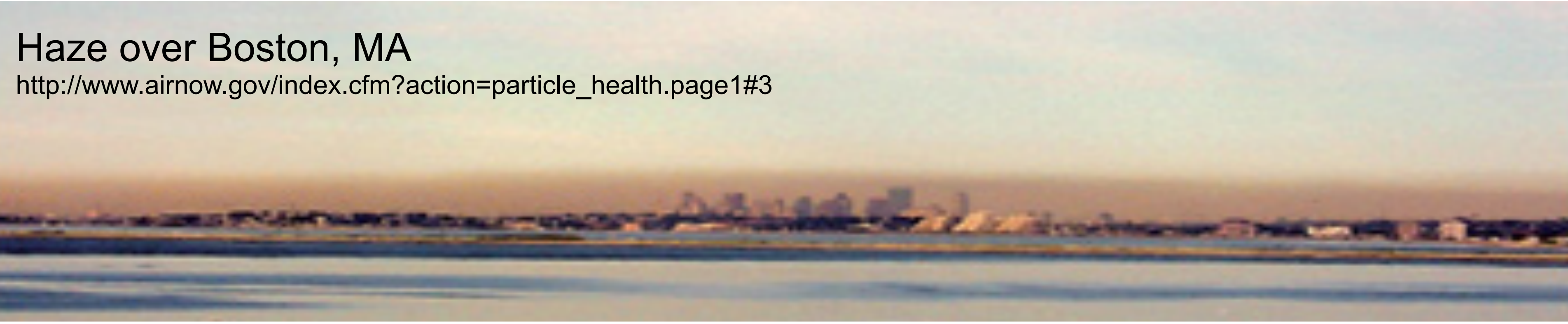

U.S. air pollution and climate: Trends, variability, and interactions

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Acknowledgments: Olivia Clifton, Gus Correa, Nora Mascioli, Lee Murray, Luke Valin (CU/LDEO), Harald Rieder (U Graz, Austria), Elizabeth Barnes (CSU), Alex Turner (Harvard) Larry Horowitz (GFDL), Vaishali Naik (UCAR/GFDL), Meiyun Lin (Princeton/GFDL)

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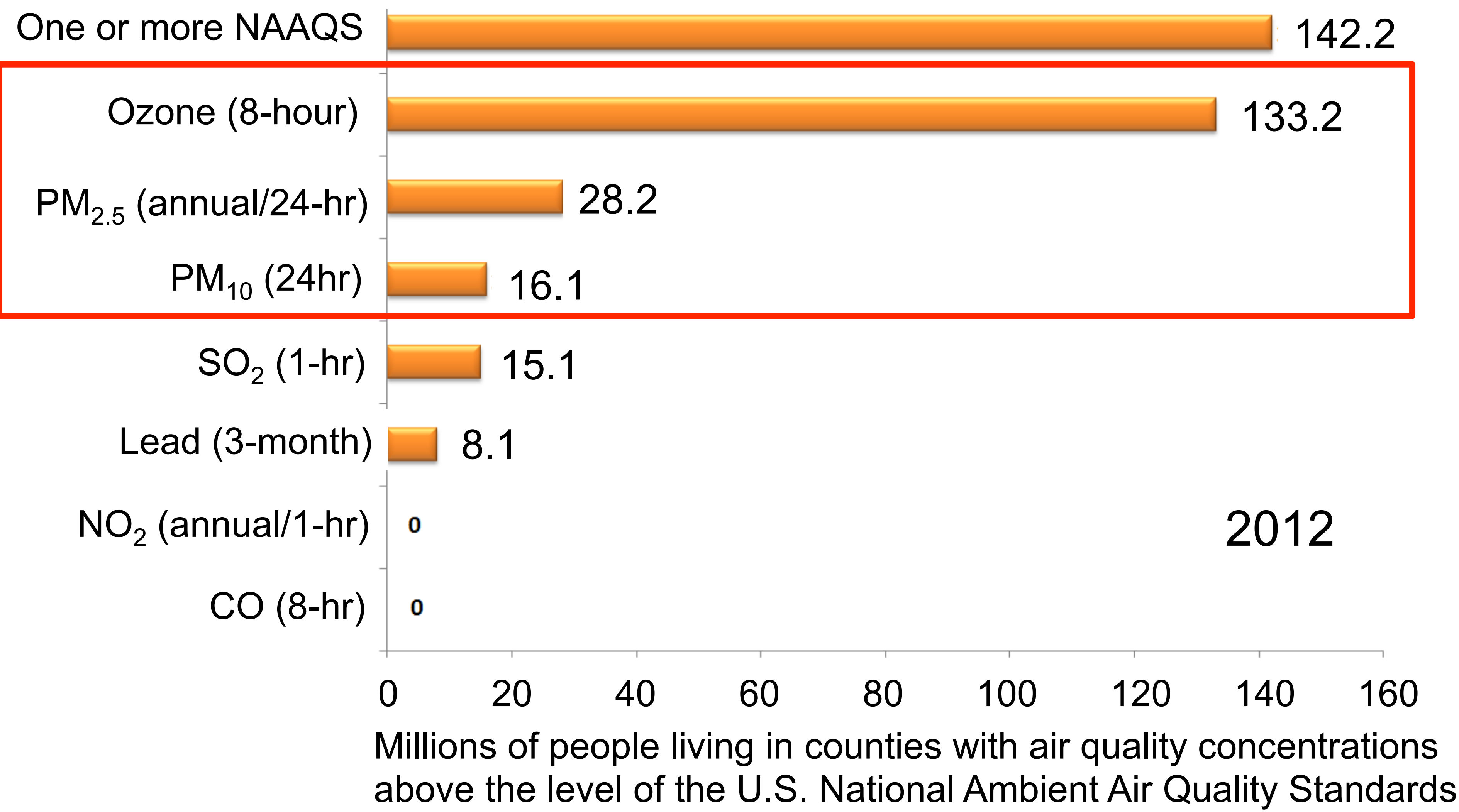
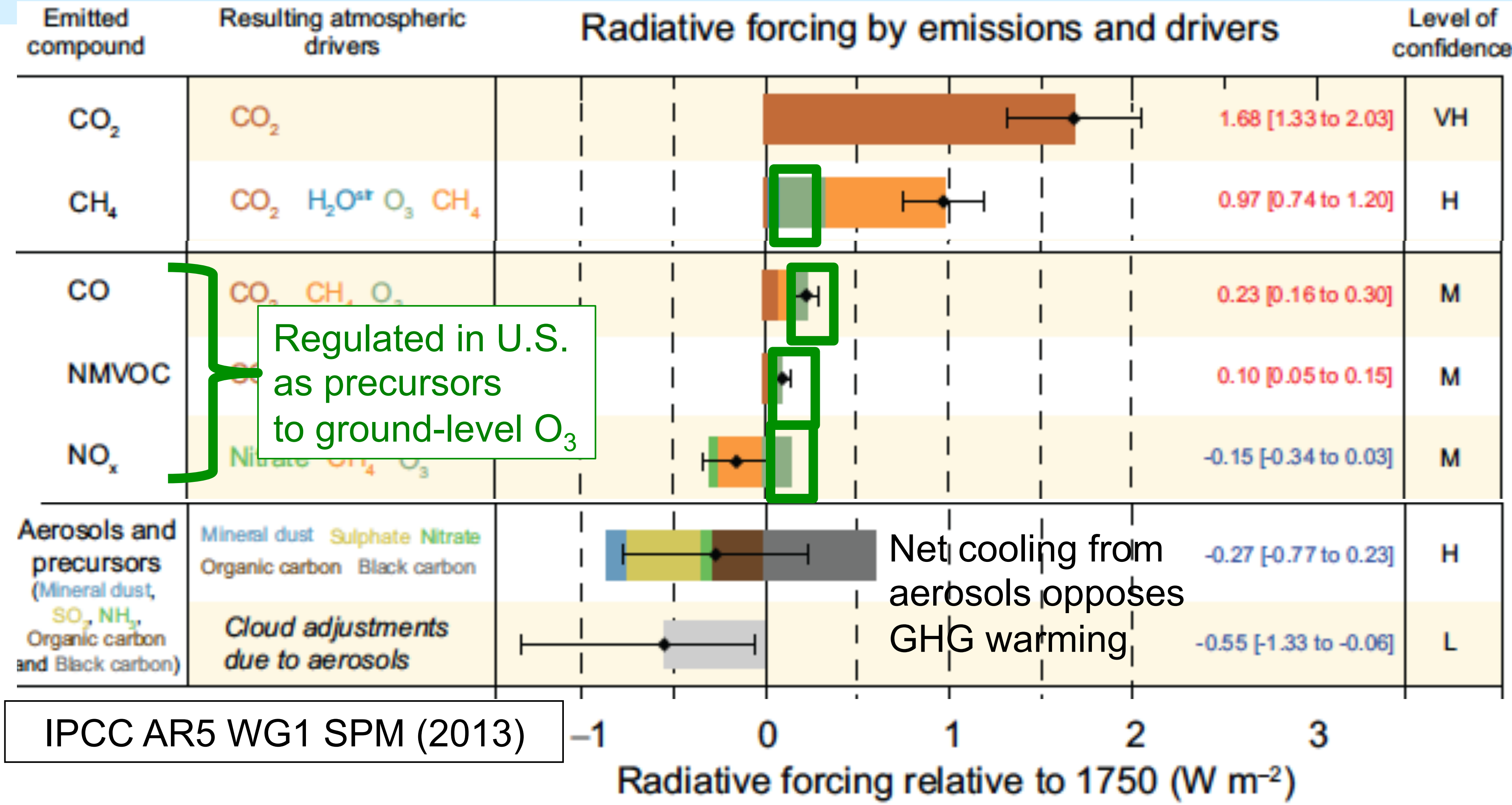
EPS Colloquium, Harvard
Cambridge, MA
May 5, 2014

Ozone and Particulate Matter (PM) are the top two U.S. air pollutants



EPA, 2014: http://www.epa.gov/airtrends/aqtrends.html#comparison

Air pollutants and their precursors contribute to climate forcing from preindustrial to present

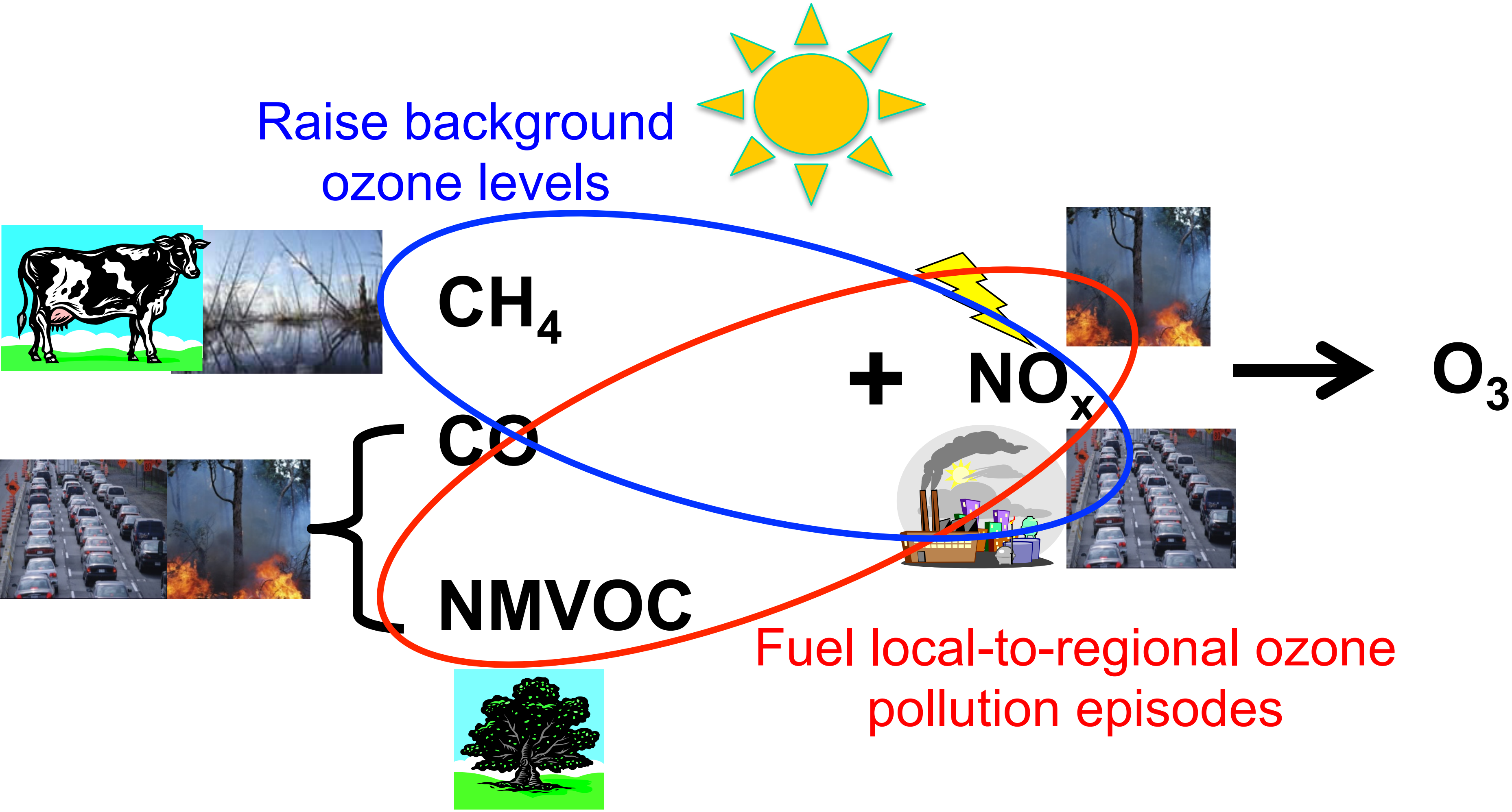


← Cooling Warming →

Anthropogenic greenhouse gases methane + tropospheric ozone together contribute ~1/2 (abundance) to 2/3 (emissions) of CO_2 radiative forcing

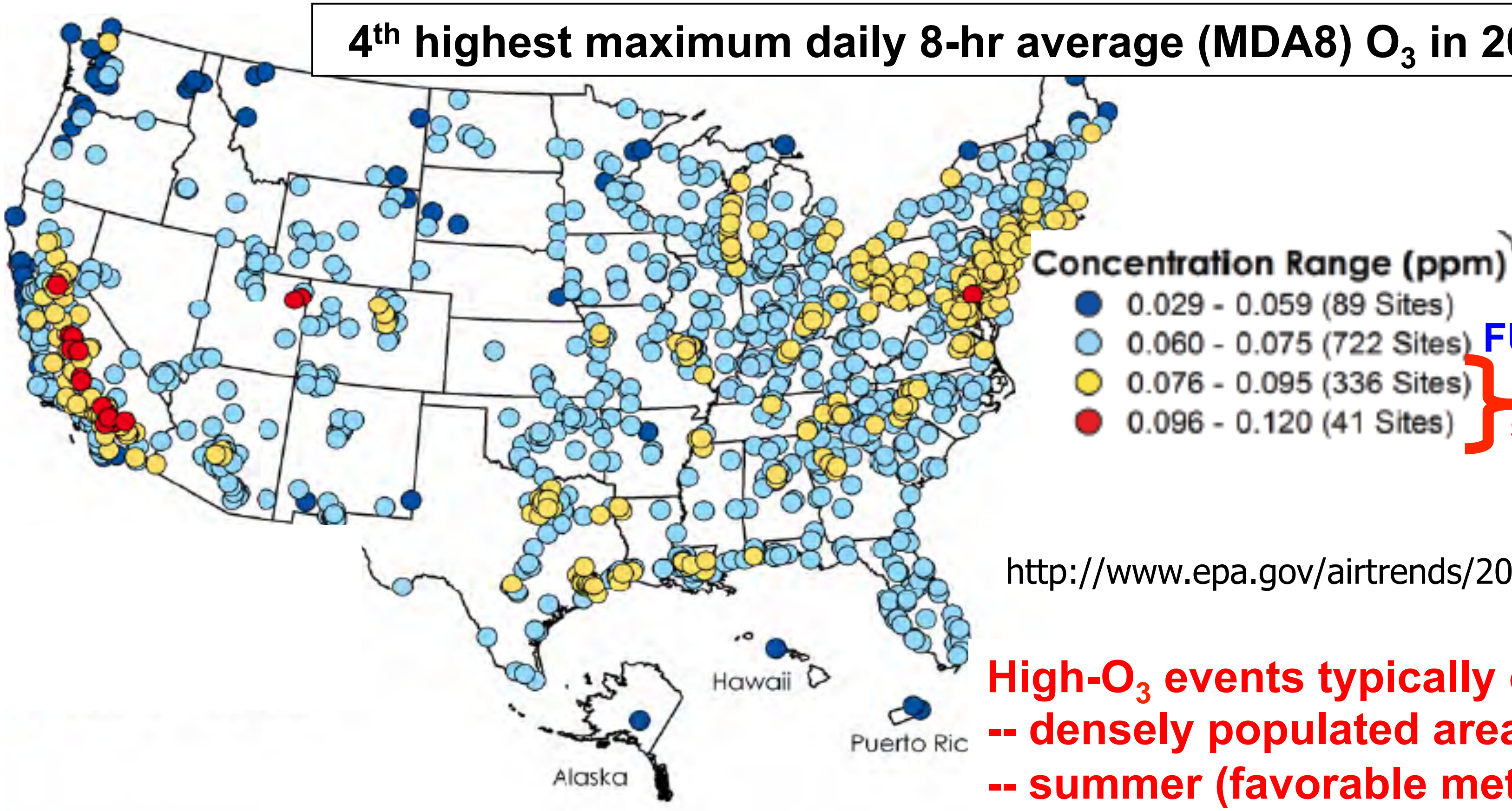
(Lifetimes must also be considered: CO_2 dominates long-term)

Ground-level O_3 is photochemically produced from regional sources (natural + anthrop.) that build on background levels



The U.S. ozone smog problem is spatially widespread

4th highest maximum daily 8-hr average (MDA8) O_3 in 2010



FUTURE?

Exceeds standard (24% of sites)

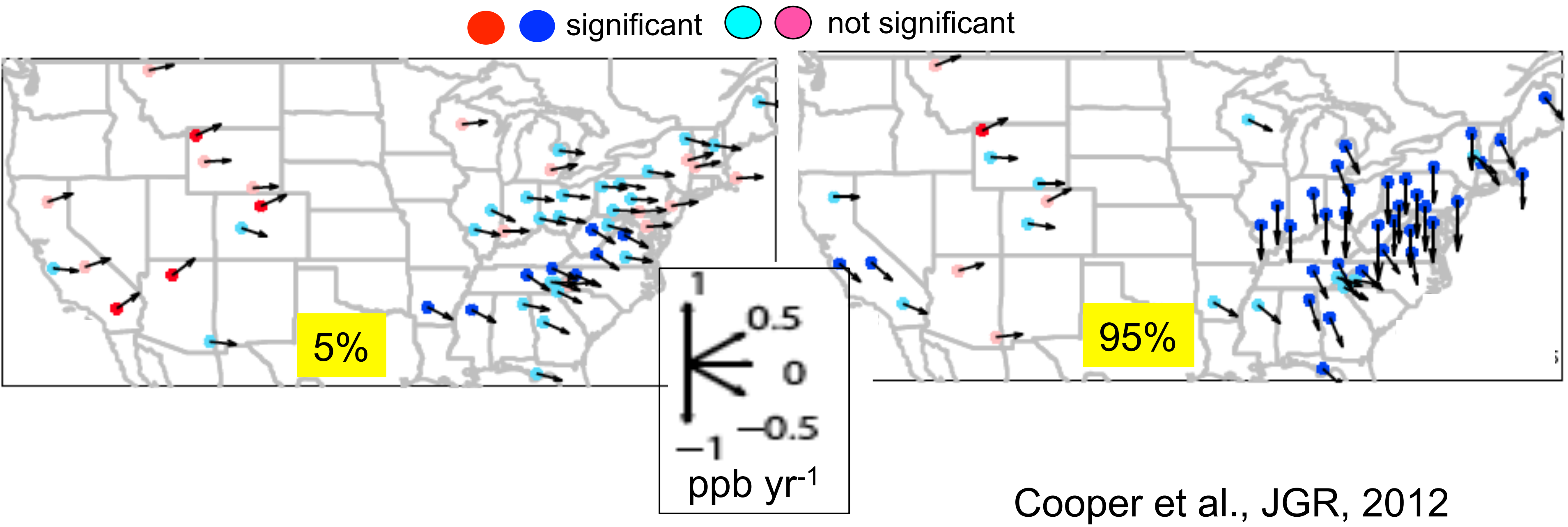
http://www.epa.gov/airtrends/2011/index.html

High-O_3 events typically occur in
-- densely populated areas (sources)
-- summer (favorable meteorology)

→ Lower threshold (60-70 ppb [Federal Register, 2010]**) would greatly expand non-attainment regions**

Estimated benefits from a ~1 ppb decrease in surface O_3:
~ $1.4 billion (agriculture, forestry, non-mortality health) within U.S. [West and Fiore, 2005]
~ 500-1000 avoided annual premature mortalities within N. America [Anenberg et al., 2009]

Trends in summer daytime (11am-4pm) average ozone at rural U.S. monitoring sites (CASTNet): 1990 to 2010

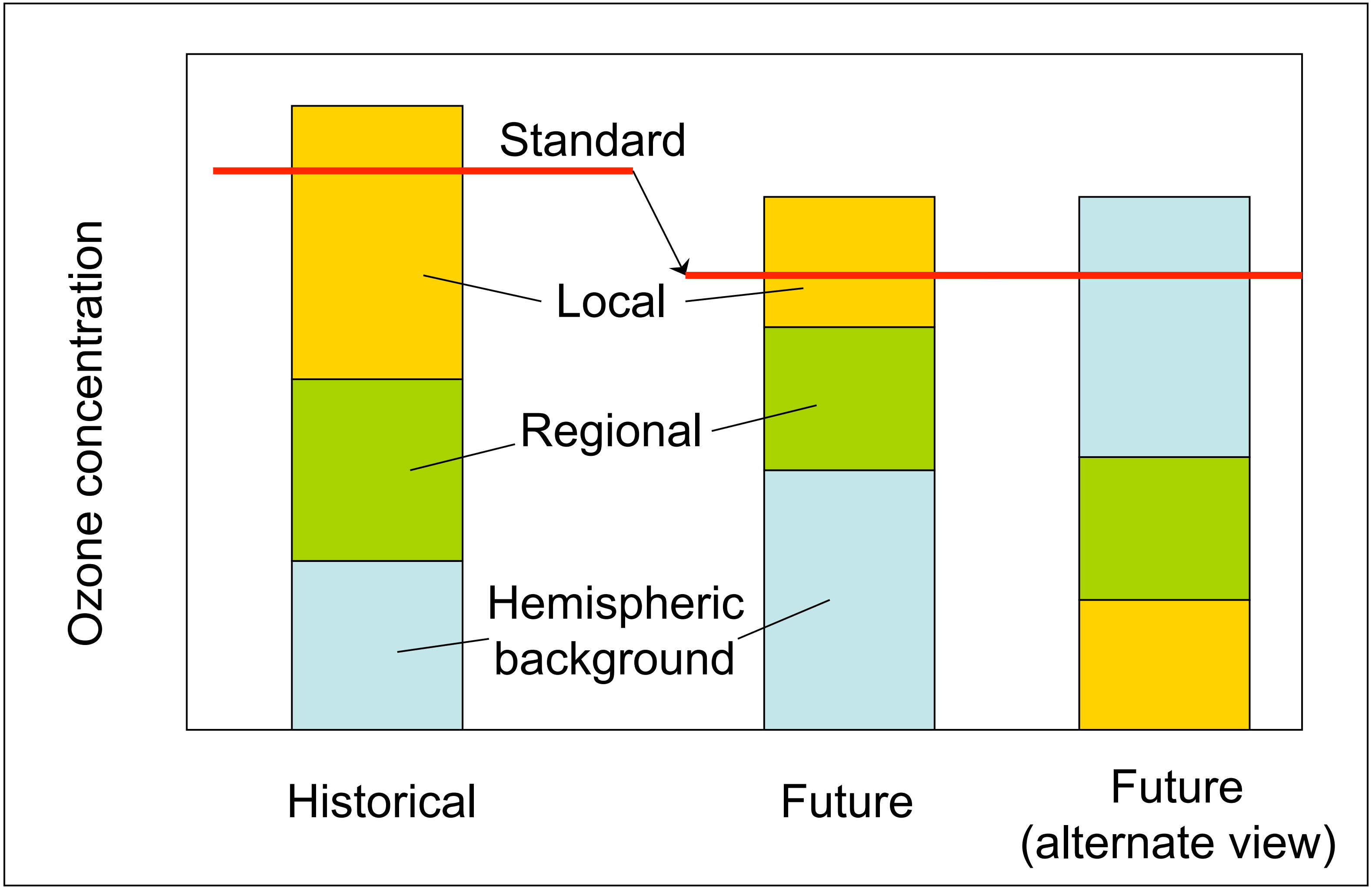


Cooper et al., JGR, 2012

→ Success in decreasing highest levels, but baseline rising (W. USA)

→ Decreases in EUS attributed in observations and models to NO_x emission controls in late 1990s, early 2000s [e.g., Frost et al., 2006; Hudman et al., 2007; van der A. et al., 2008; Stavrakou et al., 2008; Bloomer et al., 2009, 2010; Fang et al., 2010]

The "tightening vise" of ozone management

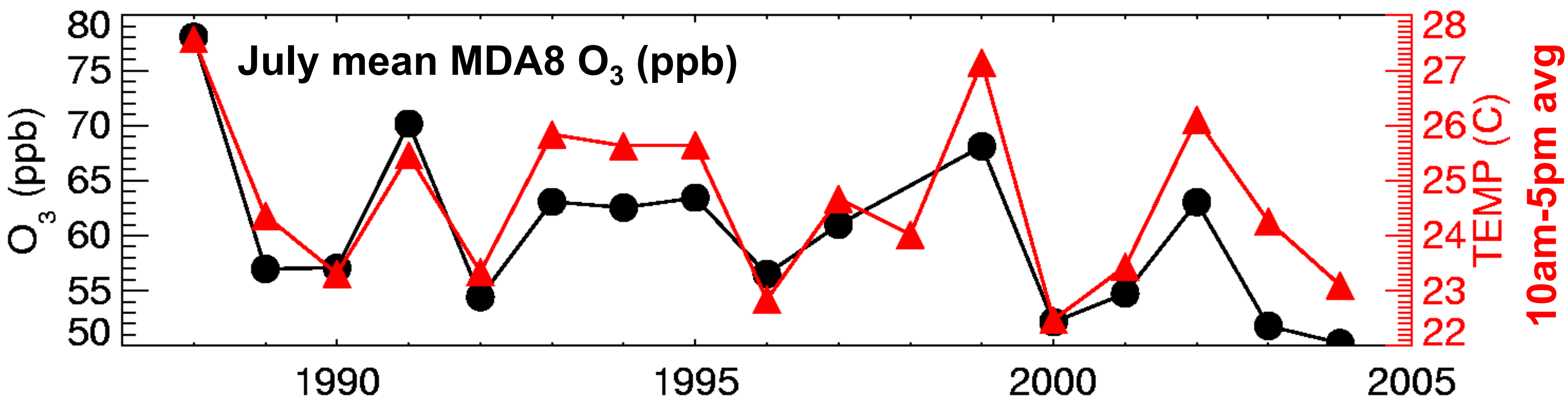


→ Future may require concerted efforts to lower background

Keating, T. J., J. J. West, and A. Farrell (2004) Prospects for international management of intercontinental air pollutant transport, in A. Stohl, Ed., *Intercontinental Transport of Air Pollution*, Springer, p. 295-320.

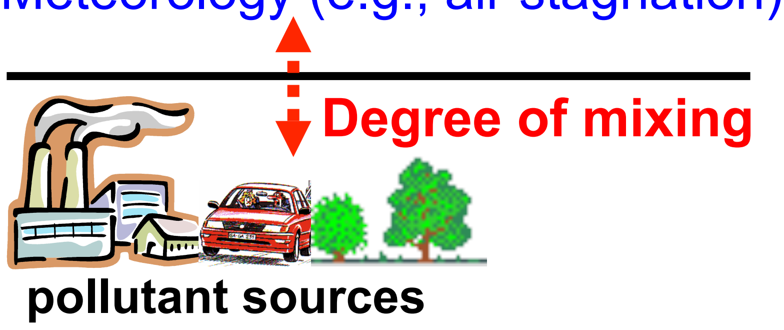
Surface temperature and O_3 are correlated on daily to inter-annual time scales in polluted regions [e.g., Bloomer et al., 2009; Camalier et al., 2007; Cardelino and Chameides, 1990; Clark and Karl, 1982; Korsog and Wolff, 1991]

Observations at U.S. EPA CASTNet site Penn State, PA 41N, 78W, 378m

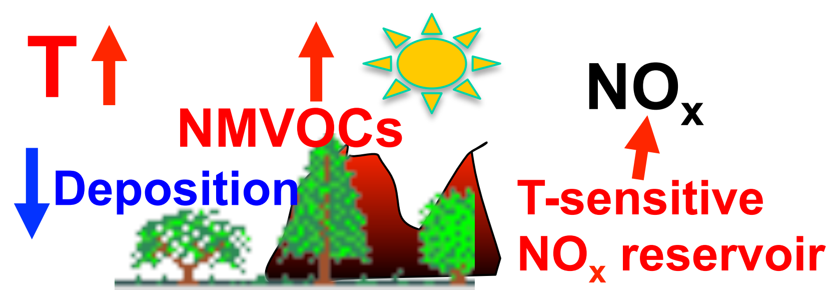


What drives the observed O_3-Temperature correlation?

1. Meteorology (e.g., air stagnation)



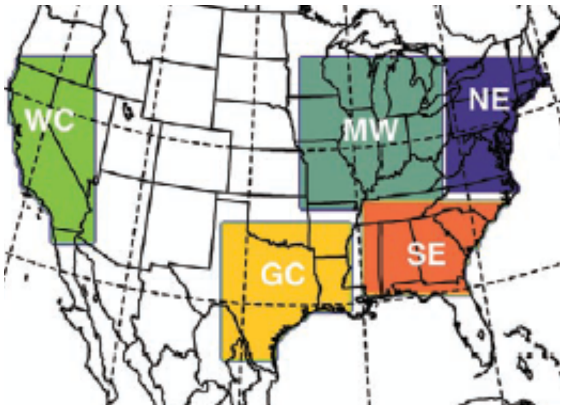
2. Feedbacks (Emis, Chem, Dep)



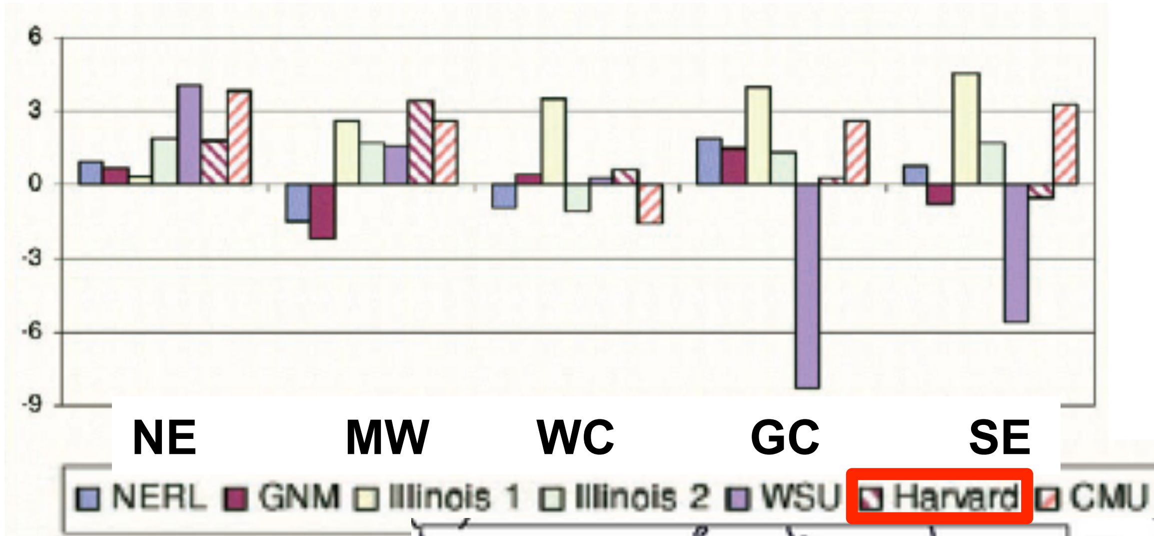
→ Implies that changes in climate will influence air quality

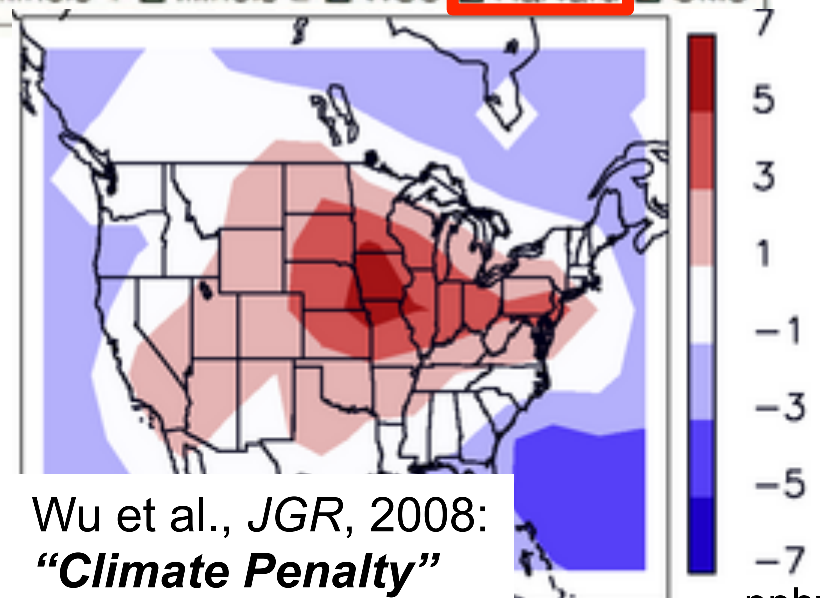
Models estimate a ‘climate change penalty’ (+2 to 8 ppb) on surface O_3 over U.S. but often disagree in sign regionally

Modeled changes in summer mean of daily max 8-hour O_3 (ppb; future – present)



Weaver et al., BAMS, 2009



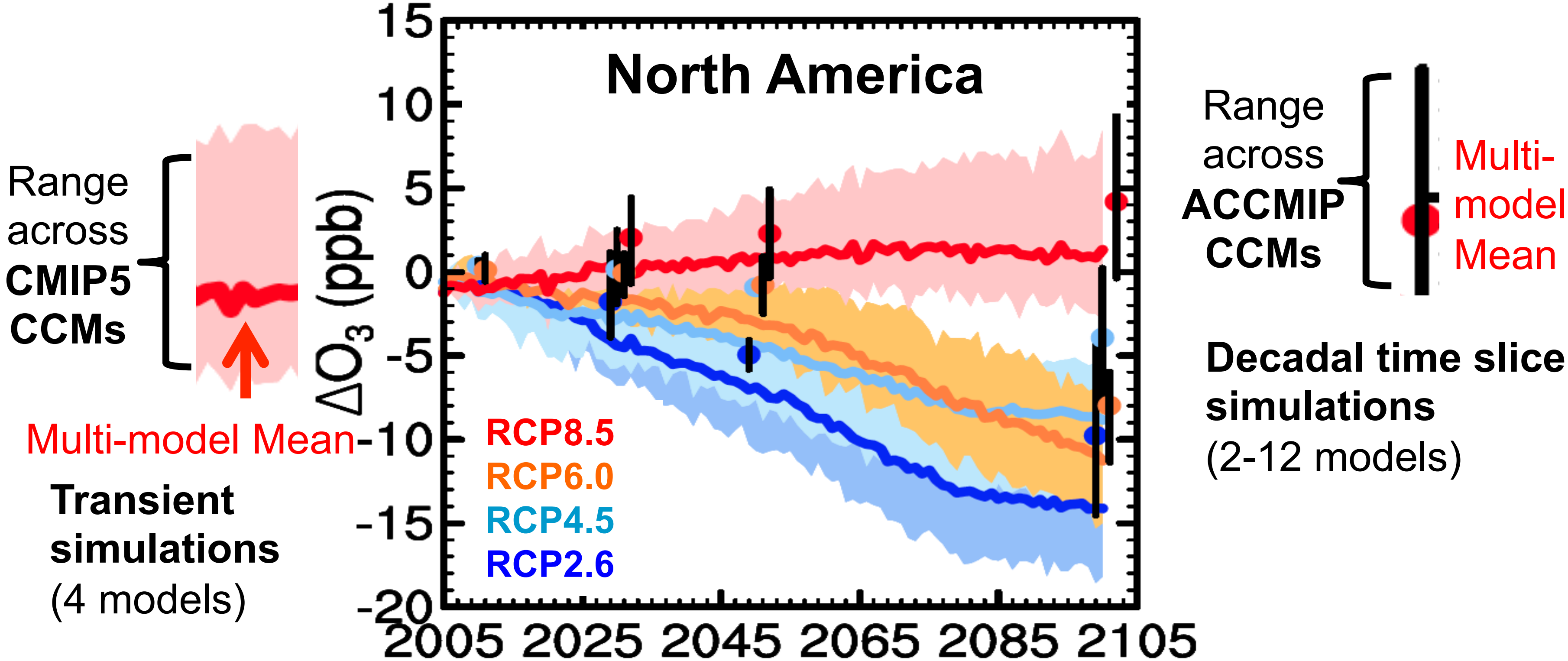


Wu et al., *JGR*, 2008: ***“Climate Penalty”***

- **Uncertain regional climate responses (and feedbacks) to global warming**
- **Model estimates typically based on a few years of present and future (often 2050s) meteorology from 1 realization of 1 GCM**

‘First-look’ future projections with current chemistry-climate models for N. Amer. Surface O_3 (emissions + climate change)

Annual mean spatially averaged (land only) O_3 in surface air



V. Naik, adapted from Fiore et al., 2012; Kirtman et al., 2013 (IPCC WG1 Ch 11)

→ **A major advance to have coupled atmospheric chemistry in climate models**
→ **Trends mainly reflect ozone precursor emission pathways**
→ **Annual, continental-scale means reveal little about drivers of regional change**

How and why might extremes change?

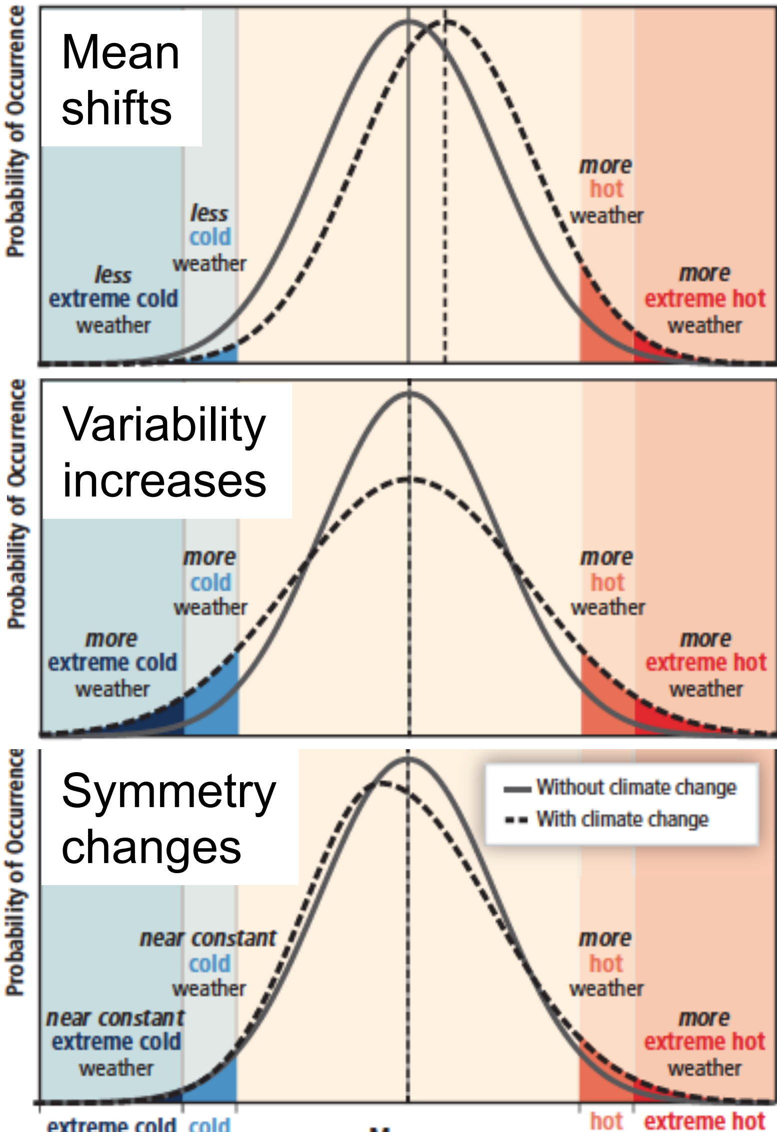


Figure SPM.3, IPCC SREX 2012
http://ipcc-wg2.gov/SREX/

→ How do different processes influence the overall distribution?

- Meteorology (*e.g.*, stagnation vs. ventilation)
- Feedbacks (Emis, Chem, Dep)
- Changing global emissions (baseline)
  → Shift in mean?
- Changing regional emissions (episodes)
  → Change in symmetry?

→ How do changes in the balance of these processes alter the seasonal cycle?

- NE US: regional photochemistry (summer) vs. transported background

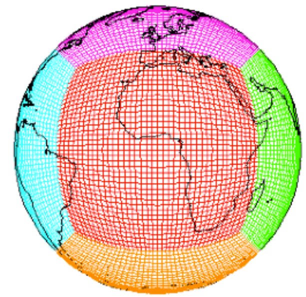
→ Does climate forcing from air pollutants influence regional climate extremes?

- Aerosols vs. greenhouse gases

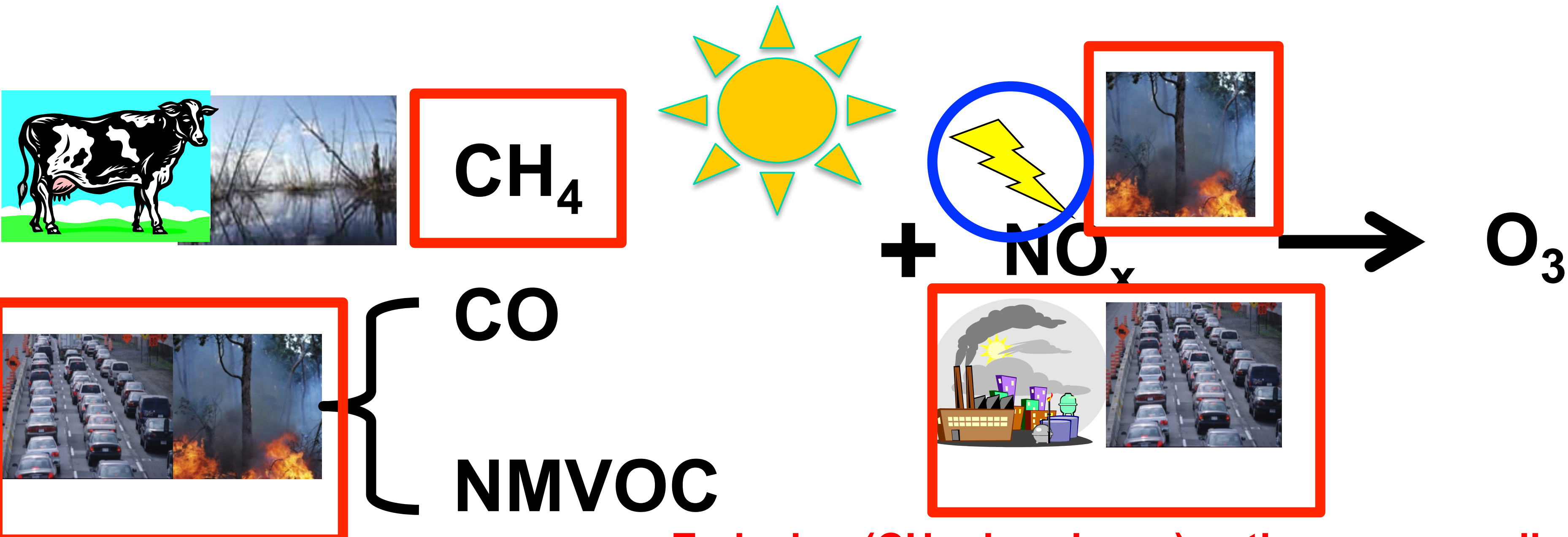
Approach: Targeted sensitivity simulations in a chemistry-climate model to examine chemistry-climate interactions

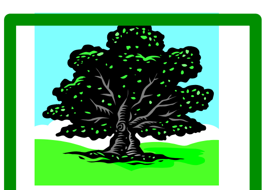
Tool: GFDL CM3 chemistry-climate model

- ~2°x2° horizontal resn.; 48 vertical levels
- Over 6000 years of climate simulations that include chemistry (air quality)
- Options for nudging to re-analysis + global high-res ~50km^2 [*Lin et al., 2012ab; 2014*]



Donner et al., J. Climate, 2011;
Golaz et al., J. Climate, 2011;
John et al., ACP, 2012
Turner et al., ACP, 2012
Levy et al., JGR, 2013
Naik et al., JGR, 2013
Barnes & Fiore, GRL, 2013





Emission (CH_4 abundance) pathways prescribed
Biogenic emissions held constant
Lightning NO_x source tied to model meteorology
O_3, (aerosols, etc.), affect simulated climate

Approach: Historical + Future global change scenarios & targeted sensitivity simulations in GFDL CM3 CCM

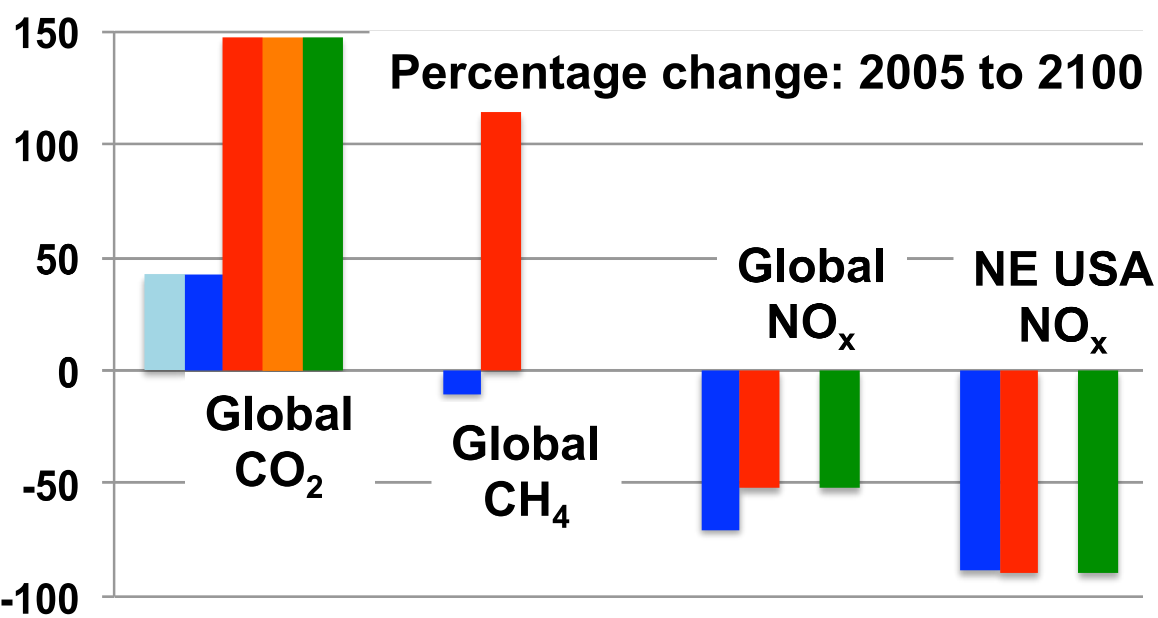
Scenarios developed by CMIP5 [Taylor et al., BAMS, 2012] in support of IPCC AR5 [*e.g.,* Cubasch et al., 2013; Ch 1 WG 1 IPCC (see Box 1.1)]

(1) Preindustrial control (perpetual 1860 conditions >800 years)

(2) Historical (1860-2005) [Lamarque et al., 2010]

- All forcings (5 ensemble members) → **evaluate with observations**
- Greenhouse gas only (3)
- Aerosol only (3)

(3) Future (2006-2100): Representative Concentration Pathways (+ perturbations)



RCP8.5 (3)
RCP4.5 (3)
→ CMIP5/AR5 [van Vuuren, 2011; Lamarque et al., 2011; Meinshausen et al., 2011]

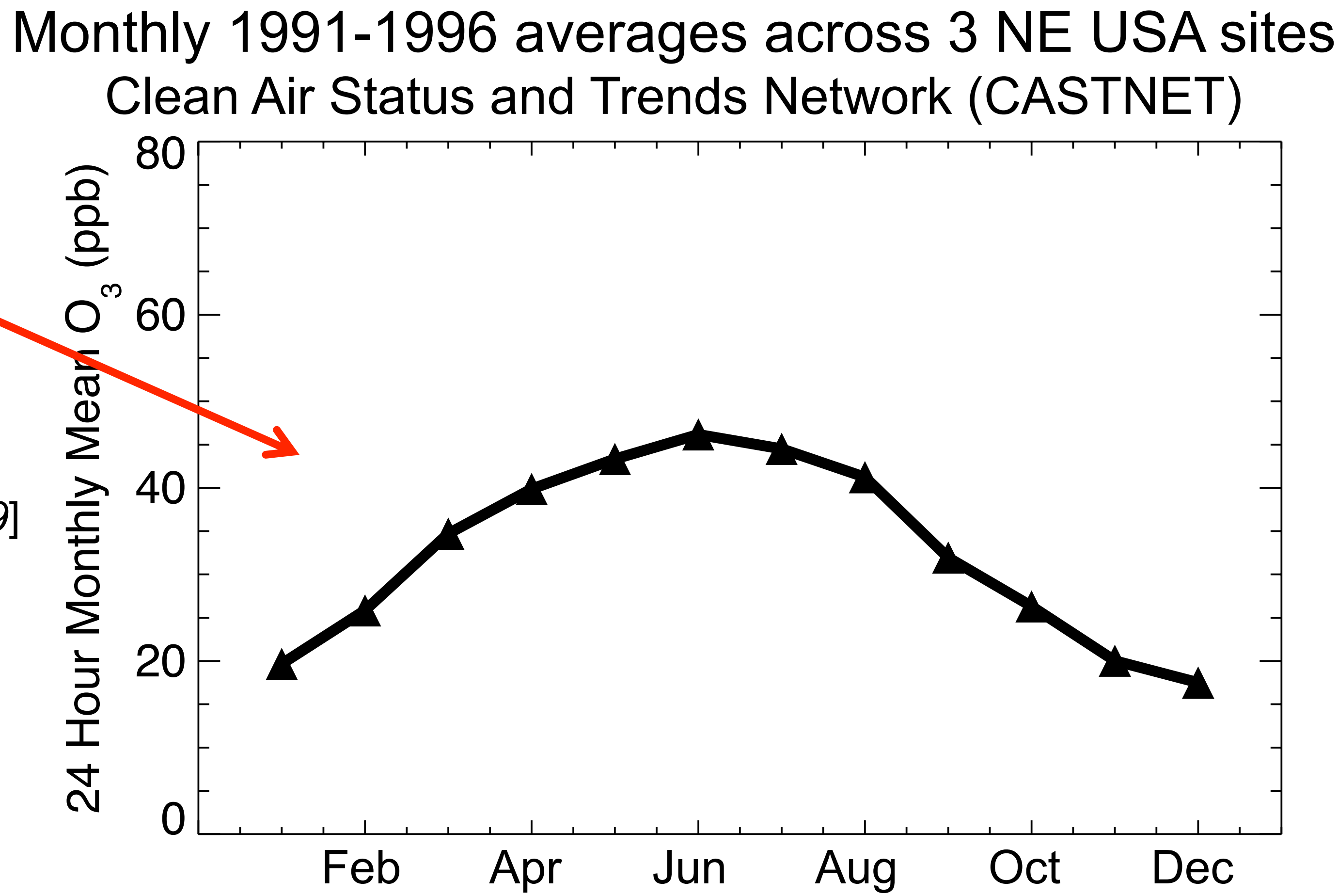
RCP8.5_WMGG (3)
RCP4.5_WMGG (3)
→ Isolate role of warming climate

RCP8.5_2005CH4
→ Quantify role of rising CH_4 (vs. RCP8.5)

In polluted (high-NO_x) regions, surface O_3 typically peaks during summer

(monthly averages at 3 NE USA measurement sites)

[*Reidmiller et al., ACP, 2009*]

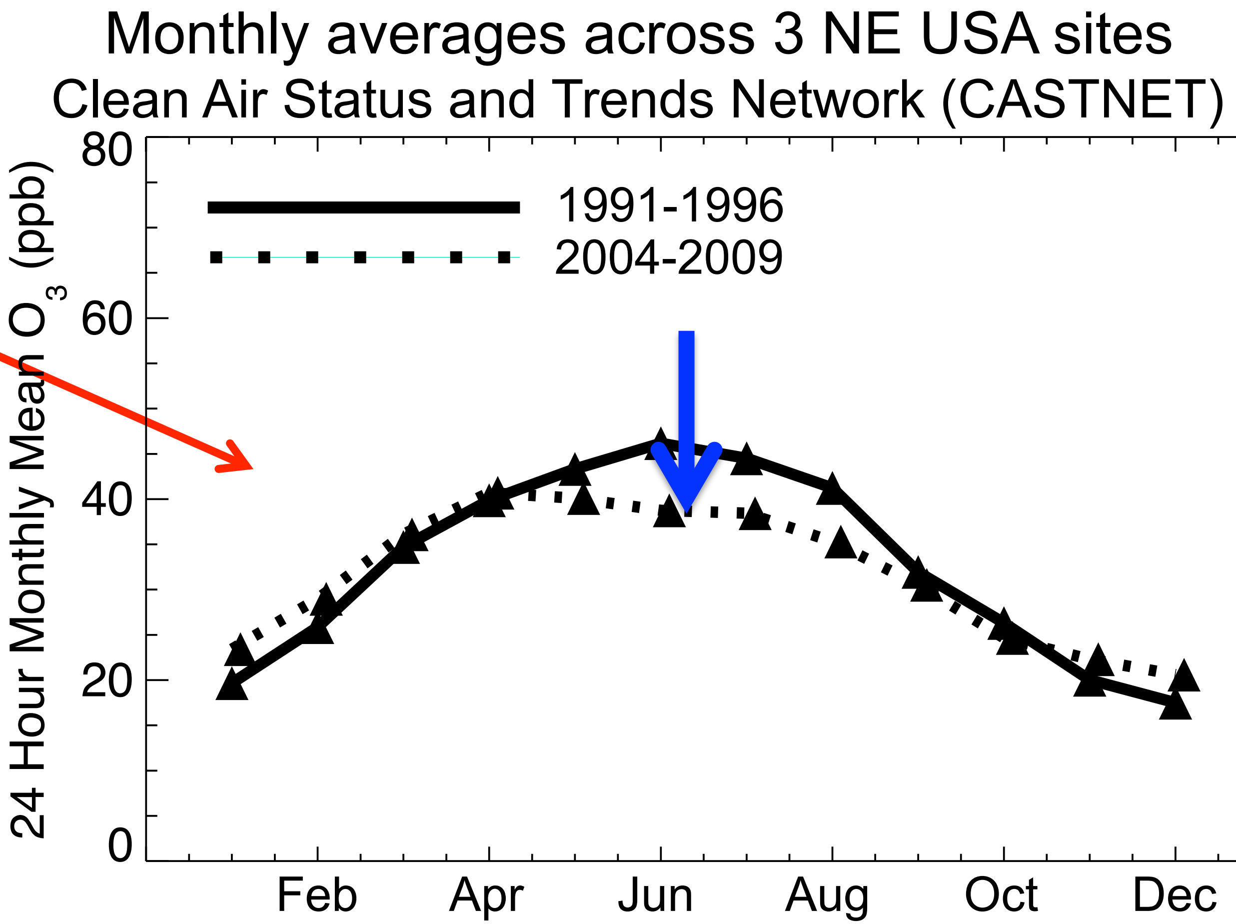


O. Clifton

Shifting surface ozone seasonal cycle evident in observations over NE USA

Regionally Representative sites

[*Reidmiller et al., ACP, 2009*]



→ Summer ozone decreases; shift towards broad spring-summer maximum following EUS NO_x controls ("NO_x SIP Call")

O. Clifton

Structure of observed changes in monthly mean ozone captured by GFDL CM3 CCM (despite mean state bias)

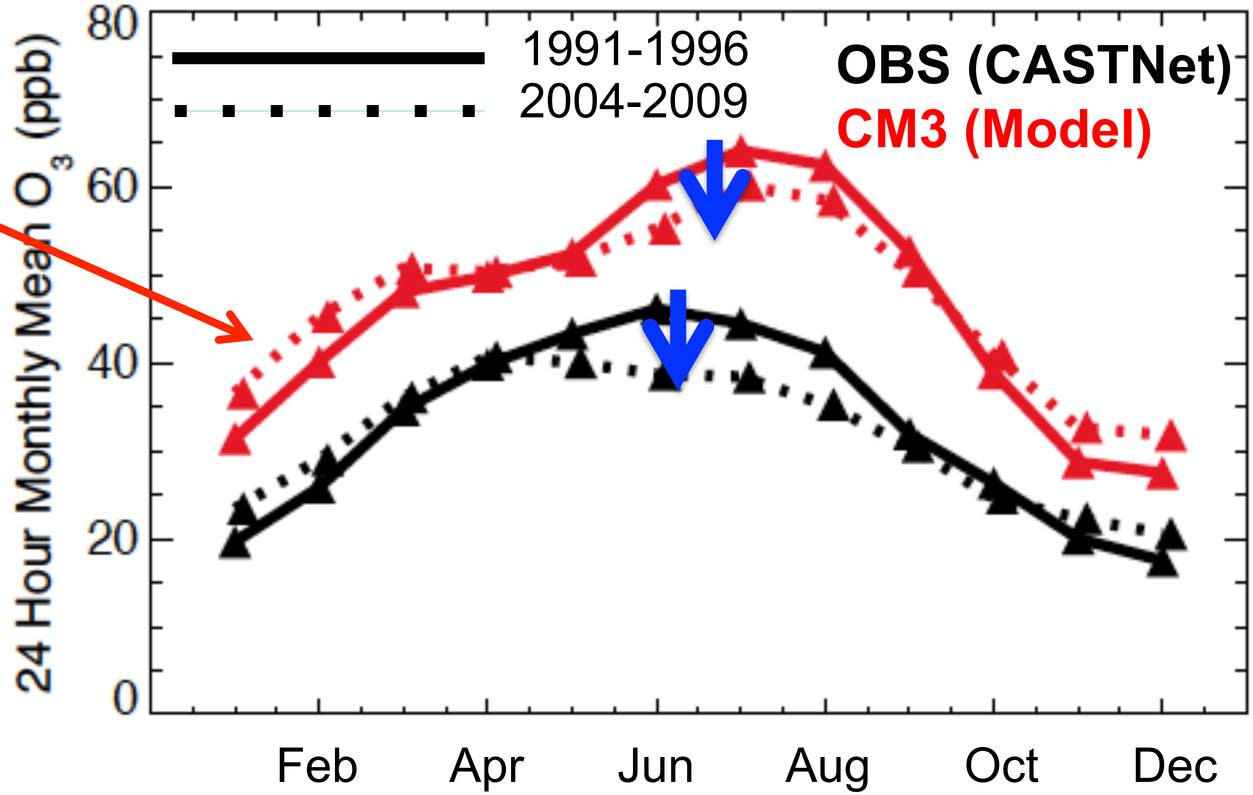
O. Clifton et al., submitted

Regionally Representative sites

[*Reidmiller et al., ACP, 2009*]

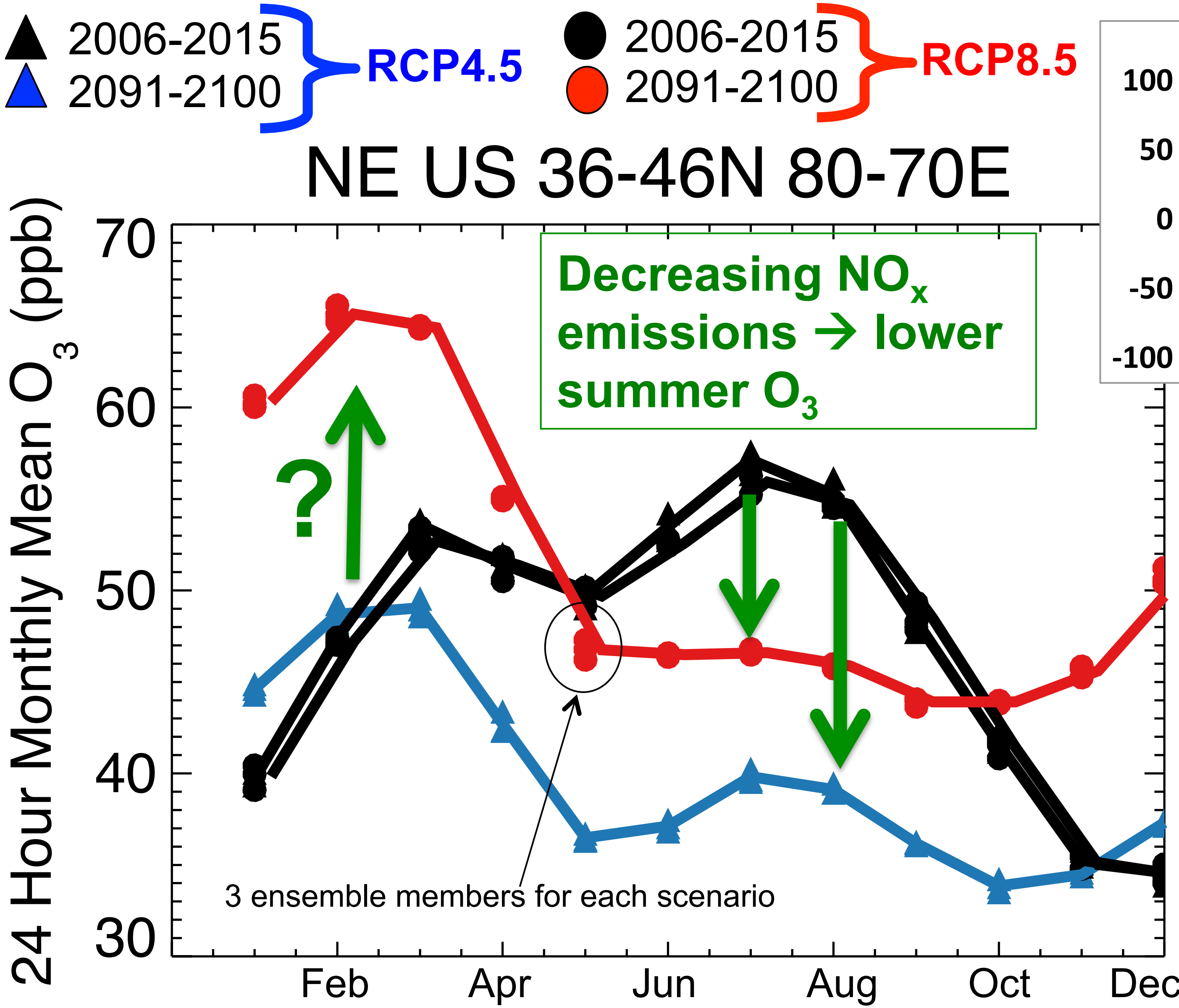
CM3 NE US shows summer O_3 decrease, small winter increase from ~25% decrease in NO_x emissions (applied year-round)

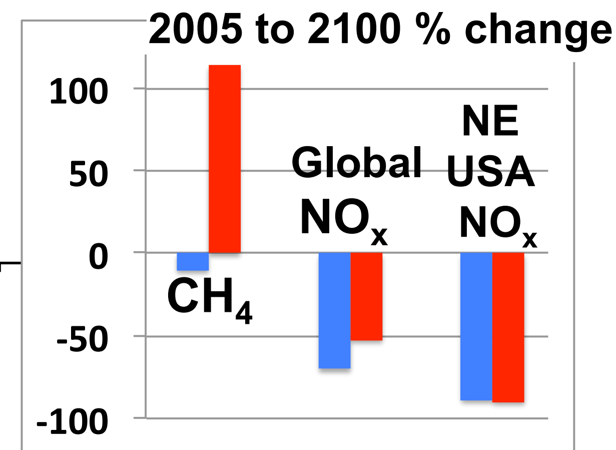
Monthly averages across 3 NE USA sites



[see also EPA, 2014; Parrish et al., GRL, 2013 find shifts at remote sites]

Reversal of surface O_3 seasonal cycle occurs in model under scenarios with dramatic regional NO_x reductions



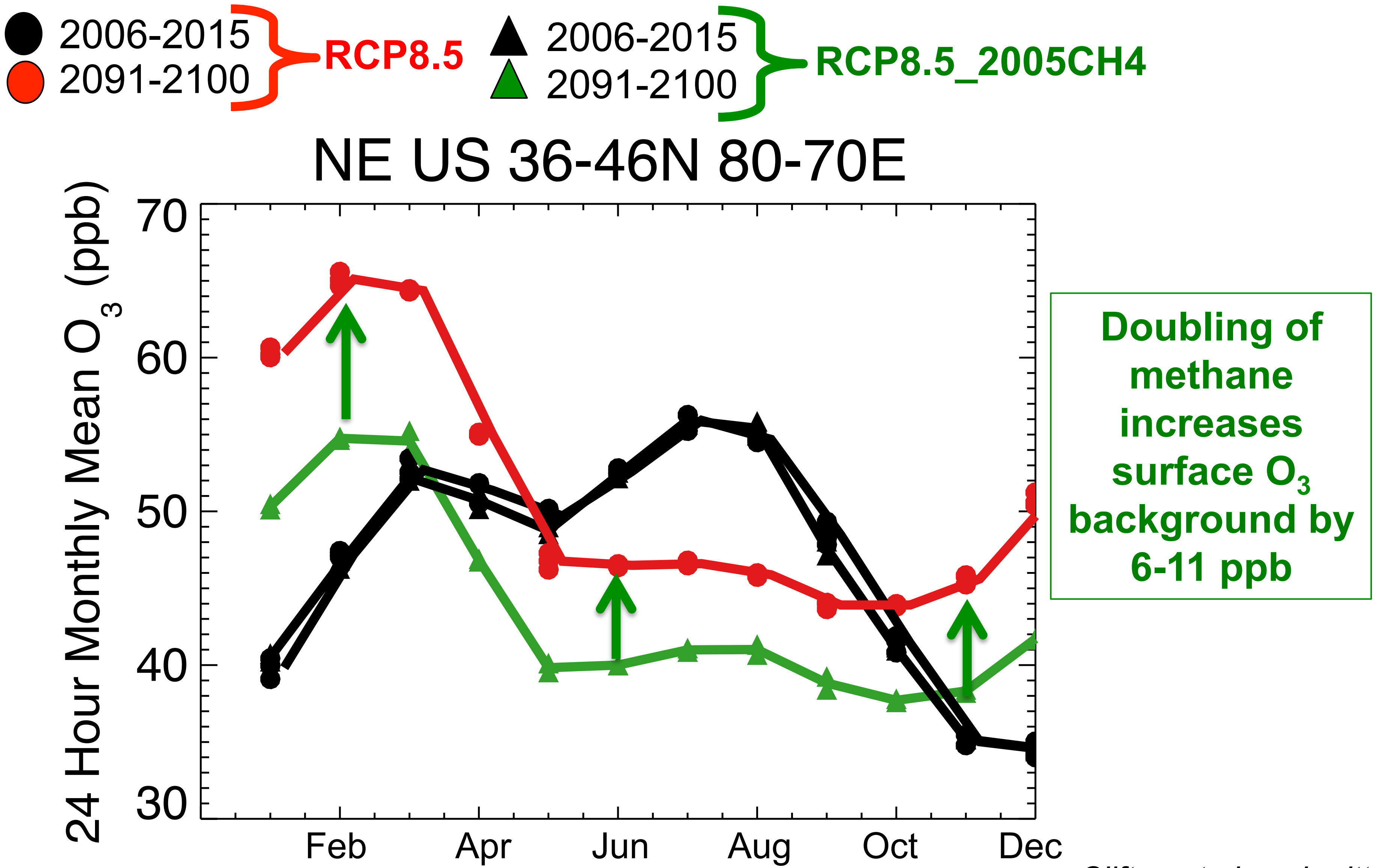


NE USA evolves from "polluted" to "background" over the 21st C

Reversal occurs after 2020s (not shown)

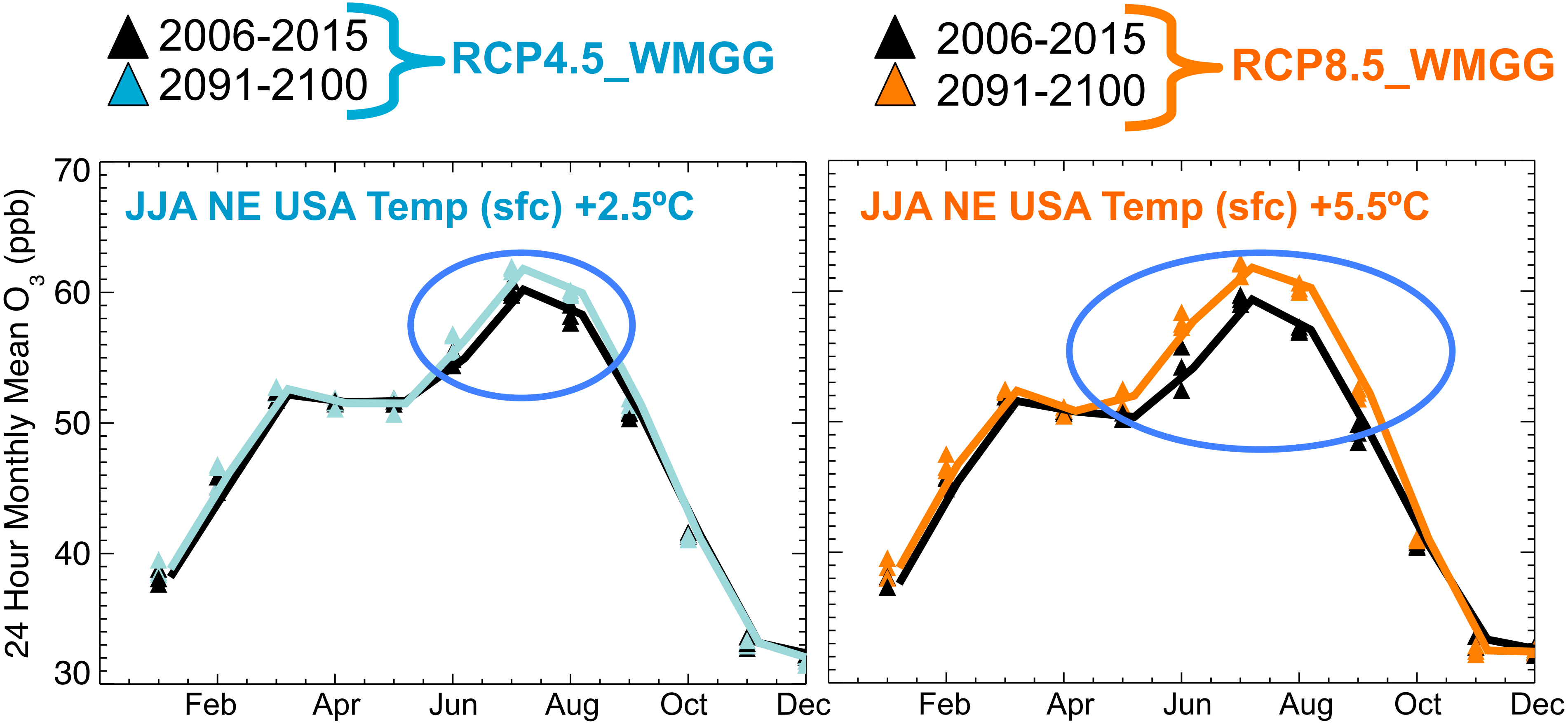
Clifton et al., submitted

Doubling of global CH_4 abundance (RCP8.5) raises NE USA surface ozone in model; largest impact during winter



Clifton et al., submitted

"Climate penalty" on monthly mean NE USA surface O_3 as simulated with the GFDL CM3 model



→ "Penalty" limited to increases during warmest months

→ Extends into May and September in high warming scenario

→ Fully offset by regional precursor emission reductions under RCPs

Clifton et al., submitted

How and why might air pollution extremes change?

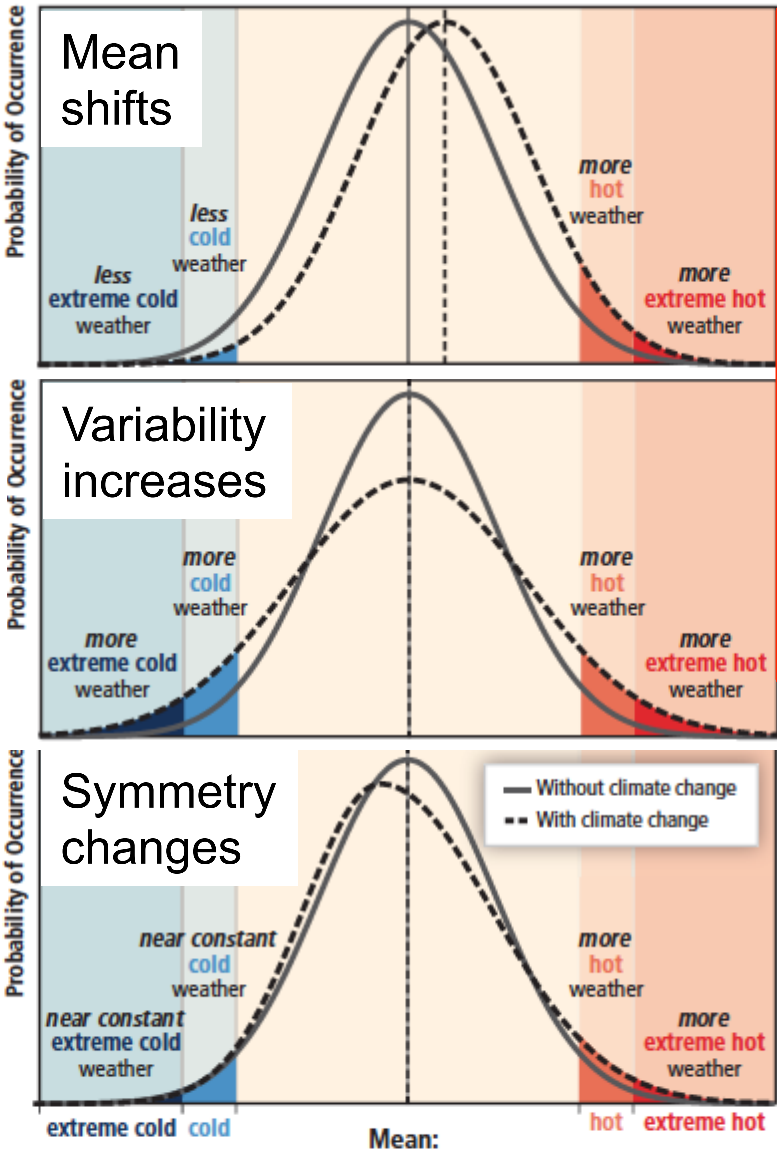


Figure SPM.3, IPCC SREX 2012
http://ipcc-wg2.gov/SREX/

→ How do different processes influence the overall distribution?

- Meteorology (*e.g.*, stagnation vs. ventilation)
- [Feedbacks (Emis, Chem, Dep) not today]
- Changing global emissions (baseline)
  → Shift in mean?
- Changing regional emissions (episodes)
  → Change in symmetry?

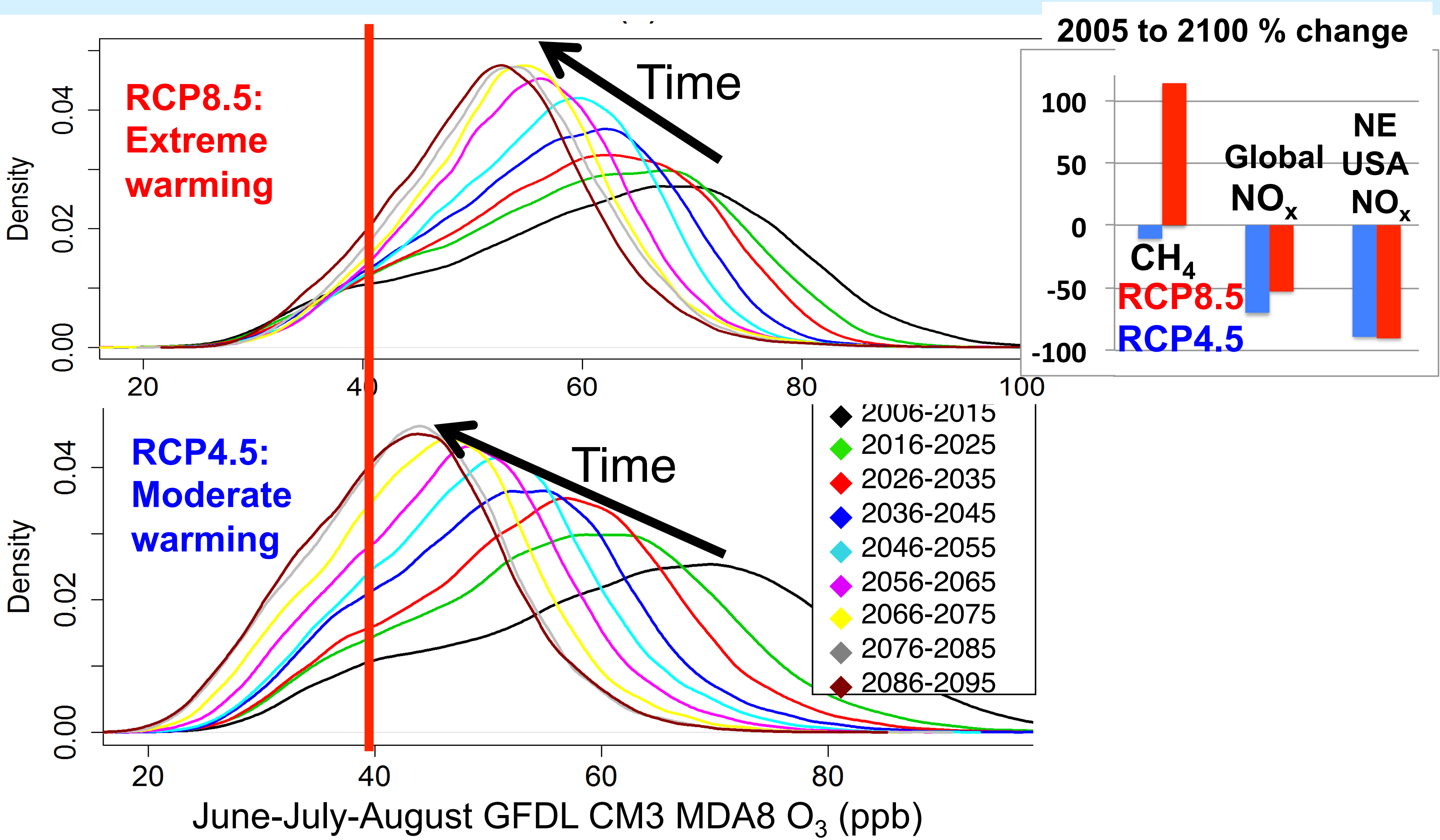
→ How do changes in the balance of these processes alter the seasonal cycle?

- NE US: regional photochemistry (summer) vs. transported background

→ Does climate forcing from air pollutants influence regional climate extremes?

- Aerosols vs. greenhouse gases

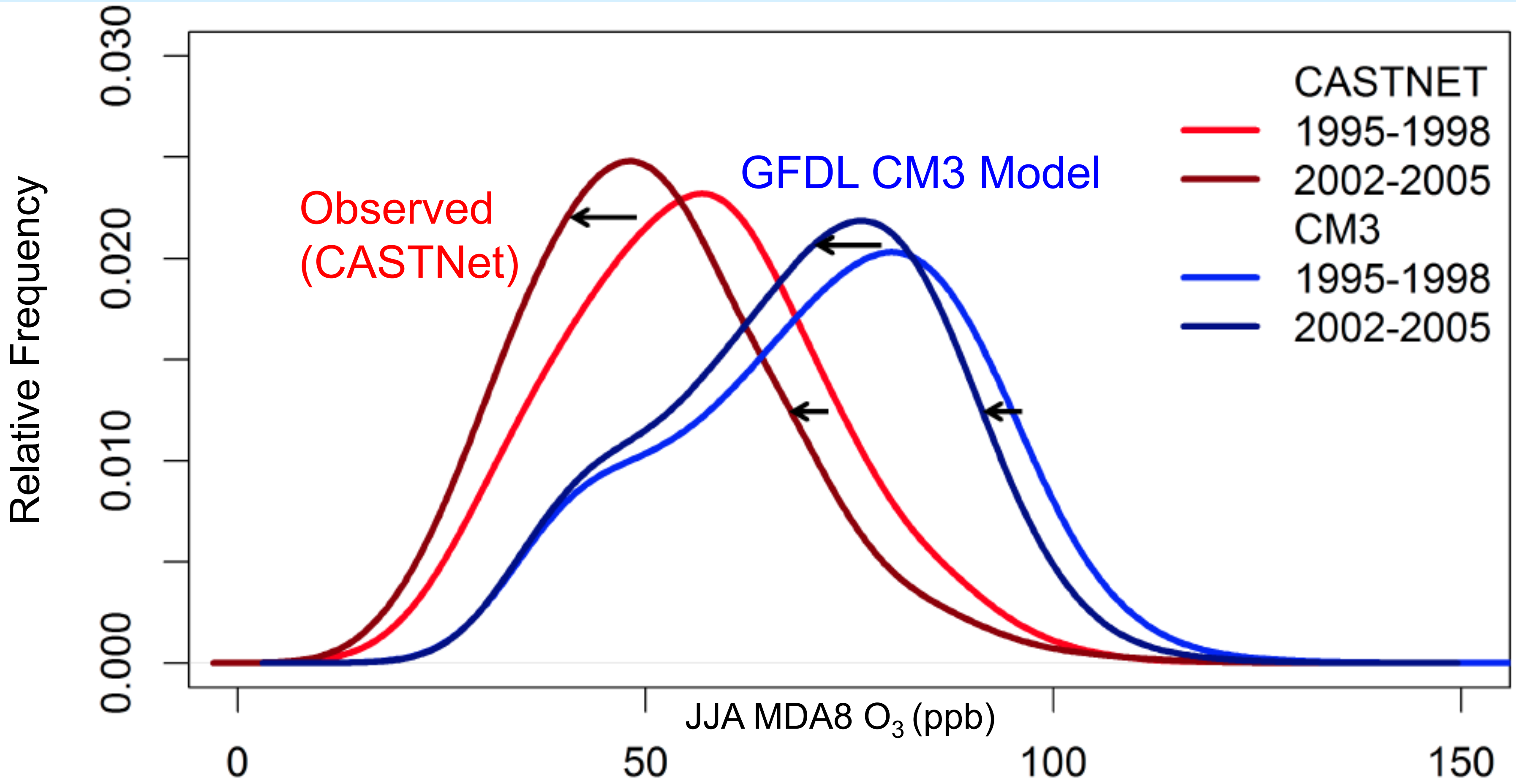
Under RCPs, NE USA high-O_3 summertime events decrease; beware 'penalty' from rising methane (via background O_3)



→ Rising CH_4 in RCP8.5 partially offsets O_3 decreases otherwise attained with regional NO_x controls (RCP4.5)

H. Rieder

GFDL CM3 generally captures NE US JJA surface O_3 decrease following NO_x emission controls (-25% early 1990s to mid-2000s)

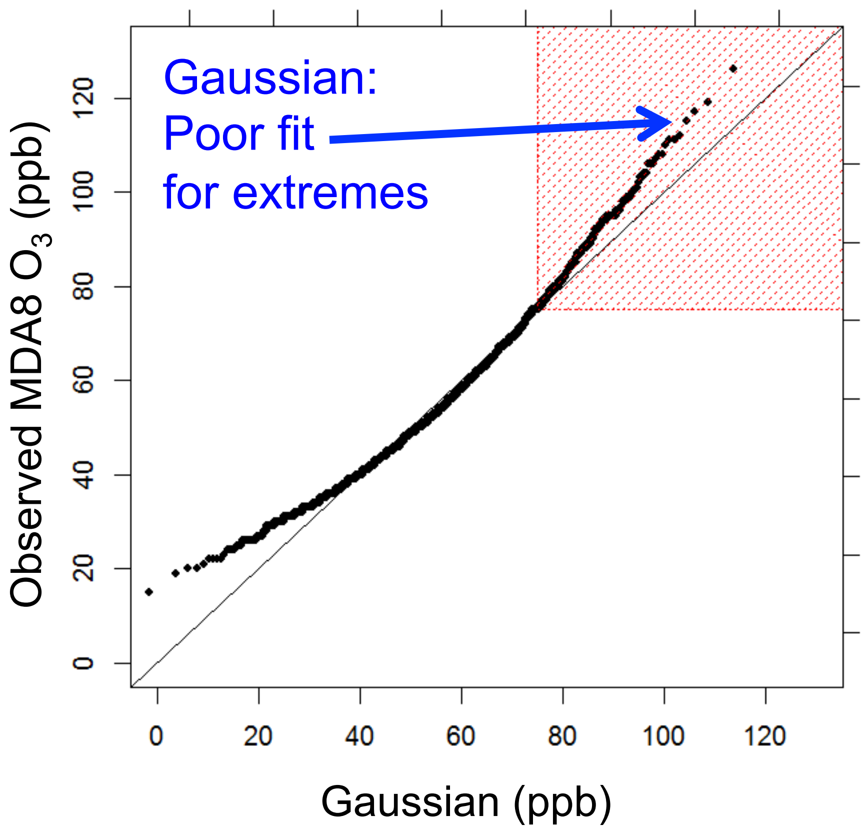


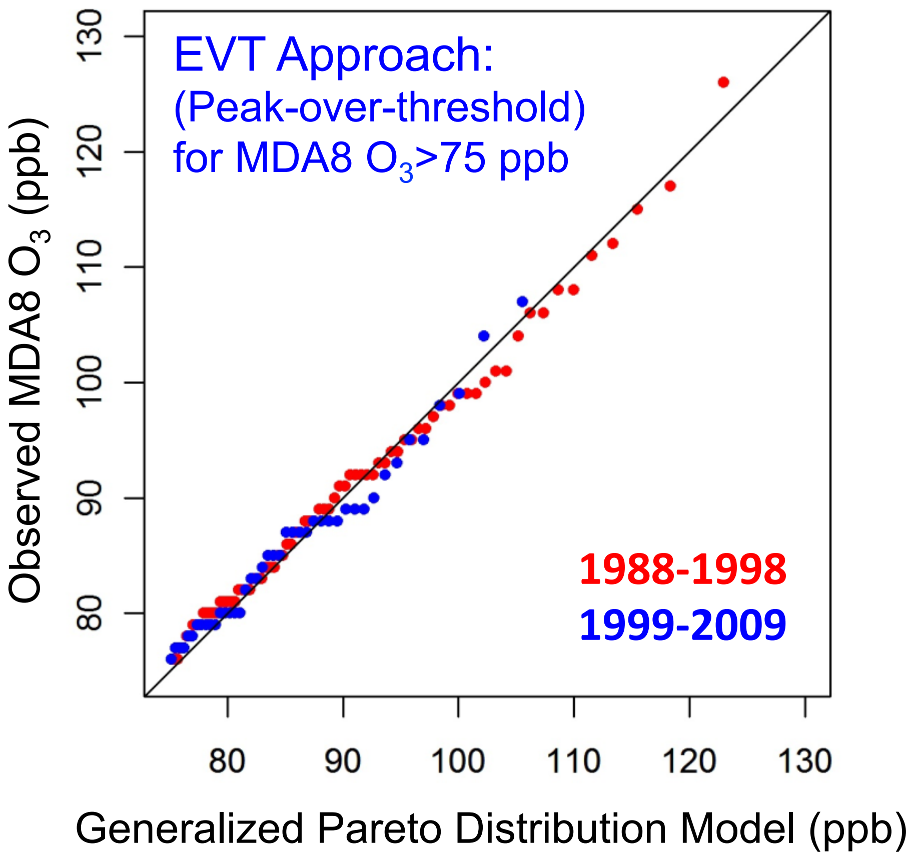
- → Implies bias correction based on present-day observations can be applied to scenarios with NO_x changes (RCPs for 21st C)
- → Focus on upper half of distribution

Rieder et al., in prep

Characterizing observed 'extreme' ozone pollution events

JJA MDA8 O_3 1987-2009 at CASTNet Penn State site

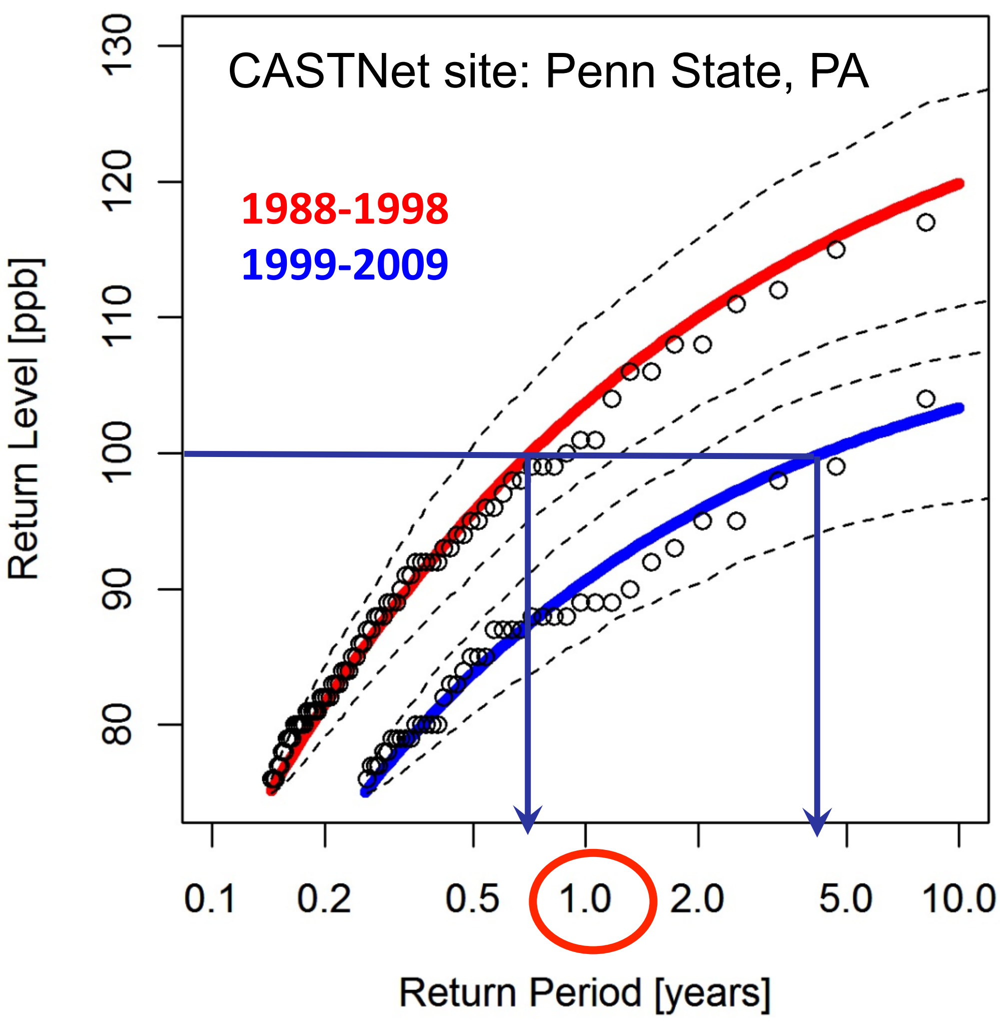




→ Extreme Value Theory (EVT) methods describe the high tail of the observed ozone distribution (not true for Gaussian)

Rieder et al., ERL 2013

EVT methods enable derivation of probabilistic "return levels" for JJA MDA8 O_3 within a given "return period"



→ Sharp decline in return levels from 1988-1998 to 1999-2009; longer return periods for a given event (attributed to NO_x emission controls)

→ Consistent with prior work [*e.g., Frost et al., 2006; Bloomer et al., 2009, 2010*]

→ New approach to translates air pollution changes into probabilistic language

Apply methods to 23 EUS CASTNet sites to derive 1-year return levels
→ Decreased by 2-16 ppb
→ Remain above 75 ppb

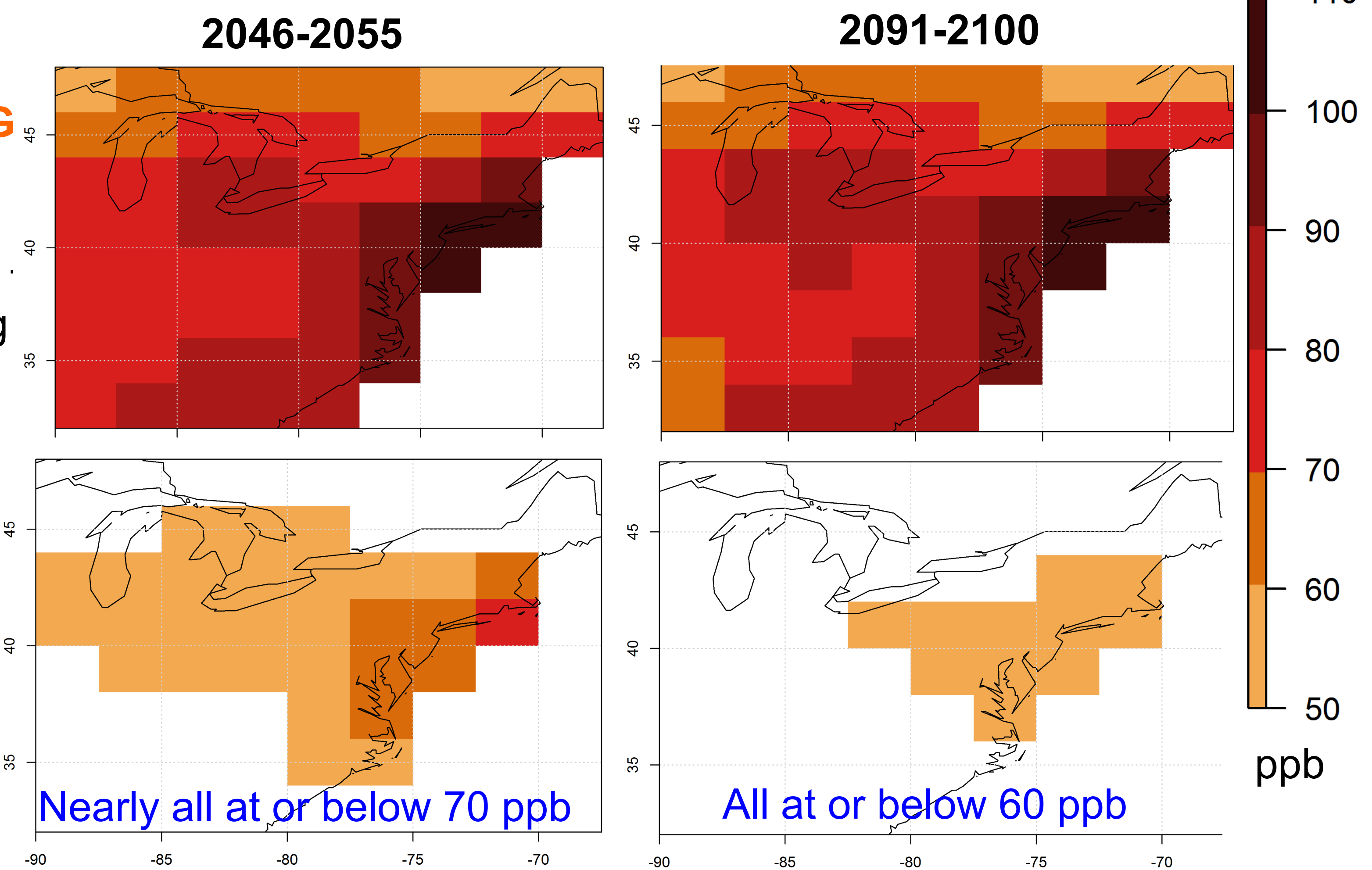
Rieder et al., ERL 2013

Large NO_x reductions offset climate penalty on O_3 extremes

1-year Return Levels in CM3 chemistry-climate model (corrected)
Summer (JJA) MDA8 Surface O_3

RCP4.5_WMGG
Pollutant emissions held constant (2005) + climate warming

RCP4.5:
Large NO_x decreases + climate warming



→ We find a simple relationship between NO_x reductions and 1-year return levels

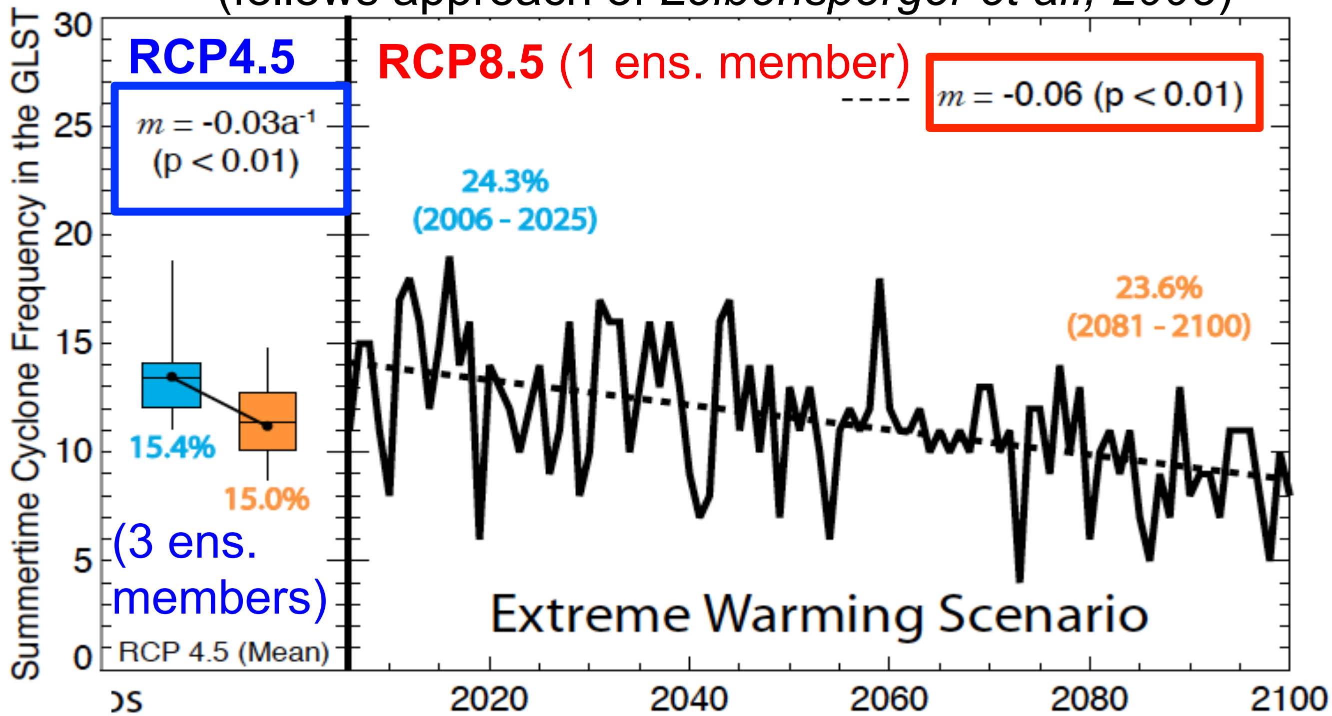
Rieder et al., in prep

A mechanism underlying 'climate penalty': Frequency of NE US summer storms decreases as the planet warms…

Region for counting storms

Region for counting O_3 events

Number of storms per summer in the GFDL CM3 model, as determined from applying the MCMS storm tracker [*Bauer et al., 2013*] to 6-hourly sea level pressure fields (follows approach of *Leibensperger et al., 2008*)

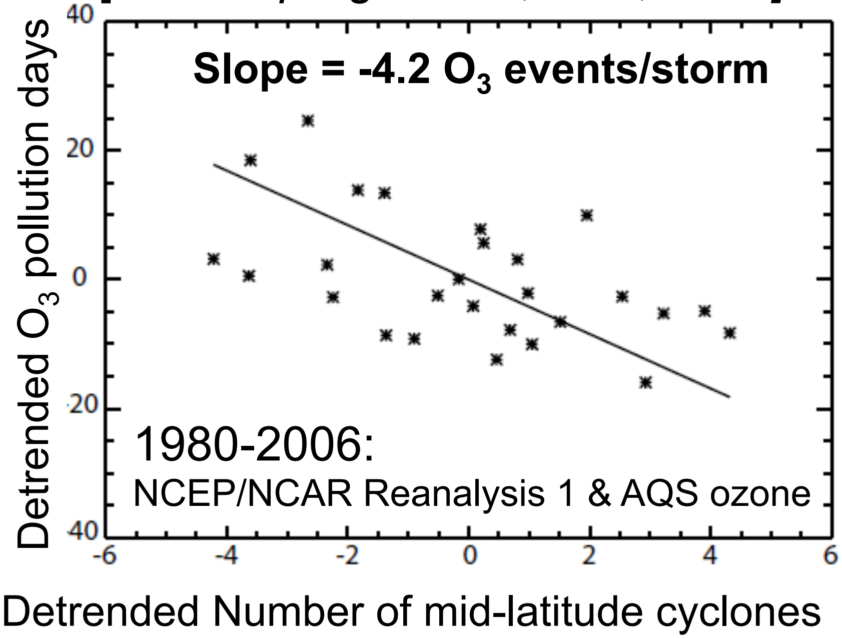


Turner et al., ACP, 2013

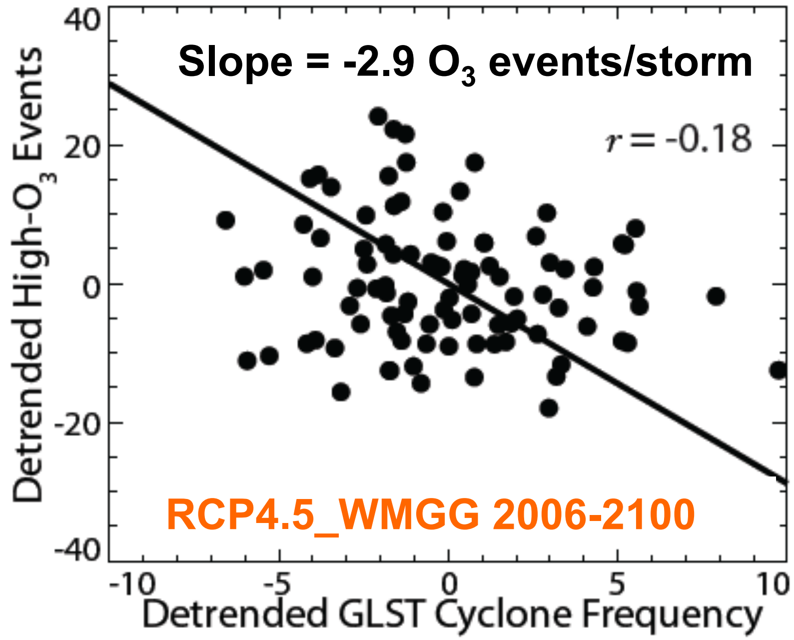
Trends are significant relative to variability in preindustrial control simulation

…but the storm count – O_3 event relationship is weaker than derived from observations

Observed relationship
[*Leibensperger et al, ACP, 2008]*



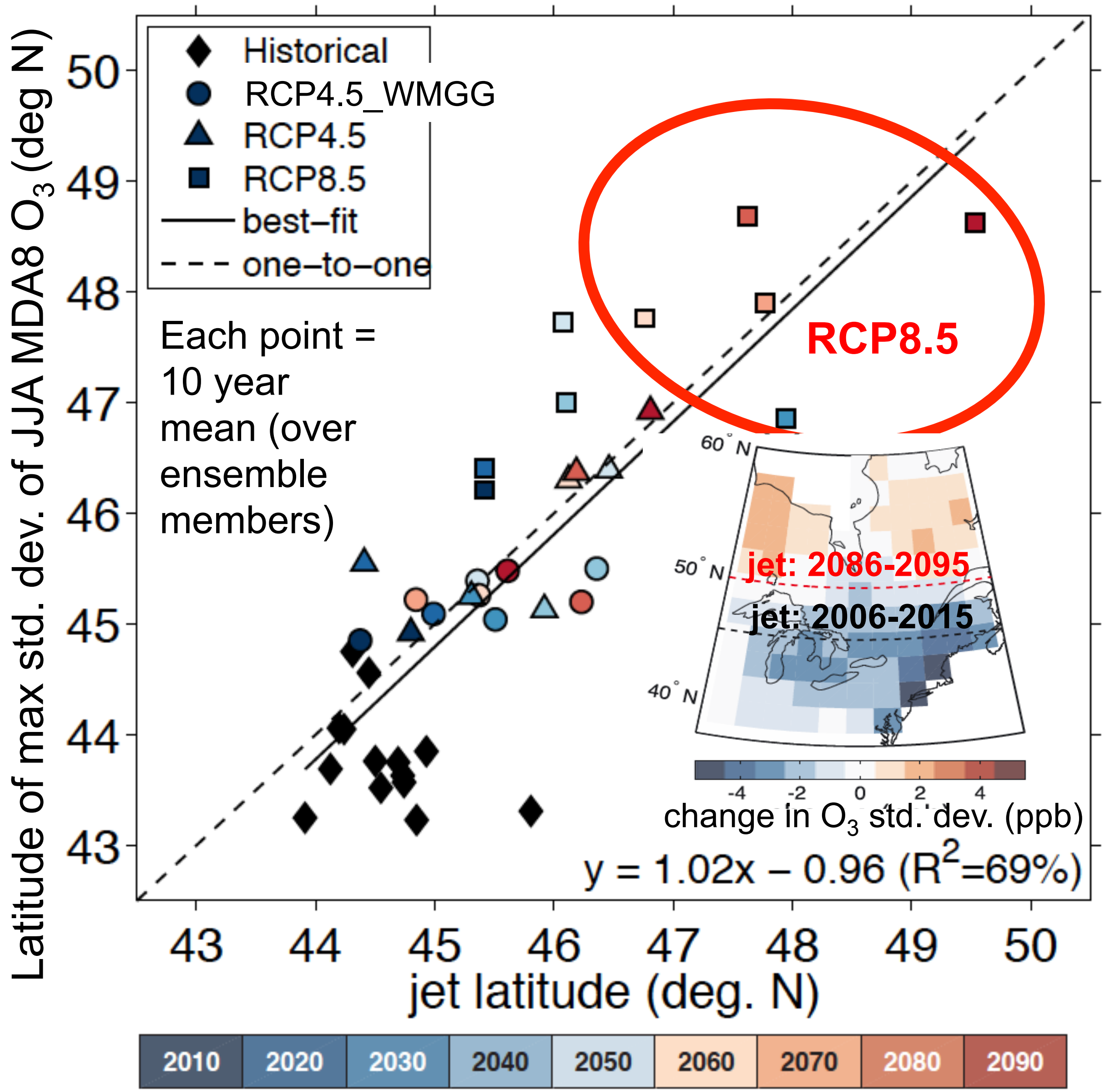
Simulated relationship (GFDL CM3)
[*Turner et al., ACP, 2013*]



→ **Model problem (bias/process representation)?**
→ **Change in drivers (under warming climate)?**
→ **Decadal variability in strength of relationship?**

Can we find a simpler diagnostic of large-scale circulation changes?

Peak latitude of summertime surface O_3 variability over Eastern N. America follows the jet (500 hPa) as climate warms



RCP8.5: most warming, Largest jet shift

→ Decadal variability

→ Relevance to shorter periods?

→ Differences in model jet position lead to inter-model differences in AQ response?

O_3-Temperature relationship (not shown) also aligns with jet latitude

→ Historically observed relationships may not hold if large-scale circulation shifts

Barnes & Fiore, GRL, 2013

How and why might air pollution extremes change?

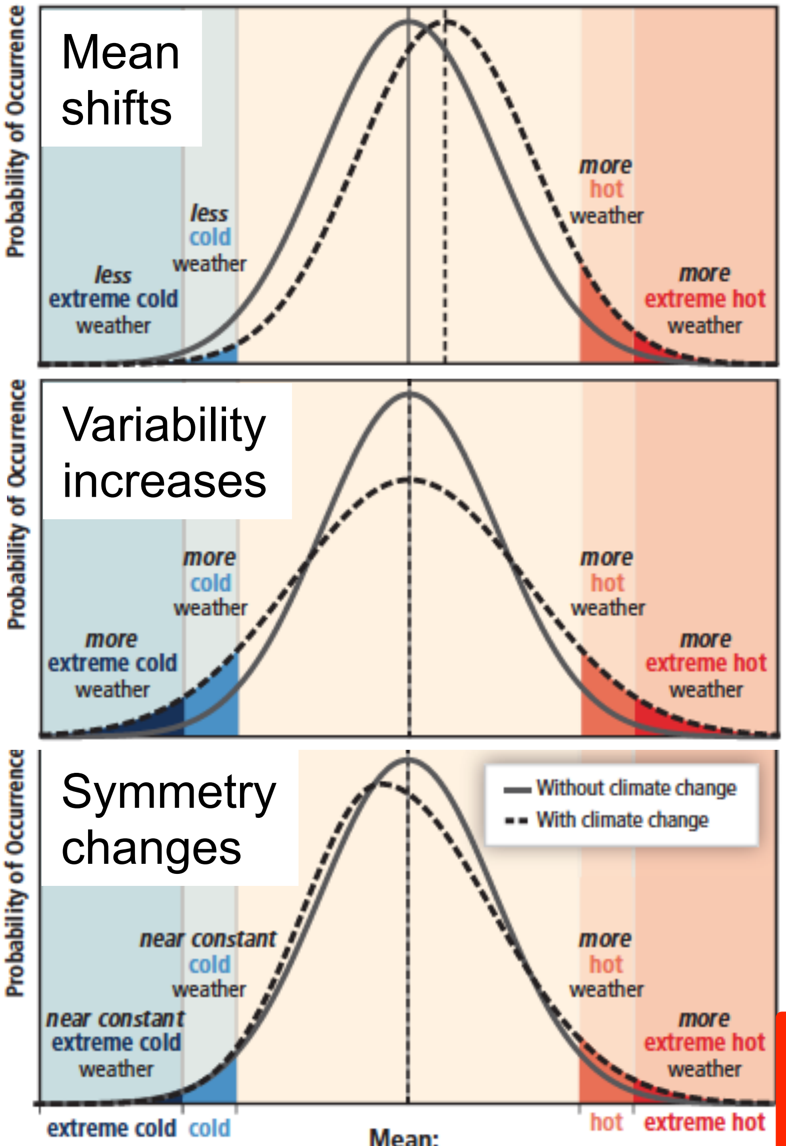


Figure SPM.3, IPCC SREX 2012
http://ipcc-wg2.gov/SREX/

→ **How do different processes influence the overall distribution?**

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- Changing global emissions (baseline)
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→ **How do changes in the balance of these processes alter the seasonal cycle?**

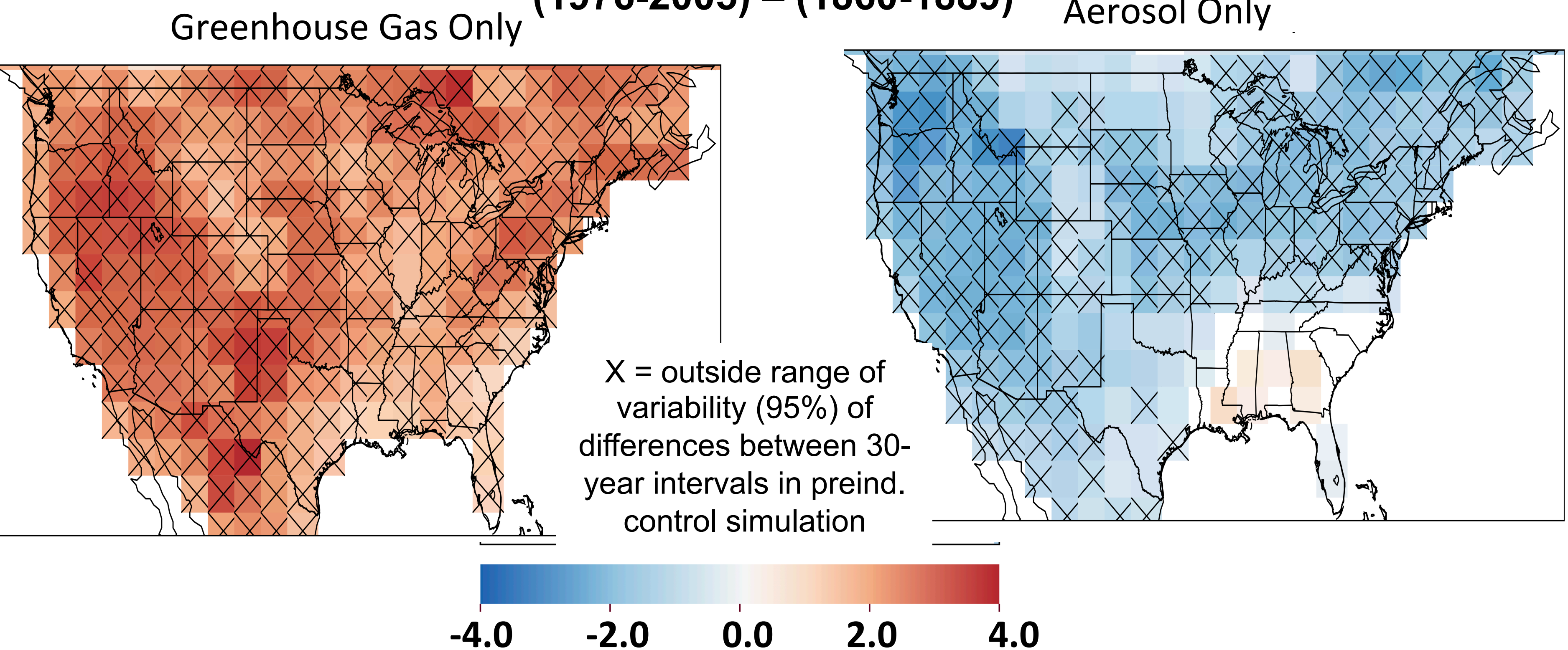
- NE US: regional photochemistry (summer) vs. transported background

→ **Does climate forcing from air pollutants influence regional climate extremes?**

- Aerosols vs. greenhouse gases

Offsetting impacts on extreme temperature events from greenhouse gases vs. aerosol over historical period

Single forcing historical simulations in GFDL CM3
(all other forcings held at 1860 conditions)
(1976-2005) – (1860-1889)



Change in Hottest Days (°C)
(annual maximum daily temperature [*e.g., Sillman et al., 2013ab*])

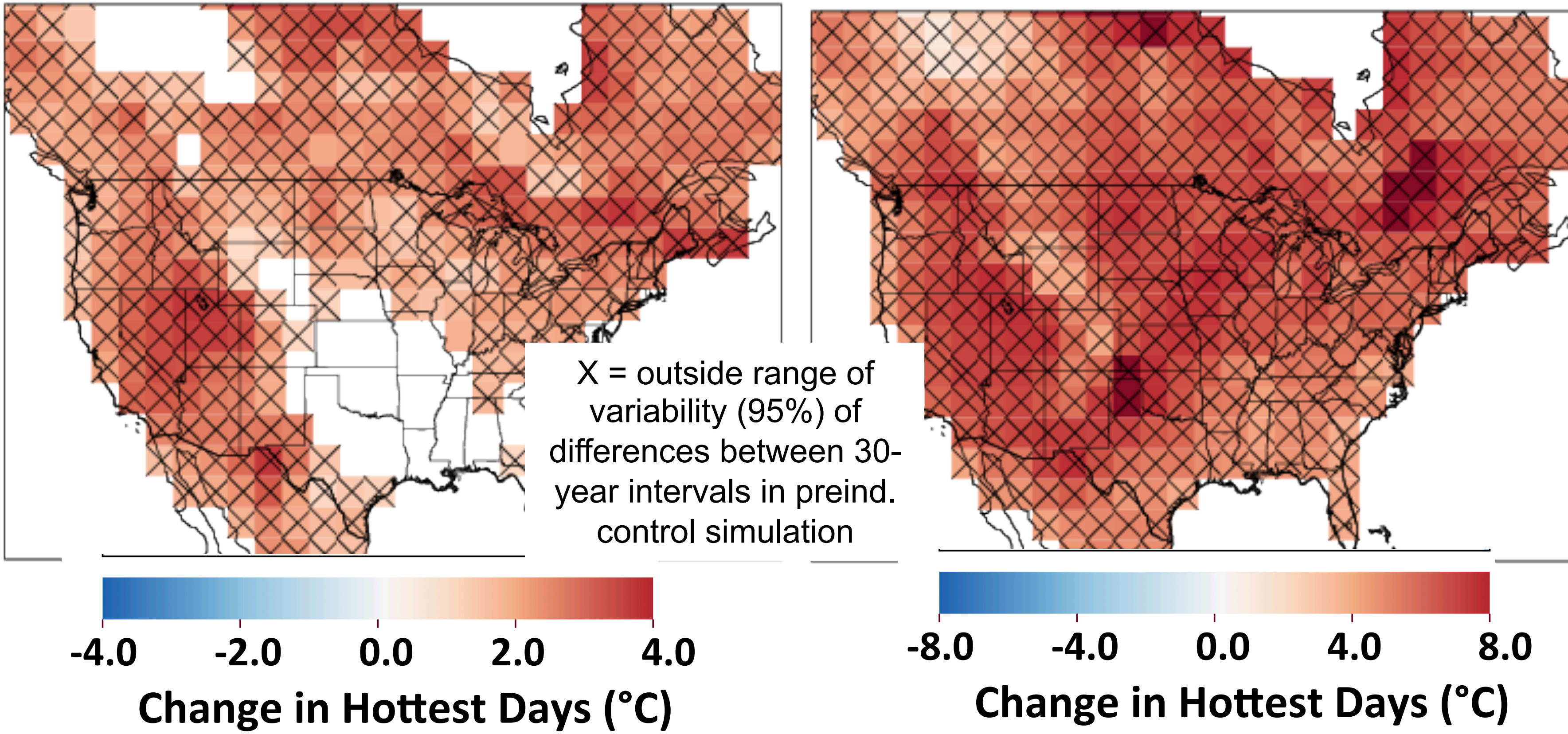
Consistent (?) patterns (spatial correlation r = 0.56)
Pollutants → regional weather events → extreme pollution?

N. Mascioli

Increase in hottest days projected throughout 21st Century under extreme warming scenario

GFDL CM3 1 ensemble member, RCP8.5 scenario: aerosols decline, GHGs rise

mid-21stC: (2035-2065) – (2006-2036) late-21stC: (2070-2100) – (2006-2036)



(annual maximum daily temperature [*e.g., Sillman et al., 2013ab*])

→ Amplified warming during extreme events from aerosol removal?

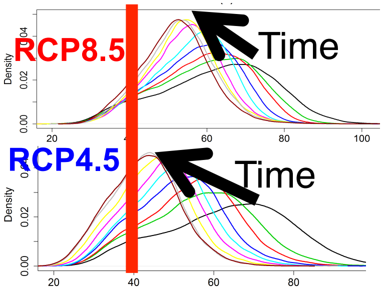
→ Preferred response patterns?

N. Mascioli

Atmospheric Chemistry Group at LDEO/CU

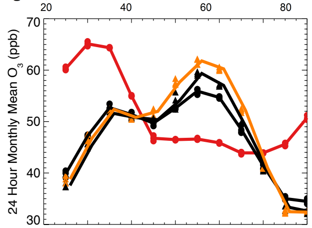
On the roof of our building following mid-Dec snowfall
(missing from photo: undergraduate researcher Jean Guo)

U.S. air pollution and climate: Trends, variability, and interactions



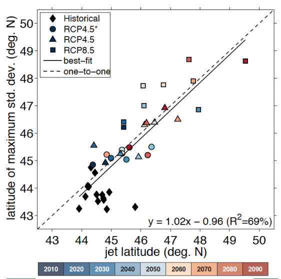
- Rising CH_4 + decreasing NO_x shift balance of regionally produced vs. transported O_3

→ Double 'penalty' on NE US O_3 from climate change + rising CH_4?



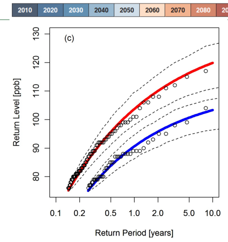
- NO_x reductions reverse the O_3 seasonal cycle over NE USA

→ Will NE US evolve to 'background' air quality over the 21st C?



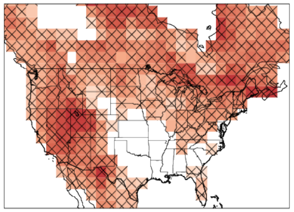
- Zonal O_3 variability aligns with the 500 hPa jet over NE NA (JJA)
- Decadal jet shifts can influence O_3:T [*Barnes & Fiore, 2013*]

→ Relevant to model differences in O_3 response to climate?
[*Weaver et al., 2009; Jacob & Winner, 2009; Fiore et al., 2012*]



- New approach to characterize pollution events [*Rieder et al., 2013*]

→ Translation to probabilistic language,"1-year event", useful for decadal planning?



- Detecting chemistry-climate interactions

→ Will (global) aerosol removal amplify response of U.S. climate extremes to rising GHGs?