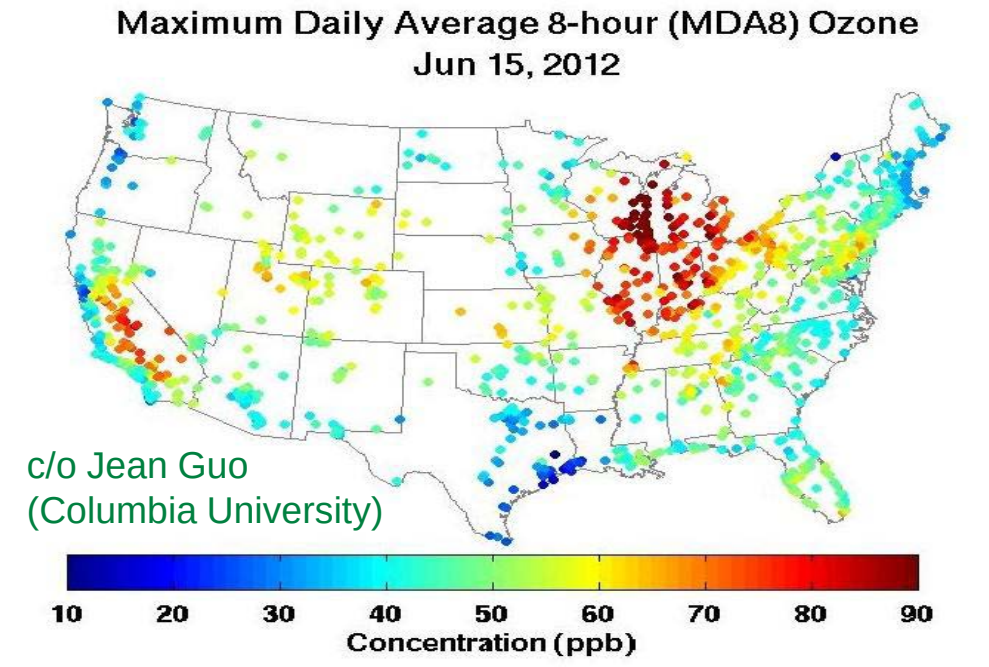
Global dimensions to ground-level ozone: Transboundary transport and climate change



c/o Jean Guo
(Columbia University)

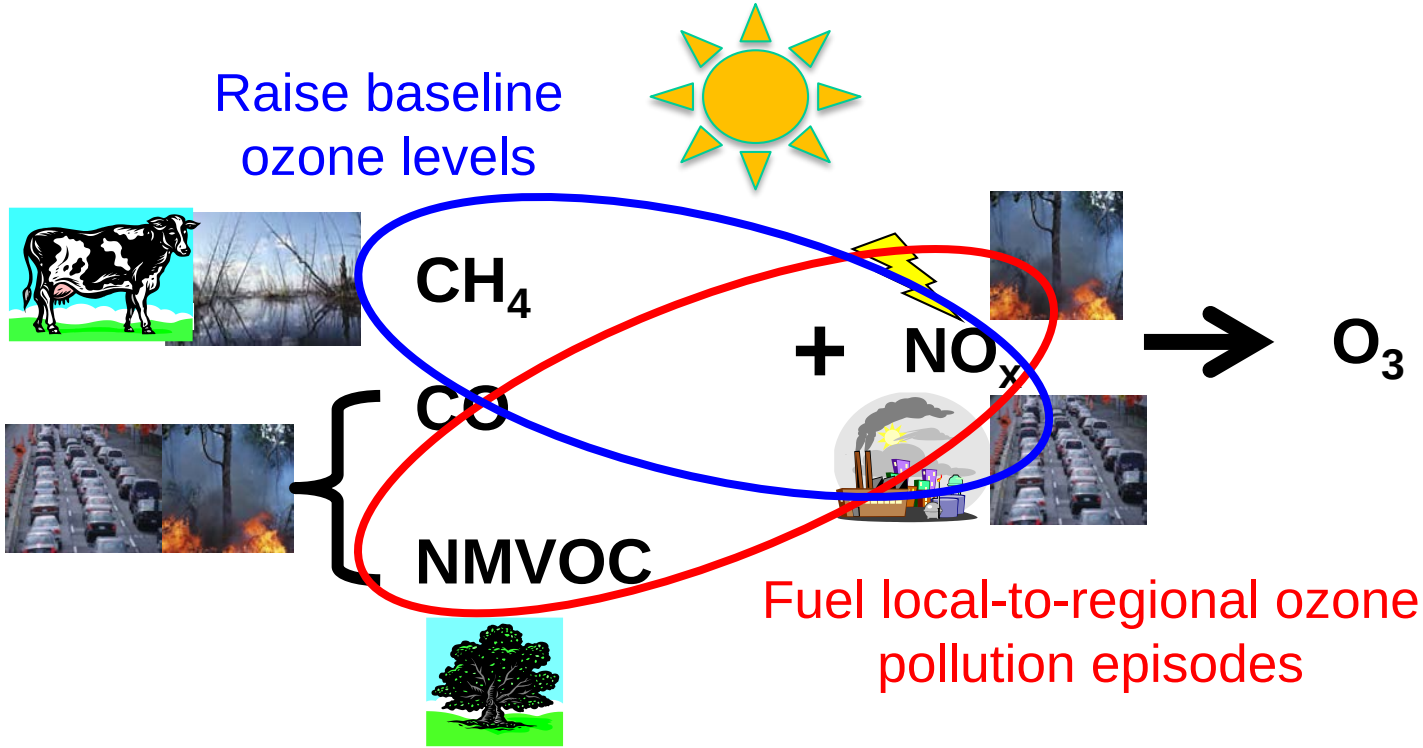
Arlene M. Fiore

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK
Lamont-Doherty Earth Observatory
COLUMBIA UNIVERSITY | EARTH INSTITUTE

http://blog.ldeo.columbia.edu/atmoschem/

External Collaborators: Larry Horowitz, Meiyun Lin, Vaishali Naik (GFDL); Harald Rieder (U Graz, Austria); Pat Kinney (Boston U)

Ground-level O_3 is photochemically produced from regional sources (natural + anthropogenic) that build on "baseline" levels



Definition: Maximum Daily Average 8-hour (MDA8) Ozone

- The metric used to assess compliance with the ozone National Ambient Air Quality Standard (NAAQS)
- (Current formulation is a 3-year average of the 4th highest value in each of the 3 individual years)

In polluted regions, O_3 correlates with surface temperature on daily to inter-annual time scales [*e.g., Bloomer et al., 2009; Camalier et al., 2007; Cardelino and Chameides, 1990; Clark and Karl, 1982; Korsog and Wolff, 1991*]

Observations at a monitoring site in Pennsylvania

July mean MDA8 O_3 and July mean daily maximum temperature

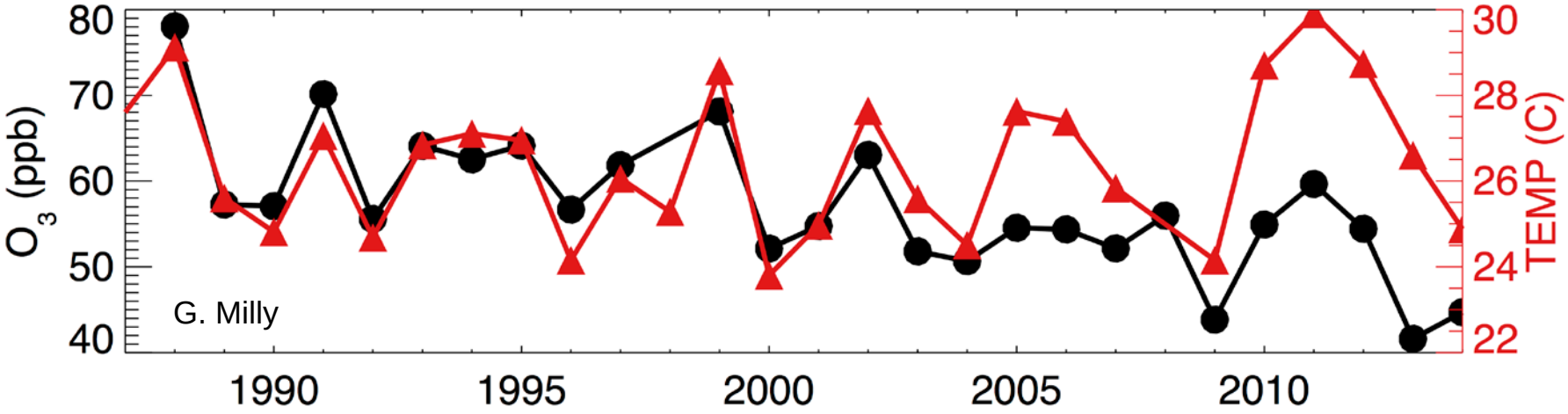
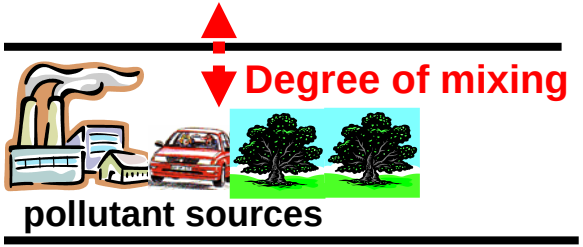


Figure 6a of Fiore, Naik, Leibensperger, JAWMA, 2015

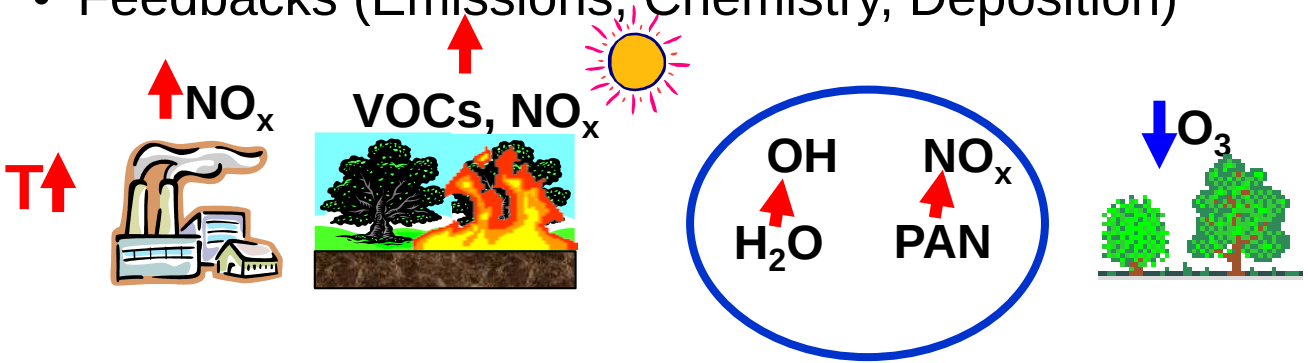
JAWMA = Journal of the Air and Waste Management Association

What drives ozone-temperature correlations? (& Why would climate change influence ozone?)

- Meteorology (e.g., stagnation vs. ventilation)



- Feedbacks (Emissions, Chemistry, Deposition)



Lowers O_3 over remote regions

Ozone is trending downward over this time period as NO_x emission controls are implemented

Observations at a monitoring site in Pennsylvania

July mean MDA8 O_3 and July mean daily maximum temperature

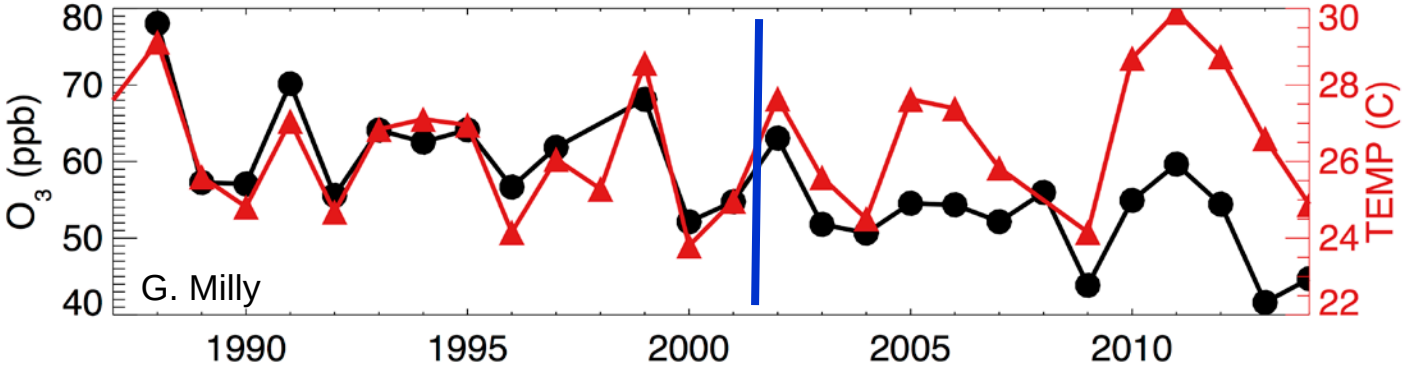


Figure 6a of Fiore, Naik, Leibensperger, JAWMA, 2015

Decreasing NO_x emissions reduces sensitivity of O_3 to temperature

[*e.g., Bloomer et al., 2009; Rasmussen et al., 2012; Brown-Steiner et al., 2015*]

Observations at a monitoring site in Pennsylvania

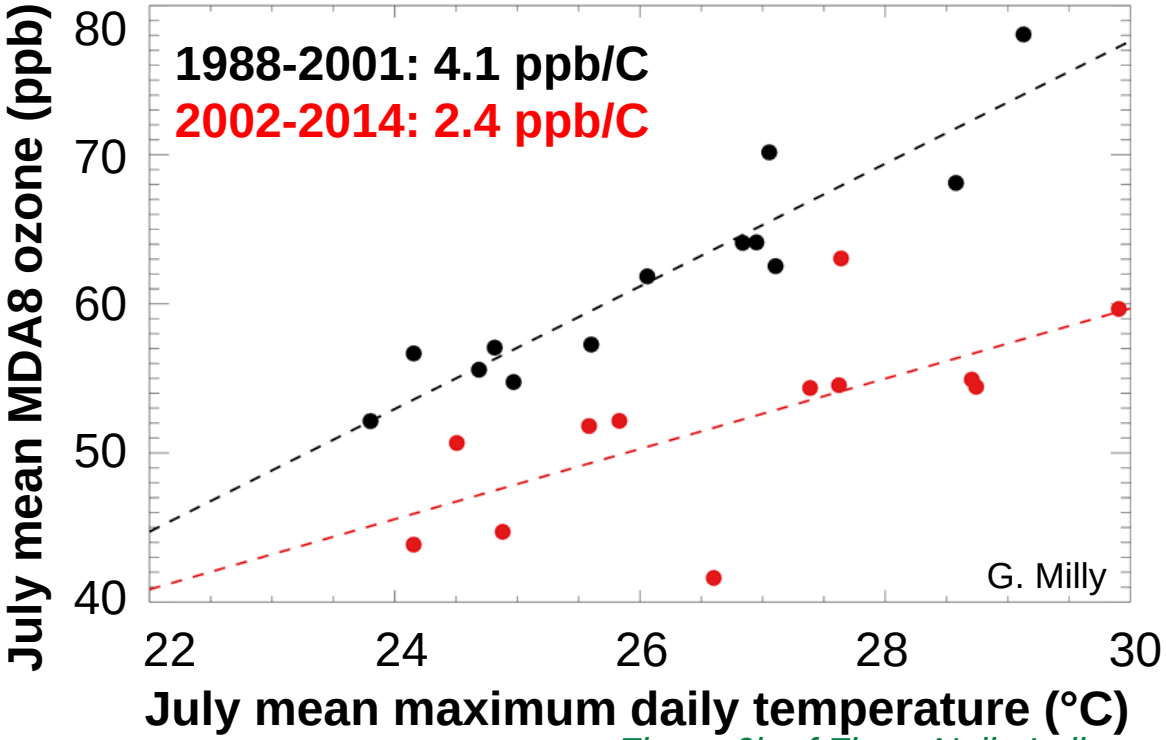
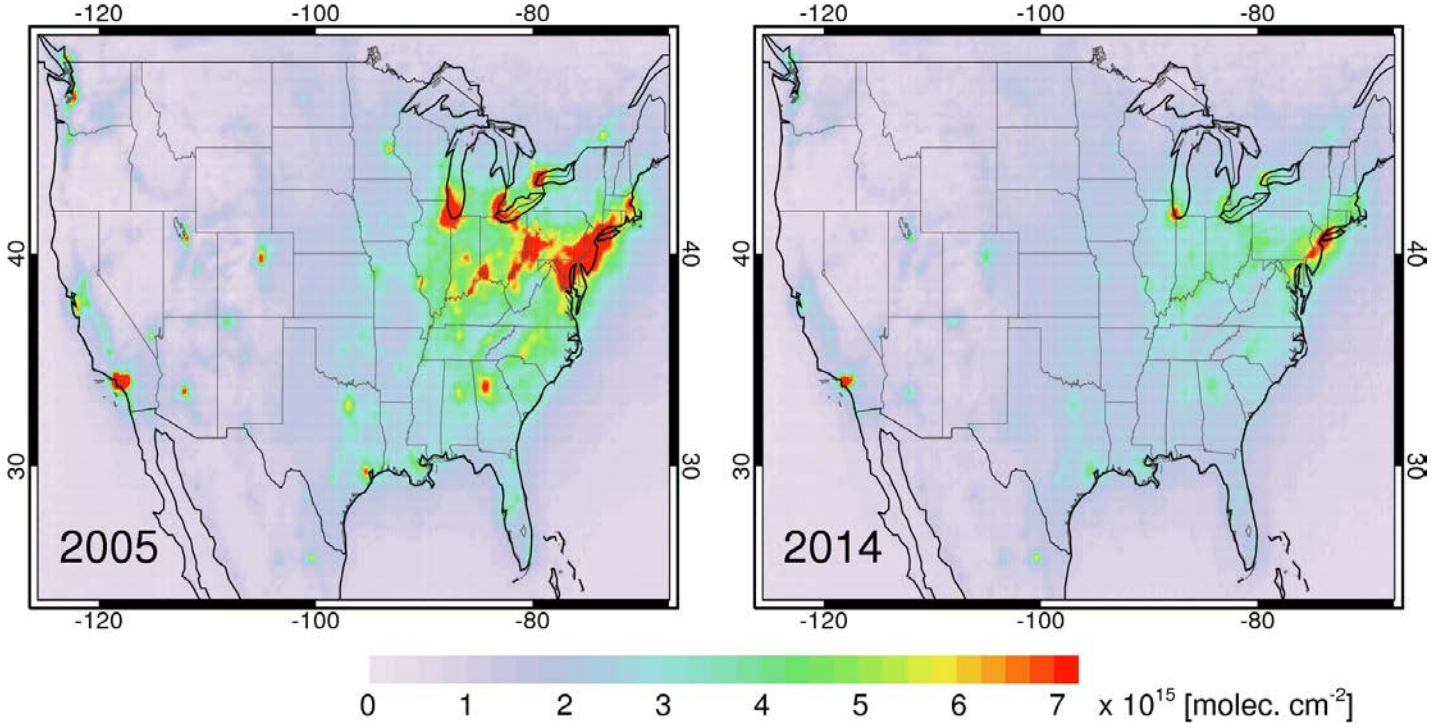


Figure 6b of Fiore, Naik, Leibensperger, JAWMA, 2015

Cleaner U.S. air is visible from space: Major changes over the last decade

Satellite (OMI) tropospheric NO_2 columns



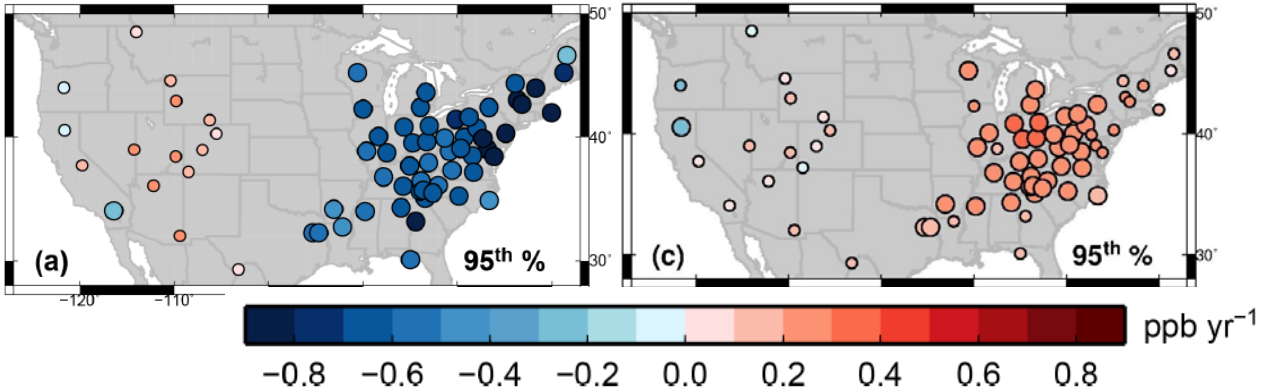
c/o Lok Lamsal & Bryan Duncan, NASA GSFC

Much more available at: airquality.gsfc.nasa.gov

"The world avoided"? In absence of emission controls, 95th percentile summer Eastern US MDA8 O_3 would have increased

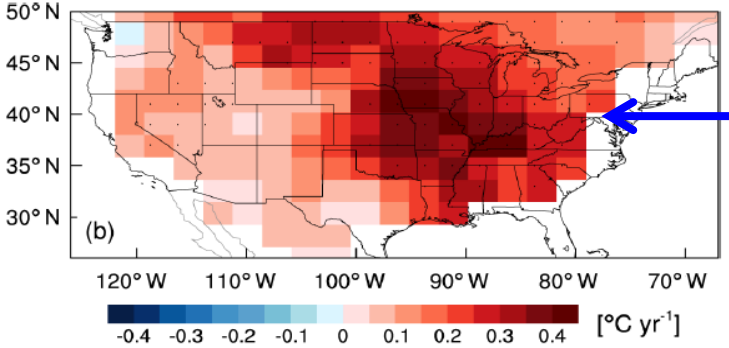
Summer (JJA) 95th percentile trends in MDA8 O_3 (1988-2014)

MODEL WITH ALL EMISSIONS ON



MODEL WITH EMISSIONS HELD FIXED

Trends in the GFDL AM3 model; Larger circles indicate significant trends ($p<0.05$)



Model trends in 90th percentile summertime daily max temperature

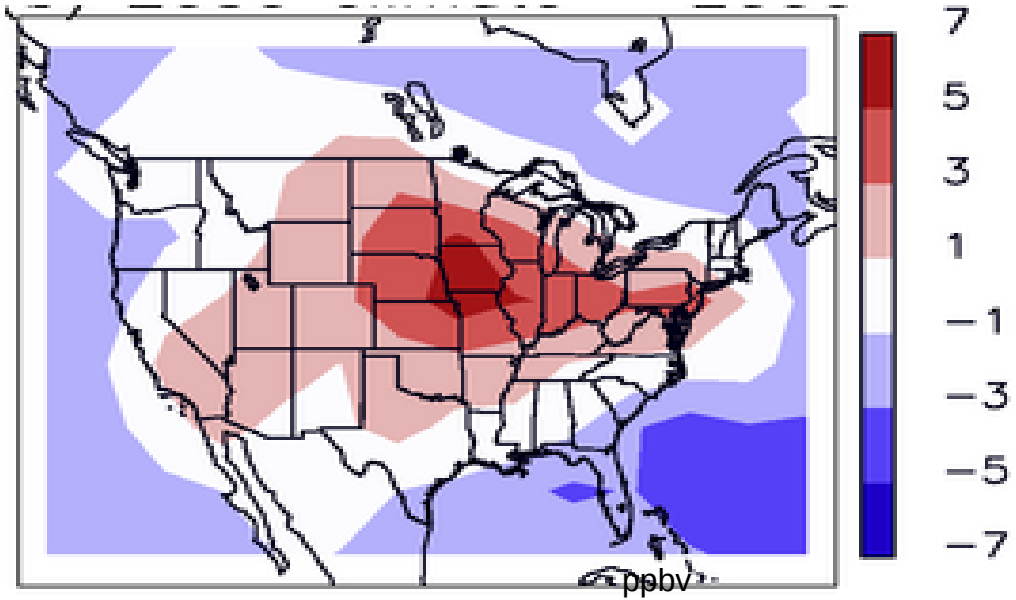
M. Lin et al., Atmospheric Chemistry & Physics, 2017

Models estimate a 'climate change penalty' on surface O_3 over U.S.A. but often disagree at regional scales

(e.g. -2 to +9 ppb in summer over Midwest [*Fiore et al., JAWMA, 2015, Table S3*])

"Climate Penalty"
[*Wu et al., JGR, 2008*]:
Change in MDA8 by O_3 solely because of climate change

(+1.6 ^{o}C global mean surface temp. 2000 → 2050)



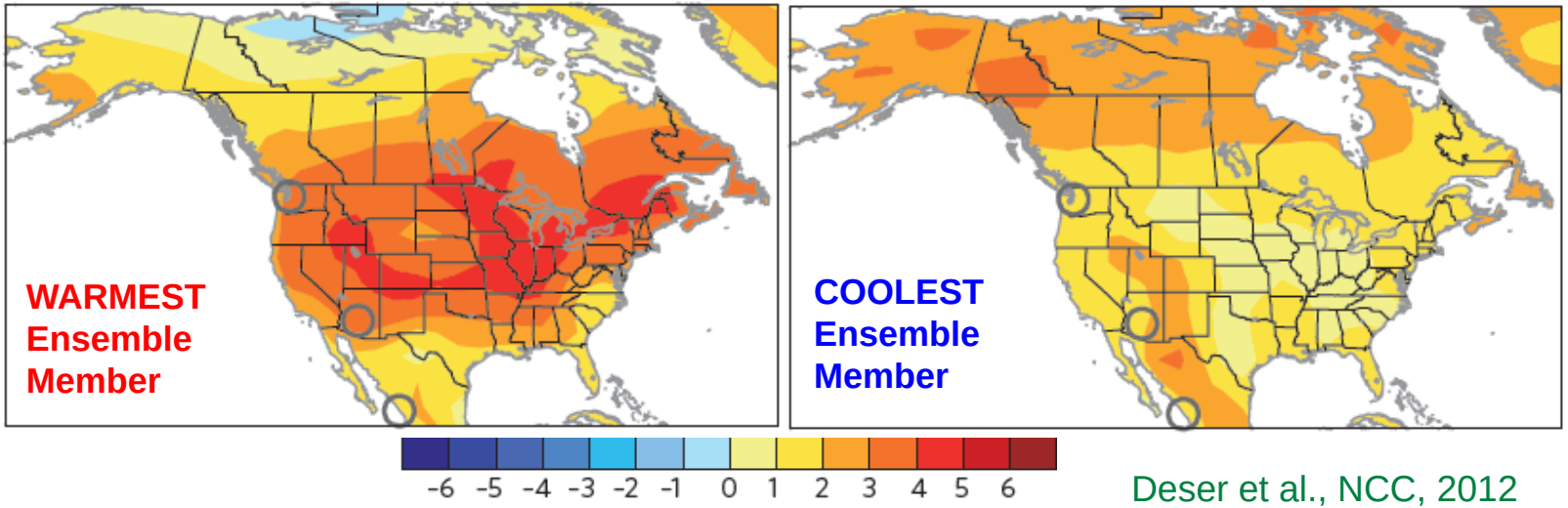
→ Uncertain regional climate responses to global warming

→ Model estimates (until recently) based on a few years of present and future meteorology from 1 realization of 1 climate model

JGR = Journal of Geographic Research

Uncertainty in surface ozone projections from climate (internal) variability

Summertime U.S. temperature trends in the warmest and coolest of 40 ensemble members (only atmosphere initial conditions differ) in a single model



°C per 55 years

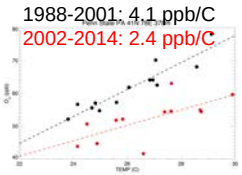
Deser et al., NCC, 2012
(excerpts from their Figure 2)
NCAR CCSM3 model, A1B scenario

→ **Ozone projections are tied to temperature projections**

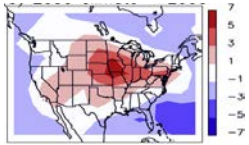
→ **Using a few years from 1 simulation with 1 climate model is not sufficient to remove this "climate noise"; need to average over an ensemble to reveal "forced" climate signal**

NCC = Nature Climate Change

Summary #1



- **Continued NO_x reductions guard against 'climate penalty' on warm season surface ozone**



- **Climate change tends to increase ozone in polluted regions**

Definitions

Baseline Ozone

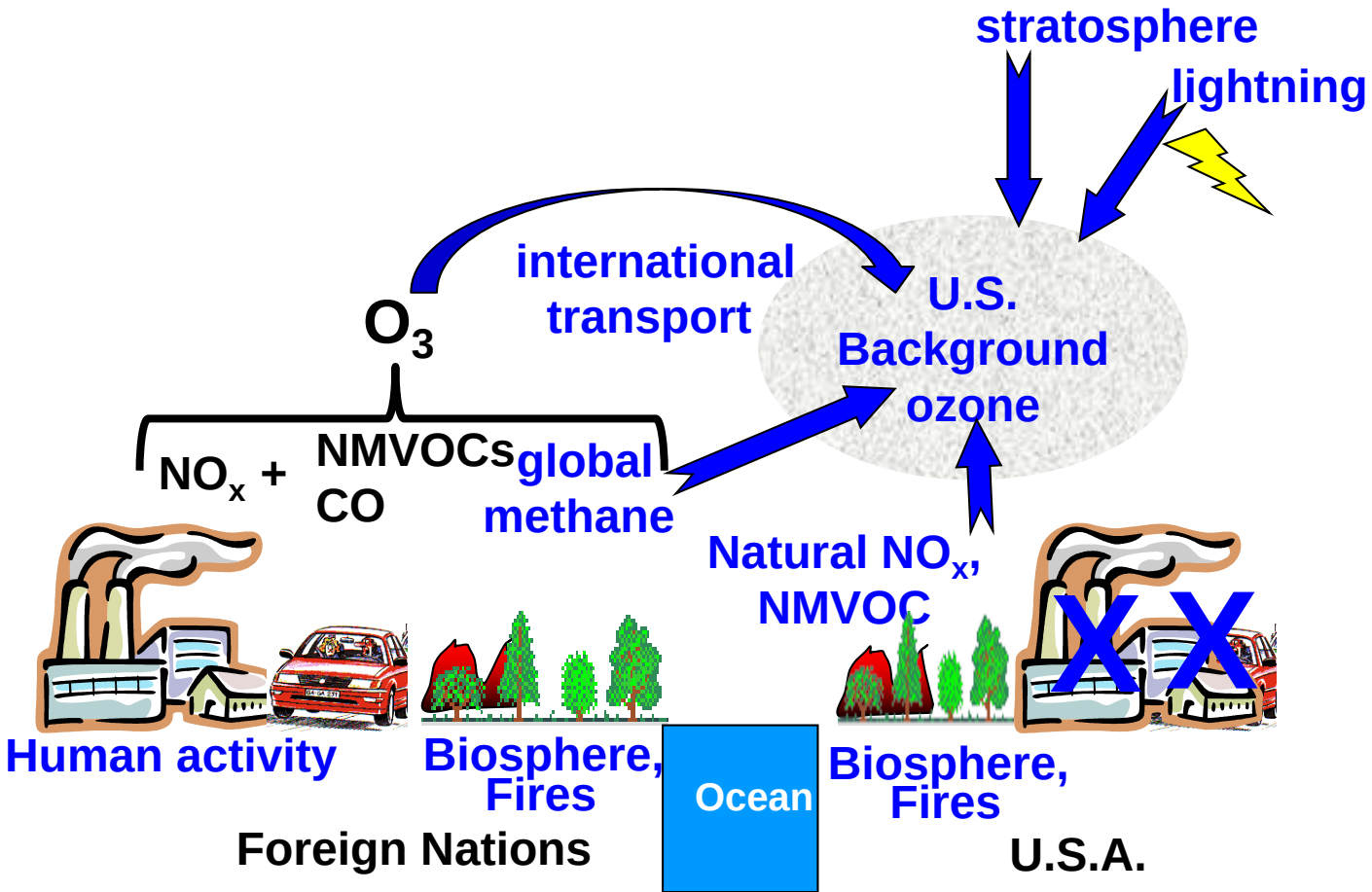
A measureable quantity. Ozone observed at remote sites with little influence from recent U.S. anthropogenic emissions

Background Ozone

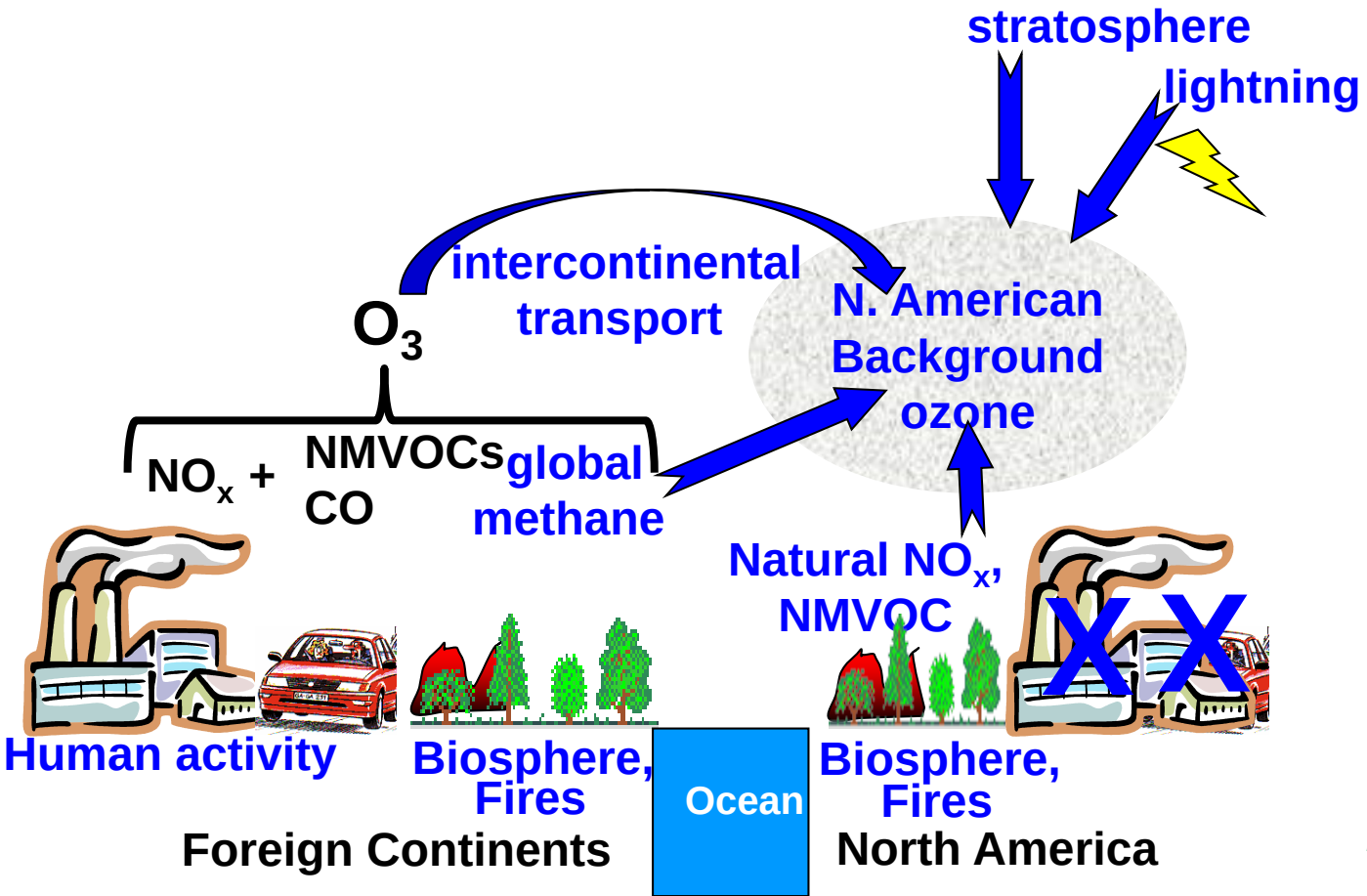
A model construct. Ozone originating from any natural sources or during methane oxidation, plus ozone produced by anthropogenic sources outside of the nation or continent*

*See next slides for more specific definitions

“U.S. Background Ozone” = USB

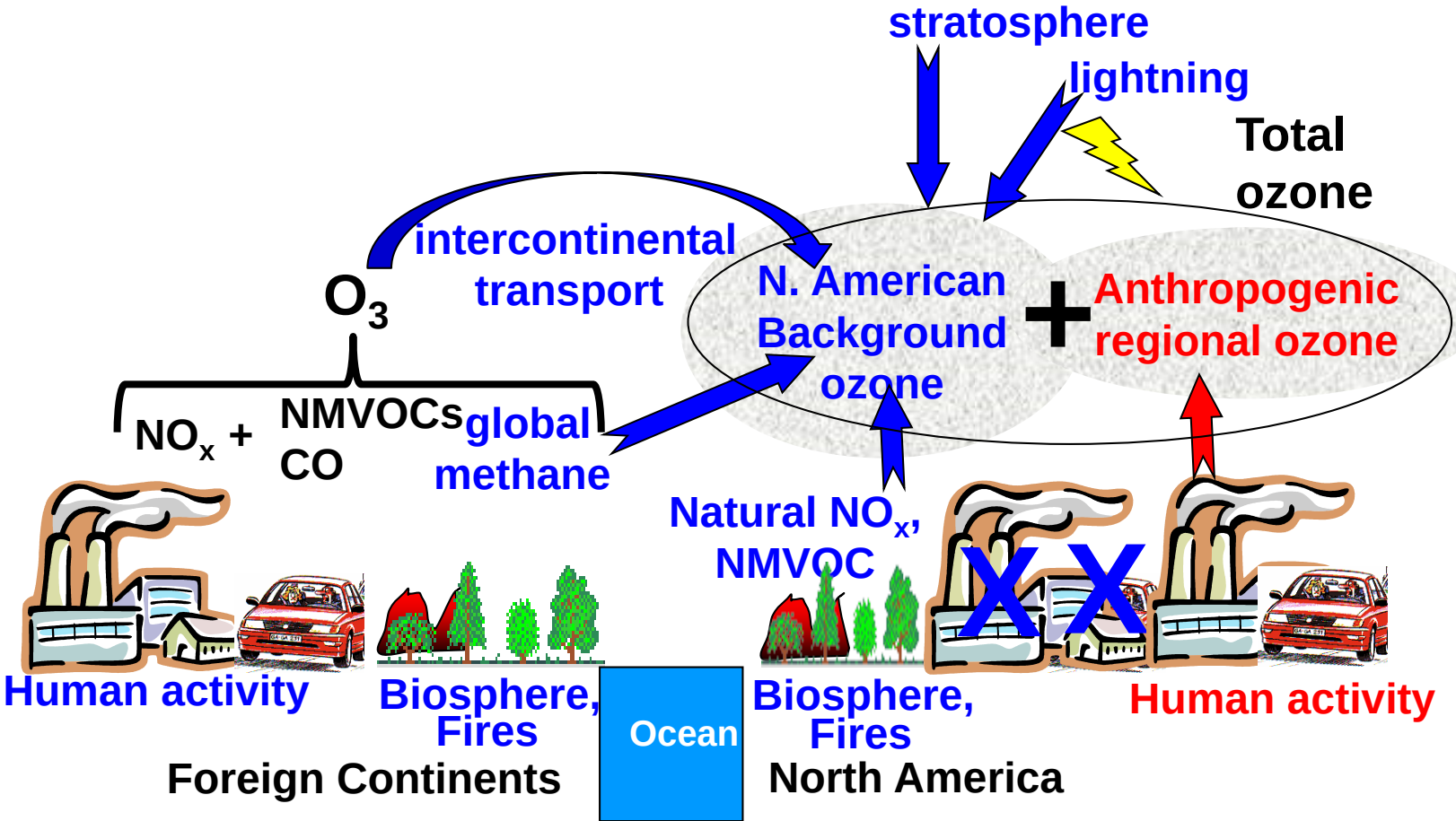


“North American Background Ozone” = NAB

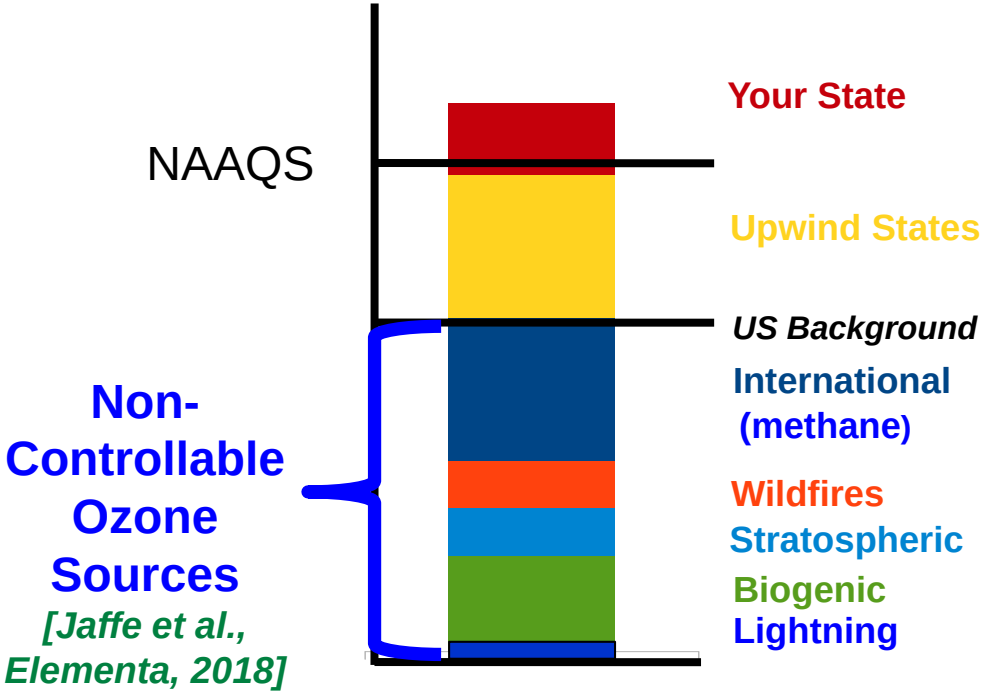


Fiore et al., EM, 2014

Total O_3 in surface air over North America = "NAB (N. Amer. Background)" + Anthropog. regional O_3



Air Quality Management Requires Source Apportionment



Clean Air Act Provisions

- **110 State Implementation Plans**
- **110(a)(2)(d) Interstate Transport**
- **182(h) Rural Transport Areas**
- **179(B) International Transport**
- **319 Exceptional Events**

We need to be able to describe the sources that contribute to each exceedance day.

adapted from T. Keating, U.S. EPA

How large is seasonal mean U.S. background ozone? Conclusions from recent review of the literature

Estimates for seasonal mean USB ozone:

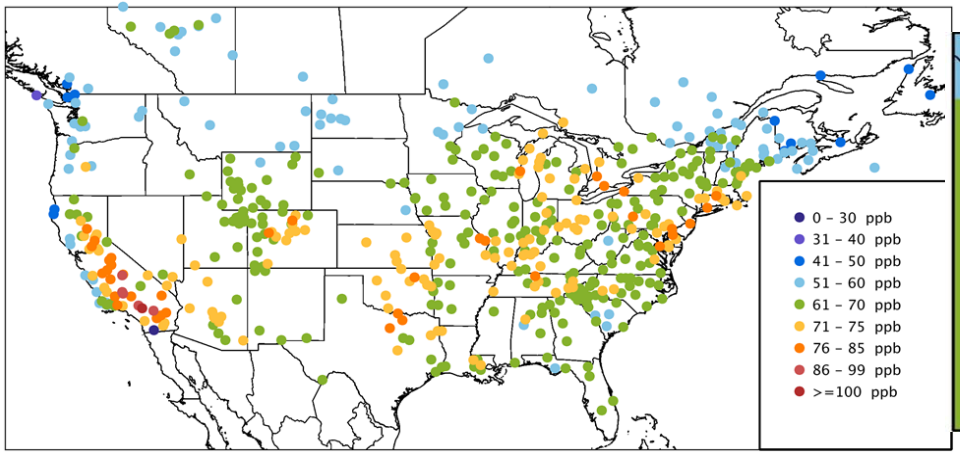
- **20-40 ppb at low elevation sites**
- **> 50 ppb at high altitude WUS sites**
- **± 10 ppb uncertainty**

Jaffe et al., Elementa, 2018

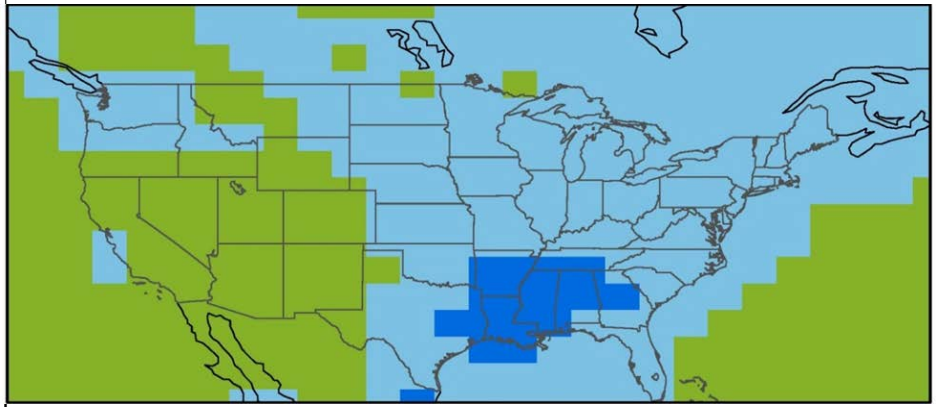
WUS = Western United States

Model estimated NAB annual 4th highest MDA8 ozone usually lower than observed (total) ozone (2010-2014 averages)

OBSERVED



MODELED NAB (GFDL-AM3)



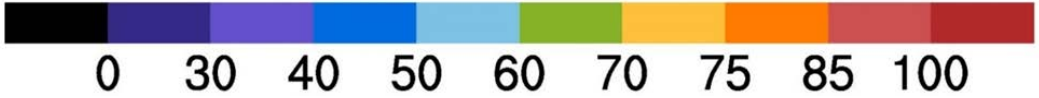


Figure 3 of Jaffe et al., 2018

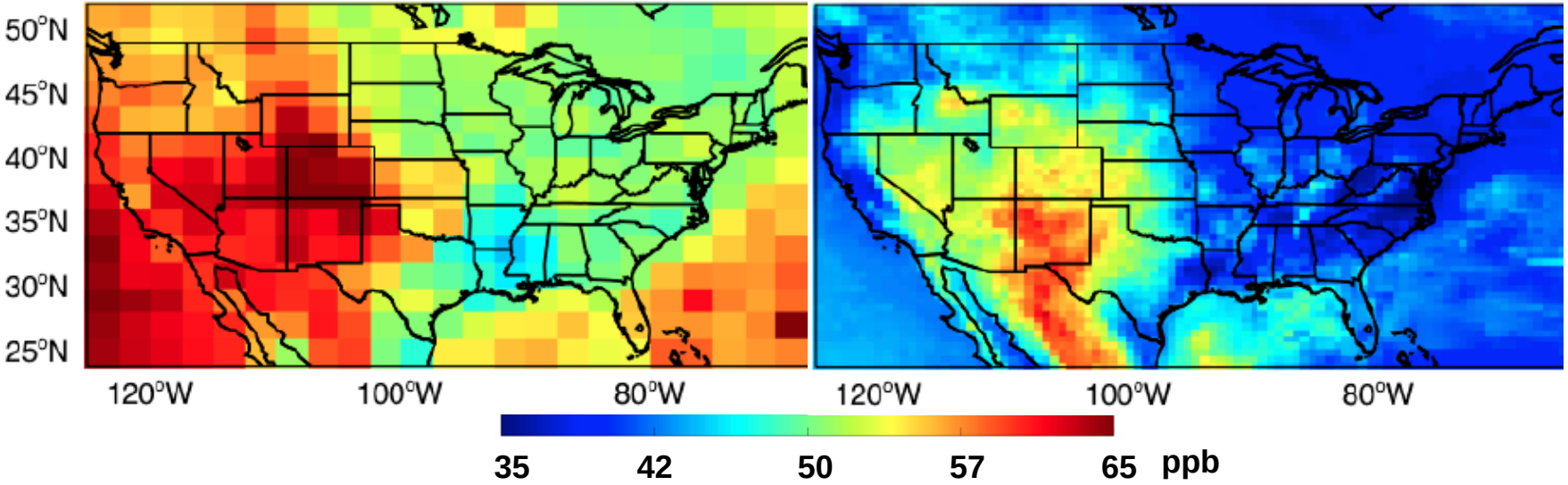
4th highest USB ozone > 60 ppb at some high altitude sites (large uncertainty)

North American Background estimates differ across models

(4th highest MDA8 ozone; Mar 1 to Aug 31, 2006)

MODEL 1 (GFDL AM3; ~2° x 2°)

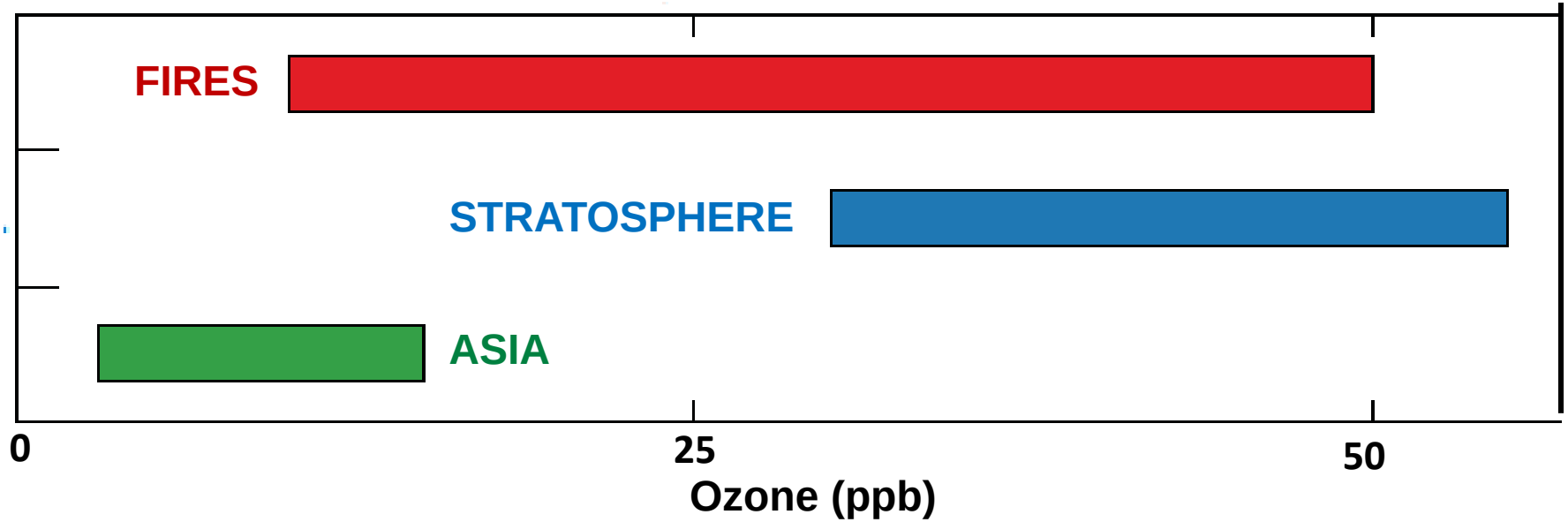
MODEL 2 (GEOS-Chem; ½° x ⅔°)



Surface ozone in simulations with N. American anthrop. emissions set to zero

Fiore et al., Atmospheric Environment, 2014

Wide range in model estimates of individual background sources, in part because these sources vary strongly in space and time



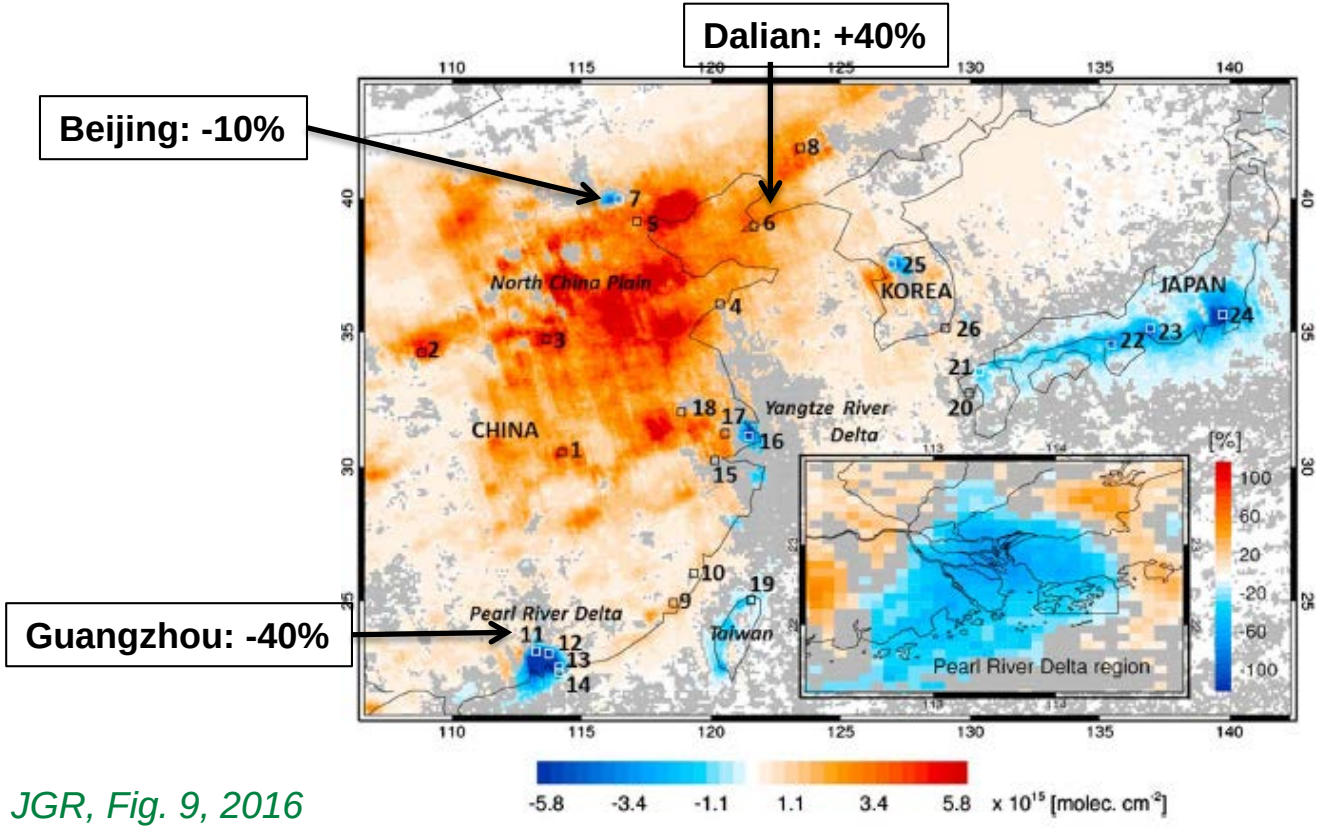
Poor understanding of ozone produced from fires

Stratospheric influence is highest in spring, early summer at high-altitude (Western US)

Asian pollution may "push" a region over the NAAQS level (but not by itself!)

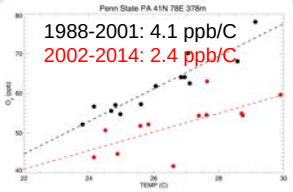
Lin et al., JGR, 2012ab; Fiore et al., EM, 2014

Upwind international emissions are changing rapidly: 2005 → 2014 changes in satellite NO_2 columns over China

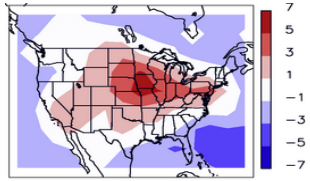


Duncan et al., JGR, Fig. 9, 2016

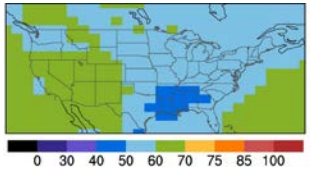
Summary #2



- **Continued NO_x reductions guard against 'climate penalty' on warm season surface ozone**



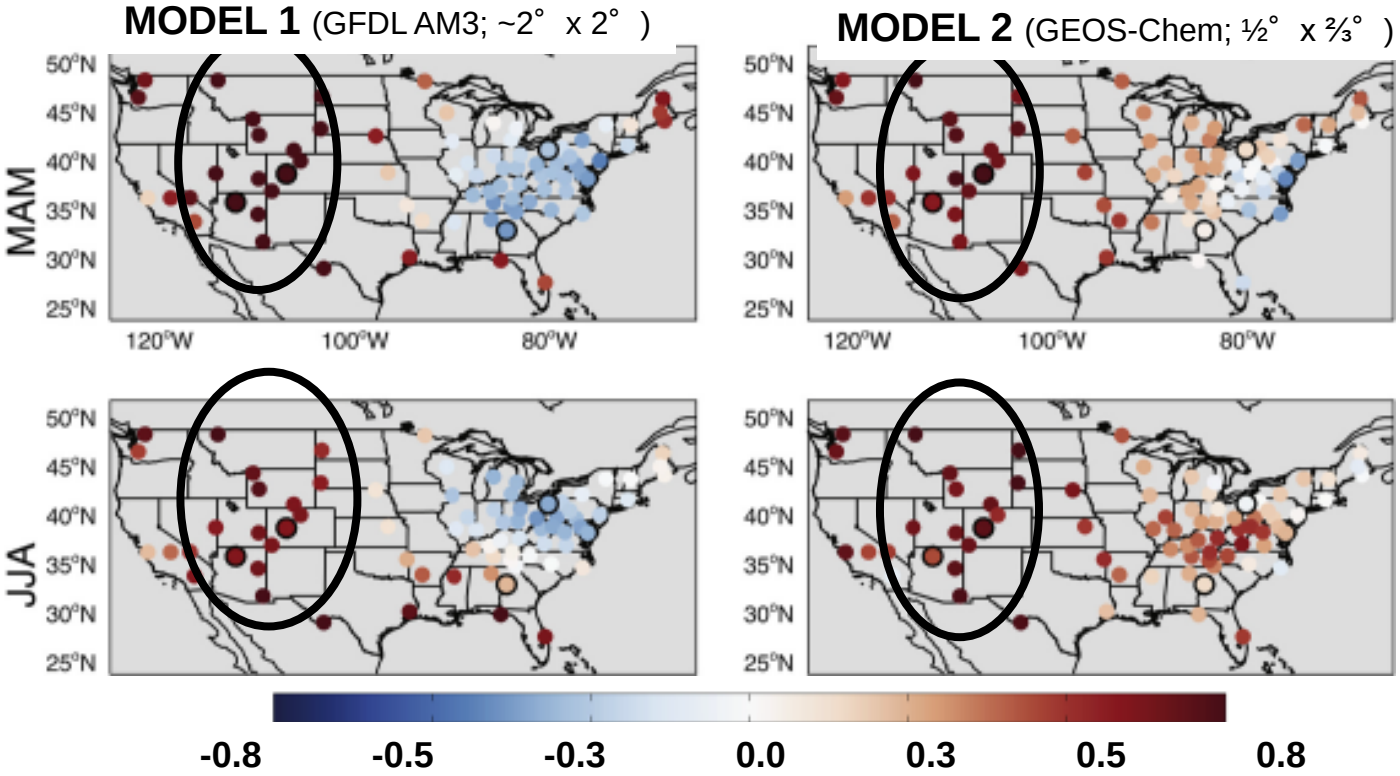
- **Climate change tends to increase ozone in polluted regions**



- **U.S. background ozone varies in space and time**

→ Highest at high-altitude Western US where stratospheric and transboundary transport are usually max (spring-early summer); see also Atmos. Chem. Phys. HTAP/MICS/AQMEII special issue

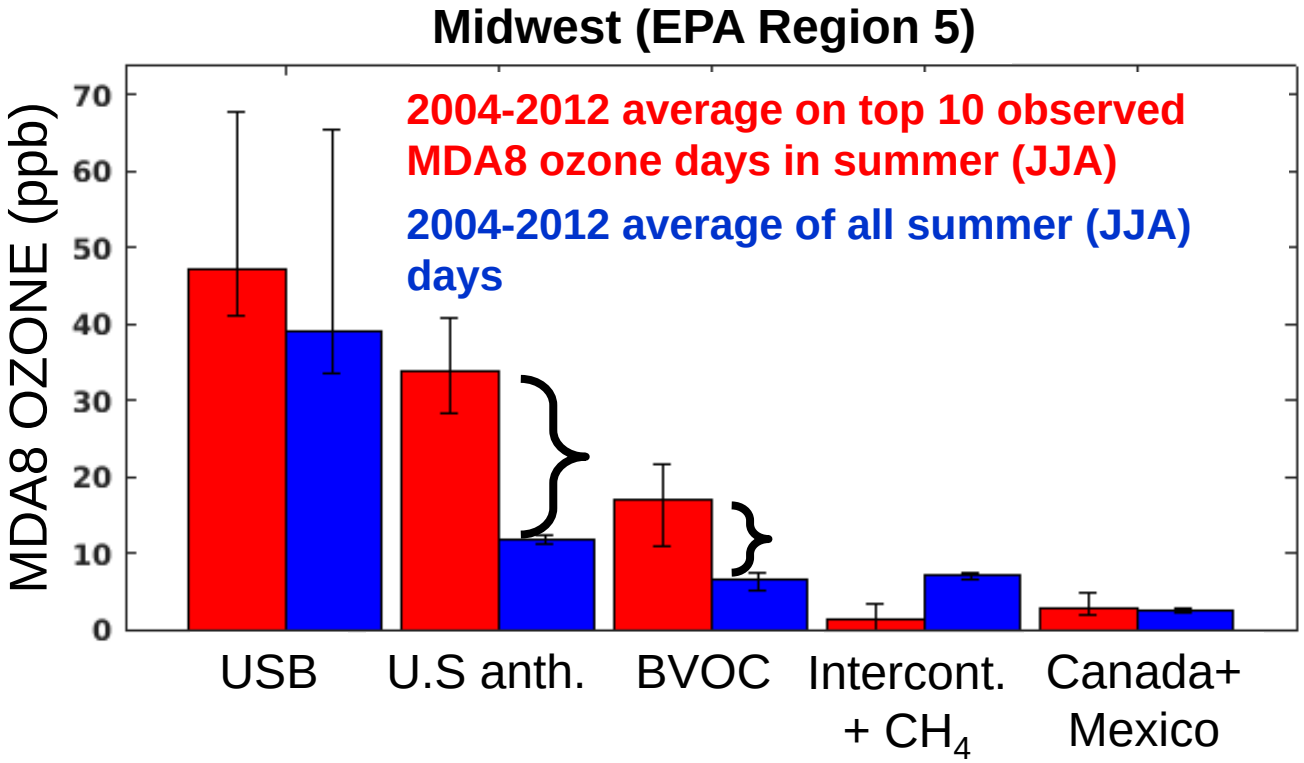
Background drives much of day-to-day variability in total surface ozone over high-altitude Western US in two models



Correlation coefficient (r) of simulated TOTAL & NAB MDA8 ozone in surface air; models are sampled at CASTNet sites

Fiore et al., Atm. Env., 2014

Top 10 observed MDA8 days in summer are enhanced by regional production, not transboundary transport



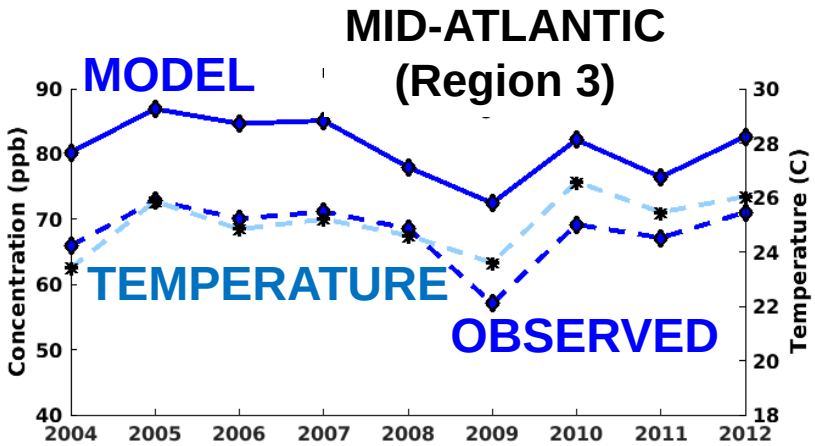
ACPD = Atmospheric Chemistry and Physics Discussions

Estimated with a series of 2004-2012 sensitivity simulations in the GEOS-Chem model (2°x2.5°), regional averages sampled at AQS monitors

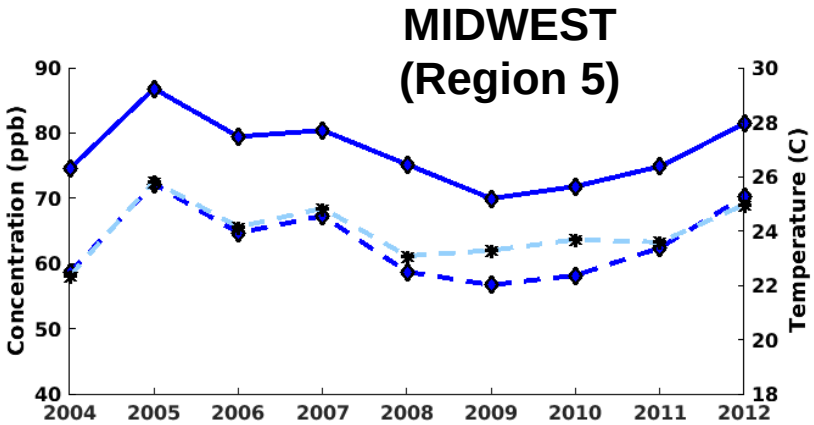
Guo et al., ACPD, 2018

The GEOS-Chem model captures much of the year-to-year variability in the top 10 observed MDA8 days in summer

2004-2012 simulations in the GEOS-Chem model (2°x2.5°);
regional averages sampled at AQS monitors



Model vs. observed: r = 0.88



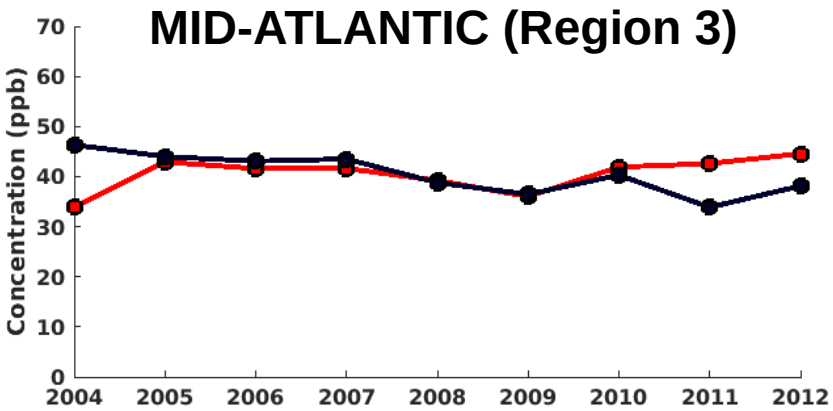
Model vs. observed: r = 0.96

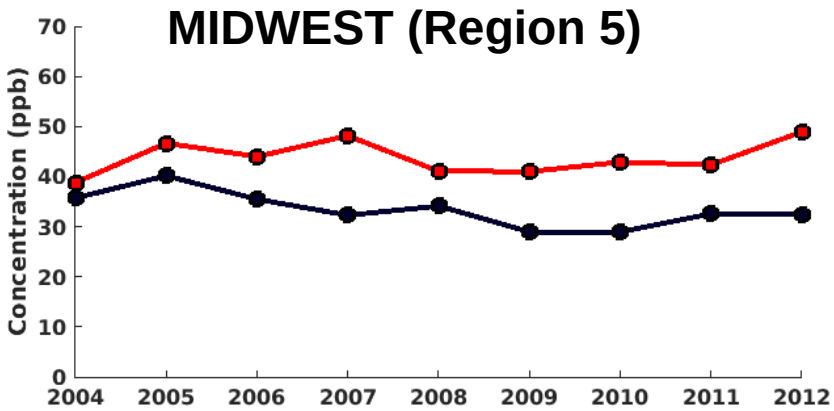
- → **Despite bias, model captures "wiggles",**
- → **Not much of a trend (only 9 years; yet NO_x declined)**
- → **Correlated with temperature**

Guo et al., ACPD, 2018

In the model, ozone produced from U.S. anthropogenic emissions declines from 2004 → 2012 but USB rises

Regionally averaged on the highest 10 observed MDA8 days during summer (JJA)





USB Ozone

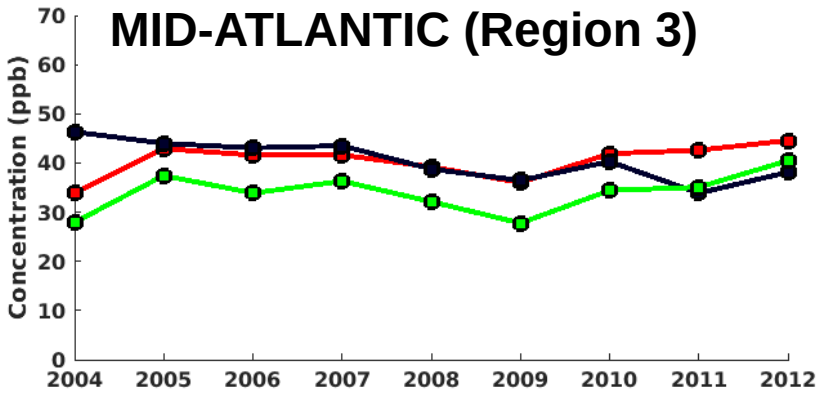
Ozone from U.S. anthrop. emissions

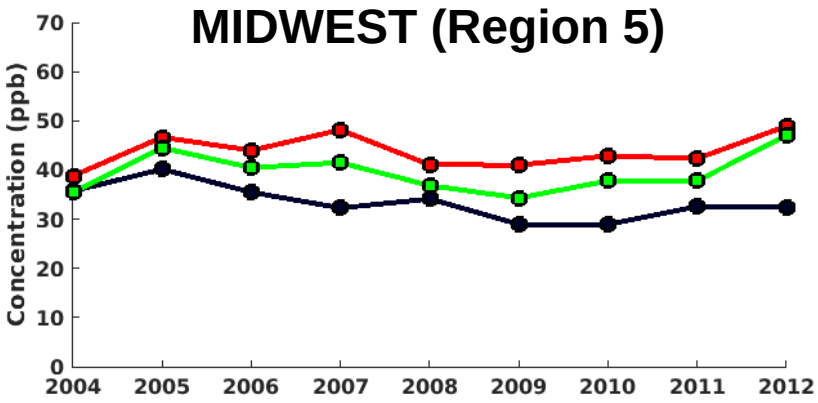
Estimated with a series of 2004-2012 sensitivity simulations in the GEOS-Chem model (2°x2.5°), regional averages sampled at AQS monitors

Guo et al., ACPD, 2018

Warmer regional climate may raise USB ozone by enhancing temperature-sensitive biogenic VOC and NO_x emissions

Regionally averaged on the highest 10 observed MDA8 days during summer (JJA)





USB Ozone

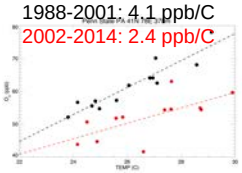
Ozone from U.S. ANTHROP. EMISSIONS

NATURAL Ozone (includes BVOC, soil NO_x)

Estimated with a series of 2004-2012 sensitivity simulations in the GEOS-Chem model (2°x2.5°), regional averages sampled at AQS monitors

Guo et al., ACPD, 2018

Summary #3



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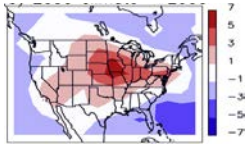
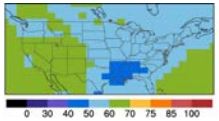


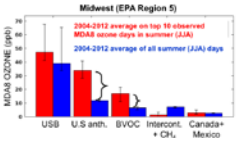
- **Climate change tends to increase ozone in polluted regions**

→ May raise "natural" background



- **U.S. background ozone varies in space and time**

→ Highest at high-altitude WUS where stratospheric and transboundary transport are usually max (spring-early summer); ACP special issue (HTAP/MICS/AQMEII)

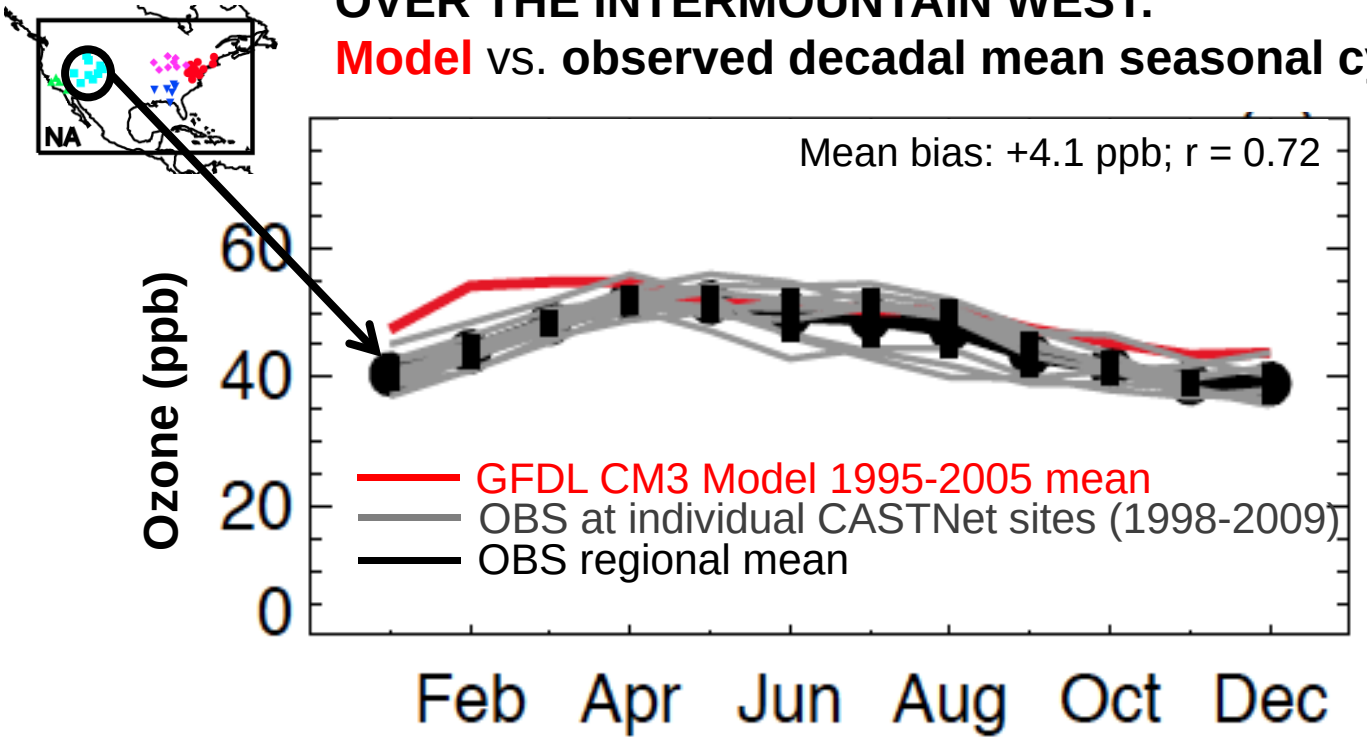


- **"Top 10" events enhanced by regional ozone production, not transboundary transport**

→ Meteorology + weather-sensitive emissions, chemistry, deposition

What might the future hold? Up first: Model Evaluation

OVER THE INTERMOUNTAIN WEST:
Model vs. **observed decadal mean seasonal cycle**

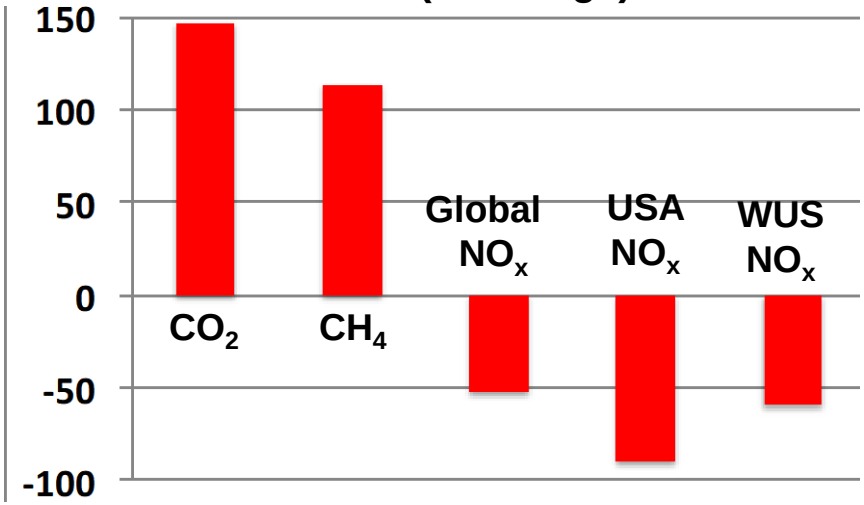


Clifton et al., Geophysical Research Letters, 2014

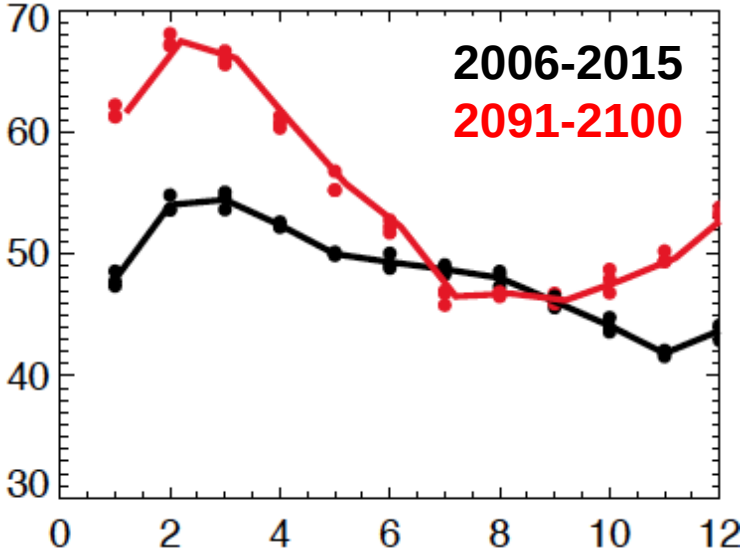
A chemistry-climate model projects 21st Century WUS ozone increase in cooler months despite U.S. NO_x decreases

EMISSION PROJECTIONS (RCP8.5)

2005 to 2100 (% change)



MONTHLY MEAN OZONE (ppb)

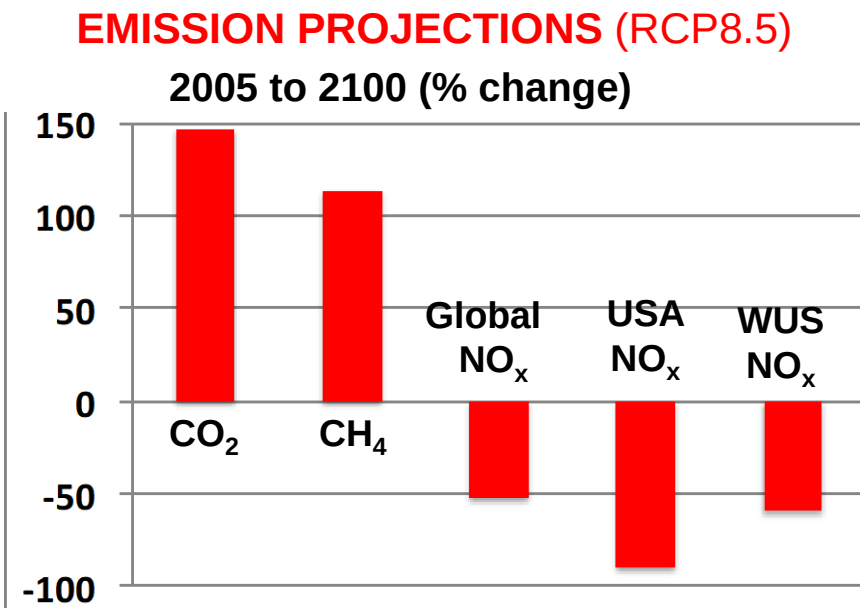


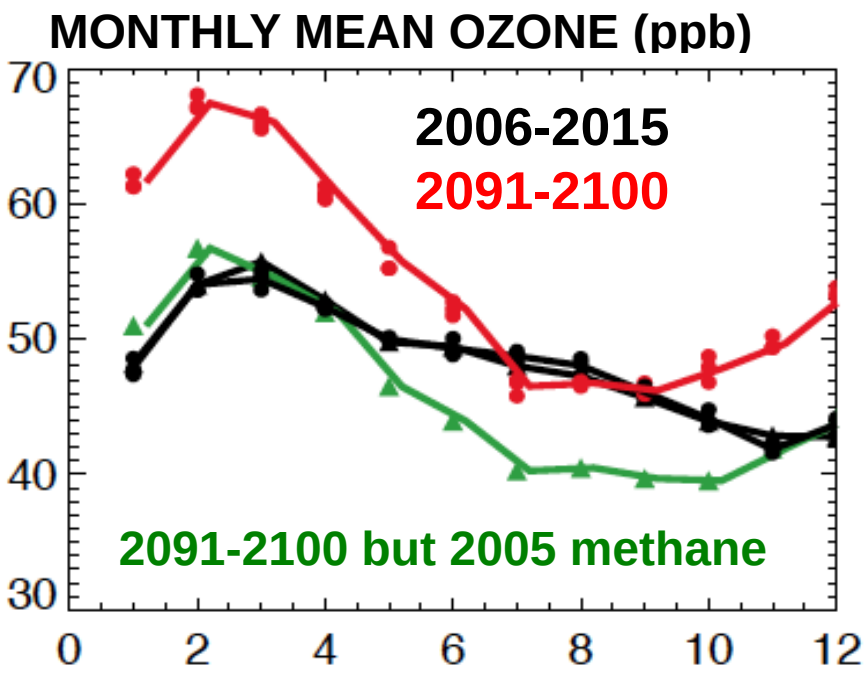
GFDL CM3 chemistry-climate model over the **high-altitude WUS**

Clifton et al., GRL, 2014

GRL = Geophysical Research Letters

Over the high-altitude WUS, cool season ozone increases as global methane rises





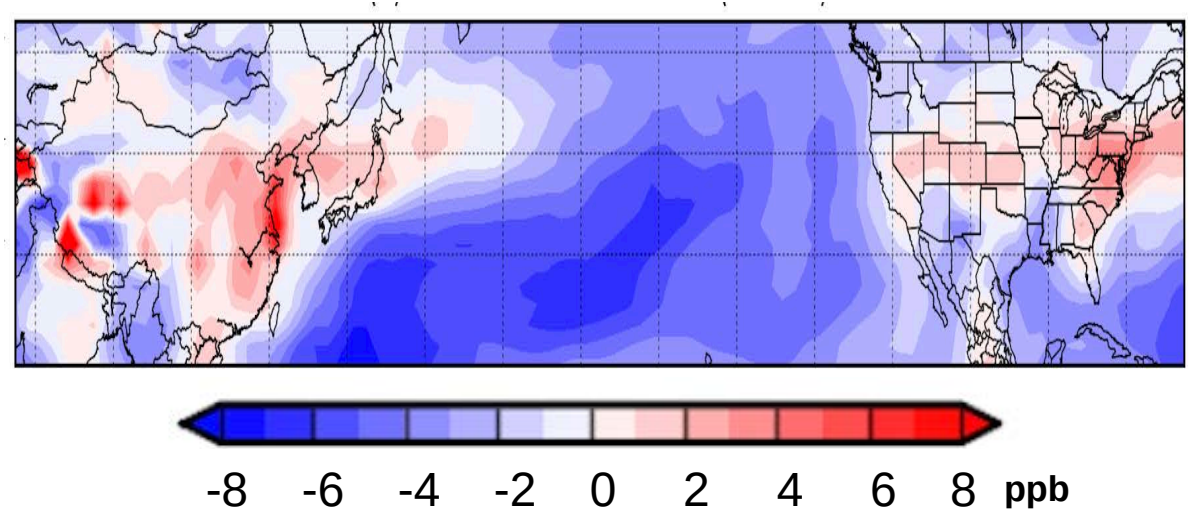
→In the warm season, more-than-doubling of global methane offsets NO_x-driven decreases

Clifton et al., GRL, 2014

Climate change (rising global mean surface temperature) tends to increase ozone pollution but decrease background

Change in summer (JJA) MDA8 surface ozone from 2010s →2050s

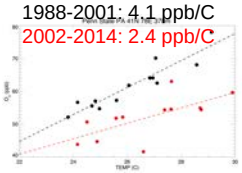
+1.5 °C Global mean surface temperature (RCP8.5 scenario)



Estimated with the GFDL AM3 model

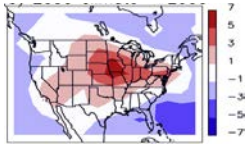
Dan Westervelt, LDEO

Summary: Global dimensions to ground-level ozone: Transboundary transport and climate change



- **Continued NO_x reductions guard against 'climate penalty' on warm season surface ozone**

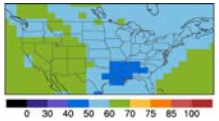
→ May incur additional "penalty" from rising global methane



- **Climate change tends to increase ozone in polluted regions**

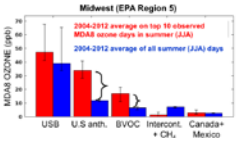
→ May raise "natural" background, lowers transported background

→ How will the biosphere respond? (source, but also a key sink!)



- **U.S. background ozone varies in space and time**

→ Highest at high-altitude WUS where stratospheric and transboundary transport are usually max (spring-early summer); ACP special issue (HTAP/MICS/AQMEII)



- **"Top 10" events enhanced by regional ozone production, not transboundary transport**

→ Meteorology + weather-sensitive emissions, chemistry, deposition

→ Advance process-level understanding (daily to multi-decadal time scales)

→ Systematic uncertainty assessments (error-vs-variability; see *Jaffe et al., 2018*)