Foreign Contributions to Texas' Ozone

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EXECUTIVE SUMMARY

Global models are used to prepare boundary conditions for regional-scale air quality modeling, including the Texas Commission on Environmental Quality (TCEQ) Continental US (CONUS) domain. In this study, the Goddard Earth Observing System Chemistry (GEOS-Chem) global model was used to examine transport of ozone and ozone precursors from outside of North America into the US.

For each model year -- 2006, 2012, and 2018— GEOS-Chem was run two times: first for a base case and secondly with all anthropogenic emissions outside of North America zeroed out (zROW – i.e., **z**ero out the **r**est **o**f the **w**orld). The difference between the two runs yielded the ozone contribution from non-North American anthropogenic sources. This "zROW" contribution is an estimate of the largest ozone reduction within the US that could be expected to result from anthropogenic emission reductions outside North America.

In all three years, the zROW ozone contributions tended to be higher in the western US since the predominant wind direction is from the west, which can transport ozone and its precursors from Asia. zROW contributions were higher in the winter months than in summer, although total ozone concentrations were highest in summer when stagnant conditions favor local ozone production and inhibit transport from foreign sources. Figure ES-1 shows the geographical variations in zROW ozone contributions for February and July in each year modeled.

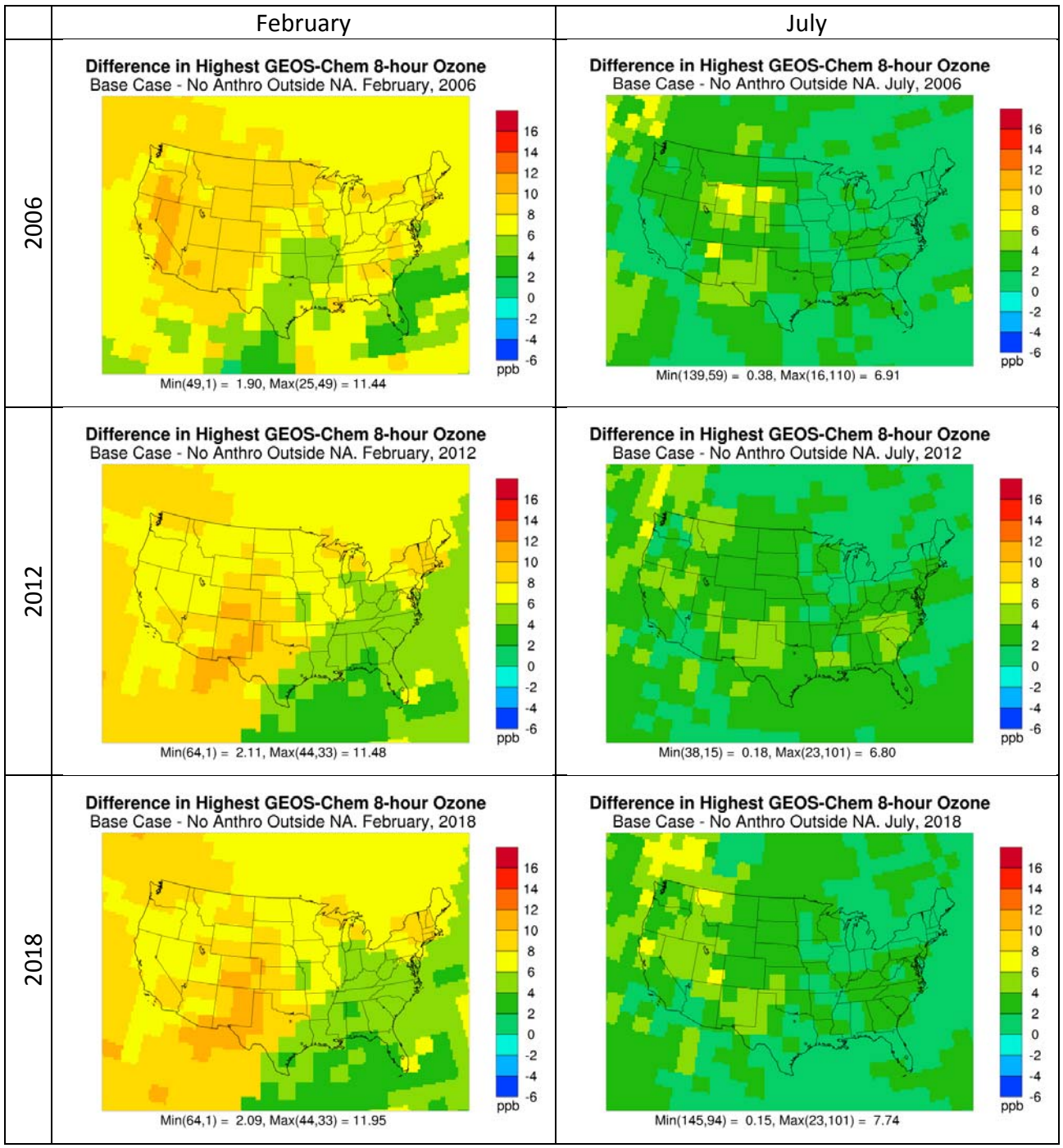


Figure ES-1. Spatial plots of ozone contributions from anthropogenic sources outside of North America (termed the zROW contribution) to February (left) and July (right) maximum 8-hour ozone in the CONUS domain for 2006 (top), 2012 (middle) and 2018 (bottom).

Among the three sites evaluated in Texas (El Paso, Dallas, and Houston), El Paso had the lowest monthly maximum 8-hour ozone during all summer months, but tended to receive the most ozone from non-North American anthropogenic sources in the winter (up to 11.6 ppb) because

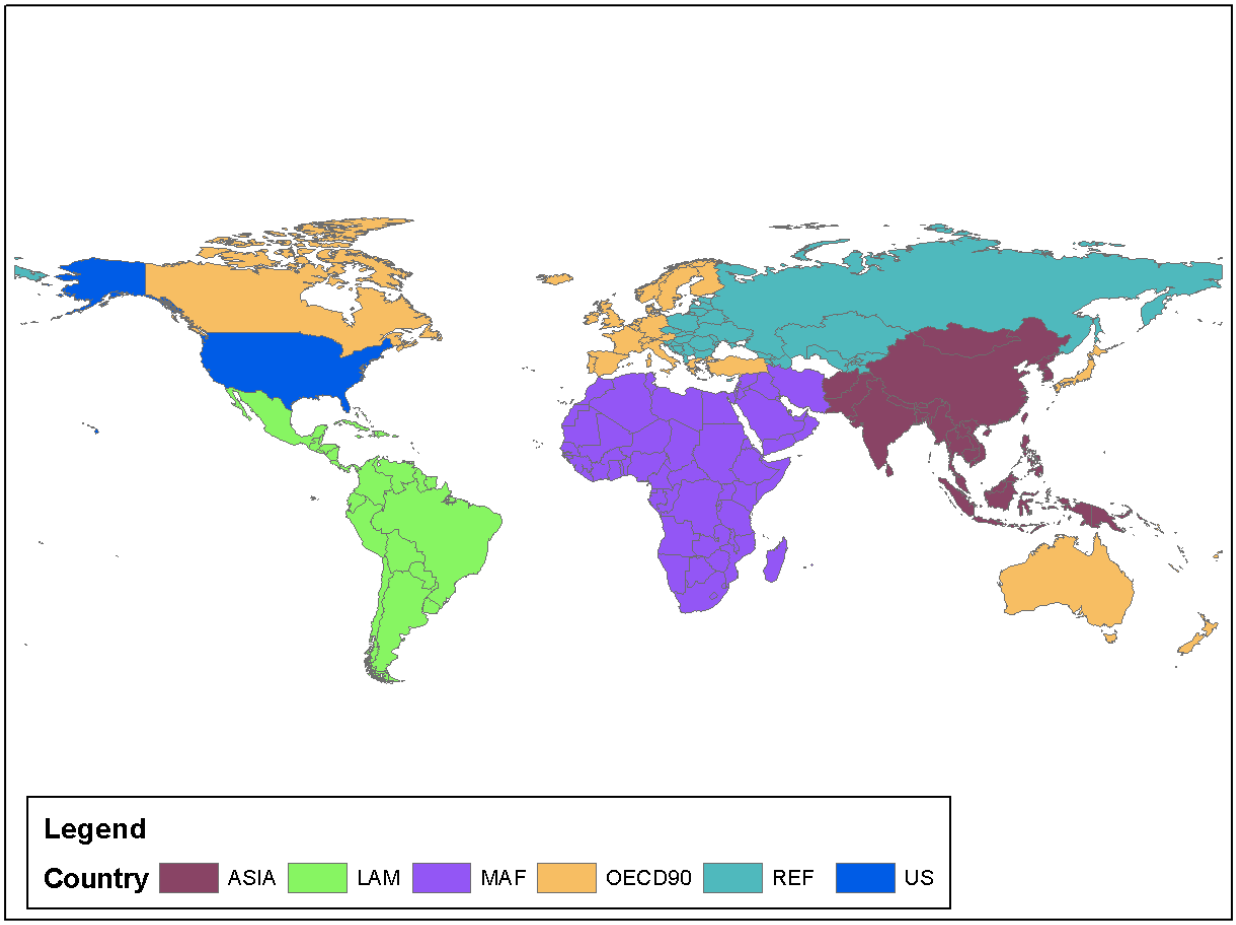
it is located furthest west and at higher altitude. The non-North American anthropogenic contributions to the highest 8-hour ozone in each model year were less than 3 ppb at all three sites, as listed in Table ES-1. Contributions to Dallas and Houston were less than 2 ppb in all months from June to September in 2018.

Table ES-1. Annual maximum 8-hour ozone (ppb) in El Paso, Dallas, and Houston, and the corresponding "zROW" ozone contribution from non-North American anthropogenic sources.

	El Paso		Dallas		Houston	
Year	Max	zROW Contribution	Max	zROW Contribution	Max	zROW Contribution
2006	74.8	1.1	88.2	1.0	89.3	1.3
2012	74.0	2.4	78.2	2.8	78.4	2.5
2018	74.4	1.8	77.4	1.8	77.2	1.4

In the three model years, 2006 used 2006 meteorology while 2012 and 2018 both used meteorology from 2012. Since 2012 and 2018 share the same meteorology and model configuration, all changes in ozone were due to differences in emissions between the two years. Emissions were determined by applying year-specific adjustments to base year emissions in broad regions that are defined in Figure ES-2. As summarized in Table ES-2, emissions in Asia and MAF (Middle East and Africa) were projected to increase over time while emissions from countries who were members of the Organisation for Economic Co-operation and Development in 1990 (OECD90) (US and Western Europe) decreased with time. In 2018, anthropogenic emissions were higher than in 2012 in all regions of the world except the OECD90 countries.

Model results from this study suggest that projected emission reductions in Western Europe between 2012 and 2018 may provide some benefit to the Eastern US, particularly in the Gulf States. The clockwise flow around the North Atlantic subtropical high pressure system may transport ozone precursor emissions from Europe into the Gulf States. If the Western Europe emissions are reduced, less ozone and ozone precursors will be transported to the eastern US, consistent with Figure ES-3. The difference in zROW ozone contributions between 2012 and 2018 to Houston and Dallas were greatest in July, when the zROW contributions were 1.9 and 1.0 ppb lower, respectively, in 2018 compared to 2012 when using the same meteorology. These ozone benefits were smaller further west in El Paso, where the largest reduction in zROW contributions between 2012 and 2018 was 0.6 ppb.



OECD90 = Includes the countries who were members of the OECD in 1990. The US is treated separately in this project
REF = Countries from the Reforming Economies region
ASIA = China, India, and other countries in Asia
MAF = the Middle East and Africa
LAM = Latin American countries

Figure ES-2. Geographic regions for emission adjustments.

Table ES-2. Anthropogenic emissions by world region in millions of tons per year

	NOx [MM tons/yr]			VOC [MM tons C/yr]		
Region	**2006**	**2012**	**2018**	**2006**	**2012**	**2018**
US	18.4	11.7	11.6	7.4	6.0	5.9
ASIA	36.3	42.2	51.9	19.8	21.7	24.7
LAM	5.0	4.7	5.1	4.9	5.1	5.4
MAF	9.0	9.8	12.6	8.3	9.3	10.4
OECD90 except US	25.1	21.0	16.3	19.7	16.0	12.4
REF	8.2	6.9	7.9	6.9	6.3	6.8
World Shipping	18.2	18.1	18.2	0.0	0.0	0.0
World Aviation	0.4	0.5	0.6	0.0	0.0	0.0

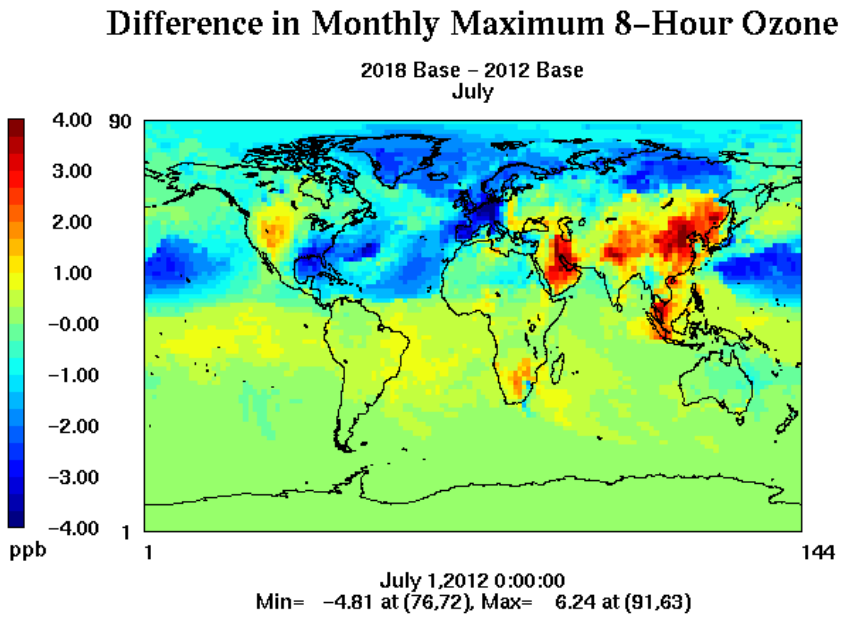


Figure ES-3. Map of the difference in monthly maximum 8-hour ozone between the July, 2012 and July, 2018 base cases.

1.0 INTRODUCTION

Transport of ozone and ozone precursors from sources outside to locations within the United States may be important when trying to attain to the national ambient ozone standard (USEPA, 2013). Global models such as the Goddard Earth Observing System Chemistry model (GEOS-Chem) are used to estimate ozone concentrations entering North America and to provide boundary conditions for regional models like the Comprehensive Air Quality Model with Extensions (CAMx), including the TCEQ continental US (CONUS) domain.

In this study, GEOS-Chem was run two times for each time period to assess the ozone contribution from foreign sources. One run was configured as a base case; the second run removed all anthropogenic emissions from these foreign sources. The difference between the two runs yielded the anthropogenic contribution from the foreign source. This project examined the ozone contributions from anthropogenic sources outside of North America to the TCEQ 36 km domain for three years – 2006, 2012, and 2018. For consistency, the same non-North America domain was windowed out as in other global transport studies (USEPA, 2013).

Section 2 describes the GEOS-Chem configuration and emission inventories for three model years. The 2006 and 2012 GEOS-Chem results are described in Sections 3 and 4, respectively. Section 5 details the 2018 future year results. Since 2018 was run with 2012 meteorology, a comparison of the 2012 and 2018 GEOS-Chem results is also included. A discussion of the results is presented in Section 6.

2.0 GEOS-CHEM INPUTS

Global modeling was performed using GEOS-Chem version 9-01-03, which was released in September, 2012, and was the latest version available upon initiation of this project.

2.1 Meteorology

Each run simulated a two-year period with the first year considered a spin-up period to limit the influence of the assumed initial concentrations. The 2006 runs were simulated using meteorology from the 2005 and 2006 Goddard Earth Observing System Model, Version 5 (GEOS5). Both the 2012 and 2018 model runs used the same 2011 and 2012 GEOS5 meteorology.

2.2 Emissions

GEOS-Chem contains many emission inventories built inside the model that vary by resolution, pollutant, source category, and regional coverage. By default, some but not all of these emission components are projected to a user-defined modeling year. For example, anthropogenic nitrogen oxide (NOx) emissions are automatically adjusted to any modeling year between 1985 and 2006; volatile organic compounds (VOC) emissions from a global inventory are held constant at a baseline year of 2000. This study developed year-specific anthropogenic emissions for all source categories. GEOS-Chem emission inventories and the development of emission projections are described below.

2.2.1 Emission Inventories Available in GEOS-Chem

The CONUS emissions were based on the National Emissions Inventory 2005 (2005 NEI) available in GEOS-Chem. The 2005 NEI came from the Weather Research and Forecasting model coupled with Chemistry (WRF-CHEM) and represents emissions for typical summer conditions. GEOS-Chem internally calculates monthly emission rate profiles from the 1999 NEI (and other sources) and uses them to adjust the 2005 NEI from summer to non-summer seasons.

The non-CONUS emissions were based on the Emissions Database for Global Atmospheric Research (EDGAR)[1] and the Reanalysis of the TROpospheric chemical composition between 1960 and 2000 (RETRO)[2] inventory. The RETRO inventory is the default VOC inventory in GEOS-Chem whereas EDGAR version 2 is the default inventory for NOx, SO_2 and CO. In this study, EDGAR v2 was replaced with a more updated version (EDGAR4.1) that is implemented in GEOS-Chem as a patch[3]. The EDGAR v4.1 implementation has been tested in GEOS-Chem v09-01-01 by Tsinghua University with the 2005 platform.

Other global emission inventories available in GEOS-Chem include:

[1] http://edgar.jrc.ec.europa.eu/index.php

[2] http://retro.enes.org/data_emissions.shtml

[3] http://wiki.seas.harvard.edu/geos-chem/index.php/EDGAR_anthropogenic_emissions#Use_EDGAR_v.4.1_in_GEOS-Chem

- NO and SO_2 aircraft emissions for a baseline year of 1992 based on scheduling data of civil aircraft and fuel burned;
- CO, NOx, and SO_2 shipping emissions from the EDGAR v4.1;
- Anthropogenic ammonia (NH_3) emissions from the Global Emission Inventory Activity (GEIA) database for a baseline year of 1990 (Benkovitz et al, 1996);
- U.S. Biofuel emissions from the 1999 NEI;
- Biomass burning emissions based on the Global Fire Emissions Database (GFED) version 3 (daily and 3-hourly emissions are available for 2003-2010);
- Natural emissions (i.e., volcanic SO_2, biogenic VOCs, soil NOx, sea-salt aerosol);
- Methane concentrations are defined in GEOS-Chem based on measurements from Climate Monitoring and Diagnostics Laboratory (CMDL) (Dlugokencky et al., 2012).

2.2.2 Data Sources for Emission Projections

U.S. emission projections

The U.S. EPA Trends database provides national-level sector-based emissions for historical years (US EPA, 2001, http://www.epa.gov/ttnchie1/trends/). These trends were used to develop emission projections from the 2005 emissions (2005 NEI inventory) available in GEOS-Chem to 2006 and 2012. The NEI trends were developed from US EPA NEI data which are considered the most comprehensive and detailed estimates of pollution emissions in the U.S for the years 1999, 2002, 2005 and 2008 and have been widely used in modeling studies. The trends go beyond the NEI by taking into account activity data and emission controls to estimate emissions over a long period (1970-2012).

The NEI was scaled to 2018 based on TCEQ's 2006 to 2018 projections in the TCEQ 36 km domain for NOx, VOC, and CO, and from the 2007 to 2020 EPA PM NAAQS rulemaking analysis projections for SO_2, $PM_{2.5}$, and NH_3.

Emissions Database for Global Atmospheric Research (EDGAR)

The EDGAR (European Commission, 2010) inventory is the default global inventory in GEOS-Chem for NOx, SO_2 and CO. Many global air quality modeling efforts for ozone and aerosols have relied on the EDGAR data base. The inventory is resolved by country, as well as on 1 degree by 1 degree grid, and available from 1970-2005. Although EDGAR version 4.2 (European Commission, 2011) is now available, version 4.1 was used as baseline emissions (for 2005) since it has been implemented and tested in GEOS-Chem. The version 4.2 was used to develop emission projections from 2005 to 2006.

Representative Concentration Pathway (RCP85) Database

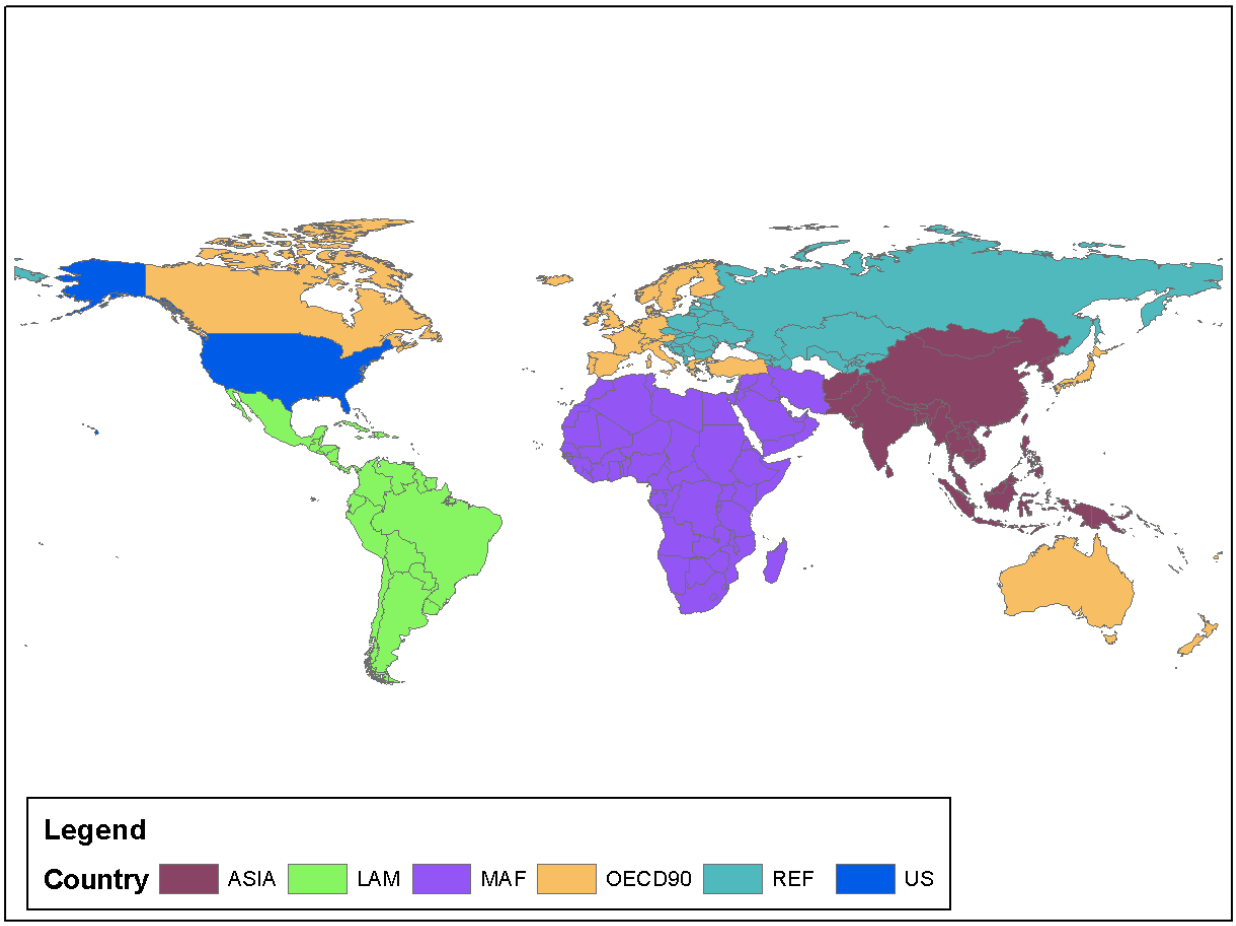
The RCP data[4] serve as input for climate and atmospheric chemistry modeling as part of the Intergovernmental Panel on Climate Change (IPCC) process and other global modeling studies. There are four RCP scenarios available and the RCP85 scenario (Riahi et al., 2007) has the least

[4] https://tntcat.iiasa.ac.at:8743/RcpDb/dsd?Action=htmlpage&page=welcome

aggressive emission reductions over the period 2000-2100 and therefore is most likely to represent actual emissions to the time horizon of this project (out to 2018). Anthropogenic emissions in this database are available at a regional level (5 regions total) covering the entire World, and gridded with 0.5x0.5 degree resolution. The RCP85 scenario was used to develop projections from the year 2006 to years 2012 and 2018.

2.2.3 Emission Projection Results

Anthropogenic emissions were adjusted outside of GEOS-Chem using emission projection factors developed for five World regions (Figure 2-1).



OECD90 = Includes the countries who were members of the Organisation for Economic Co-operation and Development in 1990. Countries included in the regions **Western Europe** (Austria, Belgium, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom), **Northern America** (Canada, United States of America) and **Pacific OECD** (Australia, Fiji, French Polynesia, Guam, Japan, New Caledonia, New Zealand, Samoa, Solomon Islands, Vanuatu); the US is treated separately in this project;
REF = Countries from the **Reforming Economies** region (Albania, Armenia, Azerbaijan, Belarus, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Estonia, Georgia, Hungary, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Malta, Poland, Republic of Moldova, Romania, Russian Federation, Slovakia, Slovenia, Tajikistan, TFYR Macedonia, Turkmenistan, Ukraine, Uzbekistan, Yugoslavia);
ASIA = The countries included in the regions **China +** (China, China Hong Kong SAR, China Macao SAR, Mongolia, Taiwan) , **India +** (Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka) and **Rest of Asia** (Brunei Darussalam, Cambodia, Democratic People's Republic of Korea, East Timor, Indonesia, Lao People's Democratic Republic, Malaysia, Myanmar, Papua New Guinea, Philippines, Republic of Korea, Singapore, Thailand, Viet Nam) are aggregated into this region;
MAF = This region includes the **Middle East** (Bahrain, Iran (Islamic Republic of), Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, United Arab Emirates, Yemen) and **Africa**n (Algeria, Angola, Benin, Botswana, Burkina Faso, Burundi, Cote d'Ivoire, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Democratic Republic of the Congo, Djibouti, Egypt, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Libyan Arab Jamahiriya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Reunion, Rwanda, Senegal, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, Togo, Tunisia, Uganda, United Republic of Tanzania, Western Sahara, Zambia, Zimbabwe) countries;
LAM = This region includes the **Latin America**n countries (Argentina, Bahamas, Barbados, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, Suriname, Trinidad and Tobago, Uruguay, Venezuela);
US = United States.

Figure 2-1. Regional aggregations of 5 regions.

The GEOS-Chem emissions for the CONUS were adjusted to represent 2006 and 2012 using available emission trends from the U.S.EPA. Wild fire emissions were excluded from the projections. CONUS emissions were scaled to 2018 using projections from TCEQ and the EPA's PM NAAQS rulemaking analysis. Emissions outside the CONUS were adjusted using projections from the RCP85. Since the RCP85 data are only available at 5-10 year intervals (e.g., 2000, 2005, 2010, 2020, etc.) emission projections were estimated from changes between the nearest available years. Thus, the 2012 projections were derived based on emission changes from 2005 to 2010, and the 2018 projections used scaling factors between 2005 and 2020. The EDGAR4.2 inventory containing 1970-2008 emissions was used to estimate emission changes from 2005 to 2006.

The EDGAR4.1 SO_2 and NOx aircraft emissions are not currently implemented in GEOS-Chem. The default 1992 aircraft emissions in GEOS-Chem were projected to the 2006, 2012, and 2018 modeling years using EDGAR4.2, RCP85, and RCP85 emissions data, respectively. The EDGAR4.1 CO aircraft emissions are implemented in GEOS-Chem; thus, the same projection methodology can be applied but using a base year of 2005. Since SO_2 and CO are not included in the RCP85 aircraft inventory, the 2012 and 2018 aircraft SO_2 and CO emissions were scaled at the same rate as NOx emissions.

The EDGAR4.1 inventory includes domestic and international shipping emissions from 1970 to 2005 for SO_2, CO and NOx. The EDGAR4.2 inventory was used to derive emission projections from 2005 to 2006; the RCP85 inventories scaled the emissions from 2005 to 2012 and from 2005 to 2018. Since the RCP85 inventory does not provide emissions separately for domestic and international shipping, inland navigation scaling factors for 2012 and 2018 were assumed the same as international shipping.

NH_3 emissions from biofuel and natural sources were held constant at 1990 level (as default in GEOS-Chem) due to a lack of information on changes and considering that NH_3 is not an ozone precursor.

Natural sources (i.e., volcanic SO_2, biogenic VOCs, soil NOx, sea-salt, lightning NOx) are calculated within GEOS-Chem as a function of local values of meteorological variables (temperature, insolation, soil moisture, precipitation, wind speed, convective cloud tops). Default GEOS-Chem procedures were applied to generate 2006 and 2012 natural emissions. Since 2018 used the same meteorology as 2012, the 2018 natural source emissions will be the same as 2012. By default, GEOS-Chem uses the 2010 GFED biomass emissions for any modeling year after 2010.

Table 2-1 provides a summary of the emission inventories and emission projections approach for the three modeling years. Emission projections are shown in Table 2-2.

Table 2-1. Emission inventories in GEOS-Chem and approaches of emission projections development.

Inventory	Pollutants	Baseline year	Inventory Grid Definition*	Modeling Year		
				2006	2012	2018
EDGAR4.1	CO, NOx, SO_2	2005	Generic 1x1	Project from 2005 by region using EDGAR 4.2	Project from 2005 using RCP85 (i.e., changes from 2005 to 2010)	Project from 2005 using RCP85 (i.e., changes from 2005 to 2020)
RETRO	VOCs	2000	GMAO 2x2.5	Project from 2000 by region using RCP85 (i.e., changes from 2000 to 2005)	Project from 2000 using RCP85 (i.e., changes from 2000 to 2010)	Project from 2000 using RCP85 (i.e., changes from 2000 to 2020)
2005 NEI	CO, NOx, SO_2, VOC,NH_3,$PM_{2.5}$	2005	GMAO 1x1	Project from 2005 to 2006 at national level using EPA trends; wild-fire emissions were excluded	Project from 2005 to 2012 at national level using EPA trends; wild-fire emissions were excluded	Project from 2006 to 2018 for NOx, VOC, and CO from TCEQ; project from 2007 to 2020 for SO2, PM2.5, and NH3 using EPA's PM NAAQS rulemaking analysis
Shipping from EDGAR4.1	CO, NOx, SO_2	2005	Generic 1x1	Project from 2005 using EDGAR4.2 separately for international shipping and inland navigation	Project from 2005 using RCP85 (i.e., changes from 2005 to 2010)	Project from 2005 using RCP85 (i.e., changes from 2005 to 2020)
Aviation	SO_2, NOx CO	1992 2005	GMAO 2x2.5 (SO_2) 1x1 grid in ASCII format (NOx) Generic 1x1	Project from 1992 using EDGAR4.2 (i.e., changes from 1992 to 2006); no distinction of domestic versus international Project from 2005 using EDGAR4.2 separately for domestic and international aviation	Project from 2005 using RCP85 (i.e., changes from 2005 to 2010); no distinction of domestic versus international SO_2 and CO projection factors are the same as NOx	Project from 2005 using RCP85 (i.e., changes from 2005 to 2020); no distinction of domestic versus international SO_2 and CO projection factors are the same as NOx
NH_3 (GEIA) anthropogenic sources only	NH_3	1990	GMAO 2x2.5	Project from 1990 to 2006 by region using EDGAR4.2	Project from 2005 to 2010 for total anthropogenic by region using RCP85	Project from 2005 to 2020 for total anthropogenic by region using RCP85
Methane	CH_4	1983-2007	--	GEOS-Chem default (2006 level)	GEOS-Chem default (2007 level)	GEOS-Chem default (2007 level)
Biomass burning	CO, NOx, SO_2, VOC,NH_3,BC,OC	2003-2010	--	GEOS-Chem default (2006 level)	GEOS-Chem default (2010 level)	GEOS-Chem default (2010 level)
Biofuel & Natural sources (biogenic, volcanic/sea-salt, etc.)	CO, NOx, SO_2, VOC,NH_3,BC,OC	Varied	--	GEOS-Chem default (2006 level)	GEOS-Chem default (2012 level or nearest year)	GEOS-Chem default (2012 level or nearest year)

*Grid definitions
GENERIC 1x1 http://acmg.seas.harvard.edu/geos/doc/archive/man.v8-01-04/appendix_2.html#A2.7
GMAO 2x2.5 http://acmg.seas.harvard.edu/geos/doc/man/appendix_2.html#A2.3
GMAO 1x1 http://acmg.seas.harvard.edu/geos/doc/man/appendix_2.html#A2.5

Table 2-2. Emission projection factors for 2006, 2012, and 2018.

Inventory	Baseline	Pollutant	Region	Projection factors		
				2006	2012	2018
EDGAR4.1	2005	CO	ASIA	1.029	1.052	1.099
		CO	LAM	1.002	1.000	1.062
		CO	MAF	1.016	1.111	1.365
		CO	OECD90	0.970	0.723	0.551
		CO	REF	0.983	0.886	0.847
		NOx	ASIA	1.055	1.224	1.505
		NOx	LAM	1.030	0.969	1.035
		NOx	MAF	1.022	1.109	1.428
		NOx	OECD90	0.980	0.821	0.637
		NOx	REF	1.022	0.860	0.981
		SO_2	ASIA	1.074	1.011	1.108
		SO_2	LAM	0.981	0.822	0.769
		SO_2	MAF	1.020	0.991	1.186
		SO_2	OECD90	0.938	0.622	0.443
		SO_2	REF	1.022	0.800	0.659
RETRO	2000	VOCs	ASIA	1.129	1.223	1.408
		VOCs	LAM	1.068	1.106	1.179
		VOCs	MAF	1.142	1.270	1.424
		VOCs	OECD90	0.754	0.604	0.475
		VOCs	REF	1.025	0.920	1.014
2005 NEI	2005	NOx	U.S.	0.967	0.612	0.609
		CO	U.S.	0.942	0.621	0.603
		SO_2	U.S.	0.899	0.457	0.279
		VOCs	U.S.	0.967	0.779	0.764
		NH_3	U.S.	1.017	1.039	1.017
		$PM_{2.5}$	U.S.	1.019	1.017	0.927
Shipping (EDGAR4.1)	2005	NOx	Inland	1.036	1.052	1.059
		NOx	International	1.065	1.052	1.059
		SO_2	Inland	1.036	0.958	0.510
		SO_2	International	1.065	0.958	0.510
		CO	Inland	0.996	1.068	1.148
		CO	International	1.065	1.068	1.148
Aviation	2005 (CO)	CO	Domestic	0.974	1.110	1.333
		CO	International	1.035	1.110	1.333
	1992	NOx	World	1.366	1.517	1.822
		SO_2	World	1.379	1.532	1.839
NH3 from GEIA	1990	NH_3	ASIA	1.397	1.469	1.656
		NH_3	LAM	1.248	1.332	1.682
		NH_3	MAF	1.680	1.877	2.465
		NH_3	OECD90	2.189	2.234	2.384
		NH_3	REF	1.071	1.204	1.407

2.2.4 Emission Summaries

A summary of the 2006, 2012, and 2018 base case emissions are shown in Tables 2-3, 2-4, and 2-5, respectively. Spatial Quality assurance of the emissions projection conducted for the project included the development of emission summaries based on the inventory data input to the GEOS-Chem before and after applying projection factors, and maps of emission totals, which can be found in Appendix A. GEOS-Chem output log files were inspected to ensure that the emissions were read in correctly.

Table 2-3. Anthropogenic emissions by world region in 2006.

Sources	World Region	Emissions (MM Tons/year or MM Tons C/year)			
		CO	NOx	SO_2	VOC
Total Anthropogenic from NEI	US	77.2	18.4	14.5	7.4
Total Anthropogenic from EDGAR4.1/RETRO inventories (excluding aviation and shipping CO/NOx/SO_2 emissions)	ASIA	198.3	36.3	54.2	19.8
	LAM	25.2	5.0	6.4	4.9
	MAF	71.9	9.0	12.5	8.3
	OECD90 (except US)	83.8	25.1	22.8	19.7
	REF	26.3	8.2	15.4	6.9
Shipping	World	6.1	18.2	11.2	0.0
Aviation	World	0.6	0.4	0.2	0.0

Table 2-4. Anthropogenic emissions by world region in 2012.

Sources	World Region	Emissions (MM Tons/year or MM Tons C/year)			
		CO	NOx	SO_2	VOC
Total Anthropogenic from NEI	US	50.9	11.7	7.4	6.0
Total Anthropogenic from EDGAR4.1/RETRO inventories (excluding aviation and shipping CO/NOx/SO_2 emissions)	ASIA	202.8	42.2	51.0	21.7
	LAM	25.2	4.7	5.4	5.1
	MAF	78.6	9.8	12.2	9.3
	OECD90 (except US)	62.5	21.0	15.1	16.0
	REF	23.7	6.9	12.0	6.3
Shipping	World	6.4	18.1	10.2	0.0
Aviation	World	0.7	0.5	0.2	0.0

Table 2-5. Anthropogenic emissions by world region in 2018.

Sources	World Region	Emissions (MM Tons/year or MM Tons C/year)			
		CO	NOx	SO_2	VOC
Total Anthropogenic from NEI	US	49.4	11.6	4.5	5.9
Total Anthropogenic from EDGAR4.1/RETRO inventories (excluding aviation and shipping CO/NOx/SO_2 emissions)	ASIA	211.9	51.9	55.9	24.7
	LAM	26.7	5.1	5.0	5.4
	MAF	96.6	12.6	14.6	10.4
	OECD90 (except US)	47.6	16.3	10.7	12.4
	REF	22.6	7.9	9.9	6.8
Shipping	World	6.9	18.2	5.4	0.0
Aviation	World	0.8	0.6	0.3	0.0

2.3 GEOS-Chem Model Configuration

GEOS-Chem v9-01-03 was chosen for this study because it was the most recent version at the time modeling task was initiated. In this study, EDGAR v2 was replaced with a more updated version (EDGAR4.1) that is implemented in GEOS-Chem as a patch[5]. The EDGAR v4.1 implementation was tested with the 2005 platform and two bugs were found and fixed[6].

The GEOS-Chem configuration is shown in Table 2-5. The GEOS-Chem model was run for three two-year periods. The first year was considered a spin-up period to limit the influence of the assumed initial concentrations. The second year covered all of 2006, 2012, and 2018. The same anthropogenic emissions were applied to both years in each two-year run.

Table 2-5. Model configuration options for GEOS-Chem

Science Options	Configurations
Version	Version 9-01-03 with EDGAR4.1 patch
Vertical Grid Mesh	47 Layers
Horizontal Grids	2x2.5 degree (Nx, Ny = 144, 91)
Initial Conditions	1 year full spin-up
Meteorology	Year-specific GEOS5 meteorology
Chemistry	
Chemistry mechanism	GEOS-Chem standard chemistry with secondary organic aerosols (SOA)
Photolysis mechanism	FAST-J updated
Horizontal Transport	
Advection Scheme	TPCORE
Vertical Transport	
Cloud convection scheme	On / Relaxed Arakawa-Schubert
Stratosphere-troposphere exchange	LINOZ
Planetary Boundary Layer (PBL) mixing	On / Full mixing in the PBL
Dry deposition scheme	Wesely
Numerics	
Chemistry Solver	SMVGEAR II
Parallelization	OMP

2.4 Model Output Processing

Daily GEOS-Chem output files contained instantaneous concentrations every three hours. The model results were first windowed onto the TCEQ 36 km domain and converted from their native binary punch file format to NetCDF format. Ozone was calculated by taking the difference between Ox (O_3 + NO_2) and NOx; any negative concentrations were set to 0. Hour 0 of the next date was merged onto each daily file so that the 3-hourly records could be time interpolated into hourly records for all 24 hours of the day. The files were then converted to a CAMx average file format and time shifted from GMT to CST. The daily maximum 8-hour ozone was computed using the CAMxPOST processor. It should be noted that the daily maximum 8-hour ozone concentrations could be under estimated if the peak hourly ozone did not line up with the 3-hourly outputs.

[5] http://wiki.seas.harvard.edu/geos-chem/index.php/EDGAR_anthropogenic_emissions#Use_EDGAR_v.4.1_in_GEOS-Chem

[6] EDGAR4.1 bugs fixed by ENVIRON include: 1) calculation of monthly scaling factors for SO_2 shipping emissions and 2) double counting of CO international aviation emissions

3.0 2006 MODEL RESULTS

Two GEOS-Chem runs were performed for 2006. One was the 2006 base case ("2006 base") and the second zeroed out anthropogenic emissions outside of the red box shown in Figure 3-1. The red box contains most of North America, including the entire TCEQ CONUS domain, shown in blue, and was defined with the coordinates listed in Table 3-1. Many previous studies that have used GEOS-Chem to investigate North American background (NAB) ozone have done so by changing emissions within the red box of Figure 3-1.

The 2006 zero out run included all North American emissions, but zeroed out all anthropogenic emissions in the rest of the world ("2006 zROW") (i.e., outside the red box). The biomass burning emissions group was assumed to be a natural source and was not zeroed out. The difference between the two runs was used to estimate the ozone contributions from non-North American anthropogenic sources.

Table 3-1. Boundaries used to zero out the anthropogenic emissions.

	Min	Max
Longitude	140W	40W
Latitude	10N	70N

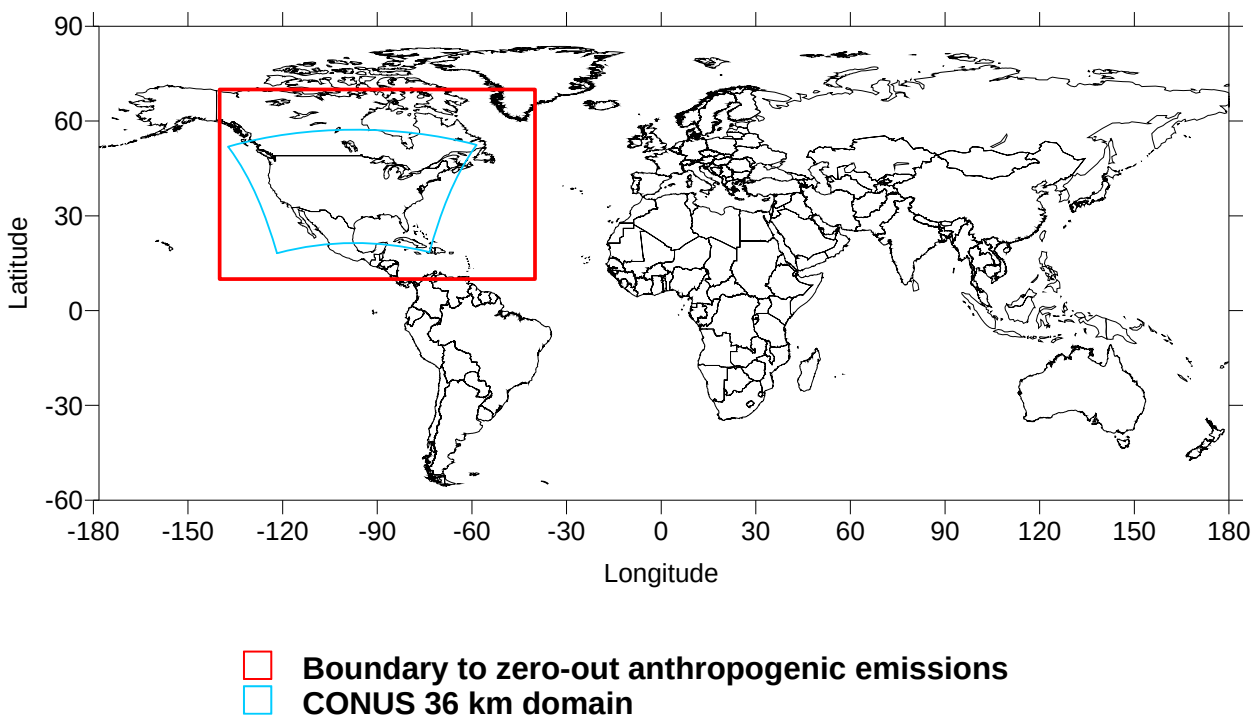


Figure 3-1. Map showing the locations of the TCEQ 36km CONUS domain and boundary to zero out emissions.

3.1 2006 8-Hour Ozone

The left and center columns of Figure 3-2 display spatial plots of the highest 8-hour ozone in each month in 2006, windowed to the CONUS domain for the 2006 base and 2006 zROW runs,

respectively. The right side shows the difference between the monthly maximum 8-hour ozone in the 2006 zROW and 2006 base runs, which provides an estimate of the ozone contribution from anthropogenic sources outside of North America. It is assumed that the highest monthly 8-hour ozone in each grid cell from the 2006 base and 2006 zROW runs are paired in time. The monthly maximum 8-hour ozone concentrations and the contributions from non-North American anthropogenic sources to three urban areas in Texas – El Paso, Dallas, and Houston – are listed in Table 3-2 for each month of the year.

The 2006 base case shows 8-hour ozone exceeding 75 ppb, the current level of the ozone NAAQS, in several areas in the CONUS domain, mostly in the eastern states. July and August were the worst ozone months with Los Angeles, the Midwest and northeastern states exceeding 75 ppb. High summer ozone concentrations (above 90 ppb) also occurred over water bodies close to major urban/industrial areas near the Great Lakes, Gulf Coast and the Northeast Seaboard, where emissions are transported over water and get confined to a shallow boundary layer. Ozone in the Texas urban areas exceeded 75 ppb from May through October. Texas peaks were generally seen over the Houston area.

The highest 8-hour ozone predicted in the three regions in Texas was 89 ppb in June in Houston. Ozone exceeding 75 ppb was predicted in Houston and Dallas from June to October (75-89 ppb) and June to September (76-88), respectively. El Paso was below 75 ppb throughout the year.

2006 zROW monthly maximum ozone spatial plots strongly resembled the base case, but with marginally lower ozone concentrations. The highest 8-hour ozone in the 2006 base case run was 107.5 ppb off the coast of New Jersey in August. The highest in the 2006 zROW run was 106.6 ppb in the same grid cell and month, meaning that the contribution from non-North American anthropogenic sources to the highest 8-hour ozone in 2006 in the CONUS domain was only 0.9 ppb.

The ozone contribution from anthropogenic sources outside North America was larger in the winter months and in the western half of the US, which would be expected since the predominant wind direction is from the west, where ozone and its precursors can be transported from Asia. The largest impact from non-North American anthropogenic sources to the continental US was 12.9 ppb in western Montana in May, where the maximum ozone in the base case was 55-60 ppb. The base case ozone tended to be low when ozone transport from non-North American sources was higher. In the eastern half of the US, the non-North American anthropogenic contribution to 8-hour ozone was highest in January and February, with contributions up to 10 ppb. Between June and October, when the base case ozone was highest, ozone contributions from anthropogenic sources outside of North America never exceeded 4 ppb in the eastern half of the US.

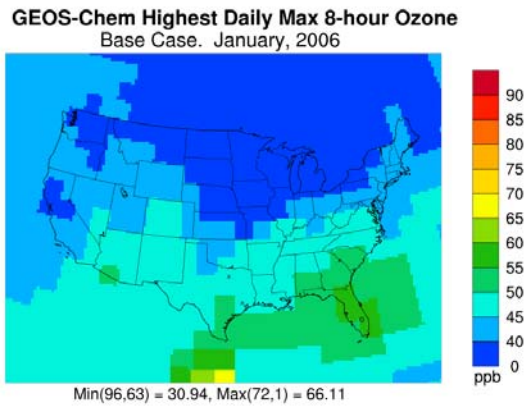
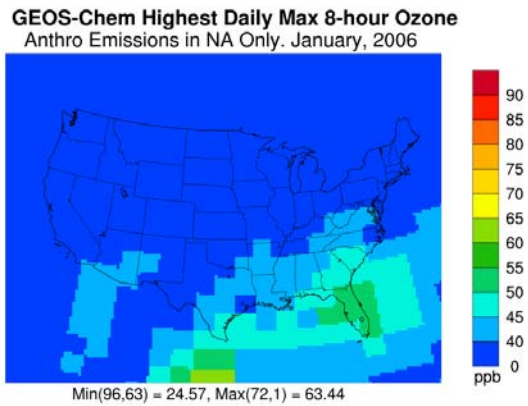
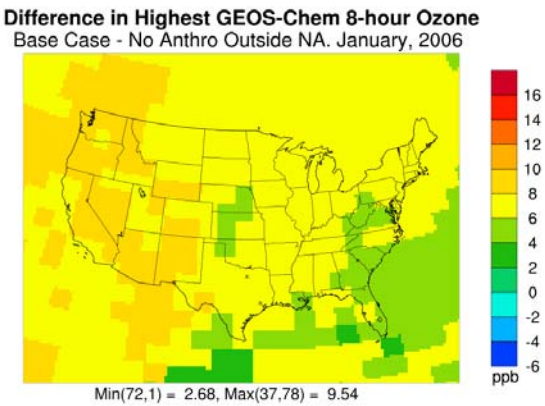
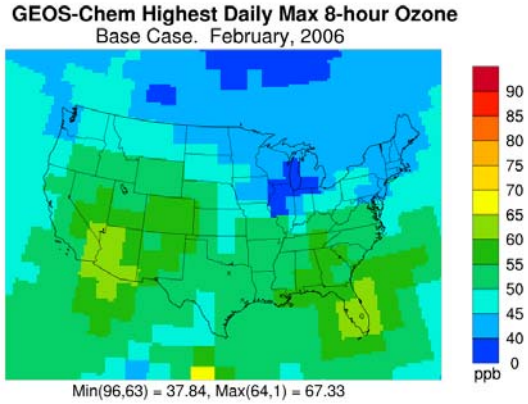
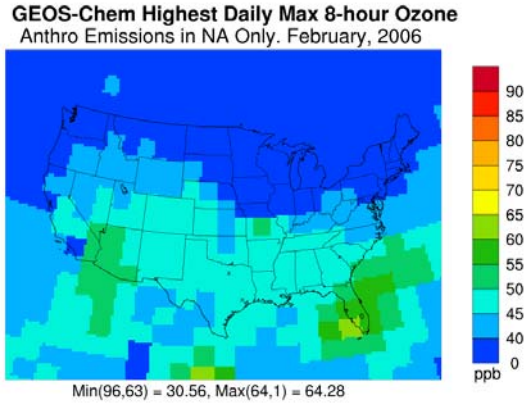
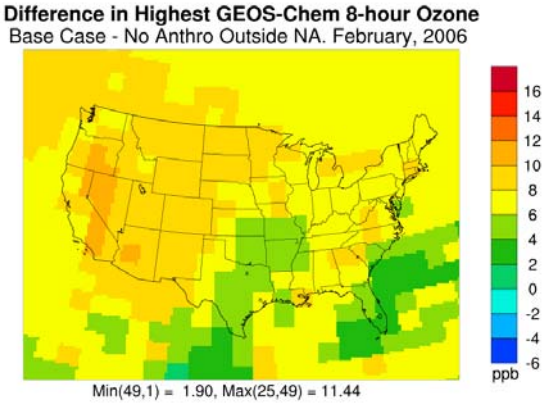
Non-North American anthropogenic contributions to Los Angeles, where GEOS-Chem predicted 95 ppb in the 2006 base case, were also lower in the summer during the high ozone episodes. This could be explained by the weather patterns. Ozone concentrations tend to build up on sunny days when the air becomes stagnant, which would limit the ability to transport ozone

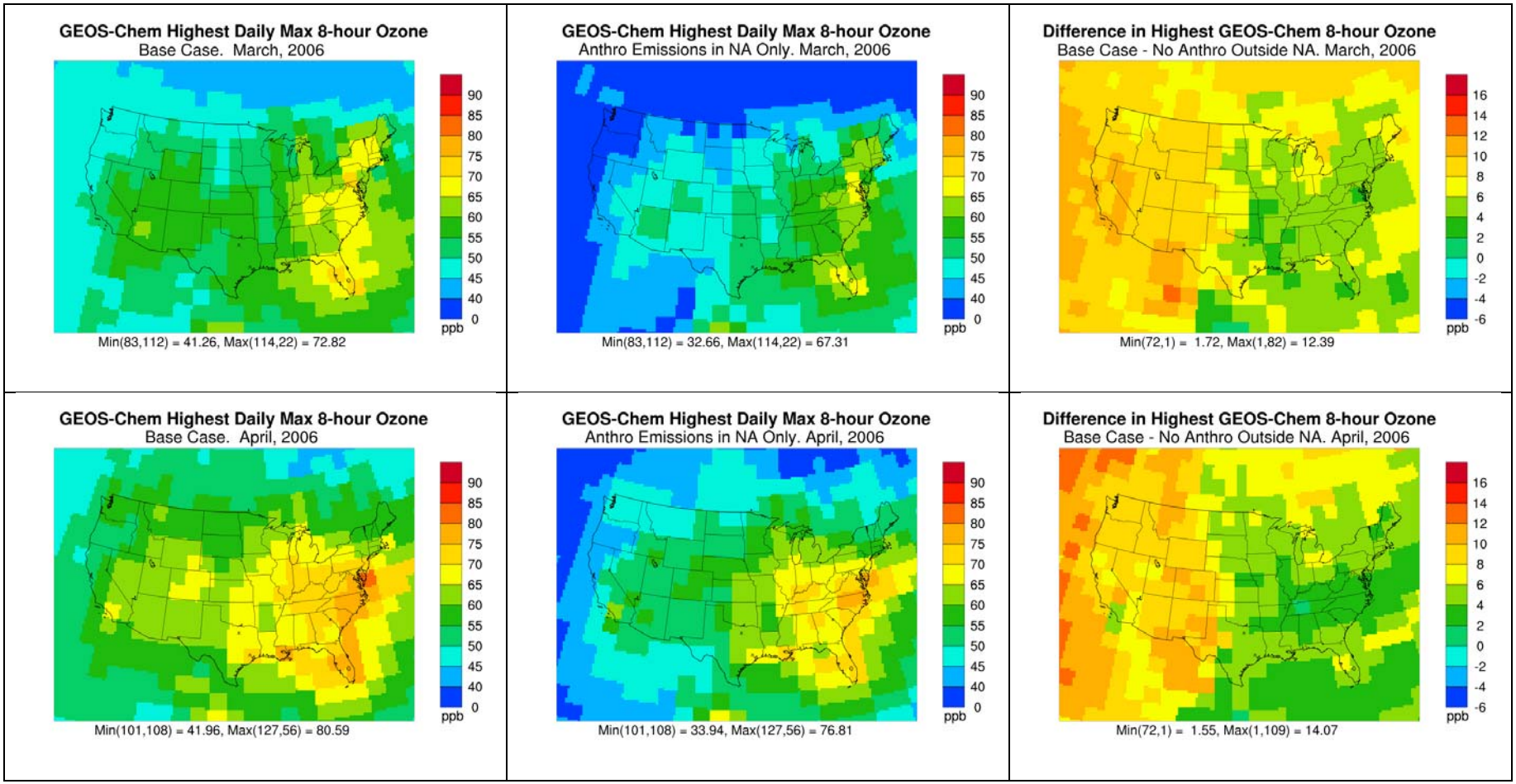
and its precursors from sources outside of North America. In addition, a ridge of higher pressure tends to occur over the western US in the summer, deflecting storms and non-North American pollutants well to the north.

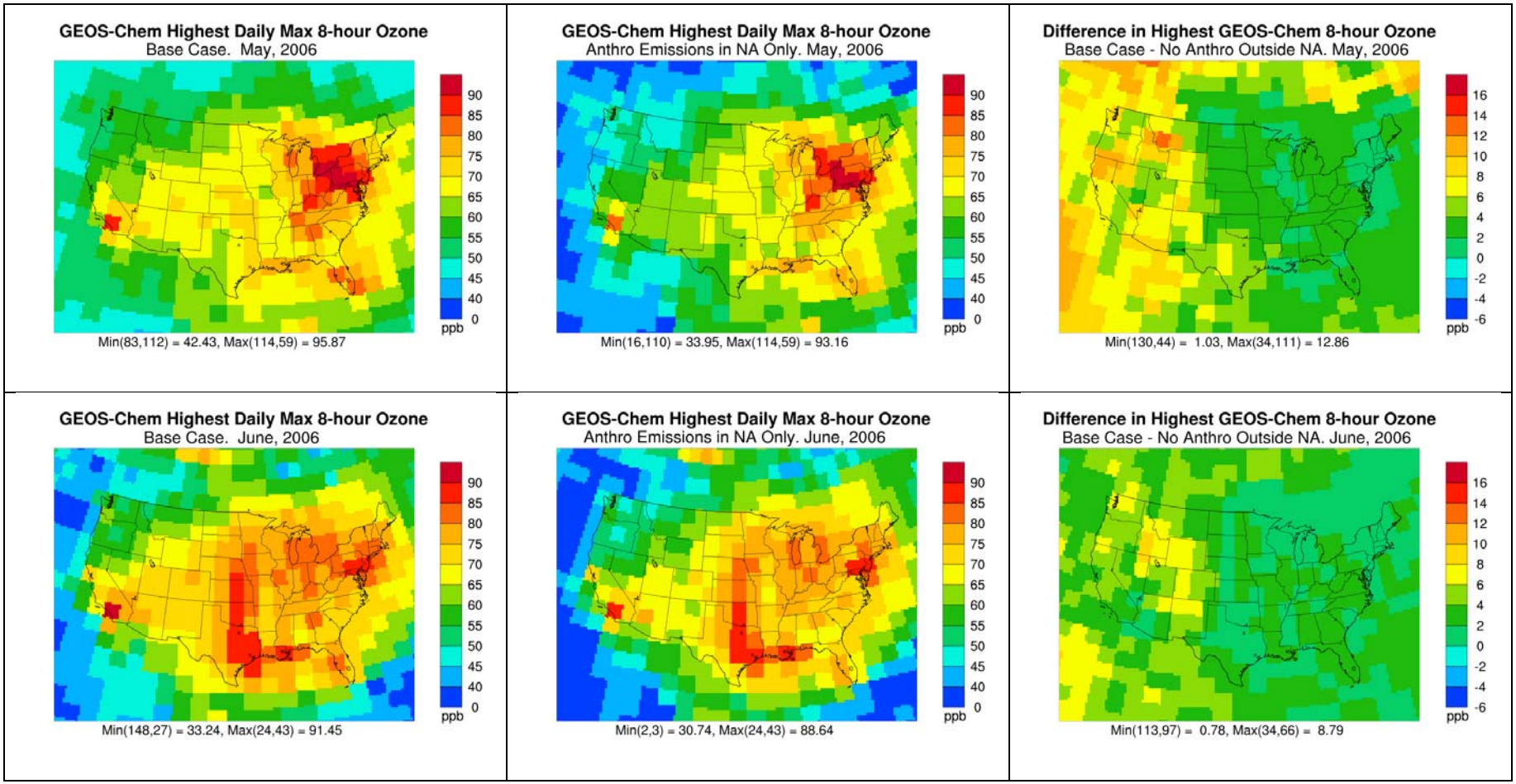
In Texas, the non-North American anthropogenic emissions added more to the monthly 8-hour ozone peaks in El Paso – the westernmost site – than to Dallas or Houston in all months except May. Although the highest 8-hour ozone peak at El Paso in the base run was 74.8 ppb in August, the non-North American contribution was the lowest in August at 1.1 ppb. The non-North American anthropogenic contribution to El Paso was highest in March at 11 ppb, when the base case ozone was 56 ppb.

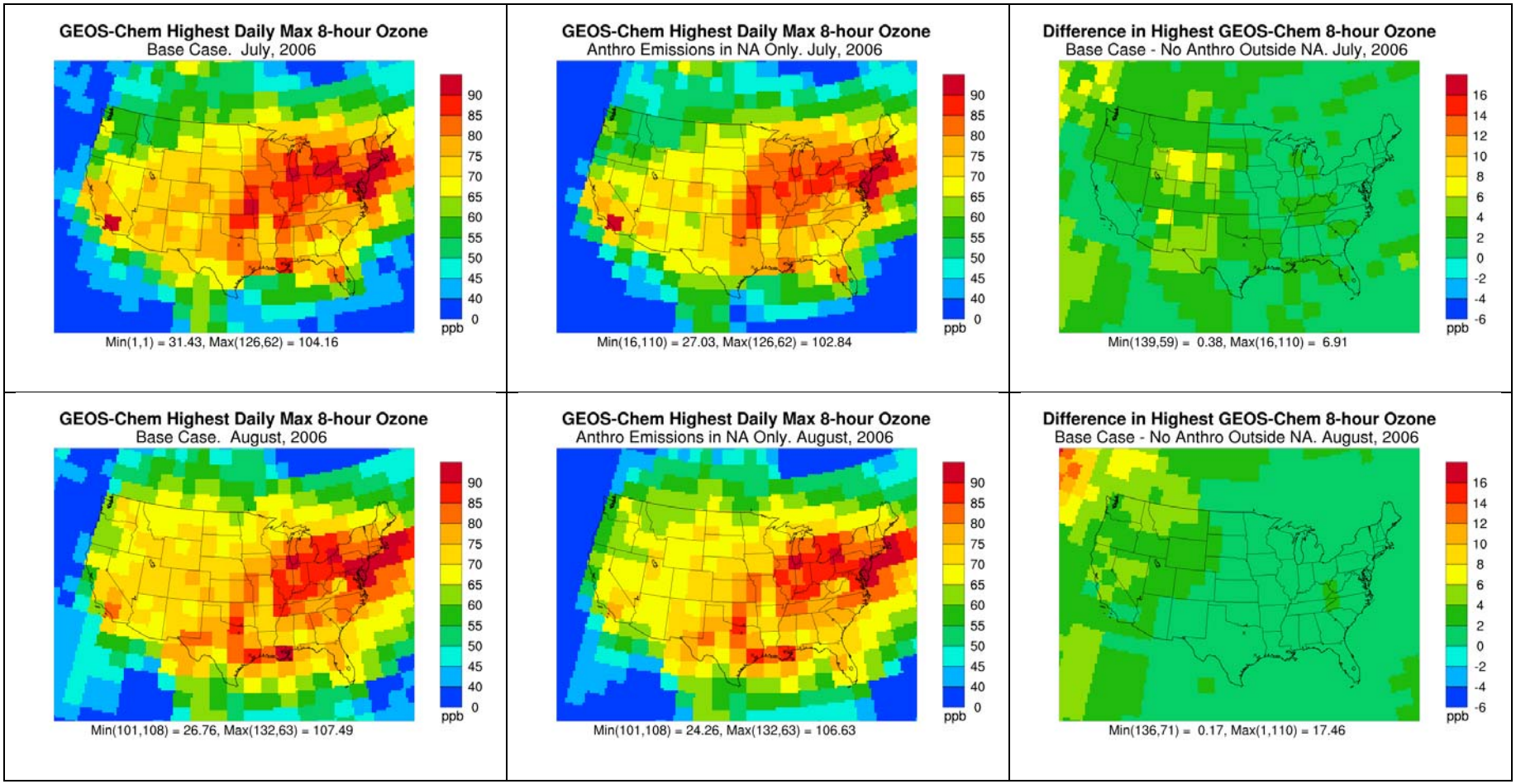
In Dallas, the 2006 GEOS-Chem base case run predicted monthly 8-hour ozone peaks exceeding 75 ppb between June and September. The non-North American anthropogenic contribution to each of these monthly peaks ranged from 1.0 to 2.5 ppb; contributions in all other months were higher with December being the highest at 6.5 ppb.

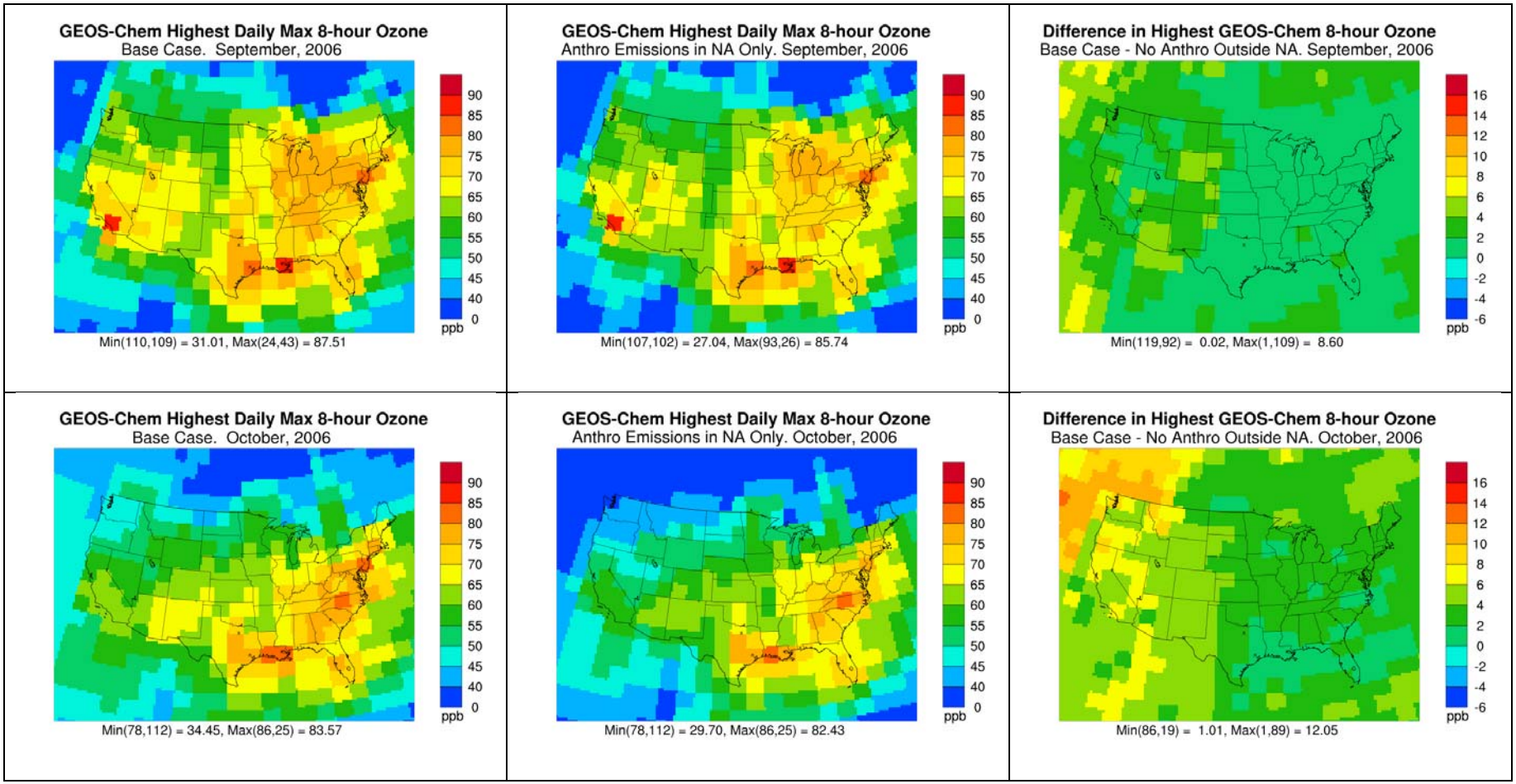
Results in Houston were similar to Dallas, with the largest anthropogenic contribution from outside North America being 7.3 ppb in January. During the five months when the monthly maximum 8-hour ozone exceeded 75 ppb, the non-North American anthropogenic ozone contributions were the lowest, ranging from 0.5 to 2.2 ppb. All five monthly maxima remained over 75 ppb in the 2006 zROW run.

2006 Base Monthly Maximum 8-hour Ozone	2006 zROW Monthly Maximum 8-hour Ozone	Contributions from non-North American Anthropogenic Sources to the Monthly Max (2006 base – 2006 zROW)
		
		


GEOS-Chem Highest Daily Max 8-hour Ozone
Base Case. March, 2006
Min(83,112) = 41.26, Max(114,22) = 72.82
GEOS-Chem Highest Daily Max 8-hour Ozone
Anthro Emissions in NA Only. March, 2006
Min(83,112) = 32.66, Max(114,22) = 67.31
Difference in Highest GEOS-Chem 8-hour Ozone
Base Case - No Anthro Outside NA. March, 2006
Min(72,1) = 1.72, Max(1,82) = 12.39
GEOS-Chem Highest Daily Max 8-hour Ozone
Base Case. April, 2006
Min(101,108) = 41.96, Max(127,56) = 80.59
GEOS-Chem Highest Daily Max 8-hour Ozone
Anthro Emissions in NA Only. April, 2006
Min(101,108) = 33.94, Max(127,56) = 76.81
Difference in Highest GEOS-Chem 8-hour Ozone
Base Case - No Anthro Outside NA. April, 2006
Min(72,1) = 1.55, Max(1,109) = 14.07
ppb


GEOS-Chem Highest Daily Max 8-hour Ozone
Base Case. May, 2006
Min(83,112) = 42.43, Max(114,59) = 95.87
GEOS-Chem Highest Daily Max 8-hour Ozone
Anthro Emissions in NA Only. May, 2006
Min(16,110) = 33.95, Max(114,59) = 93.16
Difference in Highest GEOS-Chem 8-hour Ozone
Base Case - No Anthro Outside NA. May, 2006
Min(130,44) = 1.03, Max(34,111) = 12.86
GEOS-Chem Highest Daily Max 8-hour Ozone
Base Case. June, 2006
Min(148,27) = 33.24, Max(24,43) = 91.45
GEOS-Chem Highest Daily Max 8-hour Ozone
Anthro Emissions in NA Only. June, 2006
Min(2,3) = 30.74, Max(24,43) = 88.64
Difference in Highest GEOS-Chem 8-hour Ozone
Base Case - No Anthro Outside NA. June, 2006
Min(113,97) = 0.78, Max(34,66) = 8.79
ppb


GEOS-Chem Highest Daily Max 8-hour Ozone
Base Case. July, 2006
Min(1,1) = 31.43, Max(126,62) = 104.16
GEOS-Chem Highest Daily Max 8-hour Ozone
Anthro Emissions in NA Only. July, 2006
Min(16,110) = 27.03, Max(126,62) = 102.84
Difference in Highest GEOS-Chem 8-hour Ozone
Base Case - No Anthro Outside NA. July, 2006
Min(139,59) = 0.38, Max(16,110) = 6.91
GEOS-Chem Highest Daily Max 8-hour Ozone
Base Case. August, 2006
Min(101,108) = 26.76, Max(132,63) = 107.49
GEOS-Chem Highest Daily Max 8-hour Ozone
Anthro Emissions in NA Only. August, 2006
Min(101,108) = 24.26, Max(132,63) = 106.63
Difference in Highest GEOS-Chem 8-hour Ozone
Base Case - No Anthro Outside NA. August, 2006
Min(136,71) = 0.17, Max(1,110) = 17.46
ppb


GEOS-Chem Highest Daily Max 8-hour Ozone
Base Case. September, 2006
Min(110,109) = 31.01, Max(24,43) = 87.51
GEOS-Chem Highest Daily Max 8-hour Ozone
Anthro Emissions in NA Only. September, 2006
Min(107,102) = 27.04, Max(93,26) = 85.74
Difference in Highest GEOS-Chem 8-hour Ozone
Base Case - No Anthro Outside NA. September, 2006
Min(119,92) = 0.02, Max(1,109) = 8.60
GEOS-Chem Highest Daily Max 8-hour Ozone
Base Case. October, 2006
Min(78,112) = 34.45, Max(86,25) = 83.57
GEOS-Chem Highest Daily Max 8-hour Ozone
Anthro Emissions in NA Only. October, 2006
Min(78,112) = 29.70, Max(86,25) = 82.43
Difference in Highest GEOS-Chem 8-hour Ozone
Base Case - No Anthro Outside NA. October, 2006
Min(86,19) = 1.01, Max(1,89) = 12.05
ppb

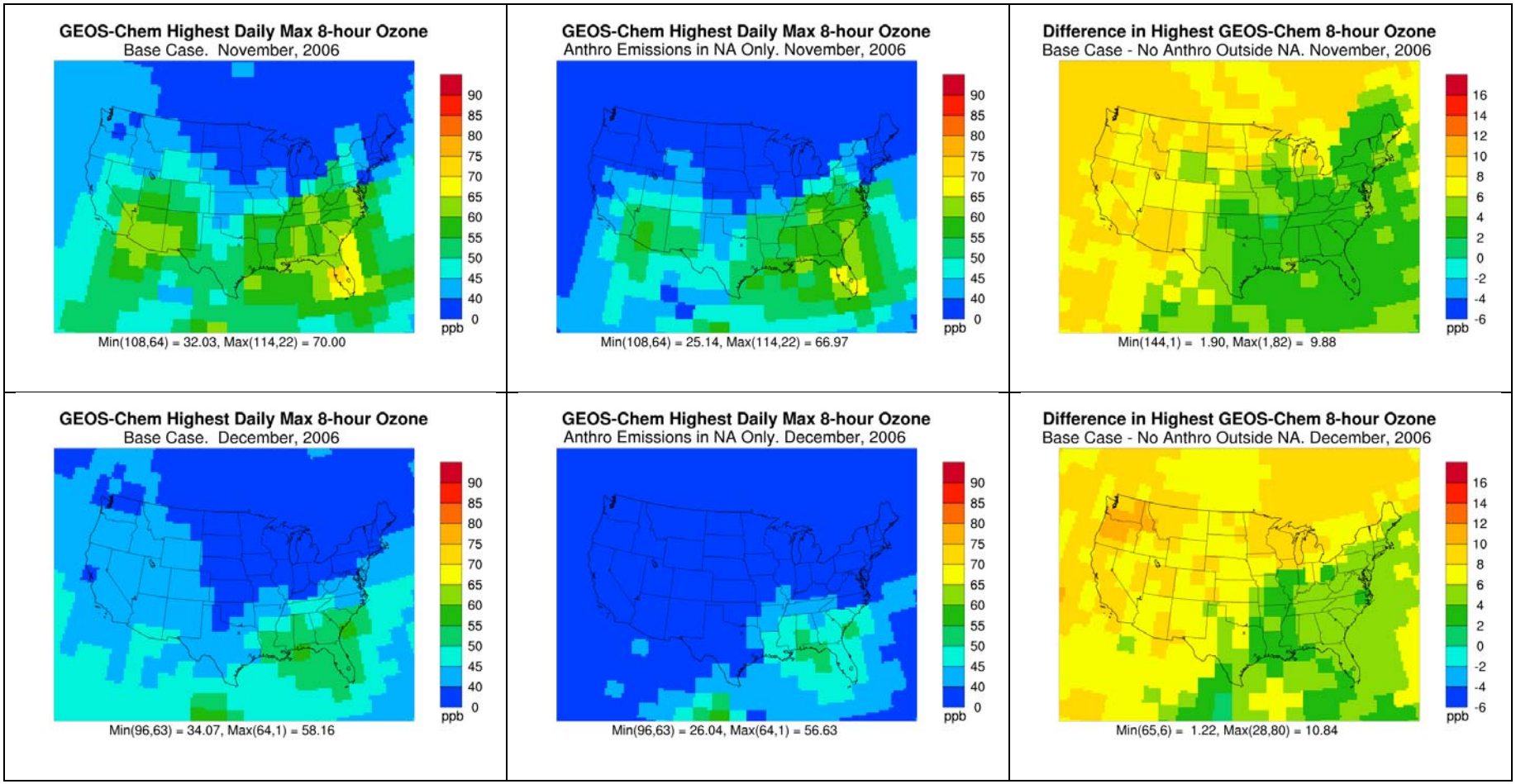


Figure 3-2. Maps of monthly maximum 8-hour ozone in the 2006 base case (left) 2006 zROW case (middle) and the ozone contribution from anthropogenic sources outside of North America (right).

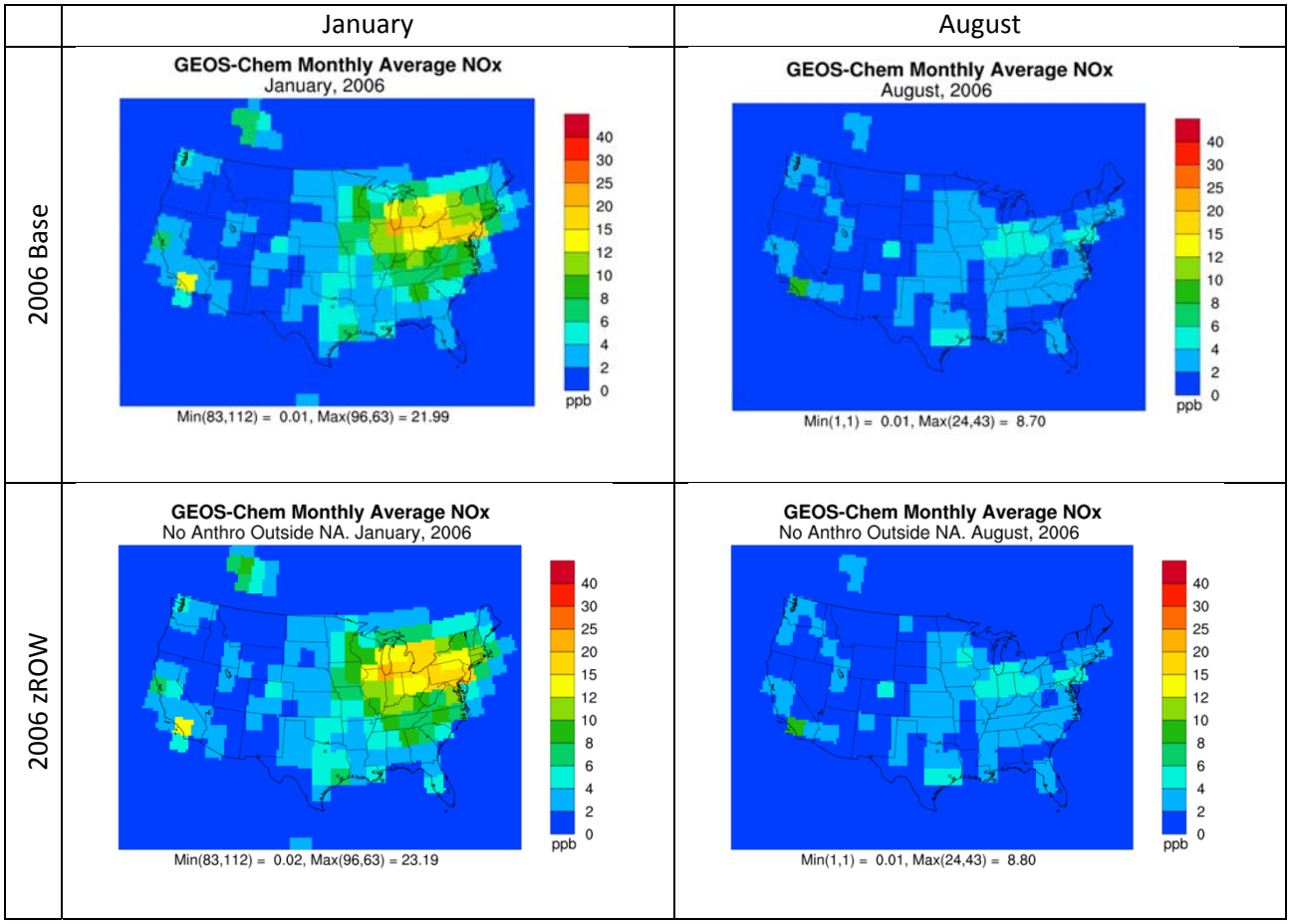
Table 3-2. Monthly maximum 8-hour ozone in El Paso, Dallas, and Houston in the 2006 base and 2006 zROW runs. Their difference is an estimate of the contribution from anthropogenic sources outside of North America.

	El Paso			Dallas			Houston		
[ppb]	2006 Base	2006 zROW	Difference	2006 Base	2006 zROW	Difference	2006 Base	2006 zROW	Difference
Jan	48.9	39.9	9.0	45.8	39.7	6.1	47.2	39.9	7.3
Feb	57.6	48.4	9.2	51.4	46.5	4.9	52.8	46.1	6.7
Mar	56.3	45.2	11.1	58.7	52.9	5.8	59.8	53.8	6.0
Apr	63.1	52.8	10.3	67.2	62.7	4.5	70.4	65.7	4.7
May	64.6	60.7	3.9	67.8	63.7	4.1	74.8	70.6	4.2
Jun	68.9	64.4	4.5	87.5	85.7	1.8	89.3	88.0	1.3
Jul	73.4	68.4	5.0	82.8	80.3	2.5	81.6	79.4	2.2
Aug	74.8	73.7	1.1	88.2	87.2	1.0	88.1	87.6	0.5
Sep	64.6	61.6	3.0	76.1	74.9	1.2	81.1	80.2	0.9
Oct	65.7	59.7	6.0	72.6	69.6	3.0	79.6	78.3	1.3
Nov	61.2	52.6	8.6	49.6	45.7	3.9	57.9	54.7	3.2
Dec	45.3	37.0	8.3	43.8	37.3	6.5	43.1	39.7	3.4

3.2 2006 Monthly Averaged NOx

NOx concentrations between the 2006 base and 2006 zROW GEOS-Chem runs were also examined. Figure 3-3 shows the monthly averaged NOx from the 2006 base case in the top row and from the 2006 zROW run in the middle row. The difference in monthly averaged NOx is shown on the bottom. January and August are shown to represent the winter and summer, respectively.

In all months, NOx was slightly higher over the continental US when non-North America anthropogenic emissions are removed. The differences were greatest in the winter months in the Northeast US, where the highest NOx in the base run was located. This result occurs because the atmospheric lifetime of NOx is longer when ozone concentrations are lower, especially in winter.



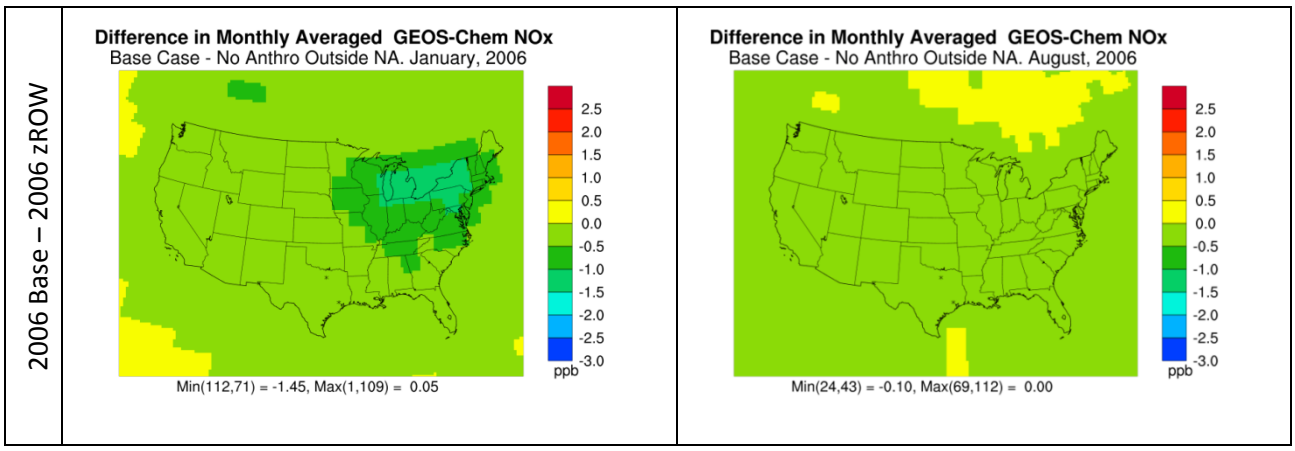


Figure 3-3. Maps of monthly averaged NOx in the 2006 base case (top), 2006 zROW run (middle), and their differences (bottom)

4.0 2012 MODEL RESULTS

In 2012, GEOS-Chem was run three times. One was for the 2012 base case. The second zeroed out anthropogenic emissions outside of North America (2012 zROW), as was done in 2006. The third zeroed out anthropogenic emissions inside North America (2012 zNA). The ozone contribution from non-North American anthropogenic sources can be calculated by taking the difference between the 2012 zROW run and the 2012 base case. The contribution from sources that cannot be controlled in attainment demonstrations, including anthropogenic sources within North America and all sources outside of North America (i.e., anthropogenic + natural + stratospheric) can be estimated from the 2012 zNA run.

All 2012 runs used year-specific meteorology. Emissions from countries who were members of the Organisation for Economic Co-operation and Development in 1990 (OECD90) (Western Europe, Northern America, and Pacific OECD), which include the US, and in the reforming economies (REF), which include Russia, were lower in 2012 than in 2006. In Asia and the Middle East/Africa (MAF), emissions of ozone precursors were higher in 2012. Shipping, aviation, and emissions in Latin America did not change significantly in 2012 compared to 2006. Table 4-1 summarizes the emission differences between the two years.

Table 4-1. Differences in anthropogenic emission totals between 2006 and 2012.

Sources	World Region	Emissions (MM Tons/year or MM Tons C/year)			
		CO	NOx	SO_2	VOC
Total Anthropogenic from 2005 NEI	US	-26.3	-6.7	-7.1	-1.4
Total Anthropogenic from EDGAR4.1/RETRO inventories (excluding aviation and shipping CO/NOx/SO_2 emissions)	ASIA	4.5	5.9	-3.2	1.9
	LAM	0.0	-0.3	-1.0	0.2
	MAF	6.7	0.8	-0.3	1.0
	OECD90 except US	-21.3	-4.1	-7.7	-3.7
	REF	-2.6	-1.3	-3.4	-0.6
Shipping	World	0.3	-0.1	-1.0	0.0
Aviation	World	0.1	0.1	0.0	0.0

4.1 2012 8-Hour Ozone

Figure 4-1 shows maps of the highest 8-hour ozone in each month in each of the three 2012 GEOS-Chem scenarios and Figure 4-2 displays the ozone contributions (2012 base – 2012 zROW) from non-North American anthropogenic sources to the monthly maximum 8-hour ozone in the CONUS domain. For comparison purposes, the 2006 contributions are also shown.

In the 2012 base case, the monthly maximum 8-hour ozone was lower than the 2006 base case across much of the CONUS from May to November. However, ozone was higher in 2012 in the Northeast in March, where 8-hour ozone exceeding 75 ppb was predicted, and was much higher in the western US in April. These differences are most likely attributed to the different meteorology than to changes in emissions between 2006 and 2012. In Texas, ozone exceeded

75 ppb in Houston (78 ppb in June and August), and at Dallas (78 and 76 ppb in July and August, respectively). No ozone over 75 ppb was predicted in the El Paso area.

Like 2006, the 2012 zROW run exhibited similar spatial patterns as in the 2012 base, but with slightly lower ozone concentrations, particularly in the western US. The highest ozone in the 2012 base case was 101.7 ppb in northern Canada in July, of which 2.1 ppb could be attributed to anthropogenic emissions from non-North American sources. Within the continental US, the highest 8-hour ozone in the 2012 base case was 90.3 ppb in New Jersey in June; non-North American anthropogenic sources contributed 1.5 ppb to the monthly maximum.

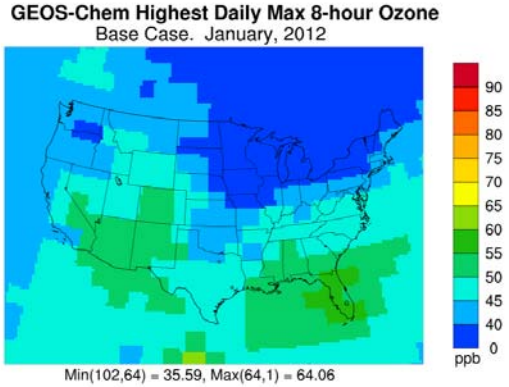
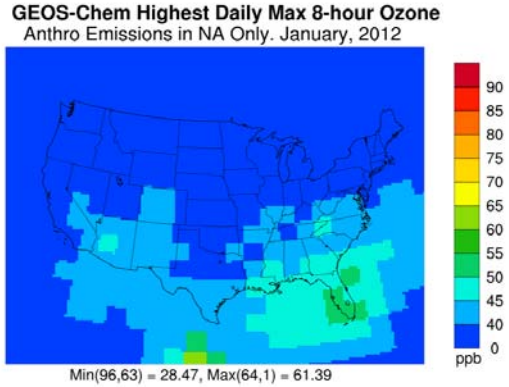
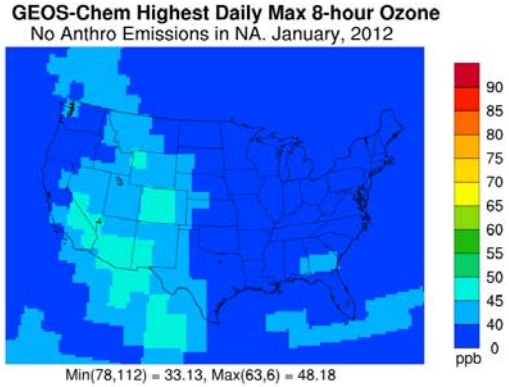
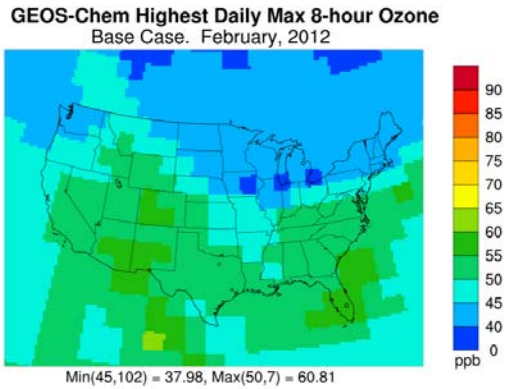
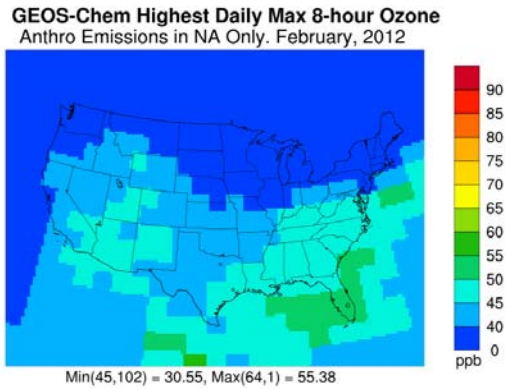
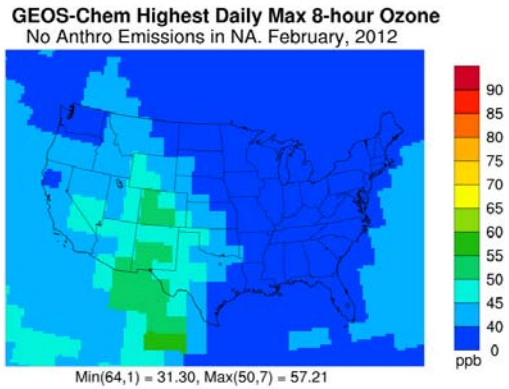
In the 2012 zNA run, the lack of anthropogenic emissions within North America significantly lowered the 8-hour ozone peaks in the summer months, especially in the eastern half of the US. Ozone in the 2012 zNA run was considerably higher than the difference between the 2012 zROW and 2012 base runs during all months, demonstrating that most of the background ozone entering North America is attributable to natural sources (i.e., natural emissions and the stratosphere) rather than anthropogenic sources. Table 4-2 lists the monthly maximum 8-hour ozone predicted by GEOS-Chem at El Paso, Dallas, and Houston from all three 2012 runs, and Table 4-3 shows the non-North American ozone impact using the two different methods. The 2012 zNA results were often an order of magnitude greater than the 2012 base – 2012 zROW method.

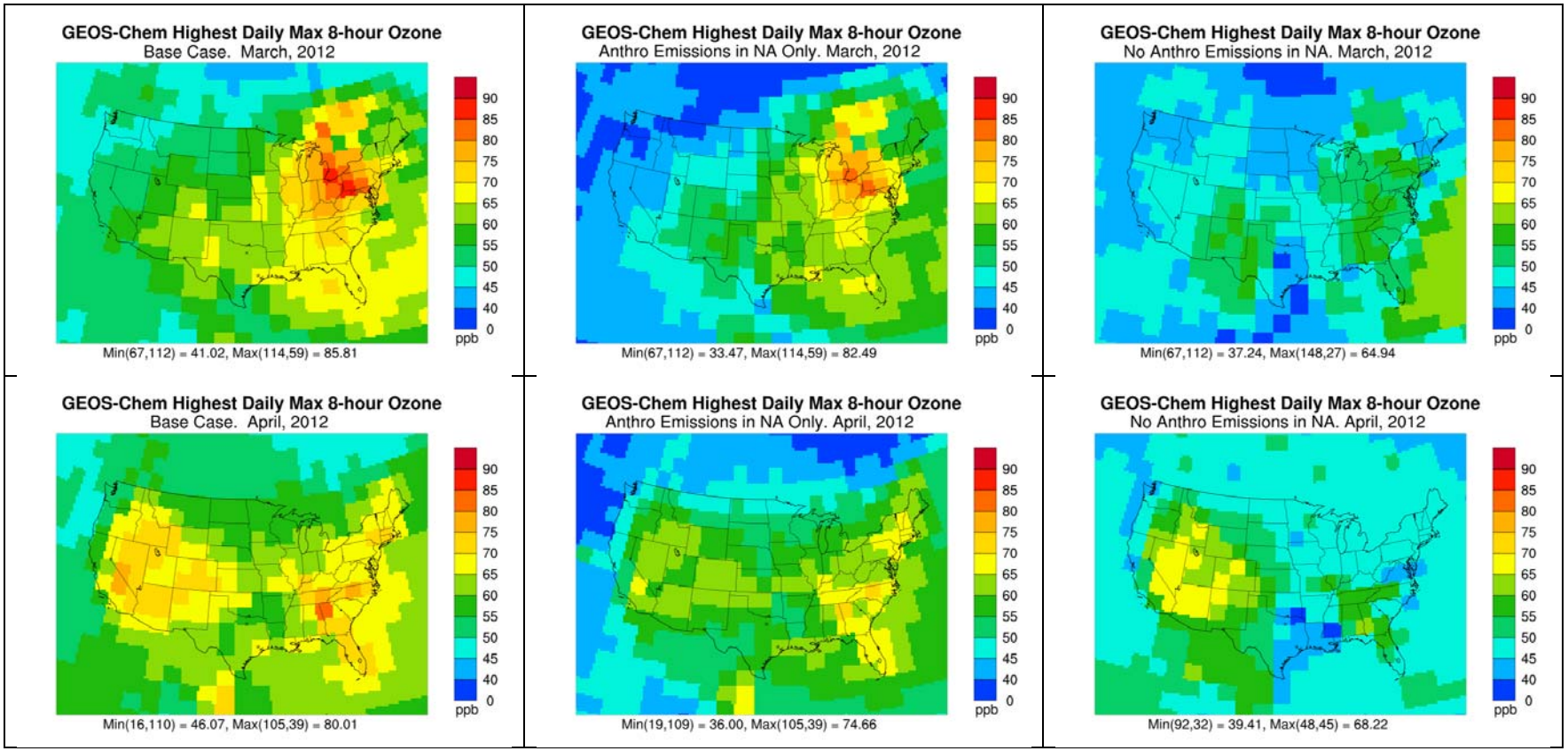
In El Paso, the base – zROW method yielded ozone contributions between 2 ppb in August to 11 ppb in February, consistent with the rest of the US in that the contributions were higher in the winter and lower in the summer. Between the two 2012 zero-out runs, the monthly ozone peaks in El Paso were within 10 ppb of one another in all months except September.

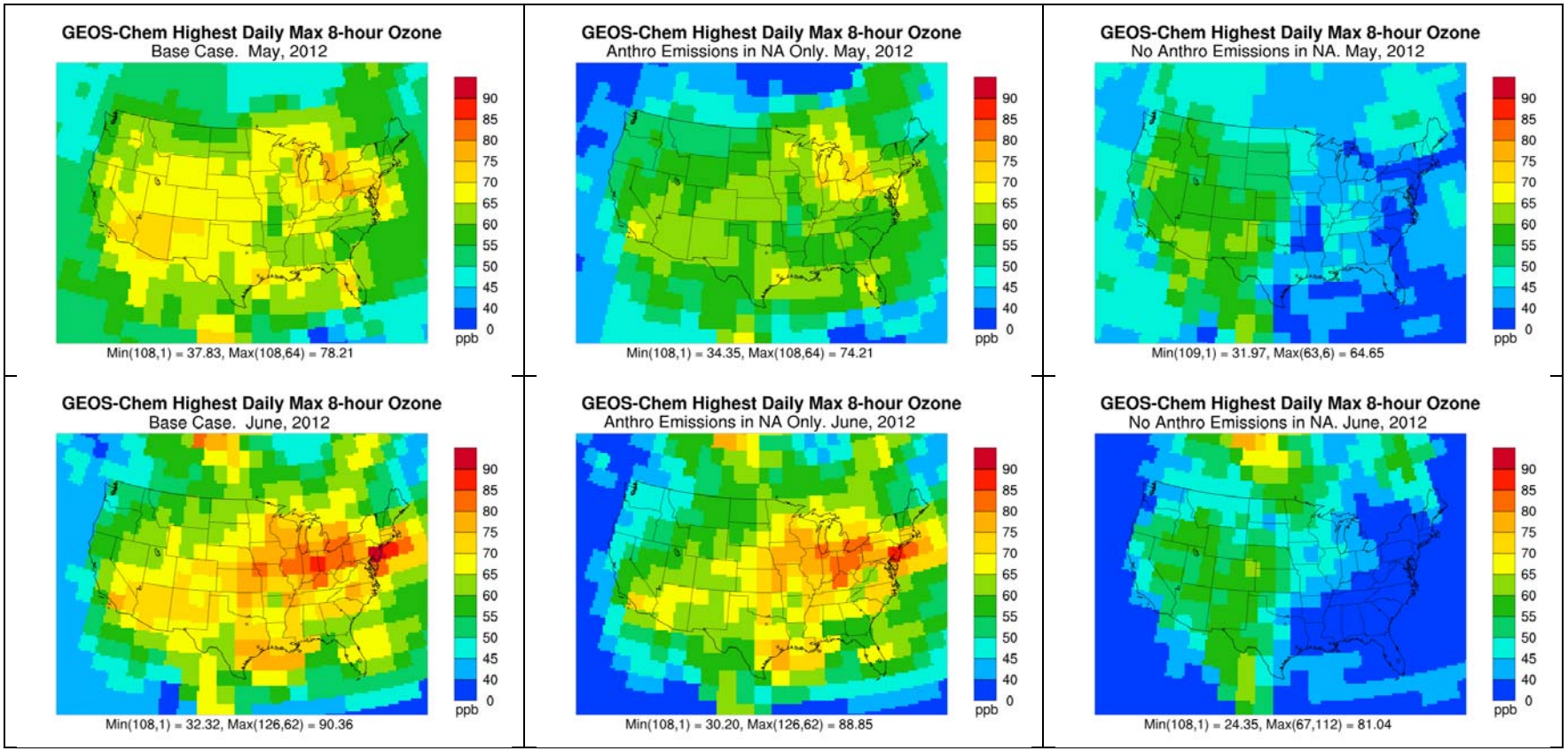
In Dallas, the 2012 base case predicted an 8-hour ozone peak of 78.2 ppb in July, of which only 2.8 ppb was attributed to anthropogenic sources outside of North America. The largest contribution to the monthly maximum 8-hour ozone from non-North America sources was 8 .7 ppb in February. In the Dallas ozone season (March to October), May's contribution was highest at 4.9 ppb; all other months were between 2.0 and 3.7 ppb.

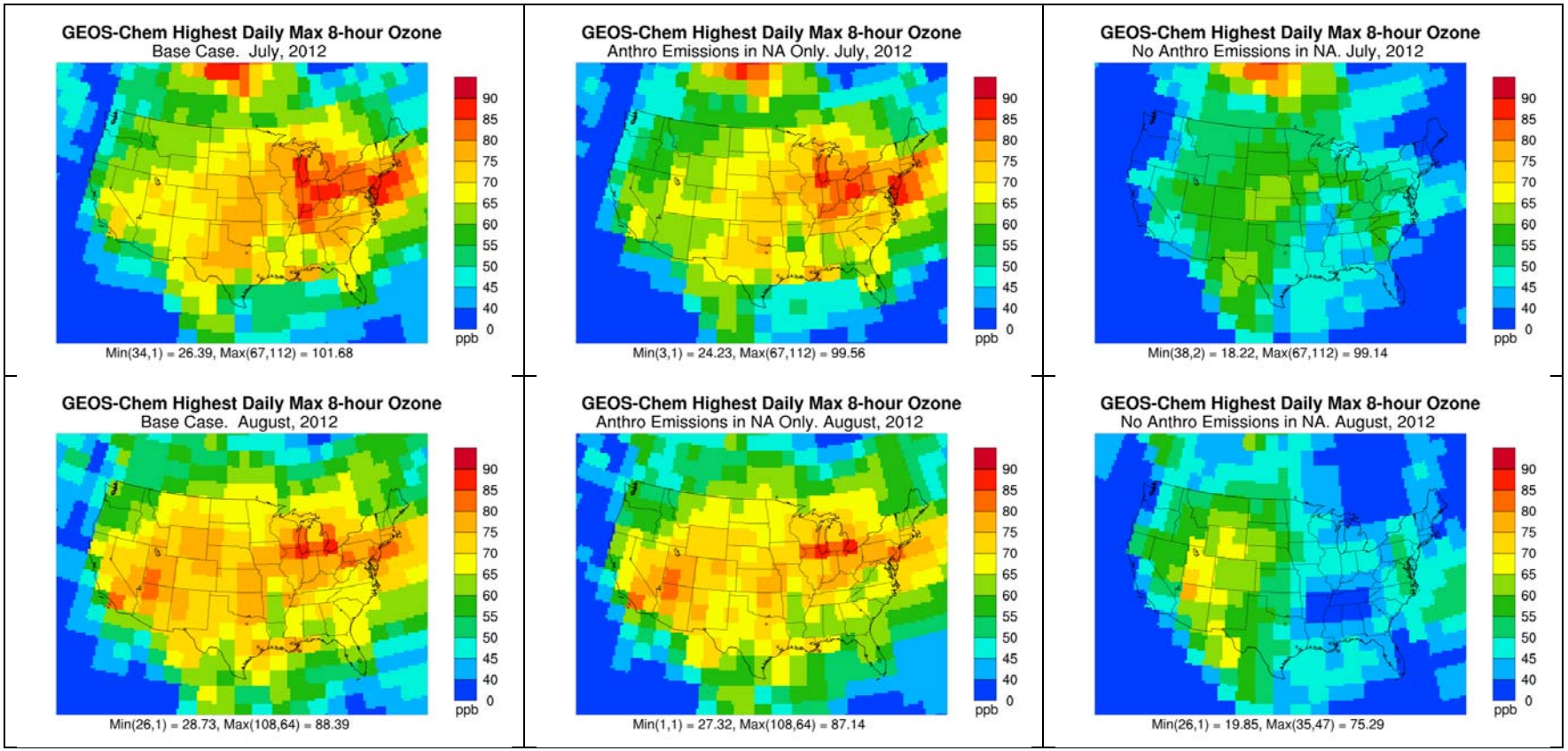
In Houston, the non-North American contribution to the monthly maximum 8-hour ozone was less than 6 ppb for all months. Like Dallas and El Paso, the largest anthropogenic contributions from outside North America occurred during the winter months, when ozone concentrations were generally low. During Houston's ozone season (March to November), the highest ozone contribution from non-North American sources to the monthly maximum 8-hour ozone was always less than 4 ppb.

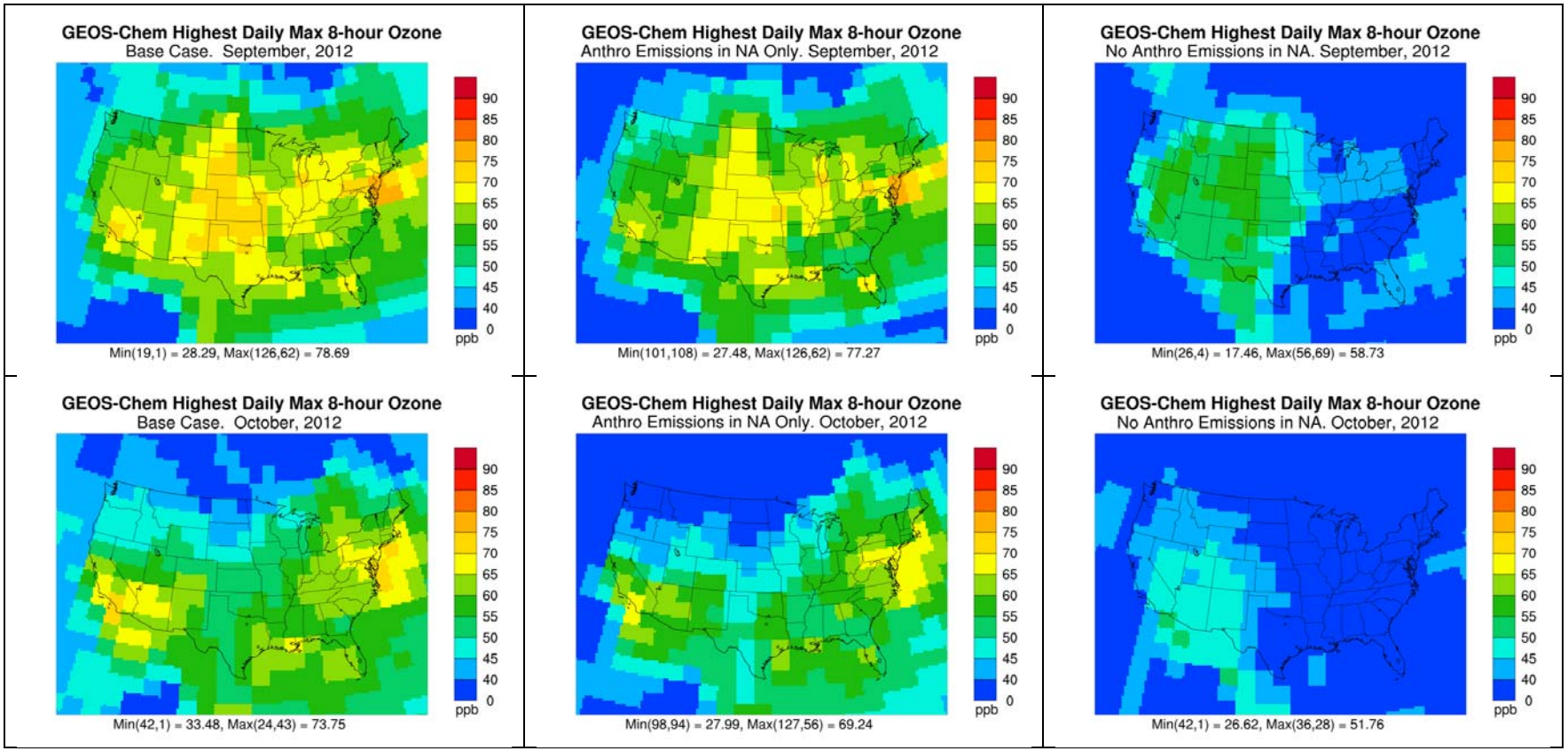
When anthropogenic emissions were removed from North America (2012 zNA), the ozone peaks in Dallas and Houston were substantially lower than in the 2012 base run in the summer months. In June, the 8-hour ozone peaks were 30 ppb and 40 ppb lower in Dallas and Houston, respectively, indicating that the North American anthropogenic sources are large contributors to ozone in Dallas and Houston. In comparison, the largest impact from North American anthropogenic sources (base – zNA) to any monthly ozone peak at El Paso was only 16 ppb.

2012 Base	2012 zROW	2012 zNA
		
		


GEOS-Chem Highest Daily Max 8-hour Ozone
Base Case. March, 2012
Min(67,112) = 41.02, Max(114,59) = 85.81
GEOS-Chem Highest Daily Max 8-hour Ozone
Anthro Emissions in NA Only. March, 2012
Min(67,112) = 33.47, Max(114,59) = 82.49
GEOS-Chem Highest Daily Max 8-hour Ozone
No Anthro Emissions in NA. March, 2012
Min(67,112) = 37.24, Max(148,27) = 64.94
GEOS-Chem Highest Daily Max 8-hour Ozone
Base Case. April, 2012
Min(16,110) = 46.07, Max(105,39) = 80.01
GEOS-Chem Highest Daily Max 8-hour Ozone
Anthro Emissions in NA Only. April, 2012
Min(19,109) = 36.00, Max(105,39) = 74.66
GEOS-Chem Highest Daily Max 8-hour Ozone
No Anthro Emissions in NA. April, 2012
Min(92,32) = 39.41, Max(48,45) = 68.22
90 85 80 75 70 65 60 55 50 45 40 0
ppb


GEOS-Chem Highest Daily Max 8-hour Ozone
Base Case. May, 2012
Min(108,1) = 37.83, Max(108,64) = 78.21
GEOS-Chem Highest Daily Max 8-hour Ozone
Anthro Emissions in NA Only. May, 2012
Min(108,1) = 34.35, Max(108,64) = 74.21
GEOS-Chem Highest Daily Max 8-hour Ozone
No Anthro Emissions in NA. May, 2012
Min(109,1) = 31.97, Max(63,6) = 64.65
GEOS-Chem Highest Daily Max 8-hour Ozone
Base Case. June, 2012
Min(108,1) = 32.32, Max(126,62) = 90.36
GEOS-Chem Highest Daily Max 8-hour Ozone
Anthro Emissions in NA Only. June, 2012
Min(108,1) = 30.20, Max(126,62) = 88.85
GEOS-Chem Highest Daily Max 8-hour Ozone
No Anthro Emissions in NA. June, 2012
Min(108,1) = 24.35, Max(67,112) = 81.04
90
85
80
75
70
65
60
55
50
45
40
0
ppb


GEOS-Chem Highest Daily Max 8-hour Ozone
Base Case. July, 2012
Min(34,1) = 26.39, Max(67,112) = 101.68
GEOS-Chem Highest Daily Max 8-hour Ozone
Anthro Emissions in NA Only. July, 2012
Min(3,1) = 24.23, Max(67,112) = 99.56
GEOS-Chem Highest Daily Max 8-hour Ozone
No Anthro Emissions in NA. July, 2012
Min(38,2) = 18.22, Max(67,112) = 99.14
GEOS-Chem Highest Daily Max 8-hour Ozone
Base Case. August, 2012
Min(26,1) = 28.73, Max(108,64) = 88.39
GEOS-Chem Highest Daily Max 8-hour Ozone
Anthro Emissions in NA Only. August, 2012
Min(1,1) = 27.32, Max(108,64) = 87.14
GEOS-Chem Highest Daily Max 8-hour Ozone
No Anthro Emissions in NA. August, 2012
Min(26,1) = 19.85, Max(35,47) = 75.29
90
85
80
75
70
65
60
55
50
45
40
0
ppb


GEOS-Chem Highest Daily Max 8-hour Ozone
Base Case. September, 2012
Min(19,1) = 28.29, Max(126,62) = 78.69
GEOS-Chem Highest Daily Max 8-hour Ozone
Anthro Emissions in NA Only. September, 2012
Min(101,108) = 27.48, Max(126,62) = 77.27
GEOS-Chem Highest Daily Max 8-hour Ozone
No Anthro Emissions in NA. September, 2012
Min(26,4) = 17.46, Max(56,69) = 58.73
GEOS-Chem Highest Daily Max 8-hour Ozone
Base Case. October, 2012
Min(42,1) = 33.48, Max(24,43) = 73.75
GEOS-Chem Highest Daily Max 8-hour Ozone
Anthro Emissions in NA Only. October, 2012
Min(98,94) = 27.99, Max(127,56) = 69.24
GEOS-Chem Highest Daily Max 8-hour Ozone
No Anthro Emissions in NA. October, 2012
Min(42,1) = 26.62, Max(36,28) = 51.76
90
85
80
75
70
65
60
55
50
45
40
0
ppb

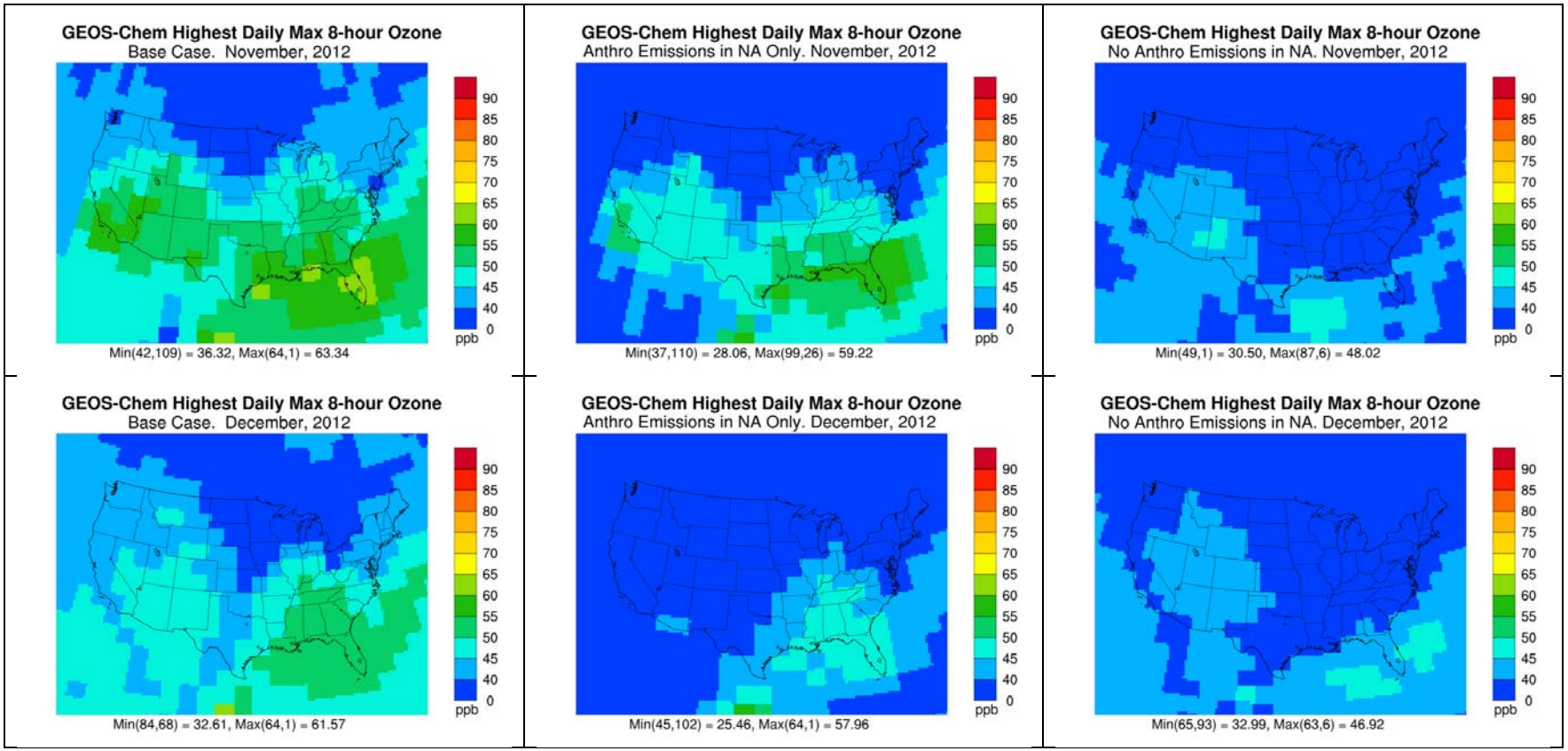


Figure 4-1. Maps of the monthly maximum 8-hour ozone in the 2012 base case (left), 2012 zROW run (middle), and 2012 zNA run (right).

Table 4-2. Monthly maximum 8-hour ozone in El Paso, Dallas, and Houston in the GEOS-Chem 2012 base, 2012 zROW, and 2012 zNA runs.

	El Paso			Dallas			Houston		
[ppb]	2012 Base	2012 zROW	2012 zNA	2012 Base	2012 zROW	2012 zNA	2012 Base	2012 zROW	2012 zNA
Jan	52.2	43.9	46.2	44.1	39.7	36.6	46.3	40.4	35.7
Feb	56.0	44.8	50.7	52.9	44.2	42.7	52.4	48.1	35.3
Mar	60.2	51.0	53.6	64.4	60.7	43.1	68.5	64.7	41.4
Apr	64.5	57.3	59.4	59.5	56.2	44.4	66.6	62.9	41.9
May	68.4	60.9	57.1	67.3	62.4	45.1	73.3	69.5	47.1
Jun	68.3	63.0	59.7	74.1	71.5	43.8	78.4	75.9	38.7
Jul	69.9	66.7	58.4	78.2	75.4	51.0	74.2	70.7	46.8
Aug	74.0	71.6	65.5	76.2	74.2	51.4	77.7	74.5	46.9
Sep	68.5	65.3	52.7	70.1	67.7	46.5	68.6	66.2	37.4
Oct	61.1	56.2	49.5	58.9	56.3	38.2	64.1	61.6	35.0
Nov	53.6	46.6	42.8	51.8	48.0	37.3	56.6	52.8	42.7
Dec	47.9	40.0	40.3	43.3	39.7	38.2	48.8	44.1	37.5

Table 4-3. Ozone contributions from non-North American sources to the monthly maximum 8-hour ozone at El Paso, Dallas, and Houston.

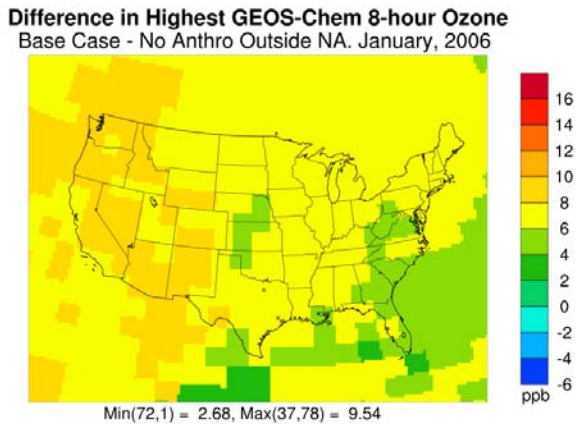
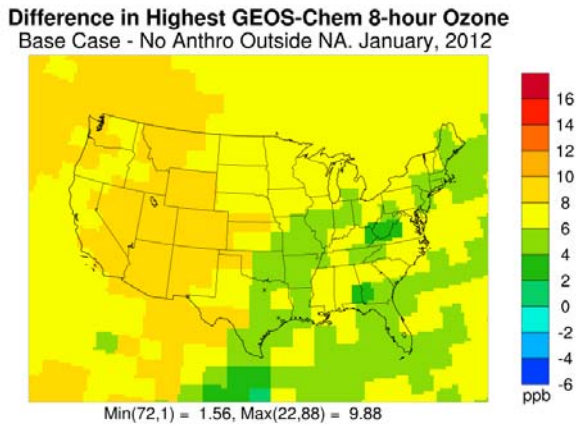
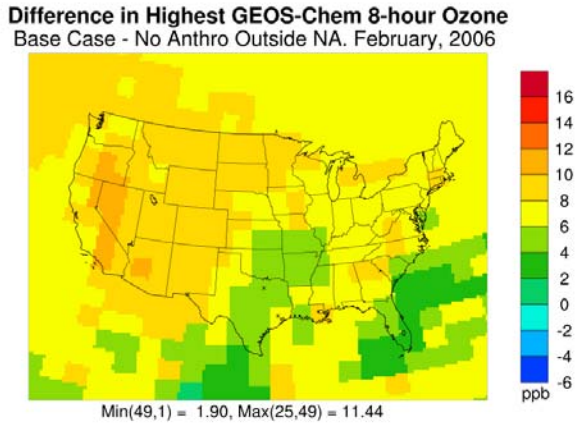
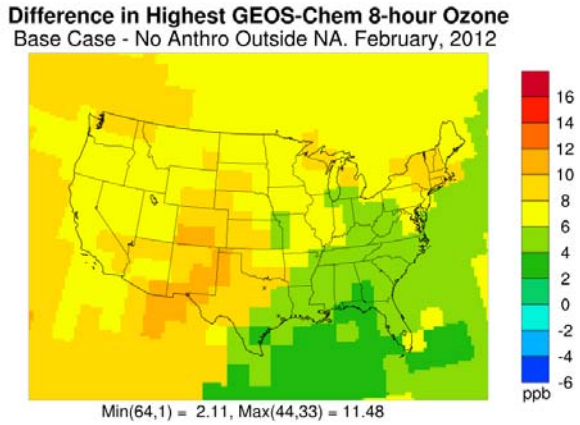
	El Paso		Dallas		Houston	
[ppb]	2012 Base – zROW	2012 zNA	2012 Base – zROW	2012 zNA	2012 Base – zROW	2012 zNA
Jan	8.3	46.2	4.4	36.6	5.9	35.7
Feb	11.2	50.7	8.7	42.7	4.3	35.3
Mar	9.2	53.6	3.7	43.1	3.8	41.4
Apr	7.2	59.4	3.3	44.4	3.7	41.9
May	7.5	57.1	4.9	45.1	3.8	47.1
Jun	5.3	59.7	2.6	43.8	2.5	38.7
Jul	3.2	58.4	2.8	51.0	3.5	46.8
Aug	2.4	65.5	2.0	51.4	3.2	46.9
Sep	3.2	52.7	2.4	46.5	2.4	37.4
Oct	4.9	49.5	2.6	38.2	2.5	35.0
Nov	7.0	42.8	3.8	37.3	3.8	42.7
Dec	7.9	40.3	3.6	38.2	4.7	37.5

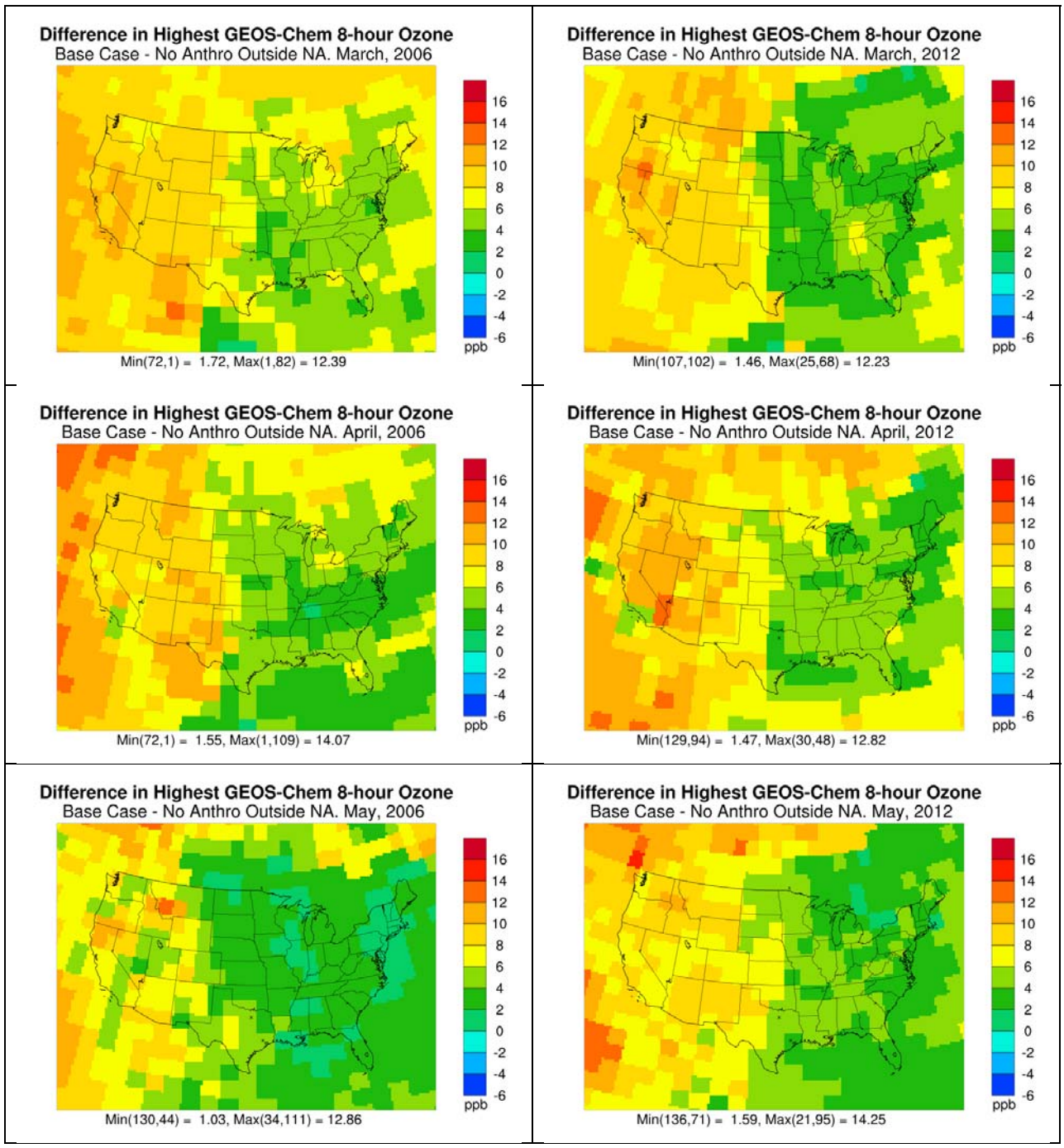
Figure 4-2 compares the ozone contributions from non-North American anthropogenic sources to the highest 8-hour ozone in the CONUS domain for each month in 2006 and 2012 on the left and right columns, respectively; differences between the zROW and base runs were used for these calculations. The contributions to the three sites in Texas are listed in Table 4-4. Both years showed greater contributions in the winter months and in the western US.

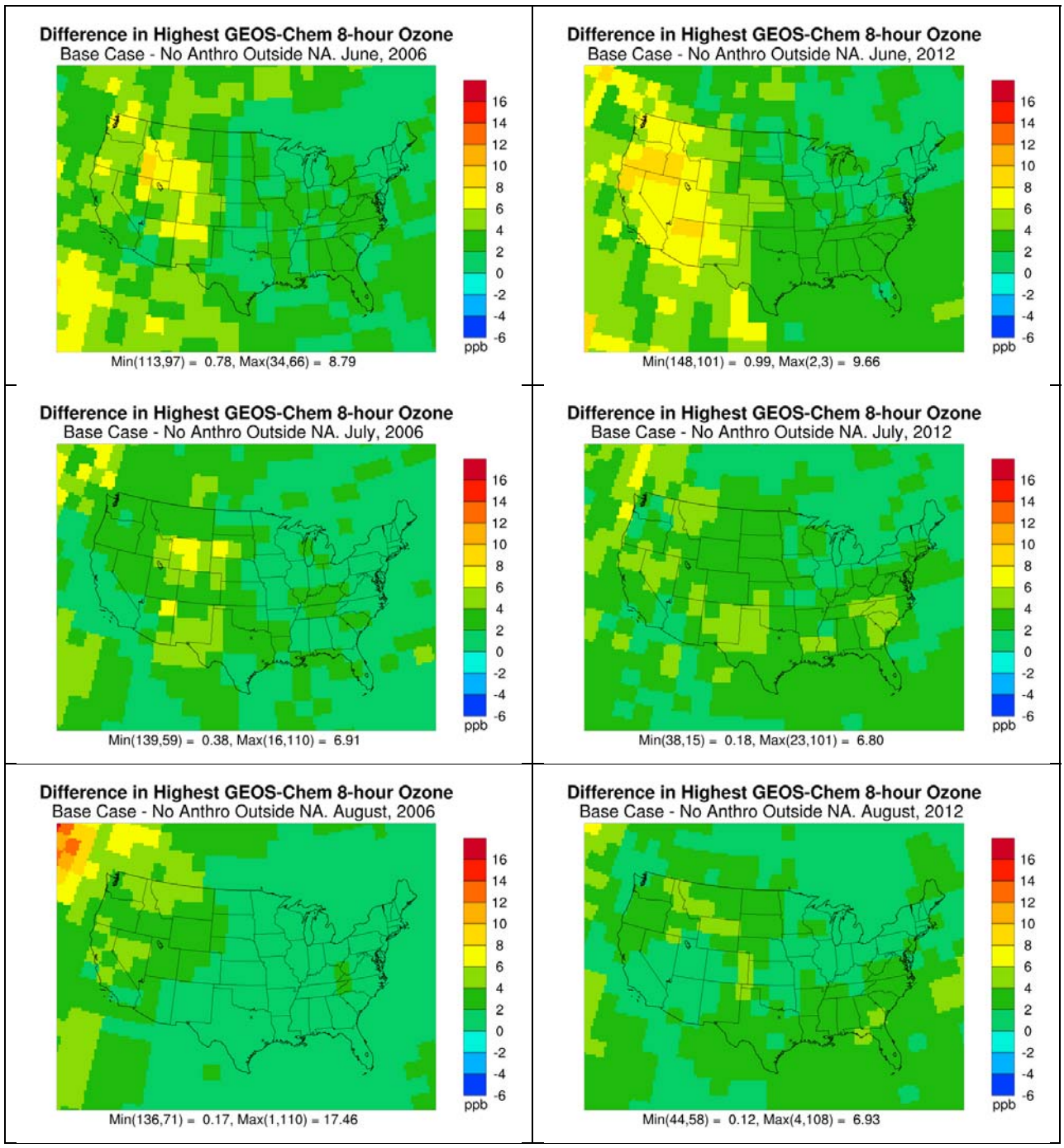
In 2006, the largest contribution from non-North American anthropogenic sources to the continental US was 12.9 ppb in Montana; in 2012, the largest contributions were 12.2 and 12.8 ppb, both located in California during March and April, respectively. Contributions were

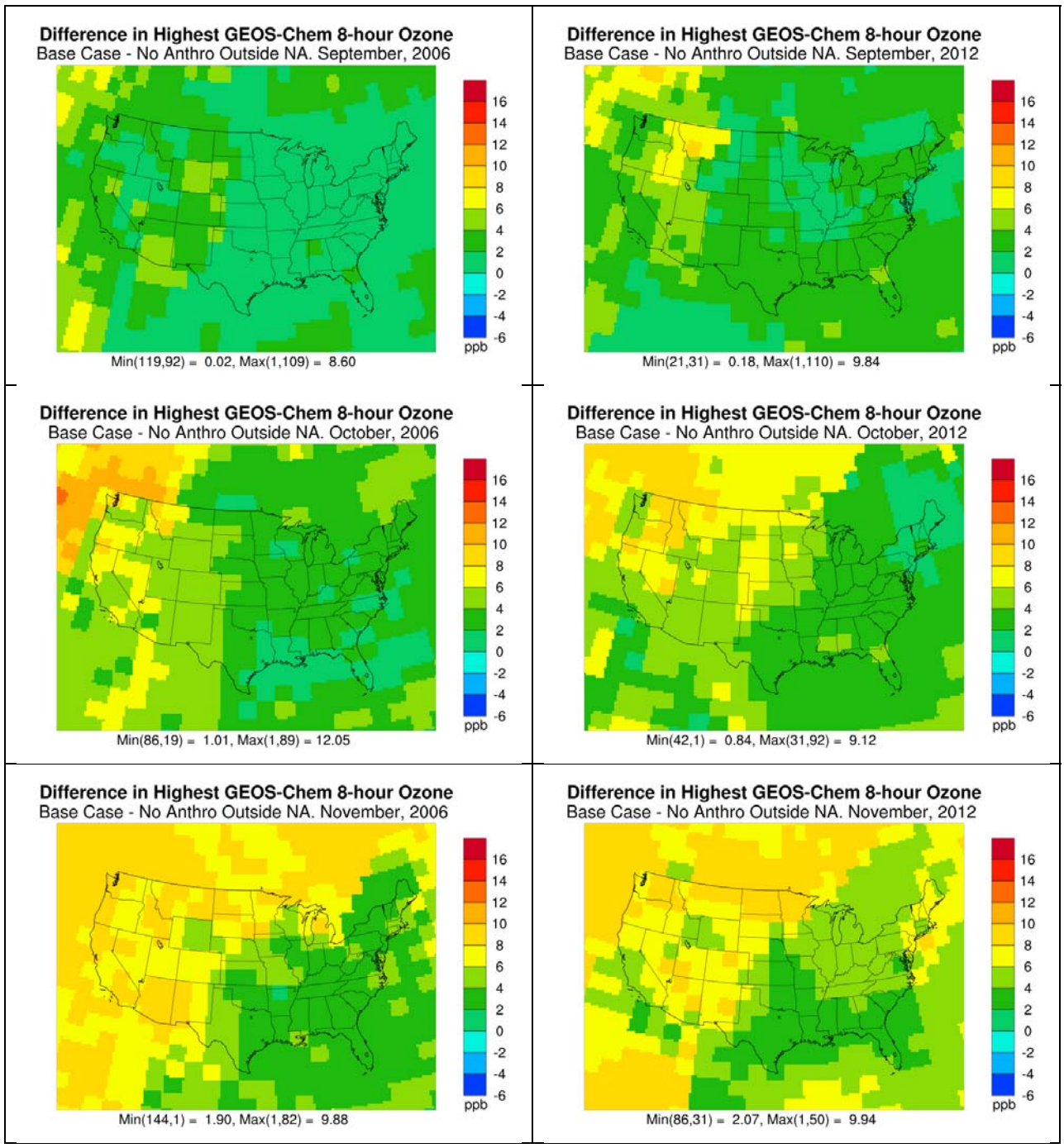
weakest in July and August, when the monthly maximum 8-hour ozone tends to be highest; during these summer months, non-North American anthropogenic emissions contributed less than 7 ppb and 6 ppb in 2006 and 2012, respectively, to the monthly maximum 8-hour ozone throughout the continental US.

In general, the 2012 contributions appeared slightly greater than in 2006 in the western US. El Paso, Dallas, and Houston all saw higher contributions from non-North American sources during most summer months in 2012 than in 2006; in the spring and winter months, 2006 tended to contribute more. Most of these differences should be attributed to the different meteorology in the two modeling episodes.

2006 Base – 2006 zROW	2012 Base – 2012 zROW
	
	


Difference in Highest GEOS-Chem 8-hour Ozone
Base Case - No Anthro Outside NA. March, 2006
Min(72,1) = 1.72, Max(1,82) = 12.39
Difference in Highest GEOS-Chem 8-hour Ozone
Base Case - No Anthro Outside NA. March, 2012
Min(107,102) = 1.46, Max(25,68) = 12.23
Difference in Highest GEOS-Chem 8-hour Ozone
Base Case - No Anthro Outside NA. April, 2006
Min(72,1) = 1.55, Max(1,109) = 14.07
Difference in Highest GEOS-Chem 8-hour Ozone
Base Case - No Anthro Outside NA. April, 2012
Min(129,94) = 1.47, Max(30,48) = 12.82
Difference in Highest GEOS-Chem 8-hour Ozone
Base Case - No Anthro Outside NA. May, 2006
Min(130,44) = 1.03, Max(34,111) = 12.86
Difference in Highest GEOS-Chem 8-hour Ozone
Base Case - No Anthro Outside NA. May, 2012
Min(136,71) = 1.59, Max(21,95) = 14.25
16
14
12
10
8
6
4
2
0
-2
-4
-6
ppb


Difference in Highest GEOS-Chem 8-hour Ozone
Base Case - No Anthro Outside NA. June, 2006
Min(113,97) = 0.78, Max(34,66) = 8.79
Difference in Highest GEOS-Chem 8-hour Ozone
Base Case - No Anthro Outside NA. June, 2012
Min(148,101) = 0.99, Max(2,3) = 9.66
Difference in Highest GEOS-Chem 8-hour Ozone
Base Case - No Anthro Outside NA. July, 2006
Min(139,59) = 0.38, Max(16,110) = 6.91
Difference in Highest GEOS-Chem 8-hour Ozone
Base Case - No Anthro Outside NA. July, 2012
Min(38,15) = 0.18, Max(23,101) = 6.80
Difference in Highest GEOS-Chem 8-hour Ozone
Base Case - No Anthro Outside NA. August, 2006
Min(136,71) = 0.17, Max(1,110) = 17.46
Difference in Highest GEOS-Chem 8-hour Ozone
Base Case - No Anthro Outside NA. August, 2012
Min(44,58) = 0.12, Max(4,108) = 6.93
16
14
12
10
8
6
4
2
0
-2
-4
-6
ppb


Difference in Highest GEOS-Chem 8-hour Ozone
Base Case - No Anthro Outside NA. September, 2006
Min(119,92) = 0.02, Max(1,109) = 8.60
Difference in Highest GEOS-Chem 8-hour Ozone
Base Case - No Anthro Outside NA. September, 2012
Min(21,31) = 0.18, Max(1,110) = 9.84
Difference in Highest GEOS-Chem 8-hour Ozone
Base Case - No Anthro Outside NA. October, 2006
Min(86,19) = 1.01, Max(1,89) = 12.05
Difference in Highest GEOS-Chem 8-hour Ozone
Base Case - No Anthro Outside NA. October, 2012
Min(42,1) = 0.84, Max(31,92) = 9.12
Difference in Highest GEOS-Chem 8-hour Ozone
Base Case - No Anthro Outside NA. November, 2006
Min(144,1) = 1.90, Max(1,82) = 9.88
Difference in Highest GEOS-Chem 8-hour Ozone
Base Case - No Anthro Outside NA. November, 2012
Min(86,31) = 2.07, Max(1,50) = 9.94
16
14
12
10
8
6
4
2
0
-2
-4
-6
ppb

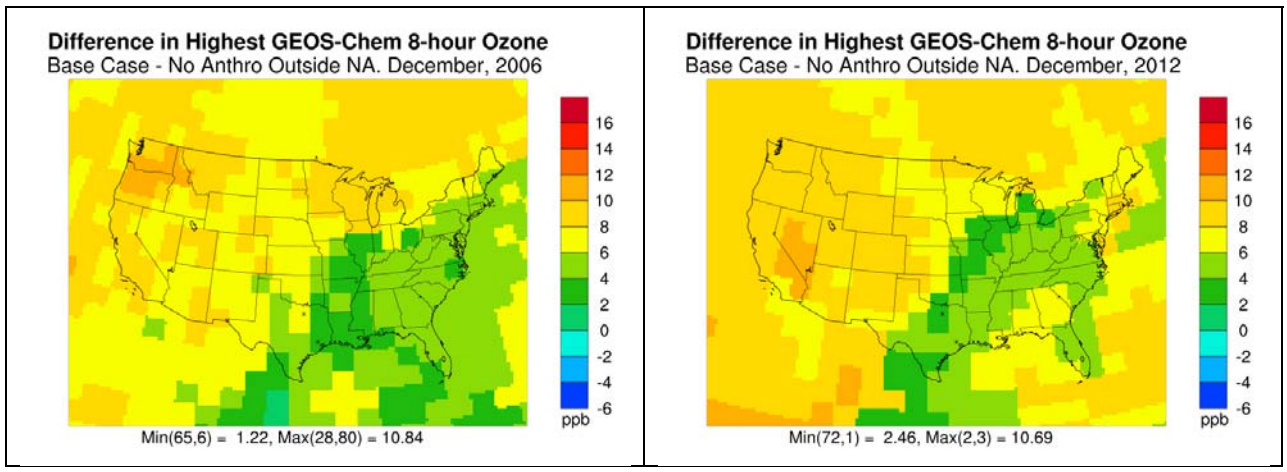


Figure 4-2. Spatial plots of ozone contributions from anthropogenic sources outside of North America to the monthly maximum 8-hour ozone in the CONUS domain for each month in 2006 (left) and 2012 (right).

Table 4-4. Ozone contributions from anthropogenic sources outside of North America to the monthly maximum 8-hour ozone in El Paso, Dallas, and Houston in 2006 and 2012.

	El Paso		Dallas		Houston	
[ppb]	2006	2012	2006	2012	2006	2012
Jan	9.0	8.3	6.1	4.4	7.3	5.9
Feb	9.2	11.2	4.9	8.7	6.7	4.3
Mar	11.1	9.2	5.8	3.7	6.0	3.8
Apr	10.3	7.2	4.5	3.3	4.7	3.7
May	3.9	7.5	4.1	4.9	4.2	3.8
Jun	4.5	5.3	1.8	2.6	1.3	2.5
Jul	5.0	3.2	2.5	2.8	2.2	3.5
Aug	1.1	2.4	1.0	2.0	0.5	3.2
Sep	3.0	3.2	1.2	2.4	0.9	2.4
Oct	6.0	4.9	3.0	2.6	1.3	2.5
Nov	8.6	7.0	3.9	3.8	3.2	3.8
Dec	8.3	7.9	6.5	3.6	3.4	4.7
Average	6.7	6.4	3.8	3.7	3.5	3.7

4.2 2012 Monthly Averaged NOx

Monthly averaged NOx was also reviewed for the 2012 runs. Figure 4-3 shows the monthly averaged NOx in the 2012 base, zROW and zNA runs for January and August, whose spatial distributions and magnitudes are indicative of all winter and summer months, respectively. Figure 4-4 shows differences in the monthly averaged NOx from the 2012 base case.

Like 2006, when anthropogenic emissions outside of North America were zeroed out, the monthly averaged NOx increased slightly throughout the continental US in all months; the NOx increase was largest in winter in the Northeast US. In the 2012 zNA run, the lack of anthropogenic sources within North America resulted in much lower NOx throughout the CONUS domain, as would be expected.

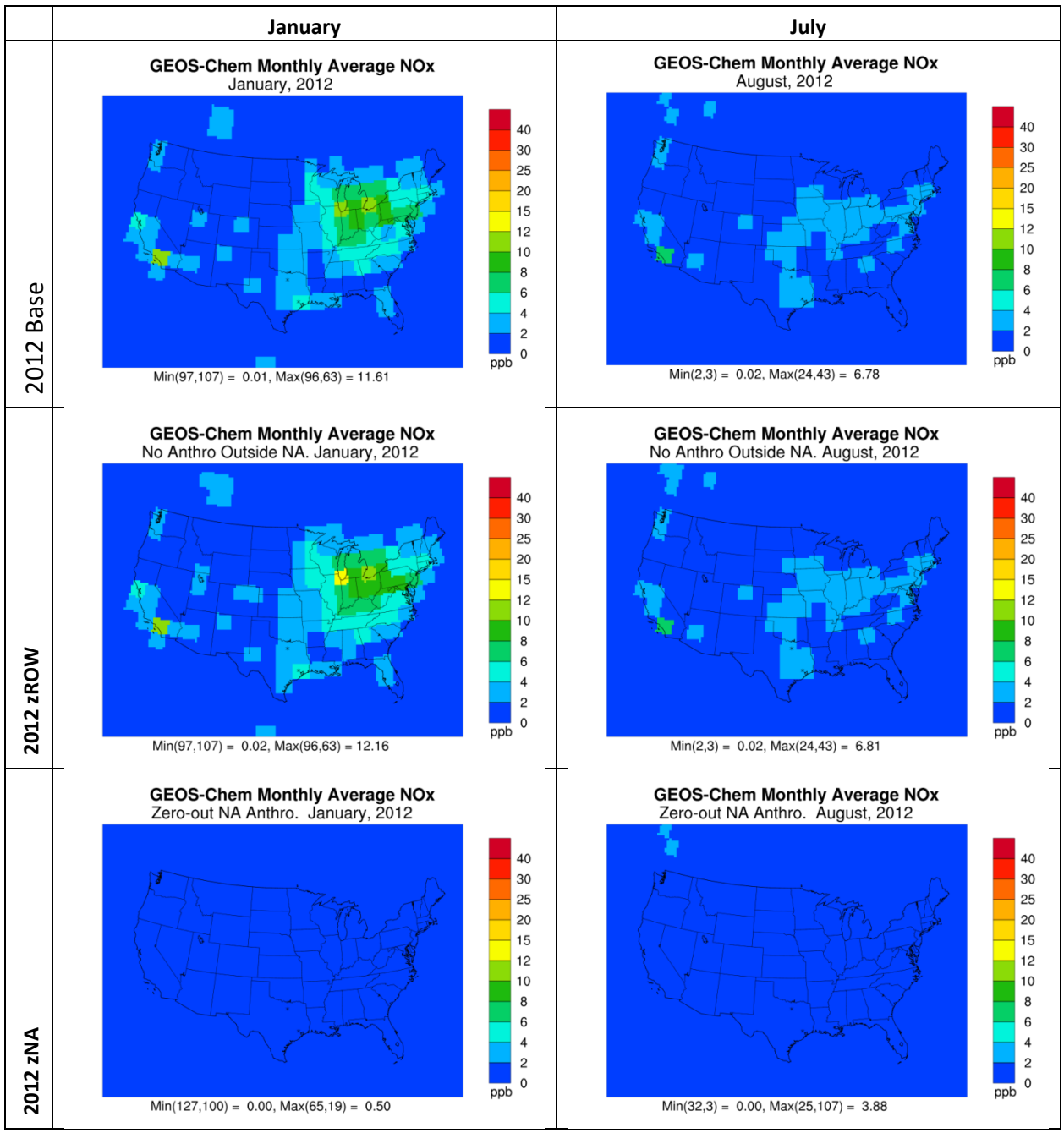


Figure 4-3. 2012 monthly averaged NOx when zeroing out anthropogenic emissions outside North America (2012 zROW, left), and inside North America (2012 zNA, right) in January and August.

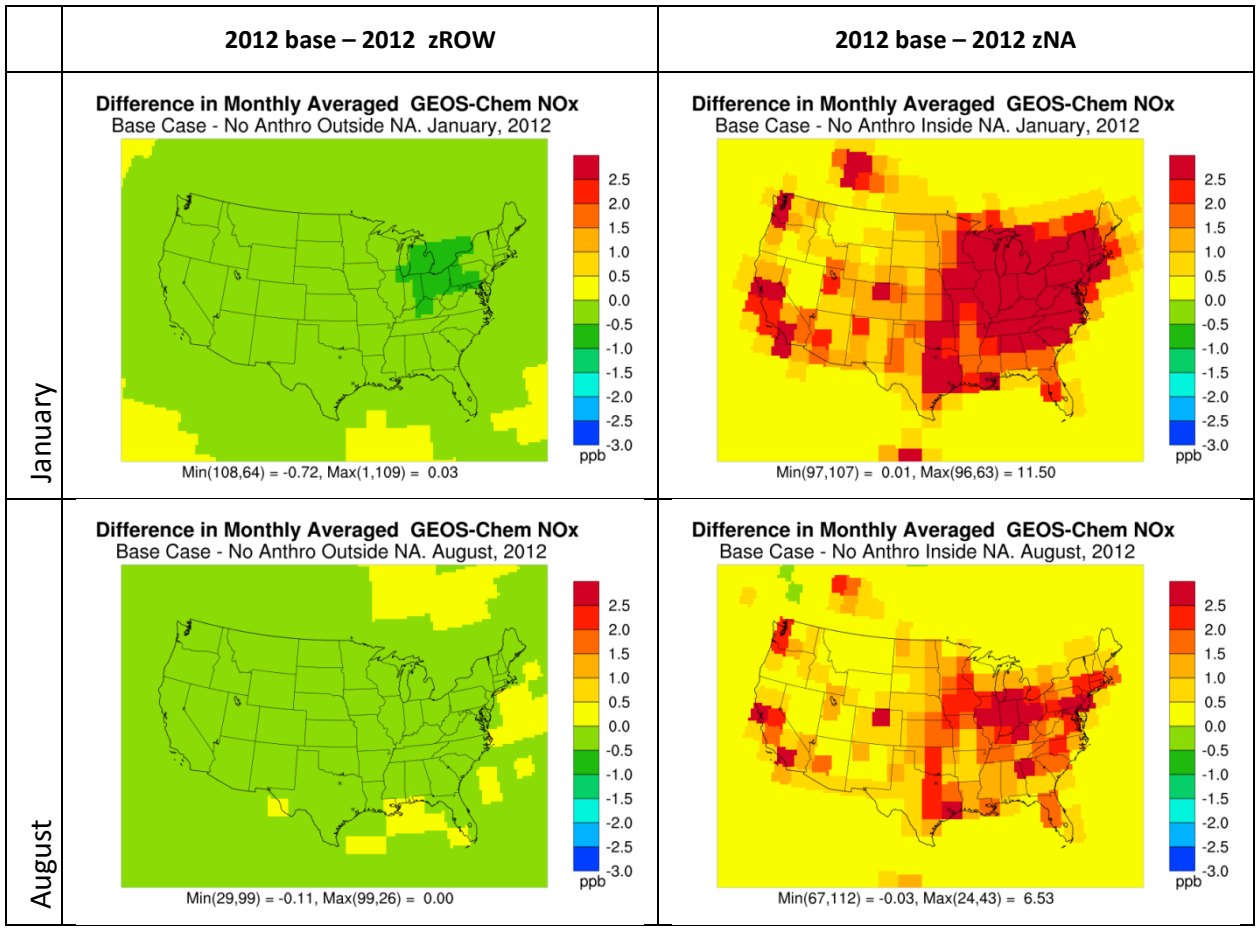


Figure 4-4. Change in the 2012 monthly averaged NOx in January (top) and August (bottom)

5.0 2018 MODEL RESULTS

GEOS-Chem was run two more times to look at ozone in the 2018 future year. Meteorology was the same as 2012 and emissions were scaled to 2018. The first run was the 2018 base case ("2018 base"). The second run zeroed out all anthropogenic emissions outside of North America; the difference between these two runs was used to estimate the ozone contributions from anthropogenic sources outside of North America. The latter run was abbreviated "2018 zROW" as anthropogenic emissions were zeroed out from the rest of the world.

The 2018 emissions were developed by making adjustments relative to 2006 emissions. Most of the 2018 emission inventories were prepared in the same way as the 2012 inventories, except that the scaling factors differed to account for the changes in the future year. Within North America, the NEI was scaled to 2018 using factors based on TCEQ's 2006 to 2018 projections in the TCEQ 36 km domain for NOx, VOC, and CO, and from the 2007 to 2020 EPA PM NAAQS rulemaking analysis projections for SO_2, $PM_{2.5}$, and NH_3. Outside North America, the EDGAR 4.2 and RETRO inventories were scaled to 2018 using emission changes in the Representative Concentration Pathway (RCP85) database[7] between the 2005 and 2000 base years, respectively, and 2020. All other inventory sectors (methane, biomass burning, biofuel, and natural sources) used the same defaults that were applied in 2012.

Table 5-1 lists the difference in emissions from 2012 to 2018. NOx, VOC, and CO emissions are projected to increase substantially in Asia and in the Middle East/Africa (MAF) between 2012 and 2018. Emissions in the OECD90 countries (Western Europe, Northern America, and Pacific OECD), including the US, are projected to decrease between 2012 and 2018. In the reforming economies (REF) including Russia minor changes in NOx, VOC and CO emissions are expected between 2012 and 2018. SO2 from shipping emissions is expected to be lower in 2018 due to improved fuel quality.

Table 5-1. Difference in anthropogenic emissions between 2012 and 2018.

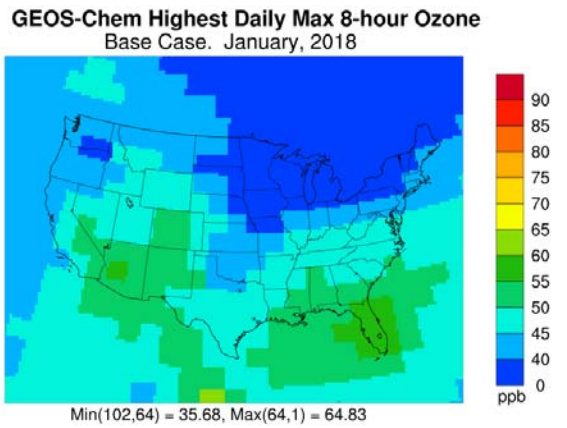
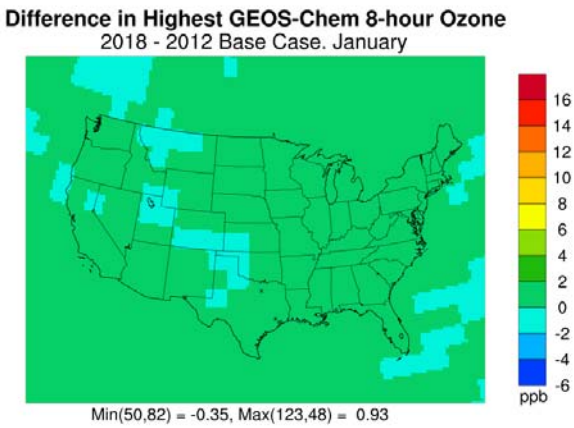
Sources	World Region	Emissions (MM Tons/year or MM Tons C/year)			
		CO	NOx	SO_2	VOC
Total Anthropogenic from 2005 NEI	US	-1.5	-0.1	-2.9	-0.1
Total Anthropogenic from EDGAR4.1/RETRO inventories (excluding aviation and shipping CO/NOx/SO_2 emissions)	ASIA	9.1	9.7	4.9	3.0
	LAM	1.5	0.4	-0.4	0.3
	MAF	18	2.8	2.4	1.1
	OECD90 except US	-14.9	-4.7	-4.4	-3.6
	REF	-1.1	1.0	-2.1	0.5
Shipping	World	0.5	0.1	-4.8	0.0
Aviation	World	0.1	0.1	0.1	0.0

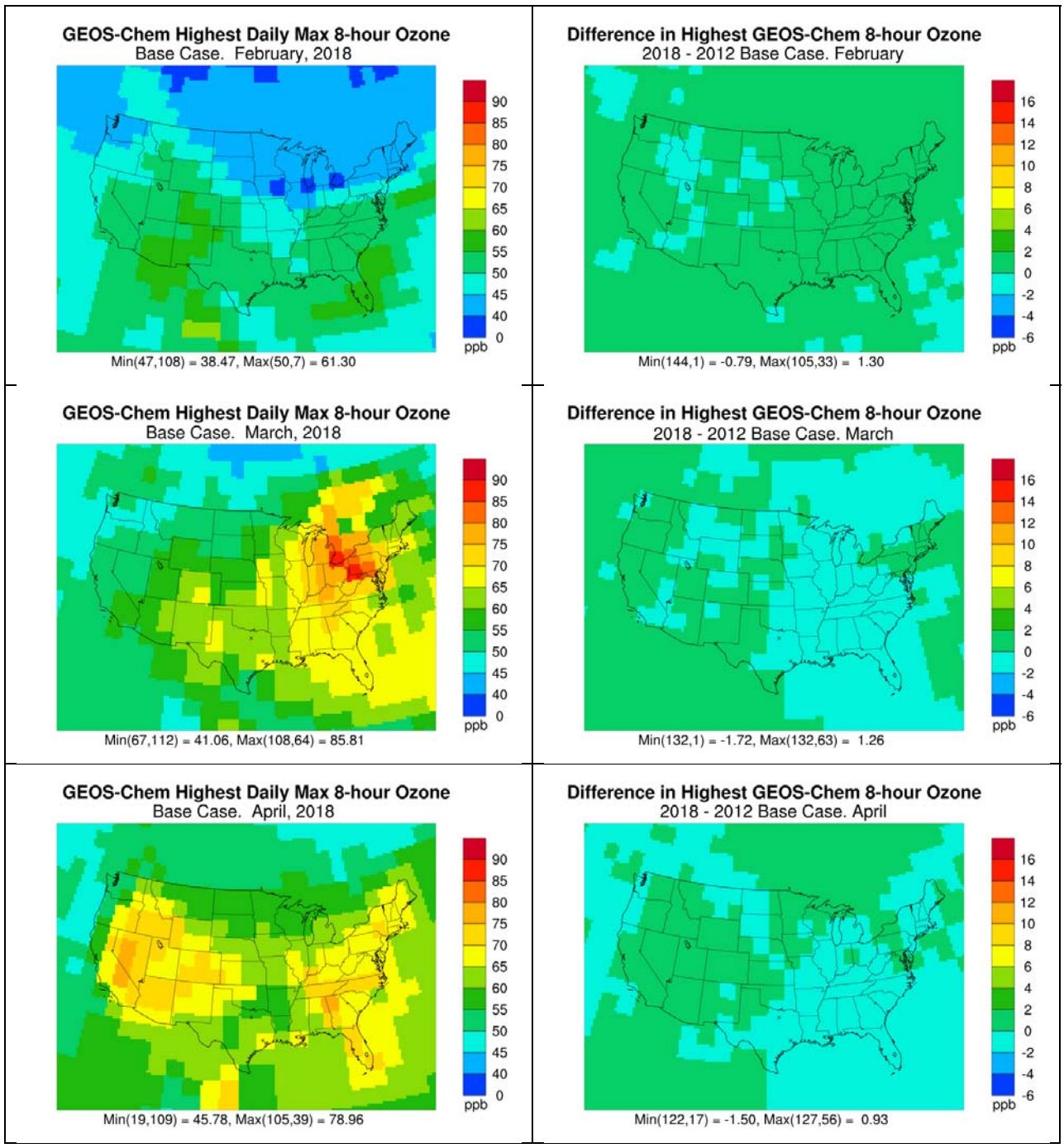
[7] https://tntcat.iiasa.ac.at:8743/RcpDb/dsd?Action=htmlpage&page=welcome

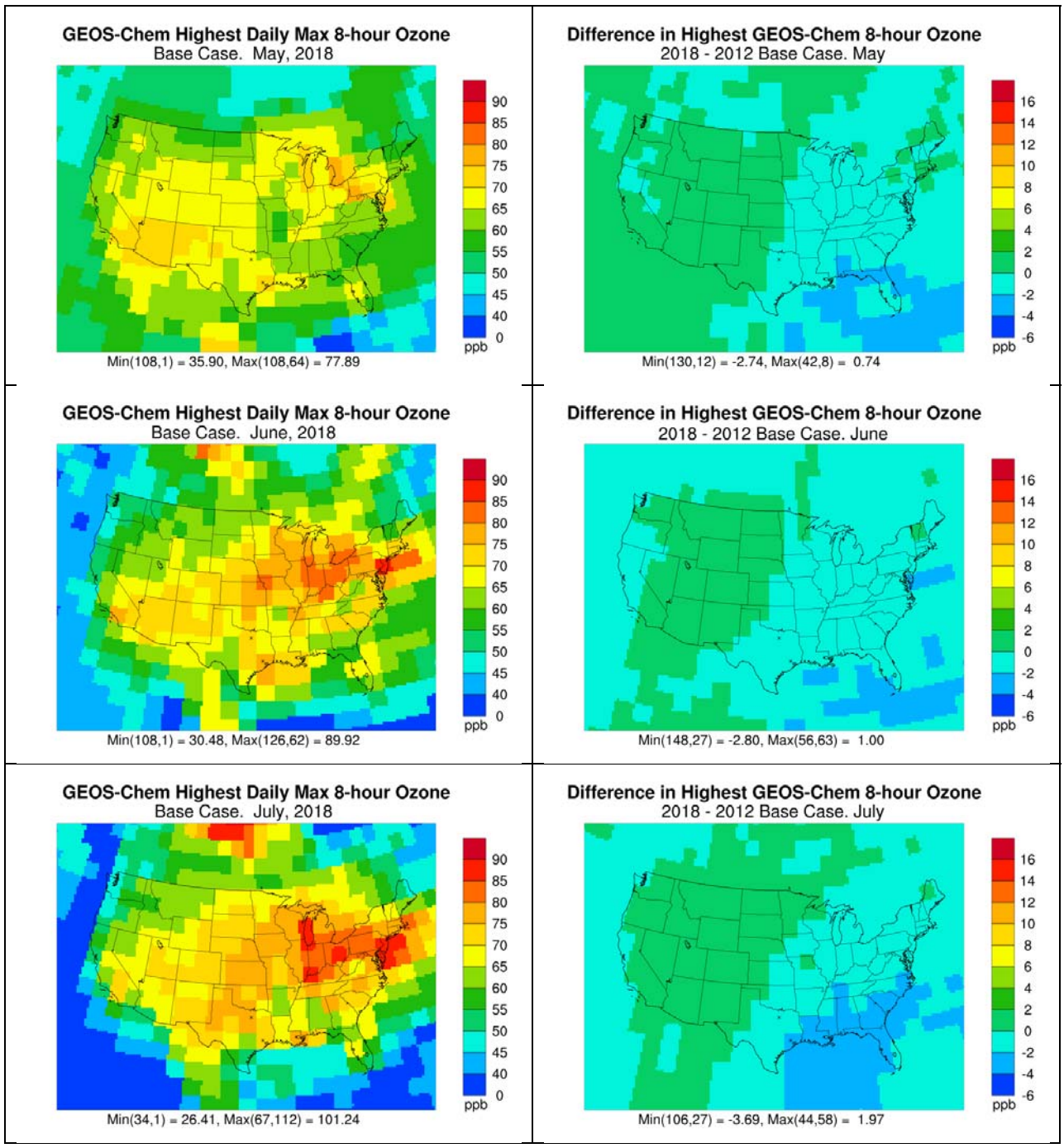
5.1 2018 8-Hour Ozone

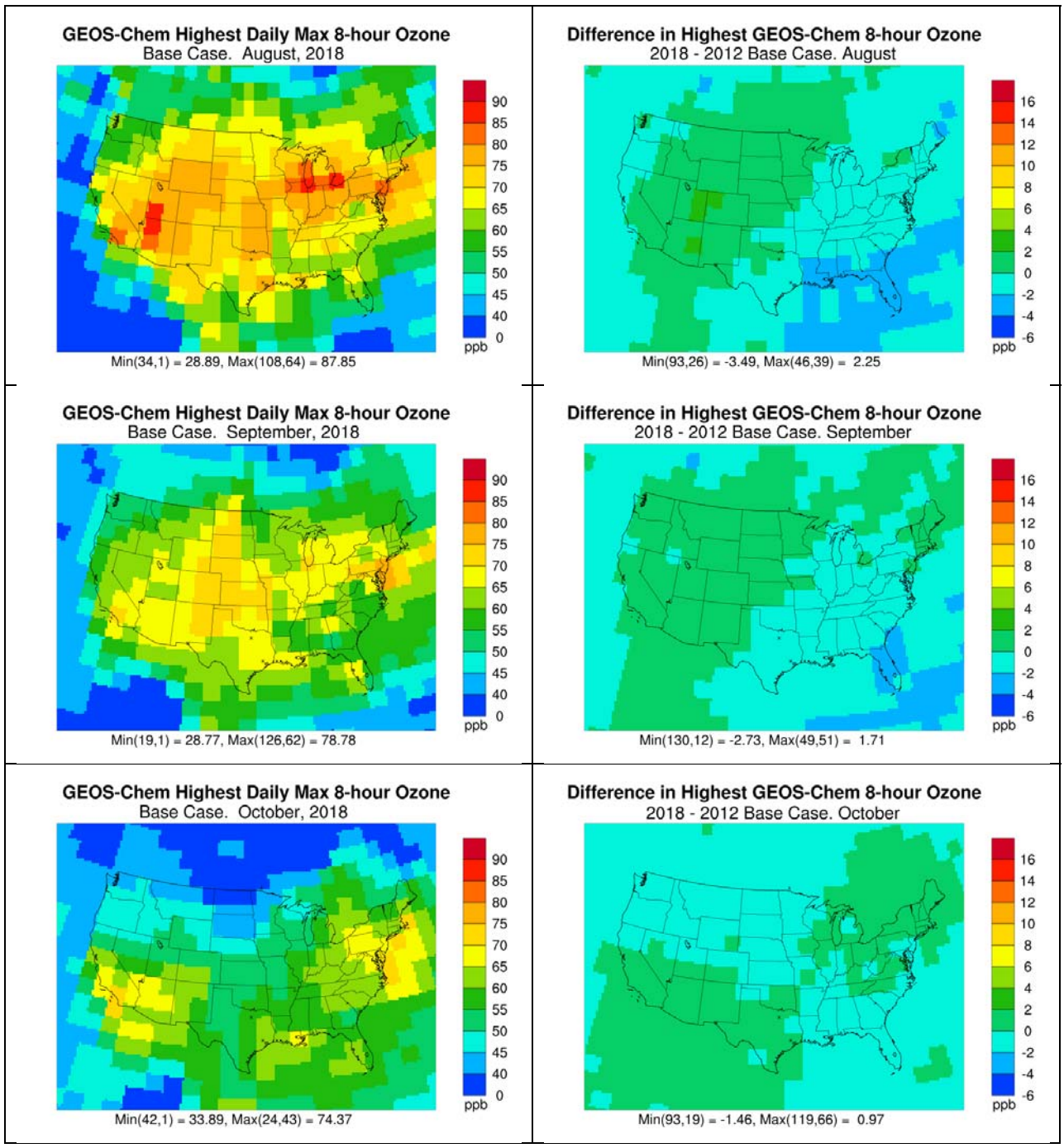
Since 2012 and 2018 used the same meteorology inputs, a comparison of the 2012 base and 2018 base years can show how the change in global emissions affects ozone transport to the CONUS. Figure 5-1 displays the GEOS-Chem monthly maximum 8-hour ozone windowed to the CONUS domain from the 2018 base case run on the left and their differences from the 2012 base case on the right. The spatial distribution in the 2018 base case was similar to the 2012 base. The highest 8-hour ozone in the 36 km domain was located near the northern border in July at 101.2 ppb; within the continental US, the highest was 88.5 ppb in New Jersey, also taking place in the month of July.

Differences between 2012 and 2018 were greatest in the summer months, when ozone was generally higher in the western US, and lower in the eastern US, including the eastern half of Texas. The largest differences between 2012 and 2018 were in the Gulf States in July, when 8-hour ozone was up to 3.7 ppb lower in 2018 compared to 2012, and near the Four Corners in August, where ozone was 2.2 ppb higher. The higher ozone in the western US is likely due to more emissions of ozone precursors originating from Asia in 2018 compared to 2012, and a predominant wind direction coming from the west. In the eastern US, the monthly maximum 8-hour ozone was lower, most likely due to reduced emissions in Europe. Figure 5-2 shows a map of the worldwide differences in monthly maximum 8-hour ozone in July between 2012 and 2018. The lower ozone in Europe appears to be rotating clockwise into the Eastern US around the subtropical high that is commonly found in the North Atlantic in the summer. Lower emissions in the US could also have contributed to the lower ozone in the Eastern US. Ozone was also lower in 2018 in the lower latitudes of the Pacific in the Northern Hemisphere during the summer months, especially in the western Pacific. Maps of the worldwide ozone differences between 2012 and 2018 for all months of the year can be viewed in Appendix B.

2018 Monthly Maximum 8-hour Ozone	Difference in Monthly Maximum 8-hour Ozone (2018 base – 2012 base)
	


GEOS-Chem Highest Daily Max 8-hour Ozone
Base Case. February, 2018
90 85 80 75 70 65 60 55 50 45 40 0
ppb
Min(47,108) = 38.47, Max(50,7) = 61.30
Difference in Highest GEOS-Chem 8-hour Ozone
2018 - 2012 Base Case. February
16 14 12 10 8 6 4 2 0 -2 -4 -6
ppb
Min(144,1) = -0.79, Max(105,33) = 1.30
GEOS-Chem Highest Daily Max 8-hour Ozone
Base Case. March, 2018
90 85 80 75 70 65 60 55 50 45 40 0
ppb
Min(67,112) = 41.06, Max(108,64) = 85.81
Difference in Highest GEOS-Chem 8-hour Ozone
2018 - 2012 Base Case. March
16 14 12 10 8 6 4 2 0 -2 -4 -6
ppb
Min(132,1) = -1.72, Max(132,63) = 1.26
GEOS-Chem Highest Daily Max 8-hour Ozone
Base Case. April, 2018
90 85 80 75 70 65 60 55 50 45 40 0
ppb
Min(19,109) = 45.78, Max(105,39) = 78.96
Difference in Highest GEOS-Chem 8-hour Ozone
2018 - 2012 Base Case. April
16 14 12 10 8 6 4 2 0 -2 -4 -6
ppb
Min(122,17) = -1.50, Max(127,56) = 0.93


GEOS-Chem Highest Daily Max 8-hour Ozone
Base Case. May, 2018
90 85 80 75 70 65 60 55 50 45 40 0
ppb
Min(108,1) = 35.90, Max(108,64) = 77.89
Difference in Highest GEOS-Chem 8-hour Ozone
2018 - 2012 Base Case. May
16 14 12 10 8 6 4 2 0 -2 -4 -6
ppb
Min(130,12) = -2.74, Max(42,8) = 0.74
GEOS-Chem Highest Daily Max 8-hour Ozone
Base Case. June, 2018
90 85 80 75 70 65 60 55 50 45 40 0
ppb
Min(108,1) = 30.48, Max(126,62) = 89.92
Difference in Highest GEOS-Chem 8-hour Ozone
2018 - 2012 Base Case. June
16 14 12 10 8 6 4 2 0 -2 -4 -6
ppb
Min(148,27) = -2.80, Max(56,63) = 1.00
GEOS-Chem Highest Daily Max 8-hour Ozone
Base Case. July, 2018
90 85 80 75 70 65 60 55 50 45 40 0
ppb
Min(34,1) = 26.41, Max(67,112) = 101.24
Difference in Highest GEOS-Chem 8-hour Ozone
2018 - 2012 Base Case. July
16 14 12 10 8 6 4 2 0 -2 -4 -6
ppb
Min(106,27) = -3.69, Max(44,58) = 1.97


GEOS-Chem Highest Daily Max 8-hour Ozone
Base Case. August, 2018
90 85 80 75 70 65 60 55 50 45 40 0
ppb
Min(34,1) = 28.89, Max(108,64) = 87.85
Difference in Highest GEOS-Chem 8-hour Ozone
2018 - 2012 Base Case. August
16 14 12 10 8 6 4 2 0 -2 -4 -6
ppb
Min(93,26) = -3.49, Max(46,39) = 2.25
GEOS-Chem Highest Daily Max 8-hour Ozone
Base Case. September, 2018
90 85 80 75 70 65 60 55 50 45 40 0
ppb
Min(19,1) = 28.77, Max(126,62) = 78.78
Difference in Highest GEOS-Chem 8-hour Ozone
2018 - 2012 Base Case. September
16 14 12 10 8 6 4 2 0 -2 -4 -6
ppb
Min(130,12) = -2.73, Max(49,51) = 1.71
GEOS-Chem Highest Daily Max 8-hour Ozone
Base Case. October, 2018
90 85 80 75 70 65 60 55 50 45 40 0
ppb
Min(42,1) = 33.89, Max(24,43) = 74.37
Difference in Highest GEOS-Chem 8-hour Ozone
2018 - 2012 Base Case. October
16 14 12 10 8 6 4 2 0 -2 -4 -6
ppb
Min(93,19) = -1.46, Max(119,66) = 0.97

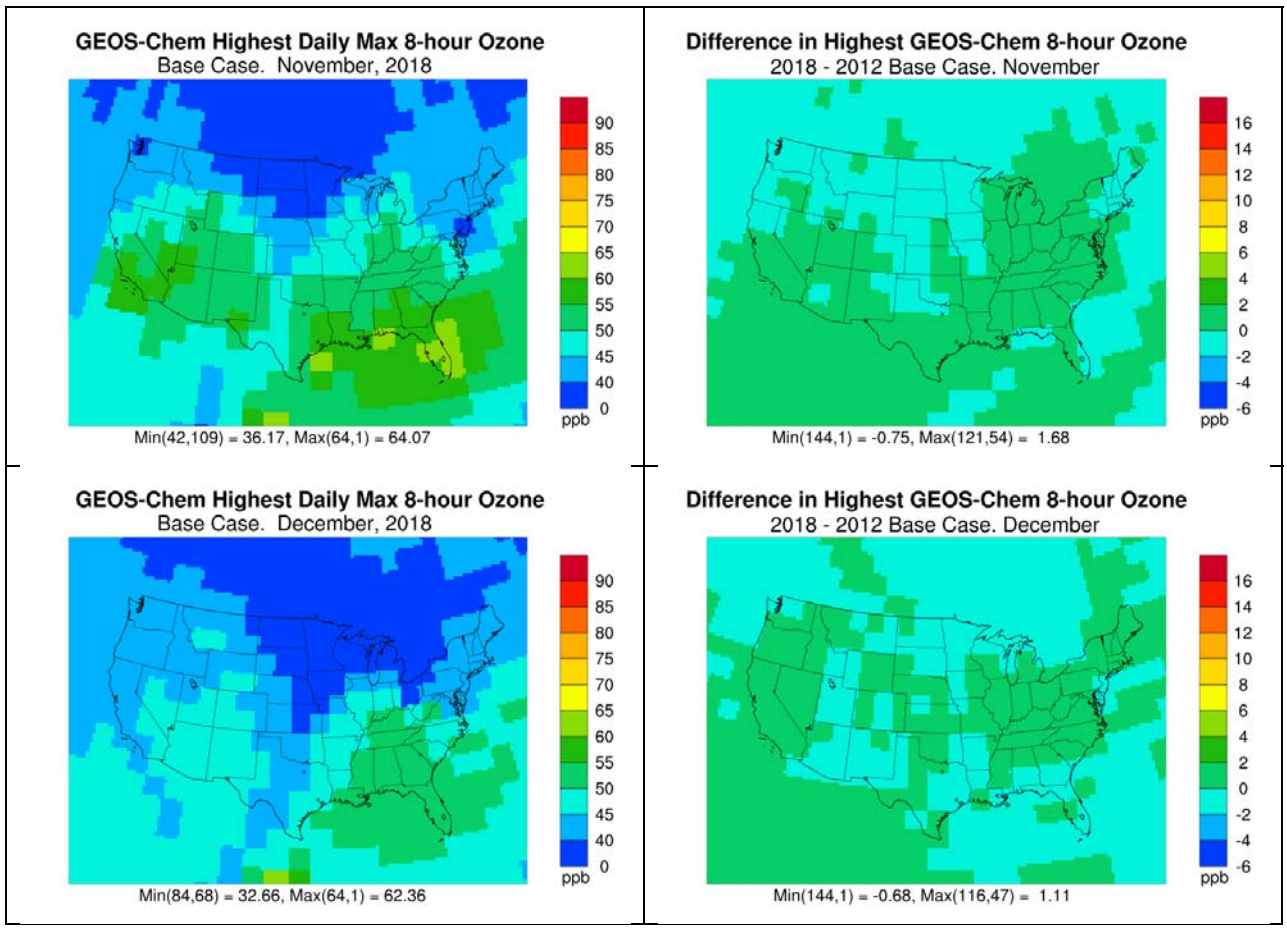


Figure 5-1. Maps of monthly maximum 8-hour ozone in the 2018 base case (left) and their differences from the 2012 base case (right) in the TCEQ 36 km domain.

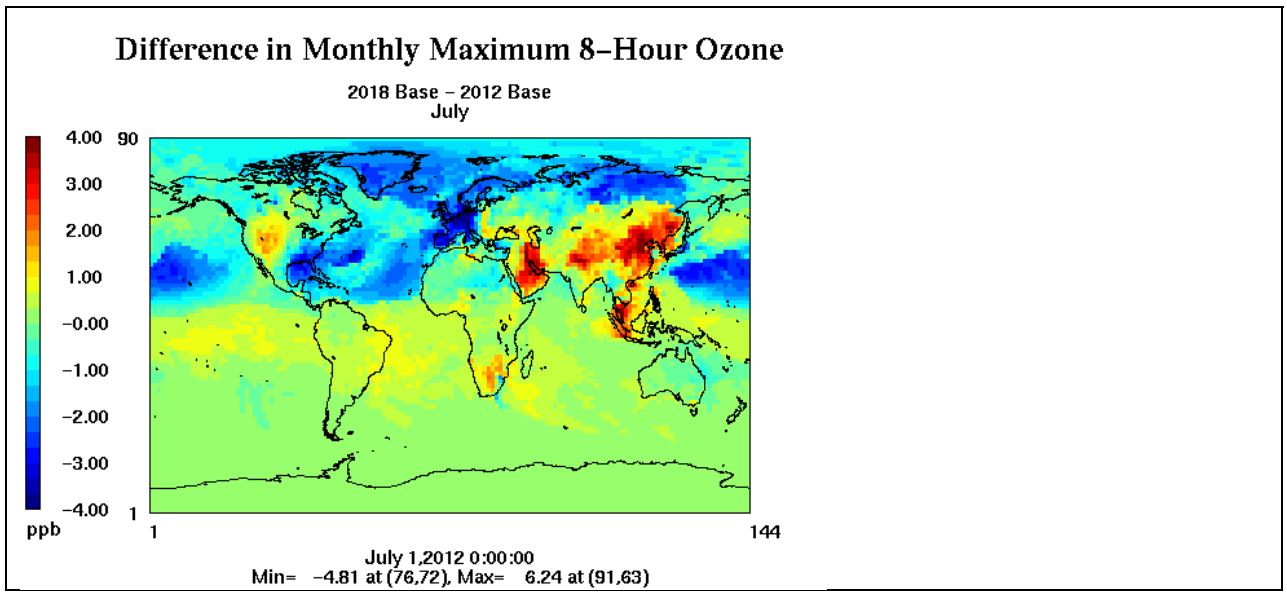


Figure 5-2. Map of the worldwide difference in monthly maximum 8-hour ozone in July between the 2012 and 2018 base cases.

In the 2018 zROW run, anthropogenic emissions of the ozone precursors were zeroed out outside of North America (rest of the world). The difference between the 2018 zROW and 2018 base case runs were used to estimate the ozone contribution from anthropogenic sources outside of North America. The left side of Figure 5-3 shows maps of the highest 8-hour ozone predicted for each month in the TCEQ 36 km domain from the 2018 zROW run. The middle column shows the ozone contribution from anthropogenic sources outside of North America to the highest monthly 8-hour ozone in the 2018 base case, and the right column shows the change in anthropogenic contributions from outside of North America between 2012 and 2018.

Like 2006 and 2012, in 2018 the non-North American anthropogenic emissions contributed more to the monthly maximum 8-hour ozone in the winter months and in the western US. The highest contributions in 2018 were 15.3 ppb in British Columbia in May and 13.6 ppb near Las Vegas in April. Compared to 2012, the 2018 ozone contributions from anthropogenic sources outside of North America were higher in the western US and lower in the eastern US. This is due to higher emissions in Asia in 2018 with westerlies being the predominant wind direction. The largest differences in 8-hour ozone contributions were a 1.9 ppb increase in Manitoba in May and a 2.4 ppb reduction in Louisiana in August.

In Texas, contributions from anthropogenic sources outside of North America to the highest monthly 8-hour ozone in El Paso, Dallas, and Houston are listed in Table 5-2. Contributions from anthropogenic sources outside of North America to El Paso were greater than to Dallas or Houston since it was the furthest west, ranging from 1.8 ppb in August to 11.6 ppb in February. Between May and October, ozone transport from non-North American sources to Houston was the lowest among the three cities in all months except September.

Like the rest of the continental US, contributions to the three Texas cities were generally higher in the winter when ozone was generally low, and lower in the summer during the high ozone season. In all three cities, the anthropogenic contributions from outside North America to the highest 8-hour ozone in 2018 (74.4 ppb in El Paso, 77.4 ppb in Dallas, and 77.2 ppb in Houston) were all less than 2 ppb (1.8 ppb in El Paso and Dallas, and 1.4 ppb in Houston).

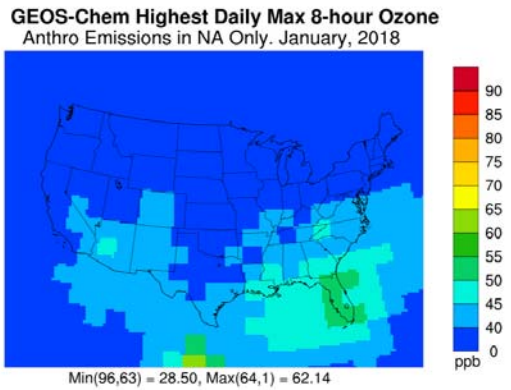
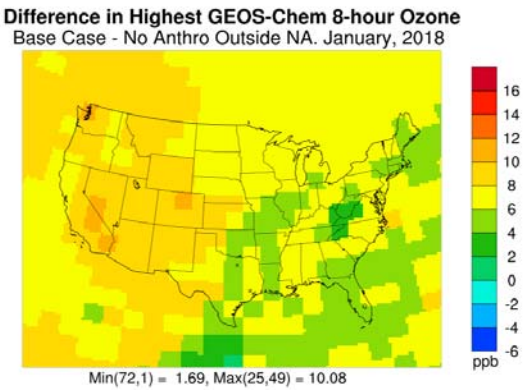
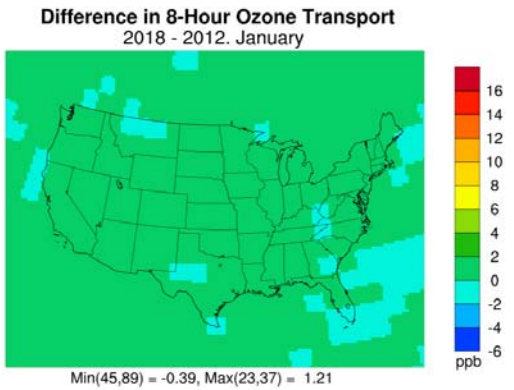
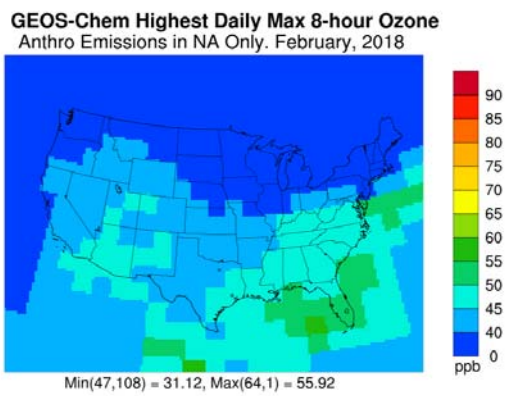
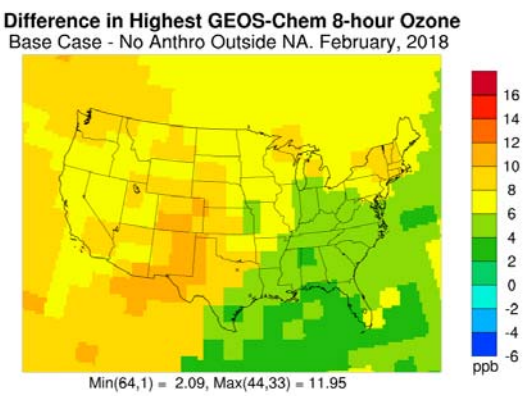
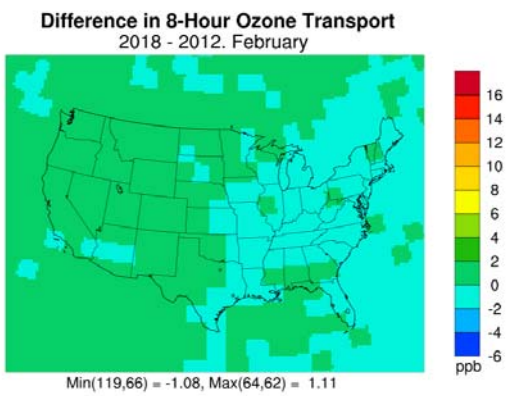
Compared to 2012, the anthropogenic contributions outside of North America were smaller in 2018 in Dallas and Houston. July had the largest differences as contributions to Dallas and Houston were 1.0 and 1.9 ppb lower in 2018 than in 2012. Contributions to El Paso were higher in 2018 during all months except July and August, when ozone was highest. A summary of the estimated ozone contributions from anthropogenic sources outside of North America can be found in Table 5-3.

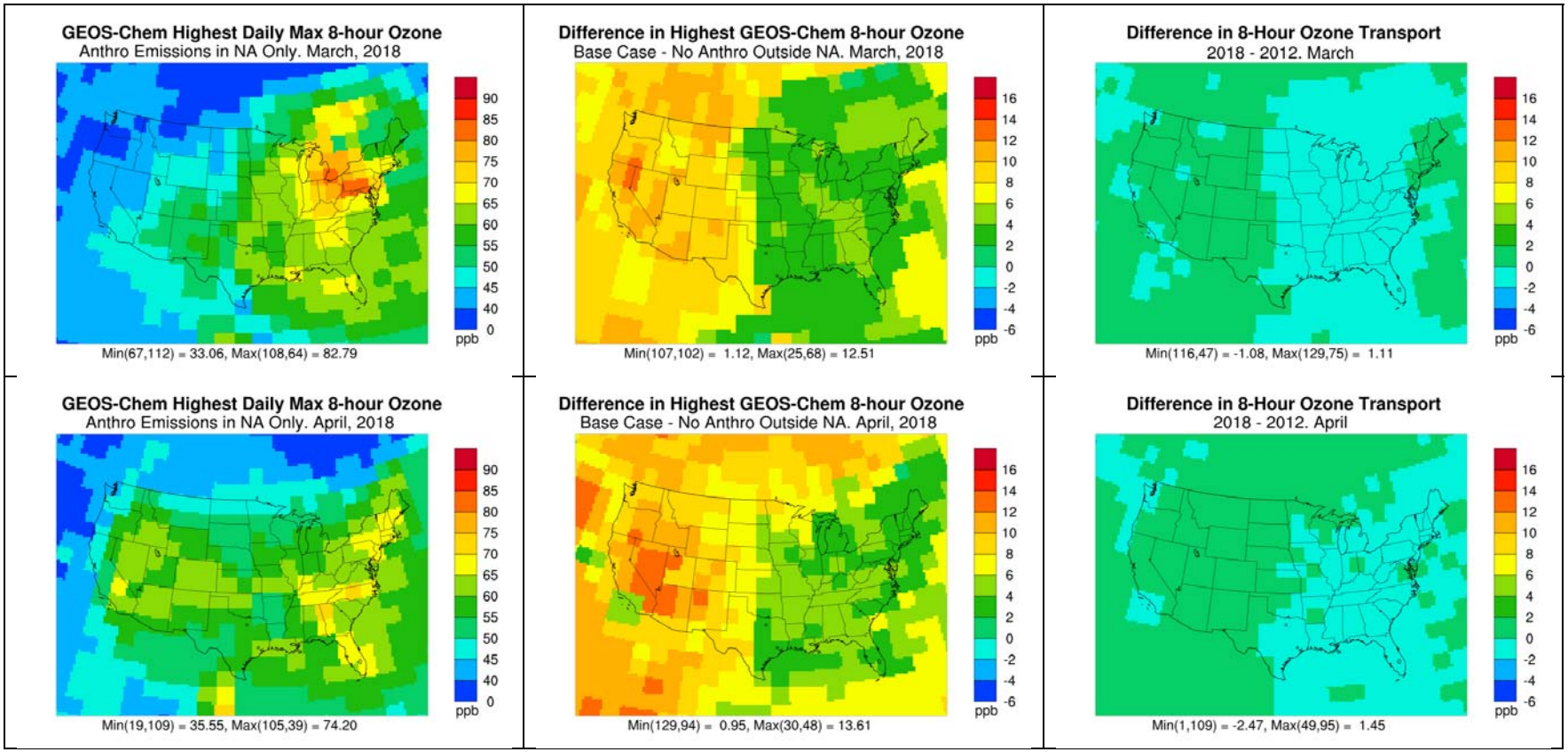
Table 5-2. Monthly maximum 8-hour ozone in El Paso, Dallas, and Houston in the 2018 base and 2018 zROW runs. Their difference is an estimate of the contribution from anthropogenic sources outside of North America.

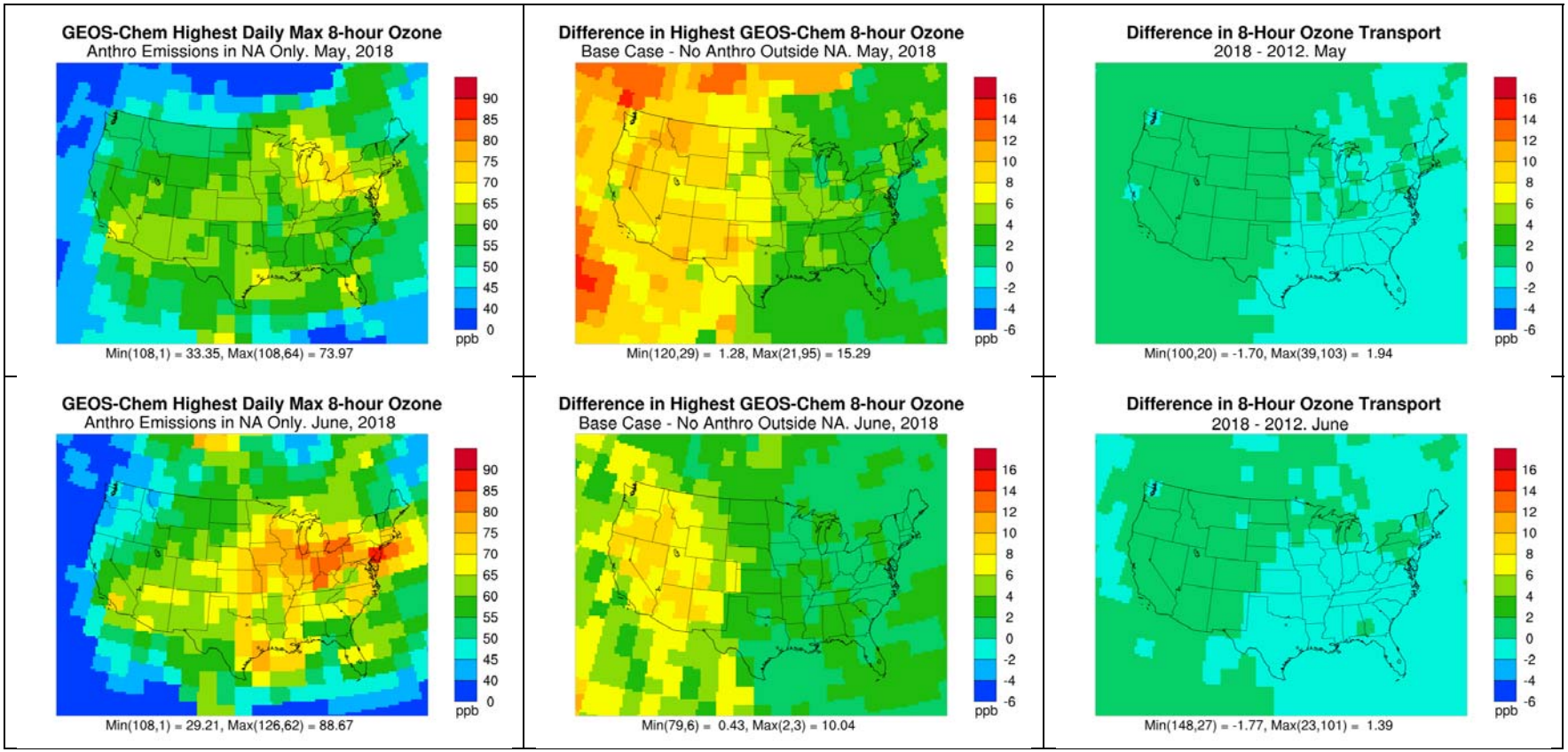
	El Paso			Dallas			Houston		
[ppb]	2018 Base	2018 zROW	Difference	2018 Base	2018 zROW	Difference	2018 Base	2018 zROW	Difference
Jan	52.3	43.6	8.7	44.2	39.5	4.7	47.0	40.5	6.5
Feb	56.4	44.8	11.6	53.2	44.4	8.8	52.8	48.7	4.1
Mar	60.6	50.9	9.7	64.4	61.1	3.3	68.1	65.0	3.1
Apr	64.8	57.2	7.6	59.4	56.7	2.7	66.1	63.2	2.9
May	68.8	60.8	8.0	67.2	62.8	4.4	72.3	69.7	2.6
Jun	68.9	63.5	5.4	73.5	71.7	1.8	77.2	75.8	1.4
Jul	70.8	67.8	3.0	77.4	75.6	1.8	71.8	70.2	1.6
Aug	74.4	72.6	1.8	76.3	74.8	1.5	76.0	74.6	1.4
Sep	69.1	65.9	3.2	69.6	68.0	1.6	68.1	66.1	2.0
Oct	61.7	56.5	5.2	59.1	56.3	2.8	64.2	61.8	2.4
Nov	53.8	46.4	7.4	51.8	48.1	3.7	57.1	53.4	3.7
Dec	47.9	39.7	8.2	43.3	40.0	3.3	48.7	44.6	4.1

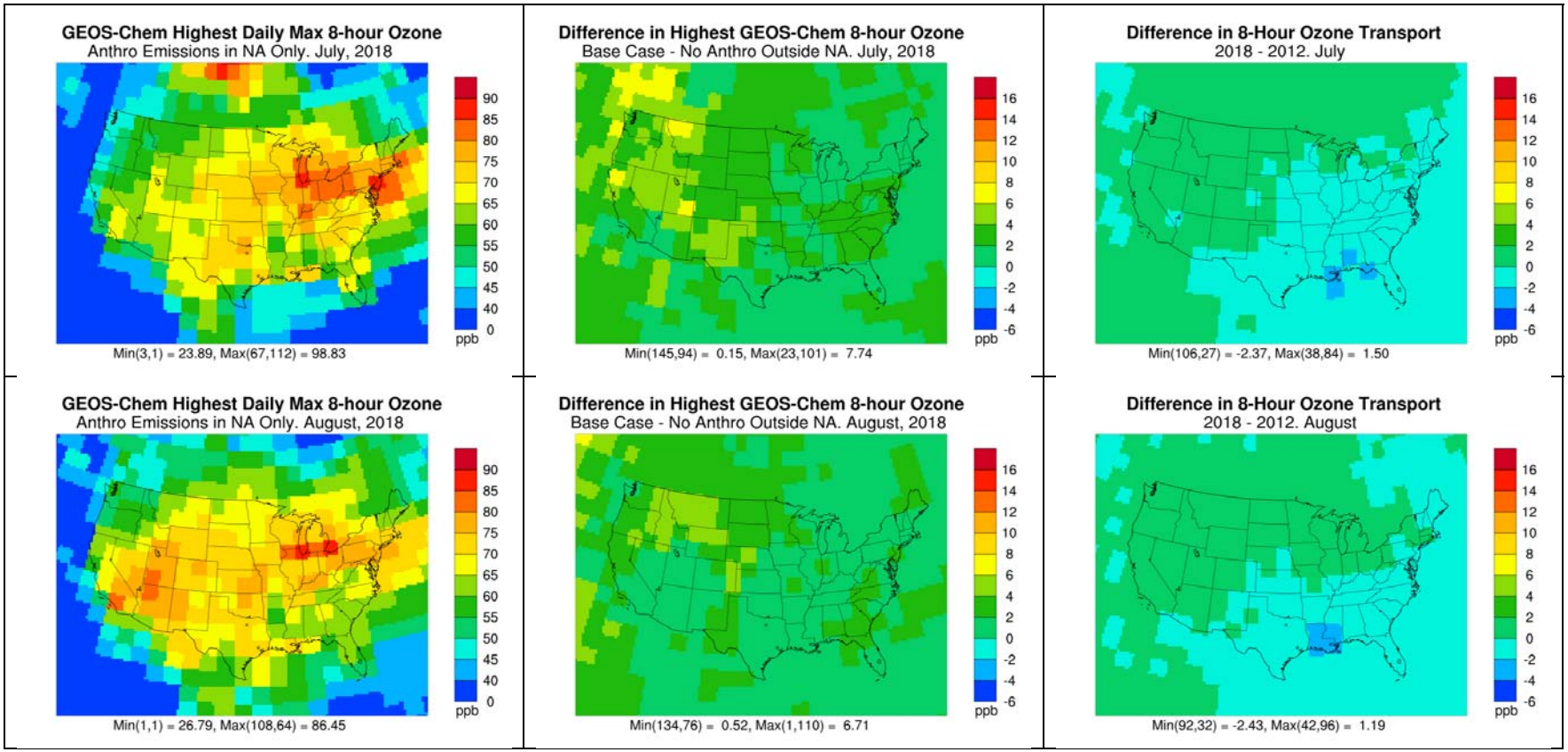
Table 5-3. Comparison of the estimated 8-hour ozone contributions from anthropogenic sources outside of North America to El Paso, Dallas, and Houston in 2012 and 2018.

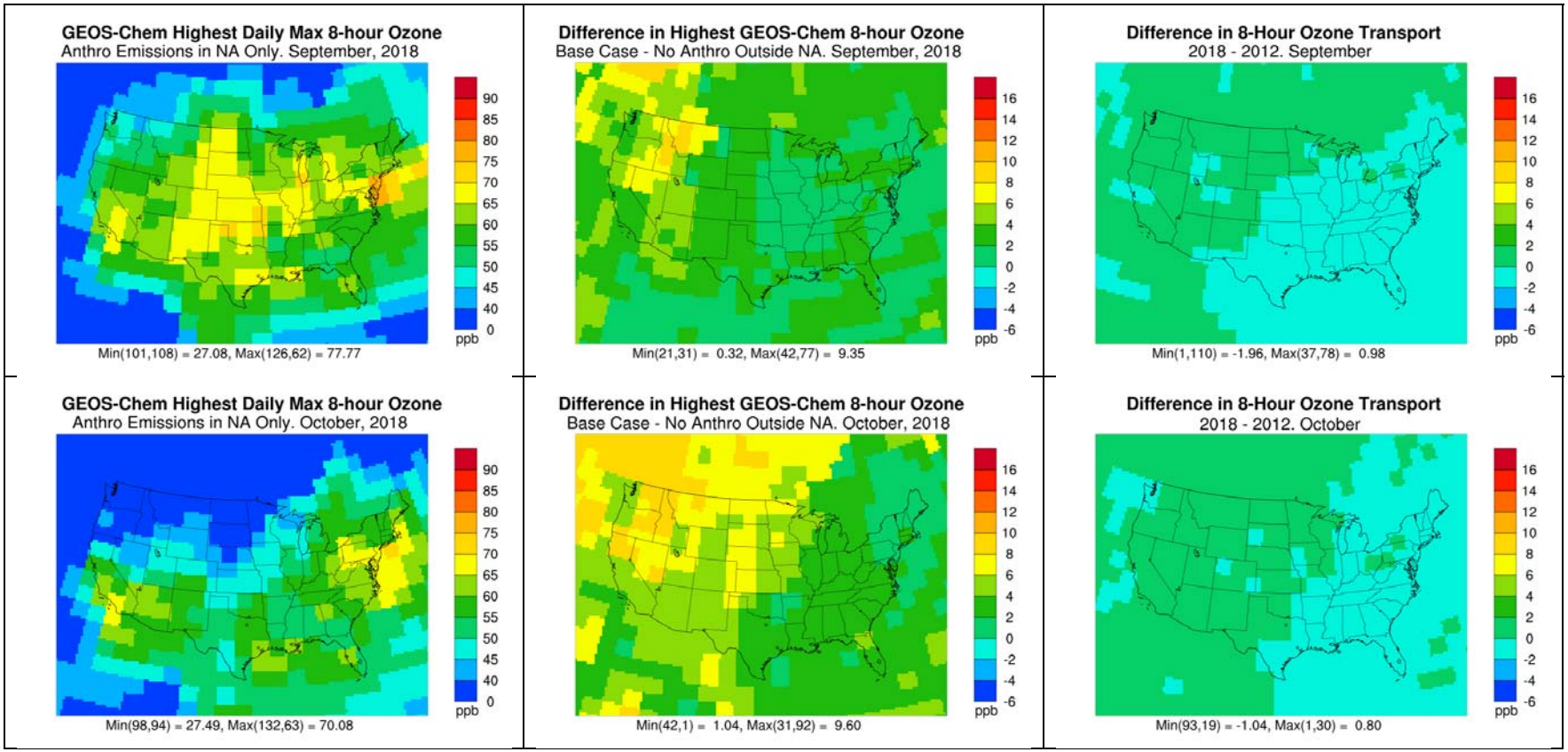
	El Paso		Dallas		Houston	
[ppb]	2012	2018	2012	2018	2012	2018
Jan	8.3	8.7	4.4	4.7	5.9	6.5
Feb	11.2	11.6	8.7	8.8	4.3	4.1
Mar	9.2	9.7	3.7	3.3	3.8	3.1
Apr	7.2	7.6	3.3	2.7	3.7	2.9
May	7.5	8.0	4.9	4.4	3.8	2.6
Jun	5.3	5.4	2.6	1.8	2.5	1.4
Jul	3.2	3.0	2.8	1.8	3.5	1.6
Aug	2.4	1.8	2.0	1.5	3.2	1.4
Sep	3.2	3.2	2.4	1.6	2.4	2.0
Oct	4.9	5.2	2.6	2.8	2.5	2.4
Nov	7.0	7.4	3.8	3.7	3.8	3.7
Dec	7.9	8.2	3.6	3.3	4.7	4.1

2018 zROW Monthly Maximum 8-hour Ozone	Contributions from non-North American Anthropogenic Sources (2018 base – 2018 zROW)	Change in Contributions from non-North American Anthropogenic Sources (2018 – 2012)
		
		


GEOS-Chem Highest Daily Max 8-hour Ozone
Anthro Emissions in NA Only. March, 2018
90 85 80 75 70 65 60 55 50 45 40 0
ppb
Min(67,112) = 33.06, Max(108,64) = 82.79
Difference in Highest GEOS-Chem 8-hour Ozone
Base Case - No Anthro Outside NA. March, 2018
16 14 12 10 8 6 4 2 0 -2 -4 -6
ppb
Min(107,102) = 1.12, Max(25,68) = 12.51
Difference in 8-Hour Ozone Transport
2018 - 2012. March
16 14 12 10 8 6 4 2 0 -2 -4 -6
ppb
Min(116,47) = -1.08, Max(129,75) = 1.11
GEOS-Chem Highest Daily Max 8-hour Ozone
Anthro Emissions in NA Only. April, 2018
90 85 80 75 70 65 60 55 50 45 40 0
ppb
Min(19,109) = 35.55, Max(105,39) = 74.20
Difference in Highest GEOS-Chem 8-hour Ozone
Base Case - No Anthro Outside NA. April, 2018
16 14 12 10 8 6 4 2 0 -2 -4 -6
ppb
Min(129,94) = 0.95, Max(30,48) = 13.61
Difference in 8-Hour Ozone Transport
2018 - 2012. April
16 14 12 10 8 6 4 2 0 -2 -4 -6
ppb
Min(1,109) = -2.47, Max(49,95) = 1.45


GEOS-Chem Highest Daily Max 8-hour Ozone
Anthro Emissions in NA Only. May, 2018
90 85 80 75 70 65 60 55 50 45 40 0
ppb
Min(108,1) = 33.35, Max(108,64) = 73.97
Difference in Highest GEOS-Chem 8-hour Ozone
Base Case - No Anthro Outside NA. May, 2018
16 14 12 10 8 6 4 2 0 -2 -4 -6
ppb
Min(120,29) = 1.28, Max(21,95) = 15.29
Difference in 8-Hour Ozone Transport
2018 - 2012. May
16 14 12 10 8 6 4 2 0 -2 -4 -6
ppb
Min(100,20) = -1.70, Max(39,103) = 1.94
GEOS-Chem Highest Daily Max 8-hour Ozone
Anthro Emissions in NA Only. June, 2018
90 85 80 75 70 65 60 55 50 45 40 0
ppb
Min(108,1) = 29.21, Max(126,62) = 88.67
Difference in Highest GEOS-Chem 8-hour Ozone
Base Case - No Anthro Outside NA. June, 2018
16 14 12 10 8 6 4 2 0 -2 -4 -6
ppb
Min(79,6) = 0.43, Max(2,3) = 10.04
Difference in 8-Hour Ozone Transport
2018 - 2012. June
16 14 12 10 8 6 4 2 0 -2 -4 -6
ppb
Min(148,27) = -1.77, Max(23,101) = 1.39


GEOS-Chem Highest Daily Max 8-hour Ozone
Anthro Emissions in NA Only. July, 2018
90 85 80 75 70 65 60 55 50 45 40 0
ppb
Min(3,1) = 23.89, Max(67,112) = 98.83
Difference in Highest GEOS-Chem 8-hour Ozone
Base Case - No Anthro Outside NA. July, 2018
16 14 12 10 8 6 4 2 0 -2 -4 -6
ppb
Min(145,94) = 0.15, Max(23,101) = 7.74
Difference in 8-Hour Ozone Transport
2018 - 2012. July
16 14 12 10 8 6 4 2 0 -2 -4 -6
ppb
Min(106,27) = -2.37, Max(38,84) = 1.50
GEOS-Chem Highest Daily Max 8-hour Ozone
Anthro Emissions in NA Only. August, 2018
90 85 80 75 70 65 60 55 50 45 40 0
ppb
Min(1,1) = 26.79, Max(108,64) = 86.45
Difference in Highest GEOS-Chem 8-hour Ozone
Base Case - No Anthro Outside NA. August, 2018
16 14 12 10 8 6 4 2 0 -2 -4 -6
ppb
Min(134,76) = 0.52, Max(1,110) = 6.71
Difference in 8-Hour Ozone Transport
2018 - 2012. August
16 14 12 10 8 6 4 2 0 -2 -4 -6
ppb
Min(92,32) = -2.43, Max(42,96) = 1.19


GEOS-Chem Highest Daily Max 8-hour Ozone
Anthro Emissions in NA Only. September, 2018
90 85 80 75 70 65 60 55 50 45 40 0
ppb
Min(101,108) = 27.08, Max(126,62) = 77.77
Difference in Highest GEOS-Chem 8-hour Ozone
Base Case - No Anthro Outside NA. September, 2018
16 14 12 10 8 6 4 2 0 -2 -4 -6
ppb
Min(21,31) = 0.32, Max(42,77) = 9.35
Difference in 8-Hour Ozone Transport
2018 - 2012. September
16 14 12 10 8 6 4 2 0 -2 -4 -6
ppb
Min(1,110) = -1.96, Max(37,78) = 0.98
GEOS-Chem Highest Daily Max 8-hour Ozone
Anthro Emissions in NA Only. October, 2018
90 85 80 75 70 65 60 55 50 45 40 0
ppb
Min(98,94) = 27.49, Max(132,63) = 70.08
Difference in Highest GEOS-Chem 8-hour Ozone
Base Case - No Anthro Outside NA. October, 2018
16 14 12 10 8 6 4 2 0 -2 -4 -6
ppb
Min(42,1) = 1.04, Max(31,92) = 9.60
Difference in 8-Hour Ozone Transport
2018 - 2012. October
16 14 12 10 8 6 4 2 0 -2 -4 -6
ppb
Min(93,19) = -1.04, Max(1,30) = 0.80

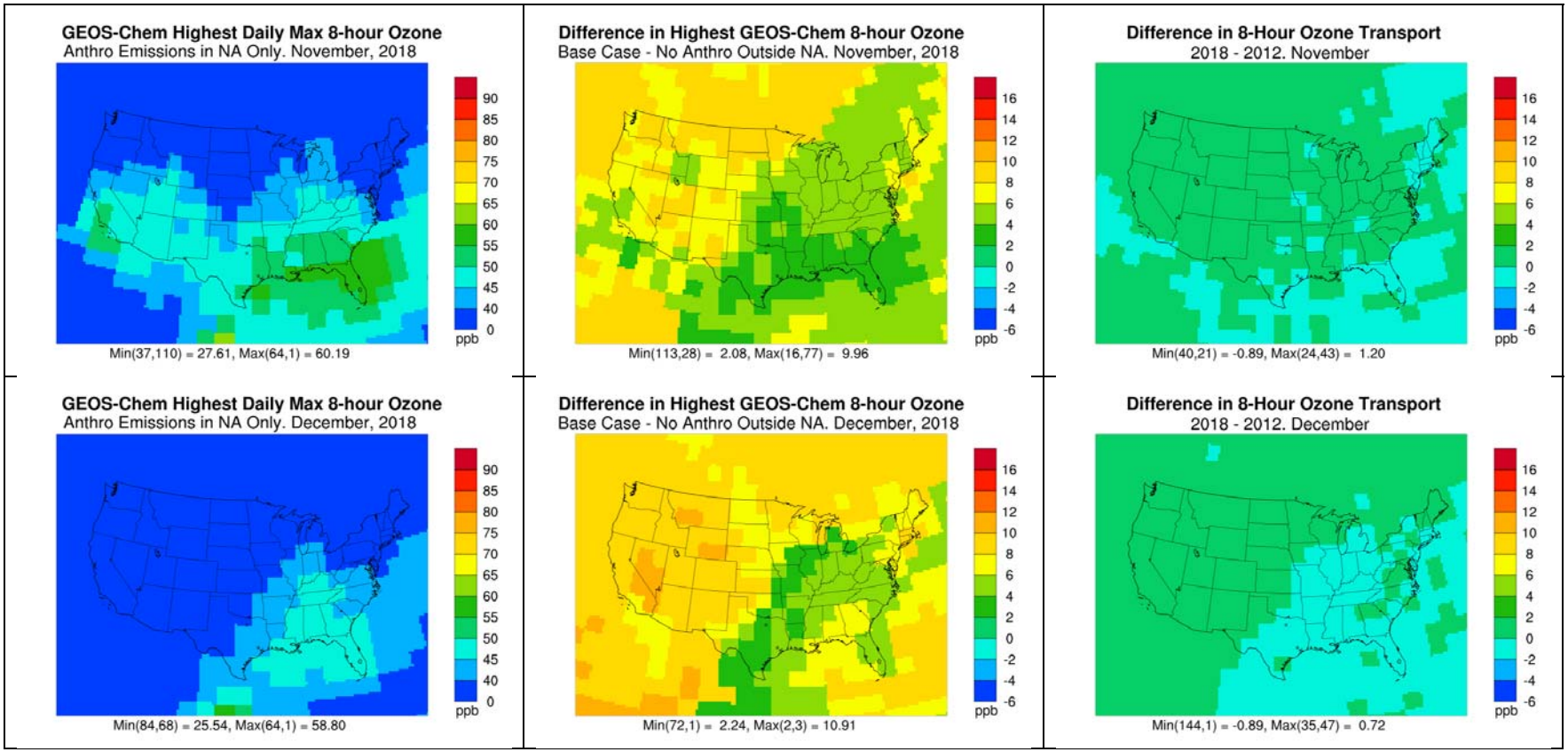
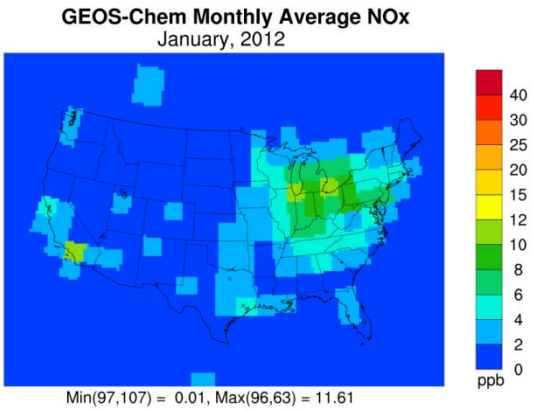
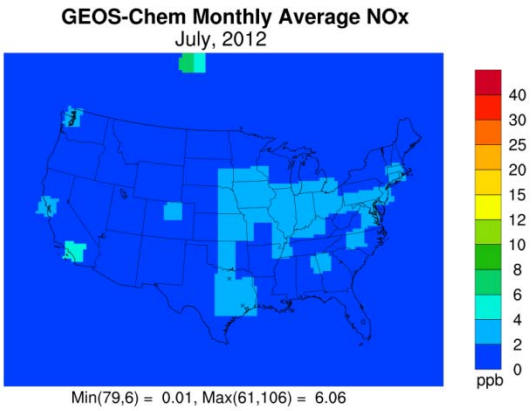
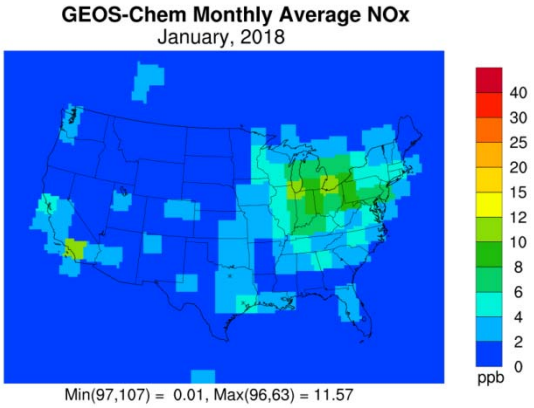
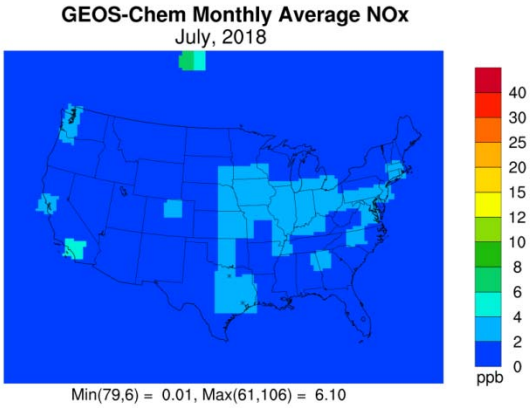


Figure 5-3. Maps of the monthly maximum 8-hour ozone in the 2018 zROW run (left), the contributions from non-North American anthropogenic sources in 2018 (middle), and the change in non-North American anthropogenic contributions between 2012 and 2018 (right).

5.2 2018 Monthly Averaged NOx

Monthly averaged NOx was also examined in 2018. In 2018, NOx remained highest in the Northeast US in the winter months. Maps in Figure 5-4 show very little difference between the monthly averaged NOx in 2012 (top) and in 2018 (middle row) for January and July, which are used to represent winter and summer, respectively. The bottom row shows NOx from the 2018 zROW run. NOx is generally higher in the 2018 zROW run than in the 2018 base case run through much of the continental US, especially in the Northeast in January. Similar findings were found in 2012.

	January	July
2012 Base		
2018 Base		

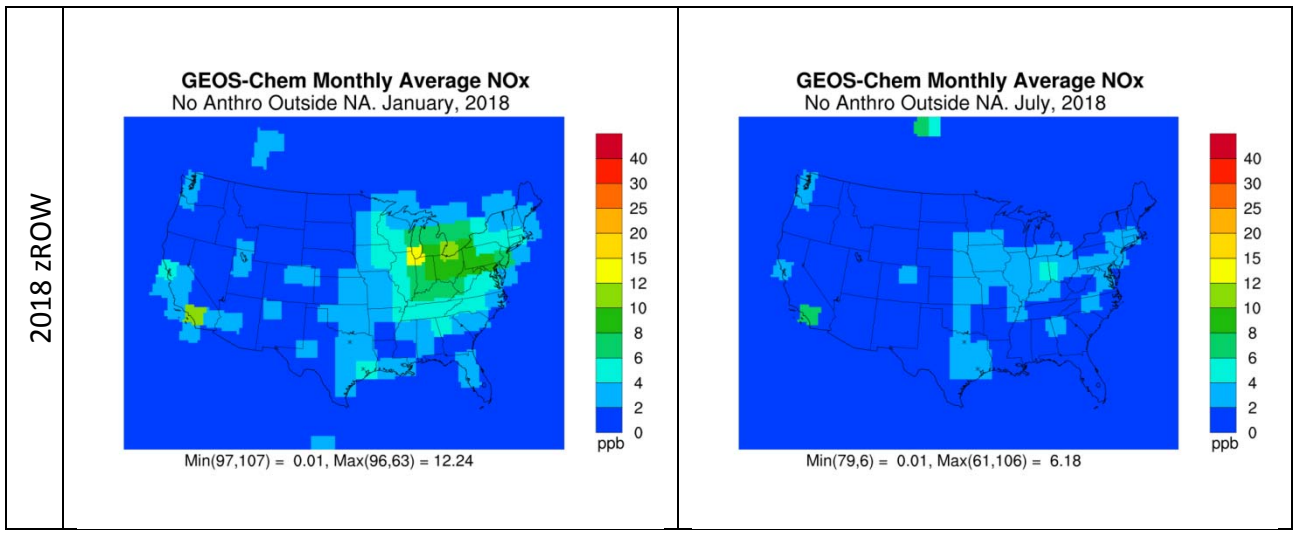


Figure 5-4. Monthly averaged NOx in January (left) and July (right) in the 2012 base case (top), 2018 base case (middle row), and 2018 zROW run (bottom).

6.0 SUMMARY AND RESULTS

The GEOS-Chem global model was used to analyze ozone transport from anthropogenic emissions outside of North America to the continental US during three years 2006, 2012, and 2018. In each of these years, GEOS-Chem was run two times. One run was configured as a base case run (base); the second run zeroed out all anthropogenic emissions outside of North America (zROW – i.e., **z**ero out the **r**est **o**f the **w**orld). The difference between the two runs represented an estimate of the ozone contributions from non-North American anthropogenic sources. Contributions to the monthly maximum 8-hour ozone were evaluated in the CONUS domain with an emphasis on three urban cities in Texas – El Paso, Dallas, and Houston.

Among the three base year runs, 2006 generally had the highest monthly maximum 8-hour ozone in the summer months in the CONUS. In 2012, the ozone precursor emissions in the CONUS, Western Europe and reforming economies (Russia) were lower than in 2006, but were higher in Asia, the Middle East, and Africa. The monthly peak 8-hour ozone in the summer months were mostly lower in 2012 compared to 2006 most likely due to the different meteorology and partially due to emission reductions within the US. This trend was evident in the summer months at the three Texas cities, as shown in Table 6-1, in which Dallas and Houston's monthly maximum 8-hour ozone were both over 10 ppb lower in August, 2012 compared to 2006. El Paso had more modest differences.

The 2018 runs used the same meteorology as 2012; the ozone precursor emissions were lower in the US and Western Europe, but higher in most other areas of the world, especially Asia, when compared to 2012. The monthly maximum 8-hour ozone was higher in 2018 than in 2012 in the western US, but lower in the eastern US in the summer months. Ozone in the western US was higher because of higher emissions from Asia in 2018. Ozone in the eastern US was lower possibly due to lower emissions in the CONUS and in Europe, where the clockwise circulation around the North Atlantic high may have resulted in less ozone and ozone precursors being transported from Europe.

El Paso was the westernmost city among the three Texas cities, and more influenced by the increase in emissions from Asia, as its monthly maximum 8-hour ozone was higher every month in 2018 compared to 2012. Houston was more representative of the eastern US, as its 2018 monthly maximum 8-hour ozone was 0.4 to 2.4 ppb lower than in 2012 from March to September. Dallas was more mixed; its largest difference was a 0.8 ppb reduction in ozone in July.

Table 6-1. Monthly maximum 8-hour ozone in the 2006, 2012, and 2018 base cases in El Paso, Dallas, and Houston.

[ppb]	El Paso			Dallas			Houston		
Month	2006 Base	2012 Base	2018 Base	2006 Base	2012 Base	2018 Base	2006 Base	2012 Base	2018 Base
Jan	48.9	52.2	52.3	45.8	44.1	44.2	47.2	46.3	47.0
Feb	57.6	56.0	56.4	51.4	52.9	53.2	52.8	52.4	52.8
Mar	56.3	60.2	60.6	58.7	64.4	64.4	59.8	68.5	68.1
Apr	63.1	64.5	64.8	67.2	59.5	59.4	70.4	66.6	66.1
May	64.6	68.4	68.8	67.8	67.3	67.2	74.8	73.3	72.3
Jun	68.9	68.3	68.9	87.5	74.1	73.5	89.3	78.4	77.2
Jul	73.4	69.9	70.8	82.8	78.2	77.4	81.6	74.2	71.8
Aug	74.8	74.0	74.4	88.2	76.2	76.3	88.1	77.7	76.0
Sep	64.6	68.5	69.1	76.1	70.1	69.6	81.1	68.6	68.1
Oct	65.7	61.1	61.7	72.6	58.9	59.1	79.6	64.1	64.2
Nov	61.2	53.6	53.8	49.6	51.8	51.8	57.9	56.6	57.1
Dec	45.3	47.9	47.9	43.8	43.3	43.3	43.1	48.8	48.7

In all three years, the ozone contributions from anthropogenic sources outside of North America were greater in the winter months when ozone tended to be lower, and lower in the summer months when ozone was higher. Since ozone typically is highest on warm summer days when wind speeds are low, the transport of non-North American pollutants to an area with high ozone would likely be inhibited. The western US tended to receive the highest contributions as the westerlies could transport ozone and its precursors from Asia.

In Texas, the ozone contributions from non-North American anthropogenic sources were typically highest in El Paso in all three years since it was furthest west, despite having the lowest monthly maximum 8-hour ozone during most months. Contributions to the monthly maximum 8-hour ozone ranged from as low as 1.1 ppb in August, 2006 to 11 ppb in February or March of each modeling year. Contributions to Dallas and Houston were highest in February, 2018 at 8.8 ppb and January, 2006 at 7.3 ppb, respectively. In the summer, the contributions were much lower; between June and September, the contributions in 2018 were all at or below 2.0 ppb in both Dallas and Houston. These summertime contributions were all lower in 2018 than in 2012, likely due to less transport from Europe since both years used the same meteorology. The July, 2018 contributions were 1.0 and 1.9 ppb lower in 2018 than in 2012 at Dallas and Houston, respectively. The full list of monthly ozone contributions from non-North American anthropogenic sources to the three Texas cities for each of the three years is listed in Table 6-2.

Table 6-2. Contributions from non-North American anthropogenic sources to the monthly maximum 8-hour ozone.

[ppb]	El Paso			Dallas			Houston		
Month	2006	2012	2018	2006	2012	2018	2006	2012	2018
Jan	9.0	8.3	8.7	6.1	4.4	4.7	7.3	5.9	6.5
Feb	9.2	11.2	11.6	4.9	8.7	8.8	6.7	4.3	4.1
Mar	11.1	9.2	9.7	5.8	3.7	3.3	6.0	3.8	3.1
Apr	10.3	7.2	7.6	4.5	3.3	2.7	4.7	3.7	2.9
May	3.9	7.5	8.0	4.1	4.9	4.4	4.2	3.8	2.6
Jun	4.5	5.3	5.4	1.8	2.6	1.8	1.3	2.5	1.4
Jul	5.0	3.2	3.0	2.5	2.8	1.8	2.2	3.5	1.6
Aug	1.1	2.4	1.8	1.0	2.0	1.5	0.5	3.2	1.4
Sep	3.0	3.2	3.2	1.2	2.4	1.6	0.9	2.4	2.0
Oct	6.0	4.9	5.2	3.0	2.6	2.8	1.3	2.5	2.4
Nov	8.6	7.0	7.4	3.9	3.8	3.7	3.2	3.8	3.7
Dec	8.3	7.9	8.2	6.5	3.6	3.3	3.4	4.7	4.1

In 2012, an additional run zeroed out all of the anthropogenic emissions from North America (2012 zNA). This run included natural source emissions within North America and all emissions (natural, anthropogenic, and stratospheric) from everywhere else in the world. The ozone outputs represented contributions that cannot be controlled for attainment demonstration. Outputs in the summer were often an order of magnitude greater than the contribution from anthropogenic emissions from outside of North America, indicating that most of the ozone transported into the CONUS is from natural sources. At the three Texas sites, the monthly maxima 8-hour ozone from the 2012 zNA run during the ozone season were mostly in the 50s ppb at El Paso, 40s to lower 50s at Dallas, and upper 30s to the 40s at Houston. The rest of the ozone would have to come from anthropogenic emissions within North America, implying that North American anthropogenic emissions contribute only up to 16 ppb to the monthly maximum 8-hour ozone at El Paso (2012 base – 2012 zNA), and up to 30 and 40 ppb in Dallas and Houston, respectively.

In this study, ozone contributions from foreign sources were estimated by zeroing out anthropogenic emissions outside of North America. Canada and Mexico were not zeroed out due to the complexity of multiple emission inventories at different resolutions and domains that are built into the GEOS-Chem model. An analysis of the ozone contributions from Mexico, which runs through the southern boundary of the TCEQ 36 km CONUS domain, would entail code modifications to ensure that the correct emission components and regions are turned on or off. An alternative would be to create CAMx boundary condition files from the base case runs and perform two CAMx runs – a base case and a run with no anthropogenic emissions in Mexico to isolate the ozone contribution from Mexican anthropogenic emissions.

This study also introduced the possibility that ozone and ozone precursor emissions in Western Europe can affect ozone in the eastern US, particularly near the Gulf States in the summer months. In order to understand the potential benefits of emission reductions in Europe on the eastern US, an additional GEOS-Chem run should be run in which only emissions in Western Europe are modified.

7.0 REFERENCES

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European Commission: Joint Research Centre (JRC)/Netherlands Environmental Assessment Agency (PBL). 2011. Emission Database for Global Atmospheric Research (EDGAR), release version 4.2., available at: http://edgar.jrc.ec.europa.eu.

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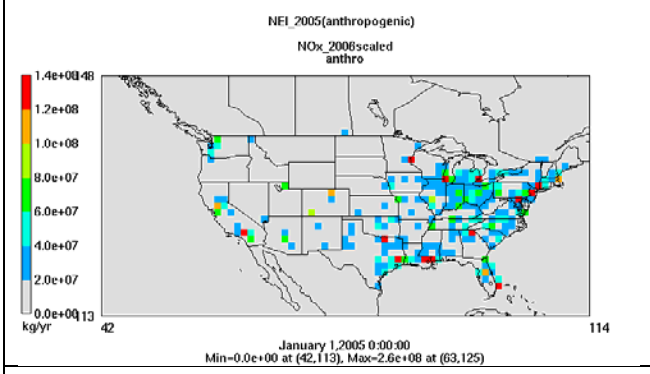
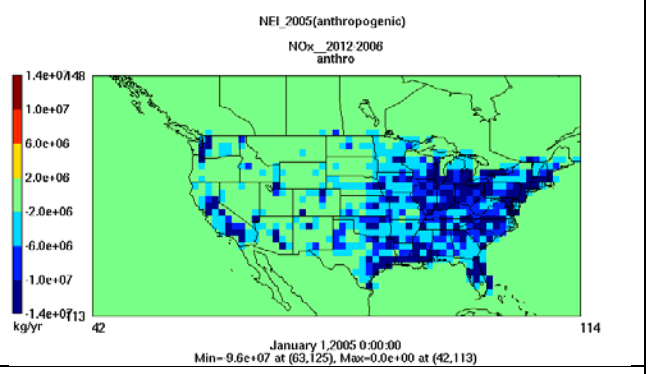
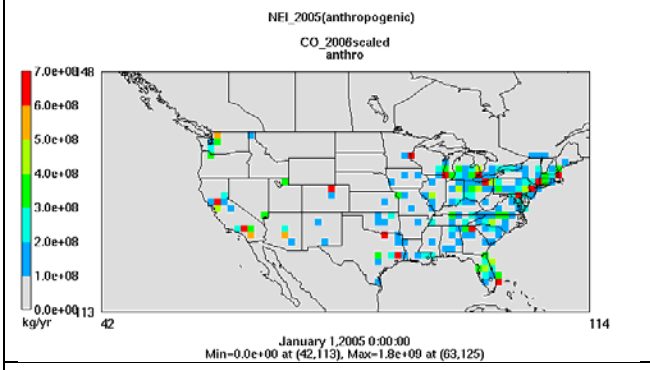
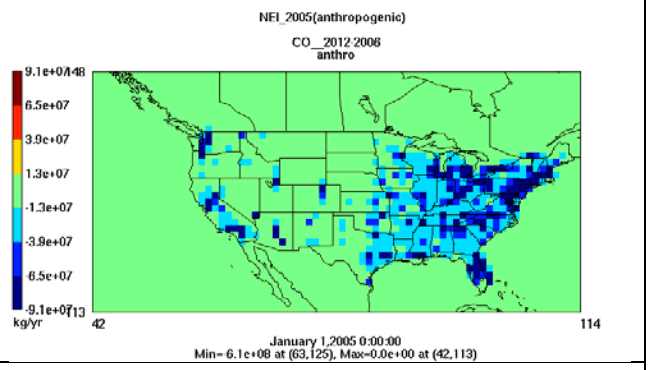
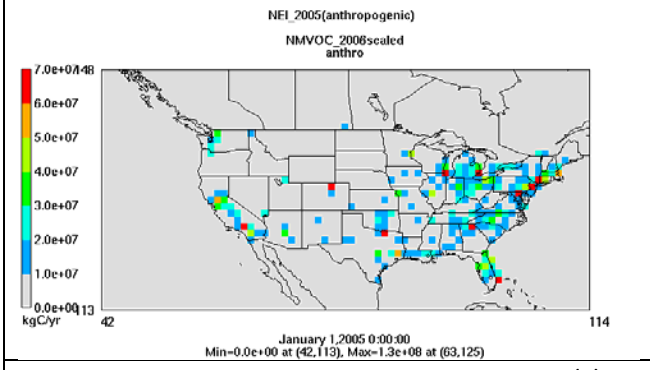
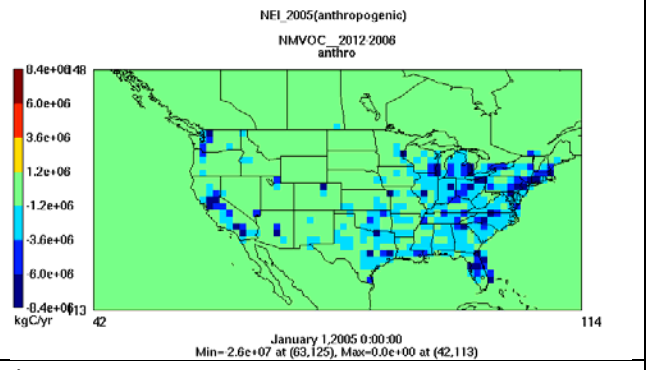
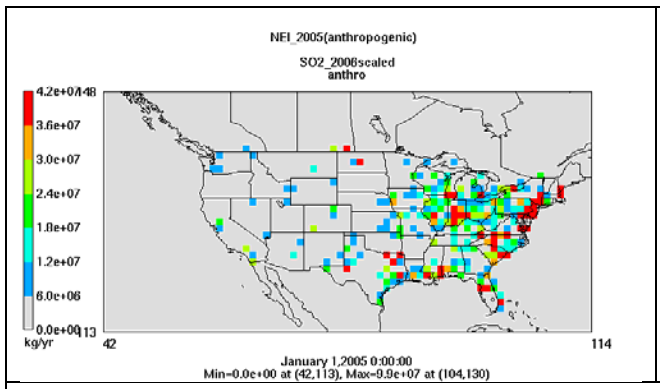
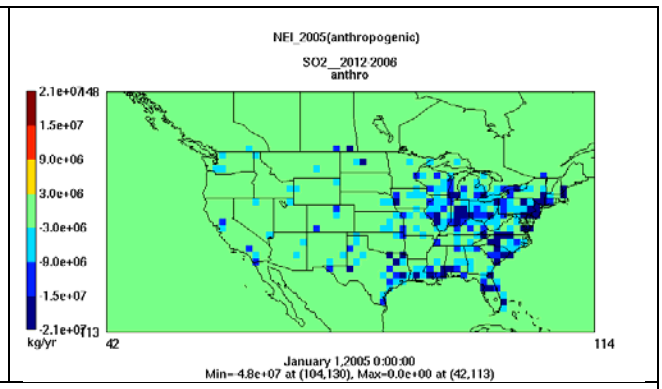
APPENDIX A

Maps of Anthropogenic Emissions in the 2006 base case and emission comparison between the 2012 and 2006 base case

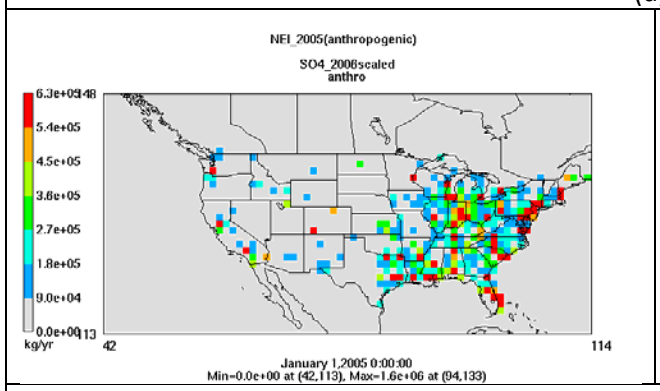
Appendix A: Anthropogenic emissions for the GEOS-Chem 2006 base case and comparison between the 2012 and 2006 base cases.

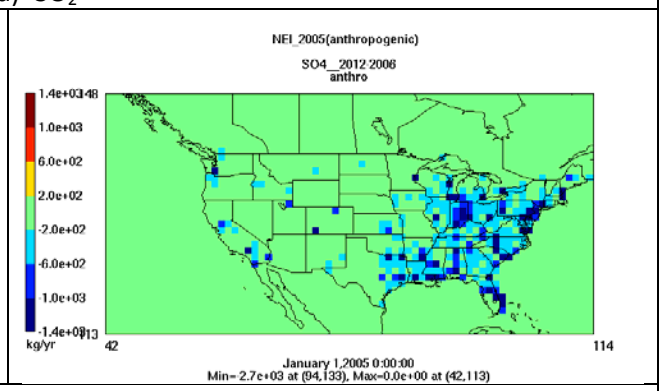
2006	Difference (2012-2006)
	
(a) NOx	
	
(b) CO	
	
(c) Total NMVOC	



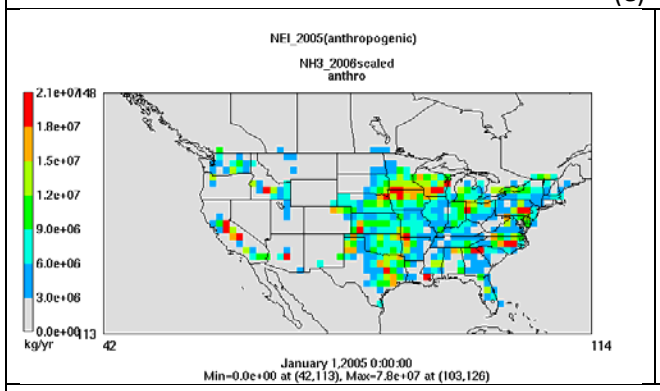


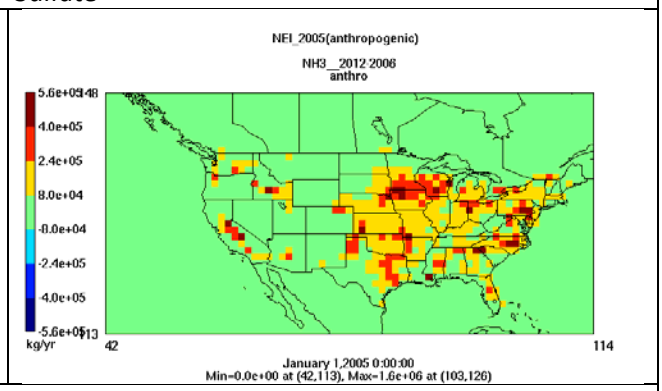
(d) SO_2





(e) Sulfate





(f) NH_3

Figure A-1. U.S. emissions (kg/yr or KgC/yr) based 2005 NEI inventory used in the 2006 base case (left) and emission comparison between the 2012 and 2006 base case (right).

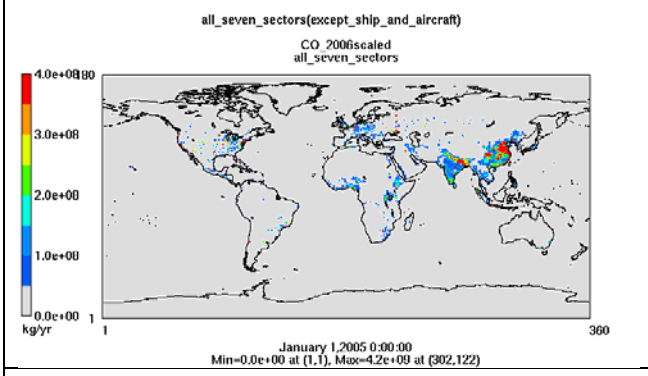
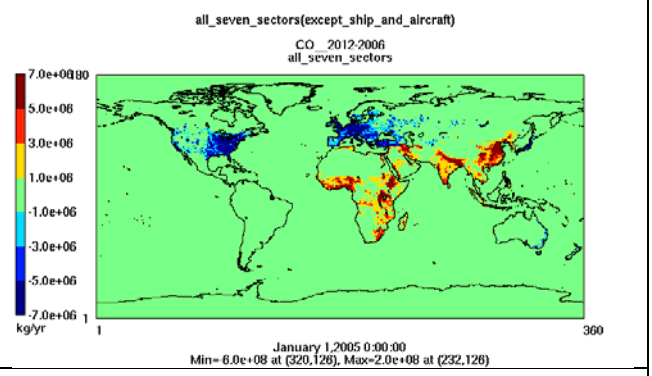
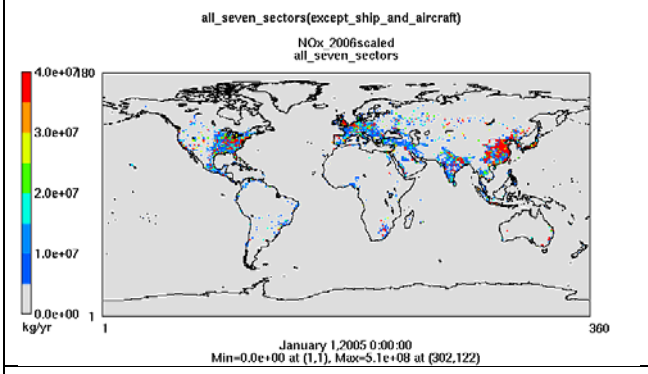
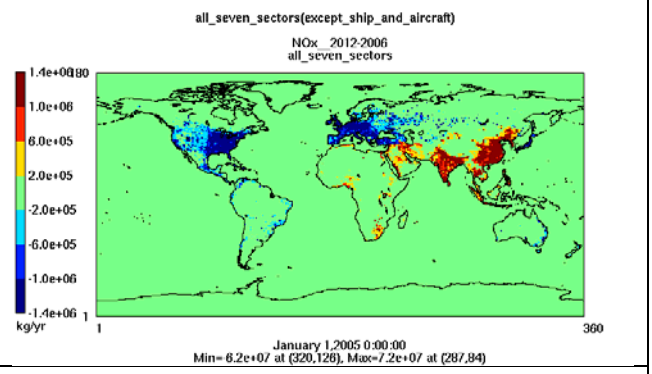
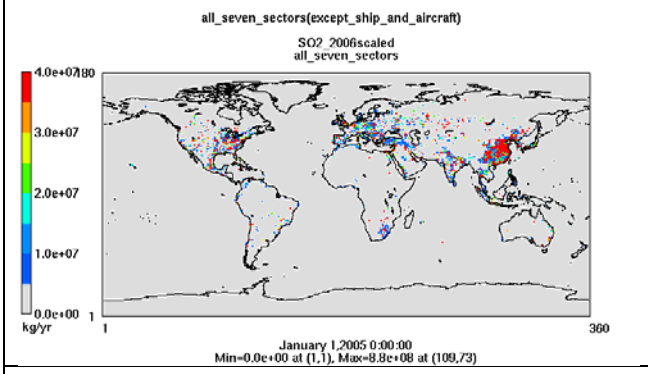
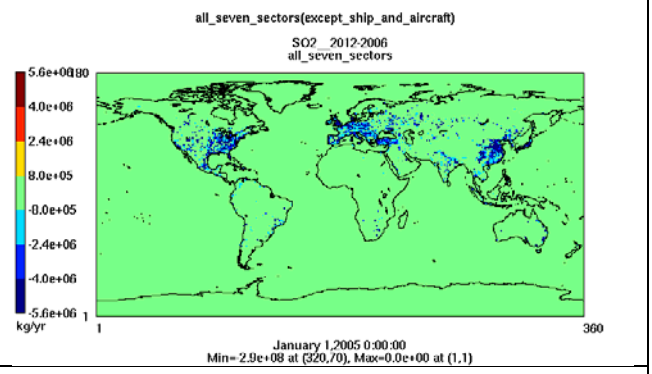
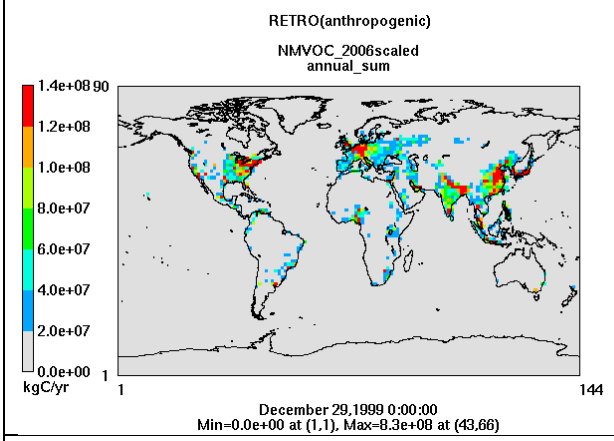
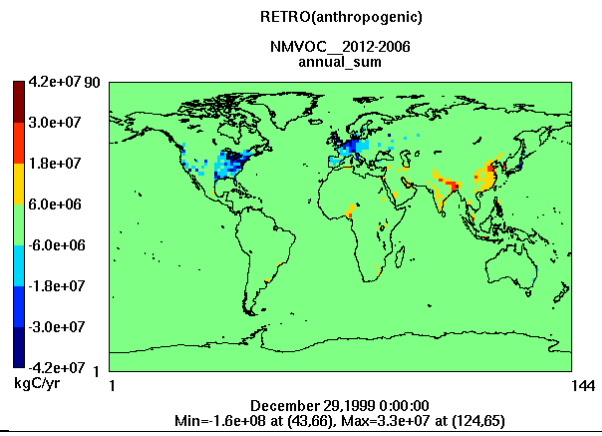
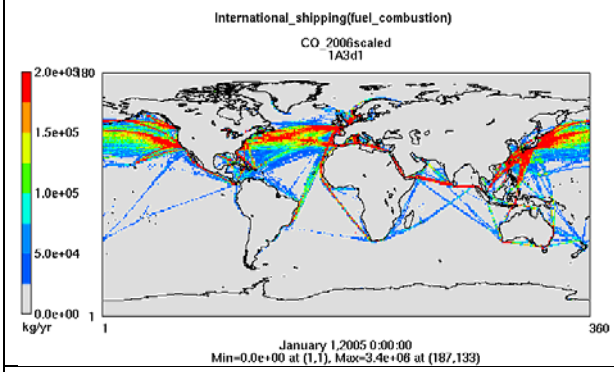
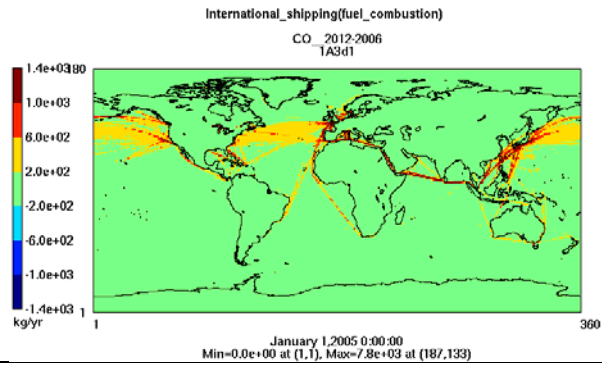
2006	Difference (2012-2006)
	
(a) CO	
	
(b) NOx	
	
(c) SO_2	

Figure A-2. Total anthropogenic CO (a), NOx (b), and SO_2(c) emissions (kg/yr) [excluding aircraft and shipping; based on EDGAR4.1] in the 2006 base case (left) and emission comparison between the 2012 and 2006 base case (right).

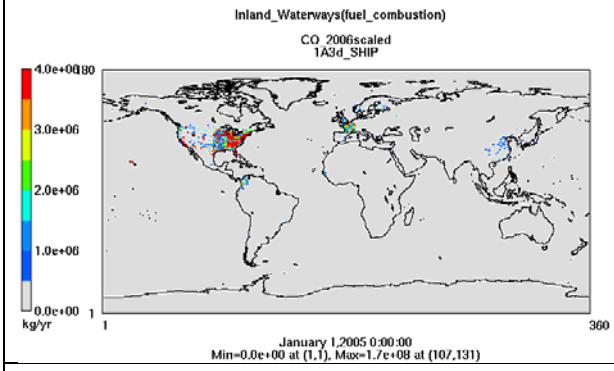
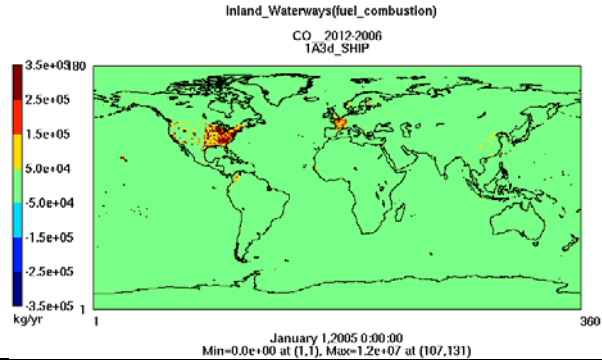
2006	Difference (2012-2006)
	

(a) Total NMVOC

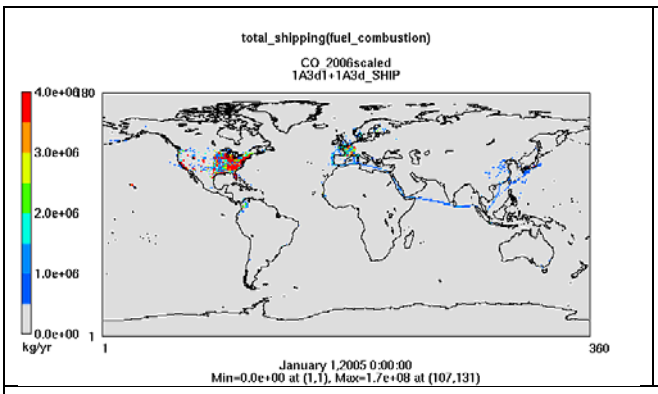
Figure A-3. RETRO NMVOC emissions (kgC/yr) in the 2006 base case (left) and emission comparison between the 2012 and 2006 base case (right).

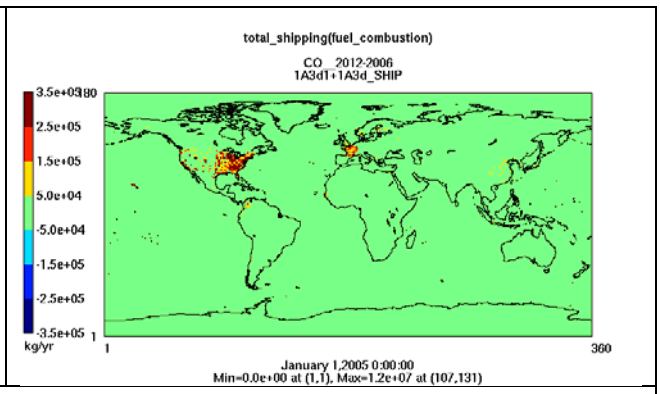
2006	Difference (2012-2006)
	

(a) CO from International Shipping

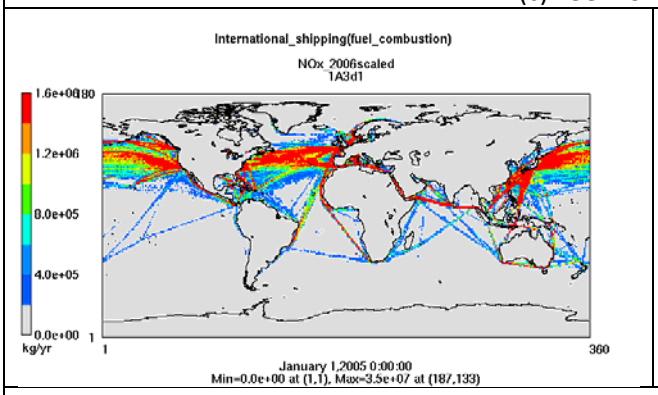
	

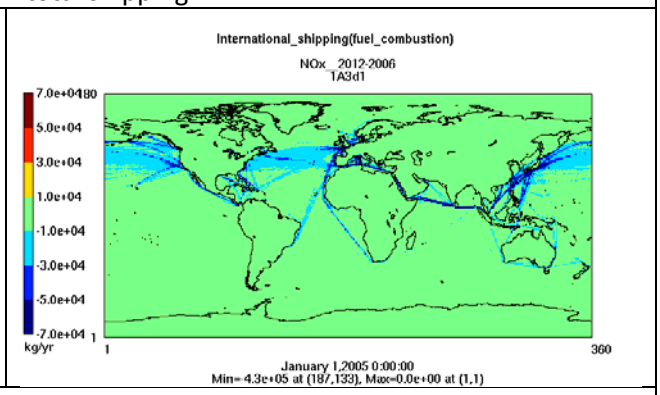
(b) CO from Inland Shipping



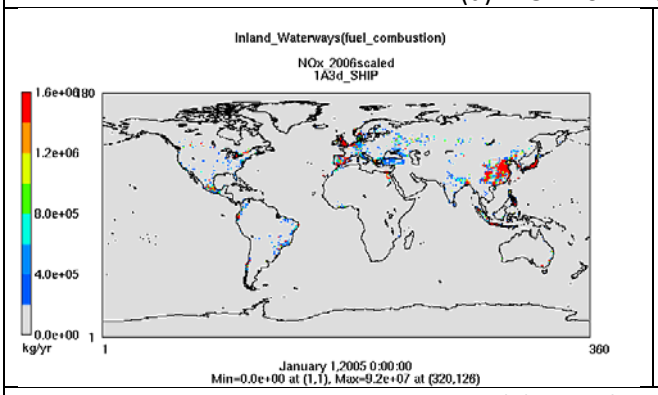


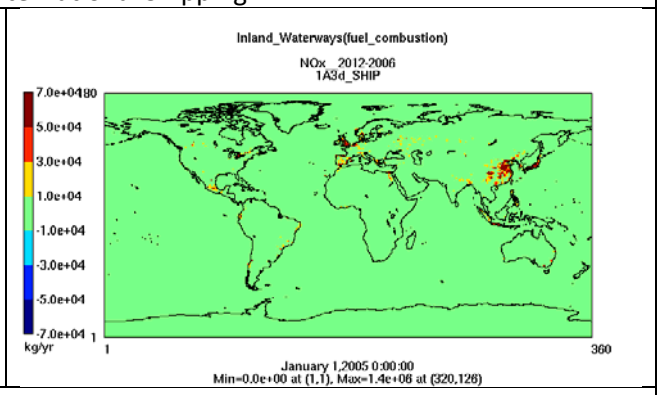
(c) CO from total shipping



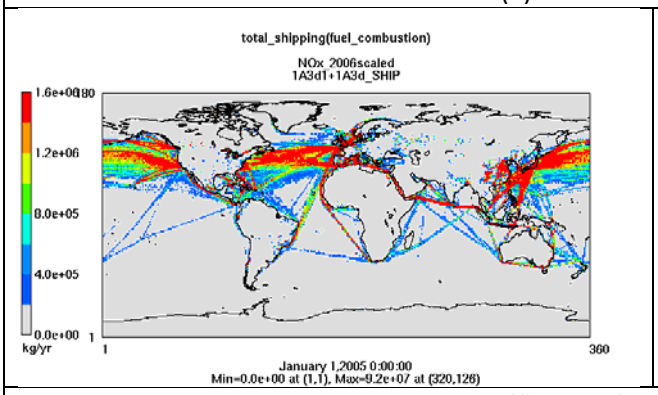


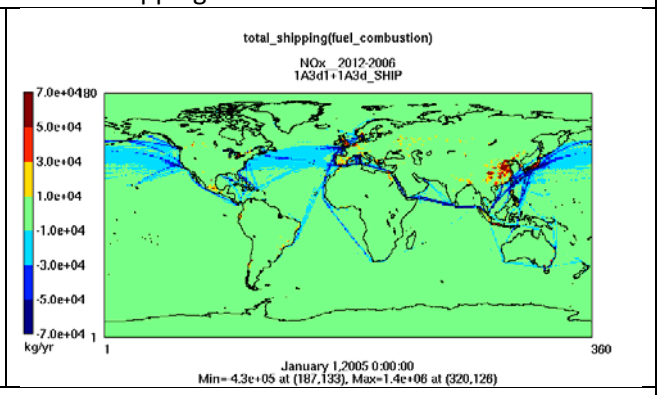
(d) NOx from International Shipping



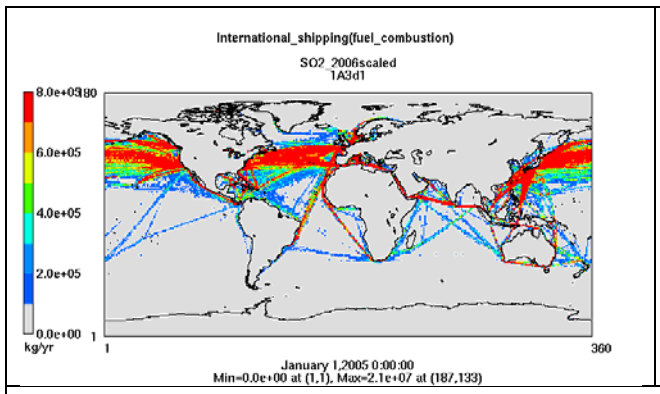


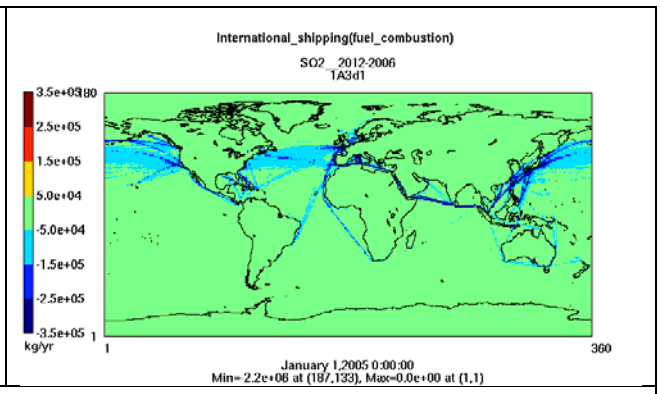
(e) NOx from Inland Shipping



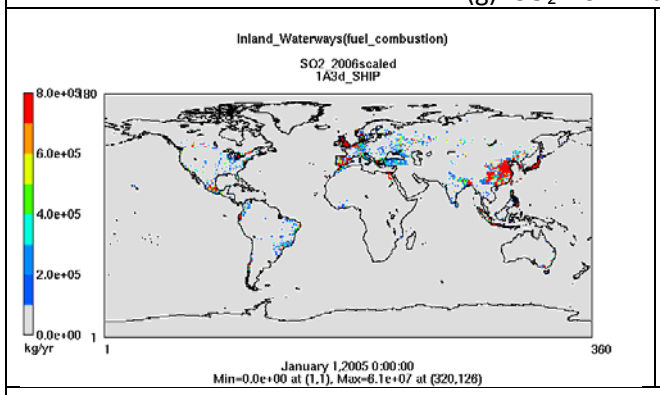


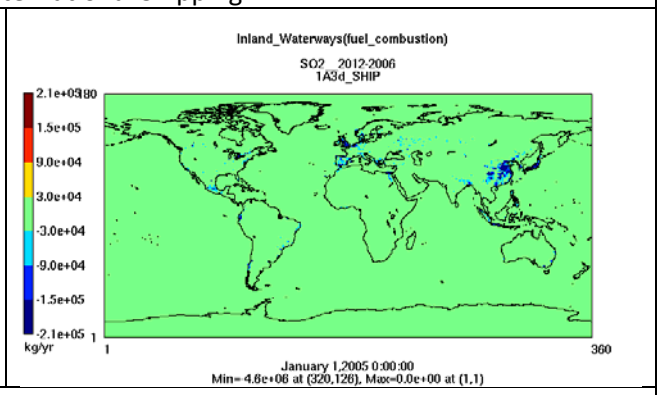
(f) NOx from Total Shipping



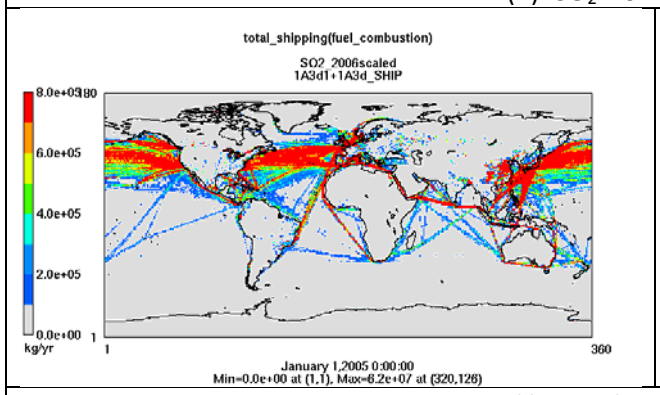


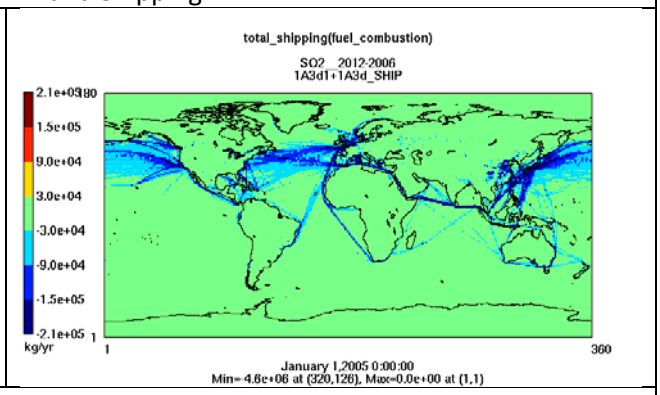
(g) SO_2 from International Shipping





(h) SO_2 from Inland Shipping





(i) SO_2 from Total Shipping

Figure A-4. Shipping CO (a-c), NOx, and SO_2 emissions (kg/yr) based on EDGAR4.1 inventory used in the 2006 base case (left) and emission comparison between the 2012 and 2006 base case (right).

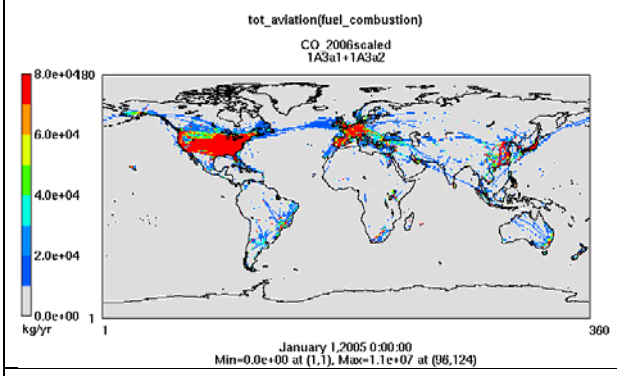
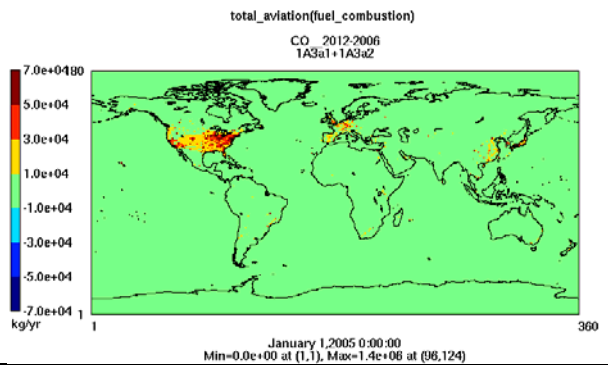
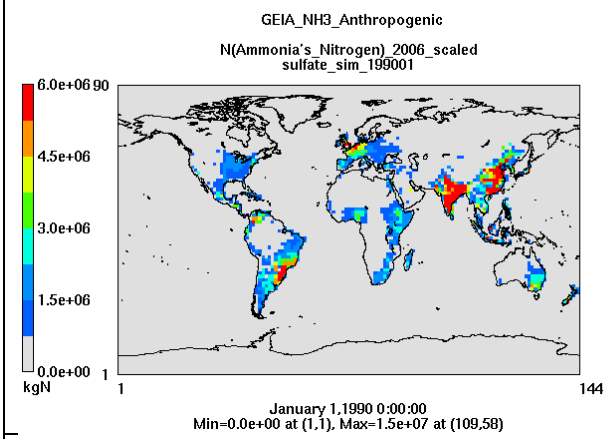
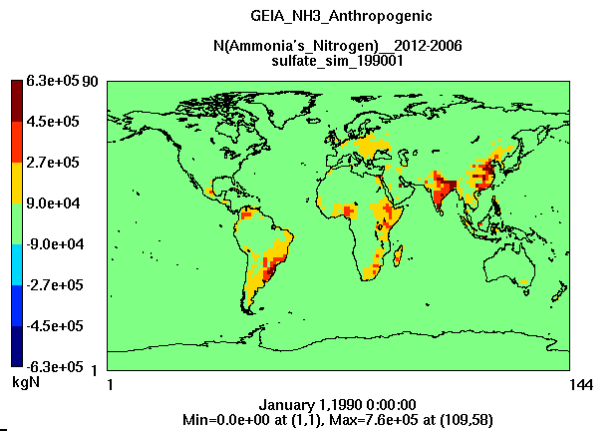
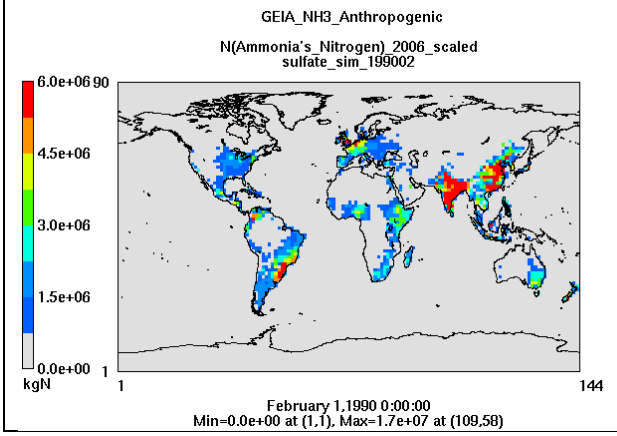
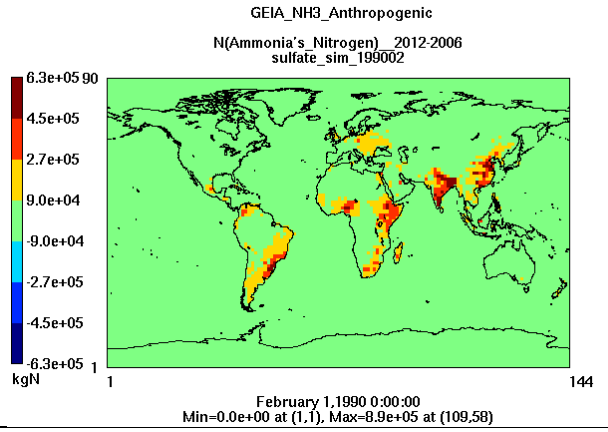
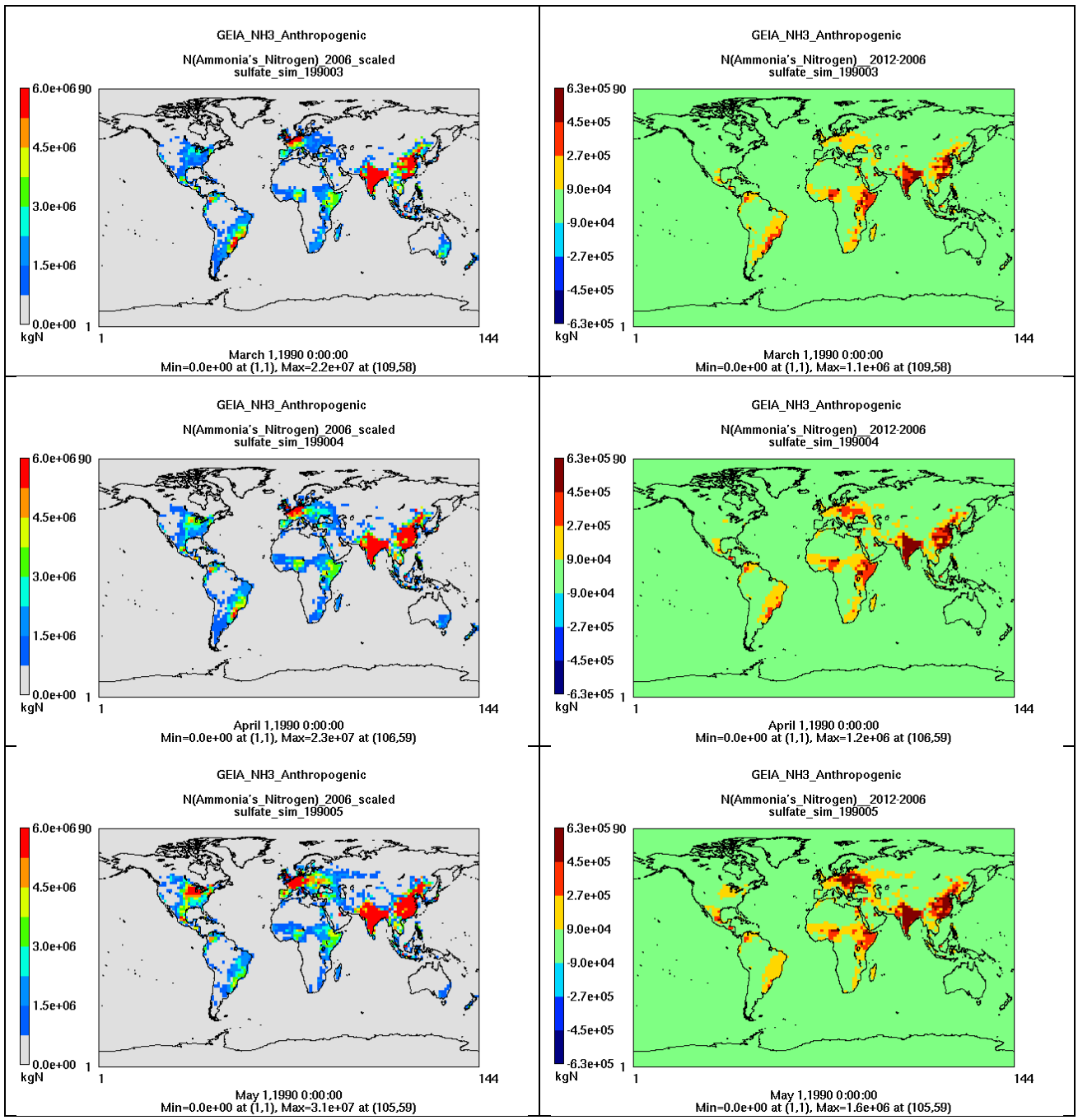
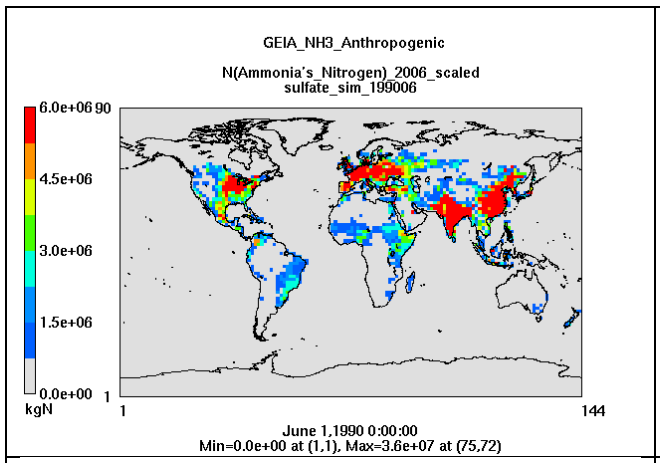
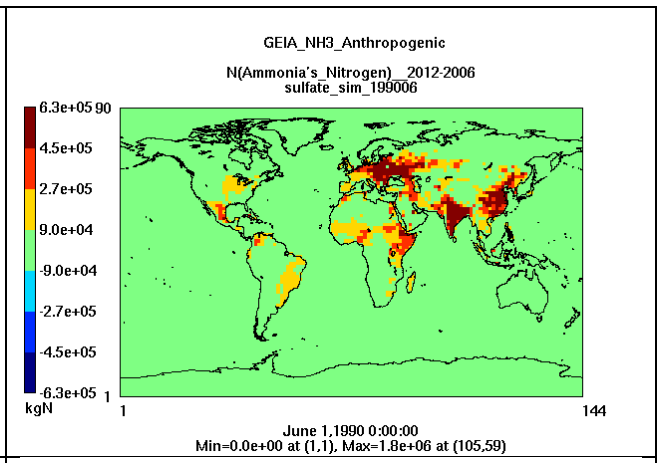
2006	Difference (2012-2006)
	

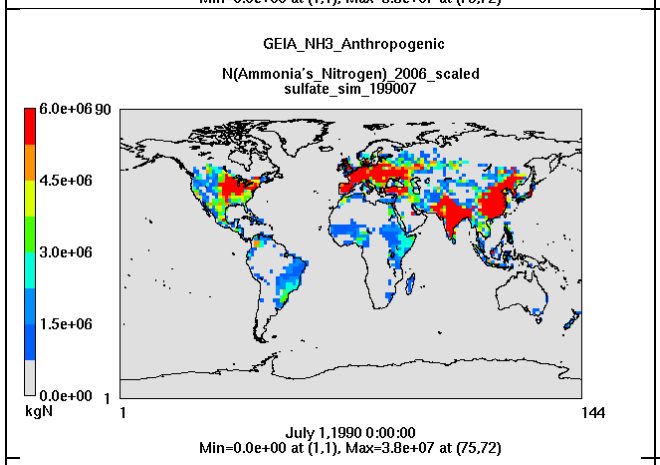
Figure A-5. Aviation CO emissions (kg/yr) in the 2006 base case (left) and emission comparison between the 2012 and 2006 base case (right).

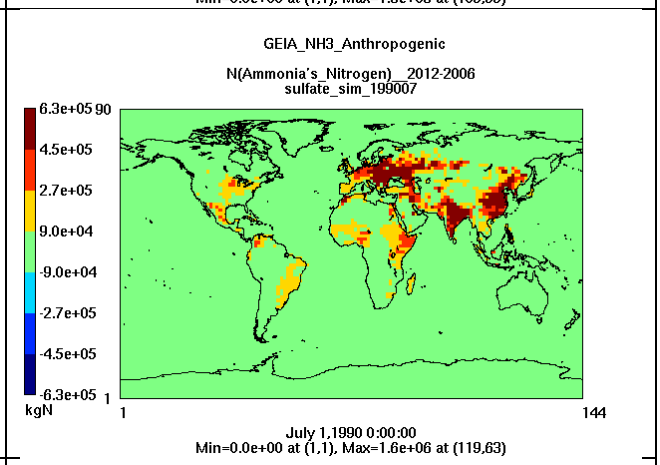
2006	Difference (2012-2006)
	
	

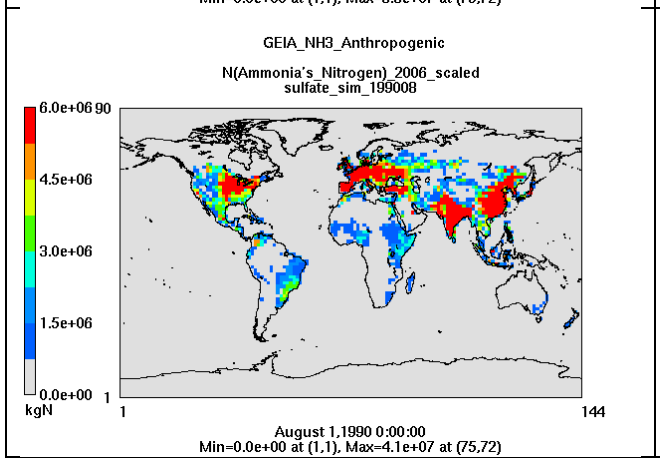

GEIA_NH3_Anthropogenic
N(Ammonia's_Nitrogen)_2006_scaled
sulfate_sim_199003
6.0e+06 90
4.5e+06
3.0e+06
1.5e+06
0.0e+00 1
kgN
1
144
March 1,1990 0:00:00
Min=0.0e+00 at (1,1), Max=2.2e+07 at (109,58)
GEIA_NH3_Anthropogenic
N(Ammonia's_Nitrogen)__2012-2006
sulfate_sim_199003
6.3e+05 90
4.5e+05
2.7e+05
9.0e+04
-9.0e+04
-2.7e+05
-4.5e+05
-6.3e+05 1
kgN
1
144
March 1,1990 0:00:00
Min=0.0e+00 at (1,1), Max=1.1e+06 at (109,58)
GEIA_NH3_Anthropogenic
N(Ammonia's_Nitrogen)_2006_scaled
sulfate_sim_199004
6.0e+06 90
4.5e+06
3.0e+06
1.5e+06
0.0e+00 1
kgN
1
144
April 1,1990 0:00:00
Min=0.0e+00 at (1,1), Max=2.3e+07 at (106,59)
GEIA_NH3_Anthropogenic
N(Ammonia's_Nitrogen)__2012-2006
sulfate_sim_199004
6.3e+05 90
4.5e+05
2.7e+05
9.0e+04
-9.0e+04
-2.7e+05
-4.5e+05
-6.3e+05 1
kgN
1
144
April 1,1990 0:00:00
Min=0.0e+00 at (1,1), Max=1.2e+06 at (106,59)
GEIA_NH3_Anthropogenic
N(Ammonia's_Nitrogen)_2006_scaled
sulfate_sim_199005
6.0e+06 90
4.5e+06
3.0e+06
1.5e+06
0.0e+00 1
kgN
1
144
May 1,1990 0:00:00
Min=0.0e+00 at (1,1), Max=3.1e+07 at (105,59)
GEIA_NH3_Anthropogenic
N(Ammonia's_Nitrogen)__2012-2006
sulfate_sim_199005
6.3e+05 90
4.5e+05
2.7e+05
9.0e+04
-9.0e+04
-2.7e+05
-4.5e+05
-6.3e+05 1
kgN
1
144
May 1,1990 0:00:00
Min=0.0e+00 at (1,1), Max=1.6e+06 at (105,59)

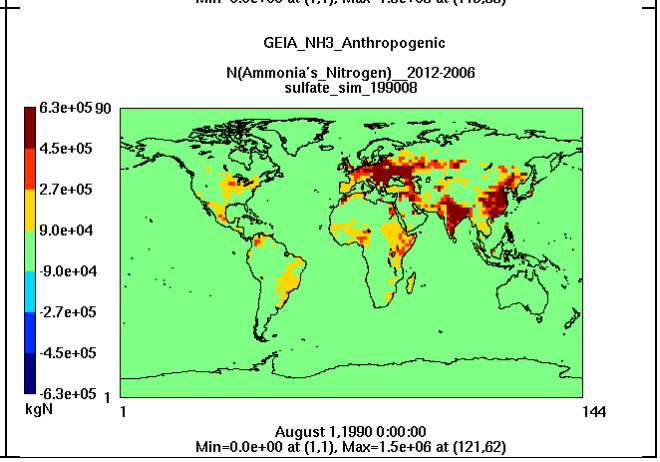

GEIA_NH3_Anthropogenic
N(Ammonia's_Nitrogen)_2006_scaled
sulfate_sim_199006
6.0e+06
4.5e+06
3.0e+06
1.5e+06
0.0e+00
kgN
90
1
1
144
June 1,1990 0:00:00
Min=0.0e+00 at (1,1), Max=3.6e+07 at (75,72)

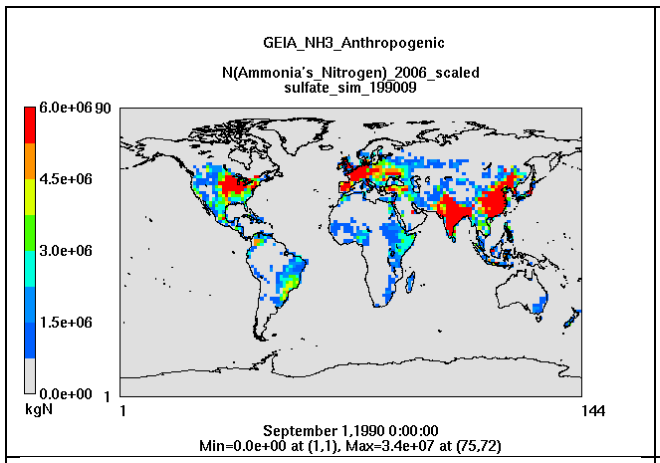

GEIA_NH3_Anthropogenic
N(Ammonia's_Nitrogen)__2012-2006
sulfate_sim_199006
6.3e+05
4.5e+05
2.7e+05
9.0e+04
-9.0e+04
-2.7e+05
-4.5e+05
-6.3e+05
kgN
90
1
1
144
June 1,1990 0:00:00
Min=0.0e+00 at (1,1), Max=1.8e+06 at (105,59)

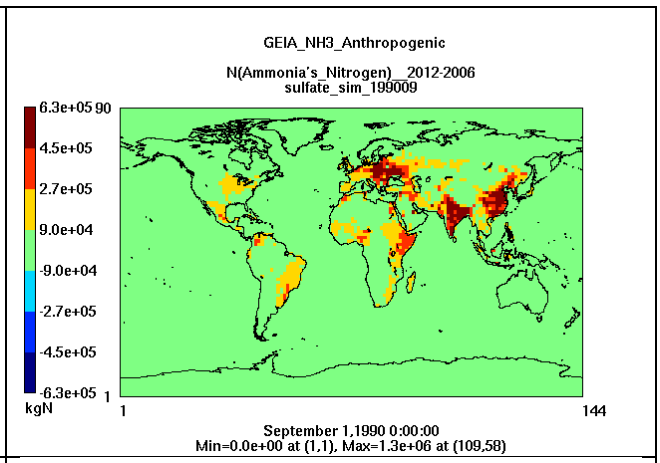

GEIA_NH3_Anthropogenic
N(Ammonia's_Nitrogen)_2006_scaled
sulfate_sim_199007
6.0e+06
4.5e+06
3.0e+06
1.5e+06
0.0e+00
kgN
90
1
1
144
July 1,1990 0:00:00
Min=0.0e+00 at (1,1), Max=3.8e+07 at (75,72)

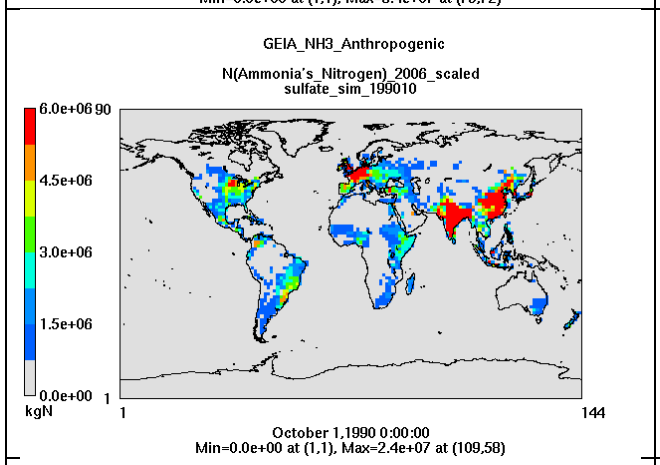

GEIA_NH3_Anthropogenic
N(Ammonia's_Nitrogen)__2012-2006
sulfate_sim_199007
6.3e+05
4.5e+05
2.7e+05
9.0e+04
-9.0e+04
-2.7e+05
-4.5e+05
-6.3e+05
kgN
90
1
1
144
July 1,1990 0:00:00
Min=0.0e+00 at (1,1), Max=1.6e+06 at (119,63)

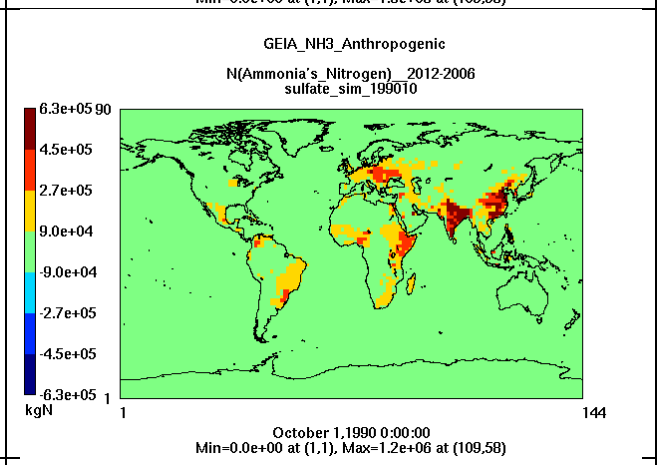

GEIA_NH3_Anthropogenic
N(Ammonia's_Nitrogen)_2006_scaled
sulfate_sim_199008
6.0e+06
4.5e+06
3.0e+06
1.5e+06
0.0e+00
kgN
90
1
1
144
August 1,1990 0:00:00
Min=0.0e+00 at (1,1), Max=4.1e+07 at (75,72)

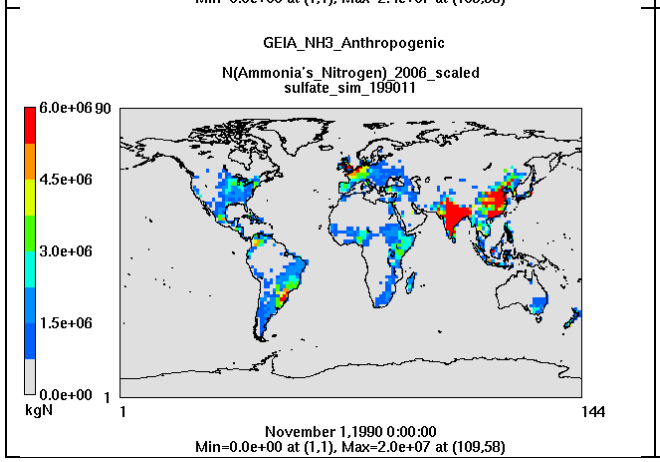

GEIA_NH3_Anthropogenic
N(Ammonia's_Nitrogen)__2012-2006
sulfate_sim_199008
6.3e+05
4.5e+05
2.7e+05
9.0e+04
-9.0e+04
-2.7e+05
-4.5e+05
-6.3e+05
kgN
90
1
1
144
August 1,1990 0:00:00
Min=0.0e+00 at (1,1), Max=1.5e+06 at (121,62)

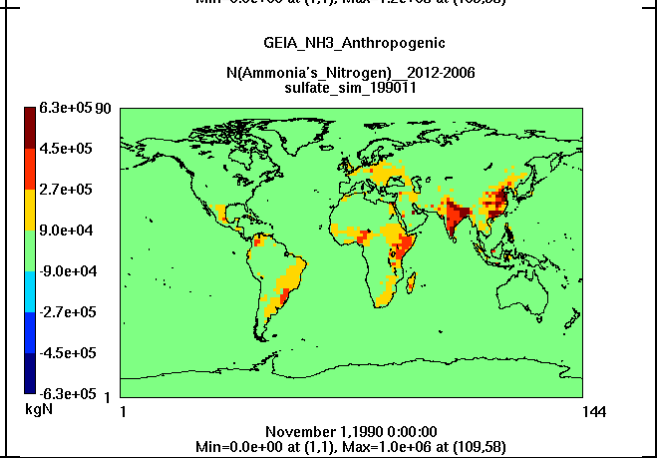

GEIA_NH3_Anthropogenic
N(Ammonia's_Nitrogen)_2006_scaled
sulfate_sim_199009
6.0e+06 90
4.5e+06
3.0e+06
1.5e+06
0.0e+00 1
kgN
1
144
September 1,1990 0:00:00
Min=0.0e+00 at (1,1), Max=3.4e+07 at (75,72)


GEIA_NH3_Anthropogenic
N(Ammonia's_Nitrogen)__2012-2006
sulfate_sim_199009
6.3e+05 90
4.5e+05
2.7e+05
9.0e+04
-9.0e+04
-2.7e+05
-4.5e+05
-6.3e+05 1
kgN
1
144
September 1,1990 0:00:00
Min=0.0e+00 at (1,1), Max=1.3e+06 at (109,58)


GEIA_NH3_Anthropogenic
N(Ammonia's_Nitrogen)_2006_scaled
sulfate_sim_199010
6.0e+06 90
4.5e+06
3.0e+06
1.5e+06
0.0e+00 1
kgN
1
144
October 1,1990 0:00:00
Min=0.0e+00 at (1,1), Max=2.4e+07 at (109,58)


GEIA_NH3_Anthropogenic
N(Ammonia's_Nitrogen)__2012-2006
sulfate_sim_199010
6.3e+05 90
4.5e+05
2.7e+05
9.0e+04
-9.0e+04
-2.7e+05
-4.5e+05
-6.3e+05 1
kgN
1
144
October 1,1990 0:00:00
Min=0.0e+00 at (1,1), Max=1.2e+06 at (109,58)


GEIA_NH3_Anthropogenic
N(Ammonia's_Nitrogen)_2006_scaled
sulfate_sim_199011
6.0e+06 90
4.5e+06
3.0e+06
1.5e+06
0.0e+00 1
kgN
1
144
November 1,1990 0:00:00
Min=0.0e+00 at (1,1), Max=2.0e+07 at (109,58)


GEIA_NH3_Anthropogenic
N(Ammonia's_Nitrogen)__2012-2006
sulfate_sim_199011
6.3e+05 90
4.5e+05
2.7e+05
9.0e+04
-9.0e+04
-2.7e+05
-4.5e+05
-6.3e+05 1
kgN
1
144
November 1,1990 0:00:00
Min=0.0e+00 at (1,1), Max=1.0e+06 at (109,58)

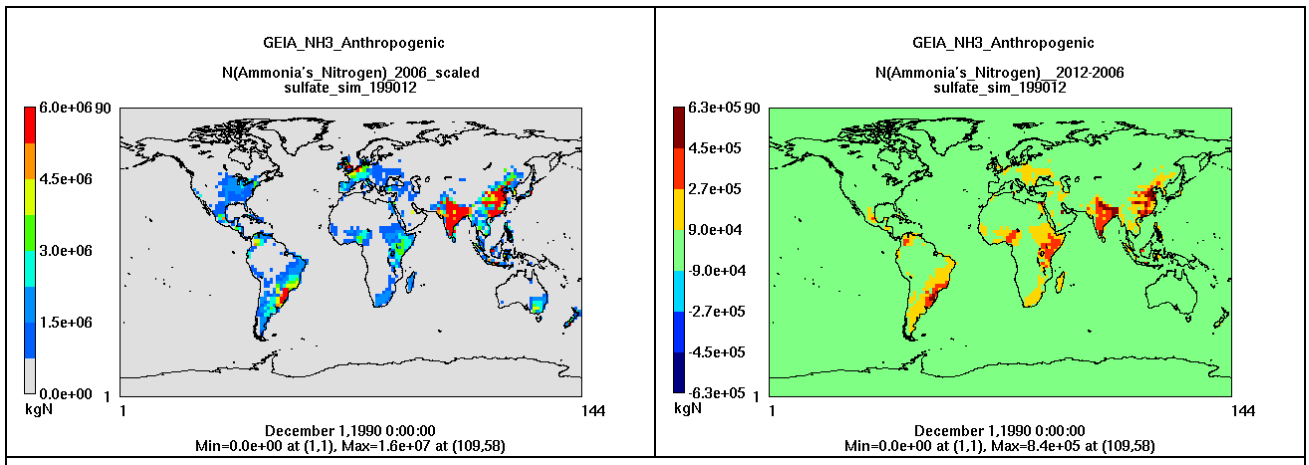
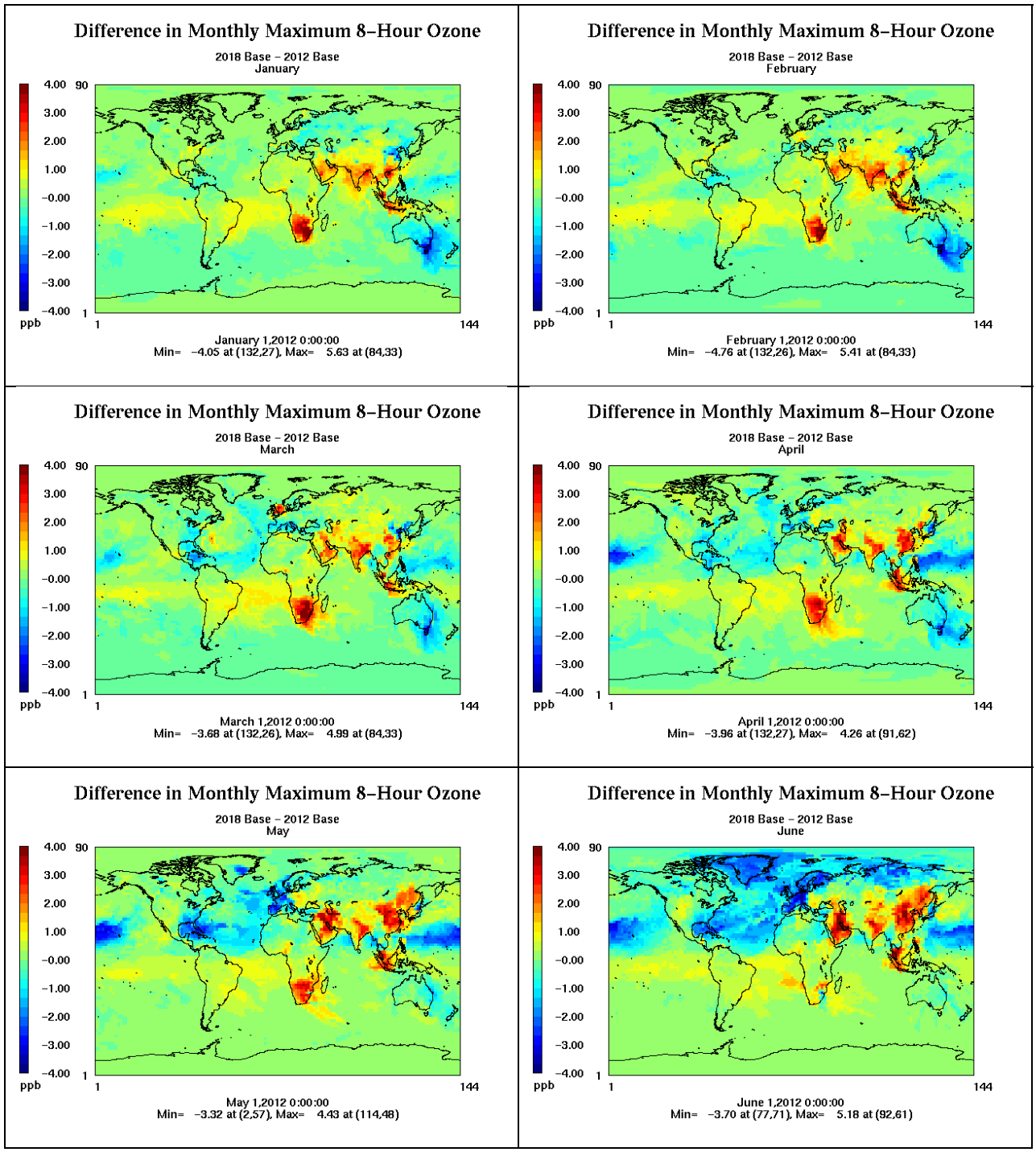


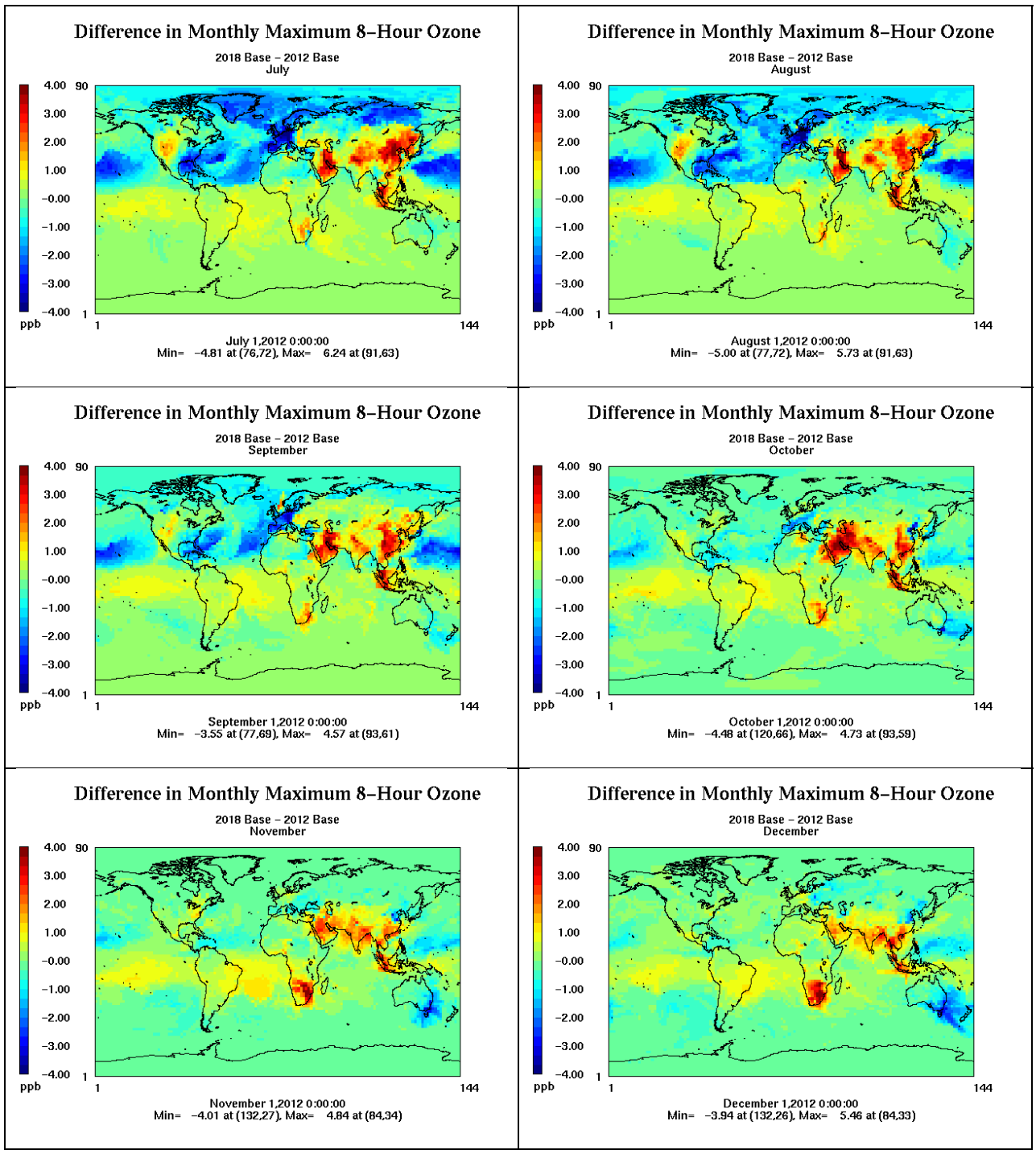
Figure A-6. Monthly anthropogenic ammonia (NH_3) emissions (kgN) based on GEIA inventory used in the 2006 base case (left) and emission comparison between the 2012 and 2006 base case (right).

APPENDIX B

Maps of the worldwide difference in monthly maximum 8-hour ozone between 2012 and 2018

APPENDIX B. Maps of the worldwide difference in monthly maximum 8-hour ozone between 2012 and 2018.




Difference in Monthly Maximum 8-Hour Ozone
2018 Base – 2012 Base
July
4.00 3.00 2.00 1.00 -0.00 -1.00 -2.00 -3.00 -4.00
ppb
90
1
1
144
July 1,2012 0:00:00
Min= -4.81 at (76,72), Max= 6.24 at (91,63)
Difference in Monthly Maximum 8-Hour Ozone
2018 Base – 2012 Base
August
4.00 3.00 2.00 1.00 -0.00 -1.00 -2.00 -3.00 -4.00
ppb
90
1
1
144
August 1,2012 0:00:00
Min= -5.00 at (77,72), Max= 5.73 at (91,63)
Difference in Monthly Maximum 8-Hour Ozone
2018 Base – 2012 Base
September
4.00 3.00 2.00 1.00 -0.00 -1.00 -2.00 -3.00 -4.00
ppb
90
1
1
144
September 1,2012 0:00:00
Min= -3.55 at (77,69), Max= 4.57 at (93,61)
Difference in Monthly Maximum 8-Hour Ozone
2018 Base – 2012 Base
October
4.00 3.00 2.00 1.00 -0.00 -1.00 -2.00 -3.00 -4.00
ppb
90
1
1
144
October 1,2012 0:00:00
Min= -4.48 at (120,66), Max= 4.73 at (93,59)
Difference in Monthly Maximum 8-Hour Ozone
2018 Base – 2012 Base
November
4.00 3.00 2.00 1.00 -0.00 -1.00 -2.00 -3.00 -4.00
ppb
90
1
1
144
November 1,2012 0:00:00
Min= -4.01 at (132,27), Max= 4.84 at (84,34)
Difference in Monthly Maximum 8-Hour Ozone
2018 Base – 2012 Base
December
4.00 3.00 2.00 1.00 -0.00 -1.00 -2.00 -3.00 -4.00
ppb
90
1
1
144
December 1,2012 0:00:00
Min= -3.94 at (132,26), Max= 5.46 at (84,33)