Quantifying the sensitivity of U.S. ozone concentrations to domestic vs international emissions through coupled GEOS-Chem Adjoint and CMAQ DDM source-receptor modeling

Or:

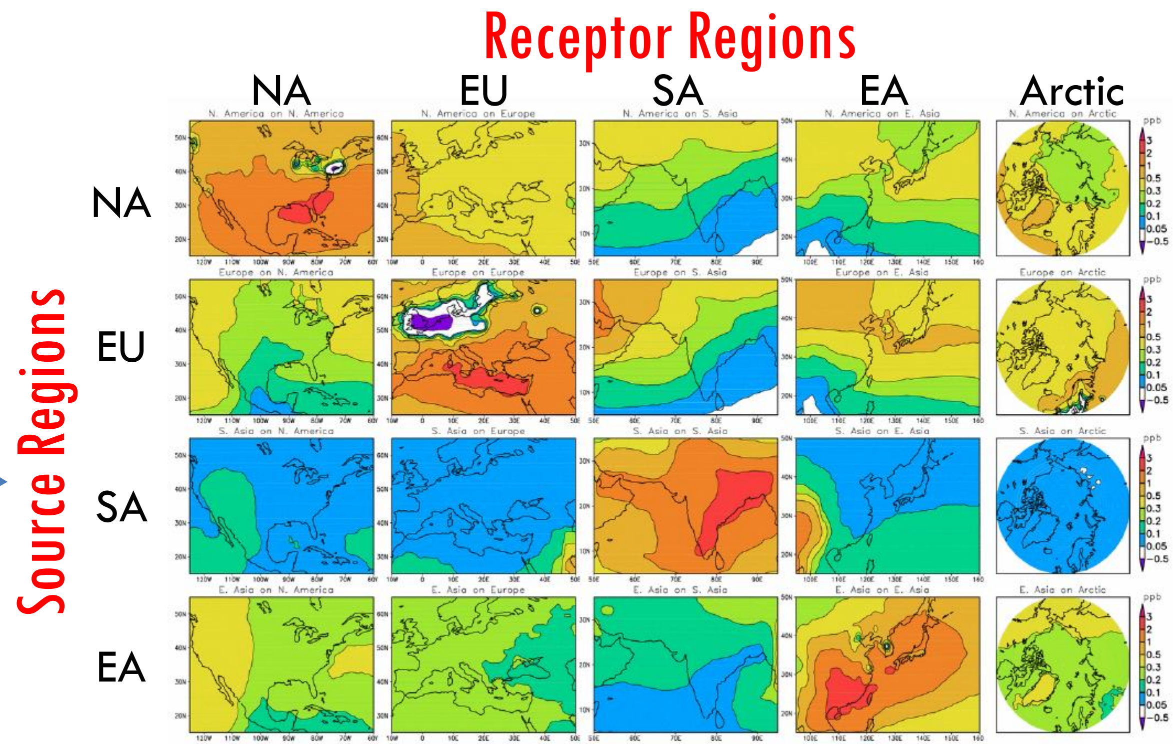
The "Boundary Sensitivity Project"

Farhan Akhtar, Barron Henderson, Sergey Napelenok,
Daven Henze, Susan Anenberg, John Langstaff, Rob Pinder

PAST WORK ON INTERNATIONAL TRANSPORT OF AIR POLLUTION

Emissions are perturbed in large regions by fixed amounts (here, 20%)

Source-receptor relationships are explored



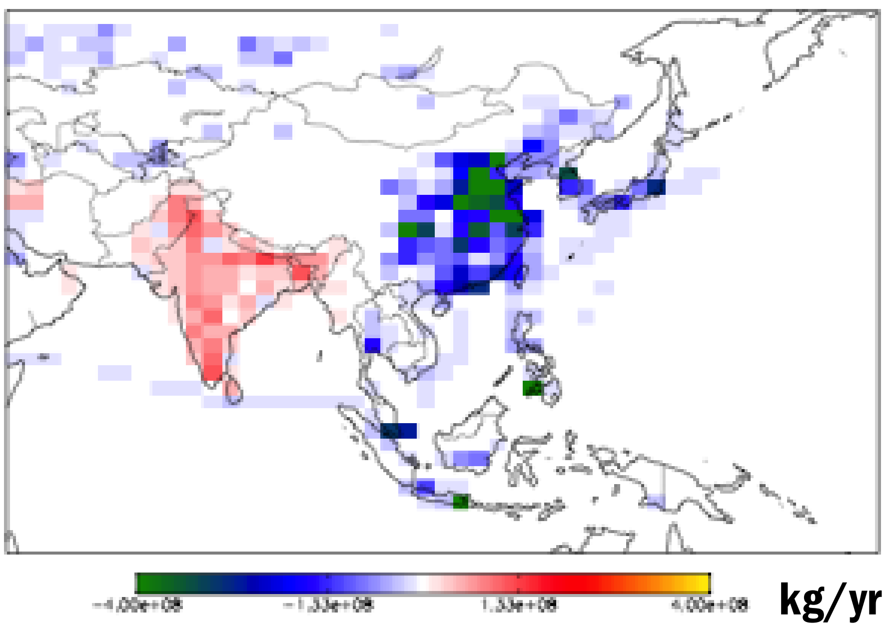
Sources: Fiore et. al. 2009; 2010 HTAP Report (Part A)

FUTURE EMISSION CHANGES DO NOT OCCUR IN LARGE RECTANGLES AT FIXED RATES

Spatial heterogeneity in SO_2 emissions changes …

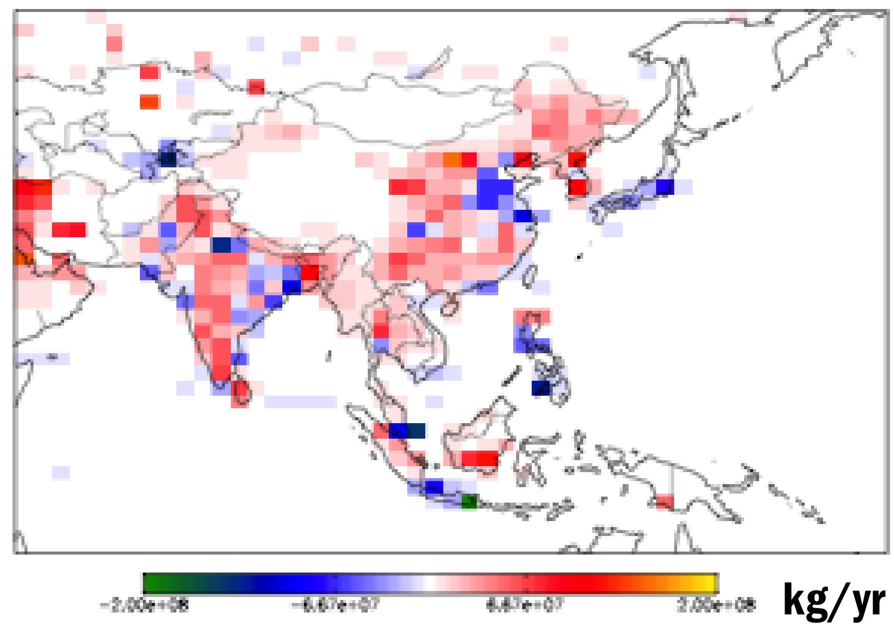
… following a single Representative Concentration Pathway for AR5:

RCP 8.5: 2050 - 2000



… in the difference between two Pathways for AR5:

RCP 8.5 2050 – RCP 4.5 2050



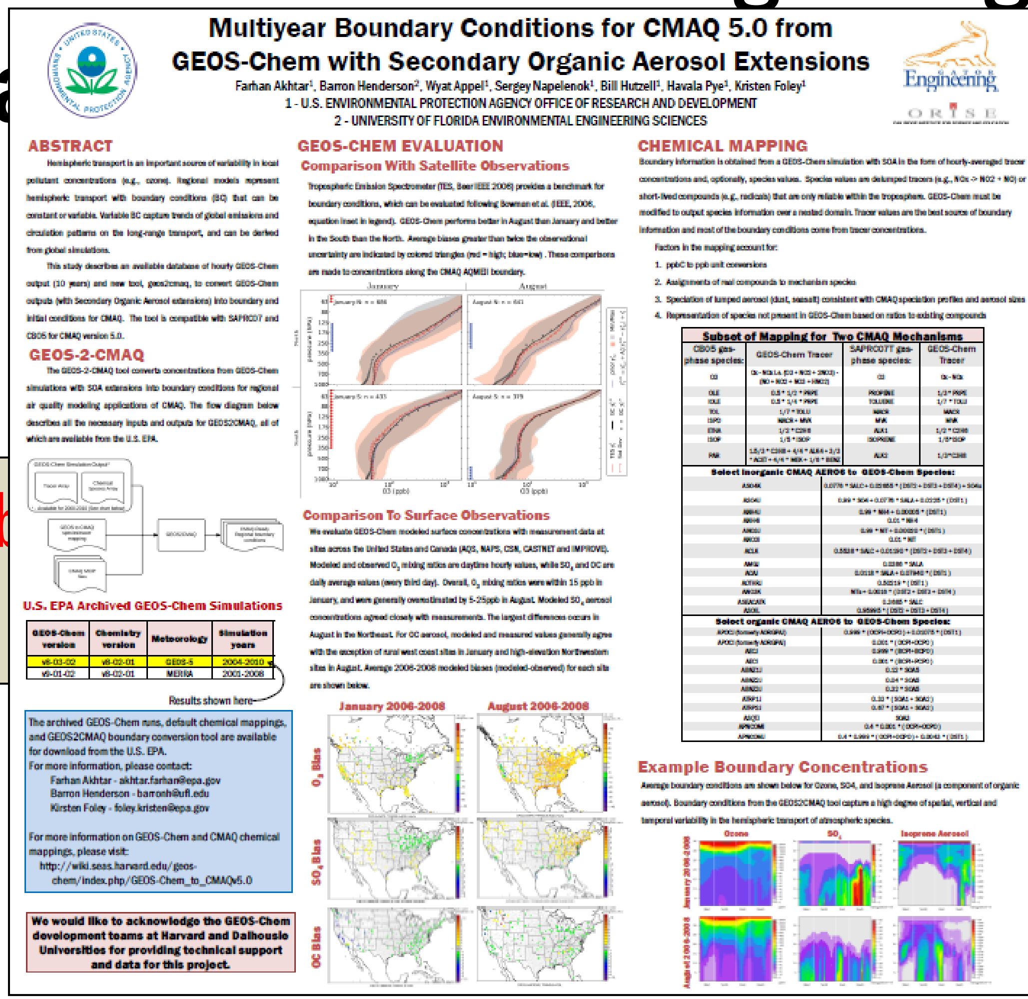
High-resolution sensitivity modeling techniques may be used to evaluate inter-regional variability in emission changes.

How can global and regional high-resolution sensitivity models be linked to provide information regarding the international transport of air pollution?

How can global and regional high-resolution sensitivity models be linked to provide information regarding the international transport of air pollution?

Global and regional modeling are linked through boundary conditions

How can global and regional high-resolution sensitivity models be linked to provide information regarding the interna… …ution?

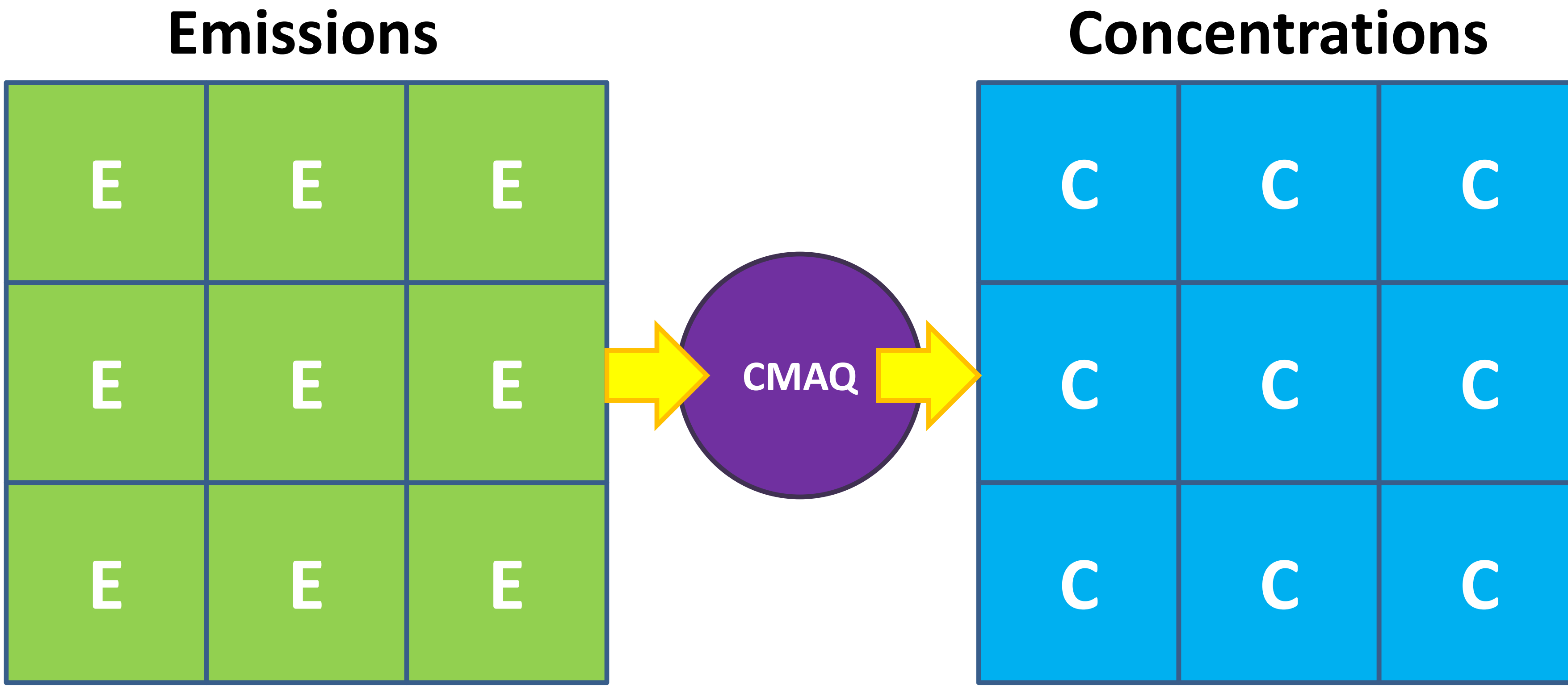


Glob… …ugh

PRESENTATION OUTLINE

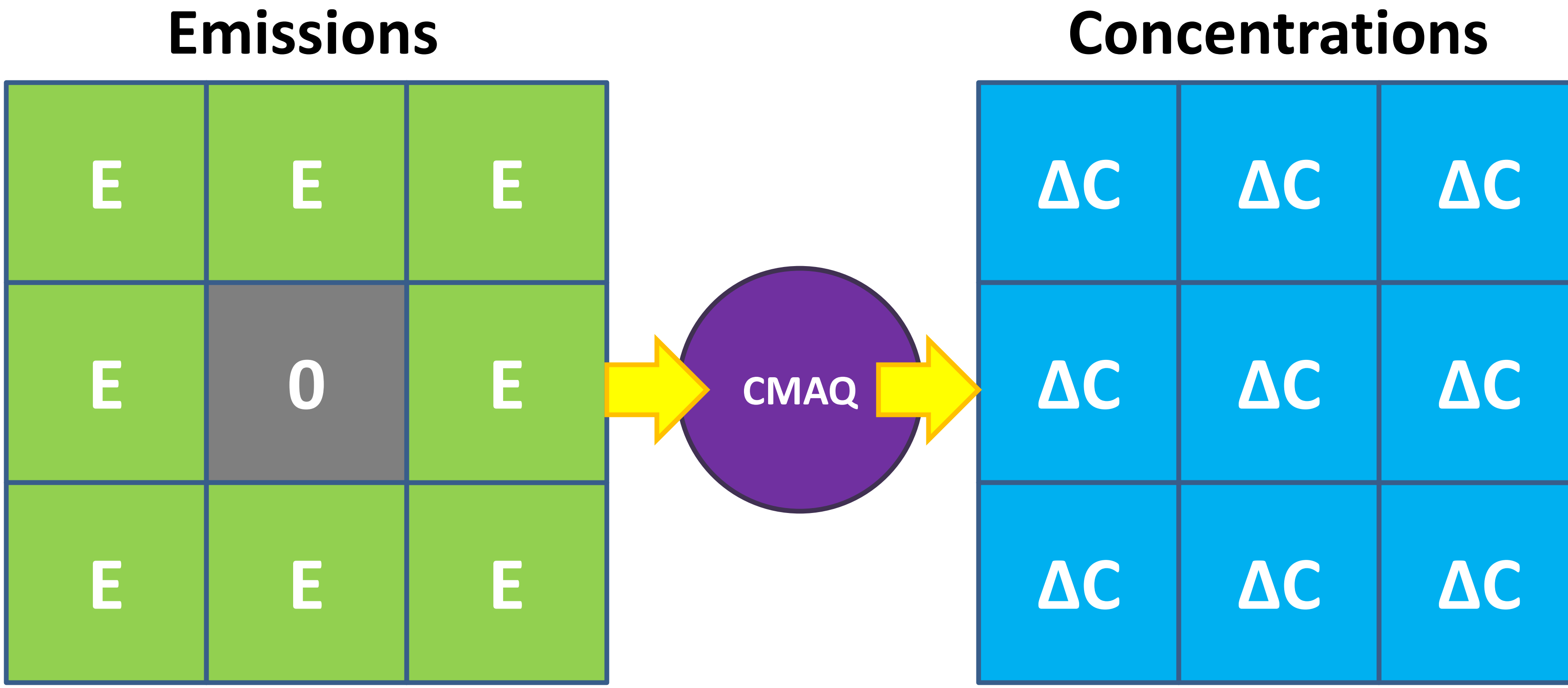
1. Primer on sensitivity modeling techniques
2. How forward and reverse sensitivities describe source-receptor relationships
3. Description of modeling of the April 2008 episode of high international transport
4. Case studies: Denver and New York City
5. Final Thoughts: How do we link global and regional sensitivity models?

CMAQ BASE MODEL



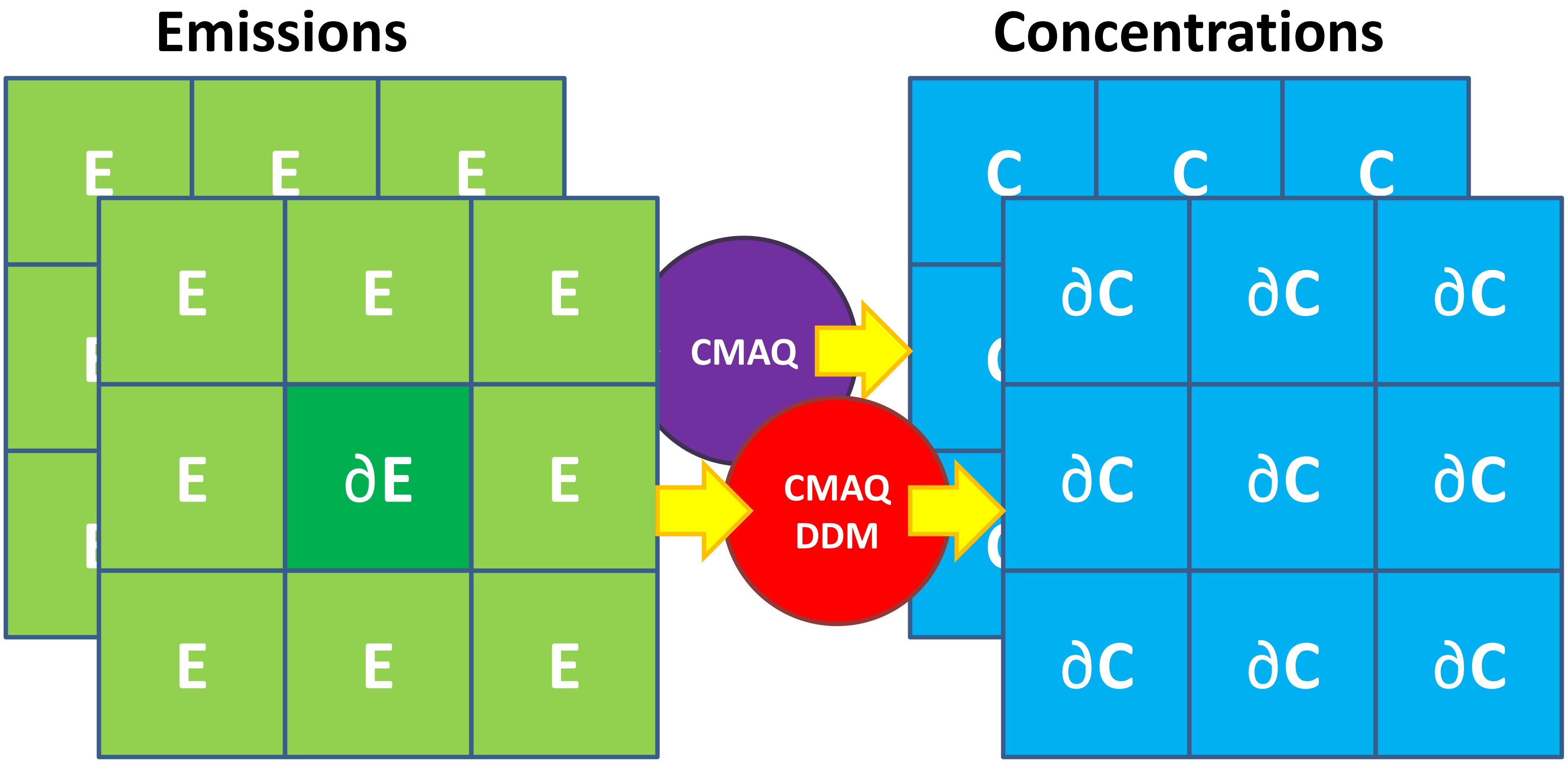
The typical application of CMAQ modeling, gridded ambient concentrations are calculated from gridded emissions using first-principle chemistry and physics.

FINITE DIFFERENCE



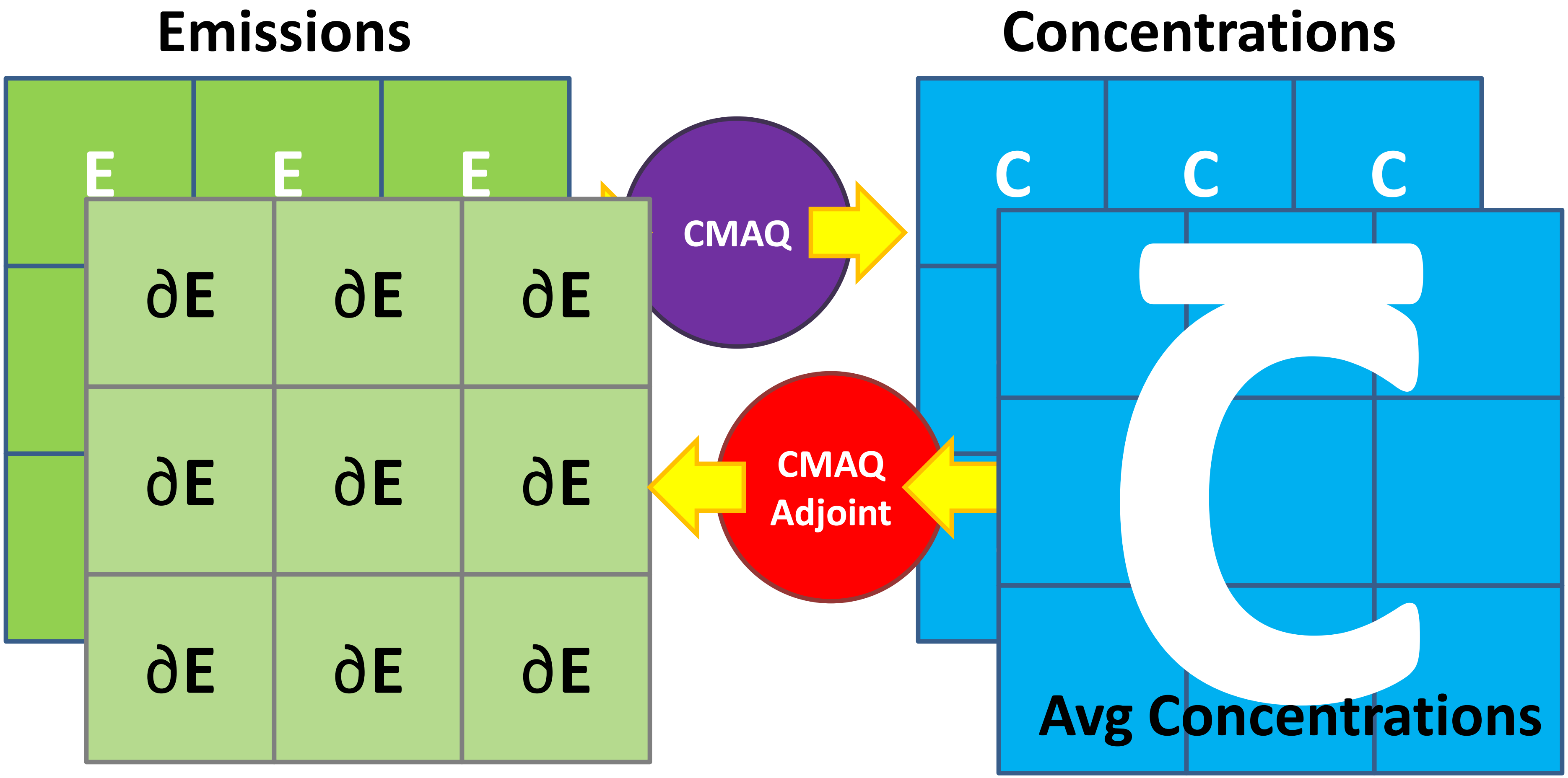
- Ambient concentrations are calculated after removing or perturbing emissions of a specific source.
- No changes are made to the CMAQ model though the alterations in input emissions can lead to significant changes in the chemical regime.

DIRECT, DECOUPLED METHOD



- The CMAQ model is updated to calculate the response in concentrations to a small change in emissions of a single source or group of sources.
- These sensitivities are calculated directly using similar equations as the base CMAQ model.
- The underlying model equations and chemical regime remain unchanged.

ADJOINT MODEL

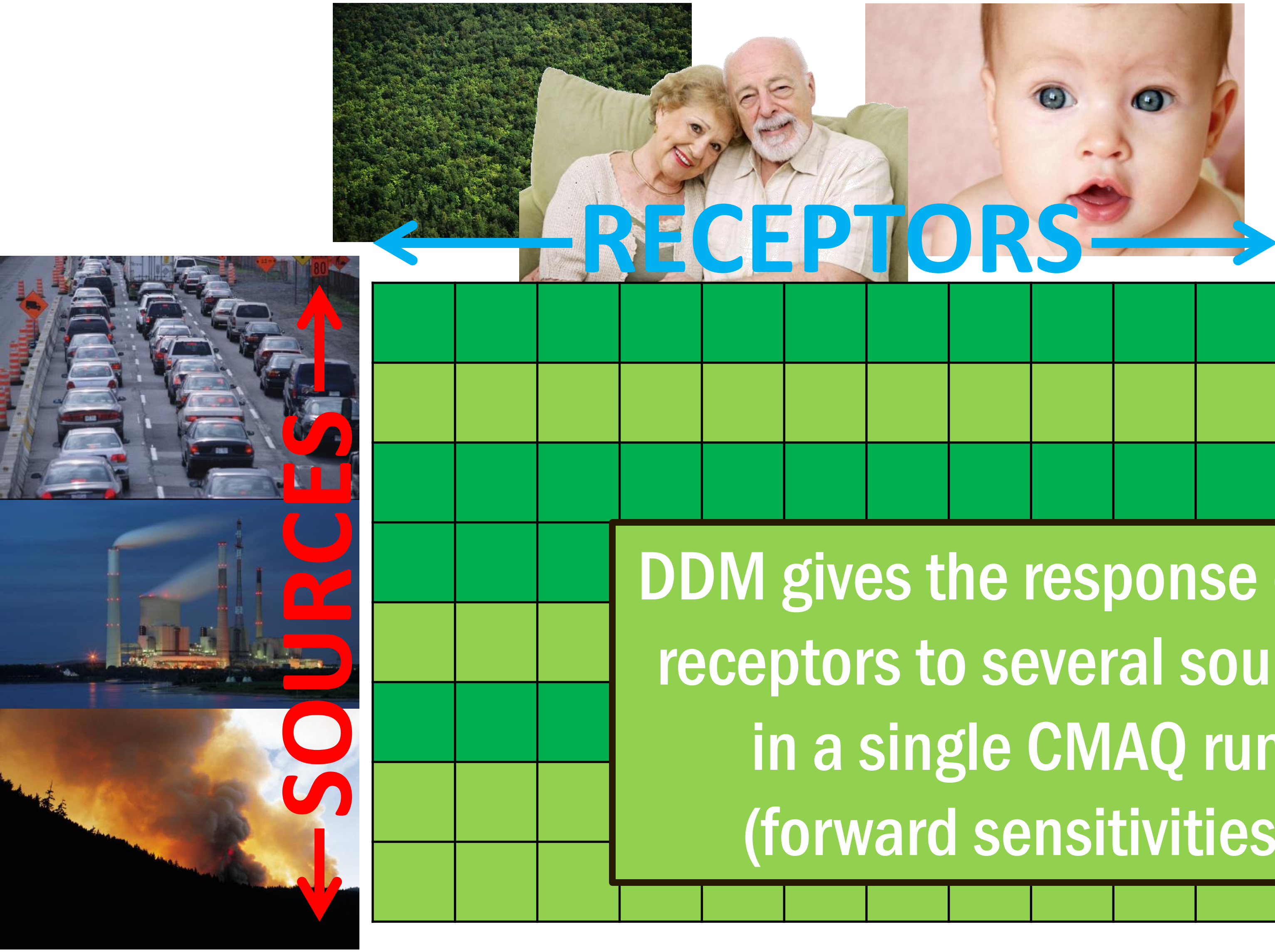


- Evaluates effect of each emission on selected concentration metric.
- Directly determines sensitivities using similar equations as the base CMAQ model.
- Emissions and concentrations remain entirely unchanged.

RESPONSE SURFACES

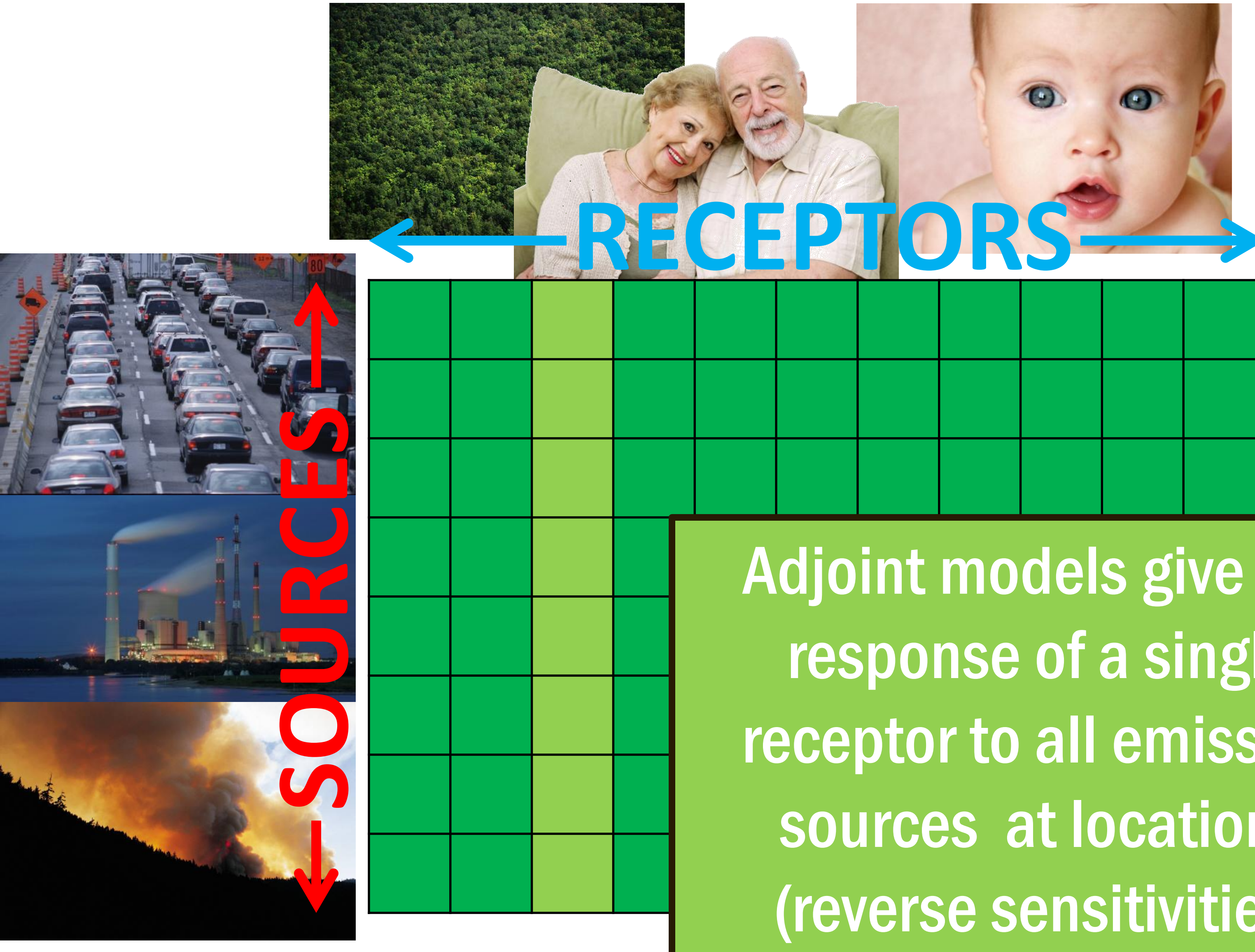
Quickly **indicate** the effects of changing emissions **(SOURCES)** on pollution concentrations **(RECPTORS)**

RESPONSE SURFACES



DDM gives the response of all receptors to several sources in a single CMAQ run (forward sensitivities)

RESPONSE SURFACES



Adjoint models give the response of a single receptor to all emission sources at locations (reverse sensitivities)

Adjoint and reverse sensitivities are best used to understand how **multiple sources** impact **specific receptors**

DDM and forward sensitivities are best used to understand how **specific sources** impact **multiple receptors**

Adjoint and reverse sensitivities are best used to understand how *International Emissions* impact *Regional Boundaries*

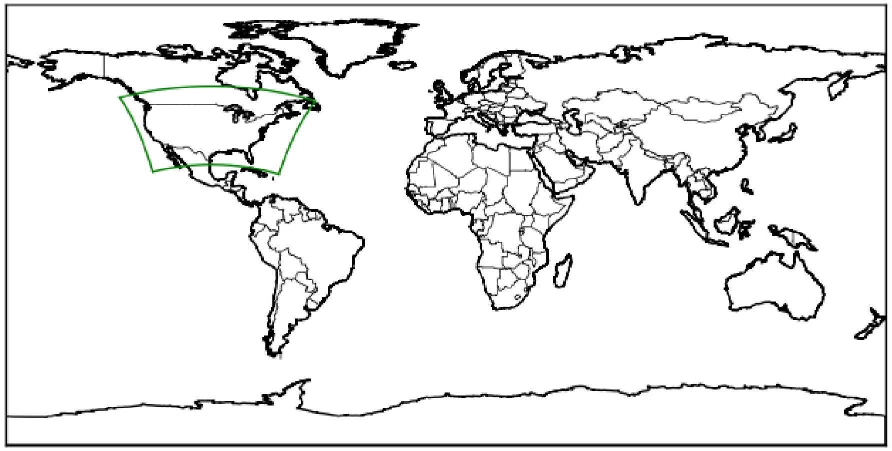
DDM and forward sensitivities are best used to understand how **specific sources** impact **multiple receptors**

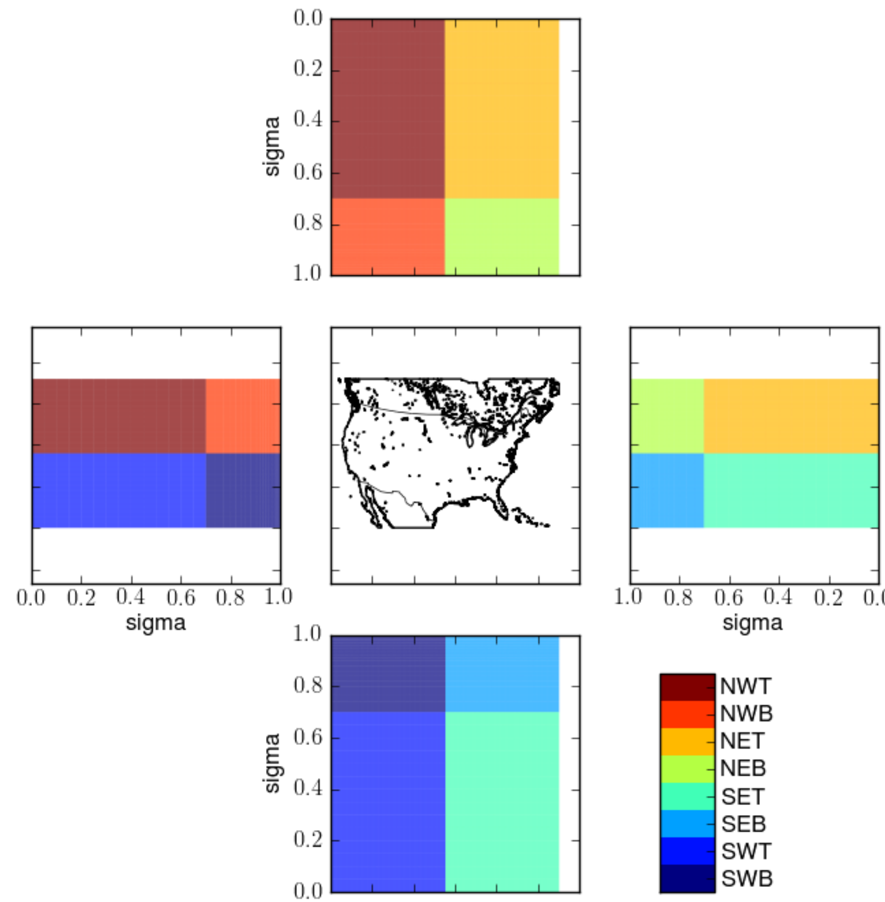
Adjoint and reverse sensitivities are best used to understand how *International Emissions* impact *Regional Boundaries*

DDM and forward sensitivities are best used to understand how *Regional Boundaries* impact *Local Concentrations*

AQMII BOUNDARY SENSITIVITIES

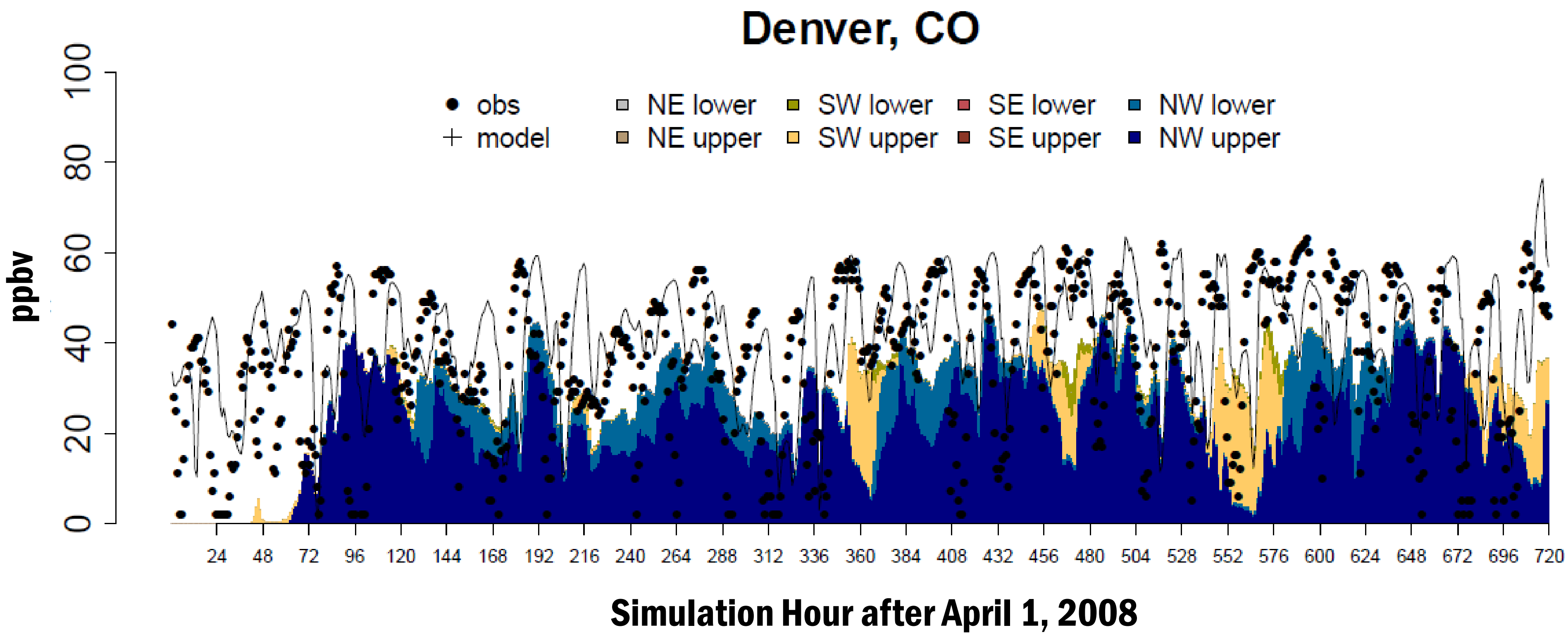
APRIL 2008 EPISODE OF HIGH INTERNATIONAL TRANSPORT





- Oltmans et al. 2010 describe a period of high influence of international transport on ozone over western North America.
- Based on a GEOS-chem adjoint run of the sensitivity of US ozone concentrations to atmospheric ozone concentrations, the boundary was divided into corners representing unique source areas of ozone.
- CMAQ boundary is further divided into “upper” and “lower” regions at 0.74 sigma (bottom 20 layers, ~3km) to separate local and long-distance transport.

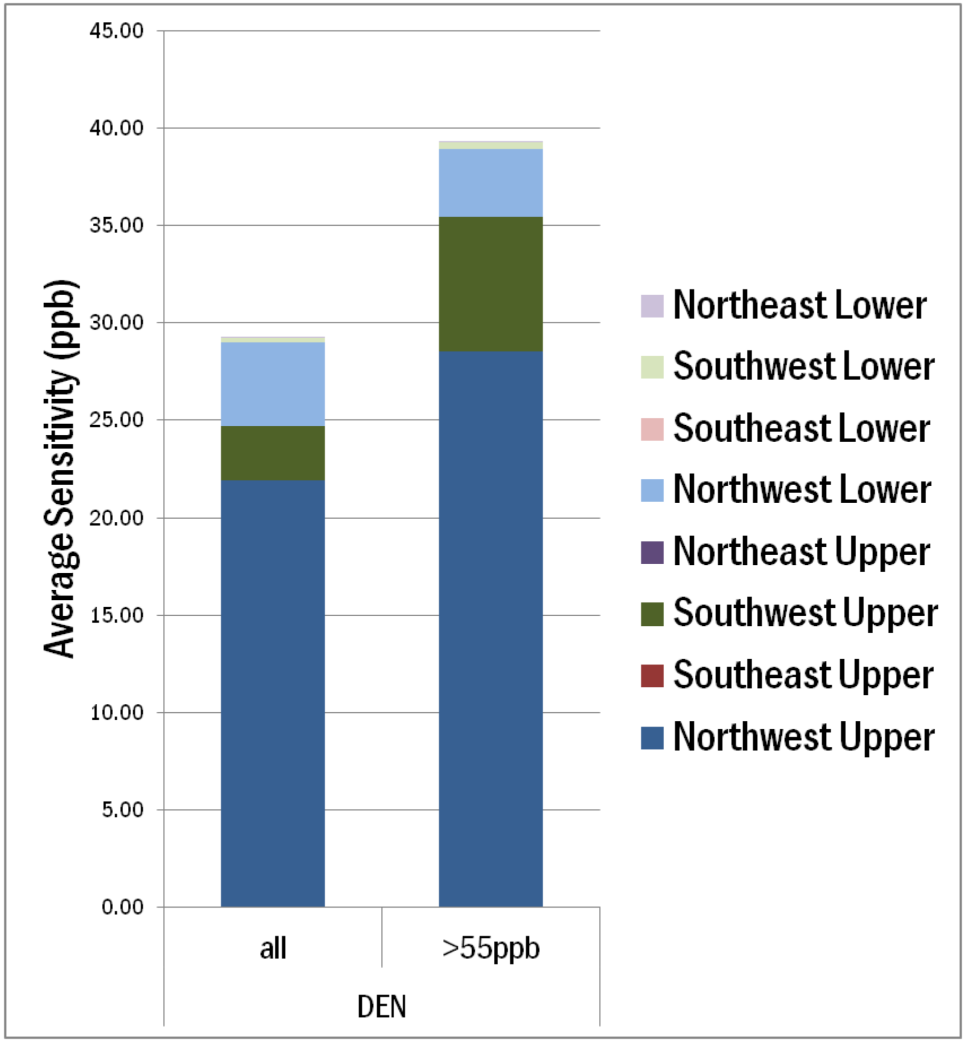
DENVER O_3 SENSITIVITY TO BOUNDARY O_3 CONCENTRATIONS



Ozone concentrations are most sensitive to O_3 concentrations at the Northwestern boundaries, primarily the upper boundary.

****-NOTE: Results are specific to period of high ozone transport and should not be extrapolated to other times or seasons***

DENVER O_3 SENSITIVITY TO BOUNDARY O_3 CONCENTRATIONS

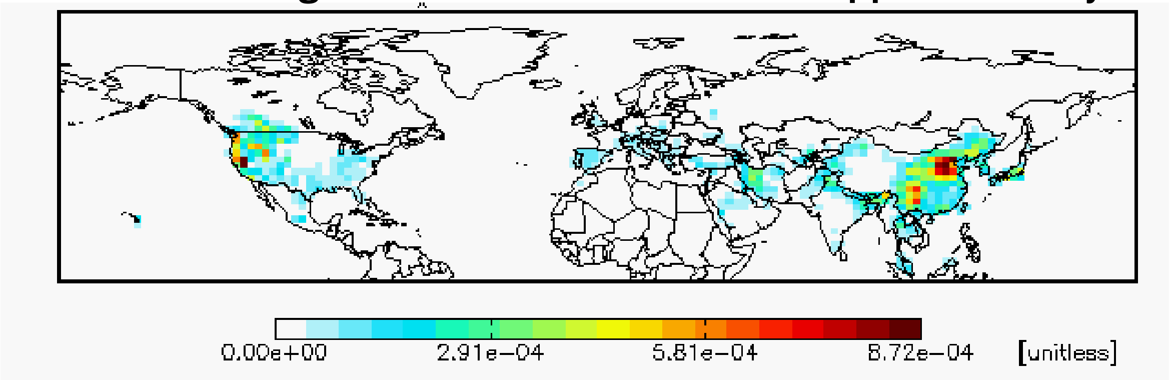


Boundary influence on Denver is dominated by the Northwest boundary

**-NOTE: Results are specific to period of high ozone transport and should not be extrapolated to other times or seasons*

NORTHWEST O_3 SENSITIVITY TO GLOBAL NO_x EMISSIONS

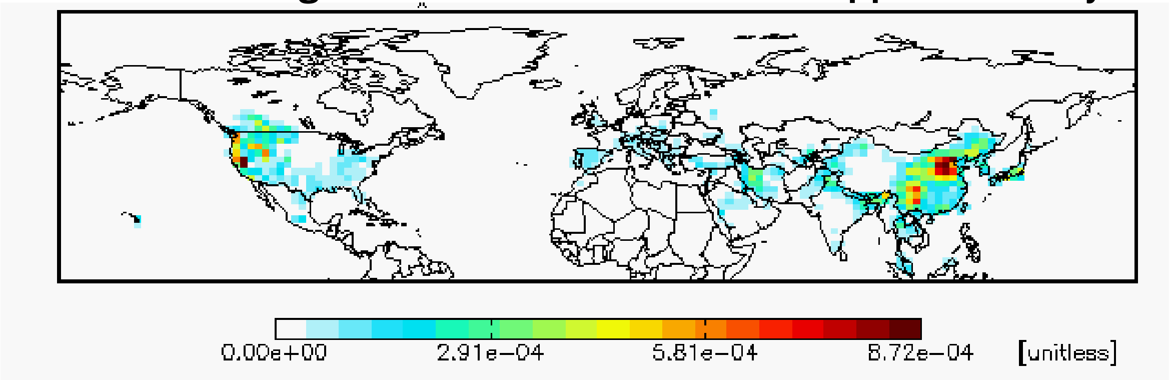
Percent change in total ozone at Northwest upper boundary



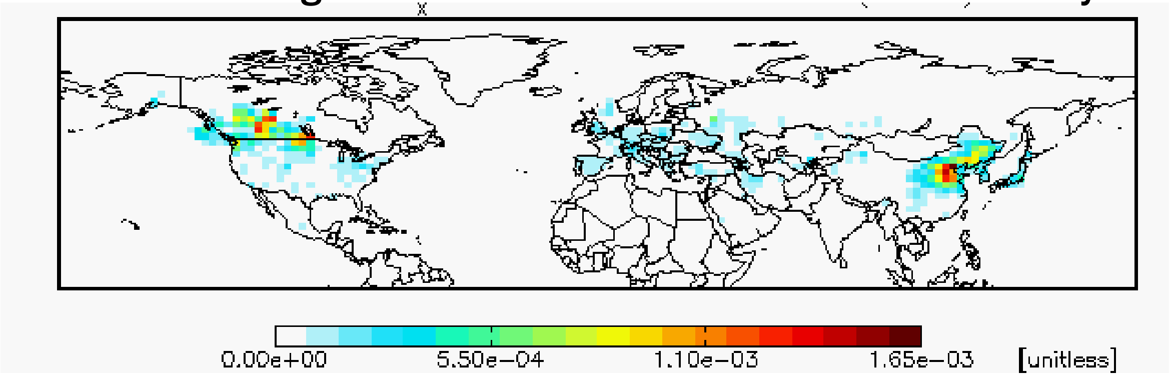
*-NOTE: Results are specific to period of high ozone transport and should not be extrapolated to other times or seasons

NORTHWEST O_3 SENSITIVITY TO GLOBAL NO_x EMISSIONS

Percent change in total ozone at Northwest upper boundary



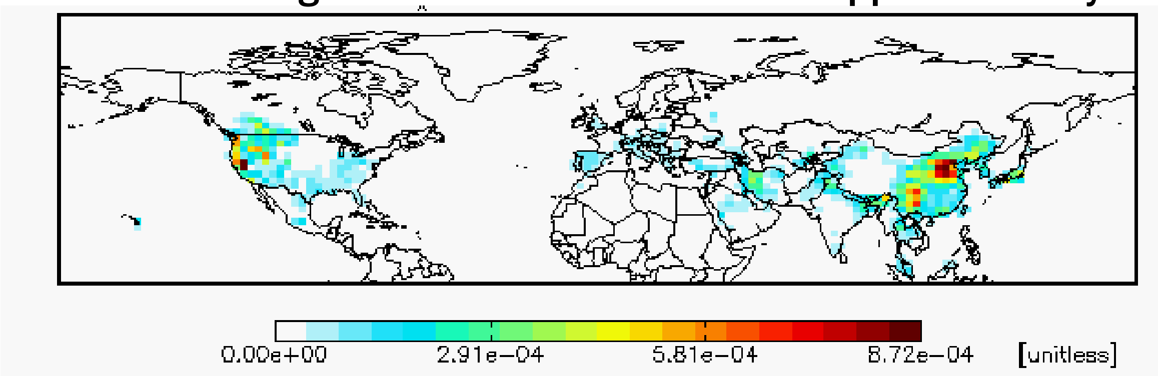
Percent change in total ozone at Northwest lower boundary



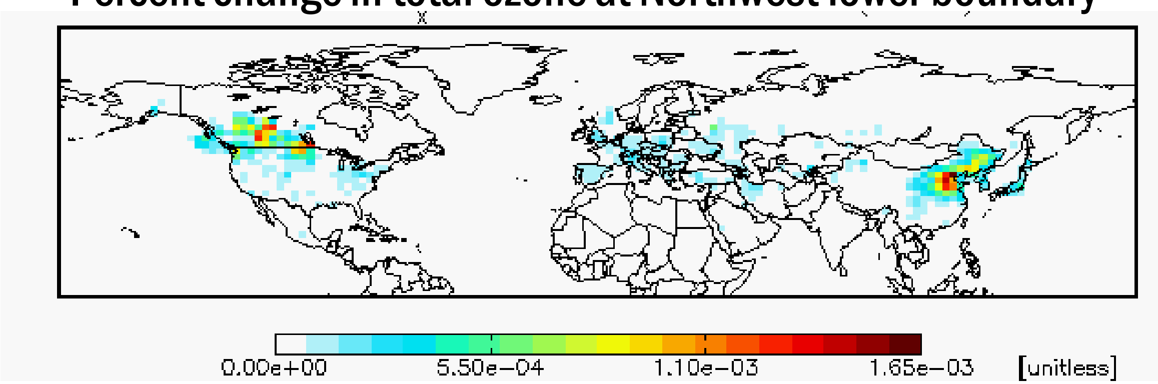
-NOTE: Results are specific to period of high ozone transport and should not be extrapolated to other times or seasons

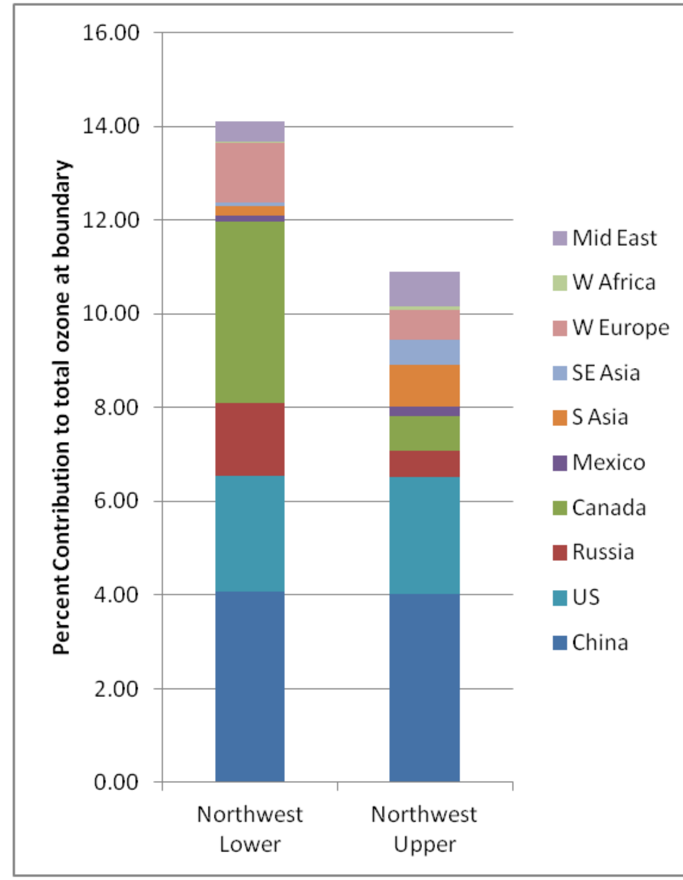
NORTHWEST O_3 SENSITIVITY TO GLOBAL NO_x EMISSIONS

Percent change in total ozone at Northwest upper boundary



Percent change in total ozone at Northwest lower boundary

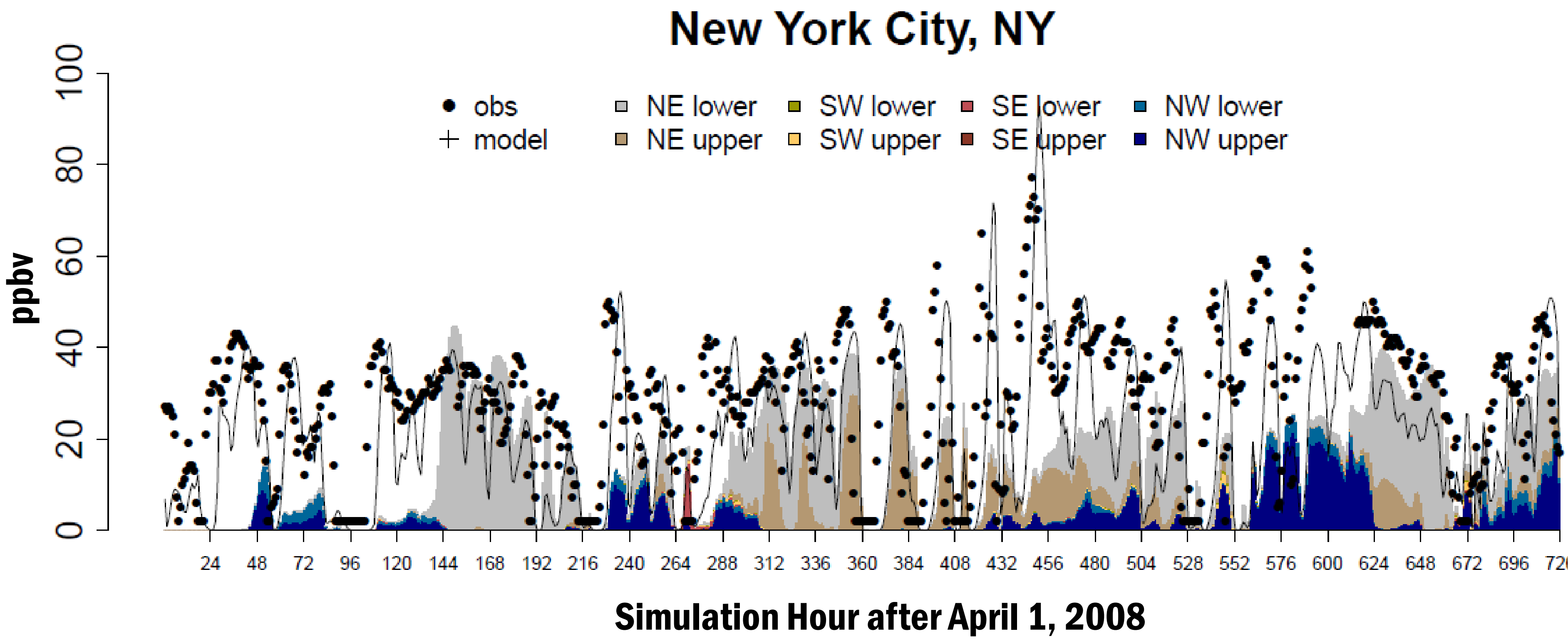




Northwest boundaries are impacted by China, United States, Russia, and Canada.

*-*NOTE: Results are specific to period of high ozone transport and should not be extrapolated to other times or seasons*

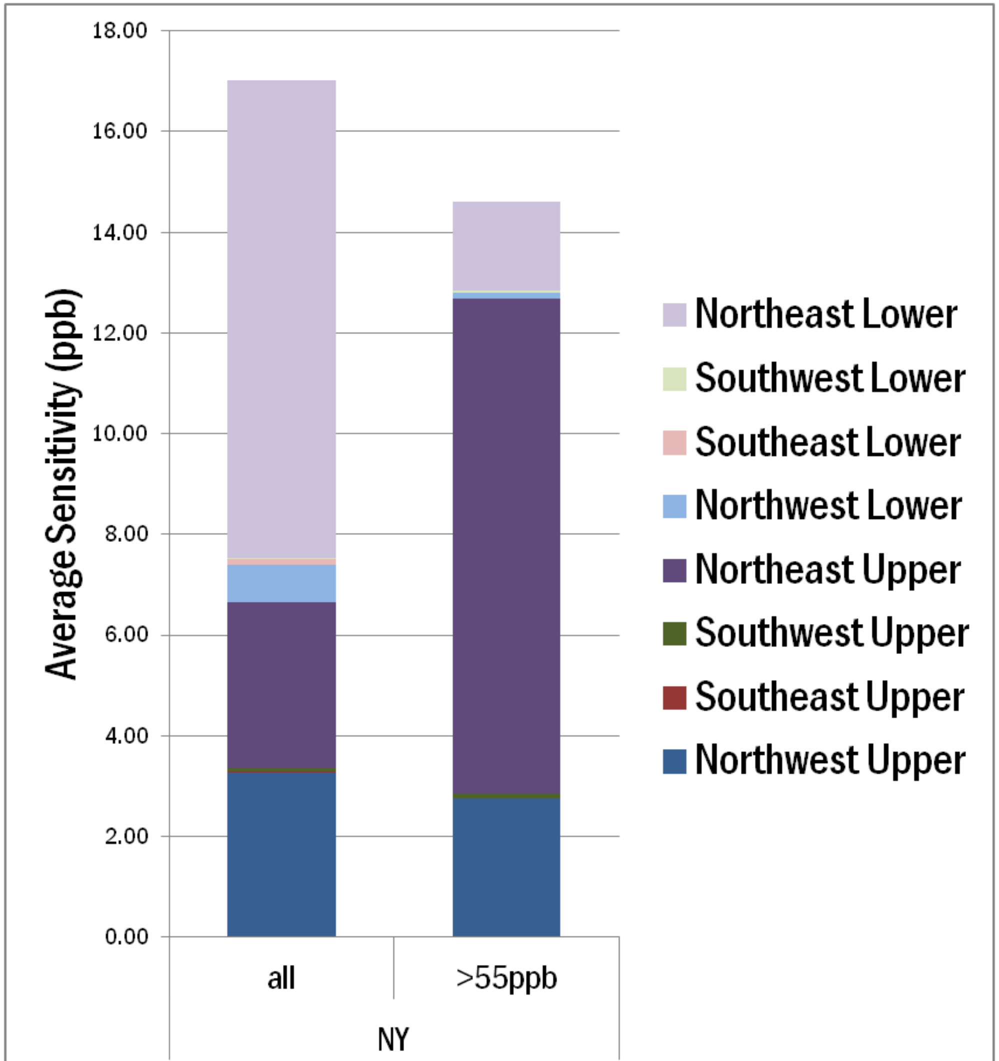
NEW YORK O_3 SENSITIVITY TO BOUNDARY O_3 CONCENTRATIONS



Ozone concentrations are mostly sensitive to O_3 concentrations at Northeastern boundaries. High period of ozone is not highly sensitive to boundary ozone.

****-NOTE: Results are specific to period of high ozone transport and should not be extrapolated to other times or seasons***

NEW YORK O_3 SENSITIVITY TO BOUNDARY O_3 CONCENTRATIONS

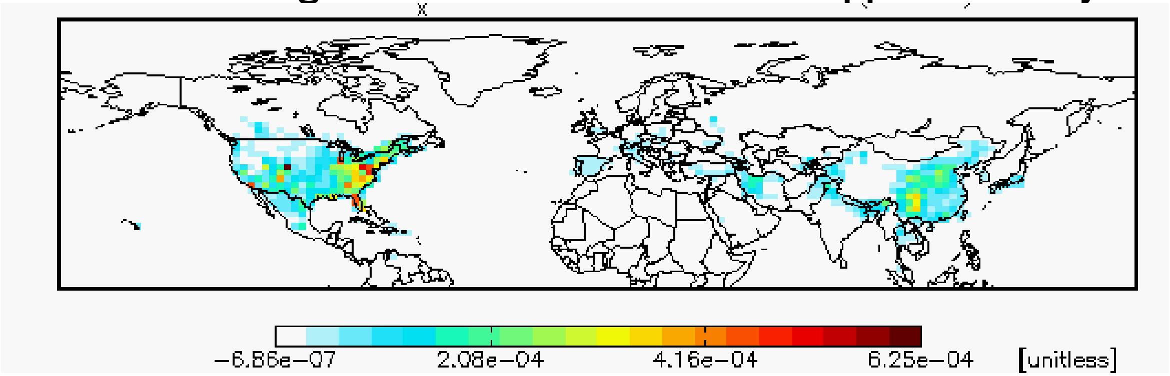


Boundary influence on New York City is dominated by the Northeast boundary

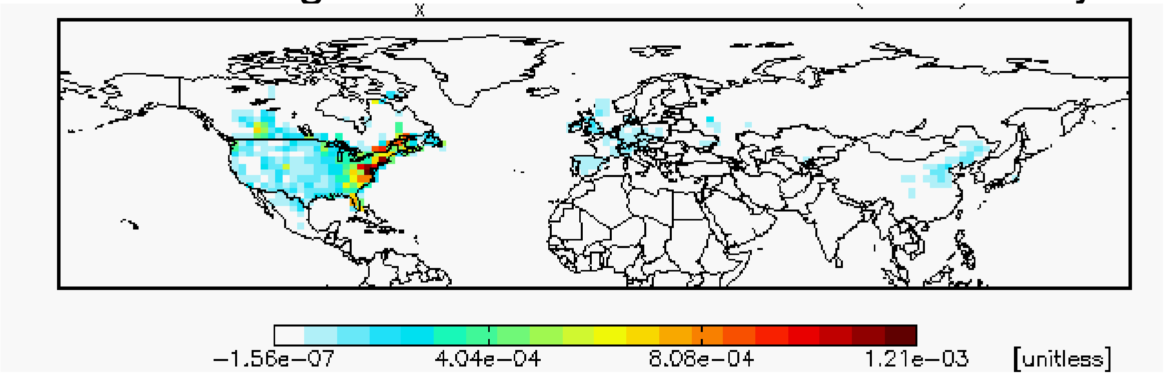
***-NOTE: Results are specific to period of high ozone transport and should not be extrapolated to other times or seasons**

NORTHEAST O_3 SENSITIVITY TO GLOBAL NO_x EMISSIONS

Percent change in total ozone at Northeast upper boundary



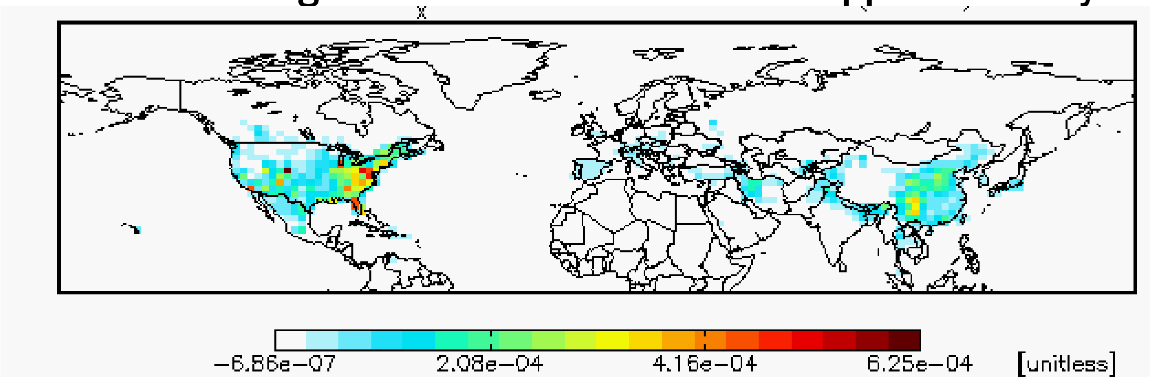
Percent change in total ozone at Northeast lower boundary



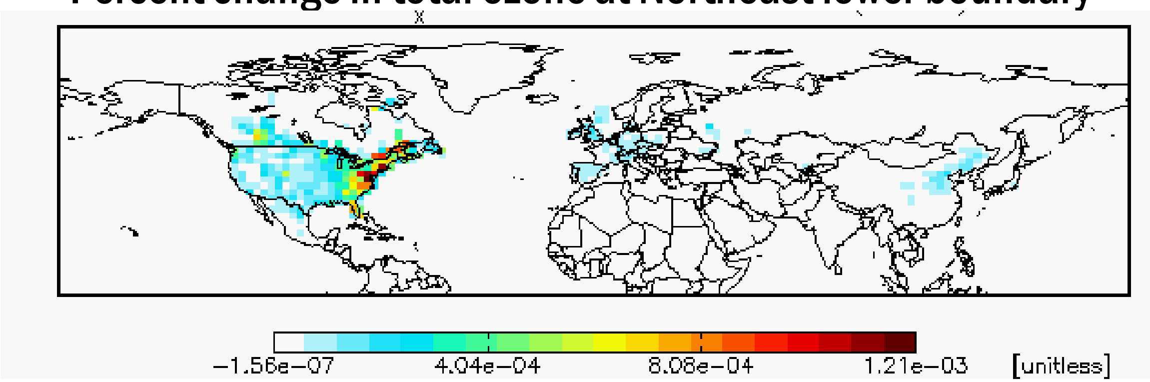
-NOTE: Results are specific to period of high ozone transport and should not be extrapolated to other times or seasons

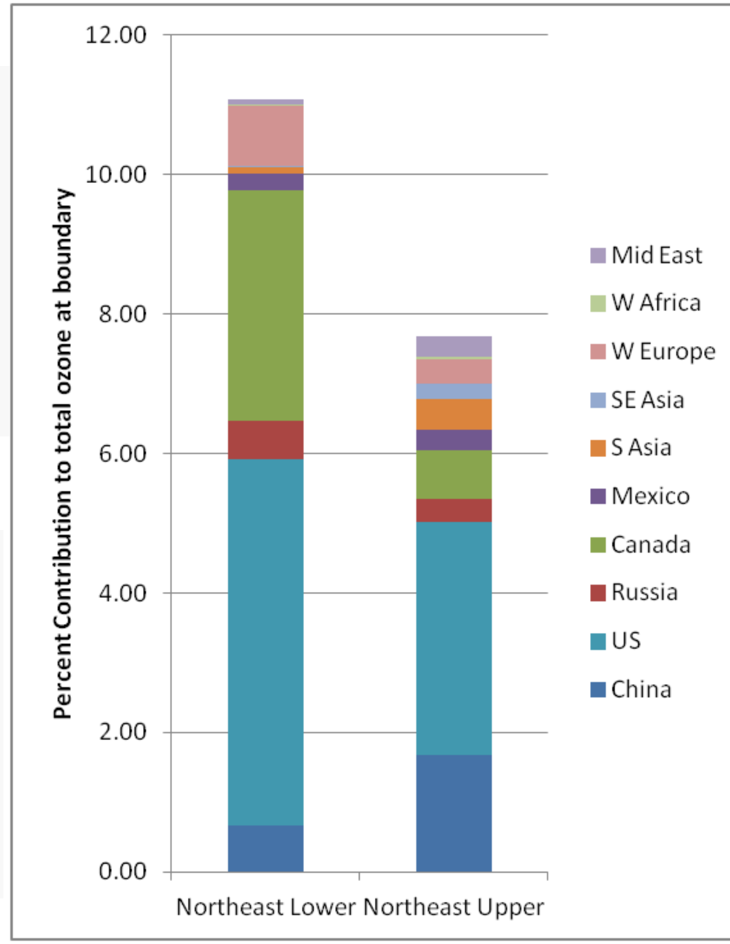
NORTHEAST O_3 SENSITIVITY TO GLOBAL NO_x EMISSIONS

Percent change in total ozone at Northeast upper boundary



Percent change in total ozone at Northeast lower boundary

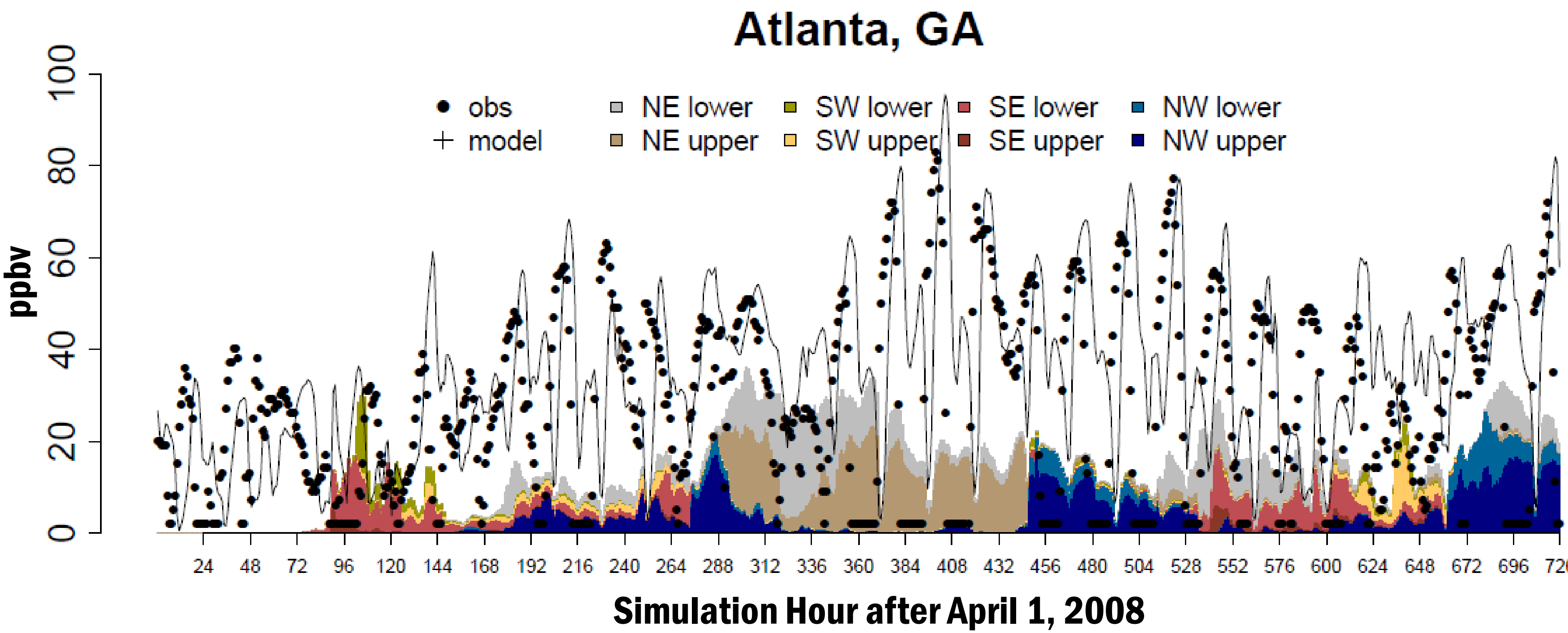




Northwest boundaries at lower levels are impacted mostly by United States and Canada. Upper boundaries are impacted more by international emissions.

-NOTE: Results are specific to period of high ozone transport and should not be extrapolated to other times or seasons

ATLANTA O_3 SENSITIVITY TO BOUNDARY O_3 CONCENTRATIONS



Boundary influence on Atlanta is highly variable, though sensitivities rarely account for a large fraction of modeled ozone.

**-NOTE: Results are specific to period of high ozone transport and should not be extrapolated to other times or seasons*

SUMMARY

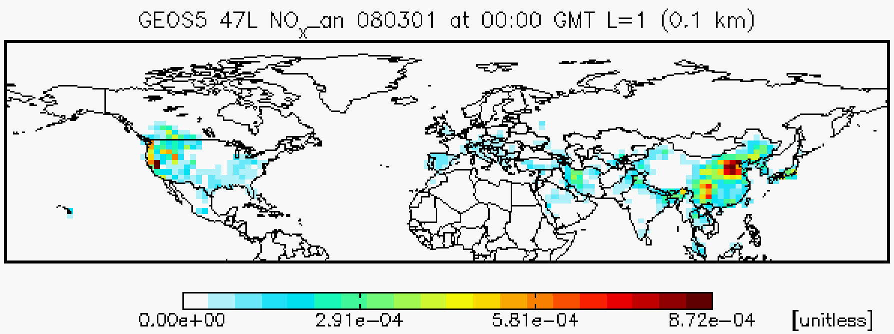
- When applied thoughtfully, HDDM and Adjoint methods can be used in concert to understand important source-receptor relationships.
- Linked global and regional sensitivity tools can be used to understand the effects of changing international sources of ozone in the United States and understand the fraction of ozone that is sensitive to inflow from the boundaries.
- The results presented here are a proof of this concept. Future work will expand the modeling period to other seasons and attempt to validate the methods with finite difference modeling.

ACKNOWLEDGEMENTS

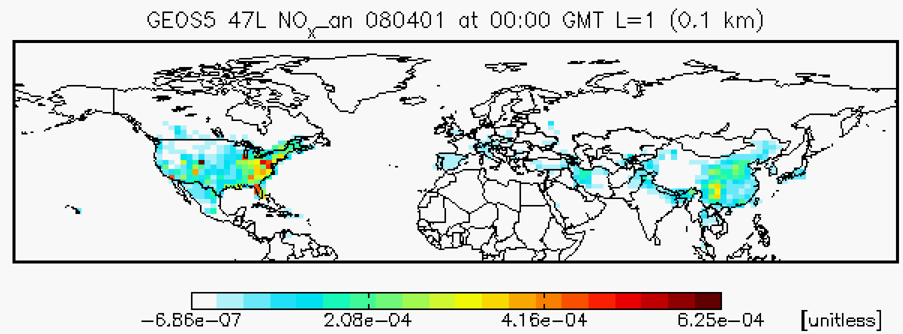
- **ORISE Postdoctoral Fellowship**
- **Kateryna Lapina at the University of Colorado, Boulder**
- **Benjamin Wells, Karen Wesson, and Bryan Hubbell at the EPA**

GEOS-Chem Adjoint: International anthropogenic NO_x emission influence on **upper boundaries**

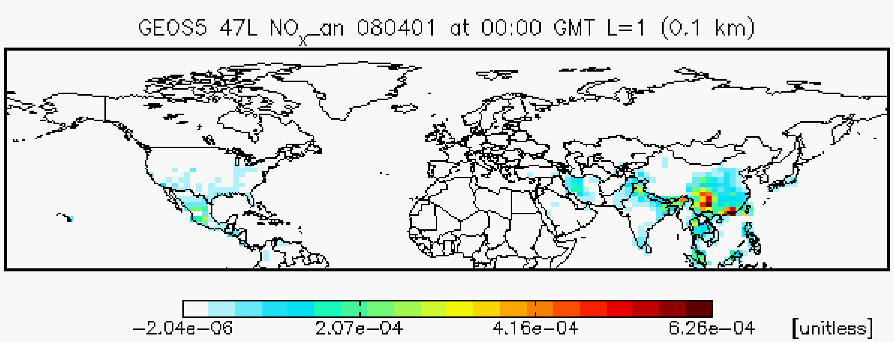
NW



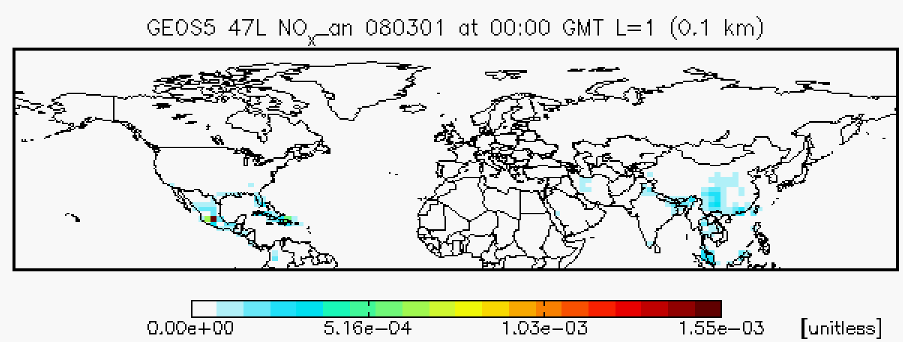
NE



SW

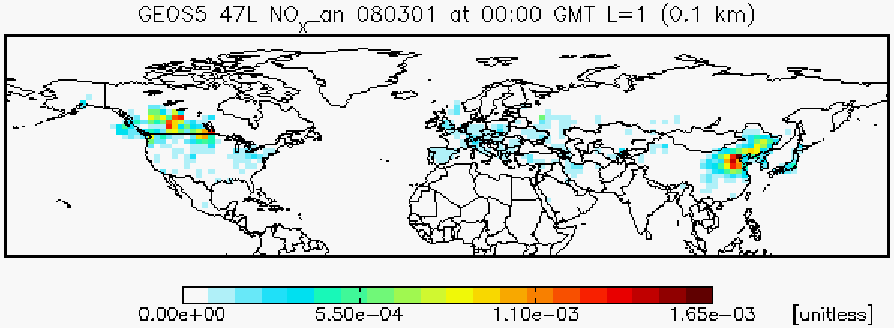


SE

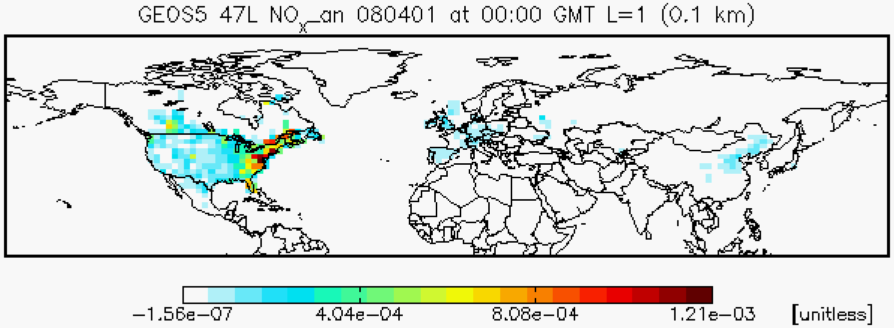


GEOS-Chem Adjoint: International anthropogenic NO_x emission influence on **lower boundaries**

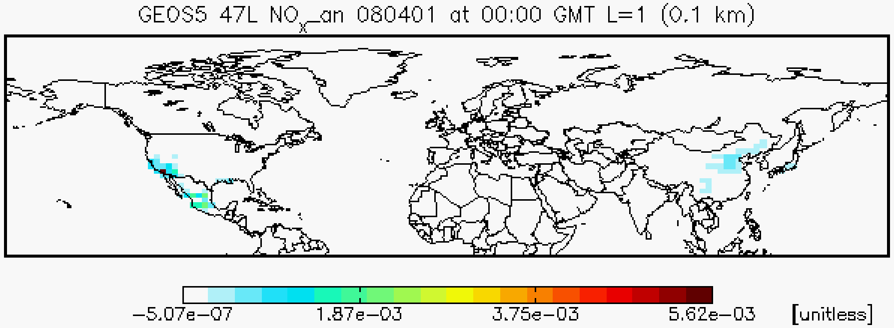
NW



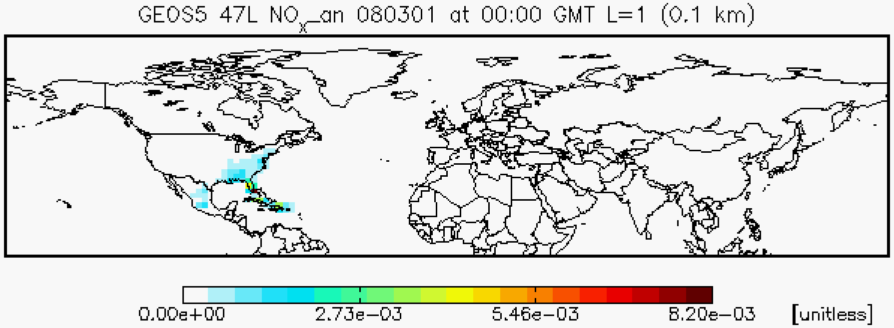
NE



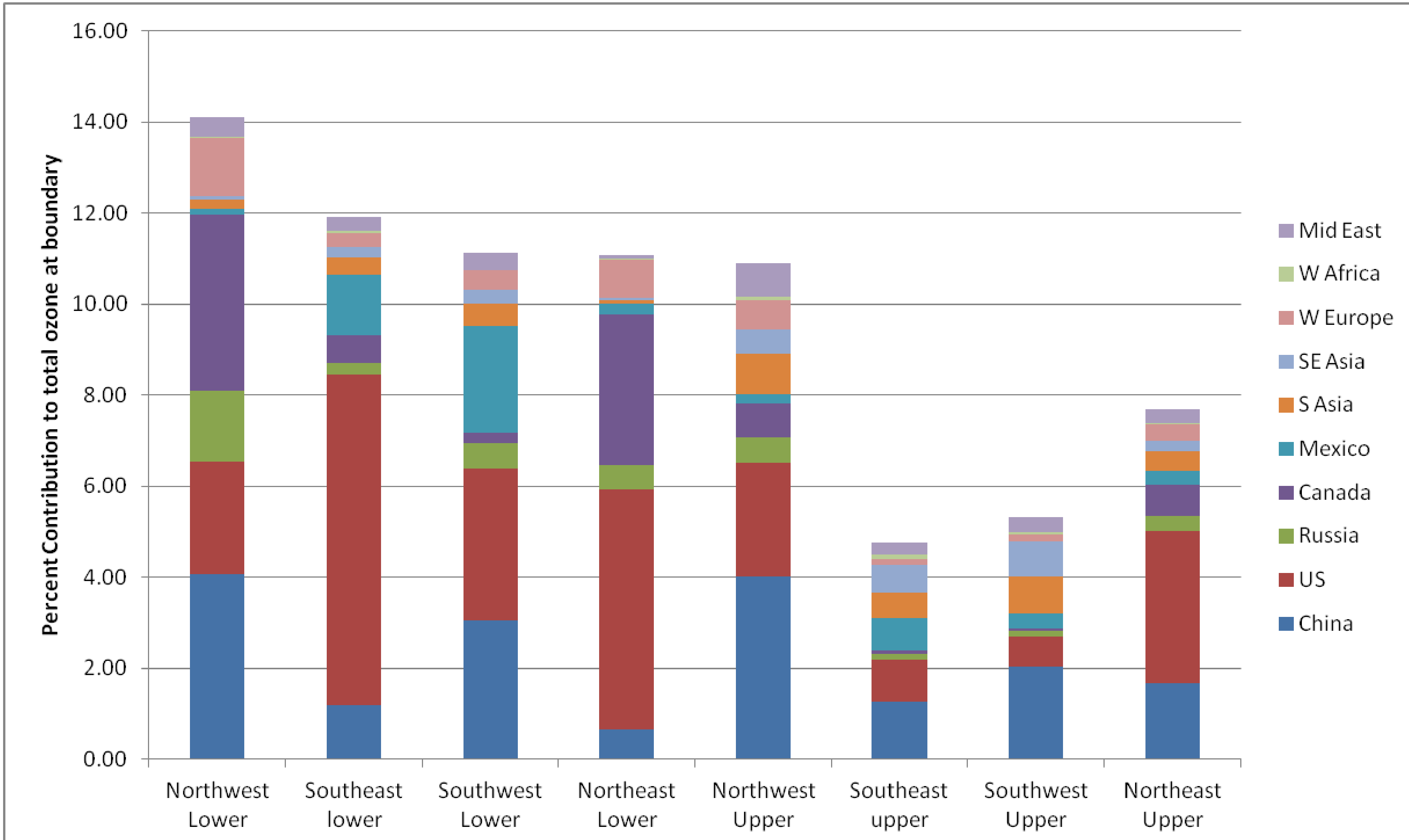
SW



SE

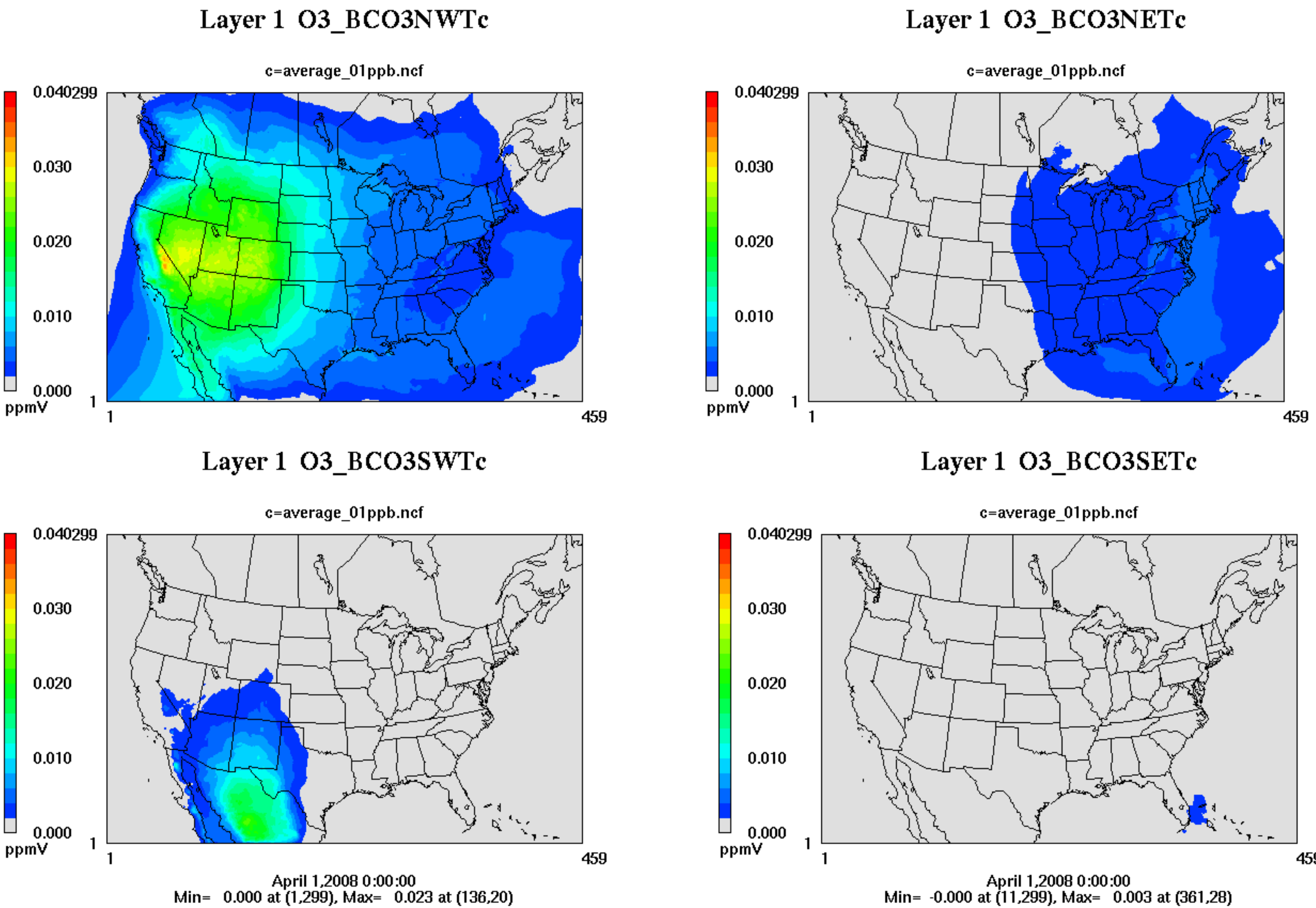


GEOS-Chem Adjoint: Average sensitivity of ozone at boundary regions to international emissions, April 2008*

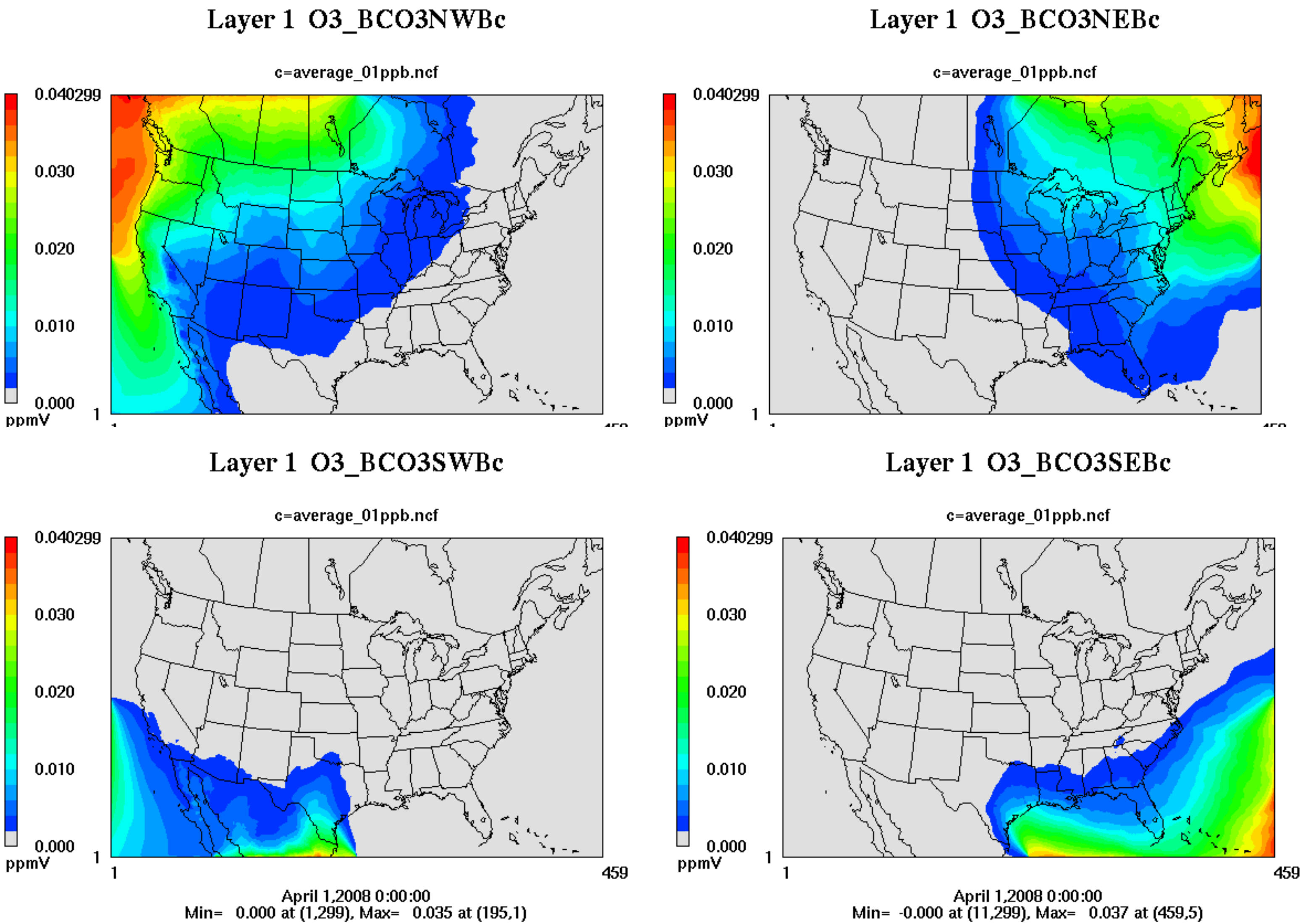


-NOTE: Results are specific to period of high ozone transport and should not be extrapolated to other times or seasons

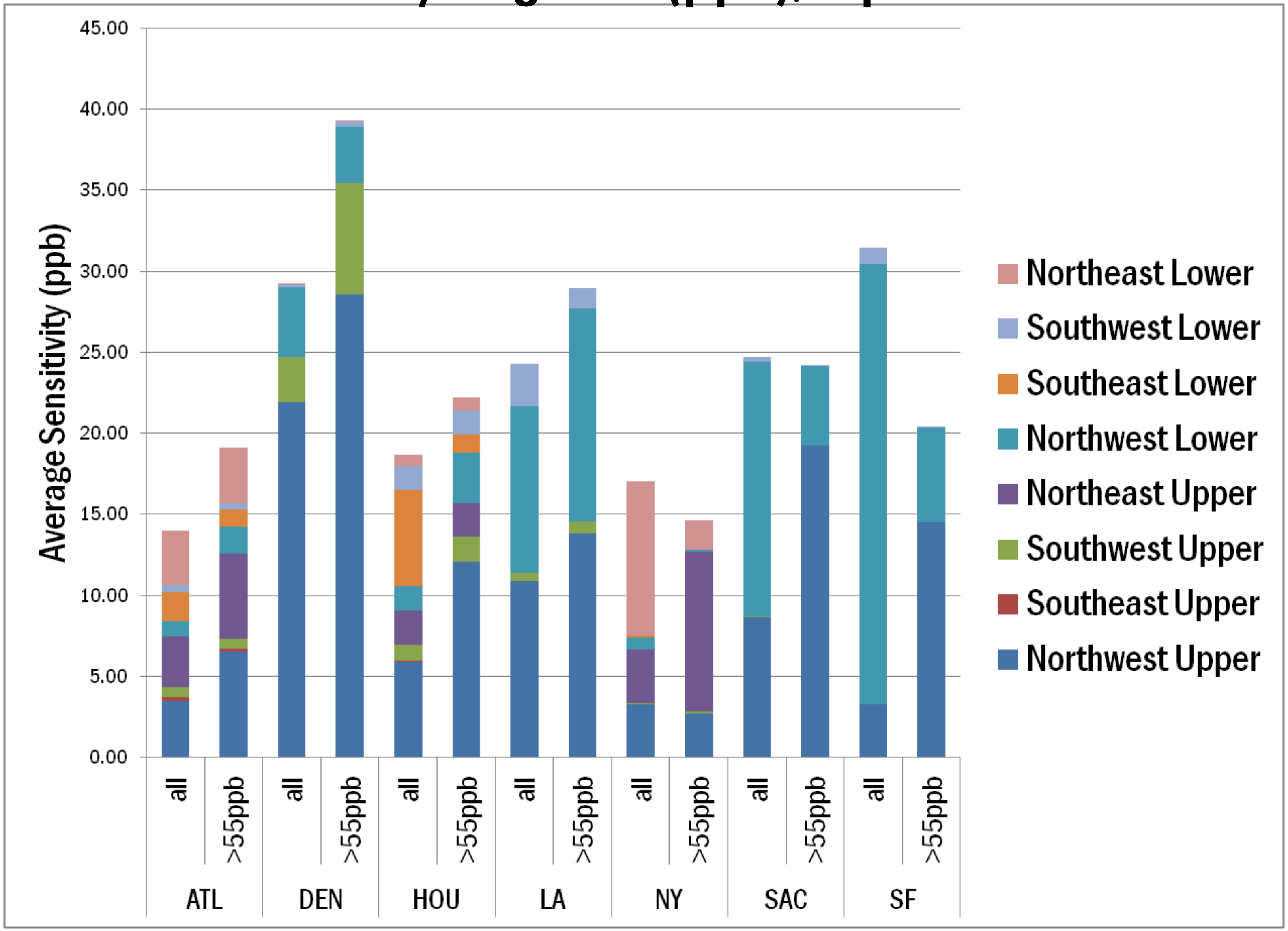
CMAQ-HDDM: Upper boundary influence on US ozone concentrations



CMAQ-HDDM: Lower boundary influence on US ozone concentrations



CMAQ-HDDM: Average sensitivity of ozone to boundary regions (ppb), April 2008*



-NOTE: Results are specific to period of high ozone transport and should not be extrapolated to other times or seasons

GEOS-CHEM ADJOINT:

how International Emissions

impact Regional Boundaries

CMAQ HDDM:

how Regional Boundaries

impact Local Concentrations