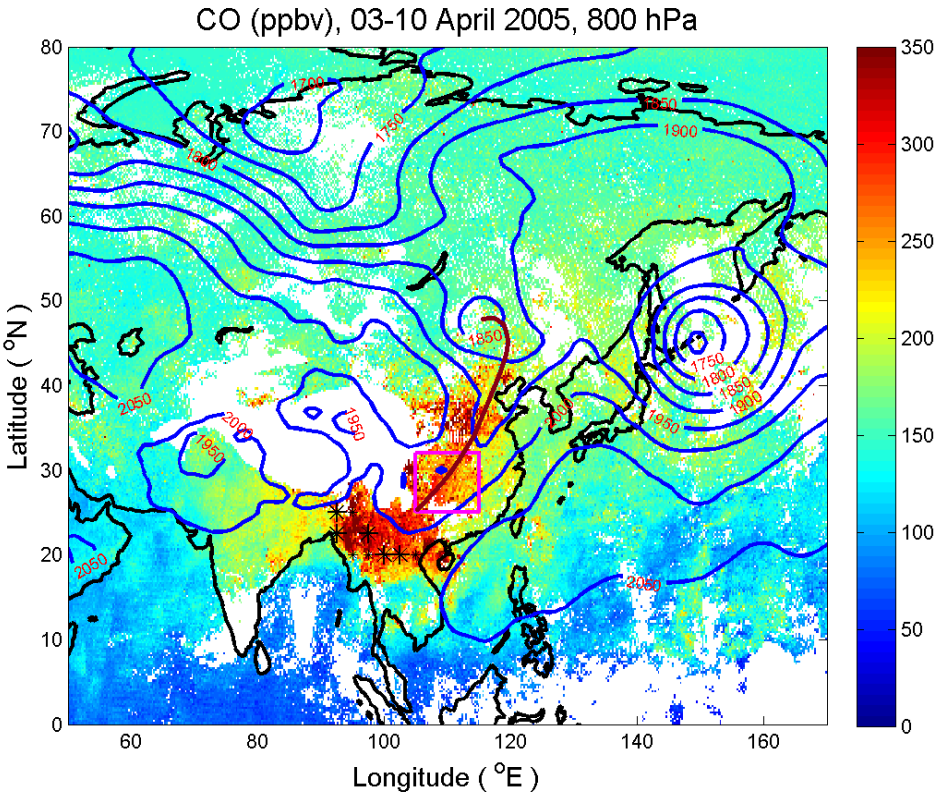
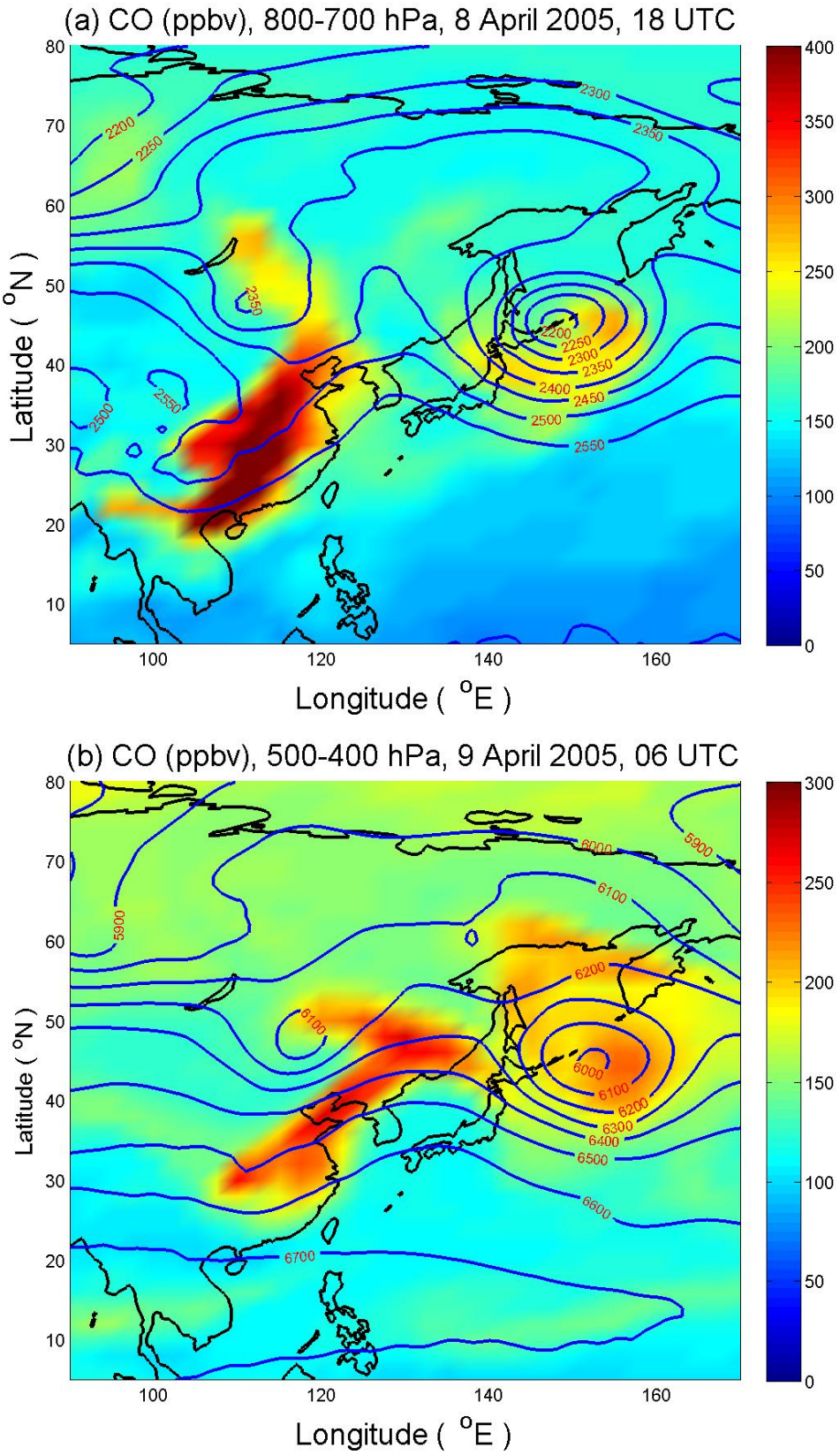


Fig. 13. MOPITT CO mixing ratio at 800 hPa from April 3-10, 2005, overlaid with the geopotential height at 850 hPa on April 9, 2005 at 0 UTC in blue contour and with a front in brown solid line. The large and small stars denote daily mean fire counts of 100-200 and over 200 per 2.5×2.5 °grid area during the period, respectively. The boxed area was identified as a major CO source region from the FLEXPART simulation (see text for detail).


(a) CO (ppbv), 800-700 hPa, 8 April 2005, 18 UTC
Latitude (°N)
Longitude (°E)
(b) CO (ppbv), 500-400 hPa, 9 April 2005, 06 UTC
Latitude (°N)
Longitude (°E)

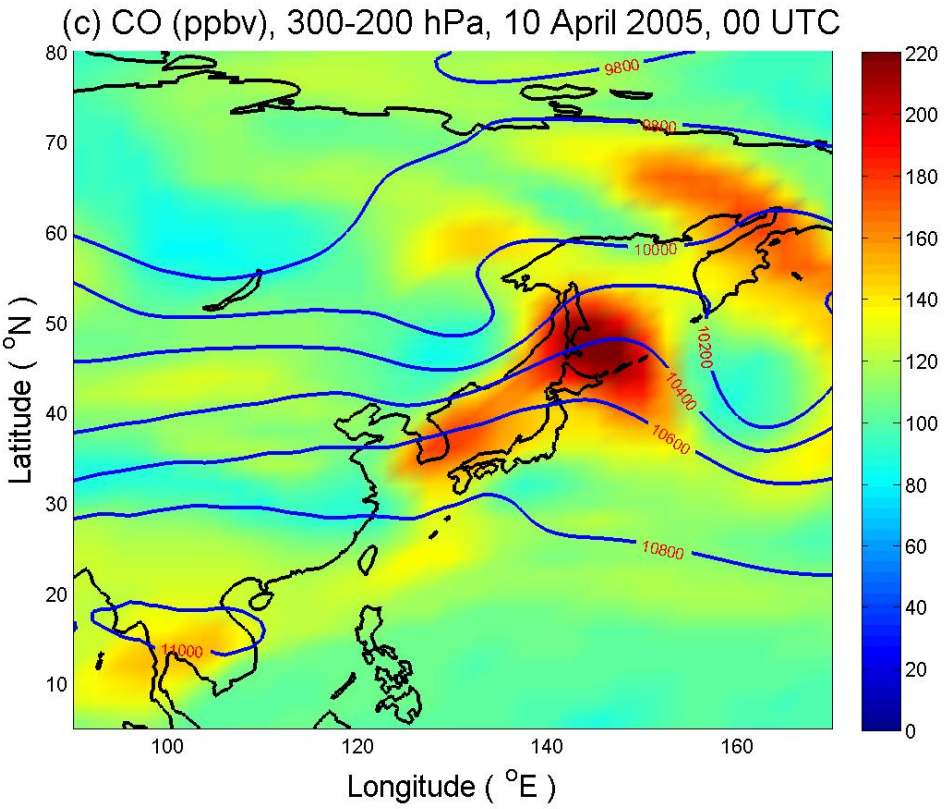
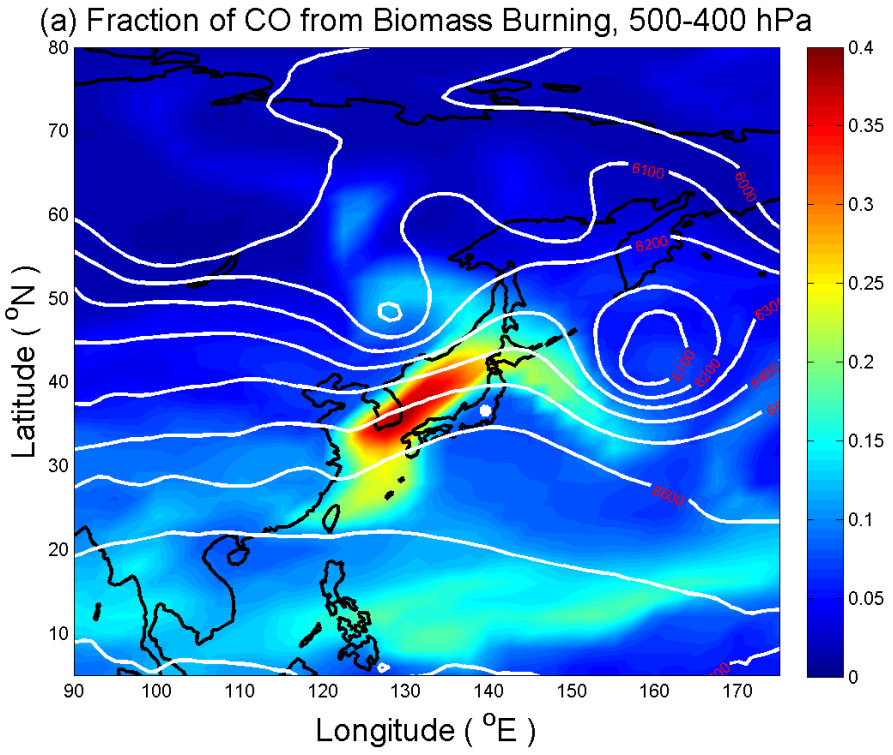
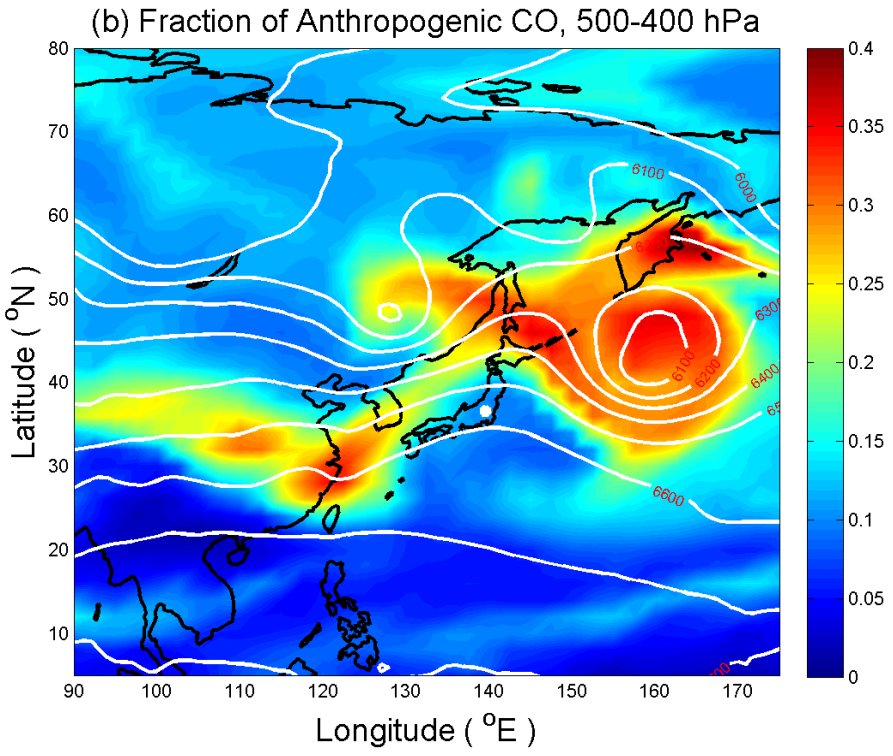


Fig. 14. The GEOS-Chem simulated CO (a) on April 8, 2005 in the lower troposphere (800-700 hPa), (b) on April 9 in the middle troposphere (500-400 hPa), and (c) on April 10 in the upper troposphere (300-200 hPa). The contours are the geopotential height at 850, 450, and 250 hPa, respectively.


(a) Fraction of CO from Biomass Burning, 500-400 hPa
Latitude (°N)
Longitude (°E)
80
70
60
50
40
30
20
10
90
100
110
120
130
140
150
160
170
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
6100
6000
6200
6600


(b) Fraction of Anthropogenic CO, 500-400 hPa
Latitude (°N)
Longitude (°E)
80
70
60
50
40
30
20
10
90
100
110
120
130
140
150
160
170
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
6100
6000
6200
6600

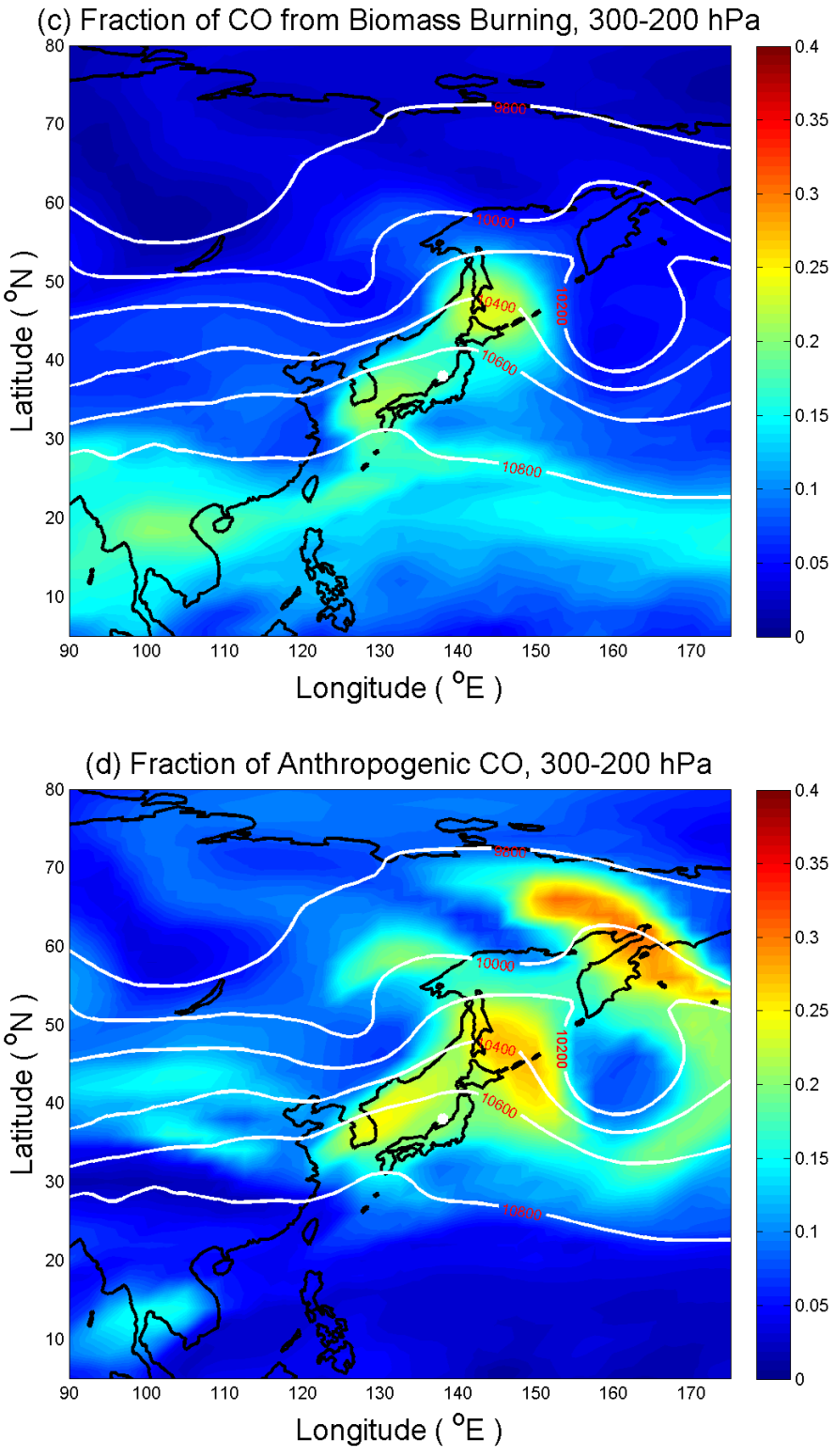


Fig. 15. The GEOS-Chem simulated fractional CO (a) from biomass burning and (b) from the anthropogenic source on April 10, 2005 at 00 UTC in the middle troposphere (500-400 hPa). (c) and (d) are the same as for (a) and (b), respectively, but in the upper troposphere (300-200 hPa). The geopotential height at 450 and 250 hPa is overlaid with the CO images in the middle and upper troposphere, respectively. White dots indicate the location of MOZAIC measurements.

Table 1. Characterization of the three cases.

Case	2003	2004	2005
Date	6 June 2003	18 March 2004	10 April 2005
Maximum CO (ppbv) in MOZAIC profiles in FT	~550	~500	~300
CO peak height (hPa) in MOZAIC profiles in FT	500-300	750-550	350-250
Maximum CO (ppbv) in MOPITT images	300-400	200-250	150-200
CO peak height (hPa) in MOPITT images	650-300	750-500	400-250
Peak CO area in MOPITT images	35-55°N 125-145°E	20-32°N 125-135°E	32-37°N 130-140°E
Major CO sources	Large fires near Lake Baikal in Russia	Fires in the Indochina peninsula, anthropogenic emissions in the North China Plain	Fires in the Indochina peninsula, anthropogenic emissions in the North China Plain and the Sichuan basin
Vertical transport mechanism	Frontal lifting	Convection (due to leeside troughs), frontal lifting, and orographic lifting	Convection, frontal lifting
Outflow	West coast of Canada	West coast of the United States	West coast of Canada

Table 2. Occurrences of various CO ranges at different altitudes in the MOZAIC measurements in the vicinity of Narita from 2001 to 2006.

Season	Pressure	Occurrence						Fractional Occurrence (%)					
		CO Concentration Range (ppbv)						CO Concentration Range (ppbv)					
	(hPa)	0-100	100-200	200-300	300-400	>400	All	0-100	100-200	200-300	300-400	>400	All
All	400-200	67	354	93	19	6	539	12	66	17	4	1	100
	600-400	36	359	69	15	8	487	7	74	14	3	2	100
	850-600	17	180	150	31	6	384	4	47	39	8	2	100
	Surface-850	4	60	142	83	88	377	1	16	38	22	23	100
Spring	400-200	11	96	28	12	2	149	7	64	19	8	1	100
	600-400	1	101	29	9	3	143	1	71	20	6	2	100
	850-600	0	38	55	20	5	118	0	32	47	17	4	100
	Surface-850	0	14	44	27	29	114	0	12	39	24	25	100
Summer	400-200	14	132	41	4	4	195	7	68	21	2	2	100
	600-400	13	138	22	1	2	176	7	78	13	1	1	100
	850-600	14	80	50	6	0	150	9	53	33	4	0	100
	Surface-850	4	32	48	30	36	150	3	21	32	20	24	100
Fall	400-200	30	61	15	2	0	108	28	56	14	2	0	100
	600-400	20	50	11	2	1	84	24	60	13	2	1	100
	850-600	3	30	17	3	0	53	6	57	32	6	0	100
	Surface-850	0	10	20	12	11	53	0	19	38	23	21	100
Winter	400-200	12	65	9	1	0	87	14	75	10	1	0	100
	600-400	2	70	7	3	2	84	2	83	8	4	2	100
	850-600	0	32	28	2	1	63	0	51	44	3	2	100
	Surface-850	0	4	30	14	12	60	0	7	50	23	20	100

Table 3. Occurrences of various CO ranges at different altitudes in GEOS-Chem simulations and MOPITT observations in the vicinity of Narita (126-140 °E 30-40 °N) in 2005.

Pressure (hPa)	GEOS-Chem: Fractional Occurrence (%) CO Range (ppbv) 0-100	100-200	200-300	300-400	>400	All
200-100	12	87	1	0	0	100
400-200	0	87	12	1	0	100
600-400	0	53	35	11	1	100
850-600	0	20	46	25	8	100
1000-850	0	7	46	35	11	100

Pressure (hPa)	MOPITT: Fractional Occurrence (%) CO Range (ppbv) 0-100	100-200	200-250	>250	All
200-100	38	45	11	6	100
400-200	4	68	18	10	100
600-400	6	86	6	1	100
800-600	7	67	20	6	100
1000-800	2	16	18	64	100