Implementation of RCP anthropogenic emission inventories in the GEOS-Chem model

Christopher Holmes
University of California, Irvine
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1. Introduction

The Representative Concentration Pathways (RCP) are emission and climate scenarios developed by IPCC for its 5th Assessment Report (AR5). RCP inventories include a historical reconstruction of 1850-2000 anthropogenic emissions and 4 future scenarios spanning 2000-2100. The RCPs are designed to replace the SRES scenarios (e.g. A1B, B2) and have already been widely adopted by global climate models and chemistry-climate models. Unlike SRES, the RCPs include scenarios with climate mitigation policies. Implementing the RCP emissions in GEOS-Chem thus expands the range of composition and air quality scenarios that can be simulated and enables comparisons with other models. Holmes et al. (2012) describe the first use of RCP emissions in GEOS-Chem. This document provides a more complete description of how the inventory is implemented in GEOS-Chem.

2. Description of the RCP emission inventory

2.1 Overview

The RCPs specify emissions of anthropogenic ozone and aerosols precursors (NOx, CO, CH_4, VOCs, BC, OC, NH_3, SO_2), as well as the long-lived greenhouse gases. These include emissions from fossil fuel and biofuel combustion and agricultural land use (e.g. fertilizer NOx and NH_3). Biomass burning emissions of the same species are also included in the RCPs, but these are currently not implemented in GEOS-Chem because they are based on the GFED2 climatology, which is already available in GEOS-Chem. Each RCP scenario is named for the anthropogenic radiative forcing it produces in 2100, in W m^{-2}. They are RCP 2.6 (also called RCP 3PD), RCP 4.5, RCP 6.0, and RCP 8.5. All historical and future RCP scenarios are now available in GEOS-Chem and can be selected through the input.geos menu.

GEOS-Chem has previously used a combination of global (GEIA, EDGAR, RETRO) and regional (EPA/NEI, EMEP, STREETS, among others) anthropogenic emission inventories. For the RCPs, historical emissions (through 2000) are based on many of the same inventories (especially EDGAR-HYDE and RETRO) and use a similar approach of overwriting the global inventory where a better regional one is available. Therefore, the RCPs should improve upon the base global inventories for some species, especially around 2000, which is the last inventory year before the 4 future projections begin.

For more information about how the inventories were constructed, see the following resources. Lamarque et al. (2010) describe how prior inventories were combined to create the RCP present-day (year 2000) and historical inventory. Van Vuuren et al. (2011a,b) provide an overview of the RCP projections. Individual RCPs and their underlying Integrated Assessment Models (IAMs) are documented in the following papers: RCP 2.6 (van Vuuren et al. 2007), RCP 4.5 (Smith and Wigley, 2006; Wise et al., 2009), RCP 6.0 (Fujino et al., 2006), and RCP 8.5 (Riahi et al., 2007). The IIASA website (http://www.iiasa.ac.at/web-apps/tnt/RcpDb) lists contact persons for each scenario and suggests papers that should be cited when using RCP data.

2.2 RCP inventory file contents

RCP data are provided as global maps in netCDF format at 0.5° × 0.5° resolution for 11 emission activities: surface transport, shipping, aviation, energy production and distribution, industrial combustion, residential and commercial fuel use, solvent use, waste management and disposal, agriculture, and agricultural waste burning. Two biomass burning types (grass fires and forest fires) are also available but

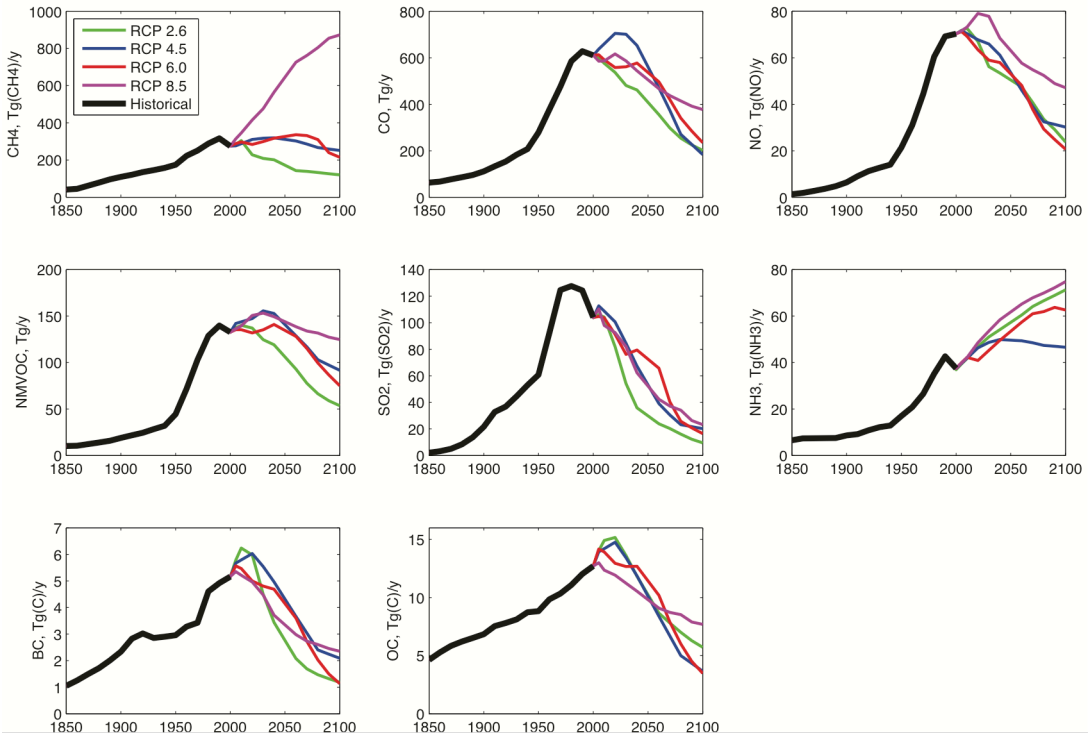


Figure 1. Anthropogenic emissions of air pollutants and their precursors in the 4 RCPs.

not used here. Emission snapshots are provided for every 10th year from 1850 to 2100, plus 2005. For years 2005 and after, there are 4 RCP scenarios for each snapshot. Each snapshot contains 12 monthly emission maps, but only shipping, aviation and biomass burning activities change monthly. Emission altitudes are given only for aviation.

Figure 1 shows the evolution of important air-quality species in the RCP inventory. Most species of interest for atmospheric chemistry are explicitly given in the inventory files: NOx, CO, CH_4, SO_2, BC, OC, NH_3, and over 20 VOC species.

All data are available in netCDF format from IIASA: http://www.iiasa.ac.at/web-apps/tnt/RcpDb

2.2 Implementation in GEOS-Chem

The RCP and RETRO inventories use similar construction methods, VOC species definitions, and netCDF file structure, so they are implemented similarly. The RCP emission files are regridded to both 2°×2.5° and 4°×5° resolution for use in GEOS-Chem. In addition, the emission activities are lumped into 4 sectors: road transport, non-road, shipping, and aviation. VOC species in the RCP inventory are mapped to GEOS-Chem species similarly to the RETRO implementation. See Table 1.

GEOS-Chem users can enable the global RCP emission inventory with switches in the input.geos file, similar to EDGAR and RETRO. The user must also specify the emission year (e.g. 2000, 2005, 2010, etc.) in input.geos. The simulation currently does not interpolate between the available decadal emission snapshots.

Since the RCP inventory includes biofuel emissions and fertilizer NOx, the other inventories that would be used for these processes in GEOS-Chem are automatically turned off when using RCP emissions.

Table 1. Mapping RCP species onto GEOS-Chem tracers

GEOS-Chem tracer	RCP species	Status[a]	Comments
NOx	NO	Y	
CO	CO	Y	
SO2	SO_2	Y	No RCP data for aviation SO_2.
NH3	NH_3	Y	
BCPO	BC	Y[b]	
OCPO	OC	Y	
C2H6	Ethane	Y	
C3H8	Propane	Y	
ALK4	Butanes	Y	
	Pentanes		
	Hexanes and higher alkanes		
ACET		Y	No RCP data. Assume 25% of "other ketones" is acetone.
MEK	Other ketones	Y	Reduce by 25% to account for acetone, above.
CH2O	Formaldehyde	Y	
ALD2	Other Alkanals	Y	
RCHO		-	No Anthropogenic emissions
PRPE	Propene	Y	
BENZ	Benzene	Y	Likely overestimated
TOLU	Toluene	Y	Likely overestimated
GLYX		-	No RCP data
MGLY		-	No RCP data
C2H4	Ethene	Y	
C2H2	Ethyne	Y	
HCOOH	Acids	Y	Assume HCOOH accounts for 25% of aggregated acids, based on RETRO implementation

[a] Status of implementation in GEOS-Chem as of January 2013. Code: Y = yes, implemented for all anthropogenic sources (surface, ship, and aviation); N = no, one or more anthropogenic emission types are not implemented. The RCP biomass burning emission inventories are not implemented for any tracers.

[b] The RCP inventory includes BC emissions from aircraft. These are not used, since past versions of GEOS-Chem have not included this source.

Warning for users of regional inventories! The CAC, BRAVO, CAC and pre-2006 STREETS regional inventories do not include biofuel emissions, only fossil fuel emissions. The RCP inventory does not distinguish emissions from biofuel and fossil fuel. Emissions from both are combined in the RCP input files and in the ND36 (ANTHSRCE) diagnostic. When using the RCP global inventory, the default biofuel inventory (Yevich and Logan, 2003) is set to zero everywhere globally. When any of the regional inventories without biofuels overwrite the RCP global inventory, then biofuels within the region are NOT included in GEOS-Chem because the biofuel inventory has been zeroed. All species are affected. The same problem affects GEOS-Chem simulations with the RETRO global inventory for VOCs because RETRO also lumps biofuel and fossil fuel emissions and both are implemented similarly in GEOS-Chem.

2.3 Inconvenient Truths

All RCPs assume aggressive worldwide policy actions to curb ozone and PM. In 3 scenarios, NOx emissions peak decline after 2010, while in RCP 8.5 the reductions begin after 2020 (Figure 1). Other ozone and aerosol precursors decline similarly. From an air quality standpoint, none of these scenarios reflect a conventional "business as usual" scenario in which primary air pollutants continue to increase as economies expand in the developing world.

Each RCP is derived from a separate IAM. Therefore differences between RCPs should not be interpreted simply as a policy choice; the differences also reflect economic modeling assumptions.

3. Comparison to existing GEOS-Chem emission inventories

3.1 Comparison to global inventories (EDGAR and RETRO)

To compare RCPs to the existing inventories, we run simulations with the following conditions:

- Version 9-01-02n dicarbonyl simulation, with bug fixes for ship NOx emissions, ship CO emissions, and double-counting of residential biofuels.
- GEOS-5, 2°×2.5°, Jan 1, 2005 to Jan 1, 2006
- Anthropogenic emissions and aerosols enabled
- EDGAR and RETRO vs. RCP 6.0 for 2005
- All regional inventories disabled
- Anthropogenic and Biofuel diagnostics for the following 15 species: NOx, CO, C2H6, C3H8, ALK4, CH2O, ALD2, C2H4, PRPE, ACET, MEK, C2H2, BENZ, TOLU, XYLE, SO2, BC, OC, NH3, plus ship diagnostics for SO2

Figure 2 shows the emissions and their differences. Anthropogenic and biofuel emission diagnostics are summed in all figures. RCP emissions are 28% larger for CO and 30% smaller for SO_2, compared to EDGAR, but this likely reflects errors in the EDGAR inventory, since the GEOS-Chem emissions with regional inventories is similar to the RCPs for CO and SO_2 (see below). Differences of 50% in global total emissions occur for many VOCs, but emissions of most of these species have similarly large uncertainties.

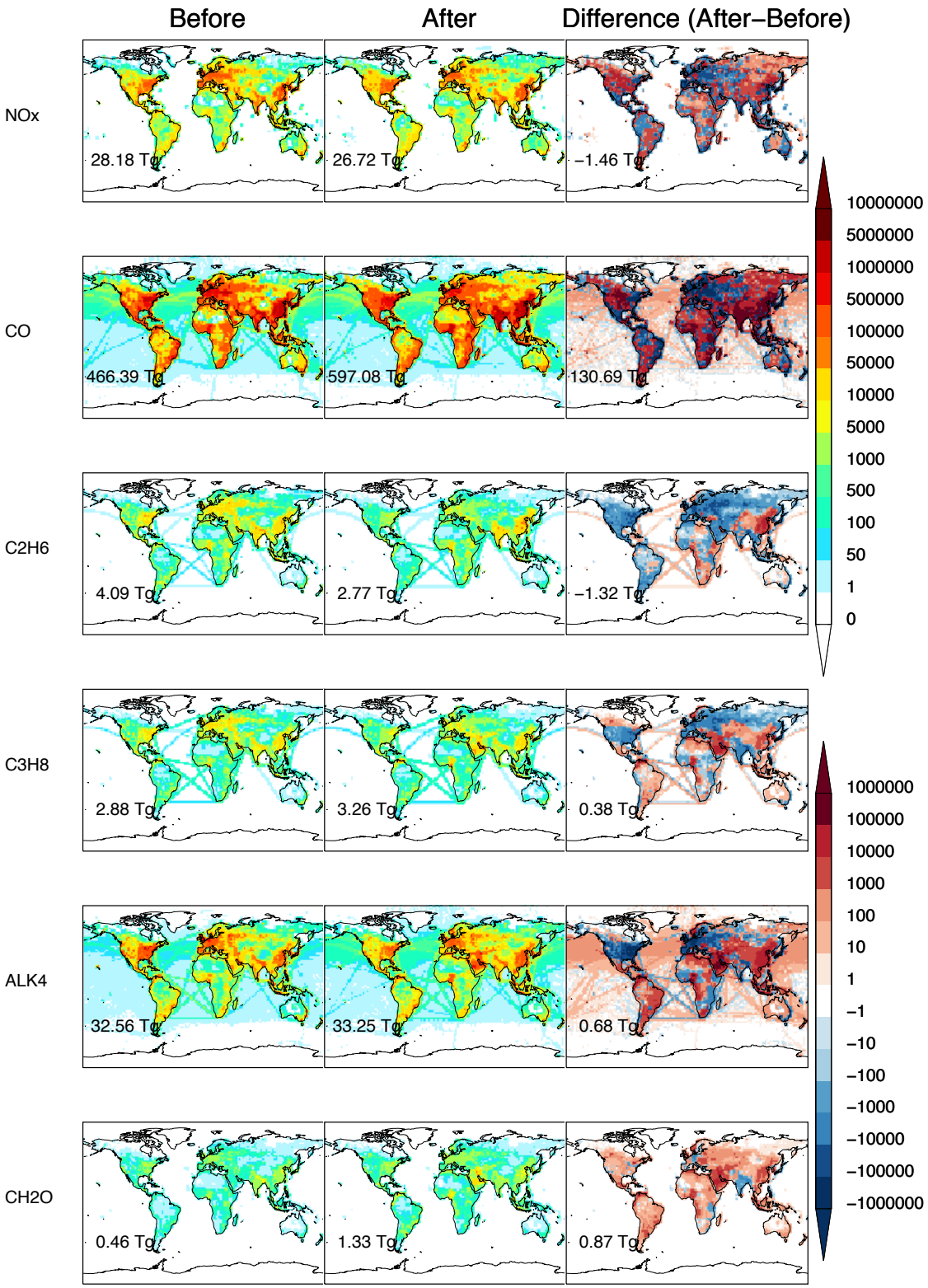
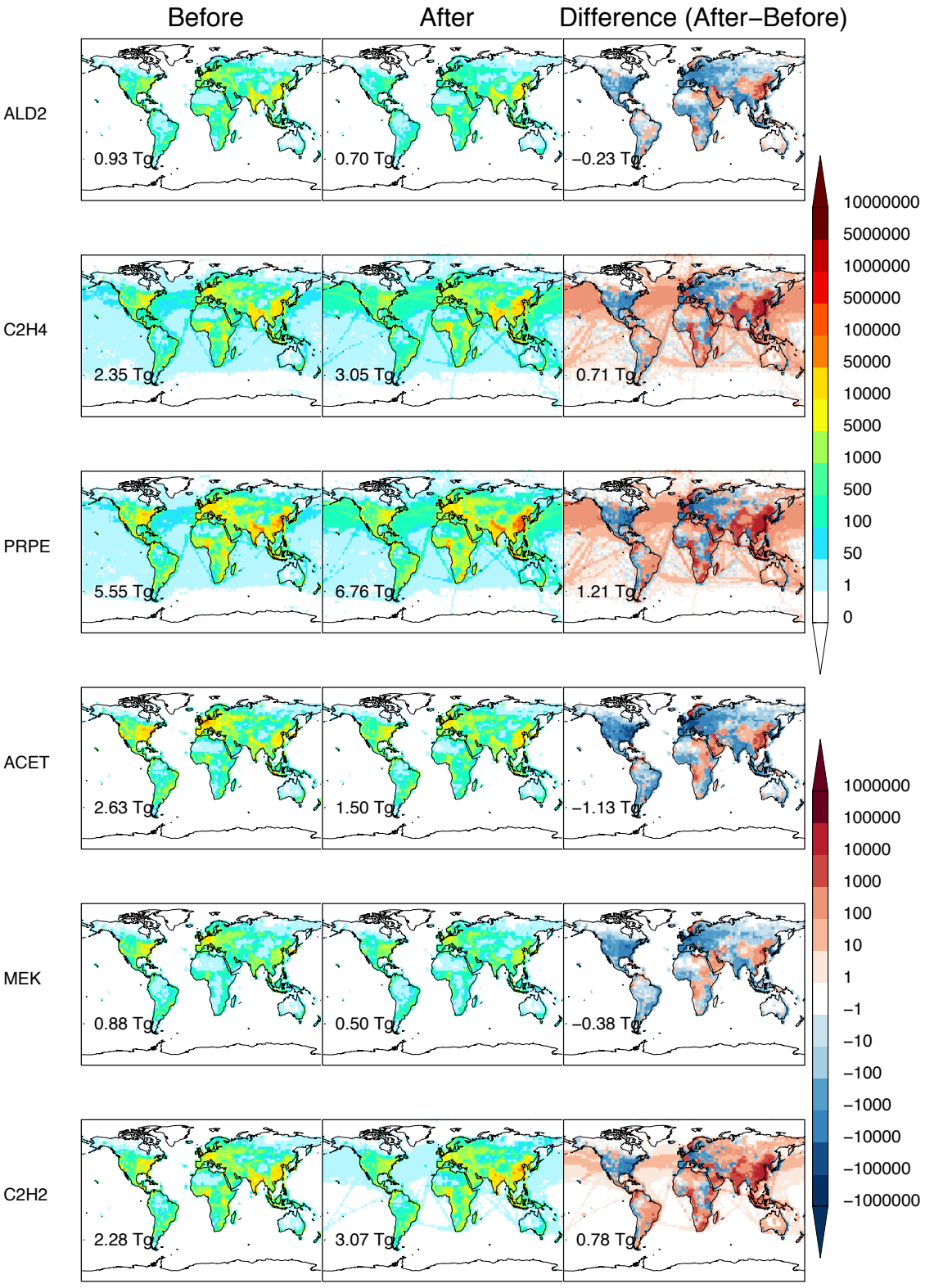


Figure 2. Anthropogenic emissions (fossil fuel and biofuel) for 2005 in EDGAR and RETRO (Before) vs. RCP 6.0 inventory (After). Units are 10^6 molecules cm^{-2} s^{-1} for NOx, CO, SO_2, and NH_3 and 10^6 atoms C cm^{-2} s^{-1} for other species.



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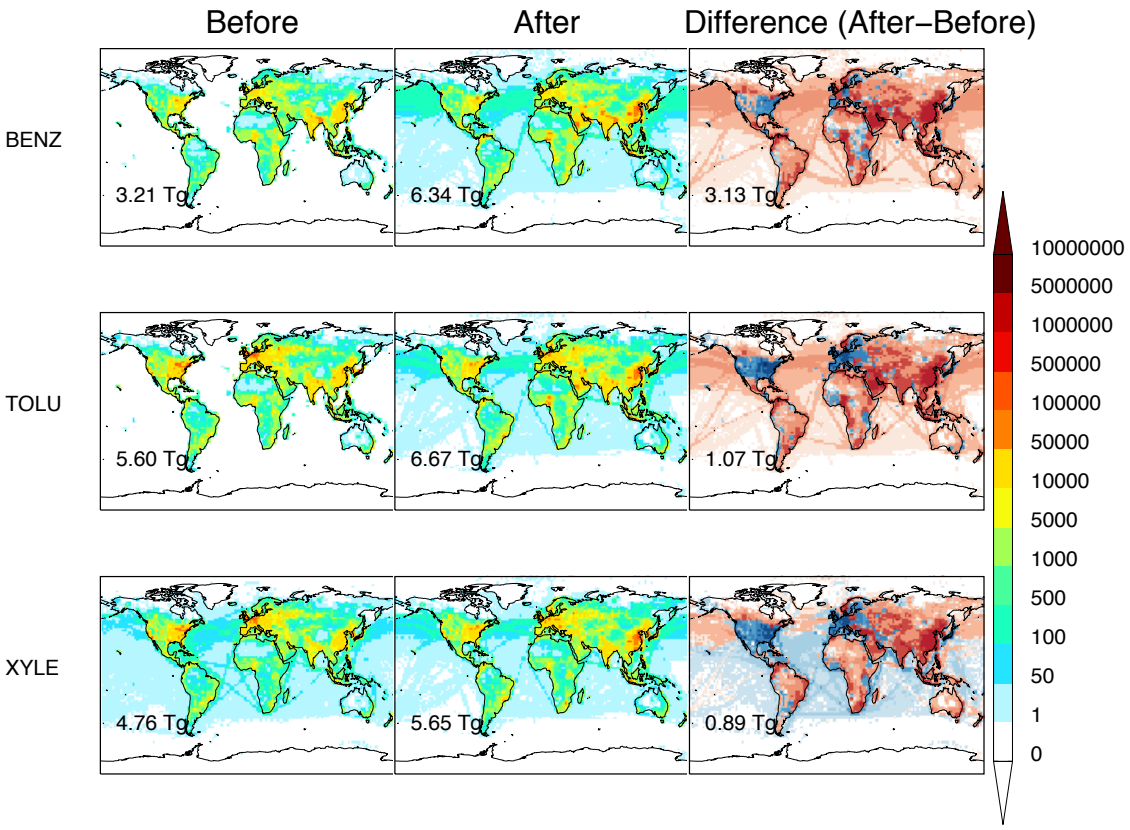

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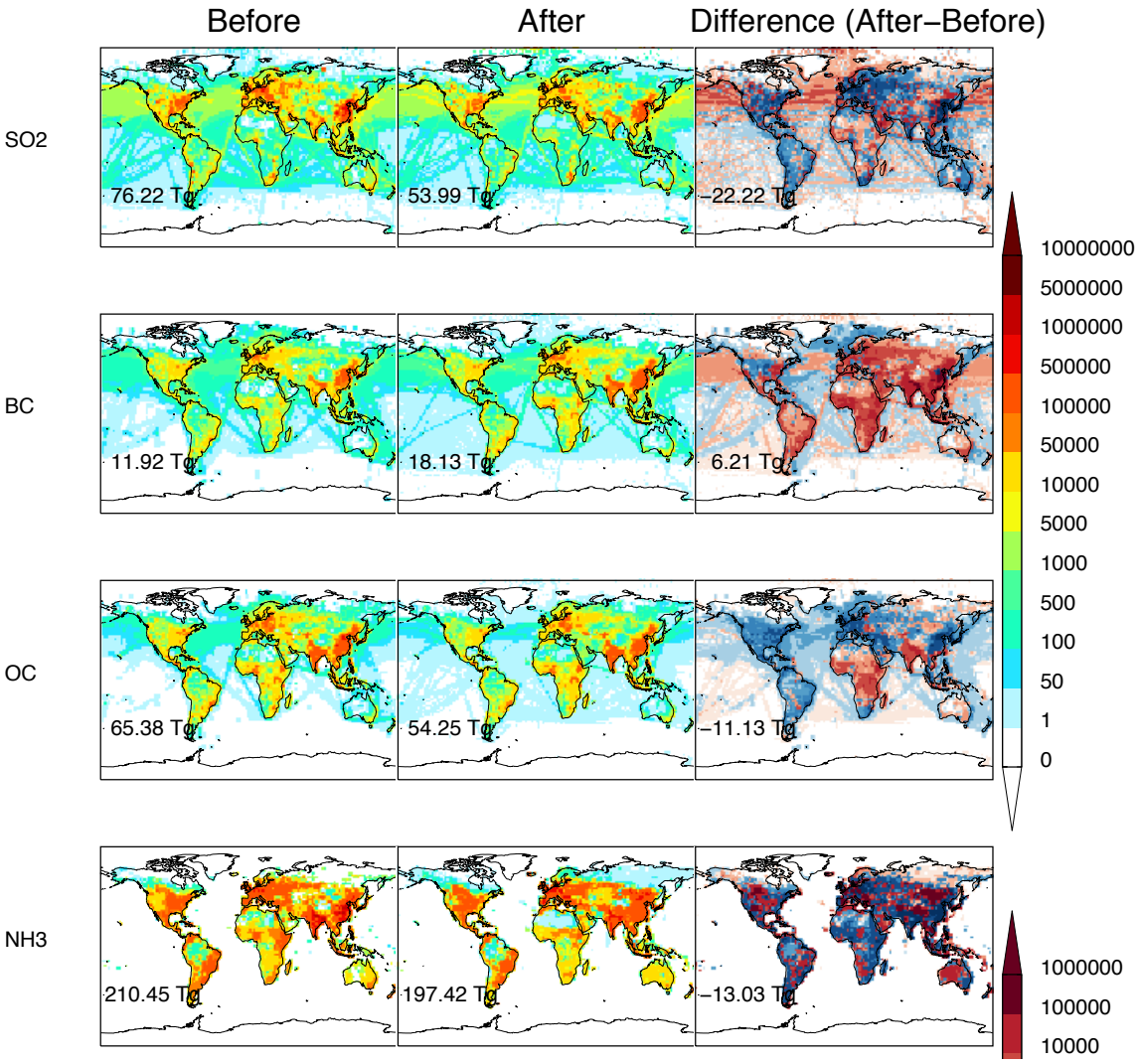

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3.2 Comparison to regional inventories

We also compare the RCP inventory to GEOS-Chem with regional inventories. The simulated conditions are:

- Version 9-01-02n dicarbonyl simulation, with bug fixes for ship NOx emissions, ship CO emissions, and double-counting of residential biofuels.
- GEOS-5, 2°×2.5°, Jan 1, 2005 to Jan 1, 2006
- Anthropogenic emissions and aerosols enabled
- EDGAR and RETRO vs. RCP 6.0 for 2005
- Regional inventories enabled only with EDGAR and RETRO: EPA/NEI 2005, CAC, BRAVO, EMEP, STREETS (Regional inventories are disabled in the RCP simulation.)
- Anthropogenic and Biofuel diagnostics for the following 15 species: NOx, CO, C2H6, C3H8, ALK4, CH2O, ALD2, C2H4, PRPE, ACET, MEK, C2H2, BENZ, TOLU, XYLE, SO2, BC, OC, NH3, plus ship diagnostics for SO2

Figure 3 compares the emissions. Anthropogenic and biofuel emission diagnostics are summed in all figures. While some large differences persist for VOCs, the RCP emissions are generally much closer to the regional inventories than to the EDGAR and RETRO global inventories. For CO and SO_2, the differences are only 3% and 1%, respectively. The modest changes in global totals, however, mask a large shift in

distributions for many species. Over ship tracks there are large increases in CO, SO2, and many VOCs, especially ALK4, C2H4, PRPE, BENZ and TOLU. Emissions of many VOCs decrease over the United States and Europe in the RCP inventory. Large changes occur over India, China, South Africa and elsewhere, but the direction of change varies by species (e.g. increases for C2H6 and decreases for C3H8).

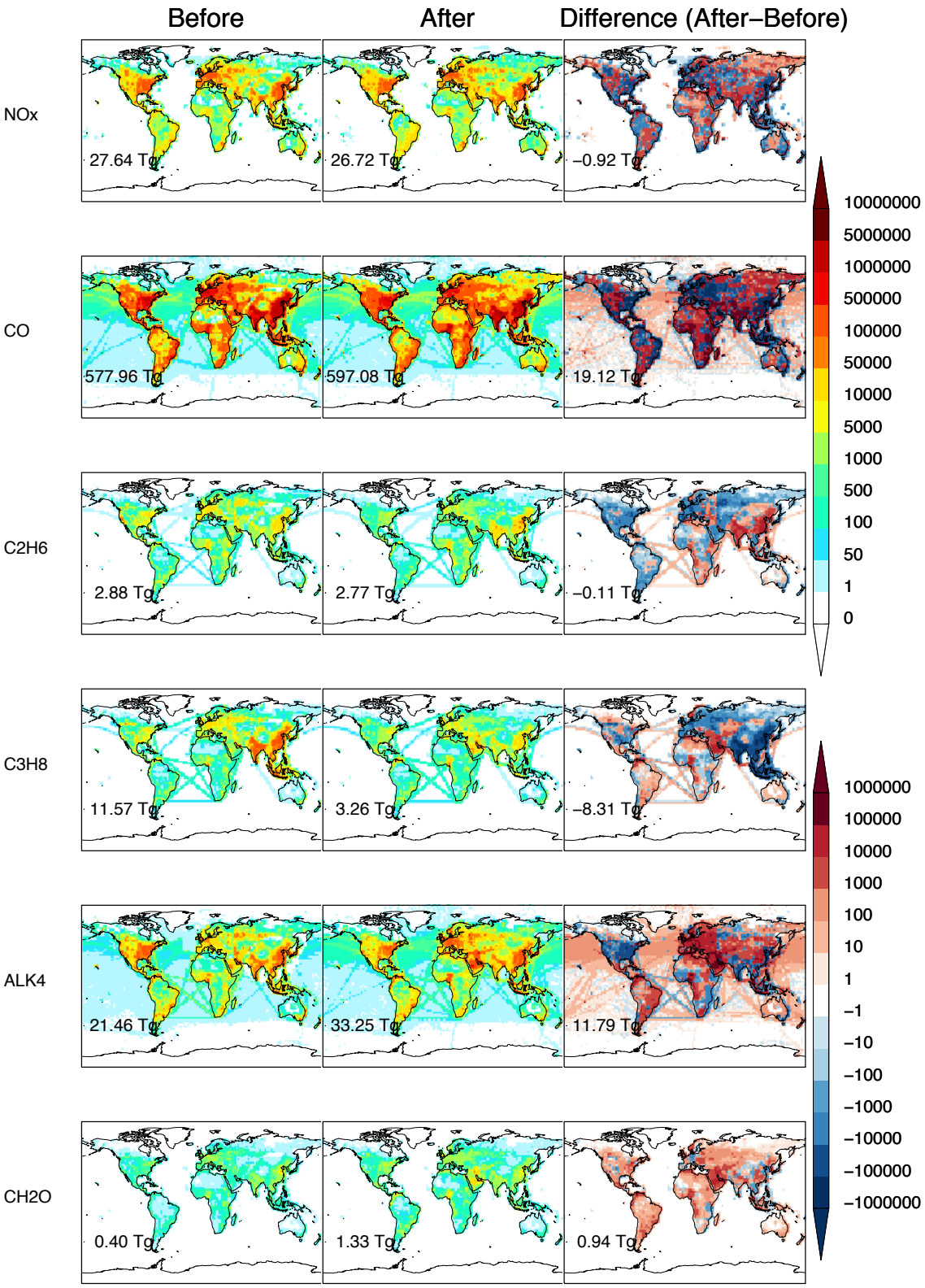
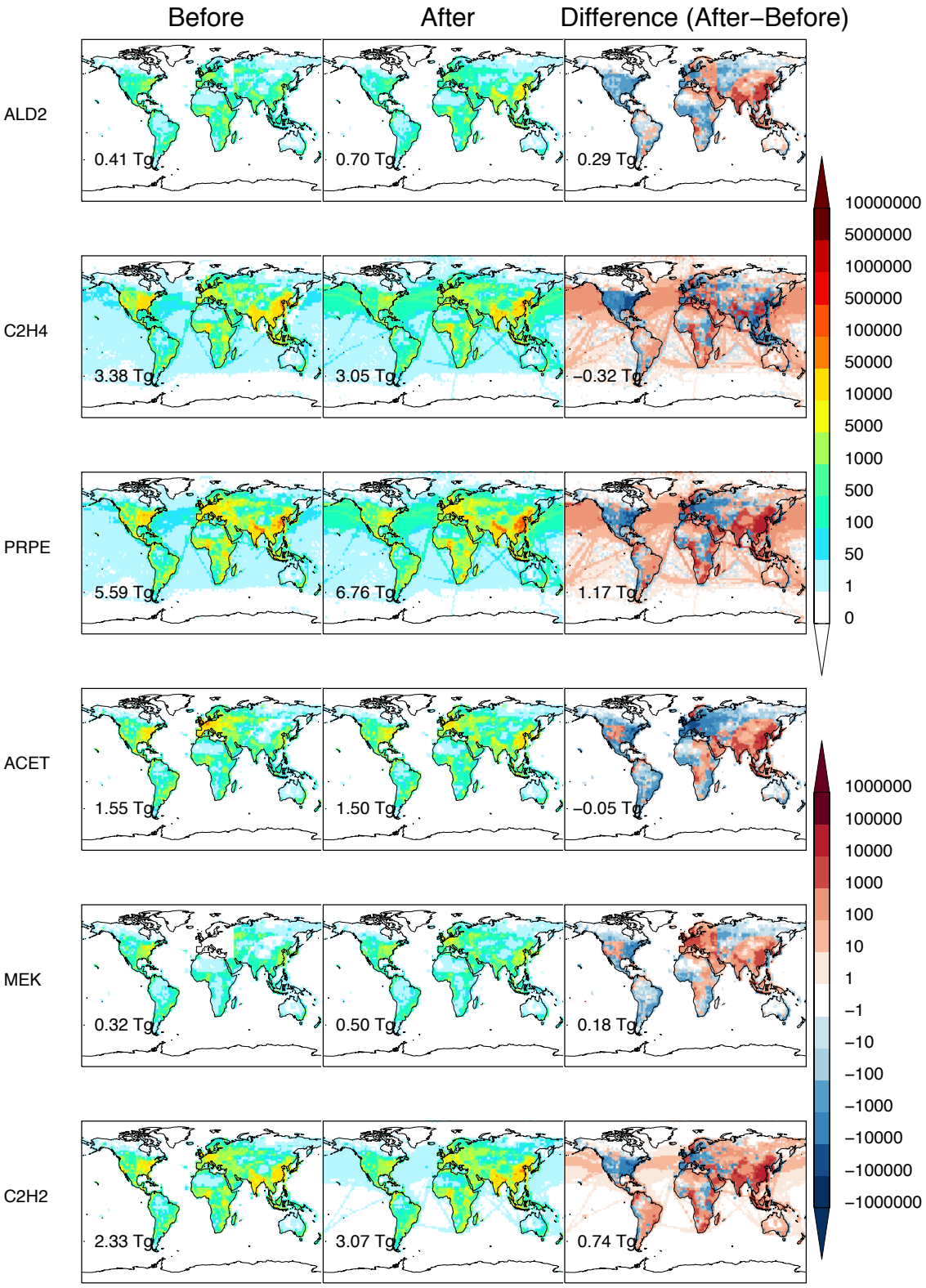


Figure 3. Anthropogenic emissions (fossil fuel and biofuel) for 2005 in EDGAR and RETRO plus regional inventories (Before) vs. RCP 6.0 inventory (After). Units are 10^6 molecules cm^{-2} s^{-1} for NOx, CO, SO_2, and NH_3 and 10^6 atoms C cm^{-2} s^{-1} for other species.



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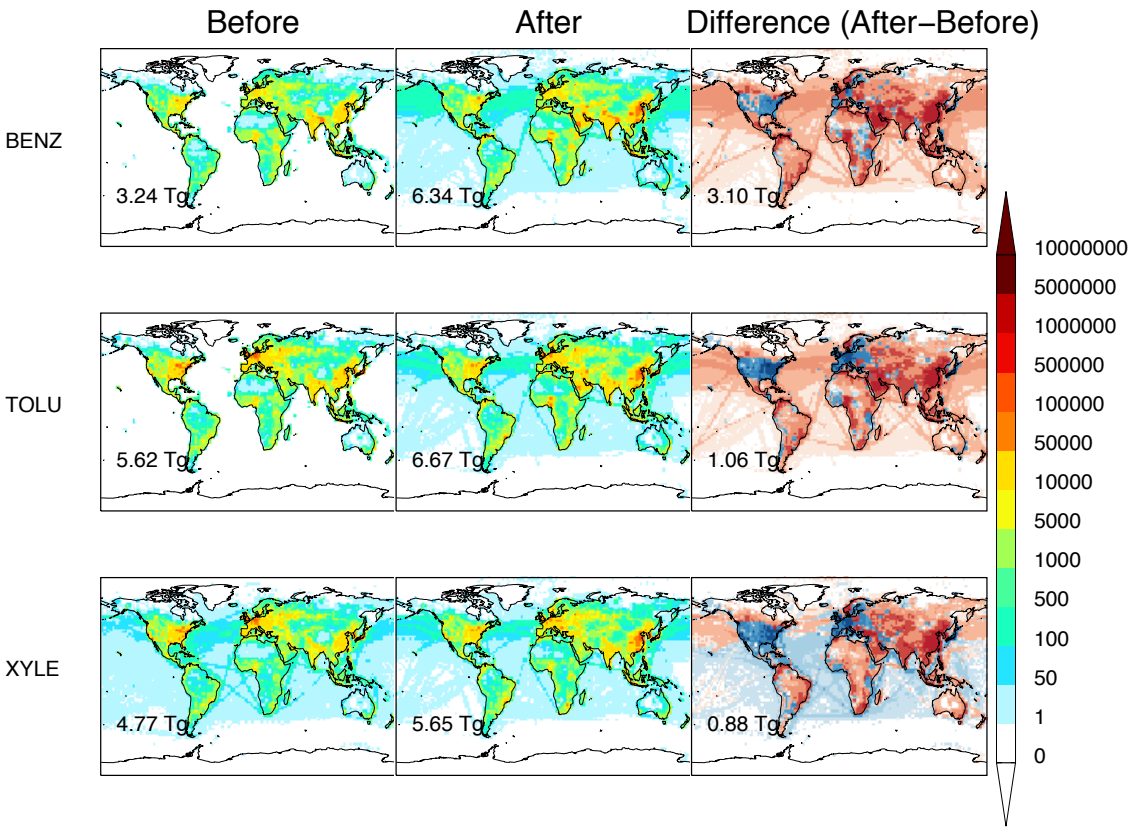

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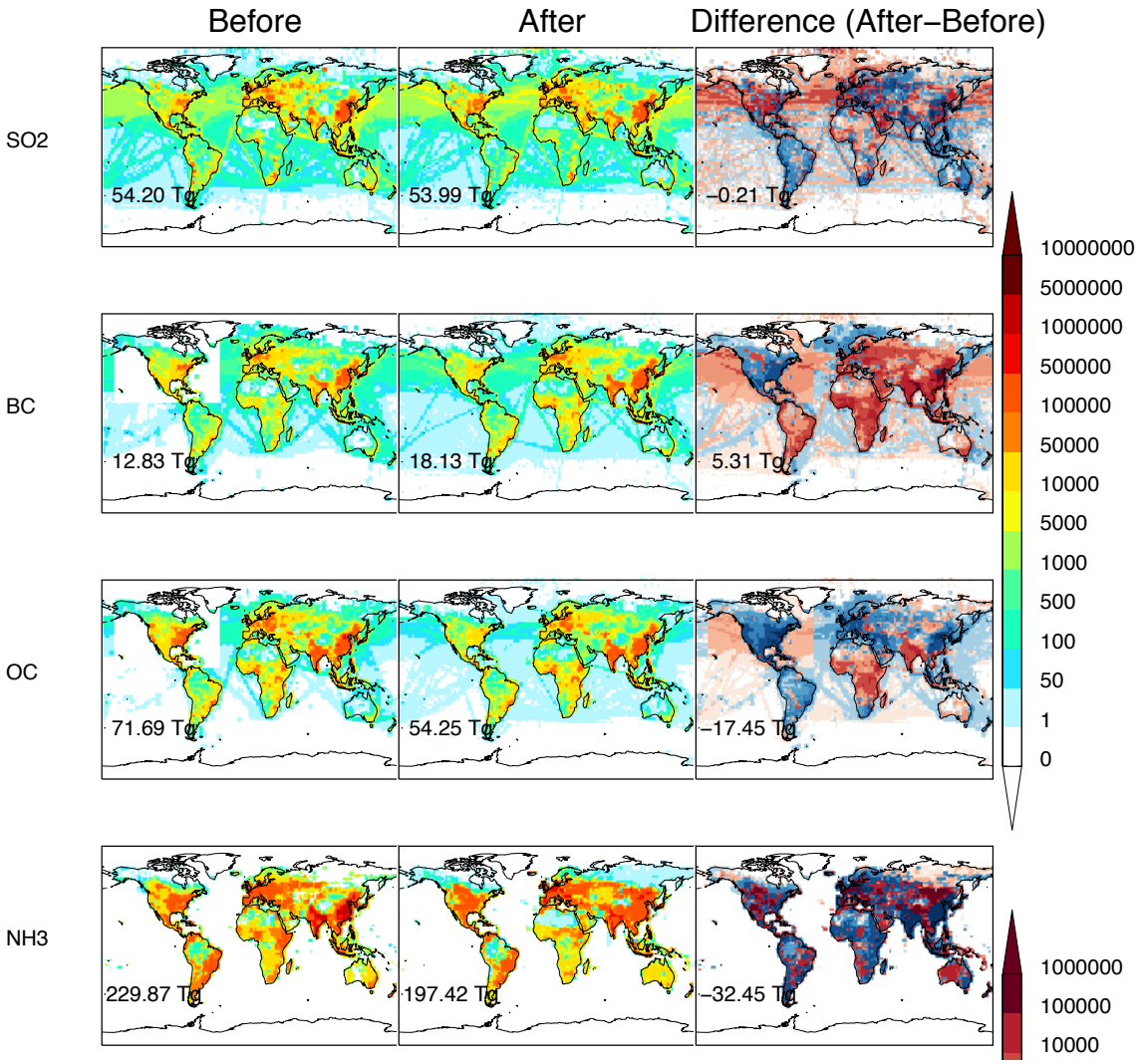

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3.3 Comparison of chemical impacts

We compare the chemical impact of RCP emissions against GEOS-Chem using regional inventories. Simulations are as described in Section 3.2. Figures 4-6 show the change in monthly mean concentrations of CO, O_3 and OH for selected months.

For CO, concentrations generally decrease in the northern hemisphere—especially the industrial areas of North America, Europe, and China—and increase in the southern hemisphere (Figure 4). The largest increases occur over India and Africa, consistent with the CO emission changes.

O_3 changes very little over continental regions (< 5 ppb), but there are increases of up to 15 ppb over the oceans (Figure 5). This increase is caused by major increases in CO and VOC precursors along ship tracks, as described above.

Global-mean OH changes are small at the surface ($< 0.2 \times 10^5$ molecule cm^{-3}) in all months, but slightly larger in the RCP simulation (Figure 6). OH is consistently higher over ship tracks in the RCP simulation, with maximum increases of 1×10^6 molecule cm^{-3} during boreal summer. Over land, changes have mixed sign, but are generally negative over industrial areas of East Asia, Europe and North America. The global-mean methane lifetime due to oxidation by tropospheric OH is 10.54 y in the RCP simulation, which is 2.2% larger than in the regional inventory simulation.

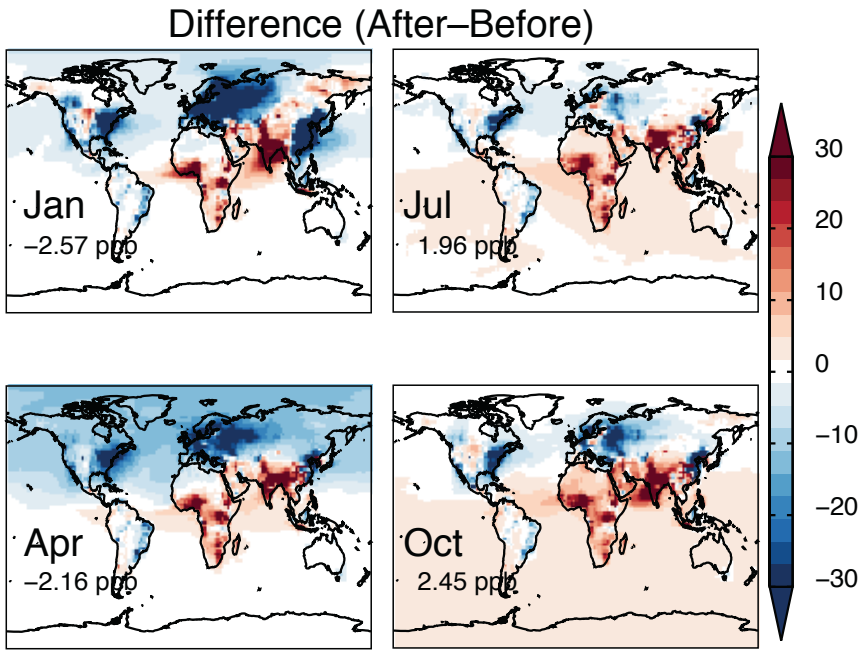

Figure 4. Surface CO changes (ppb) due to emissions for January, April, July and October. Inset numbers give the global mean change in surface layer concentrations. EDGAR and RETRO plus regional inventories (Before) vs. RCP 6.0 inventory (After).

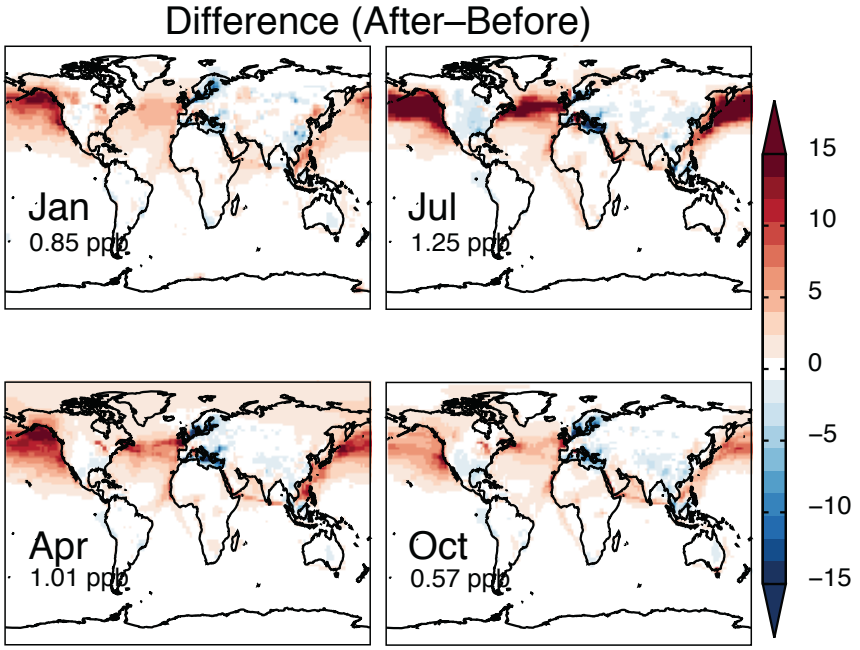

Figure 5. Surface O_3 changes (ppb) due to emissions for January, April, July and October. Inset numbers give the global mean change in surface layer concentrations. EDGAR and RETRO plus regional inventories (Before) vs. RCP 6.0 inventory (After).

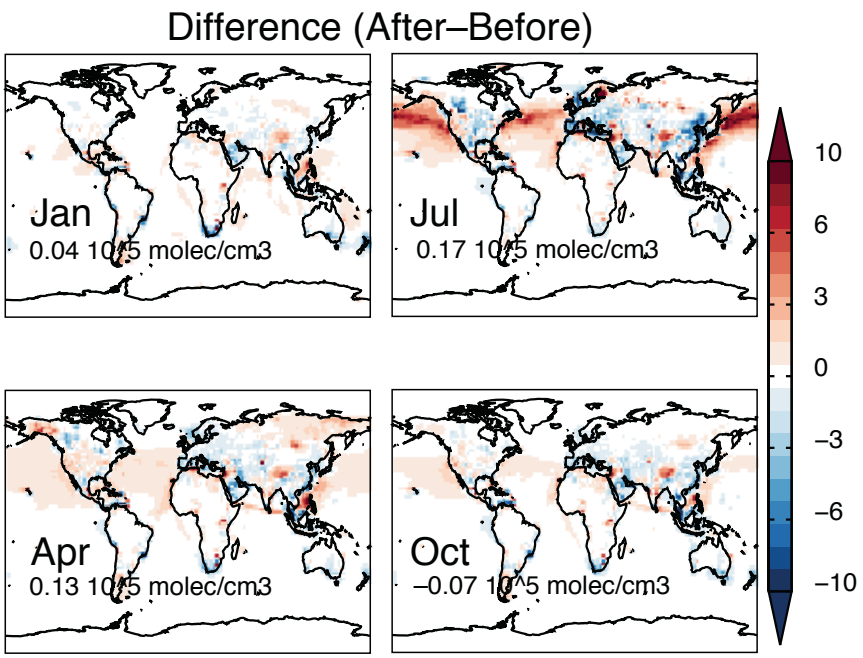

Figure 6. Surface OH changes (10^5 molecule cm^{-3}) due to emissions for January, April, July and October. Inset numbers give the global mean change in surface layer concentrations. EDGAR and RETRO plus regional inventories (Before) vs. RCP 6.0 inventory (After).

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