# OZONE AIR QUALITY IN THE UNITED STATES: POLICY-RELEVANT BACKGROUND, TRANSBOUNDARY POLLUTION, AND CLIMATE CHANGE

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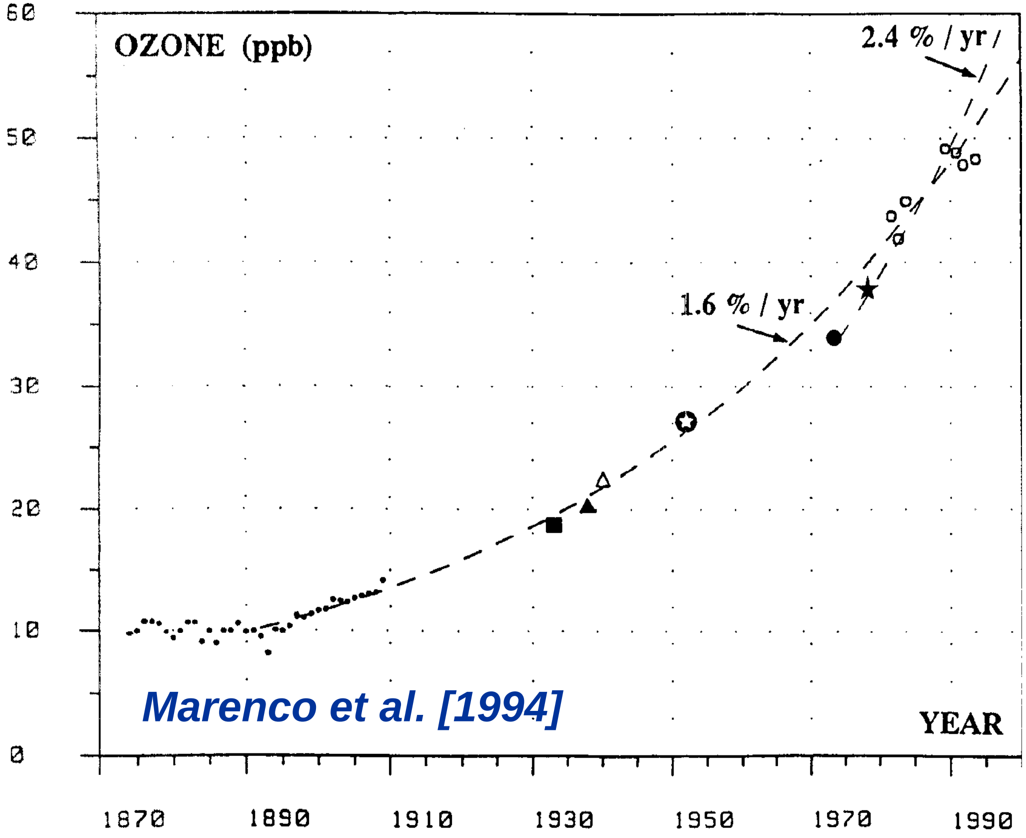
and funding from DOE, NASA, EPA, EPRI

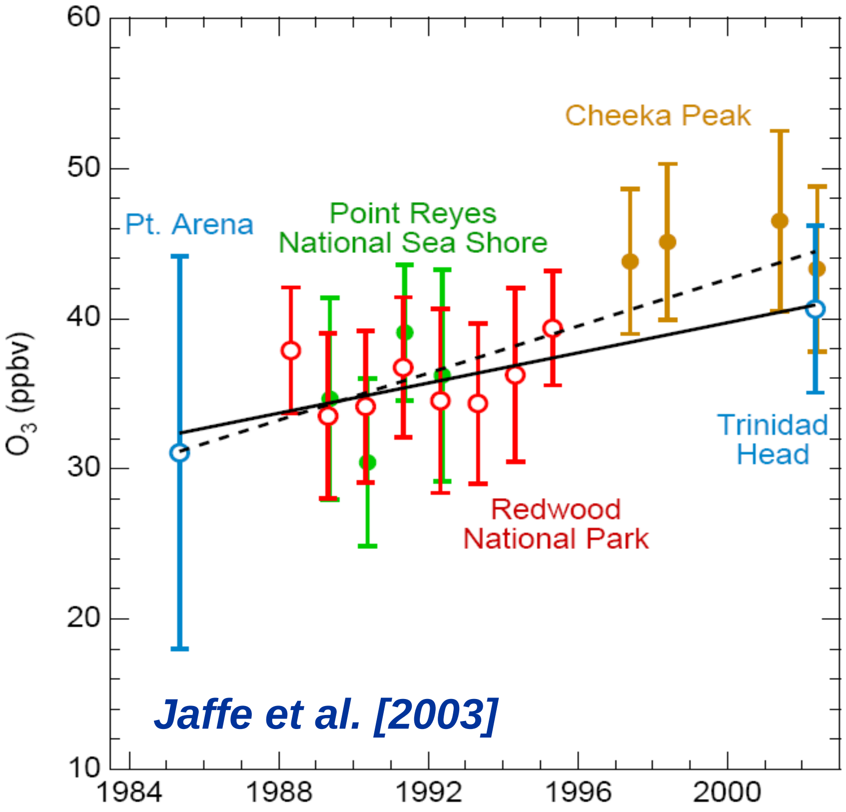
# RISING OZONE BACKGROUND AT NORTHERN MID-LATITUDES

## Mountain sites in Europe
1870-1990



*Marenco et al. [1994]*

## U.S. Pacific coastal sites
1985-2002

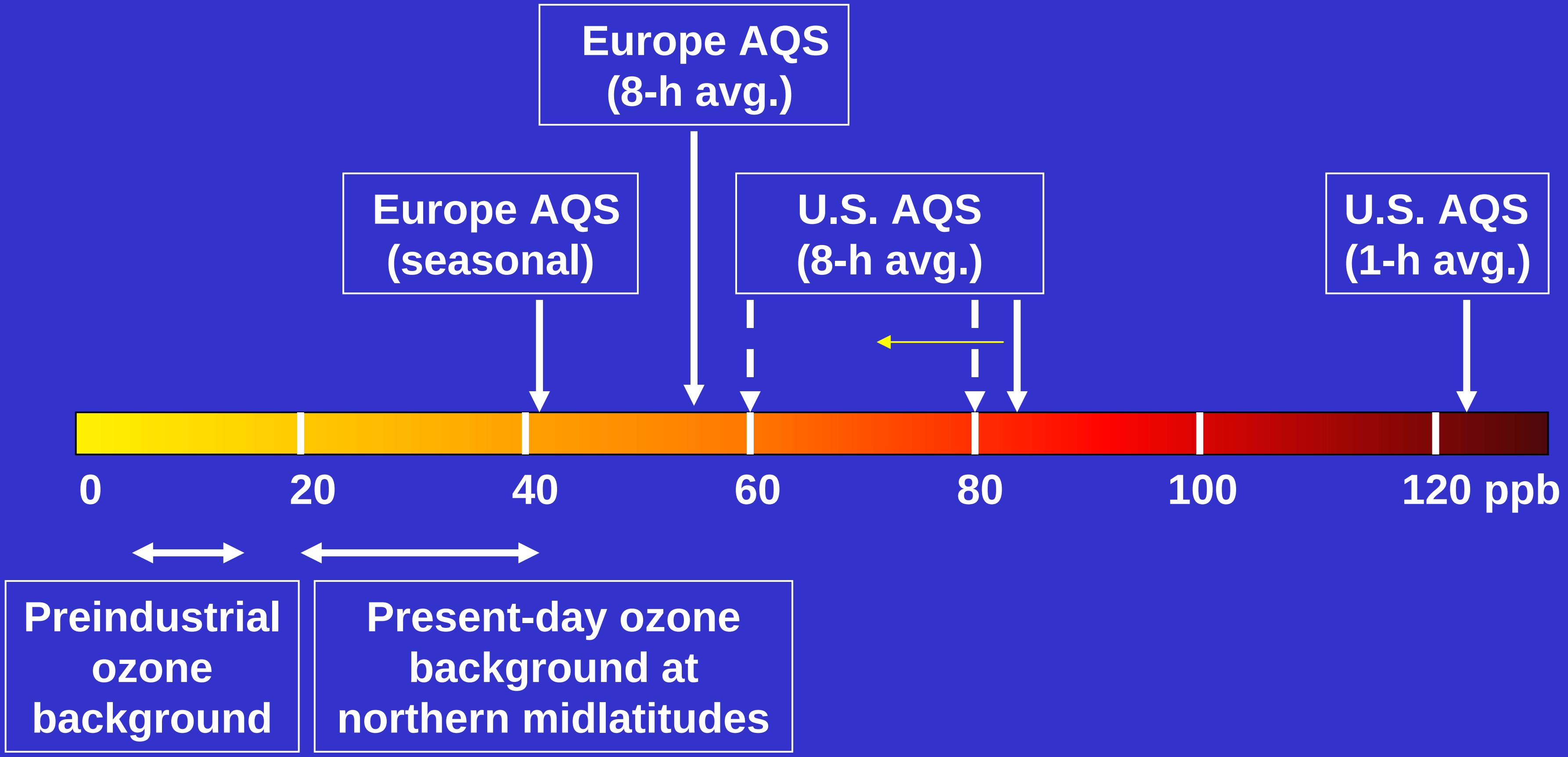


*Jaffe et al. [2003]*

**Ozone has a lifetime of weeks in the free troposphere**

**→ can be transported on a hemispheric scale**

# IMPLICATION OF RISING OZONE BACKGROUND FOR MEETING AIR QUALITY STANDARDS



Europe AQS
(8-h avg.)

Europe AQS
(seasonal)

U.S. AQS
(8-h avg.)

U.S. AQS
(1-h avg.)

0 20 40 60 80 100 120 ppb

Preindustrial ozone background

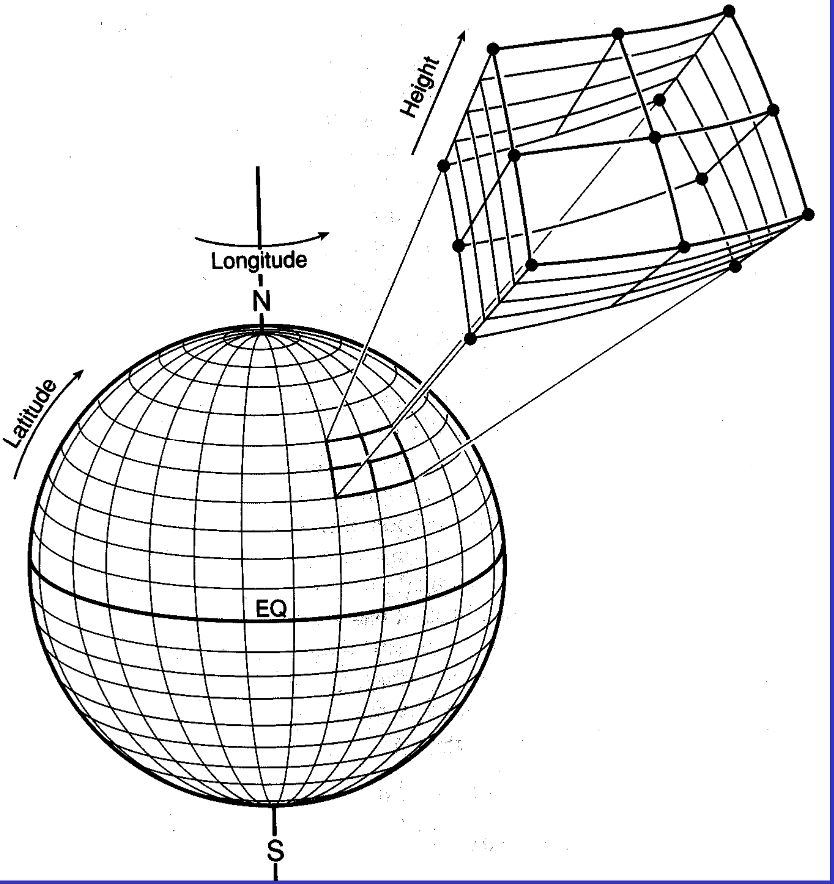
Present-day ozone background at northern midlatitudes

**EPA policy-relevant background (PRB) : U.S. surface ozone concentrations that would be present in absence of North American anthropogenic emissions**

***PRB is not directly observable and must be estimated from global models***

# GEOS-Chem GLOBAL MODEL OF TROPOSPHERIC CHEMISTRY

http://www.as.harvard.edu/chemistry/trop/geos



- Driven by NASA/GEOS assimilated meteorological data with 6-h temporal resolution (3-h for surface quantities)

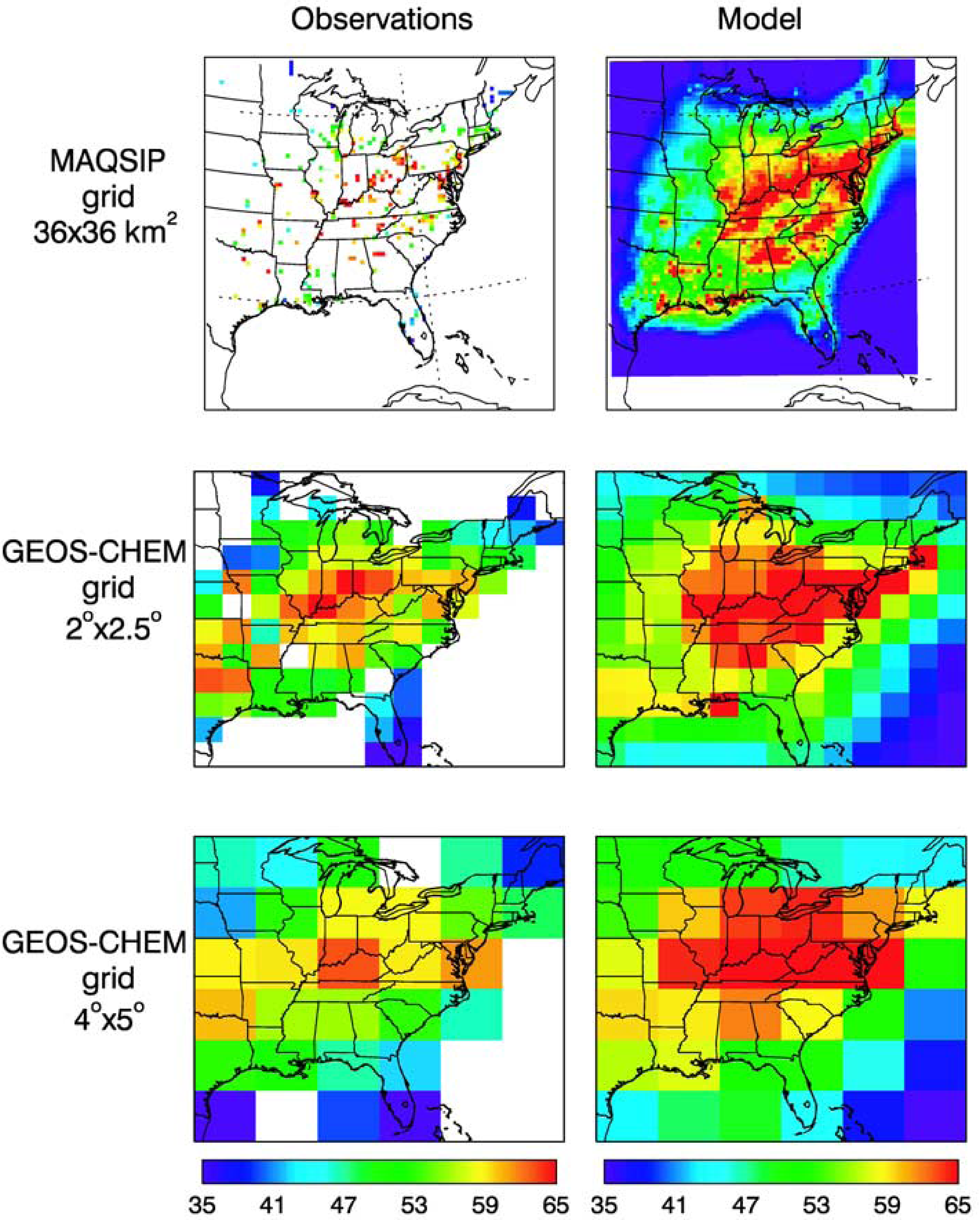
- Horizontal resolution of 1°x1°, 2°x2.5°, or 4°x5°; 48-72 levels in vertical

- Detailed ozone-$NO_x$-VOC-PM chemical mechanism

- Applied by over 30 research groups in U.S. and elsewhere to a wide range of problems in atmospheric chemistry

- Extensively evaluated with observations for ozone and other species (~200 papers in journal literature)

# GEOS-Chem vs. REGIONAL MODEL CAPABILITIES FOR U.S. OZONE



**1-5 pm ozone in eastern U.S., Jun-Aug 1995**

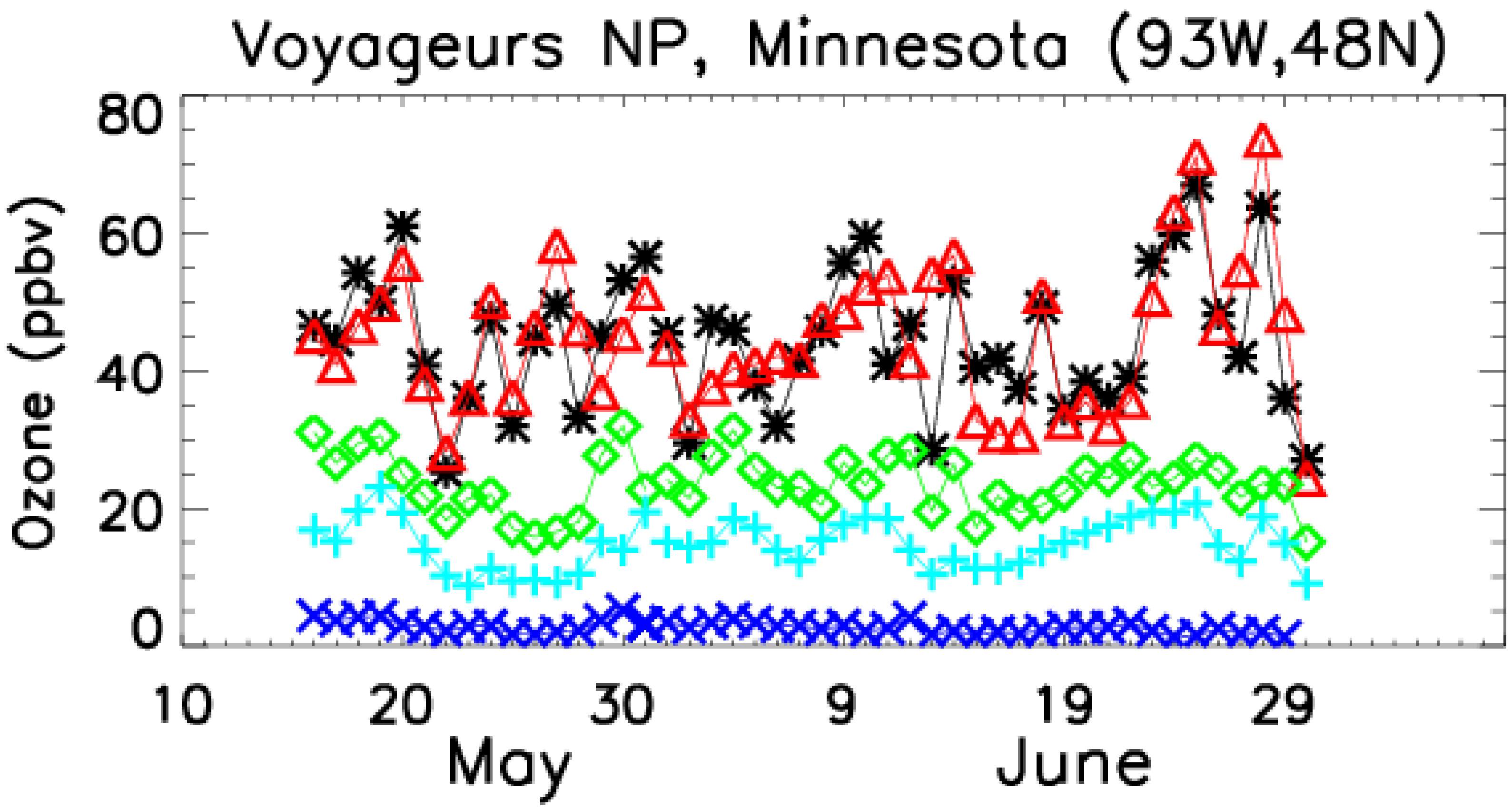
**MAQSIP is precursor to CMAQ**

| | Mean observed | Mean model | Corr. coeff. (R) |
|---|---|---|---|
| MAQSIP 36x36 km$^2$ | 56 ± 8 | 60 ± 9 | 0.59 |
| GEOS-Chem 2°x2.5° | 52 ± 8 | 59 ± 7 | 0.70 |
| GEOS-Chem 4°x5° | 51 ± 8 | 56 ± 7 | 0.90 |

*Fiore et al. [JGR 2003a]*

# TESTING THE GEOS-Chem SIMULATION OF PRB OZONE

## Comparison with observations at remote U.S. sites



**Observations (1-5 pm)**

**Standard model**

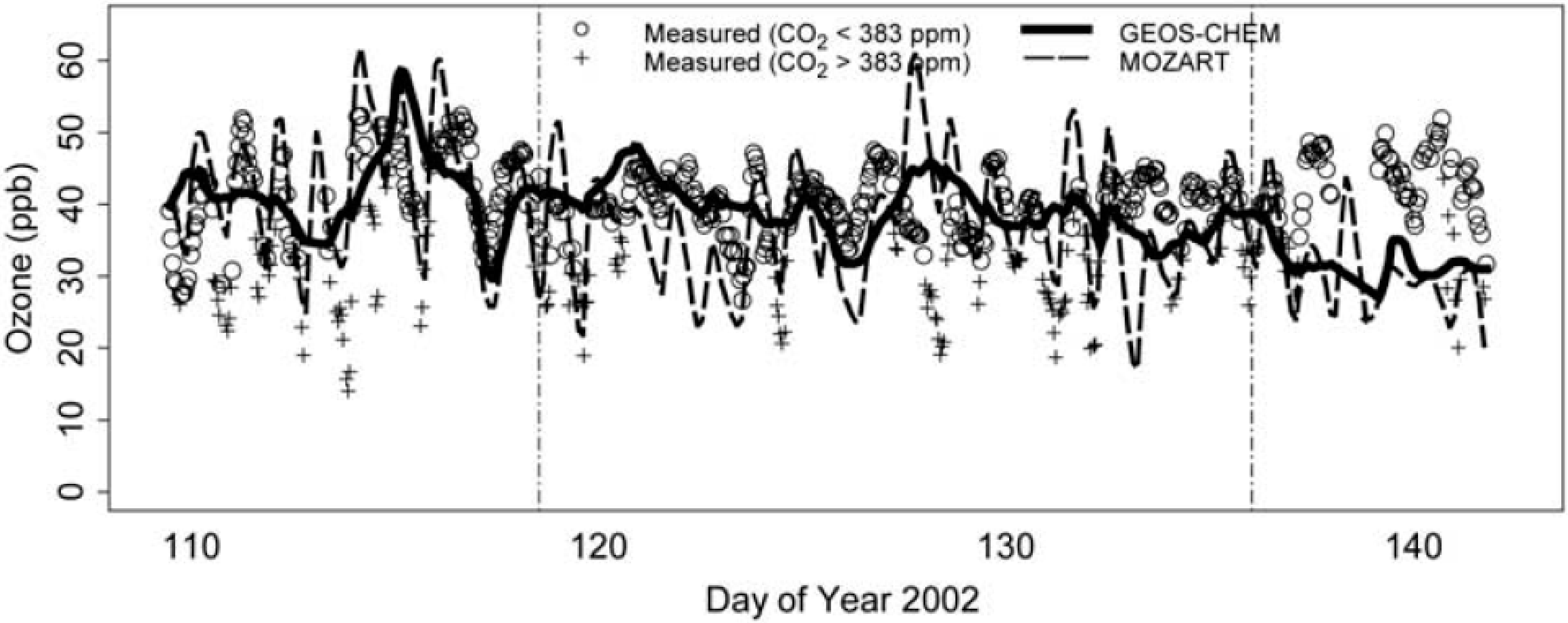
**Model with zero anthropogenic emissions in N. America: PRB ozone**

**Model with zero anthropogenic emissions worldwide: natural ozone**

**Model stratospheric contribution**

*Fiore et al. [JGR 2003b]*

# MODEL vs. OBSERVATIONS AT TRINIDAD HEAD, CA (April-May 2002)



**Observations: 38 ± 7 ppb (unfiltered)**

**41 ± 5 ppb (filtered against local influence)**

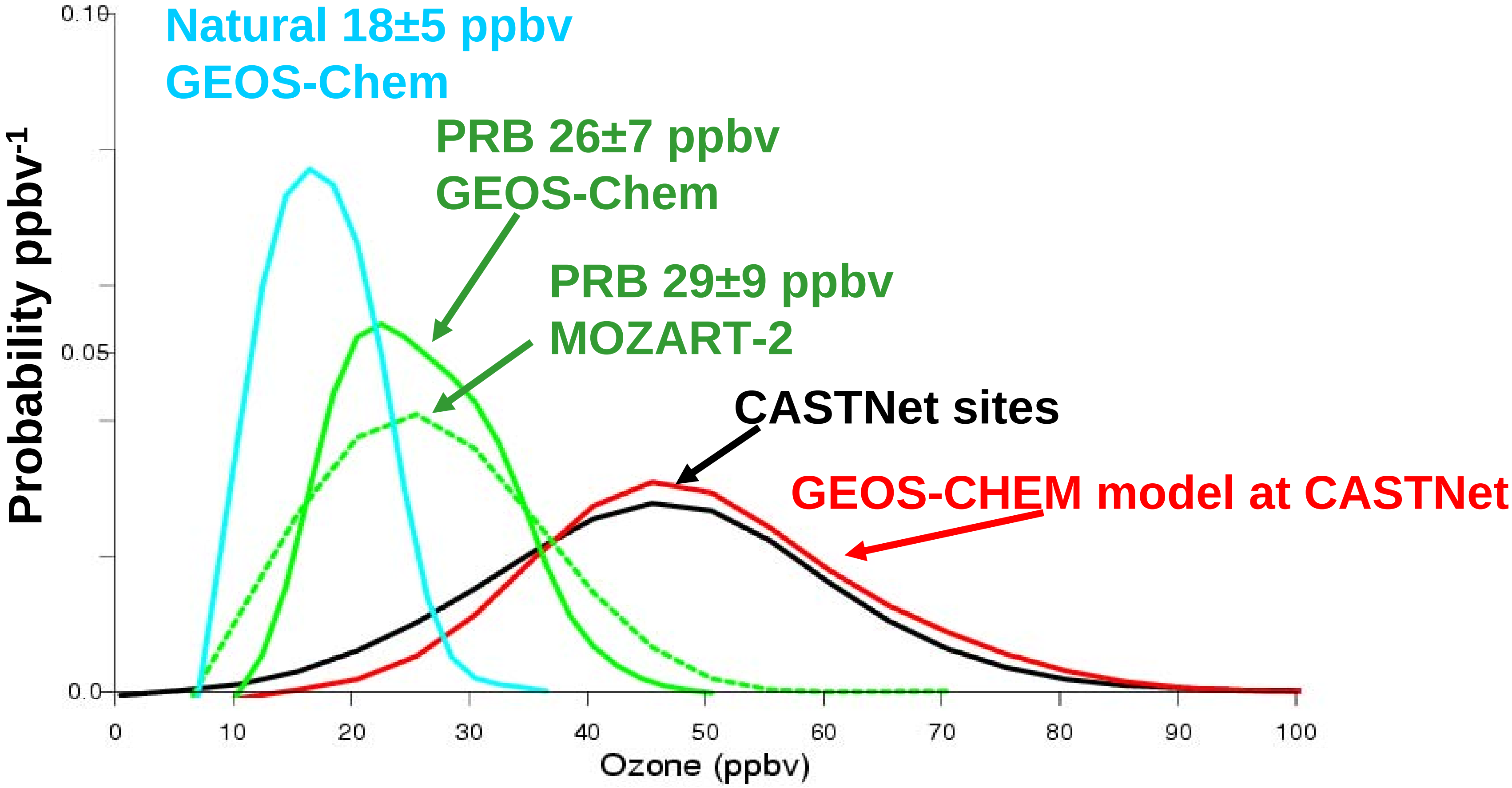
**GEOS-Chem model: 39 ± 5 ppb**

**MOZART-2 global model: 37 ± 9 ppb**

***Goldstein et al. [JGR 2004]***

# OZONE BACKGROUND STATISTICS AT U.S. CASTNet SITES

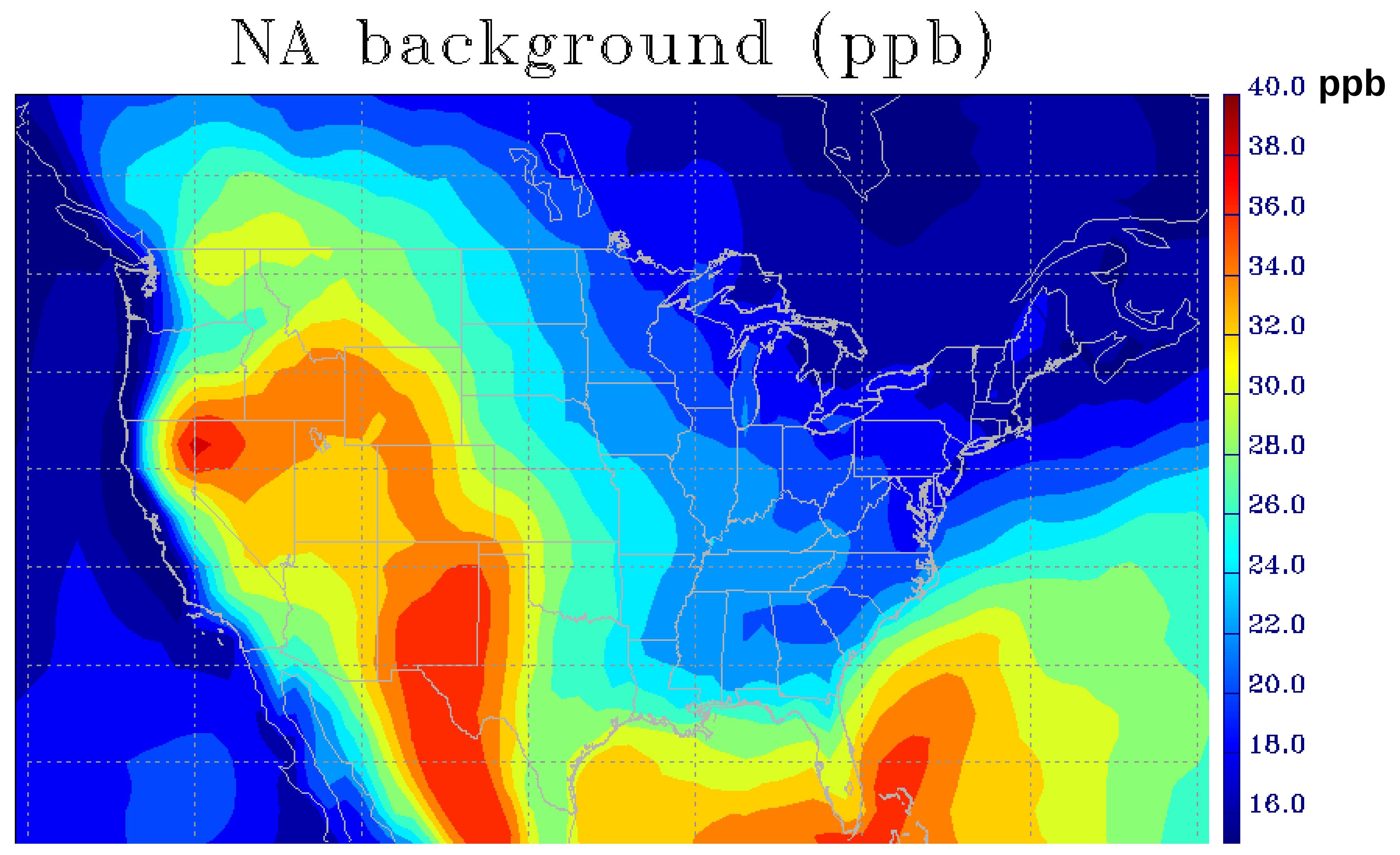
**March-October 2001**



*Fiore et al. [JGR 2003b]*

# SPATIAL DISTRIBUTION OF PRB OZONE

## Mean max-8h-avg values for Jun-Aug 2001

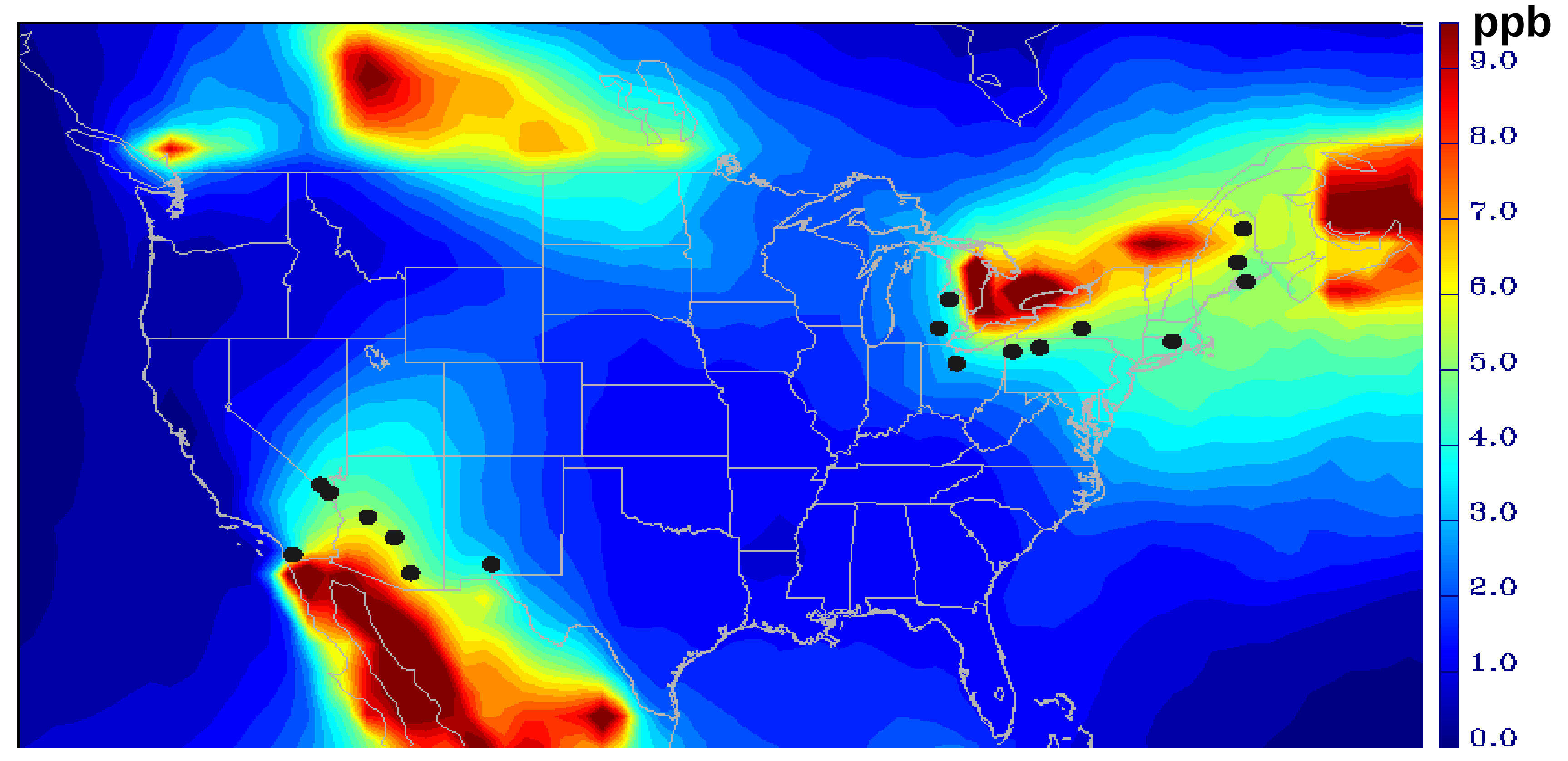


PRB is highest in (1) mountainous, (2) arid, (3) subtropical regions

*Wang et al. [in prep.]*

# OZONE BACKGROUND ENHANCEMENTS FROM CANADIAN AND MEXICAN POLLUTION

**Jun-Aug 2001 mean max-8h-avg values from GEOS-Chem (1ºx1º resolution) with zero U.S. anthropogenic emissions and with PRB subtracted**



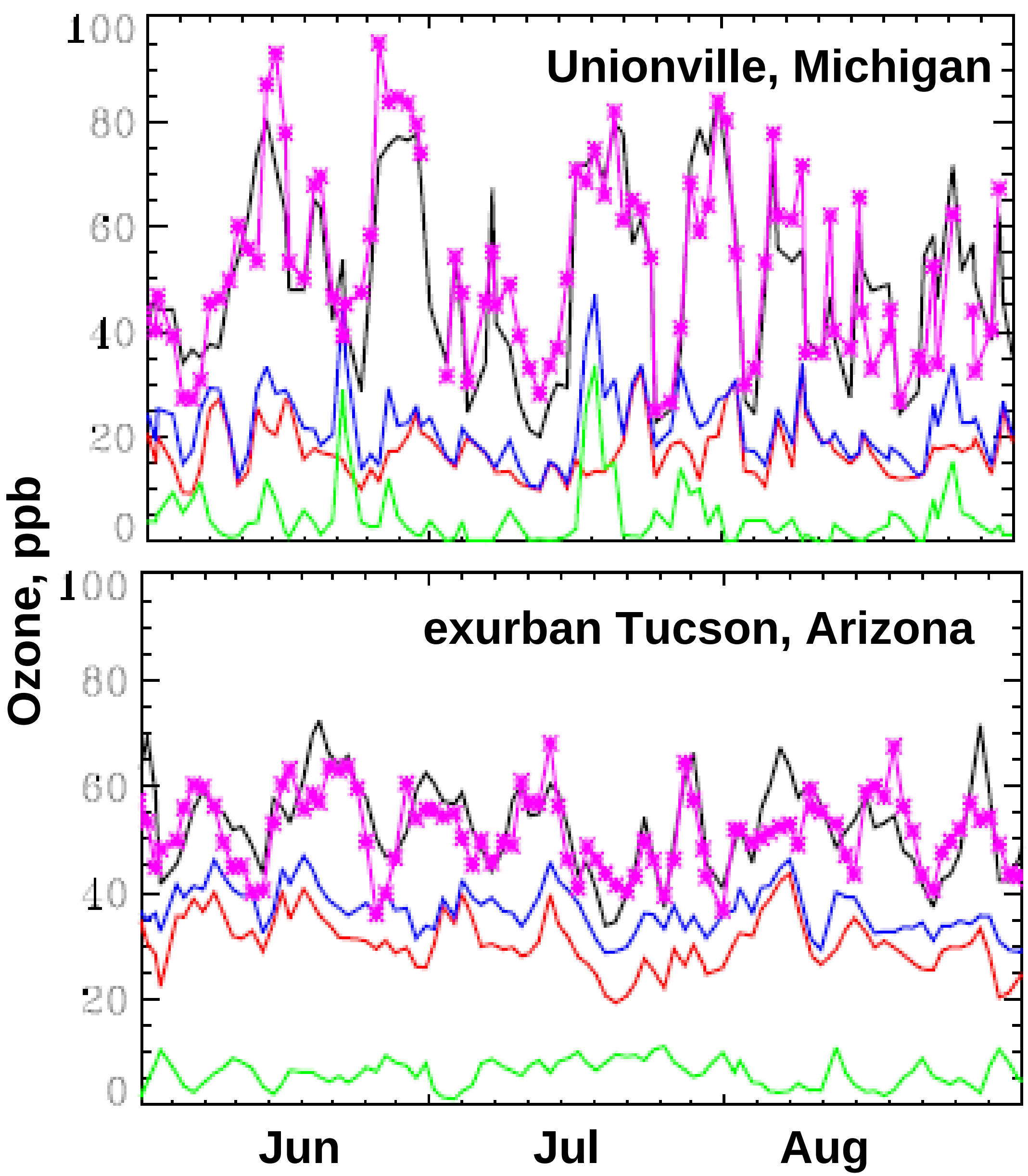
**Regions of maximum influence: Northeast for Canada, Southwest for Mexico**
**Maximum influence is in summer for both regions**

**Select rural CASTNet and AQS sites in influence regions (dots) for further analysis**

***Wang et al. , in prep.***

# CANADIAN AND MEXICAN POLLUTION INFLUENCE

## Jun-Aug 2001 time series at the sites most affected



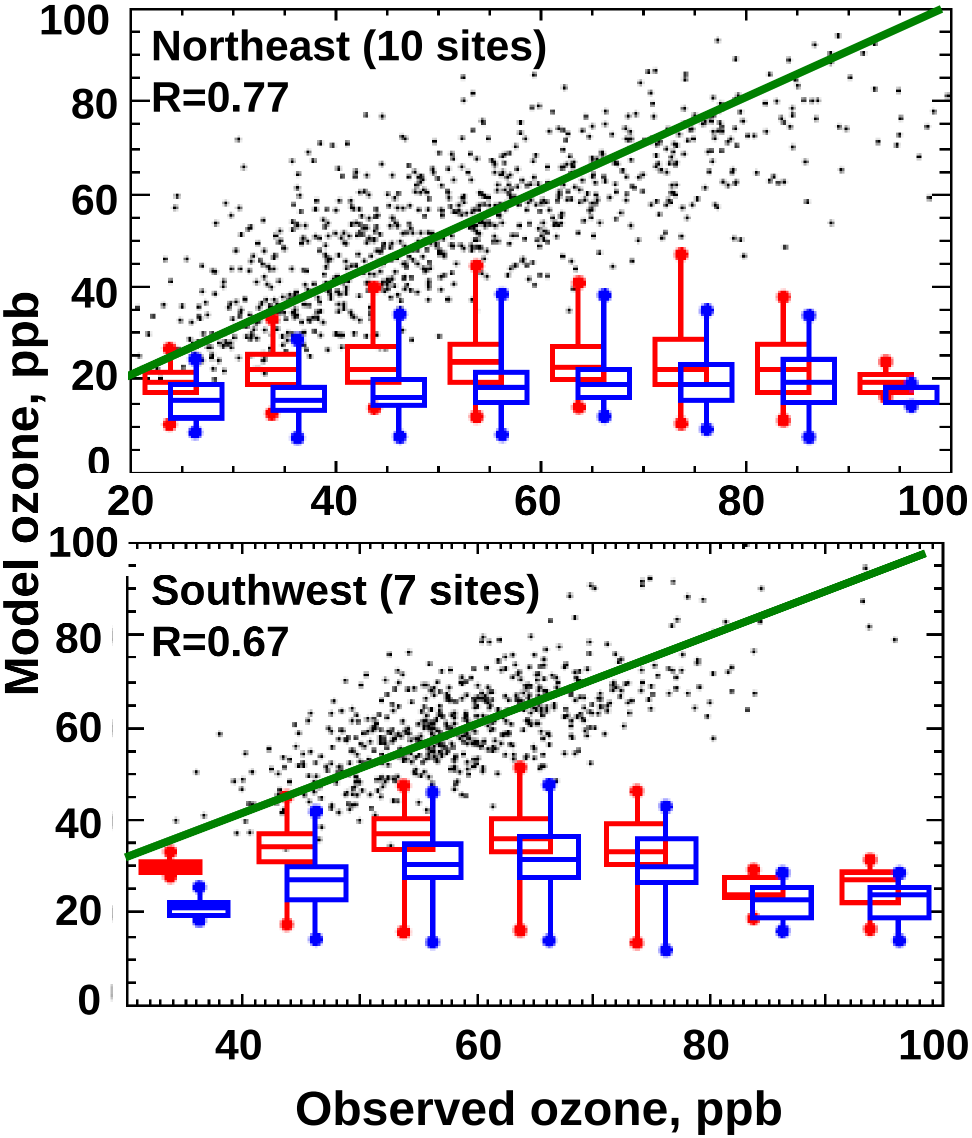
Canadian episodic influence up to 45 ppb; Mexican influence is lower and less episodic

— Observations
— Model (standard)
— US background
— NA background (PRB)
— Canada + Mexico

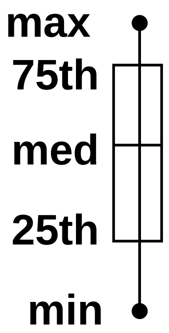
*Wang et al., in prep.*

# N. AMERICAN AND U.S. BACKGROUND STATISTICS FOR NORTHEAST AND SOUTHWEST REGIONS

Scatterplot of model vs. observed max-8h-avg ozone at NE and SW sites with maximum Canadian or Mexican influence (Jun-Aug 2001)



Box-whisker bars show background concentration statistics in 10-ppb ozone bins:



- N. American background (PRB)
- U.S. background including Can/Mex pollution influence

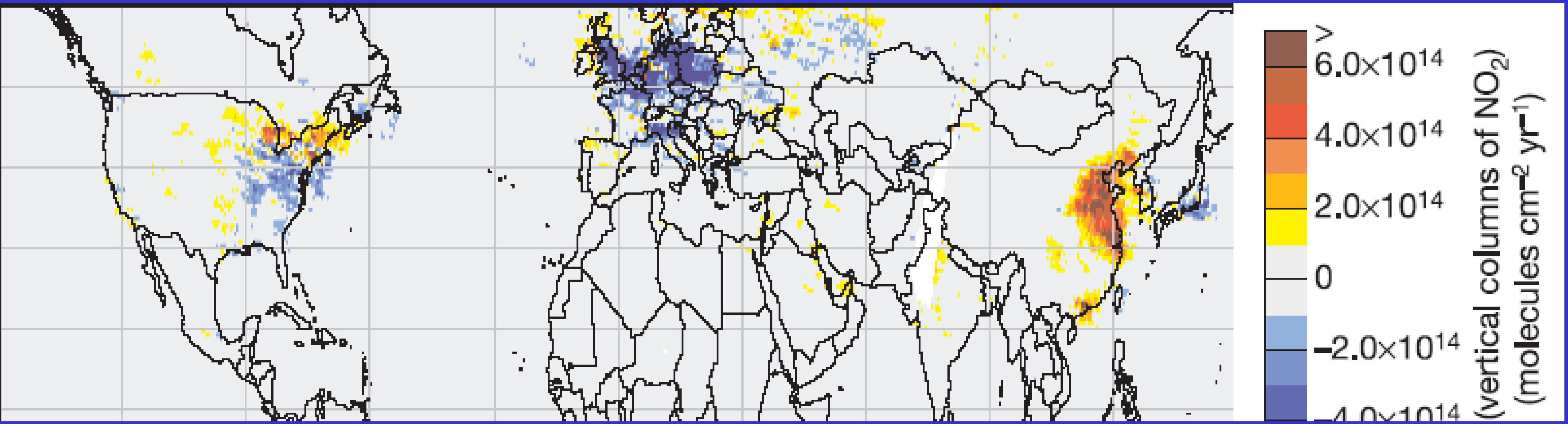
Green line is 1:1 relationship

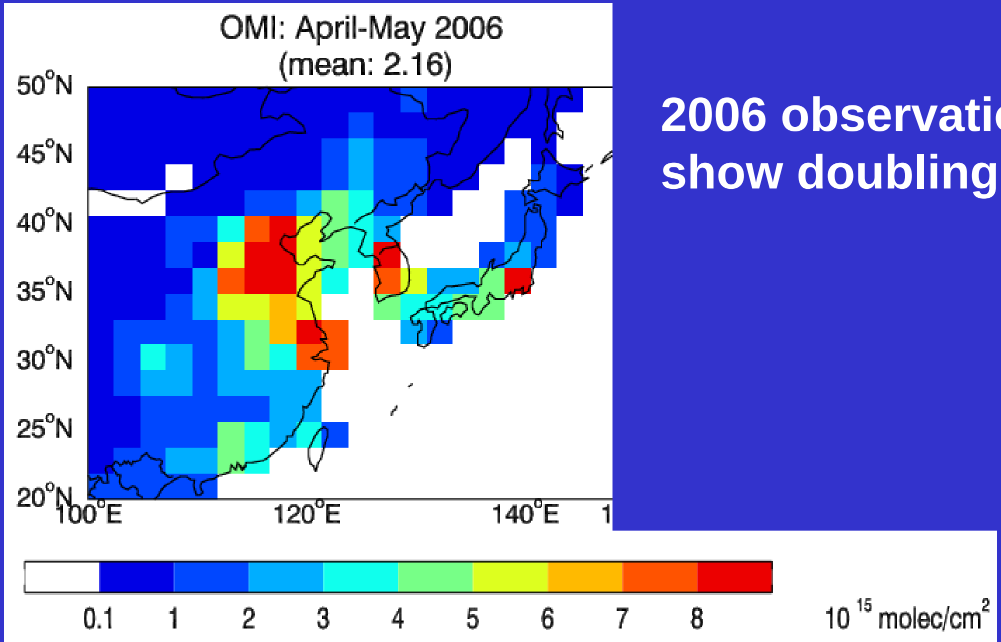
Background influence is often dominant for ozone < 60 ppb, but drops rapidly for higher ozone values

*Wang et al., in prep.*

# RISING ASIAN EMISSIONS AS SEEN FROM SPACE

1996-2002 trend in tropospheric $NO_2$ columns from GOME [Richter et al., 2005]




OMI: April-May 2006
(mean: 2.16)

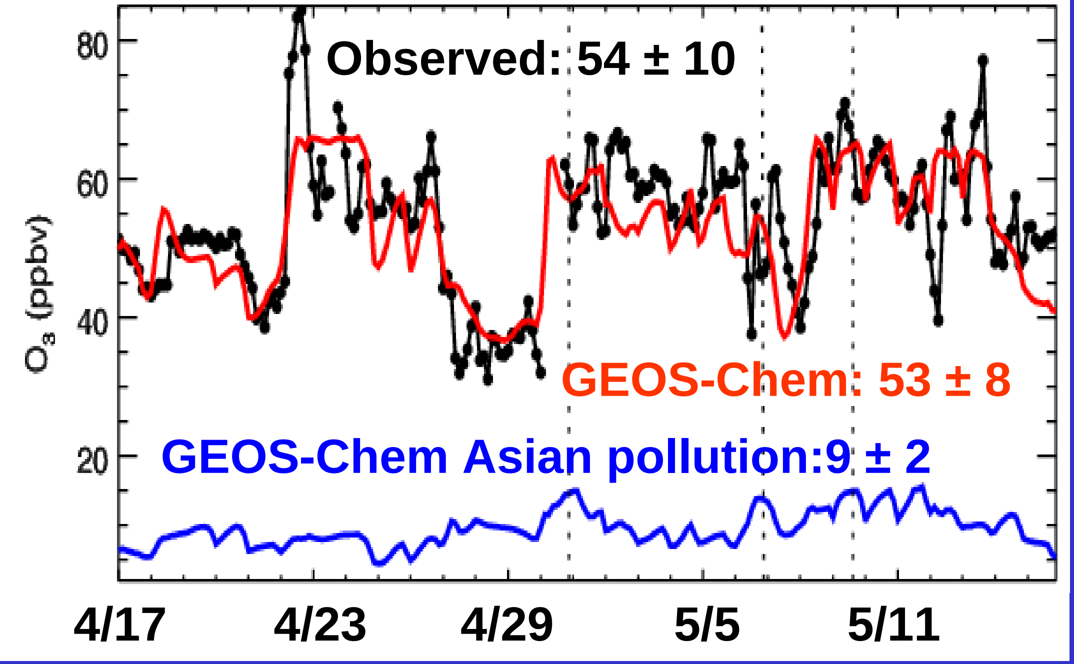
2006 observations of $NO_2$ columns from OMI show doubling of Chinese emissions since 2000

*Zhang et al., in prep.*

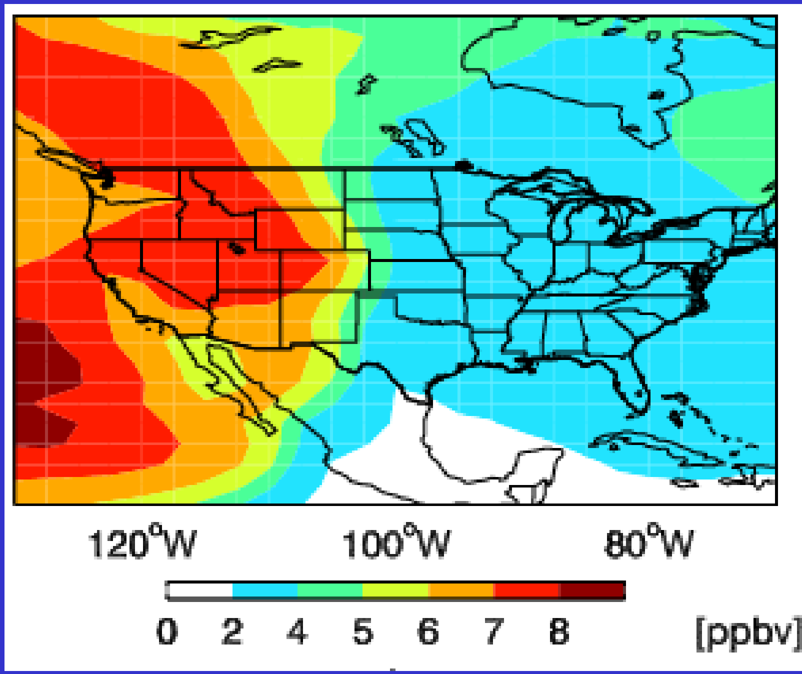
# CONSEQUENCES FOR U.S. SURFACE OZONE

**NASA INTEX-B aircraft/satellite campaign (April-May 2006)**

**Observations (Dan Jaffe, UW) and GEOS-Chem at Mt. Batchelor, Oregon (2,700 m)**



**Mean Asian surface pollution enhancement (GEOS-Chem)**



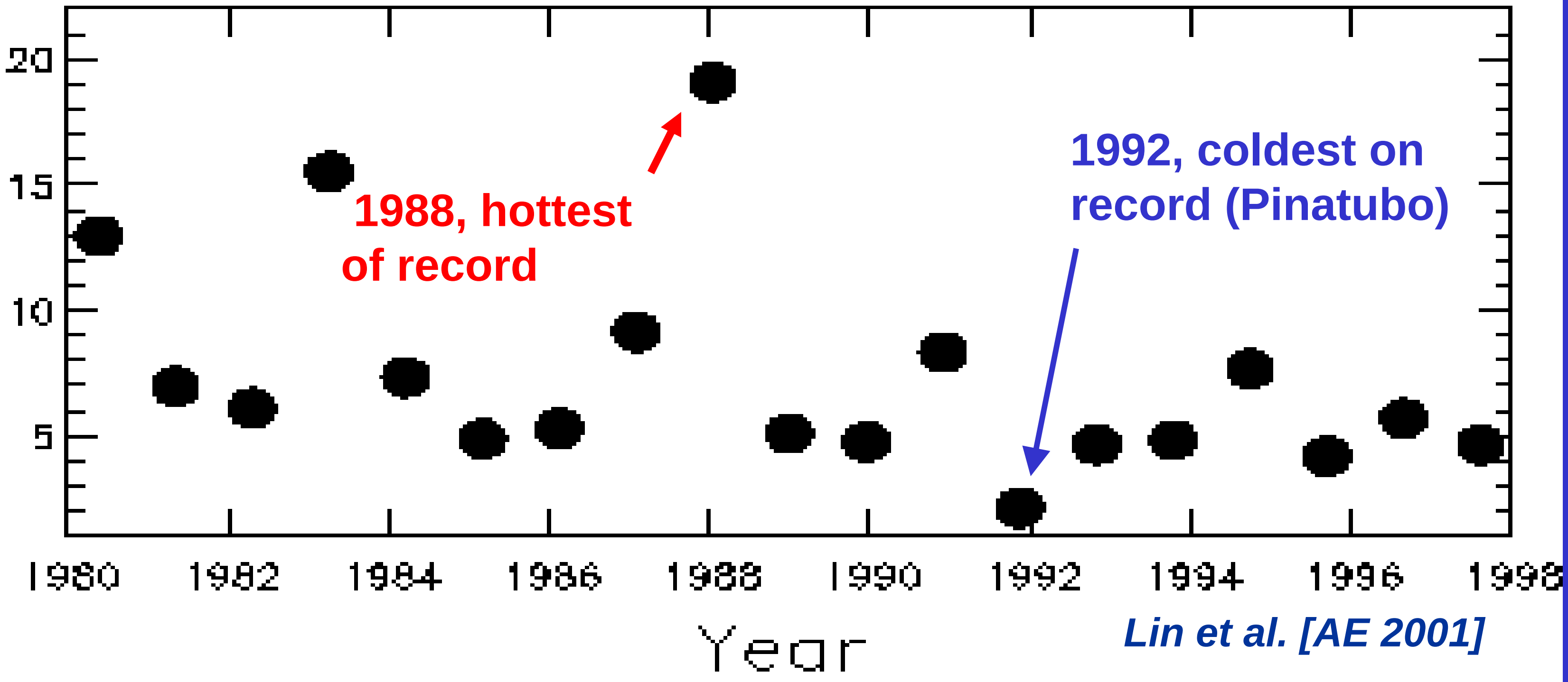
**2000-2006 rise in Asian emissions has increased U.S. surface ozone by 1-3 ppbv in the West**

*Zhang et al. , in prep.*

# OBSERVED DEPENDENCE OF AIR QUALITY ON WEATHER WARNS OF POTENTIALLY LARGE EFFECT OF CLIMATE CHANGE

**Interannual variability of exceedances of ozone NAAQS in the Northeast**

**# summer days with 8-hour ozone > 84 ppbv, average for 257 northeast U.S. AIRS sites**



**1988, hottest of record**

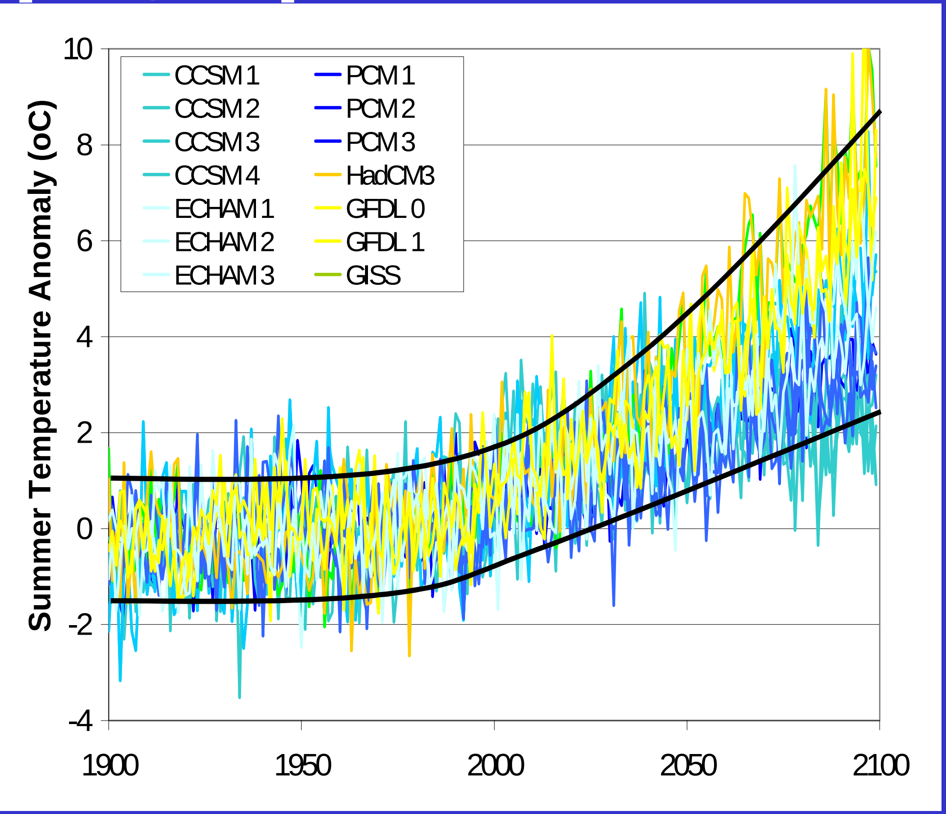
**1992, coldest on record (Pinatubo)**

*Lin et al. [AE 2001]*

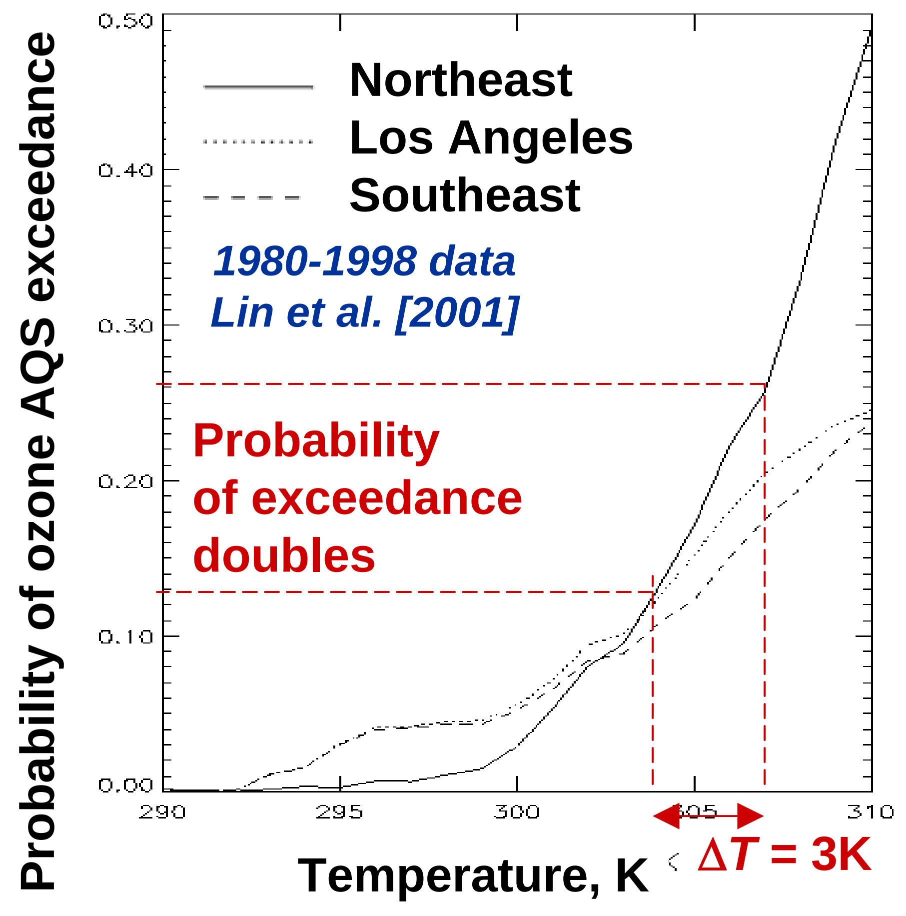
**Ozone correlation with temperature is due to (1) chemistry, (2) biogenic VOC emissions, (3) joint association with stagnation**

# PROJECTING EFFECT OF CLIMATE CHANGE ON OZONE AIR QUALITY USING OBSERVED OZONE-TEMPERATURE CORRELATIONS

**Projected *T* change for northeast U.S. in 2000-2100 simulated with ensemble of downscaled GCMs for different scenarios [IPCC, 2007]**



**Probability of max 8-h $O_3$ > 84 ppbv vs. daily max. temperature**

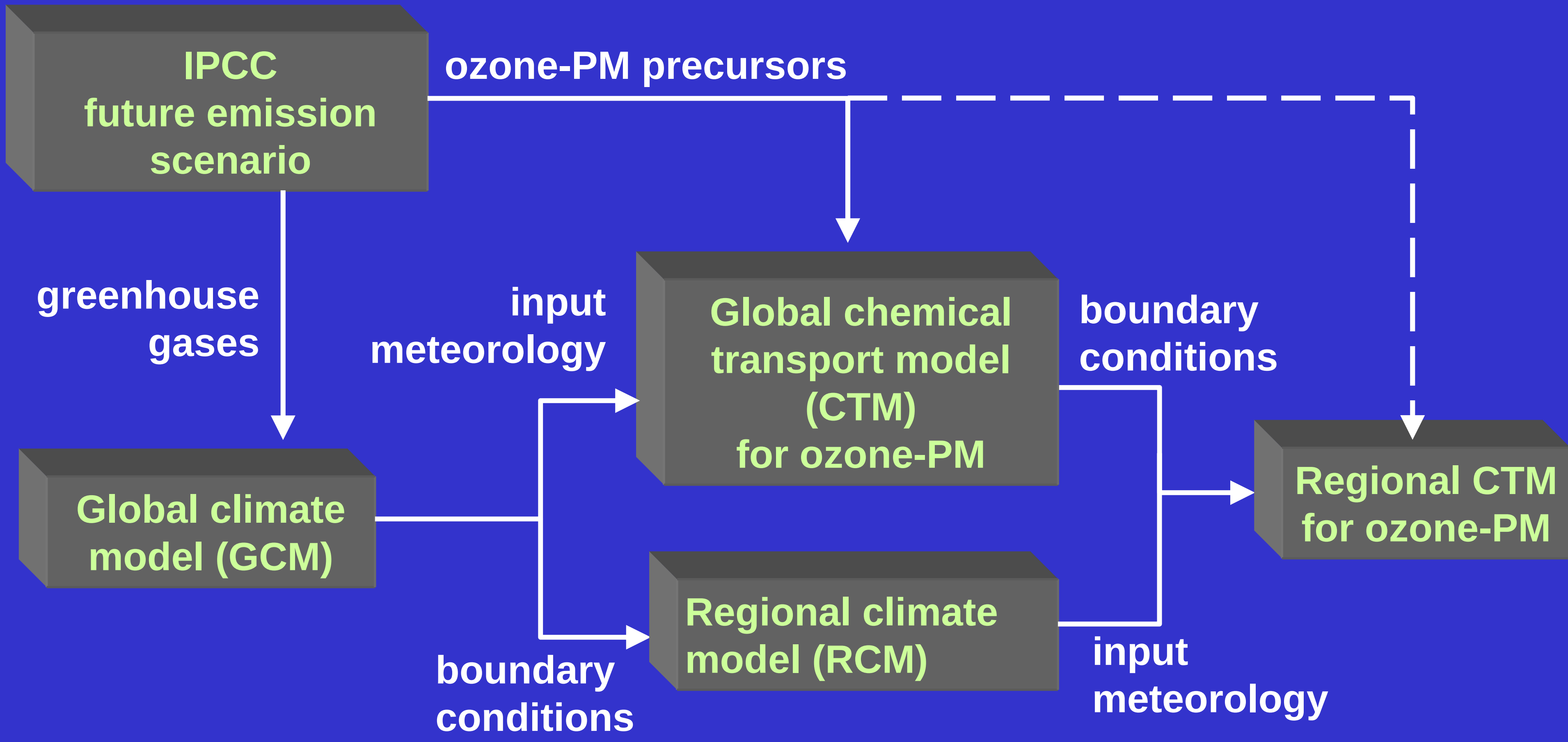


**By 2025, Δ*T* = 1-3 K depending on model and scenario; use statistical approach at right to infer increased probability of ozone exceedance for a given region or city assuming nothing else changes. Effect is large!**

*Lin et al. [AE, submitted].*

# COMPREHENSIVE MODEL APPROACH FOR INVESTIGATING EFFECT OF CLIMATE CHANGE ON AIR QUALITY

internal EPA project (CIRAQ) and several EPA-STAR projects



IPCC
future emission
scenario

ozone-PM precursors

greenhouse
gases

input
meteorology

Global chemical
transport model
(CTM)
for ozone-PM

boundary
conditions

Global climate
model (GCM)

Regional CTM
for ozone-PM

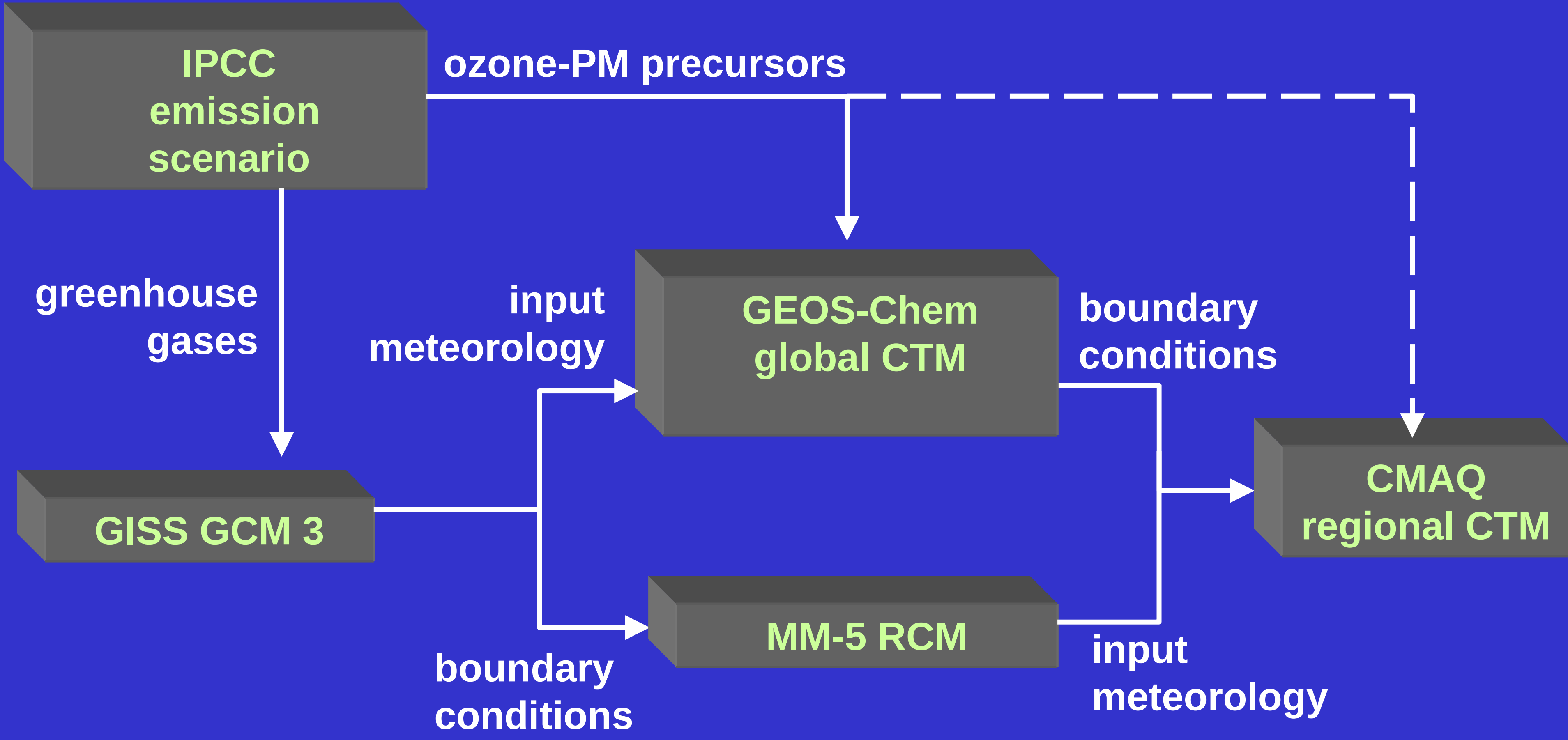
Regional climate
model (RCM)

boundary
conditions

input
meteorology

# EPA-STAR GLOBAL CHANGE AND AIR POLLUTION (GCAP) PROJECT

D.J. Jacob and L.J. Mickley (Harvard), J.H. Seinfeld (Caltech),
D. Rind (NASA/GISS), D.G. Streets (ANL), J. Fu (U. Tenn.) , D. Byun (U. Houston)



IPCC emission scenario

ozone-PM precursors

greenhouse gases

input meteorology

GEOS-Chem global CTM

boundary conditions

GISS GCM 3

CMAQ regional CTM

MM-5 RCM

boundary conditions

input meteorology

Applied to 2000-2050 global change simulations with IPCC SRES A1 scenario; compare 2050 climate (GCM 2049-2051, 3-y averages) to 2000 (1999-2001)

# 2000-2050 EMISSIONS OF OZONE PRECURSORS (A1)

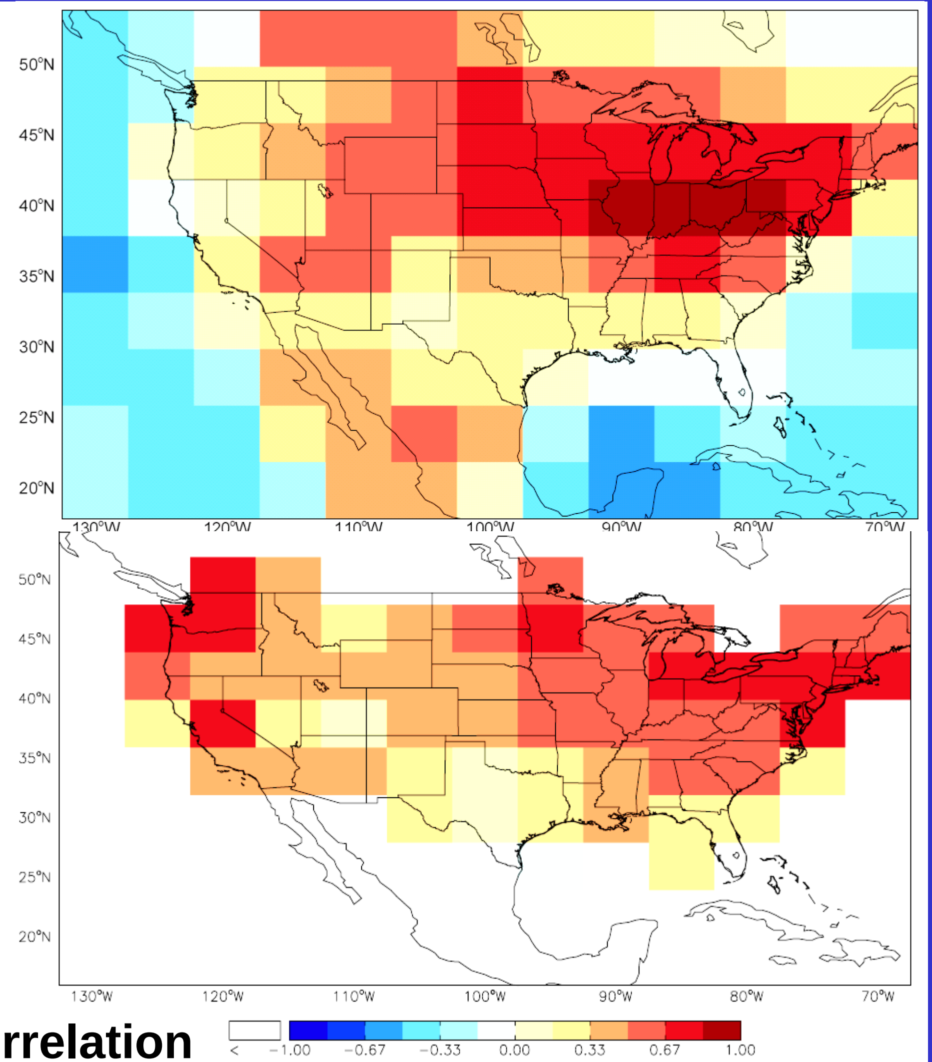
| | Global | | United States | |
|---|---|---|---|---|
| | 2000 emissions | % change, 2000-2050 | 2000 emissions | % change, 2000-2050 |
| **$NO_x$, Tg N $y^{-1}$** | | | | |
| Anthropogenic | 34 | +71% | 6.0 | -39% |
| Lightning | 4.9 | +18% | 0.14 | +21% |
| Soils (natural) | 6.1 | +8% | 0.35 | +11% |
| **NMVOCs, Tg C $y^{-1}$** | | | | |
| Anthropogenic | 46 | +150% | 9.3 | -52% |
| Biogenic | 610 | +23% | 40 | +23% |
| **CO, Tg $y^{-1}$** | 1020 | +25% | 87 | -47% |
| **Methane, ppbv** | 1750 | 2400 (+37%) | | |

- Global increase in anthropogenic emissions but 40-50% decreases in U.S.
- Climate-driven increases in natural $NO_x$, NMVOC emissions

*Wu et al. [JGR, in press]*

# OZONE-TEMPERATURE CORRELATION AS TEST OF MODEL SENSITIVITY TO CLIMATE CHANGE

**Correlate daily max-8h-avg ozone with daily max temperature in Jun-Aug**



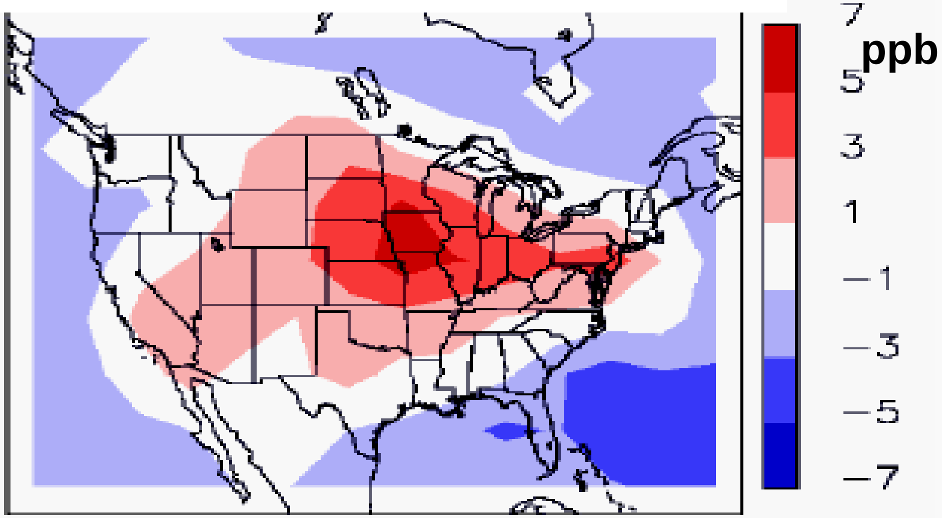
**GCAP/GEOS-Chem model present-day climate (3 years)**

**Observations (1980-1998)**

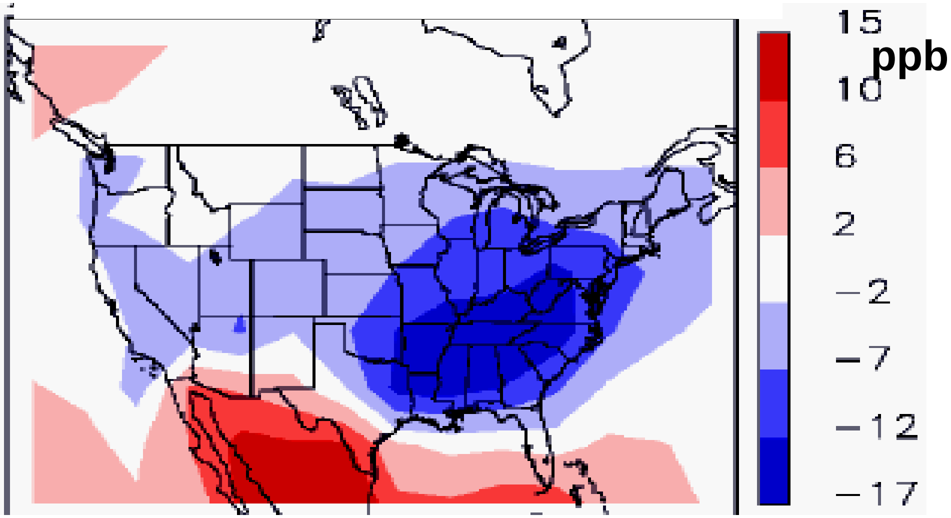
**correlation coefficient R** -1 -.5 0 .5 1

*Yoshitomi et al. [in progress]*

# CHANGES IN SUMMER MEAN 8-h AVG. DAILY MAXMUM OZONE FROM 2000-2050 CHANGES IN CLIMATE AND GLOBAL EMISSIONS



**Effect of changing climate**



**Effect of changing emissions**

- Models agree that 2000-2050 climate change will decrease background ozone but increase surface ozone in U.S. by generally 1-10 ppb

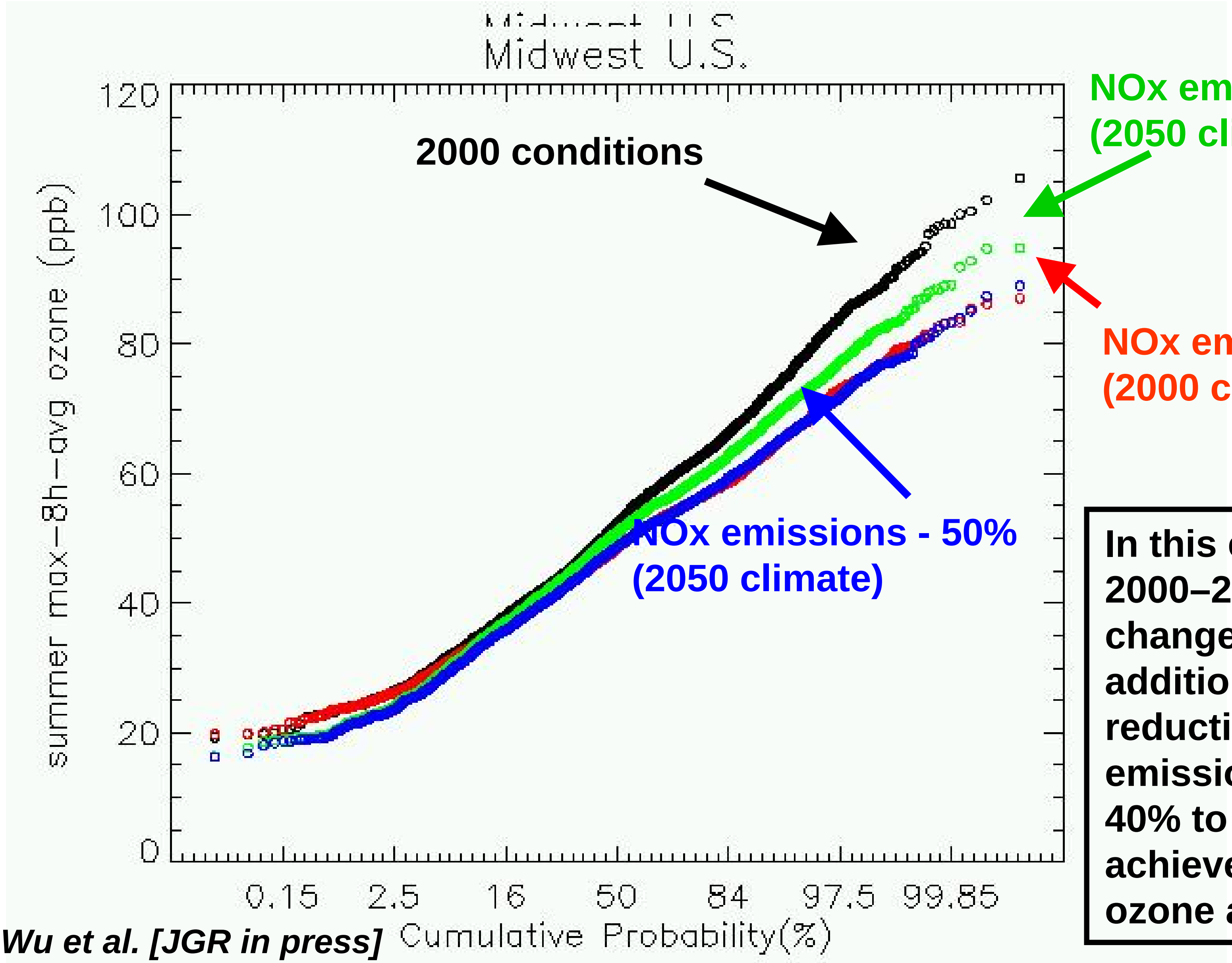
- Most but not all models find maximum effect during pollution episodes

- All models find significant effect in Northeast but disagree in other regions

- Differences in Southeast partly due to different isoprene oxidation mechanisms

*Wu et al. [JGR in press]*

# CLIMATE CHANGE PENALTY: MEETING A GIVEN AIR QUALITY GOAL WILL REQUIRE GREATER EMISSION REDUCTIONS IN FUTURE CLIMATE



**2000 conditions**

**NOx emission - 40% (2050 climate)**

**NOx emission - 40% (2000 climate)**

**NOx emissions - 50% (2050 climate)**

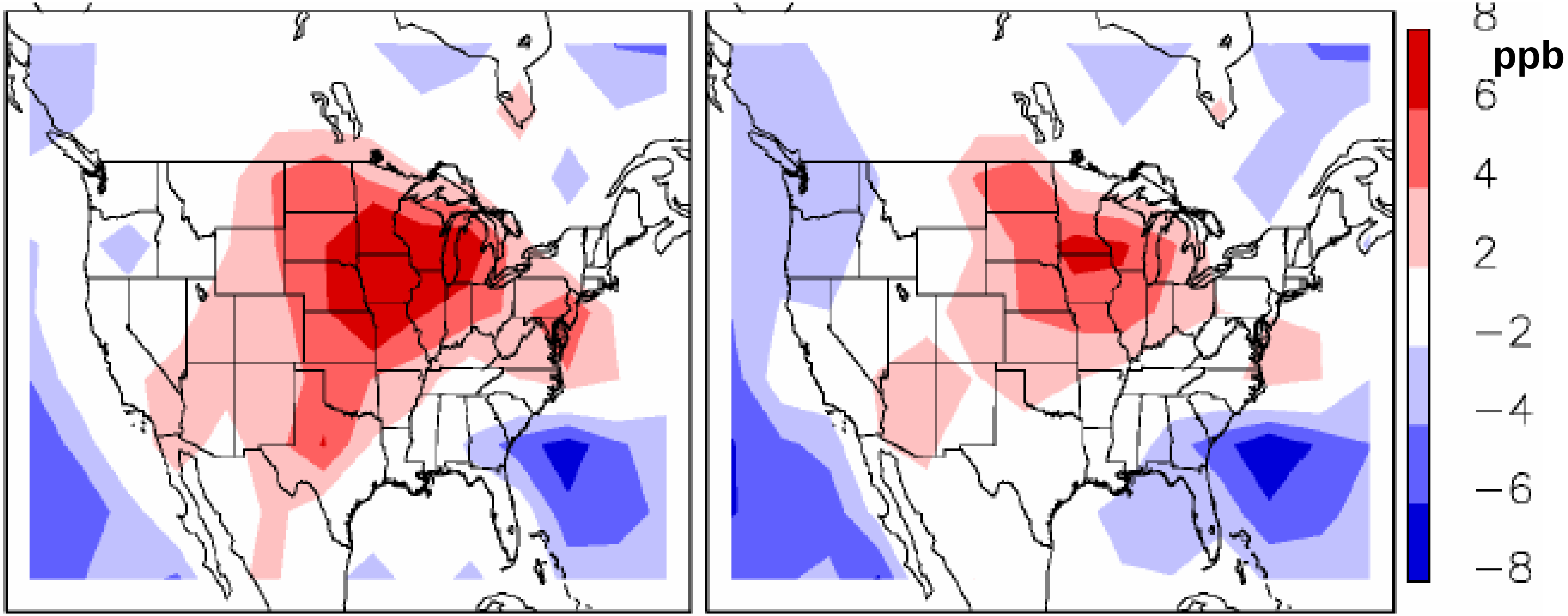
*Wu et al. [JGR in press]*

**In this example, 2000–2050 climate change implies an additional 25% reduction in NOx emissions (from 40% to 50%) to achieve the same ozone air quality.**

# NO$_x$ EMISSION REDUCTIONS DECREASE CLIMATE CHANGE PENALTY

## …and can even turn it into a climate benefit

**Change in summer 90th percentile max-8h-avg surface ozone (ppb) from 2000-2050 climate change**



**with 2000 emissions**

**with 2050 emissions**

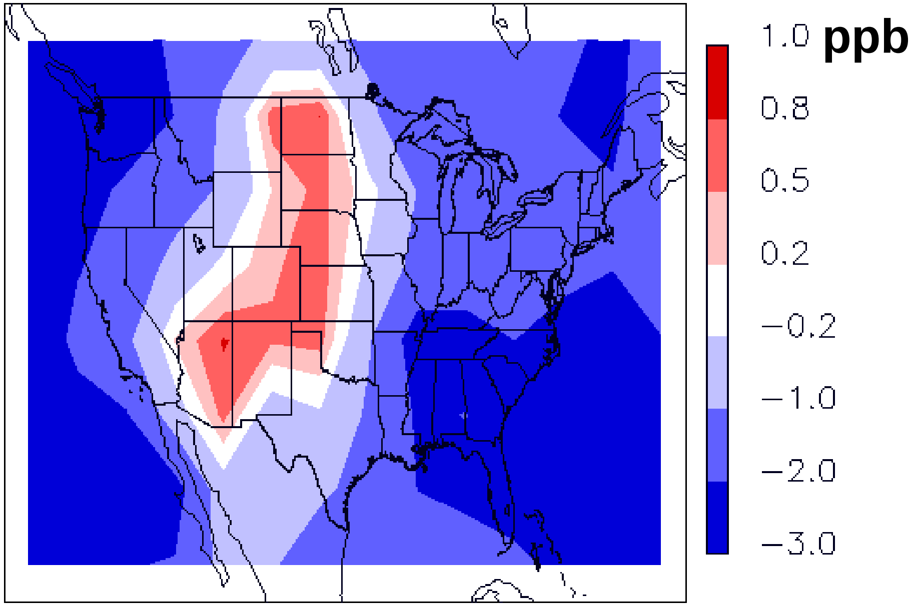
**Reducing U.S. anthrop. emissions (1) increases relative influence of background, (2) decreases isoprene efficiency for making ozone**

*Wu et al. [JGR in press]*

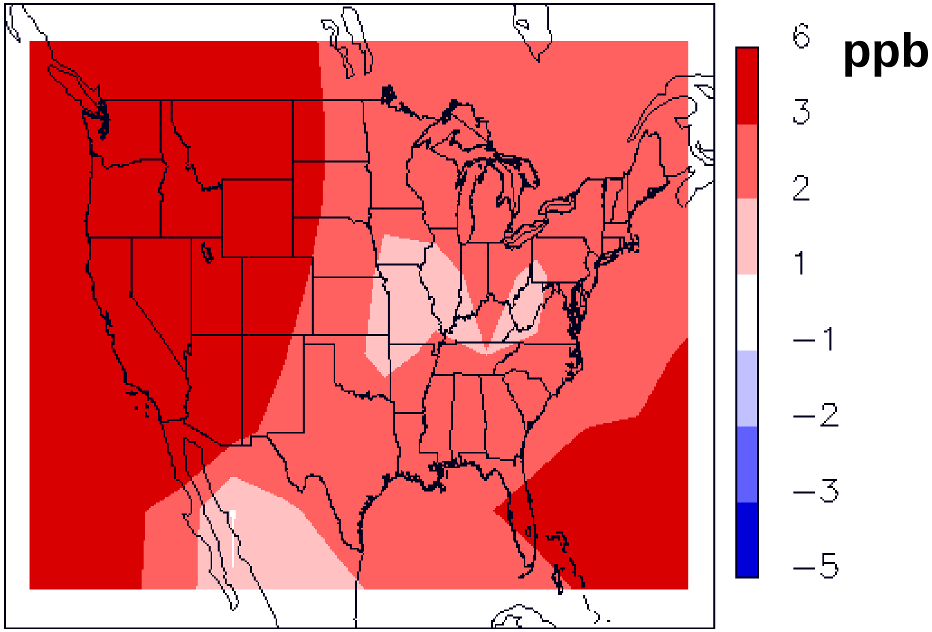
# EFFECT OF 2000-2050 GLOBAL CHANGE ON THE NORTH AMERICAN OZONE BACKGROUND (PRB)

## June-August PRB values

### Effect of changing climate



### Effect of changing emissions

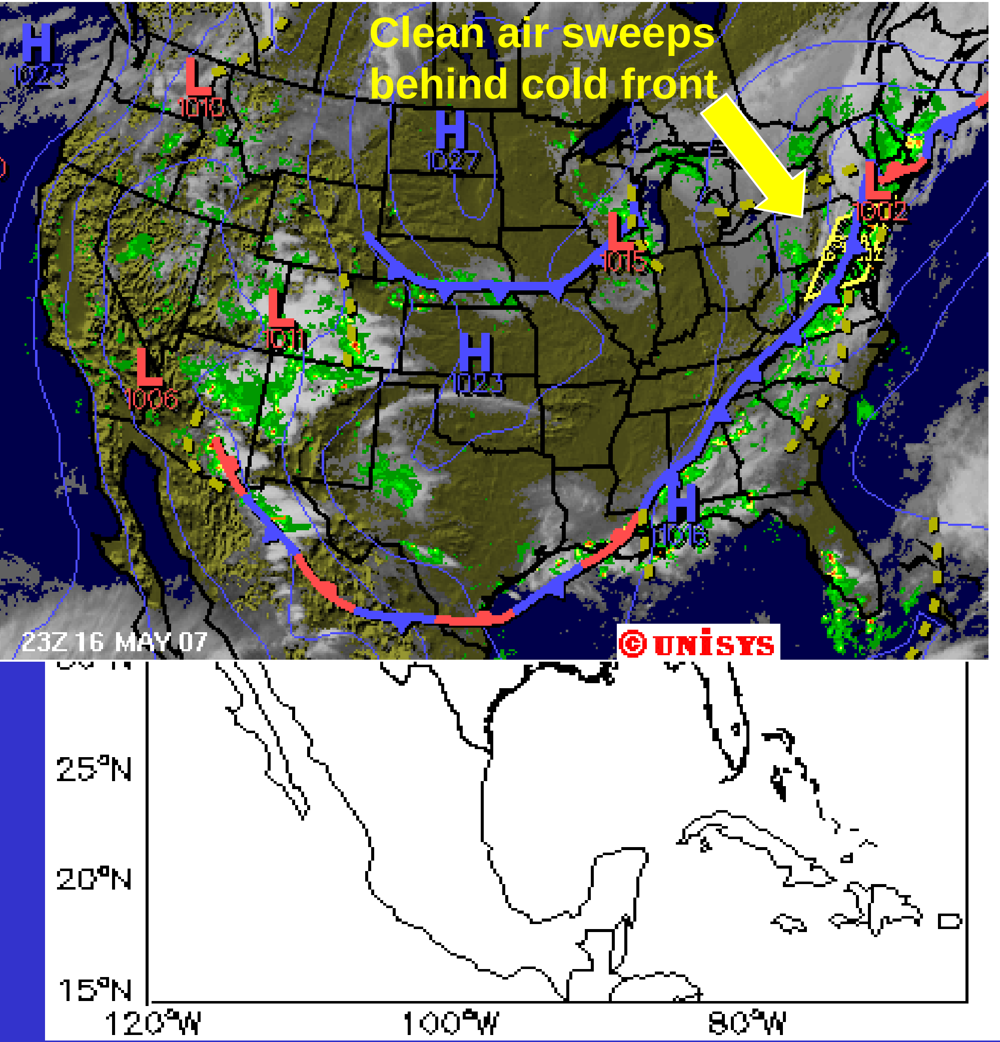


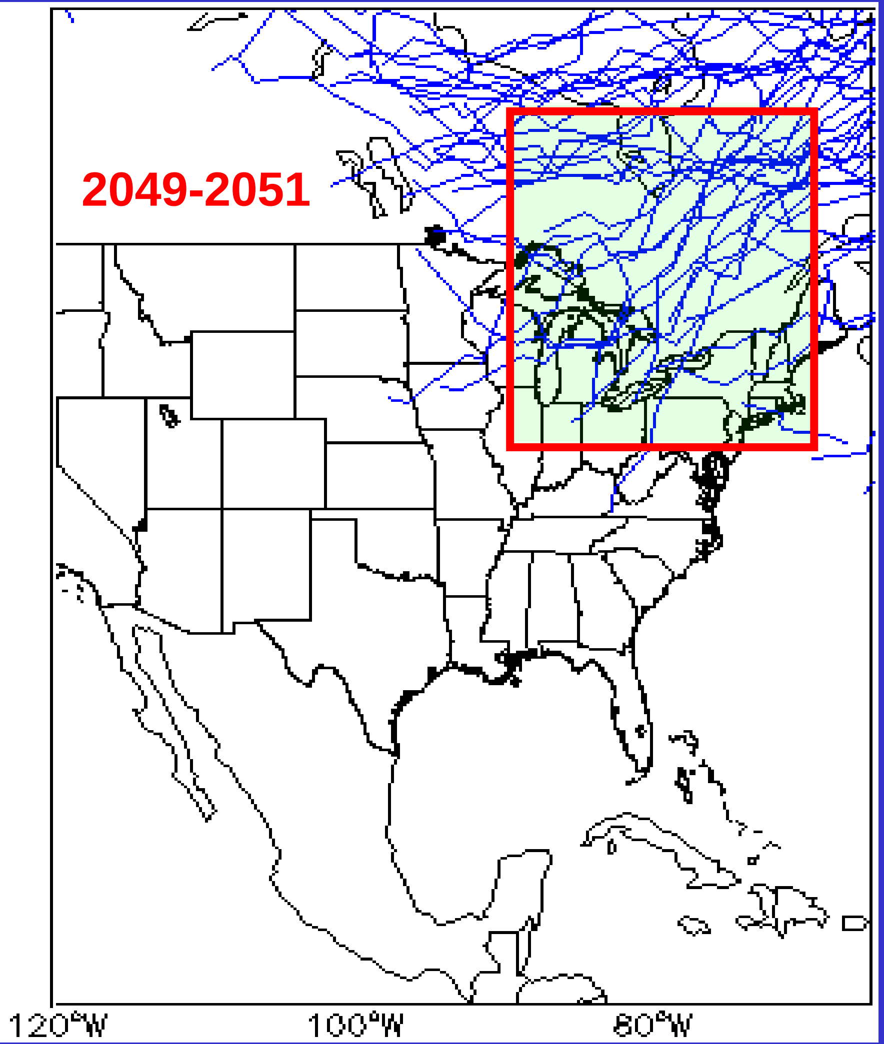
- Large increase in West from rising Asian emissions
- Canceling effects in the East from changing climate and emissions

*Wu et al., in prep.*

# 2000-2050 DECREASE OF CYCLONE FREQUENCY

**Cold fronts associated with mid-latitude cyclones tracking across Canada are the principal process ventilating Midwest and Northeast**


Clean air sweeps behind cold front

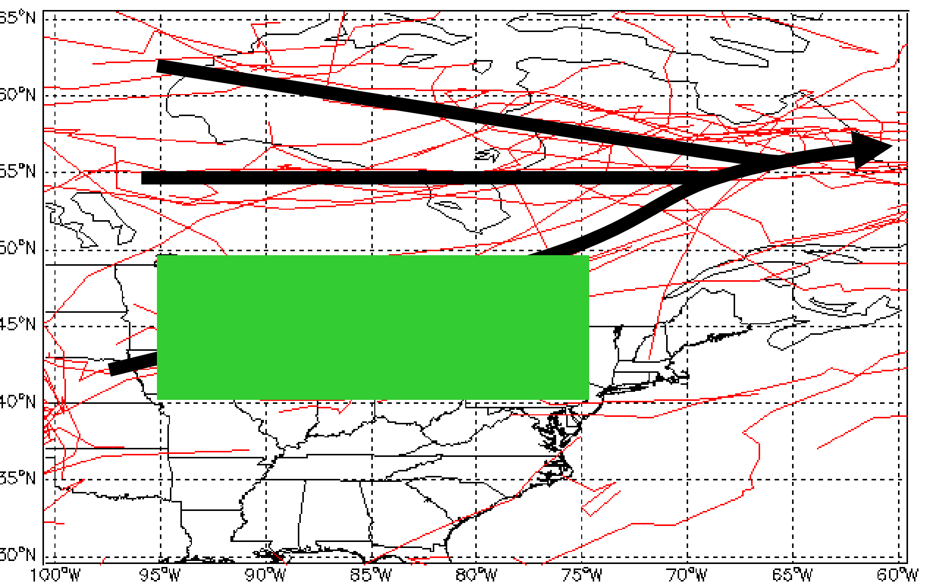

2049-2051

**Summertime cyclone frequency decreases by 17% in 2050 climate (GISS GCM A1 scenario)**

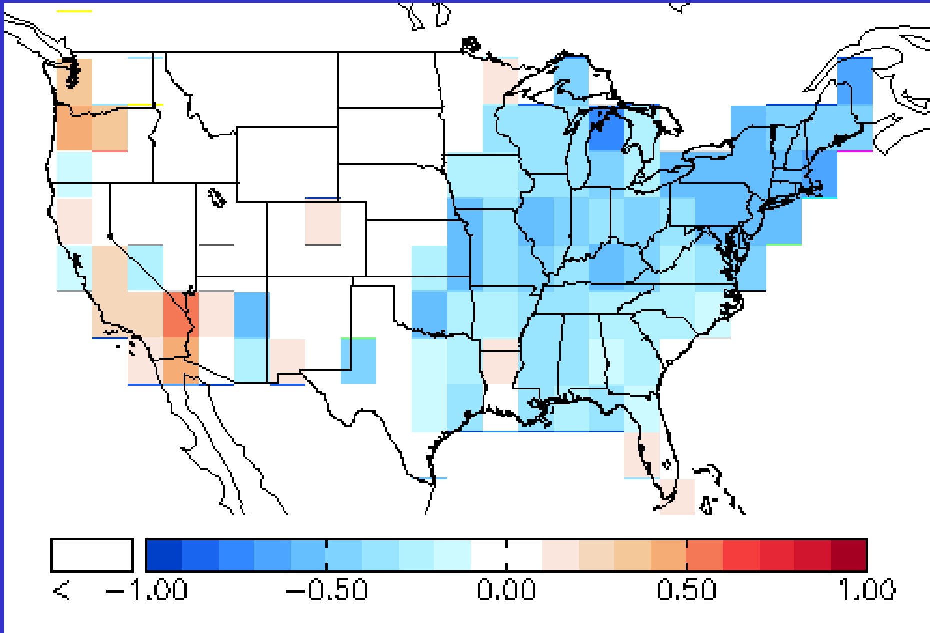
*Wu et al. [iJGR n press]*

# CORRELATION BETWEEN 40-50°N CYCLONE FREQUENCY AND OZONE AIR QUALITY STANDARD EXCEEDANCES, 1980-1998

observed summer cyclone tracks
(NCEP reanalysis)

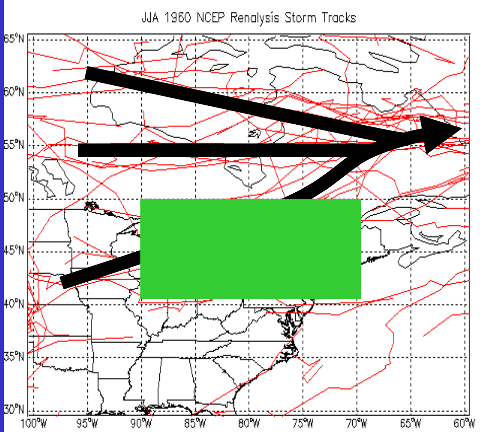


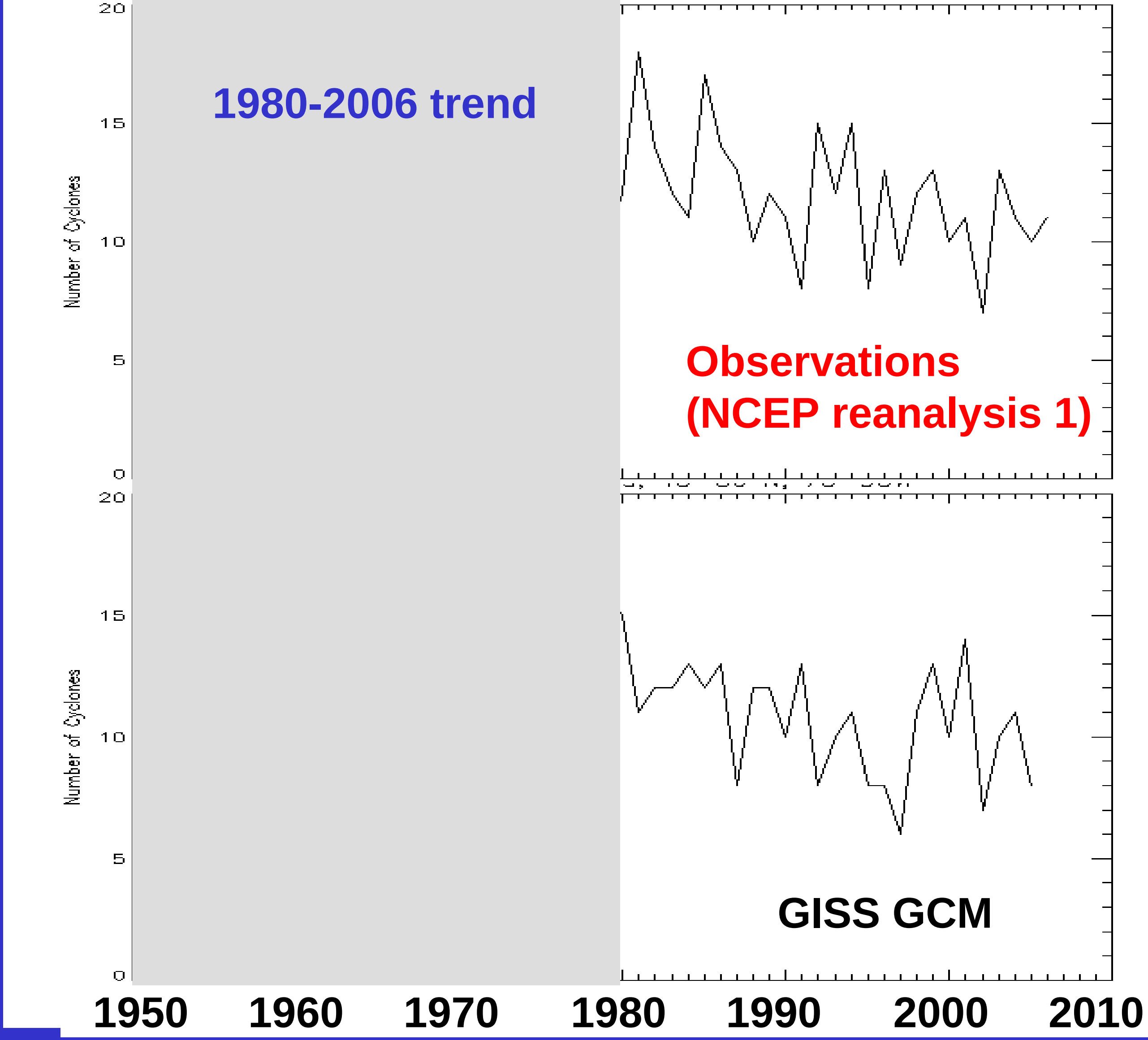
Correlation coefficient (R) between
# ozone AQS exceedances per summer
and # 40-50° N cyclones



*Leibensperger et al. , in prep.*

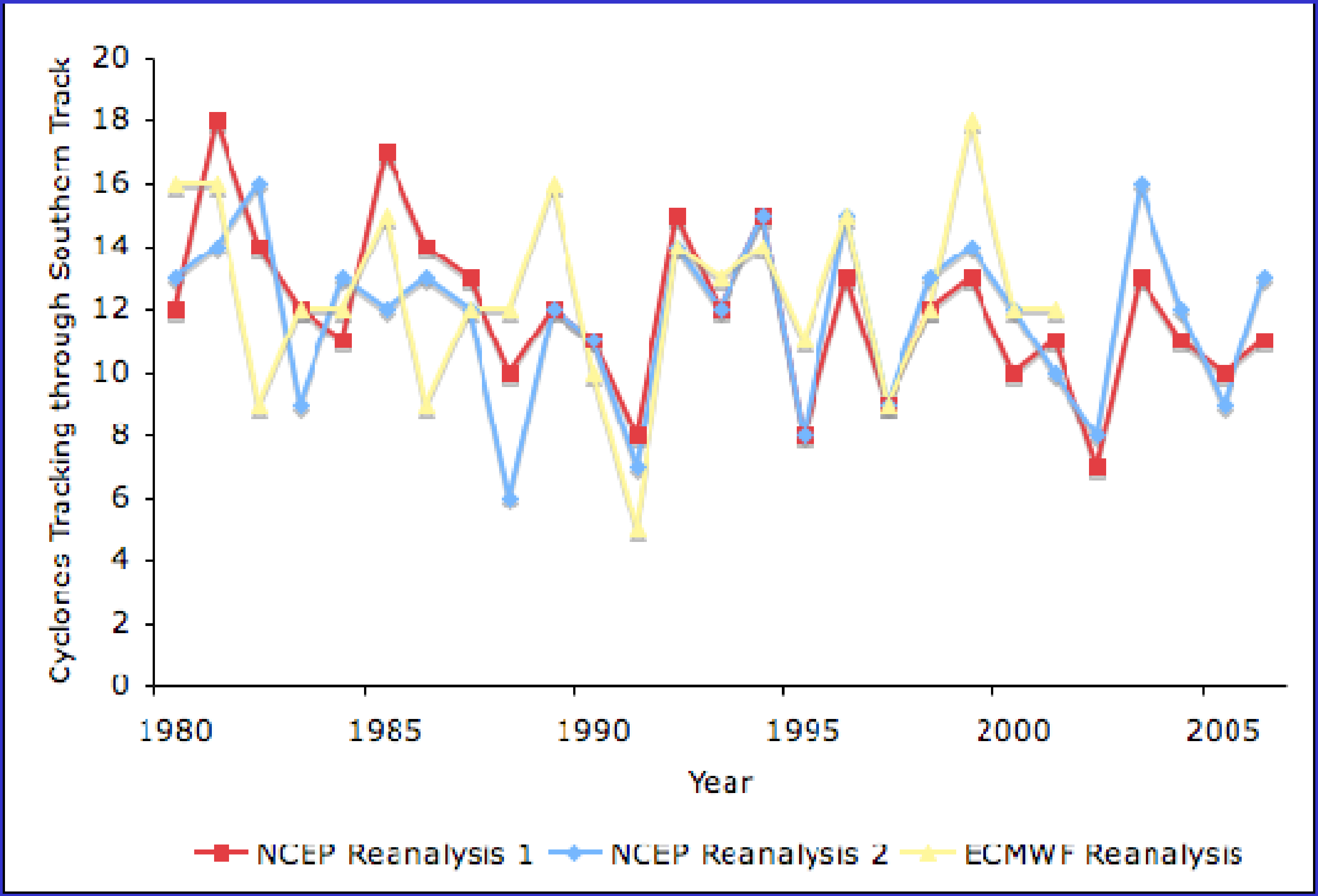
# TREND IN SUMMERTIME CYCLONE FREQUENCY, 1950-2006





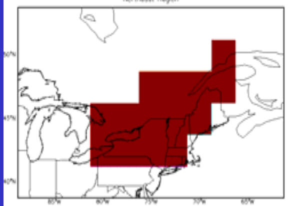
*Leibensperger et al., in prep.*

# MORE RECENT REANALYSES (NCEP 2 AND ECMWF) SHOW LARGE 1980-2005 CYCLONE VARIABILITY BUT NO TREND



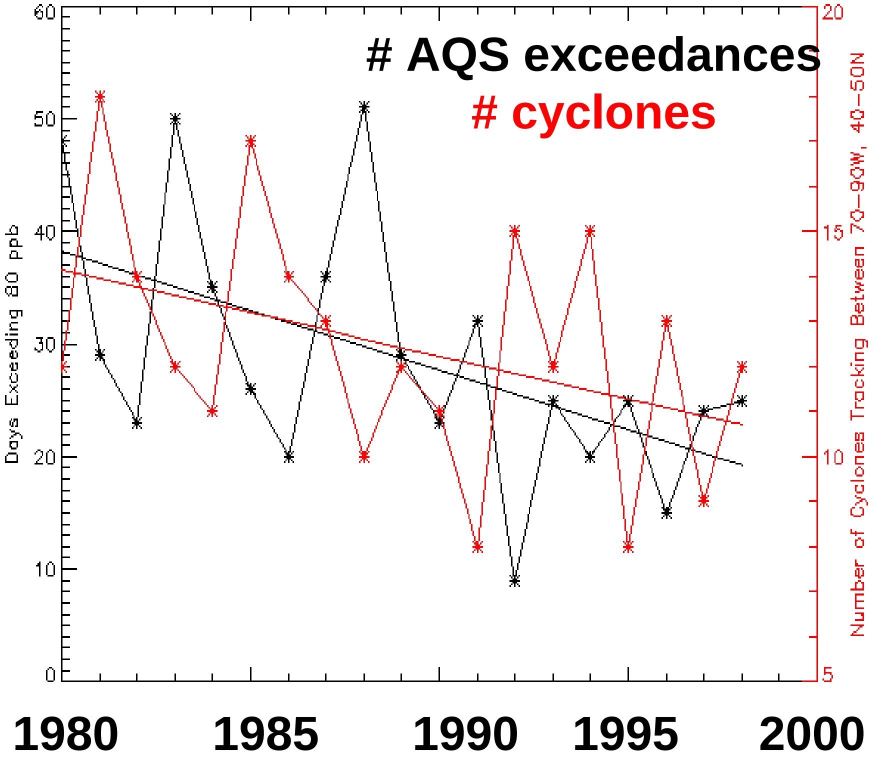
*Leibensperger et al., in prep.*

# CYCLONE FREQUENCY TREND FROM NCEP 1 REANALYSIS WOULD IMPLY LARGE EFFECT ON OZONE TRENDS

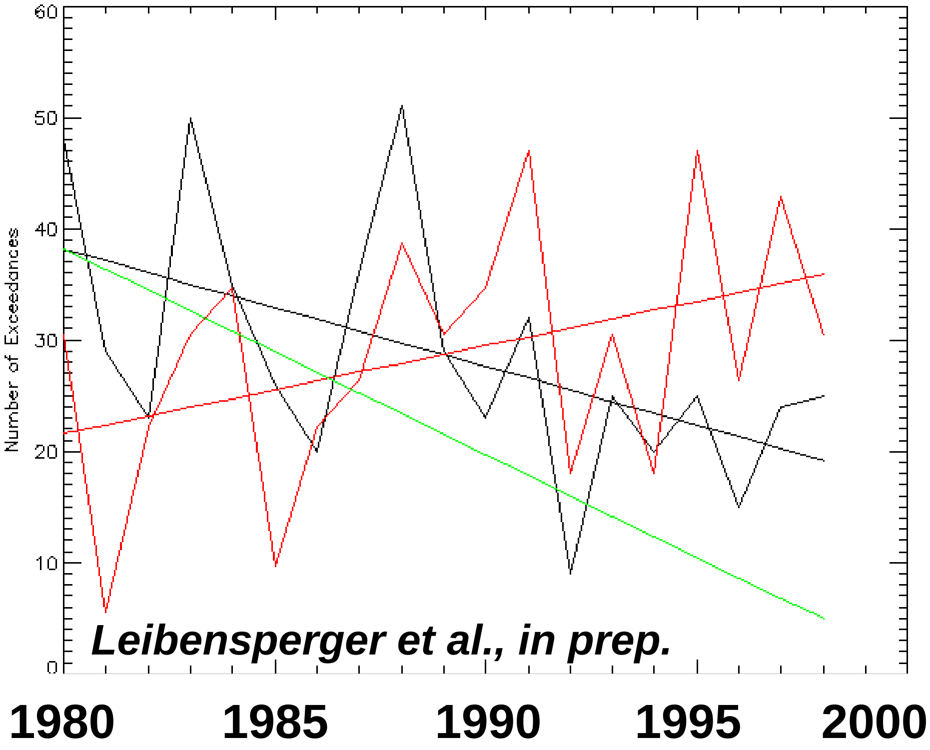


**# 80 ppb exceedance days in Northeast dropped from 38 in 1980 to 19 in 1998, but would have dropped to 5 in absence of cyclone trend**

**Observed 1980-1998 JJA trends in daily**
**# 40-50N cyclones**
**# 80 ppb $O_3$ AQS exceedances**
**Interannual variability in the two is highly anticorrelated (*r* = - 0.64)**



**Black: observed AQS exceedances**
**Red: AQS exceedances predicted from trend in cyclone frequency**
**Green: AQS exceedances predicted in absence of trend in cyclone frequency**



***Leibensperger et al., in prep.***