Effects of intercontinental transport on surface ozone over the United States: Present and future assessment with a global model

Jin-Tai Lin, Donald J. Wuebbles, and Xin-Zhong Liang

1Department of Atmospheric Sciences, University of Illinois at Urbana-Champaign, Urbana, Illinois, USA.
2Illinois State Water Survey, Champaign, Illinois, USA.

Received 24 July 2007; revised 9 November 2007; accepted 10 December 2007; published 22 January 2008.

[1] Future changes in intercontinental transport (ICT) of European and Asian (EURA) pollutants can have substantial consequences on U.S. pollution. This is investigated with 27 simulations using a newly improved version of the Model for Ozone And Related chemical Tracers to simulate ICT contributions to summertime U.S. surface ozone for 1999, 2049 and 2099, with future climate and emissions perturbations following the Intergovernmental Panel on Climate Change A1fi and B1 scenarios. We find that projected ICT changes are primarily affected by changes in EURA anthropogenic emissions, whose increases under A1fi lead to 3–8 ppb, 2–6 ppb due to Asian emissions increases alone, more ozone from 1999 to both 2049 and 2099 over the western U.S.; whereas EURA emissions changes under B1 lead to 0–0.7 ppb and 1–2 ppb less ozone by 2049 and 2099, respectively. Therefore global, especially Asian, emission control is important for U.S. pollution mitigation. Citation: Lin, J.-T., D. J. Wuebbles, and X.-Z. Liang (2008), Effects of intercontinental transport on surface ozone over the United States: Present and future assessment with a global model, Geophys. Res. Lett., 35, L02805, doi:10.1029/2007GL031415.

1. Introduction

[2] Surface air quality over the contiguous United States is being affected by the intercontinental transport (ICT), through transpacific and transatlantic pathways, of European and Asian (EURA) pollutants as a result of anthropogenic/natural emissions [Wilkening et al., 2000; Biscaye et al., 2000; Akimoto, 2003; Zhao et al., 2006; Wuebbles et al., 2007]. In particular, the transpacific transport (TPT) is the primary process to bring EURA pollutants to the U.S. Jaffe et al. [1999] found that the observed ground-level chemical concentrations over the northwest U.S. were greatly affected by episodic pollutant plumes from Asia. A global modeling simulation by Jacob et al. [1999] indicated an increasing TPT effects on U.S. ozone from 1985–2010 with tripling Asian anthropogenic emissions. Since then, various ground-level observation analyses, field campaigns, and model simulations have been conducted to understand the current pathways and characteristics of TPT, as well as their influence on U.S. air quality [e.g., Yienger et al., 2000; Jaeglé et al., 2003; Hudman et al., 2004; Parrish et al., 2004; Bertschi and Jaffe, 2005; Heald et al., 2006]. These studies confirmed an important source of U.S. pollutants from Europe and Asia, especially the latter, in recent years. As compared to the TPT, transatlantic transport of EURA pollutants has minor effects on U.S. air quality [Li et al., 2002] due to the prevailing westerly at the northern mid-latitudes.

[3] One critical issue related to the ICT is its changes and resulting impacts on downwind regions over the coming century [Wuebbles et al., 2007]. In future years, the changing EURA anthropogenic emissions are likely to affect U.S. air quality. Specifically, if EURA anthropogenic emissions increase (decrease) in the future, there will likely be more (less) pollutants over the U.S. as a result of the enhancing (reducing) ICT. In addition, climate changes (e.g., air temperature, water vapor) will also influence the ICT by affecting biogenic emissions over source regions, pollutant lifetimes [Fiore et al., 2002; Murazaki and Hess, 2006] and transport pathways. While many modeling studies have investigated the overall effects of projected global climate and emissions perturbations on U.S. pollution in future years [e.g., Intergovernmental Panel on Climate Change (IPCC), 2001], and references therein; Murazaki and Hess, 2006; Lin et al., 2008], changes in ICT and their specific effects on U.S. air quality are seldom examined [Wuebbles et al., 2007].

[4] To investigate the effects of future ICT changes on U.S. pollution, this study uses the global chemical transport model (CTM), Model for Ozone And Related chemical Tracers version 2.4 (MOZART-2.4), with additional improvements in model chemistry/physics, to simulate the effects of ICT on U.S. ozone levels for the year of 1999 and project their changes from 1999 to 2049 and to 2099 due to changes in global climate and EURA anthropogenic and biogenic emissions. However, future changes in climate and emissions are determined by both natural variability and human activities, projections of which contain large uncertainties. Therefore two distinct climate/emissions pathways from the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES, http://sres.ciesin.org/final_data.html) are considered, including the A1fi and B1 scenarios representing upper and lower bounds of climate warming over the 21st century, respectively. The latest estimate of global temperature change from 1980–1999 to 2080–2099 is 4.0°C under the A1fi scenario and 1.8°C under the B1 scenario [IPCC, 2007]. The corresponding changes in ozone precursor emissions are more complicated and dependent on individual species, as shown in Table 1. These two scenarios have been used by Lin et al. [2008] to study the overall surface ozone changes over the U.S. and China. The analyses focus on summer months (June–August), when the U.S. ozone concentrations typically maximize and when any increases in ICT
would have significant consequences, e.g., increasing non-
attainment of the national ozone standard.

2. Experiment Design

[5] MOZART-2.4 (described and evaluated in detail by 
Horowitz et al. [2003]) is a state-of-the-art CTM in studying 
distributions and changes of ozone and related tracer gases 
in the troposphere [e.g., Wuebbles et al., 2001; Wei et al., 
2002; Horowitz et al., 2003; Lamarque et al., 2005; Tie et 
al., 2005; Murazaki and Hess, 2006; Lin et al., 2008]. This 
study incorporates in MOZART-2.4 three improvements in 
model chemistry and physical parameterizations, following 
Lin et al. [2008]. First, there is a likely underprediction of 
the removal of nitrogen oxides (NOx) through isoprene 
nitrate chemistry in the original MOZART-2.4 (i.e., the 
model prior to the improvements incorporated here) because it 
likely underestimates the yield of isoprene nitrates and the 
conversion from isoprene nitrates to nitric acid [see Fiore et 
al., 2005, and references therein]. In the improved model, 
the yield of isoprene nitrate is determined as 12% instead of 
the original 8%, which is then converted immediately to 
nitric acid as the permanent sink of NOx, following Fiore et 
al. [2005]. Second, the original MOZART-2.4 may under-
estimate, by over 30%, the summertime ozone dry deposi-
tion over the deciduous forest prevailing in the eastern U.S. 
[Padro, 1996; Zhang et al., 1996; Wesely and Hicks, 2000]. Here 
the summertime ozone dry deposition is increased by 30% 
over the eastern U.S. (east of 100°W) as a conservative 
improvement. Third, the critical Richardson number is 
increased from the original 0.3 to 1.0, which is suggested 
to be more realistic by more recent research [Stull, 1997; 
Cheng et al., 2002, and references therein]. Lin et al. [2008] 
found that the simulated summer average ozone concen-
trations by the improved version of MOZART-2.4 are 
within 20 ppb, often within 10 ppb, of the ground-level 
measurements over most of the U.S.; overall, the model 
improvements reduced the simulation biases by 10–20 ppb 
over the eastern U.S. and have minor effects over the 
western U.S. Hereafter the model is referred to as the 
improved version of MOZART-2.4 driven by 

\[
\text{Table 1. Projected Summer Emission Budgets of Ozone Precursor} 
\text{Over Europe and Asia Together for 1999 and Their Fractional} 
\text{Changes by 2049 and 2099} 
\]

<table>
<thead>
<tr>
<th>Species</th>
<th>Year</th>
<th>Anthropogenic</th>
<th>Biogenic</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO\textsubscript{x}</td>
<td>1999</td>
<td>4.5 TgN</td>
<td>1.6 TgN</td>
<td>6.2 TgN</td>
</tr>
<tr>
<td>NO\textsubscript{x}</td>
<td>2049</td>
<td>294% / 23% \textsuperscript{a}</td>
<td>0% / 0%</td>
<td>217% / 17%</td>
</tr>
<tr>
<td>NO\textsubscript{x}</td>
<td>2099</td>
<td>314% / –45%</td>
<td>0% / 0%</td>
<td>232% / –33%</td>
</tr>
<tr>
<td>CO</td>
<td>1999</td>
<td>109.7 Tg</td>
<td>26.7 Tg</td>
<td>136.4 Tg</td>
</tr>
<tr>
<td>CO</td>
<td>2049</td>
<td>296% / –30%</td>
<td>2% / 1%</td>
<td>239% / –24%</td>
</tr>
<tr>
<td>CO</td>
<td>2099</td>
<td>332% / –42%</td>
<td>4% / 2%</td>
<td>267% / –34%</td>
</tr>
<tr>
<td>Isoprene</td>
<td>1999</td>
<td>—</td>
<td>47.9 TgC</td>
<td>47.9 TgC</td>
</tr>
<tr>
<td>Isoprene</td>
<td>2049</td>
<td>—</td>
<td>41% / 20%</td>
<td>41% / 20%</td>
</tr>
<tr>
<td>Isoprene</td>
<td>2099</td>
<td>—</td>
<td>74% / 35%</td>
<td>74% / 35%</td>
</tr>
</tbody>
</table>

\textsuperscript{a}The numbers before and after '/' denote projected fractional emissions 
changes under the A1fi and B1 scenarios, respectively, relative to the 1999 
budgets.

\[
\text{Table 2. Experiment Design of Climate and Ozone Precursor} 
\text{Emissions} 
\]

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Climate \textsuperscript{a}</th>
<th>Anthropogenic Emissions \textsuperscript{b}</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) CURRemis</td>
<td>1999</td>
<td>C / C / C \textsuperscript{c}</td>
</tr>
<tr>
<td>(2) noEURAaant</td>
<td>1999</td>
<td>0 / 0 / C</td>
</tr>
<tr>
<td>(3) noASIAaant</td>
<td>1999</td>
<td>C / 0 / C</td>
</tr>
<tr>
<td>(4) A_CURRemis_M</td>
<td>A1fi 2049</td>
<td>C / C / C</td>
</tr>
<tr>
<td>(5) A_noEURAaant_M</td>
<td>A1fi 2049</td>
<td>0 / 0 / C</td>
</tr>
<tr>
<td>(6) A_EURaanth_M</td>
<td>A1fi 2049</td>
<td>M\textsubscript{x} / M\textsubscript{x} / C</td>
</tr>
<tr>
<td>(7) A_ASIaanth_M</td>
<td>A1fi 2049</td>
<td>C / M\textsubscript{x} / C</td>
</tr>
<tr>
<td>(8) A_ASIaB_EUROPE_M</td>
<td>A1fi 2049</td>
<td>M\textsubscript{x} / M\textsubscript{x} / C</td>
</tr>
<tr>
<td>(9) A_EURaaghALL_M\textsuperscript{f}</td>
<td>A1fi 2049</td>
<td>M\textsubscript{x} / M\textsubscript{x} / C</td>
</tr>
<tr>
<td>(10) A_EURaaghANT_nox_M\textsuperscript{f}</td>
<td>A1fi 2049</td>
<td>M\textsubscript{x} / M\textsubscript{x} / C</td>
</tr>
<tr>
<td>(11) A_EURaaghANT_voc_M\textsuperscript{f}</td>
<td>A1fi 2049</td>
<td>M\textsubscript{x} / M\textsubscript{x} / C</td>
</tr>
<tr>
<td>(12) A_CURRemis_L</td>
<td>A1fi 2099</td>
<td>C / C / C</td>
</tr>
<tr>
<td>(13) A noEURAaant_L</td>
<td>A1fi 2099</td>
<td>0 / 0 / C</td>
</tr>
<tr>
<td>(14) A EURaaghANT_L</td>
<td>A1fi 2099</td>
<td>L\textsubscript{b} / L\textsubscript{b} / C</td>
</tr>
<tr>
<td>(15) A EURaaghANT_L</td>
<td>A1fi 2099</td>
<td>L\textsubscript{b} / L\textsubscript{b} / C</td>
</tr>
<tr>
<td>(16) A_ASIaB_EUROPE_L</td>
<td>A1fi 2099</td>
<td>L\textsubscript{b} / L\textsubscript{b} / C</td>
</tr>
<tr>
<td>(17) A EURaaghALL_L\textsuperscript{d}</td>
<td>A1fi 2099</td>
<td>L\textsubscript{b} / L\textsubscript{b} / C</td>
</tr>
<tr>
<td>(18) B CURRemis_M</td>
<td>B1 2049</td>
<td>C / C / C</td>
</tr>
<tr>
<td>(19) B noEURAaant_M</td>
<td>B1 2049</td>
<td>0 / 0 / C</td>
</tr>
<tr>
<td>(20) B EURaaghANT_M</td>
<td>B1 2049</td>
<td>M\textsubscript{x} / M\textsubscript{x} / C</td>
</tr>
<tr>
<td>(21) B EURaaghALL_M\textsuperscript{d}</td>
<td>B1 2049</td>
<td>M\textsubscript{x} / M\textsubscript{x} / C</td>
</tr>
<tr>
<td>(22) B EURaaghANT_nox_M\textsuperscript{d}</td>
<td>B1 2049</td>
<td>M\textsubscript{x} / M\textsubscript{x} / C</td>
</tr>
<tr>
<td>(23) B EURaaghANT_voc_M\textsuperscript{d}</td>
<td>B1 2049</td>
<td>M\textsubscript{x} / M\textsubscript{x} / C</td>
</tr>
<tr>
<td>(24) B CURRemis_L</td>
<td>B1 2099</td>
<td>C / C / C</td>
</tr>
<tr>
<td>(25) B noEURAaant_L</td>
<td>B1 2099</td>
<td>0 / 0 / C</td>
</tr>
<tr>
<td>(26) B EURaaghANT_L</td>
<td>B1 2099</td>
<td>L\textsubscript{b} / L\textsubscript{b} / C</td>
</tr>
<tr>
<td>(27) B EURaaghALL_L\textsuperscript{d}</td>
<td>B1 2099</td>
<td>L\textsubscript{b} / L\textsubscript{b} / C</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Physical environment of the troposphere, including temperature, water 
vapor, etc.

\textsuperscript{b}Including emissions from fossil fuel, industry, transportation, biofuel, 
etc.

\textsuperscript{c}The three symbols separated by '/' denote the emissions over Europe, 
Asia and the rest of the world, respectively (from left to right), designed for 
each experiment. Symbol 'C' denotes current emissions; 'M\textsubscript{x}' and 'M\textsubscript{x}' 
denote future emissions for the mid 21st century (i.e., 2049) under the A1fi 
and B1 scenarios, respectively; 'L\textsubscript{b}' and 'L\textsubscript{b}' denote future emissions for 
the late 21st century (i.e., 2099) under A1fi and B1 scenarios, respectively; 
'0' denotes zero emissions. Europe and Asia are separated by 60°E in this 
study.

\textsuperscript{d}Changes in biogenic and soil emissions are incorporated, corresponding 
to the specified climate scenarios (A1fi or B1) and future years (2049 or 
2099) for each experiment.

\textsuperscript{e}Changes in anthropogenic emissions are for NO\textsubscript{x} only.

\textsuperscript{f}Changes in anthropogenic emissions are for CO and VOC only.
Guenther, 1997] and carbon dioxide (CO₂) level [after Potosnak, 2002]. Changes in soil emissions of carbon monoxide (CO) due to the temperature dependence of net primary production (NPP) were also considered [Lin et al., 2008]. However, soil emissions of NOₓ and oceanic emissions of all ozone precursors were kept at the same present-day levels in all experiments because of the large uncertainties in emissions estimations and the difficulty in future projections. The fractional changes in emissions of NOₓ,
CO and isoprene from 1999 to 2099 under both the A1fi and B1 scenarios are presented in Table 1.

3. Results

3.1. Current ICT Effects

Figure 1a shows that, during 1999, EURA anthropogenic emissions contribute 4–5 ppb to the summer average daily mean (as calculated from the 3-hour MOZART outputs) surface ozone levels over the northwest U.S. and 3–4 ppb over California. Over the eastern U.S., the ICT effect is less than 2 ppb. The interannual variability of ICT effects is very small during 1996–2000, with the 5-year standard deviation less than 0.5 ppb over the U.S. (see discussions in section 4). Anthropogenic emissions over Asia (east of 10°E) alone contribute 2–4 ppb over the western U.S. and less than 1 ppb over the eastern U.S. (Figure 1b). Our results are similar to those of Jacob et al. [1999], who found that tripling Asian anthropogenic emissions upon the 1985 levels, with 12 TgN/yr increases in NOx emissions, a magnitude of increase similar to this study (10 TgN/yr), would lead to an increase of 1–4 ppb in U.S. surface ozone averaged over the summer months.

Using the global model, GEOS-Chem, Fiore et al. [2002] found that 4–7 ppb out of the 1995 summer average afternoon (1:00 pm–5:00 pm) mean U.S. background ozone levels were contributed by EURA anthropogenic emissions. The differences between the results here and those given by Fiore et al. [2002] are due to many factors such as meteorology, emissions, resolution, model physics/chemistry and evaluation metric (daily mean ozone vs. afternoon mean ozone). As one factor, for the vertical mixing in the planetary boundary layer (PBL), MOZART incorporates the non-local scheme by Holtslag and Boville [1993] capable of simulating various PBL states from unstable in the afternoon to stable in the nighttime; while GEOS-Chem assumes a fully mixed PBL throughout the day, resulting in stronger interaction between the surface and higher altitudes in favor of the ICT. In addition, the horizontal resolution here is much finer than that of 4° × 5° used by Fiore et al. [2002], and thus should generally lead to better simulation of the dynamical, physical and chemical processes important to ozone formation and transport.

3.2. Projected Future ICT Effects

Projected future climate change, especially increasing tropospheric water vapor content, is likely to result in a shorter atmospheric lifetime for ozone and thus weaker ICT, if global precursor emissions are fixed at the present-day levels [see also Fiore et al., 2002; Murazaki and Hess, 2006]. It is found that, from 1999 to 2049, the northern hemisphere tropospheric (below 220 hPa) water vapor content derived by PCM is increased by about 9% under A1fi and 2% under B1; the derived increases from 1999 to 2099 are 26% under A1fi and 5% under B1. As a result, from 1999 to 2049, projected contributions of ICT to U.S. ozone are slightly reduced, i.e., by less than 0.5 ppb over most of the country, under both scenarios (comparing Figures 1a, 1c, and 1d); the ICT reductions from 1999 to 2099 are more significant, especially under the A1fi scenario where the reduction exceeds 1 ppb over the western U.S. (comparing Figures 1a, 1i, and 1j).

Projected changes in EURA anthropogenic emissions can have significant impacts on the ICT. Over the coming century, anthropogenic emissions of ozone precursors over Europe and Asia are projected to change greatly and distinctively under the A1fi and B1 scenarios, relative to the present-day levels (Table 1). As a result, from 1999 to 2049, increases in EURA anthropogenic emissions under A1fi lead to 3–8 ppb more surface ozone over the western U.S. and 1–3 ppb more ozone over the eastern U.S. (Figure 1e), about one third of which are contributed by the increased NOx emissions and two thirds by the increased emissions of CO and VOC together (not shown). Under B1, by comparison, the ICT effect is slightly reduced, i.e., by not more than 0.7 ppb (Figure 1f). The magnitudes of ICT changes from 1999 to 2099 are about 0.5 ppb larger than those from 1999 to 2049 under both scenarios due to the greater emissions changes (Figures 1k and 1l). Overall, under A1fi, total EURA anthropogenic emissions contribute to 3–11 ppb of surface ozone over the western U.S. and 2–4 ppb over the eastern U.S. in both 2049 and 2099; whereas under B1, contributions of total EURA anthropogenic emissions reduce to less than 4 ppb in 2049 and less than 3 ppb in 2099 over the western U.S.

Over the coming decades, it is more likely that anthropogenic emissions over Europe will be reduced as a result of the pollution control policies while Asian emissions will likely grow, at least for the next few decades as a result of the fast on-going industrialization and economic/population growth, although in the longer term, these emissions may also be reduced under stronger policy controls. Therefore it is of interest to investigate the effects of this likely emission trend on the ICT. To this regard, we find that, from 1999 to 2049, the summer average U.S. ozone concentrations increase 2–6 ppb over the western region and 1–2 ppb over the eastern region due to the increasing Asian anthropogenic emissions following the A1fi scenario, whether European anthropogenic emissions are fixed at present-day levels (Figure 1g) or even allowed to change following the B1 scenario (Figure 1h). The corresponding ICT changes from 1999 to 2099 are about 0.5 ppb higher (Figures 1m and 1n). This suggests that the projected Asian emissions increases dominate the future ICT enhancement and, if indeed they occurred, would greatly impact the U.S. pollution levels. Projected changes in European emissions, by comparison, have a much smaller effect on U.S. ozone, i.e., for both 2049 and 2099, calculated surface ozone concentrations increase 1–3 ppb over the western U.S. when European emissions increase from the B1 to A1fi case.

Projected future changes in EURA biogenic emissions impact the ICT as well. From 1999 to 2049 and 2099, projected EURA biogenic emissions of isoprene greatly increase, more under the A1fi than B1 scenario (Table 1). In response, relative to 1999, the U.S. surface ozone concentrations are increased by less than 0.9 ppb under A1fi and less than 0.4 ppb under B1 by 2049; the ozone increases from 1999 to 2099 are less than 1.4 ppb under A1fi and less than 0.6 ppb under B1 (not shown). Therefore projected future changes in ICT due to potential changes in...
EURÁ biogenic emissions are not as significant as those due to potential changes in EURÁ anthropogenic emissions.

4. Conclusions and Discussions

[14] Through 27 model experiments conducted with a newly improved version of MOZART-2.4, this study finds that future changes in intercontinental transport may have significant consequences on summertime U.S. ozone mitigation.

[15] Projected changes in EURÁ anthropogenic emissions dominate the summertime ICT changes when considering IPCC SRES scenarios. From 1999 to both 2049 and 2099, projected increases in EURÁ anthropogenic emissions under A1fi lead to 3–8 ppb more ozone over the western U.S., with the ICT effect being about 0.5 ppb larger in 2099 than in 2049. In particular, a 2–6 ppb increase of ozone over the western U.S. is due to the Asian emissions enhancements alone, suggesting the importance of Asian emissions changes to U.S. pollution. On the other hand, relative to 1999, projected changes in EURÁ anthropogenic emissions under B1 lead to up to 0.7 ppb less ozone by 2049 and 1–2 ppb less ozone by 2099 over the western U.S. This reveals that the success of U.S. ozone mitigation depends on not only the country-wide emission reductions but also on what happens to emissions in Asia and Europe, especially in Asia. Holloway et al. [2003] similarly concluded that emissions controls in Asia may be crucial to the future of ozone mitigation in the U.S.

[16] Projected changes in EURÁ biogenic emissions have a secondary effect on the summertime ICT as compared to changes in EURÁ anthropogenic emissions. They lead to a summertime ozone increase of less than 0.9 ppb by 2049 and less than 1.4 ppb by 2099 under the A1fi scenario throughout the U.S.; the corresponding ozone increases under B1 are even smaller. Nevertheless, this amount of ozone increase is a result of the climate warming and not affected by local emission reductions. Thus, global climate change could also impact regional pollution outside of the direct effects of the local temperature changes.

[17] It is noted that the present-day ICT calculated here is (1) affected insignificantly by current model improvements, and (2) largely independent on the year of choice, i.e., 1999. Previously we have used the original MOZART-2.4 (without improvements) to conduct two experiments for 1996–2000 where EURÁ anthropogenic emissions are included and excluded, respectively, to simulate the climatological level of the present-day ICT. We find that the simulated summertime ICT effects on U.S. ozone for 1999 with and without the model improvements, respectively, and the ICT effects averaged over 1996–2000 are very similar, i.e., the differences among the three cases are less than 0.5 ppb in most regions (not shown). Moreover, the 5-year standard deviation of ICT effects calculated without the model improvements is also less than 0.5 ppb (less than 17% of the 5-year mean) over the U.S. Therefore our findings here are largely climatological, at least for the present-day ICT, despite of the 1-year rather than multi-year simulations. Future research should focus on better understanding the dependence of soil emissions of NOx on climate and resulting impacts on the ICT, given their significant contribution to NOx budget and thus ozone production.

[18] Acknowledgments. The research was supported in part by the United States Environmental Protection Agency Science to Achieve Results (STAR) Program under award number EPA RD-83337301-0. The authors acknowledge NCSA/UIUC for the supercomputing support. We thank Katharine Hayhoe for processing the PCM data; Peter Hess, Jean-François Lamarque and Larry Horowitz for discussions on the model performance and uncertainties. The views expressed are those of the authors and do not necessarily reflect those of the sponsoring agencies and other organizations including the Illinois State Water Survey.

References


---

X.-Z. Liang, Illinois State Water Survey, 2204 Griffith Drive, Champaign, IL 61820-7495, USA.

J.-T. Lin and D. J. Wuebbles, Department of Atmospheric Sciences, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA. (wuebbles@atmos.uiuc.edu)