**Atmospheric
Chemistry
and Physics
Discussions**

Interactive comment on "Regional CO pollution in China simulated by the high-resolution nested-grid GEOS-Chem model" *by* D. Chen et al.

D. CHEN

rainycd@gmail.com

Received and published: 29 May 2009

We would like to thank Referee 2 for careful reading of the manuscript and for thoughtful comments. We have addressed the comments below: original reviews are in italics followed by our responses.(The revised paper and new figures are attached as the supplement *.zip file)

Review of "Regional CO pollution in China simulated by the high resolution nested-grid GEOS-Chem model" Chen et al., [2009]

This paper introduces an updated, high horizontal and vertical resolution, nested version of the global chemical transport model GEOS-Chem applied to China. They use this model to examine the emission locations and meteorological conditions respon-

sible for high pollution episodes in the Beijing region. They go onto to provide new seasonal estimates/regional contributions of CO export to the Eastern Pacific.

I think this paper is very well written and provides surprising finding on the causes of high pollution episodes over Beijing (i.e., high % regional emissions) as well as a better understanding of the seasonal variations in export from Asia. I think the authors can improve the paper significantly in the following areas as described in the comments below: 1) by doing a much better job of citing previous literature, 2) by clarifying assumptions and previous validation efforts, and 3) by strengthening some conclusions (e.g., improved representation of low-level vortex)

General Comments:

Comments 1: You mention in your introduction that there has been little study on outflow in the summer. But, there have been several studies looking at the summertime export of pollution from Asia with GEOS-Chem. In particular, a series of papers by Q. Liang. You mention one, but don't compare results at all. I suggest comparing your results more carefully to this previous work.

Liang, Q., L. Jaeglé , and J. M. Wallace, Meteorological indices for Asian outflow and transpacific transport on daily to interannual timescales, J.Geophys. Res., 110, D18308, doi:10.1029/2005JD005788, 2005.

Liang, Q., L. Jaeglé, et al., Summertime influence of Asian pollution in the free troposphere over North America, J. Geophys. Res., 112, D12S11, doi:10.1029/2006JD007919, 2007.

Liang, Q., L. Jaeglé, D.A. Jaffe, P. Weiss-Penzias, A. Heckman, J.A. Snow, Longrange transport of Asian pollution to the Northeast Pacific: Seasonal variations and transport pathways of carbon monoxide, J. Geophys. Res., 109(D23), D23S07, doi:10.1029/2003JD004402, 2004.

Holzer, M., T. M. Hall, and R. B. Stull (2005), Seasonality and weather-driven variability

of transpacific transport, J. Geophys. Res., 110, D23103, doi:10.1029/2005JD006261.

Reply: Thanks for the suggestions. The four papers suggested by the reviewer are cited in the revised manuscript and summarized in the Introduction (Section 1, Pg. 6, line 88-97) and discussion of the summer export in Section 5 (Pg. 22-23, line 413-430; Pg. 23, line 440-443; Pg. 26, line 492-497).

(Pg. 6, line 88-97): "Many previous studies have examined the mechanisms controlling the outflow of CO from Asia to the NW Pacific in springtime, the season with maximum export fluxes (Liu et al., 2003; Fuelberg et al., 2003; Liang et al., 2004, 2005, 2007; Miyazaki et al., 2003; Koile et al., 2003; Holzer et al., 2005). Liang et al. (2004, 2005, 2007) and Koile et al. (2003) have studied the pollution outflow from East Asia in summertime. However, all these studies took China or East Asia as a whole, whereas there exits significant regional differences within East Asia and China in terms of meteorology and emission characteristics. The present study will examine the outflow pattern and efficiencies for export of CO from different administrative regions of China, focusing also on seasonal differences between spring and summer."

(Pg. 22-23, line 413-430): "Many previous studies have used CO as a tracer to examine the patterns and mechanisms of Asian outflow to the Pacific, and much of the attention has thus far been paid to springtime (Liu et al., 2003; Fuelburg et al., 2003; Liang et al., 2004, 2005, 2007; Miyazaki et al., 2003; Koile et al., 2003; Holzer et al., 2005). They found that the major process responsible for the export of Asian anthropogenic pollution to the western Pacific during spring is frontal lifting to the free troposphere (FT) ahead of southeastward-moving cold fronts and transport in the boundary layer (BL) behind the cold front. Orographic lifting over central and eastern China combines with the cold fronts to promote the transport of Chinese pollution to the FT. Liang et al. (2004; 2005; 2007) and Holzer et al. (2005) studied the seasonal variations of Asian outflow by using continuous CO measurements at a coastal site in Washington state and GEOS-Chem model. Liang et al. (2004; 2005; 2007) found maximum export of Asian pollution to the western Pacific occurs at 20°–50°N during spring throughout

C1332

the tropospheric column, shifting to 30°-60°N during summer, mostly in the upper troposphere. They also developed three new sea-level pressure indices, which capture variations in transpacific transport on daily to inter-annual timescales and found that during summer, the Asian outflow displayed lower levels of CO due to shorter lifetime of CO in summer. Convective injection into the upper troposphere occurrs predominantly in summer, as compared to the frontal mechanisms dominated in spring in the export (Liang et al., 2005; 2007)."

(Pg. 23, line 440-443): "The overall fluxes in springtime are larger by a factor of 2-3 than the fluxes in summertime, consistent with the seasonality suggested by Liu et al. (2003) and Liang et al. (2004) for the export of Asian anthropogenic CO to the NW Pacific."

(Pg. 26, line 492-497): "Consistent to the seasonality study of Asian export carried out by Liang et al. (2004; 2005; 2007), the convection is expected to be stronger in summer than in spring, resulting in more efficient lifting and subsequently, stronger outflow in the free troposphere. While in summer, the eastward fluxes of Chinese CO all take the common pathway confined to north of 35°N in the free troposphere, regardless of the latitudes from which emissions originated. In contrast, outflow in springtime is strongest over the same latitudes of emissions."

Comments 2: P5860, CO Emissions: I suggest a table with CO emissions similar to Wang et al., 2004b and some discussion of how these have changed and been validated (including biomass burning since it is important for your export work). Can you breifly describe how these Zhang et al., 2009 emissions differ from previous estimates? Seasonality imposed? Are their previous validation studies (i.e., how good are your emissions)?

Reply: The paper of Zhang et al. has become available on ACPD after submitted in Jan 2009, we updated the reference as follows:

Zhang, Q., Streets, D., Carmichael, G., et al.: Asian emissions in 2006 for the NASA

C1333

INTEX-B mission, Atmos. Chem. Phys. Discuss., 9, 4081-4139, 2009

The detailed description about the methodology and difference to the previous estimates of emission inventories are given in the reference. The seasonality in CO emissions was not imposed when we carried out the study. As a way of validation, tropospheric CO columns retrieved from MOPITT are added in the revised manuscript to compare with the model results (Section 3.2, Pg. 12 , line 206-220), in response to comments by another referee. We have added a brief description of the inventory in Section 3 (Pg. 9-10, line 162-171).

"A series of improved methodologies were implemented in the study of Zhang et al. (2009), to gain a better understanding of emissions from China, including a detailed technology-base approach, a dynamic methodology representing rapid technology renewal and critical examination of energy statistics. The inventory was based upon the studies of Streets et al. (2006), which improved estimations for emissions from Chinese industrial sources that had been underestimated in the inventory developed earlier in support of the TRACE-P aircraft mission (Streets et al., 2003). Zhang et al. (2009), found that Chinese emissions of CO increased by 18% from 2001 to 2006. The anthropogenic CO emissions in 2006 from Asia and China used in the model are 298.2 and 166.9 Tg/year respectively, with no month-to-month variations."

Comments 3: P5862: I don't see this Sichuan Basin low level vorticies argument at all from Figure 2. To do this properly I think you need a new figure to zoom in and show the topography and wind barbs similar to what Wang et al. 2004a did in Figure 2 & 7. To me it looks like you are just resolving the emissions in that region from Figure 1. It would be really interesting to prove though that the higher resolution captures some important meteorological feature, not standard in global model resolutions, so I hope you pursue showing this better.

Reply: We added new figures (Figure 4a-c) showing the terrain elevations, winds, and surface pressure over the Sichuan Basin. With help of these figures, we added discus-

C1334

sions of the Sichuan Basin Vortex in Section 3.2 (Pg. 13-14, line 232-259):

"It is interesting to note that the CO daytime total columns displays a distinct peak over the Sichuan Basin (the dark regions centered at (105°E, 30°N) in Figure 2) in the high-resolution nested-grid model, but the peak is not so obvious in the intermediate global model. The terrain elevations, winds and surface pressure for the Tibetan Plateau- Sichuan Basin Area are presented in Figure 4. Figure 4a displays the terrain elevations at a resolution of 3 arc-minute (http://www.ngdc.noaa.gov/mgg/topo/pictures/GLOBALeb3colshade.jpg), illustrating the rapid change in elevation from the Tibetan Plateau (4-5km elevation) and Yunan-Guizhou Plateau (2-3 km elevation) to the Sichuan Basin (0.5 km elevation). As shown in Figure 4a, the Sichuan Basin locates in the center between the Tibetan Plateau and Yunnan-Guizhou Plateau, making it a saddle pattern for topography. Figure 4b-c are the winds at 2km overlaid with surface pressure simulated by the model at 0.5°×0.667° (b) and 2°×2.5° resolutions (c). In summer, influenced by the southwesterly East Asian summer monsoon, winds blow in a cyclonic pattern over the southeast part of the Sichuan basin. The Tibetan High formed over the middle part of the Tibetan Plateau as the western Pacific Subtropical High shifted westward to the west of the Sichuan Basin (Chen D et al., 2007). Figure 4b clearly shows the pattern described above. Under the influence of the large scale circulations, strong northwesterly flow enters the basin around the east edge of the Tibetan Plateau, while southwesterly flow enters the eastern part of the Sichuan Basin around the northwest edge of the Yunnan-Guizhou Plateau. The interaction between the two flows forms a convergent zone of northward jet stream over the east of the Sichuan Basin due to the blocking effect of topography and the westward shift of the Western Pacific Subtropical High. Chen D et al. (2007) also found that since dry air continuously entered the upper level over the Sichuan basin, strong instability of vertical convection formed over the basin and developed toward the northeast of the basin, which maintained and continuously intensified cyclonic vorticity. The process makes the Sichuan Basin a favorable location for stationary low-level vortices, or the so-called the southwest vortex (Chang et al., 2002),

C1335

which tend to trap pollutants within the columns above the Basin. As shown in Figure 4c, the resolution of the intermediate global model is too coarse to resolve the terrain effects of the Basin and the meteorological features accordingly."

Comments 4: Can you offer any indication of the improvement in the model due to increased vertical levels?

Reply: The vertical levels in the high resolution and standard models are the same, so we hadn't carried out any study on the improvement due to increased vertical levels.

Comments 5: The model is never going to capture those huge peaks (I think due to errors in winds) and that 1300 ppbv cut off seems arbitrary. It also makes the 7/19 peak look more important than it is. Maybe a better comparison would be to compare the % anomalies from the mean CO for obs and model, this would show that the model captures the variability in ventilation, which is what you are trying to show. It would also be good to report the r2 of your model/obs comparison.

Reply: We have removed the original figure and added the day-to-day variability in terms of percentage anomalies from the mean CO. No data was cut off and the variability shows that the high resolution model does a better job during the days when observed CO values are lower than 1500 ppbv. We added the following discussions in Section 3.2 (Pg. 17-18, line 315-331).

"To examine whether increasing spatial resolutions improves the model's ability to capture the variability, the percentage anomalies from the mean CO for observation and model are compared in Figure 6b. The Figure includes results from the high-resolution nested-grid model and the intermediate-resolution global model. When the observed CO levels are lower than 1500 ppbv, the high-resolution nested-grid model performs better than the global model in capturing the temporal variability of observations, such as for Jul 3, 14 and 26. For other days with observed CO exceeding 1500 ppbv, the performance of the two models is almost the same in comparison to observations. The correlate coefficients between model and observations for July 2005 are 0.5 and 0.4 for

C1336

the high-resolution and inter-mediate resolution simulations, respectively, while the correlate coefficients for the whole summer are around 0.60 for both models. The day-to-day variability of CO simulated by the models are generally weaker than observations, which is often the case when point measurements are compared with grid-averaged model predictions, as the DL site is easily impacted by urban pollution plumes whose exact timing and scale are difficult to simulate at the spatial resolution of the nested-grid model. Other possible explanations for the bias of the model results include uncertainties in CO emissions (both in spatial and temporal distribution)."

Comments 6: If you have it, and the DL site is not so influenced by local met a wind direction comparison may be useful (if it is v. locally influenced you shouldn't be showing wind speed).I think the wind direction would really strengthen your processes governing ventilation argument.

Reply: Actually, we think the DL site is locally influenced and the wind speeds we used in the paper are the averaged results from DL site and other 9 monitoring sites. This is clarified (Pg. 18, line 336-338). "As the DL site may be influenced by local meteorology, the wind speeds here are the averaged results from not only DL sites but also the other 9 monitoring sites in this area."

Comments 7: P5866 L15, " : : :BJ tracer (representing local emissions) and the TH tracer is 0.52" Does this suggest transport from these regions is favorable on high CO days?

Reply: The tracer correlations between BJ and TH is 0.52, showing that there are relatively large regional influences. Considering the day-to-day variations in mixing ratios of individual tagged tracers, we concluded that the transport is favorable on high CO days.

Comments 8: P5867: I think your description of the meteorology doesn't match the figure and recommend the following changes. On Jul 3, the winds seems much stronger than 1 m/s that you say they are, that seems consistent with Jul 2. So, July 2 weak

C1337

winds leads to regional scale buildup. Then on Jul 3 the flow switched to southwesterly flow in advance of the front bringing in regional pollution. Then was cleaned out on the back edge of the system (northwesterly) bringing clean air from the North. This is consistent with the correlation between TF & BJ.

Reply: Thanks for the suggestion! It was a typo error of Jul 2 and the flow switching on Jul 3 has been added in Section 4.3 (Pg. 21, line 396-406).

"On Jul 2, a weak low-pressure system was centered over Mongolia, northwest of Beijing. The Beijing area was not strongly influenced by either the low-pressure system to the northwest or the high-pressure system to the southeast. A weak high-pressure system was located over the North China Plain, and the atmosphere was relatively static over Beijing on 2 July, with surface wind speeds below 1 m/s. The static conditions favored accumulation of the regional CO emissions from the heavily polluted Tianjin-Hebei area and local Beijing emissions, resulting in rapid rises in CO mixing ratios. Then on Jul 3 the flow switched to southwesterly flow in advance of the front bringing in regional pollution. The low-pressure system strengthened on 3 and 4 July and moved toward the southeast. By 4 July, the low-pressure center was to the east of Beijing, with the associated strong northwesterly winds bringing relatively clean air to Beijing with CO levels over Beijing dropping accordingly."

Comments 9: Section 5: I would suggest comparing your export calculations to previous work. There is extensive Trace-P work on lofting (i.e., Miyazaki, Koike, I think also something out of Henry Fuelbergs group – a multi-model CO comparison). Also, it would be useful to compare the Liang et al, seasonality work in this section.

Reply: The papers of Miyazaki and Koike have studied the export of anthropogenic reactive nitrogen and sulfur compounds from the East Asia region and the synoptic-scale transport of reactive nitrogen over the western pacific in spring. Generally, their conclusion on the major process responsible for the export of Asian anthropogenic pollution to the western Pacific during spring is the same to other literatures cited in

our paper, so we cited the two papers in the export discussion of Section 5.

Specifically, they have done quantitative calculation of the NOy and SOx export efficiency and the airstream classification associated with the cyclone, focusing on the dynamic mechanism of the transport. There are several differences compared to our paper: (1) The purpose of our paper is to examine the spatial pattern and seasonal change of the CO outflow in different areas of China, that's why we defined several tagged-CO tracers among these regions. Different areas in China are discussed separately, not treated as a whole. (2) the specie of CO export is studied, not reactive nitrogen nor sulfur as in their papers. We have discussed the difference and made a simple comparison in Section 5 (Pg. 25, line 468-483).

"Miyazaki et al. (2003) and Koike et al. (2003) studied the export of anthropogenic reactive nitrogen and sulfur compounds from the East Asia region and the synoptic-scale transport mechanisms of the two chemical species over the western pacific in spring. Specifically, they calculated quantitatively the export efficiency of NOy and SOx using the P-3B and DC-8 aircraft observation data over the western Pacific during the TRACE-P campaign. Their results showed that 20–40% and 15% of NOx emitted over the northeastern part of China remained as NOy at 0–2 km (boundary layer) and 2–7 km (free troposphere), respectively. In the free troposphere, PAN was found to be the dominant form, while only 0.5% of emitted NOx remained as NOx. The transport efficiency of SOx was estimated to be 25–45% and 15–20% in the boundary layer and free troposphere, respectively. The results obtained in their study indicate that more than half of NOy and SOx were lost over the continent and that the vertical transport from the boundary layer to the free troposphere further reduced their amounts by a factor of 2. The present study calculated the outflow of CO from different areas of China. Due to the longer lifetime associated with simple chemical loss and less efficient deposition of CO as compared to NOy or SOx, the export efficiency of CO calculated here is relatively higher than that for NOy and SOx reported by Miyazaki et al. (2003) and Koike et al. (2003)."

Comments 10: How does your export calculation vary with the nested vs. standard resolution? How dies the improved vertical resolution impact our understanding of Asian export?

Reply: The total export efficiency results for China as a whole simulated by the nested-grid and standard resolution are almost the same for the whole column (troposphere plus stratosphere), as the two models meet the mass conservation in the nested domain. However we didn't carry out for the tagged-tracer simulation for different administrative regions in China in the standard global simulation because of the resolution limitation. As one $2° \times 2.5°$ grid has 15 high-resolution grids, it's difficult to cut the regions into the exactly same parts as in the high resolution, thus the inconsistency of the geographic partition will make the results difficult to compare. We think the export efficiency on the administrative regional scale should be carried by the nested-grid simulation only. In fact, the main advantage of the nested-grid model over the coarse-resolution global model is the former can resolve better regional differences in meteorology and emissions. In addition, the model-to-model comparison in terms of resolution differences is not the main focus of the section on export efficiency. Adding the global-model results for comparison with the nested-grid results in each section of the paper would make the paper too long.

Comments 11: There was work during TRACE-P (Heald et al) suggestion that the biomass emissions are overestimated in GEOS-Chem, so would your export be an upper limit?

Reply: Heald et al. suggested that biomass burning emission from Southeast Asia were overestimated in the GEOS-Chem model compared with TRACE-P aircraft data in 2001, when the model uses the climatological inventory from Yevich and Logan (2003) and Duncan et al. (2003). The overestimate is thought to be caused by comparing a climatological emission inventory with year-specific observations. As our study is on the seasonal variations of CO export from Asia, we choose to adopt the climatological biomass burning inventory. The main focus of our paper is on Chinese emissions and

associated export. In contrast to Southeast Asia, biomass burning is not a significant CO source for China. To examine the uncertainty in biomass burning inventory for Southeast Asia emissions is out of the scope of this paper.

Specific/Minor Comments:

Comments 12: I would suggest including "export" somewhere in your title since you offer the literature new numbers for export

Reply: Thanks for the suggestion! The title has been revised to "Regional CO pollution and export in China simulated by the high-resolution nested-grid GEOS-Chem model"

Comments 13: P5854 L27: typo: influences "of" physical

Reply: Corrected

Comments 14: P5857, L5-7 Introduction: I would suggest adding to the end of sentence : The high resolution nested grid : : :.as the GEOS-Chem model "allows for consistent propagation of features into the domain".

Reply: It has been added.

"The high-resolution, nested-grid simulation employed the same meteorology, dynamics, and chemistry as the global GEOS-Chem model, thus allows for consistent propagation of features into the domain."

Comments 15: P5858, L1-3 Introduction: I suggest referring to Figure 1 here.

Reply: It has been added.

Comments 16: P5858, L23: Suggest renaming "Modeling Approach" or "Nested Modeling Approach"

Reply: It has been changed to "Modeling Approach".

Comments 17: P5858, L15: Suggest changing "retains a generic high resolution" to " retains the native high resolution"

Reply: Changed

Comments 18: P5859, L12: should be one year, not one month right?

Reply: It's one month.

Comments 19: P5860, Section 3: I think section three is confusing. I would suggest moving the information below 3 and 3.1 to sub sections of section 2 (e.g., 2. Modeling Approach, 2.1 Nested Grid Formulation, 2.2 Tagged-CO simulation, 2.3 CO Emissions over Asia), these are model descriptions, not science.

Comments 20: Then, you can compare the two resolutions cleanly in section 3. I suggest renaming Section 3 to something like "Effect of Model Resolution on CO over Asia", with appropriate sub sections, this would allow the reader to really follow your arguments.

Reply: Good suggestion. The structure of Section 2 and 3 has been rearranged as follows.

1 Introduction

2 Modelling Approach

2.1 Nested Grid Formulation

2.2 CO simulation

2.3 CO Emissions

3 Effect of Model Resolution on CO over Asia

3.1 Heterogeneity of CO Emission

3.2 CO Mixing Ratios

3.3 Sichuan-Bain Low-Level Vortex

3.4 Differences between urban and suburban grids

Comments 21: P5861 L15: A general comment: Be sure to say simulated CO mixing ratios when identifying the model results

Reply: Corrected.

Comments 22: Figure 1. I cannot see the dots of the cities in 1b, I suggest changing them to black and in general darken the lines of the countries/coasts. Also a box in figure 1a of the BTH region would be useful.

Reply: It maybe a problem of the typesetting, the figure is much smaller than the original version in the manual script which is much easier to see the dots and boundaries. It this is not improved in the next typesetting process, we will reprocess the figures then.

Comments 23: Figure 3. What are the dark vs. light features in Figure 3c., please describe in caption? Would suggest changing that panel for a topographical map

Reply: It's an administrative map that illustrated the urban and suburban districts in Beijing. The dark and light features represent the two different types. This has been clarified (Pg. 15, line 268-269) and added into the figure caption.

"Their locations are shown in an administrative map of Beijing in Figure 5c."

"The dark areas are eight urban districts of Beijing, and the light areas are the suburban districts, with DL site illustrated as a triangle."

Comments 24: P5866 L23, extra space before comma

Reply: It's a typesetting error.

Comments 25: Figure 7. Suggest putting an L with a circle on successive days to identify the low.

Reply: Changed.

Please also note the Supplement to this comment.

———————————————————

C1344