University of Toronto Noble Seminar Series (Oct 31, 2016)

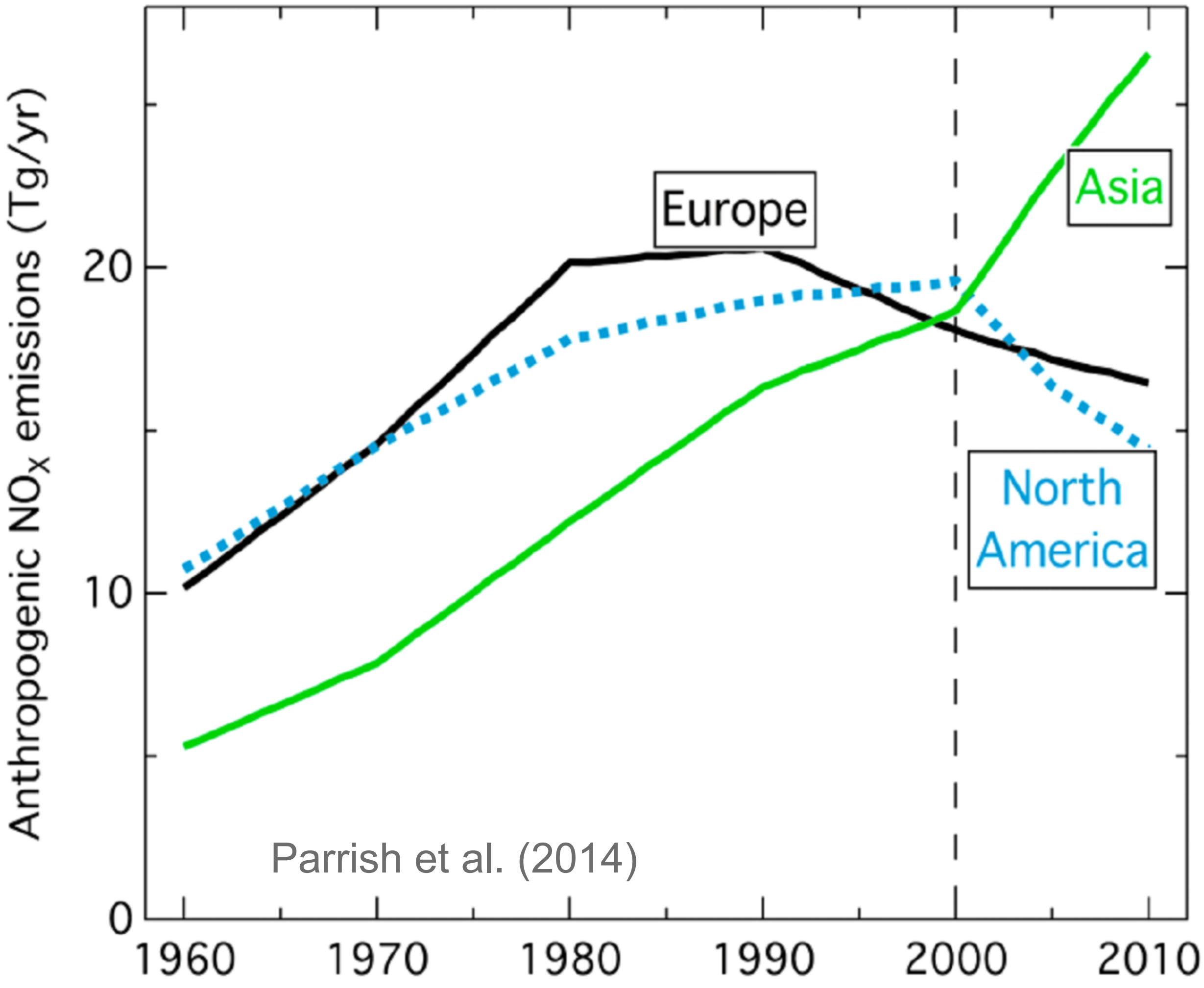
# Linking climate variability to surface ozone trends and extremes

MEIYUN LIN
(Princeton University & NOAA GFDL)

**Acknowledgements to:**
L.W. Horowitz (NOAA GFDL); S.J. Oltmans, A.O. Langford, O.R. Cooper, D.D. Parrish and B.J. Jonson (NOAA ESRL); A.M. Fiore and H. Rieder (Columbia); D. Tarasick (Environment Canada); L. Iranci and E. Yates (NASA); R. Payton and G. Tonnesen (US EPA)

Geophysical Fluid Dynamics Laboratory

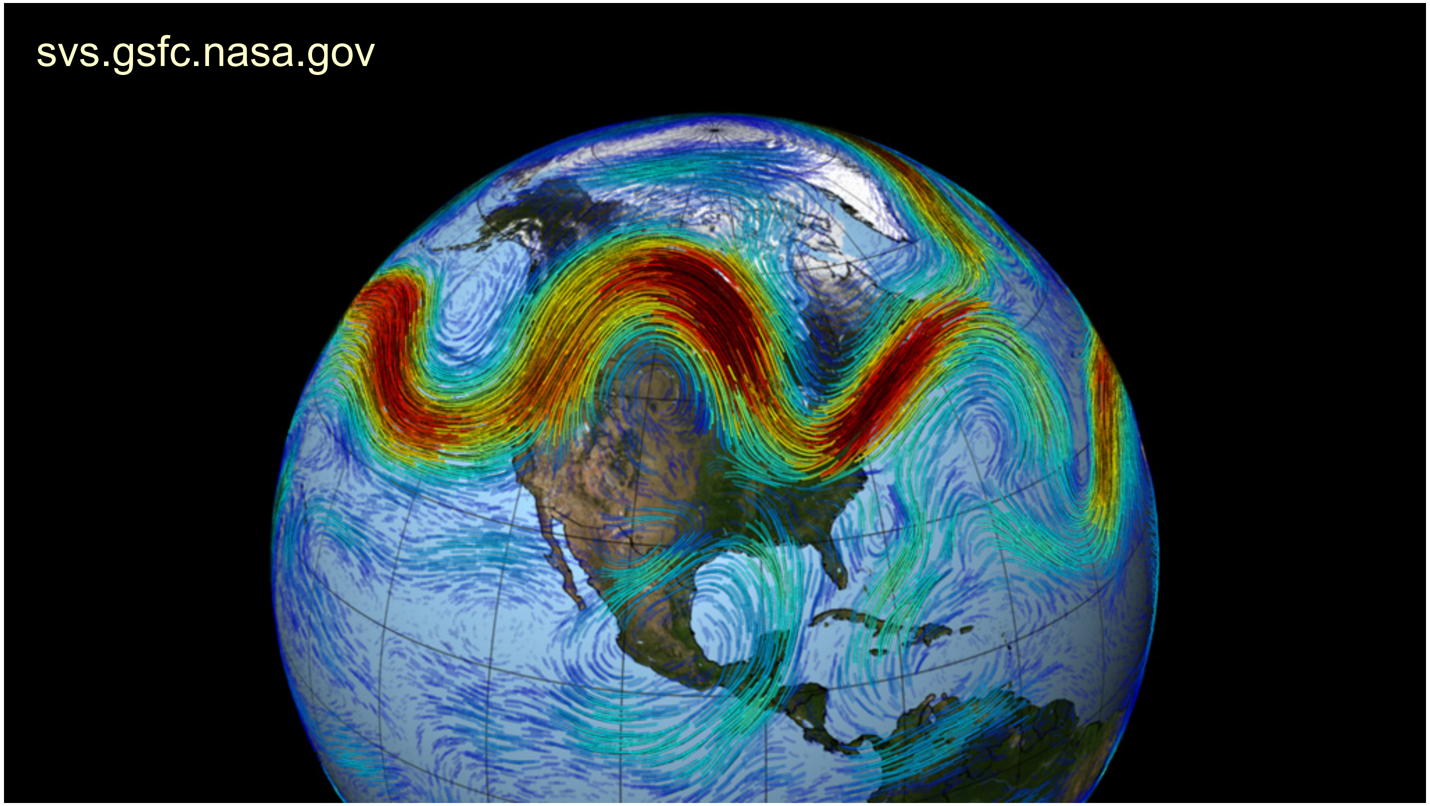
# Changes in anthropogenic emissions of $NO_x$




→ **From the MACCity Emission Inventory** [Granier et al., 2011] based on historical emissions from Lamarque et al. [2010] with annual interpolation after 2000 to RCP8.5

→ **Used in the GFDL-AM3 BASE simulation (this talk)**

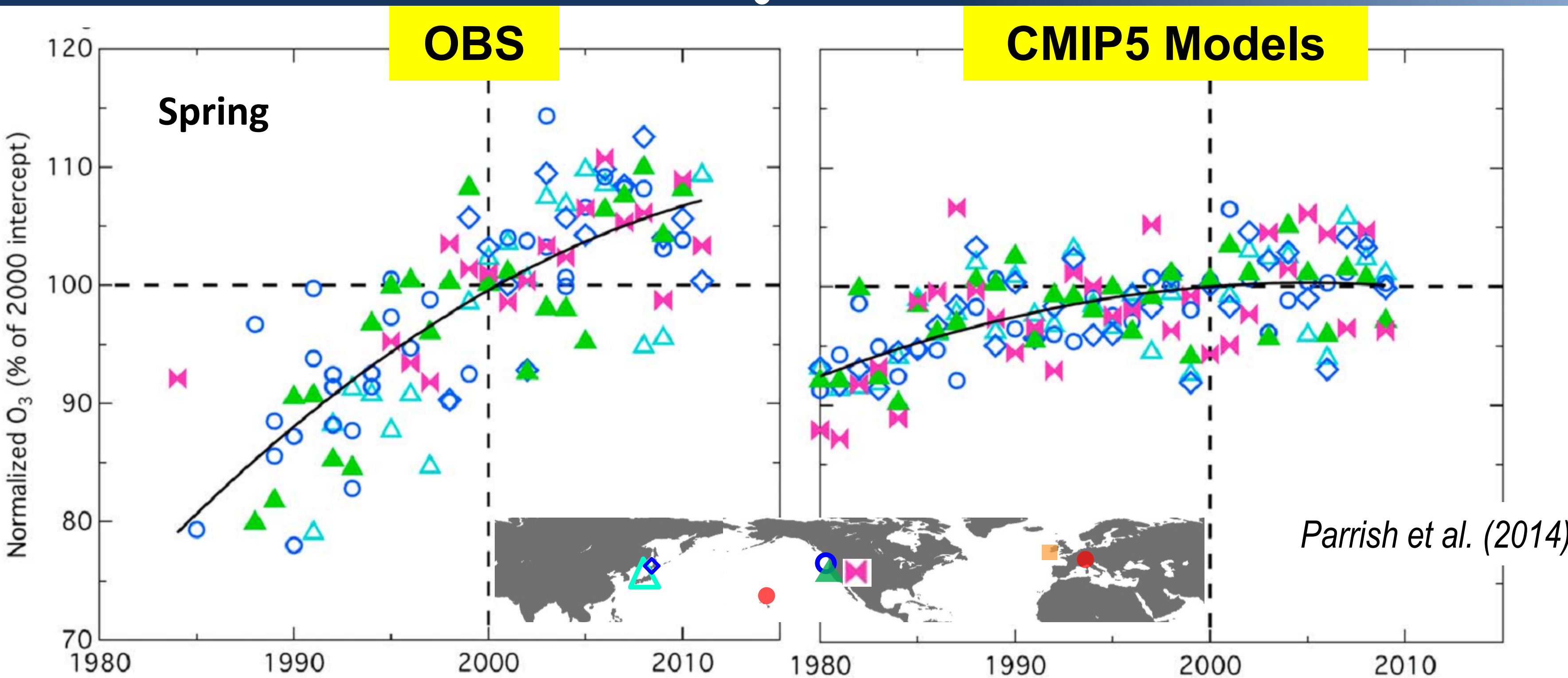
# The chaotic internal variability of the climate system → pollutant buildup; long-range transport; natural emissions




**Climate Variability**

- **Manifested in shifts in atmospheric circulation on interannual** (e.g., ENSO; NAO) **to decadal** (e.g., PDO; PNA; AMO) **time scales**
- **A source of uncertainty in climate change projections** [e.g., Deser et al., 2012; Shepherd et al., 2014]
- **Influence on atmospheric composition is poorly understood**

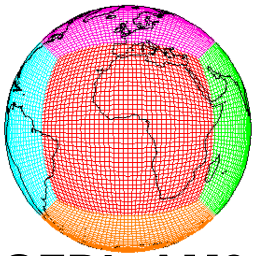
# A long-standing model-observation discrepancy on trends of *baseline* $O_3$ at northern mid-latitudes



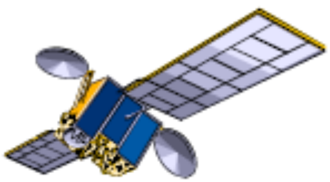

- **CTMs with varying emissions but fixed meteorology** [*Fusco & Logan 2003; Zhang et al., 2008; Fiore et al., 2009; Wild et al., 2012*]
- **Free-running CCMs driven by historical emissions** [*Lamarque et al. 2010; Parrish et al.2014*]
- **Simulations with obs. meteorology** [Koumoutsaris 2012; Brown-Steiner 2014; Strode 2015]

**Today's talk**
- **Internal climate variability**
- **Measurement sampling biases**
- **Model representation of baseline vs. polluted conditions**

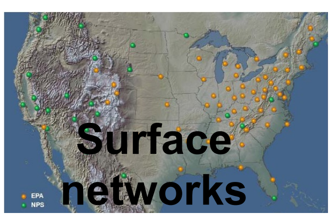
# GFDL AM3 chemistry-climate model hindcasts (1960-2014)



GFDL-AM3



Satellites


- **Cubed-sphere FV3 dynamical core, options for global Hi-Res (~50x50 km$^2$)** [*Putman and Lin, 2007*]
- **Height-dependent nudging to "real" winds**
  [*Lin M. et al., 2012a; 2012b*]
- **A suite of multi-decadal hindcast simulations designed to isolate the response of $O_3$ to changes in anthrop. emissions, meteorology, methane, and wildfires**
  [*Lin M. et al., 2014; 2015a; 2015b*]
- **Full strat & trop chem** [*Donner et al., 2011; Austin et al., 2015*]
- **Natural sources** (e.g., lightning $NO_x$ and biogenic isoprene) **are tied to model meteorology**
  [*Horowitz et al., 2003; Rasmussen et al., 2012*]

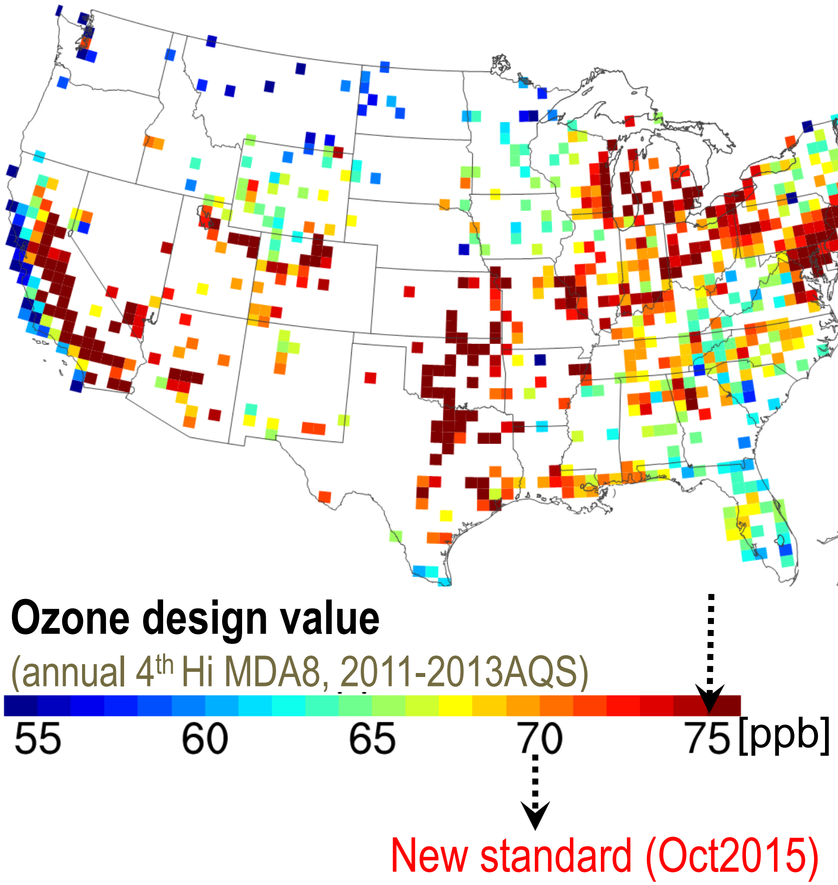
# Today's Talk

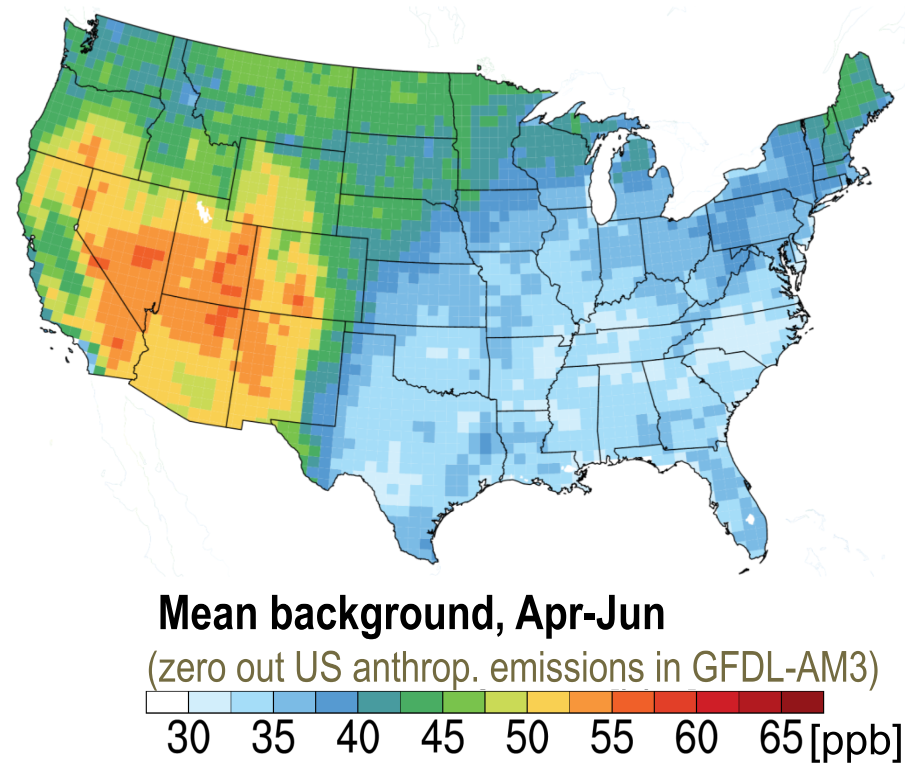
**Part I**: Role of **interannual** climate variability on deep stratospheric $O_3$ intrusions over WUS

**Part II**: **Decadal** modulation of hemispheric pollution transport and $O_3$ trends by internal climate variability

**Part III: Heat waves, regional $NO_x$ controls and changing ozone pollution over the eastern US**

# Major challenges for western US air quality management



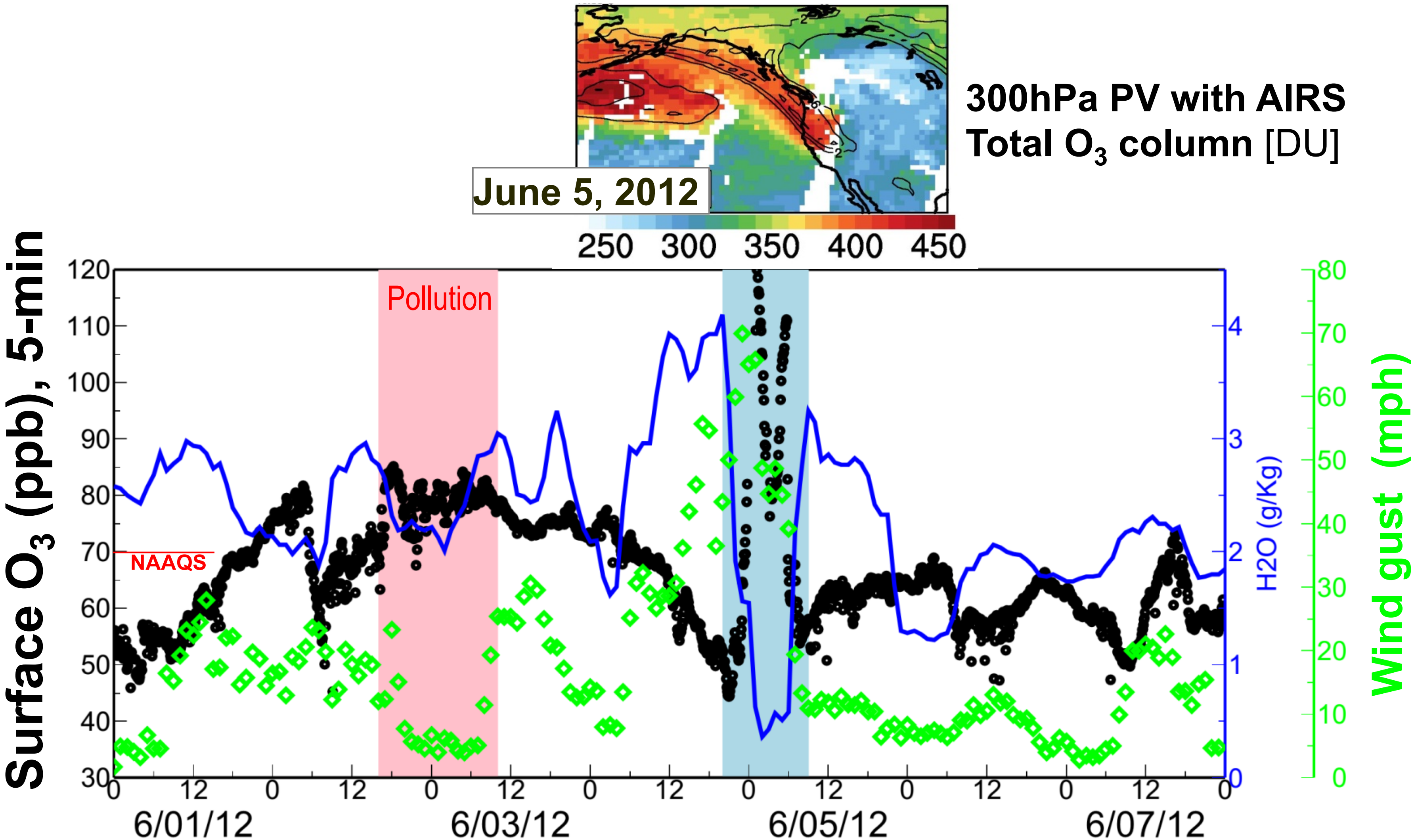




**MAJOR CHALLENGES:**

- **Rising Asian emissions and global $CH_4$** [e.g. *Jacob et al.* 1999; Cooper et al., 2010]
- **More frequent wildfires in summer** [e.g. *Westerling et al.* 2006; *Jaffe 2011*]
- **Frequency of stratospheric intrusions in spring** [e.g. *Langford et al.* 2009; *Lin et al.* 2012b; *Lin et al.*, 2015a]

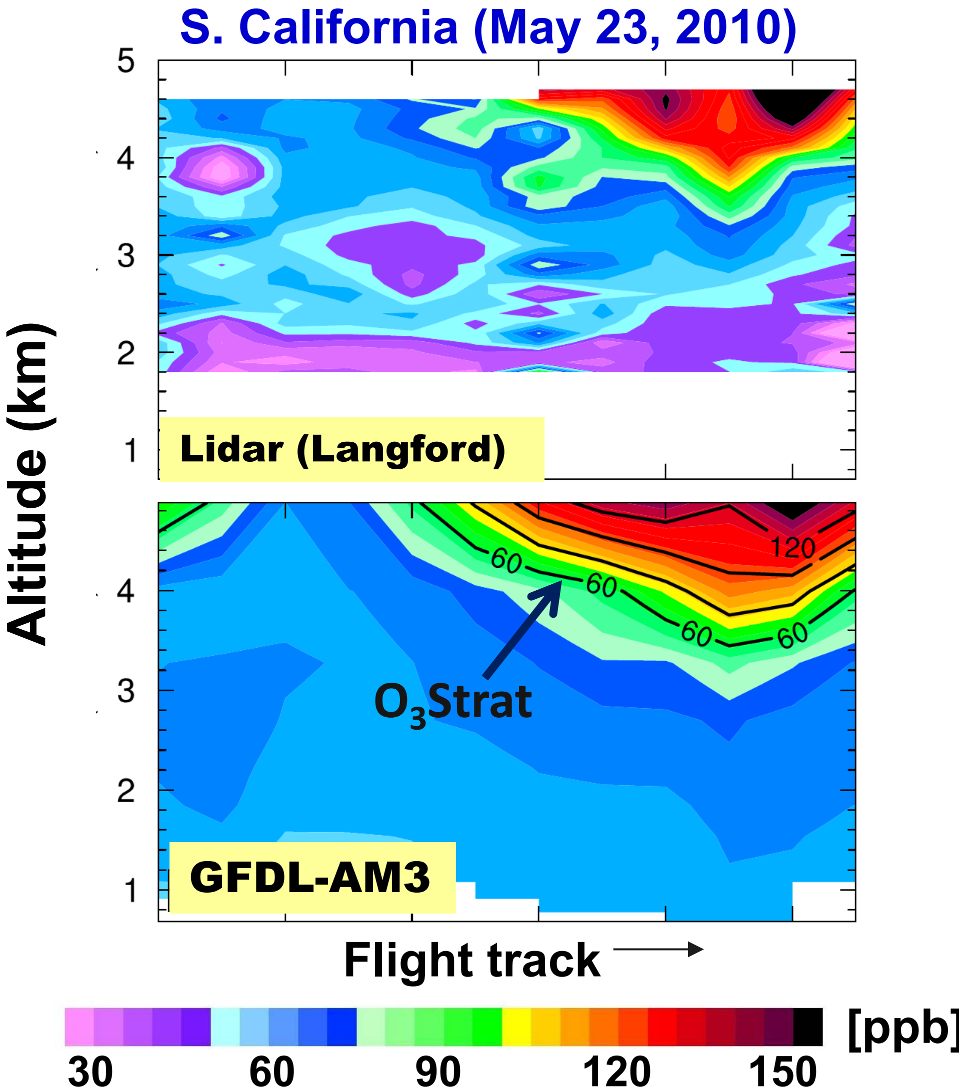
**→ NEED PROCESS-LEVEL UNDERSTANDING ON DAILY TO MULTI-DECADAL TIME SCALES**

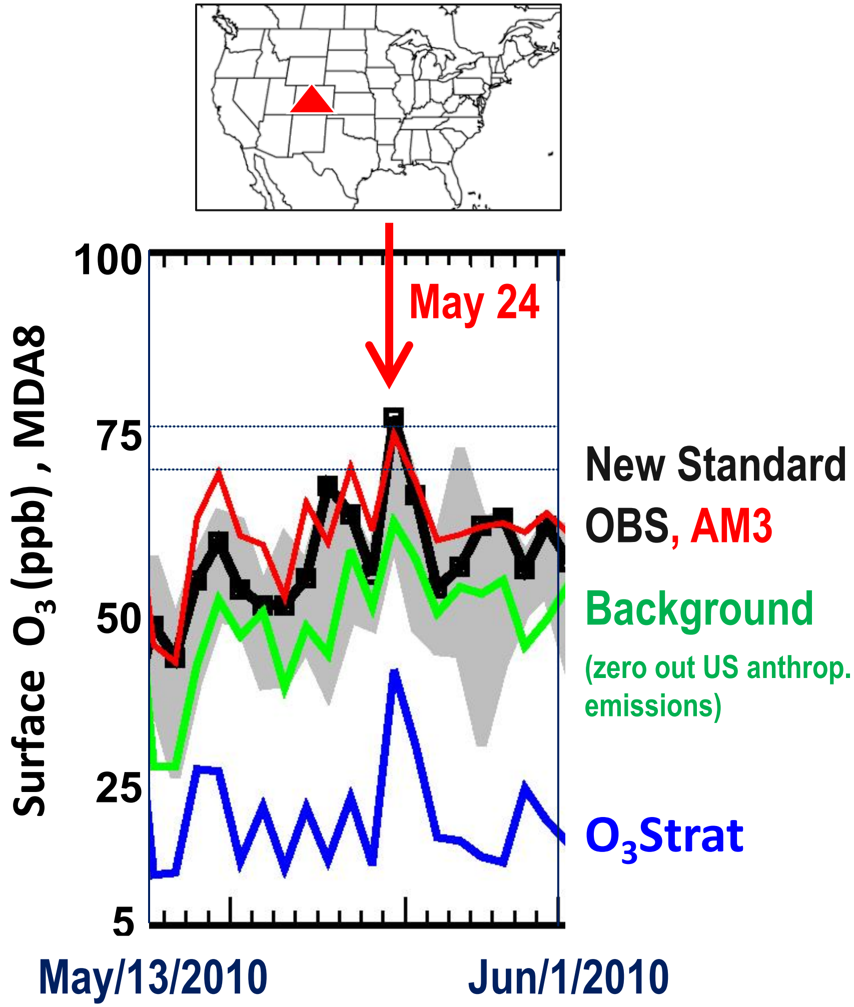
# Observed evidence of high surface $O_3$ events resulting from deep stratospheric intrusions




**Spring Mtn Youth Camp, Nevada (2.6 km altitude)**

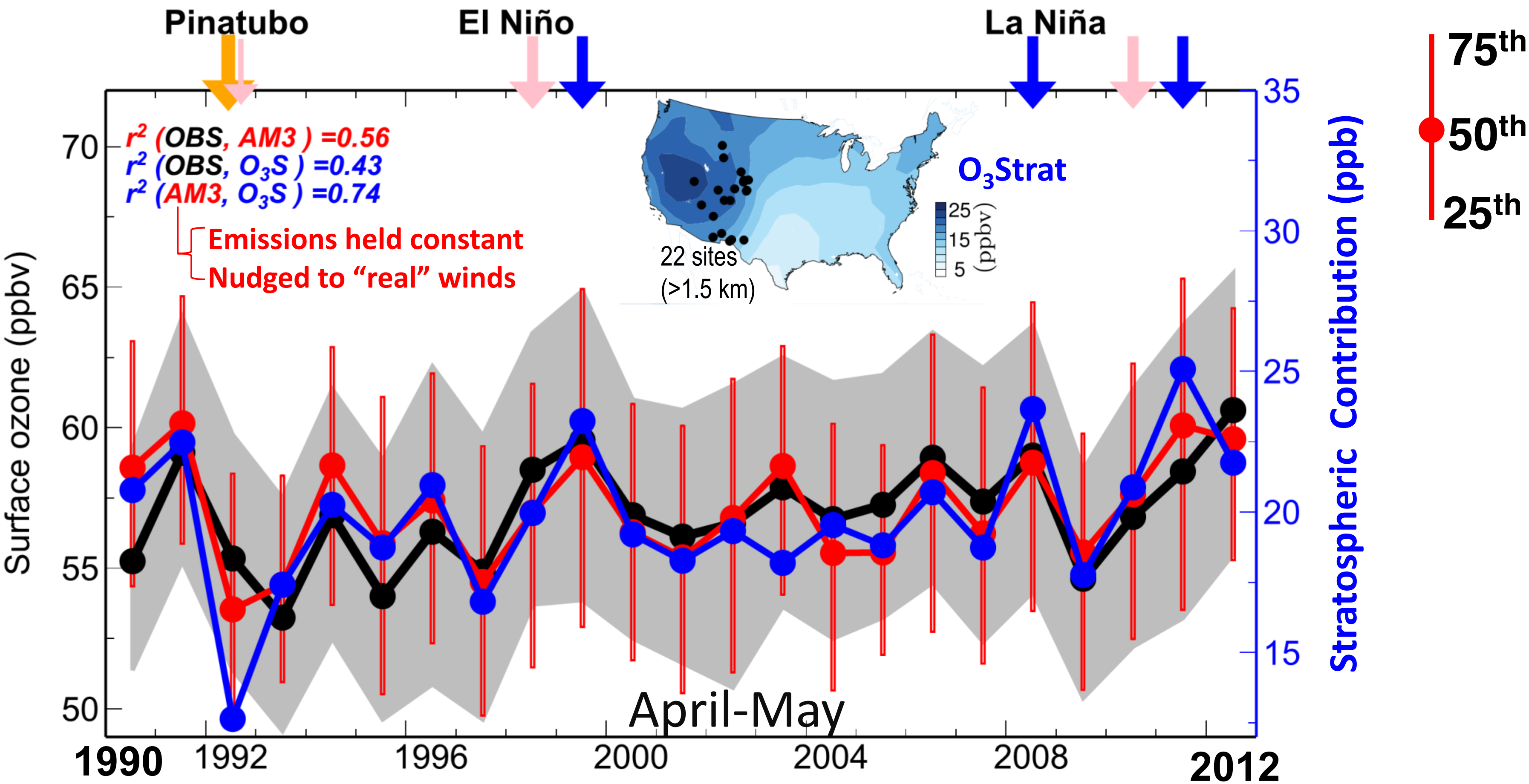

# GFDL-AM3 model captures observed deep stratospheric intrusions over WUS




***Lin M.Y. et al (JGR, 2012b),*** *Springtime high surface ozone events over the WUS: Quantifying the role of stratospheric intrusions*

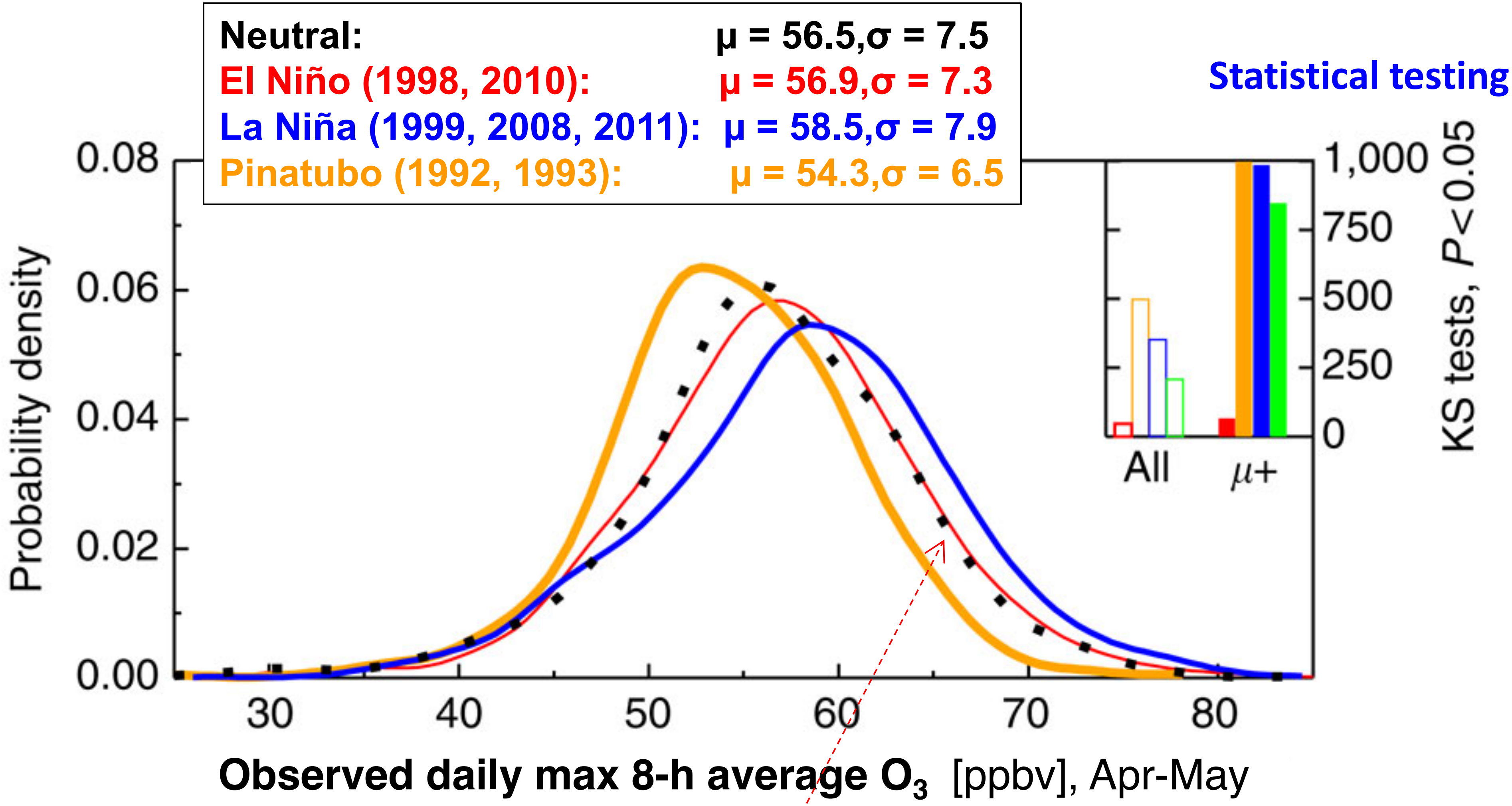
# Climate variability can modulate frequency of deep stratospheric intrusions over WUS




- **Strong stratospheric influence on WUS $O_3$ IAV**
- **Greatest following a strong La Niña winter**

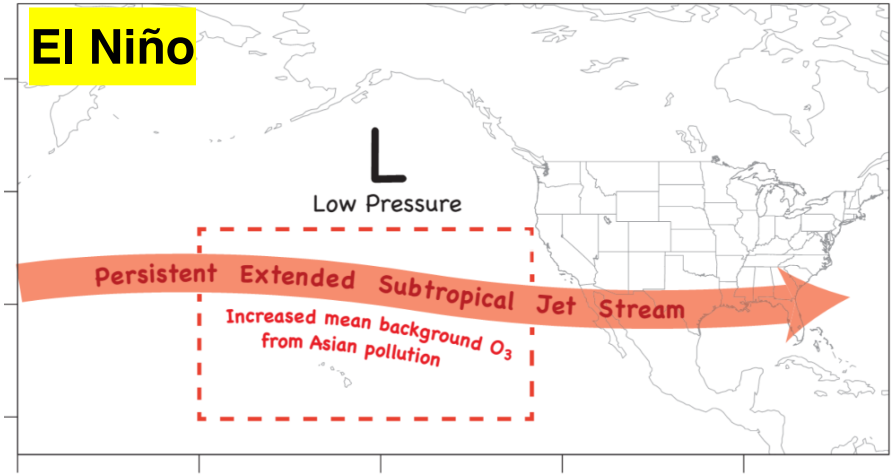
*Lin M.Y. et al., Nature Communications, 2015*

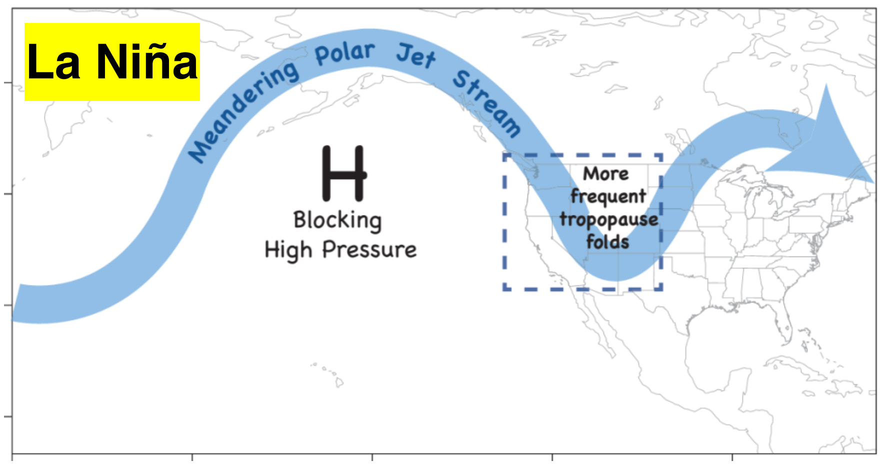
# Observed changes in surface $O_3$ distribution, particularly in the upper tail

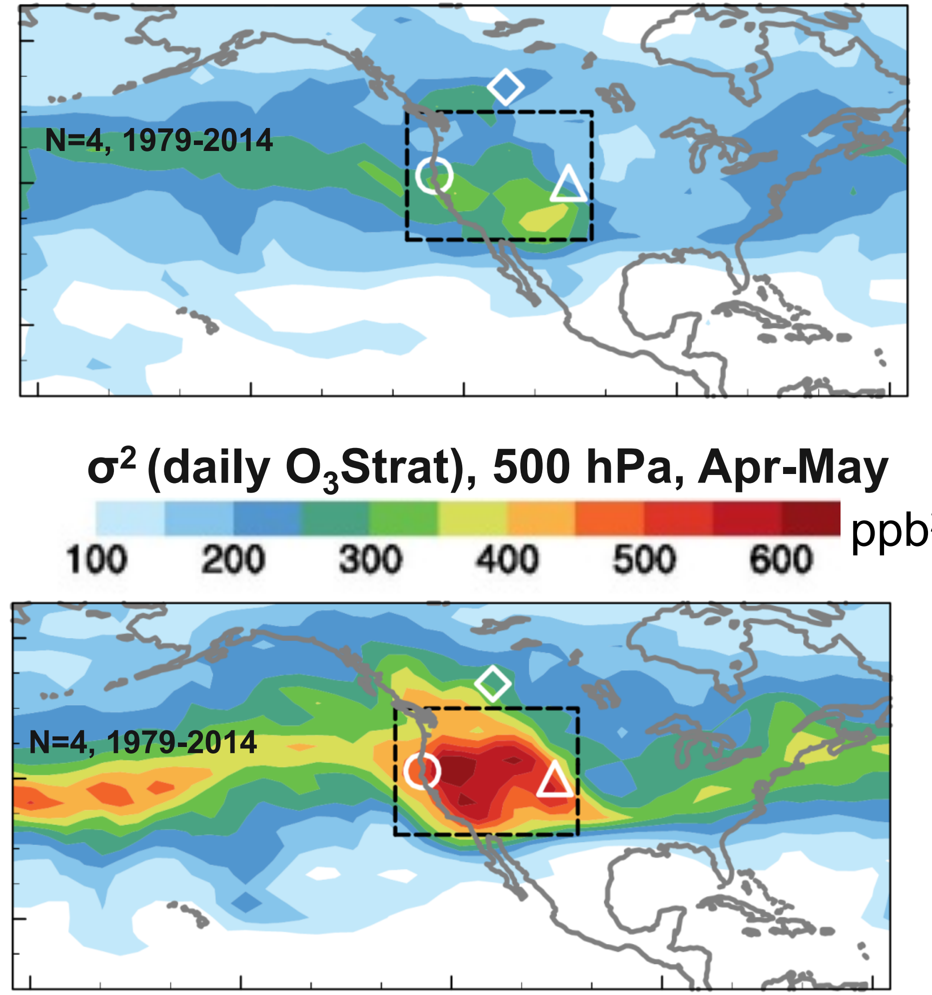



- **Little change in WUS surface air during El Niño despite increased UTLS $O_3$ burdens reported previously** [e.g. Langford1998; Bronnimann2004; Neu2014].

# ENSO and tropopause folds over western N. America



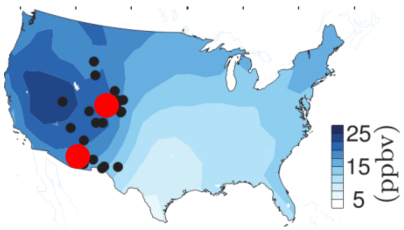



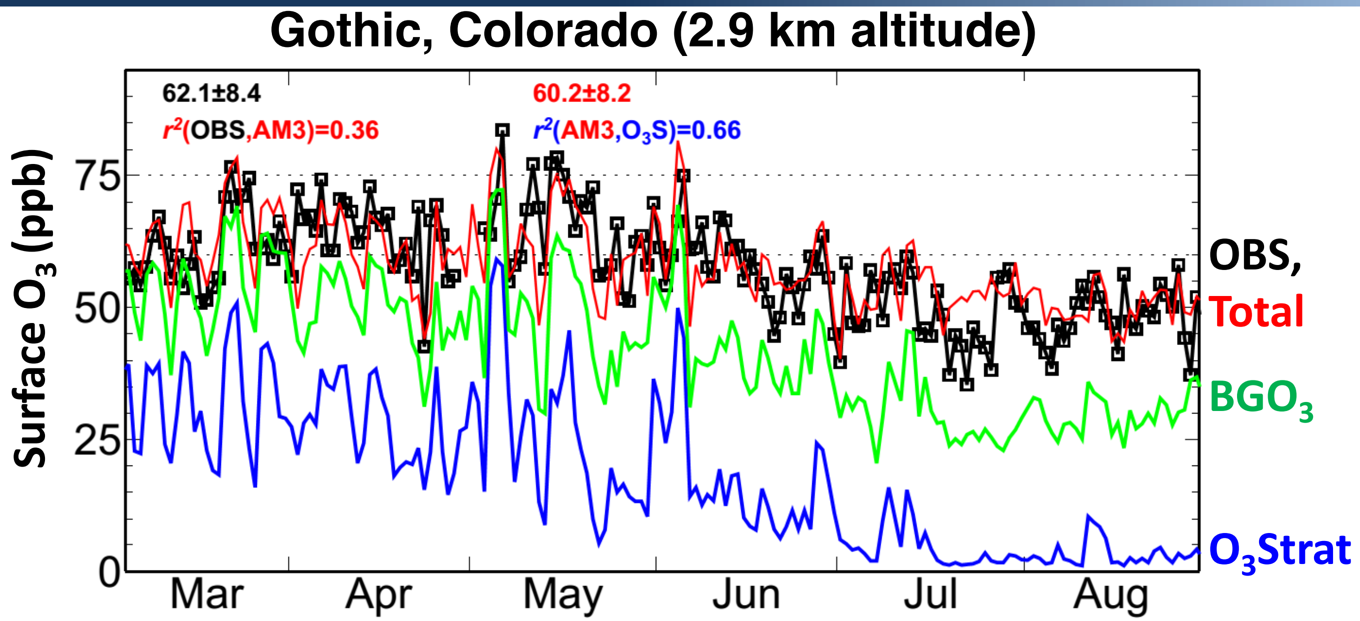

**Tropopause folds at the polar jet stream** penetrate much deeper into the troposphere than **those at the subtropical jet stream**

*Lin M.Y. et al. (Nature Communications, 2015)*

# Following a La Niña **winter**, more frequent stratospheric intrusions reaching WUS surface air in **spring**




1999 (La Niña)




2011 (La Niña)

**Developing seasonal prediction to aid regional AQ planning:**

- Deploy targeted measurements aimed at identifying "exceptional events"
- Conduct daily forecast for public health alerts

**(Lin M.Y. et al., Nature Commun., 2015)**

# Implications for $O_3$ trends analysis

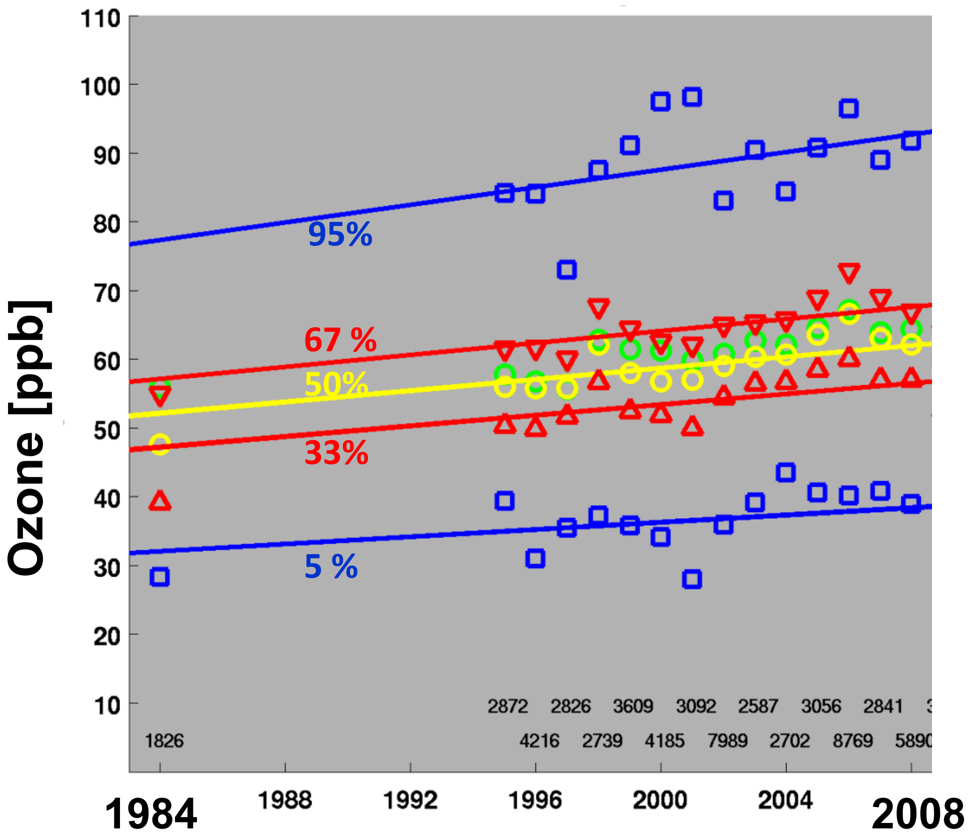
nature Vol 463|21 January 2010|doi:10.1038/nature08708

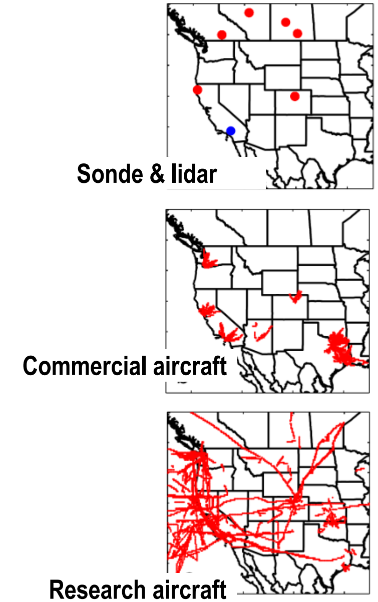
LETTERS

# Increasing springtime ozone mixing ratios in the free troposphere over western North America

O. R. Cooper[1,2], D. D. Parrish[2], A. Stohl[3], M. Trainer[2], P. Nédélec[4], V. Thouret[4], J. P. Cammas[4], S. J. Oltmans[2], B. J. Johnson[2], D. Tarasick[5], T. Leblanc[6], I. S. McDermid[6], D. Jaffe[7], R. Gao[2], J. Stith[8], T. Ryerson[2], K. Aikin[1,2], T. Campos[9], A. Weinheimer[9] & M. A. Avery[10]

**~0.6 ppbv yr$^{-1}$ over 1995-2008**

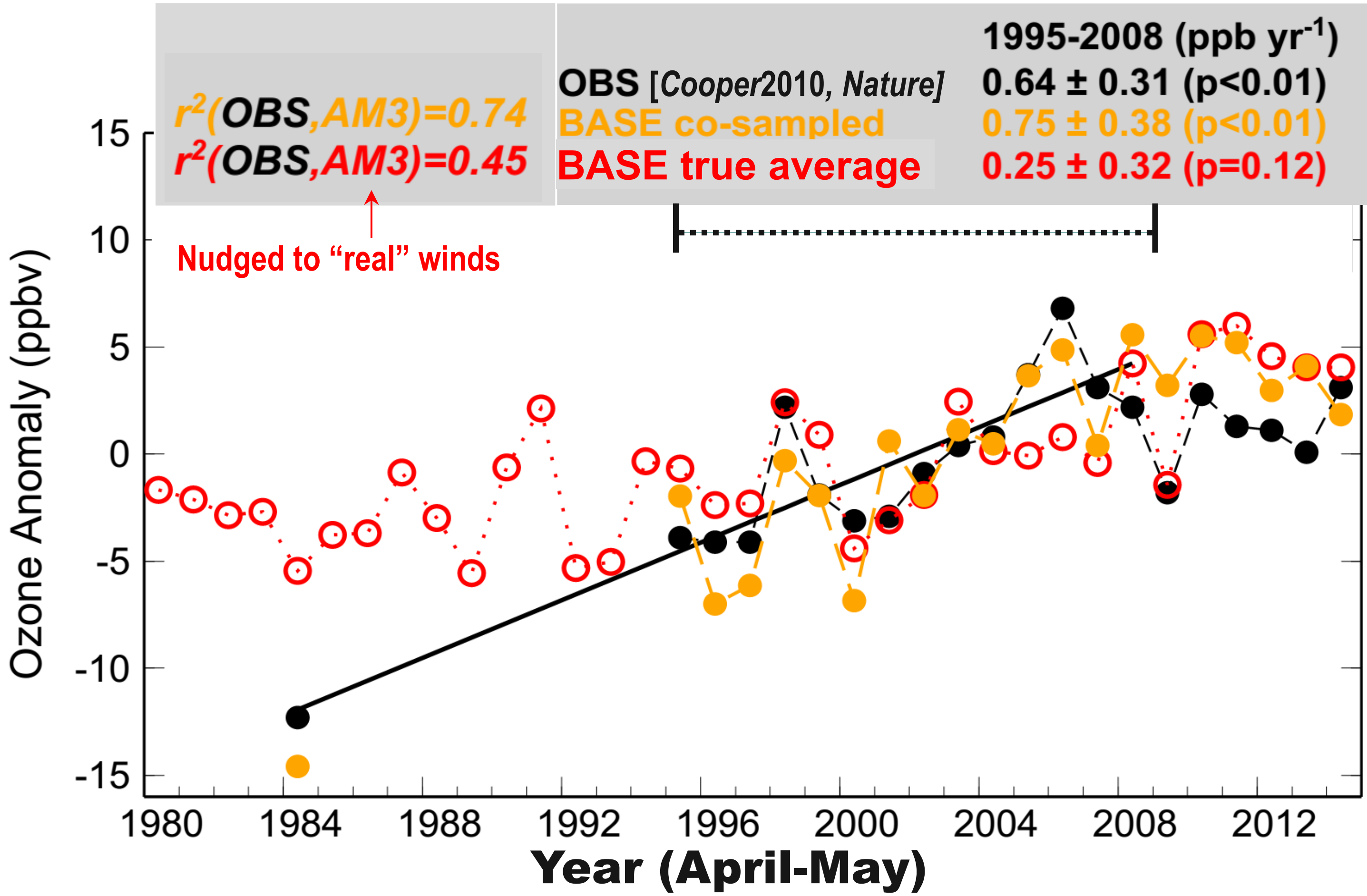


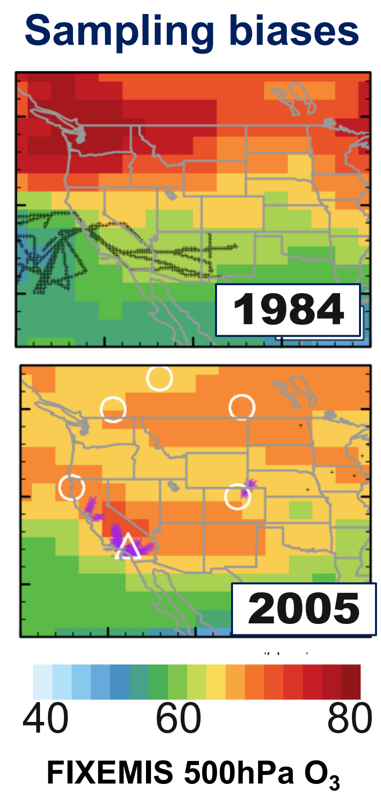




**Observing frequency, timing, and locations change from year to year.**

**Free-running CCMs capture only 50% of observed $O_3$ increases** [*Lamarque et al., 2010; Parrish et al., 2014*].

# Is springtime $O_3$ in the free troposphere over western N. America *actually* increasing over 1995-2008 ?

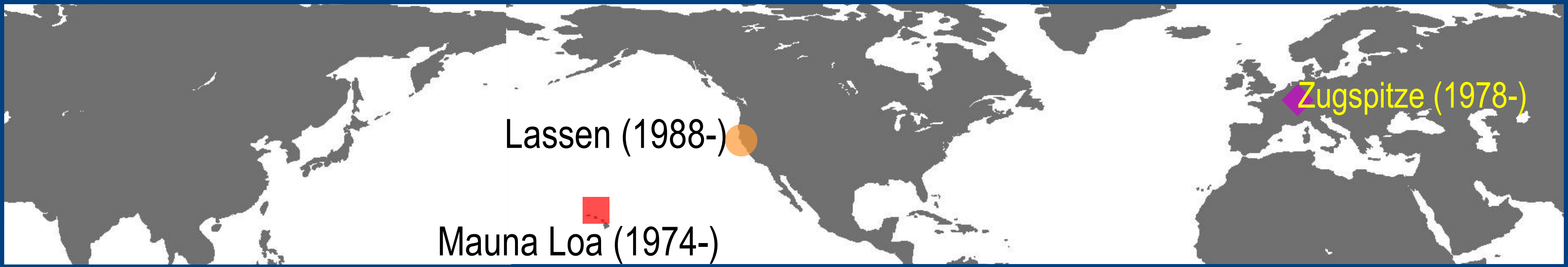


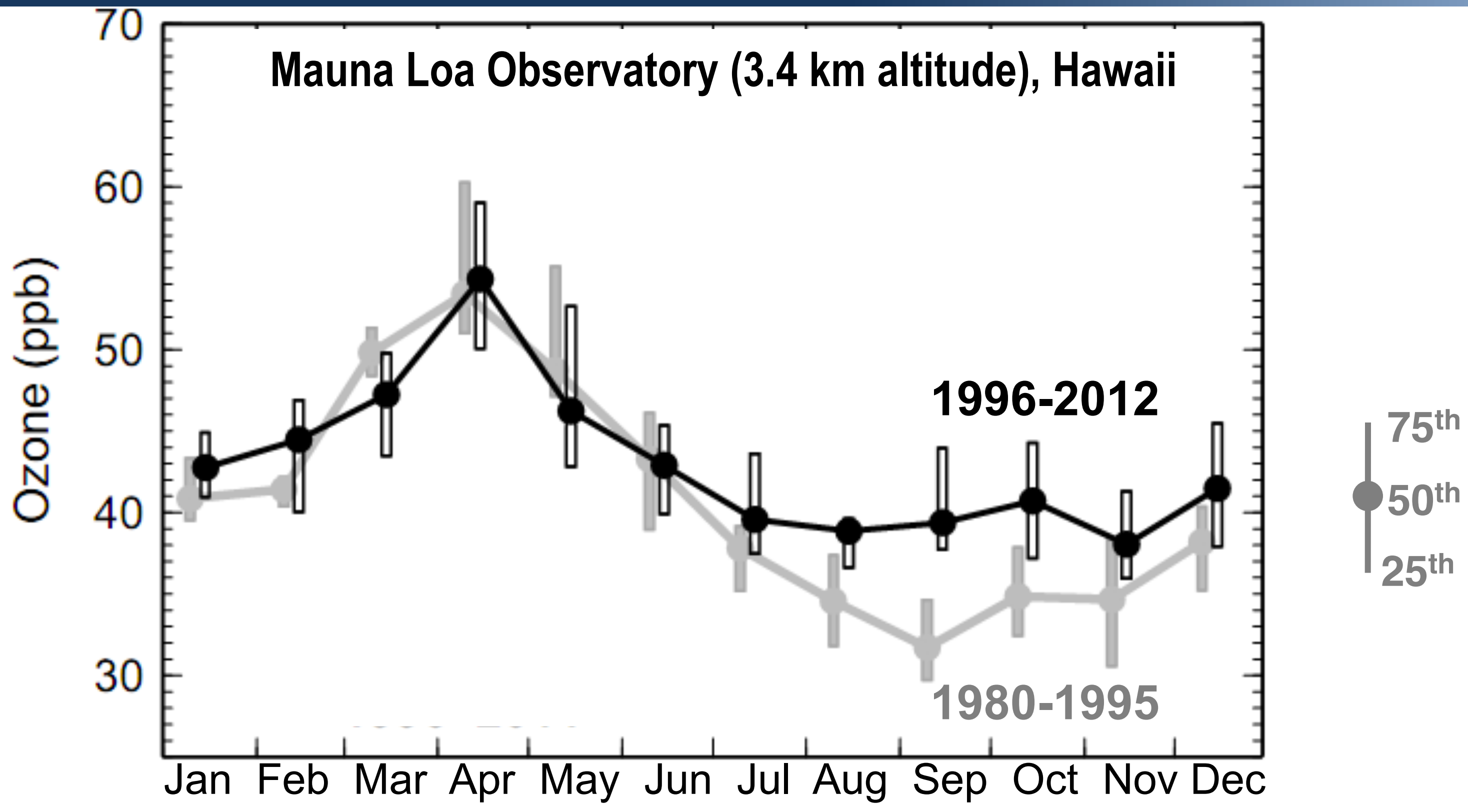

→ 15-year trends driven by internal climate variability can be as large as emission-driven trends.
→ Even with co-sampling, free-running CCMs are not expected to reproduce the trends.

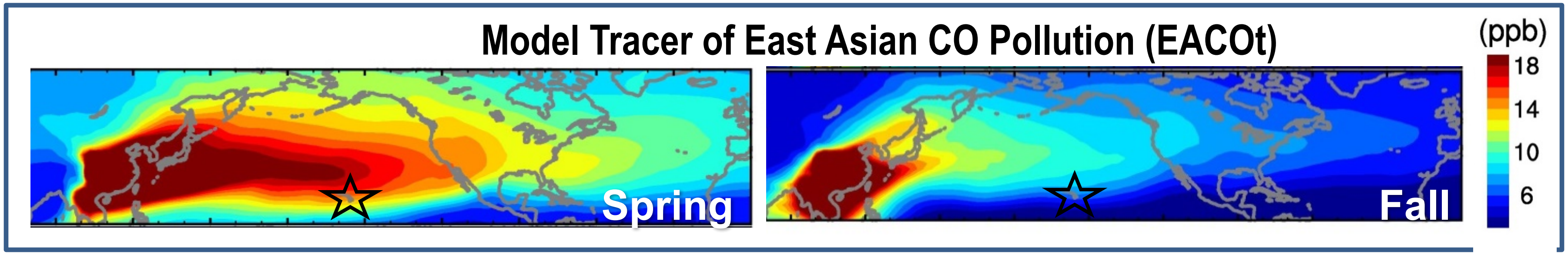
*Lin M.Y. et al.* [GRL, 2015]

# **Part II:** Decadal modulation of hemispheric pollution transport and $O_3$ trends by climate variability

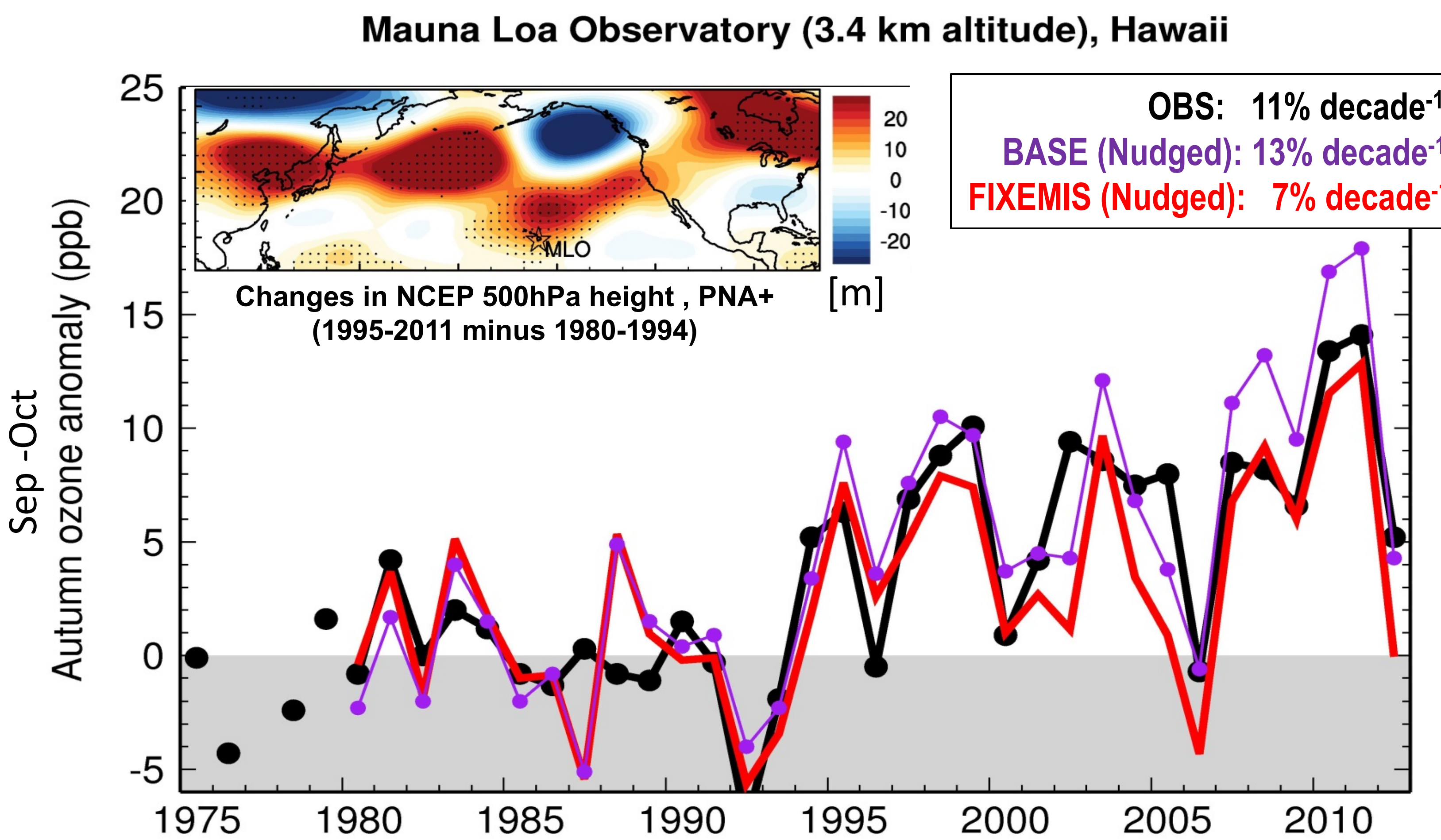


# The puzzle:
# Ozone at Mauna Loa shows little change in spring but a rise in fall



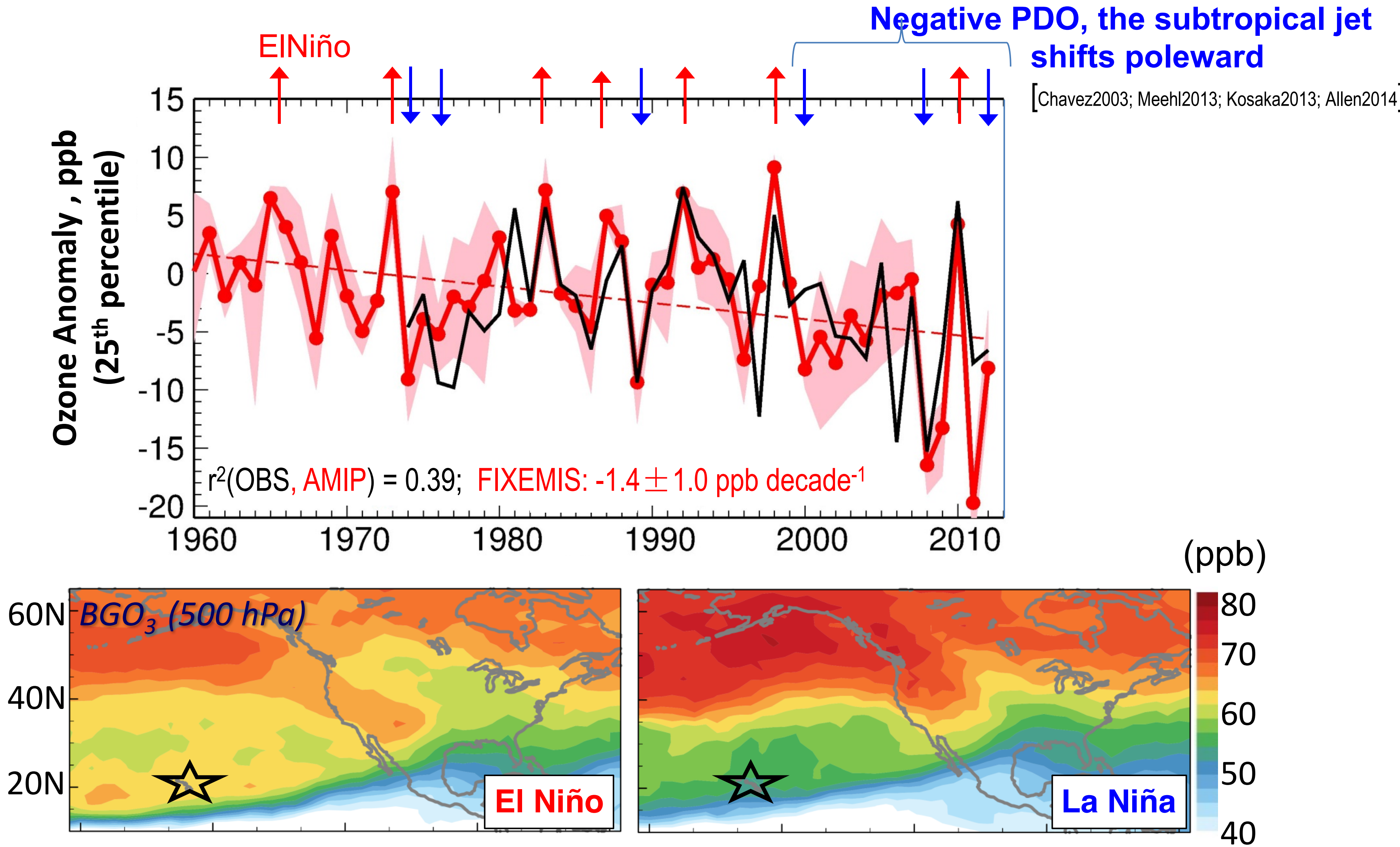
# Increasing ozone at Mauna Loa in FALL tied to a positive PNA pattern since the mid-1990s




→ Circulation shifts can explain almost 70% of observed trends

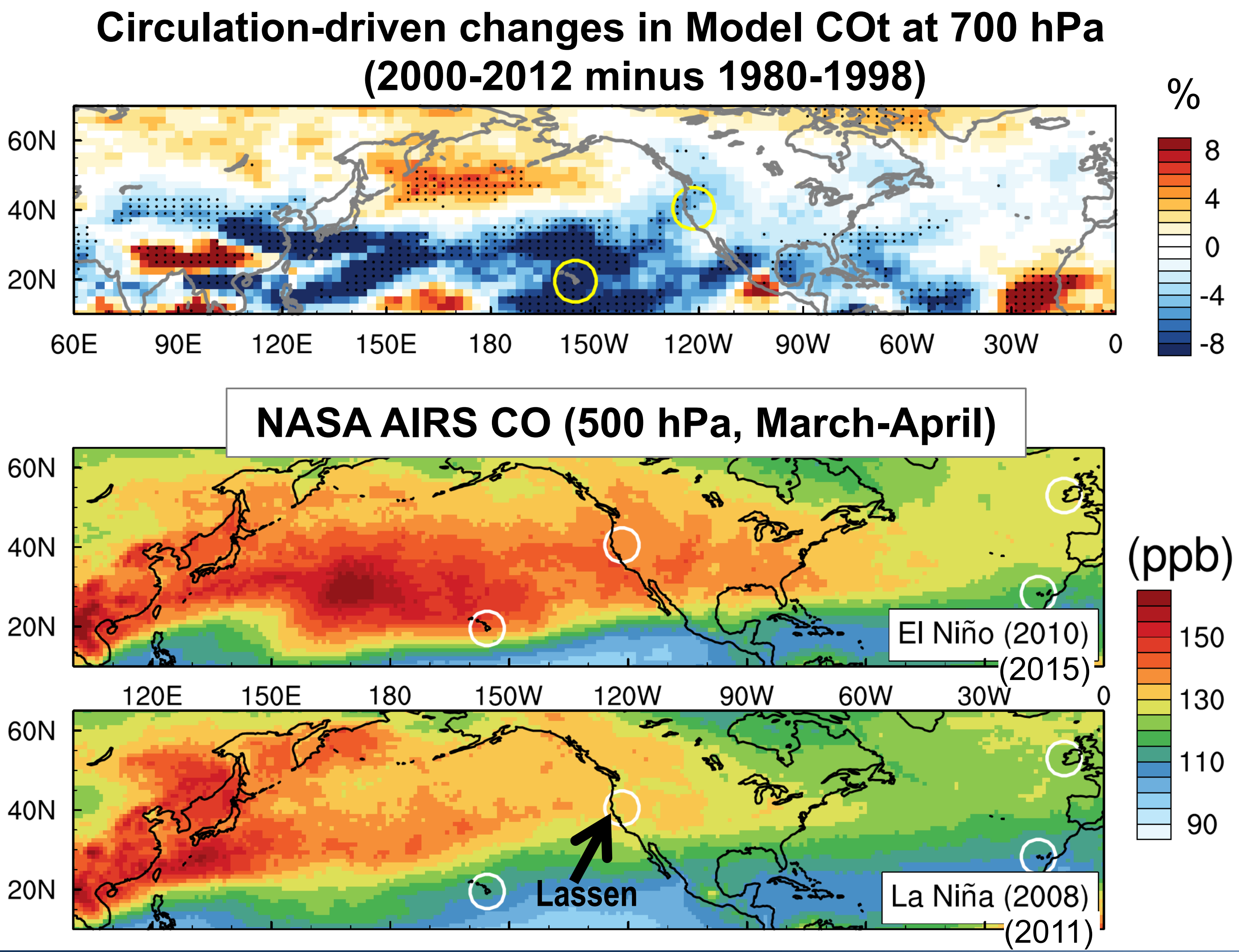
→ Must consider internal climate variability when interpreting pollutant trends

# Springtime airflow from Eurasia towards the NE Pacific weakens in the 2000s as a result of the negative phase of PDO

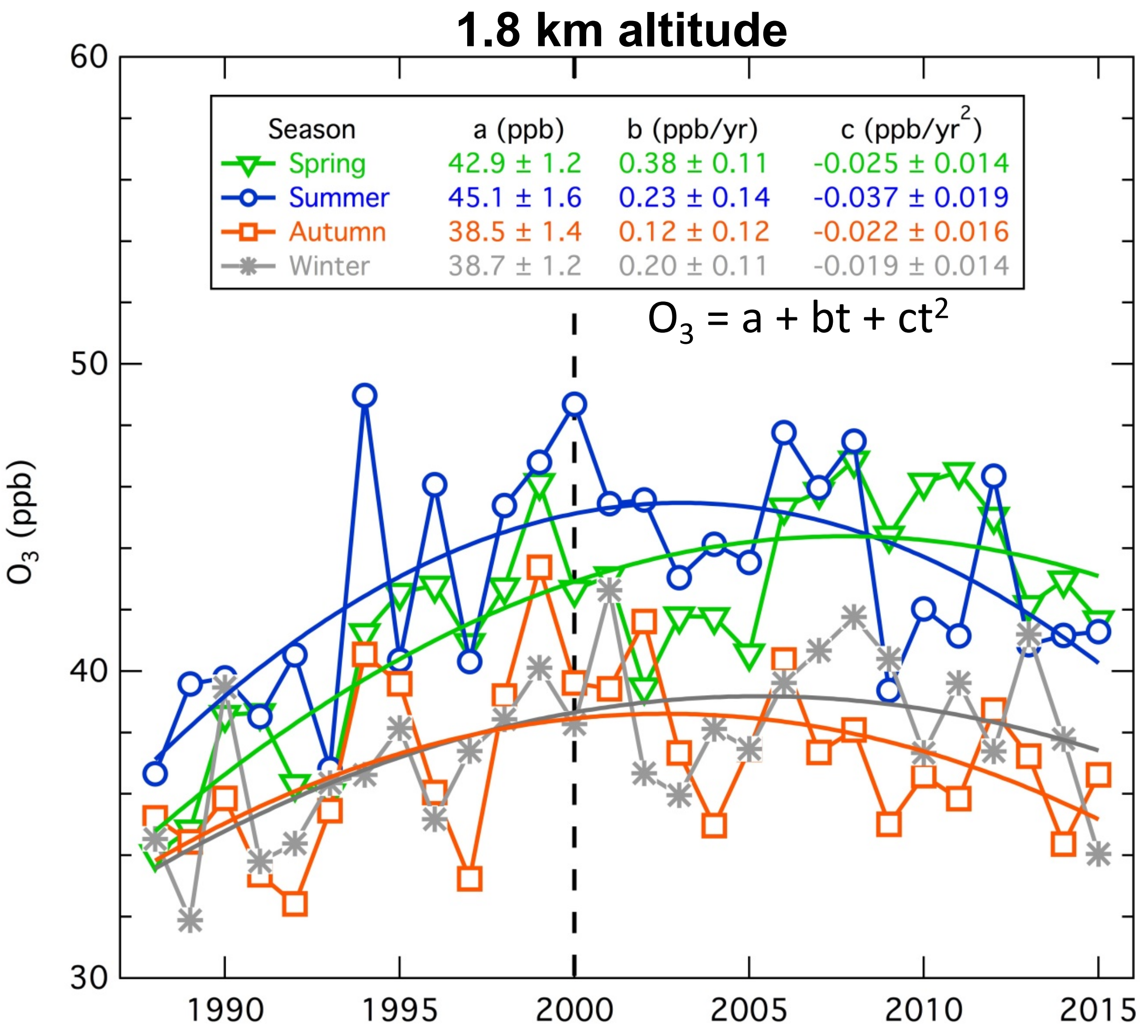



*Lin M.Y. et al (Nature GeoSci., 2014)*

# Weakening hemispheric pollution transport in spring during the 2000s



# Observations at Lassen California show a leveling-off of $O_3$ across all seasons in the 2000s

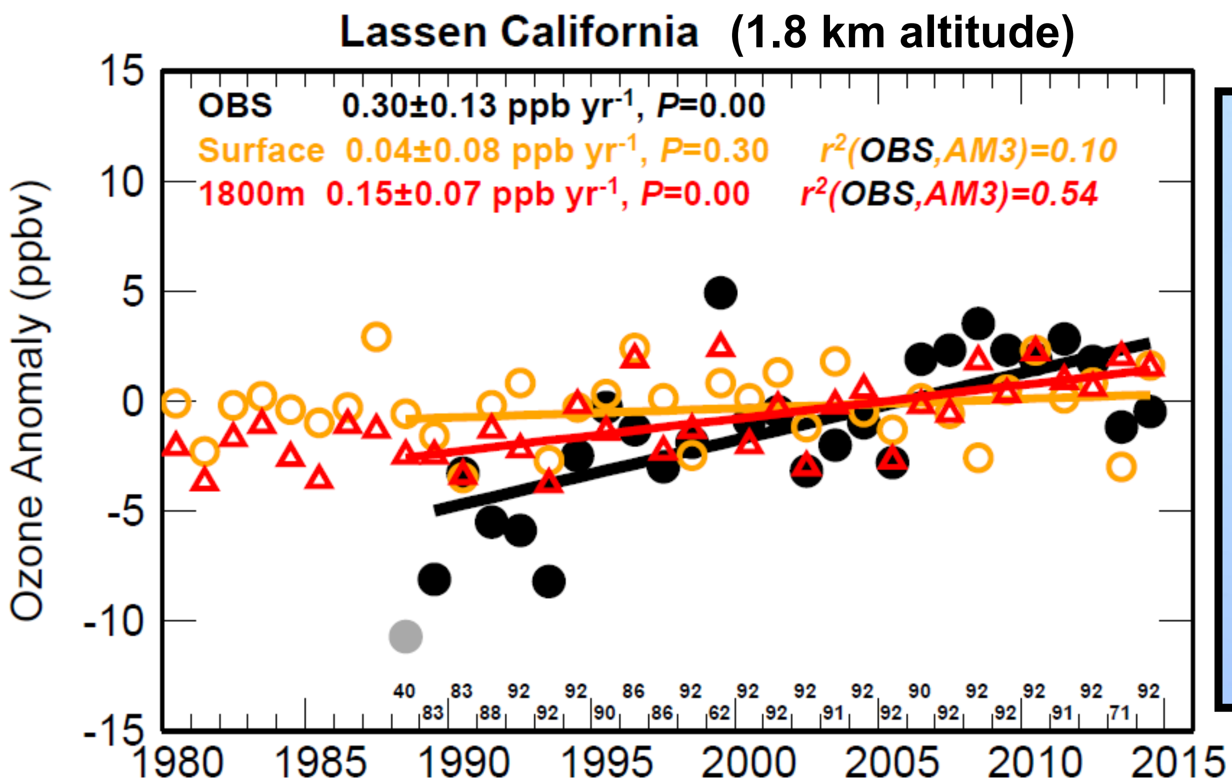


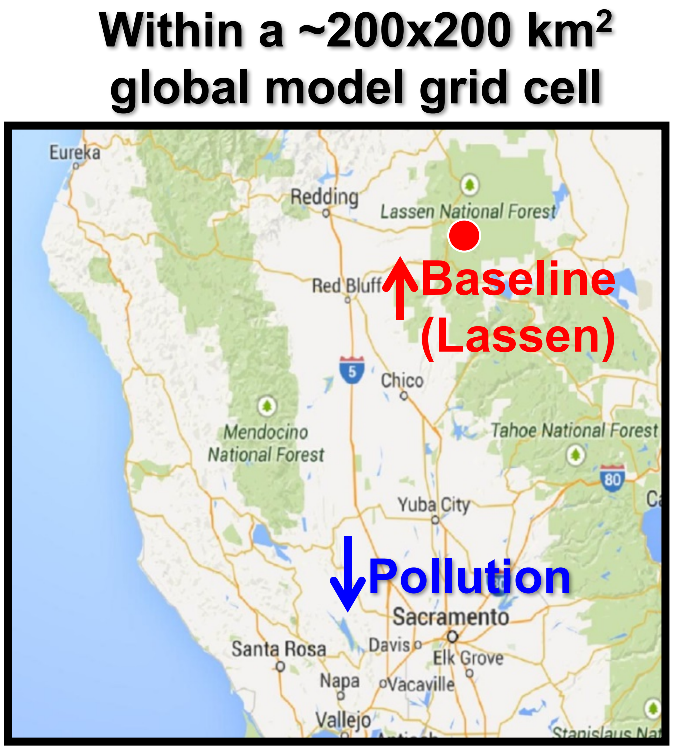

Attributed to:

→ weakening hemispheric pollution transport in the 2000s for spring

→ U.S. domestic emission controls for summer

# Neither AM3 sampled at the surface nor at site elevation captures observed $O_3$ increases at Lassen in spring

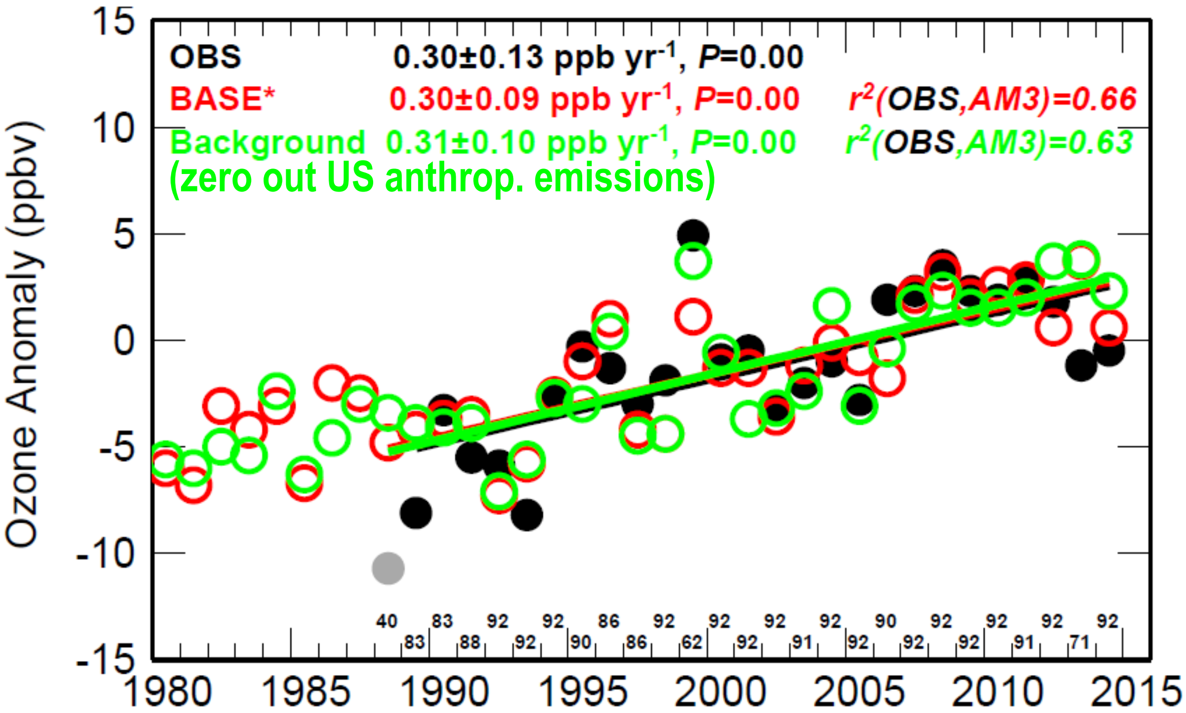


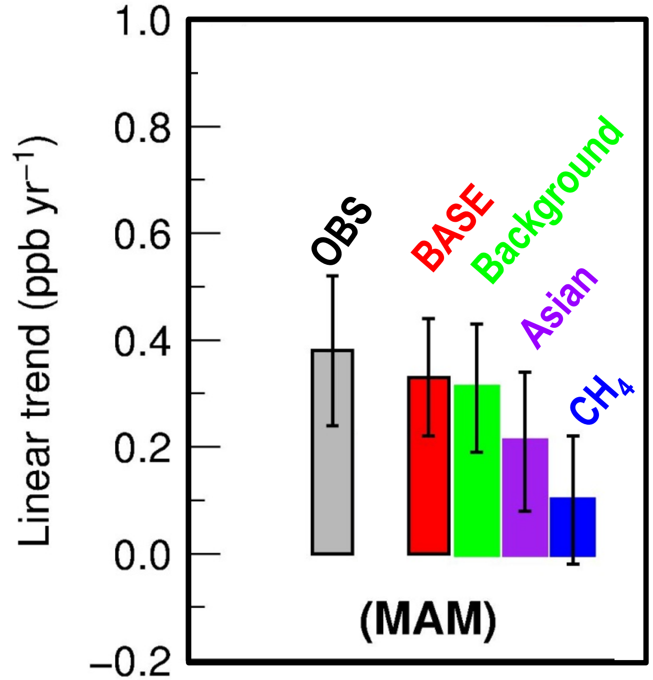




**Problem**: Coarse-resolution models → an artificial offset of increased baseline $O_3$ at remote sites by decreased urban pollution within the same model grid cell

# When filtered to remove the influence from fresh local pollution, AM3_BASE captures observed springtime $O_3$ increases at Lassen

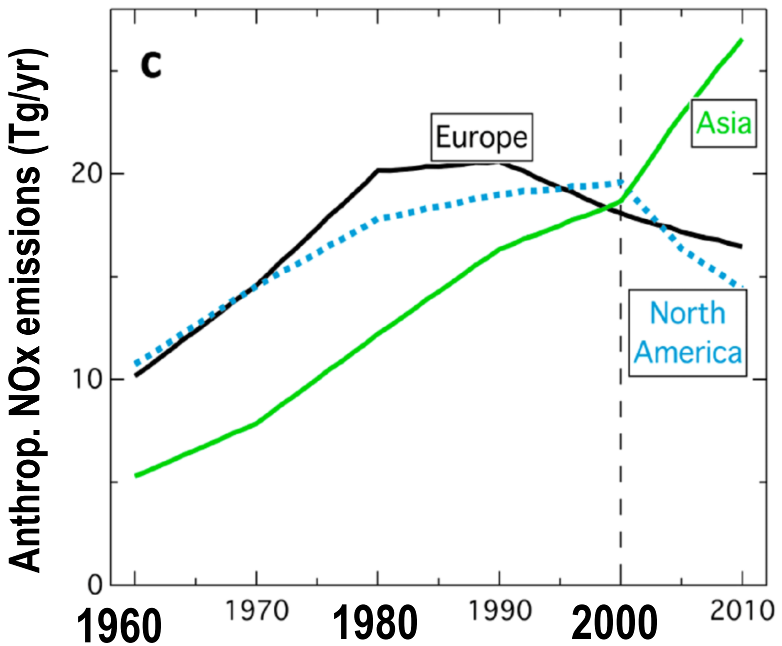
**New Approach:** Sampled at 700 hPa and filter the model to exclude data on days when N. American CO tracer ≥ 67th percentile

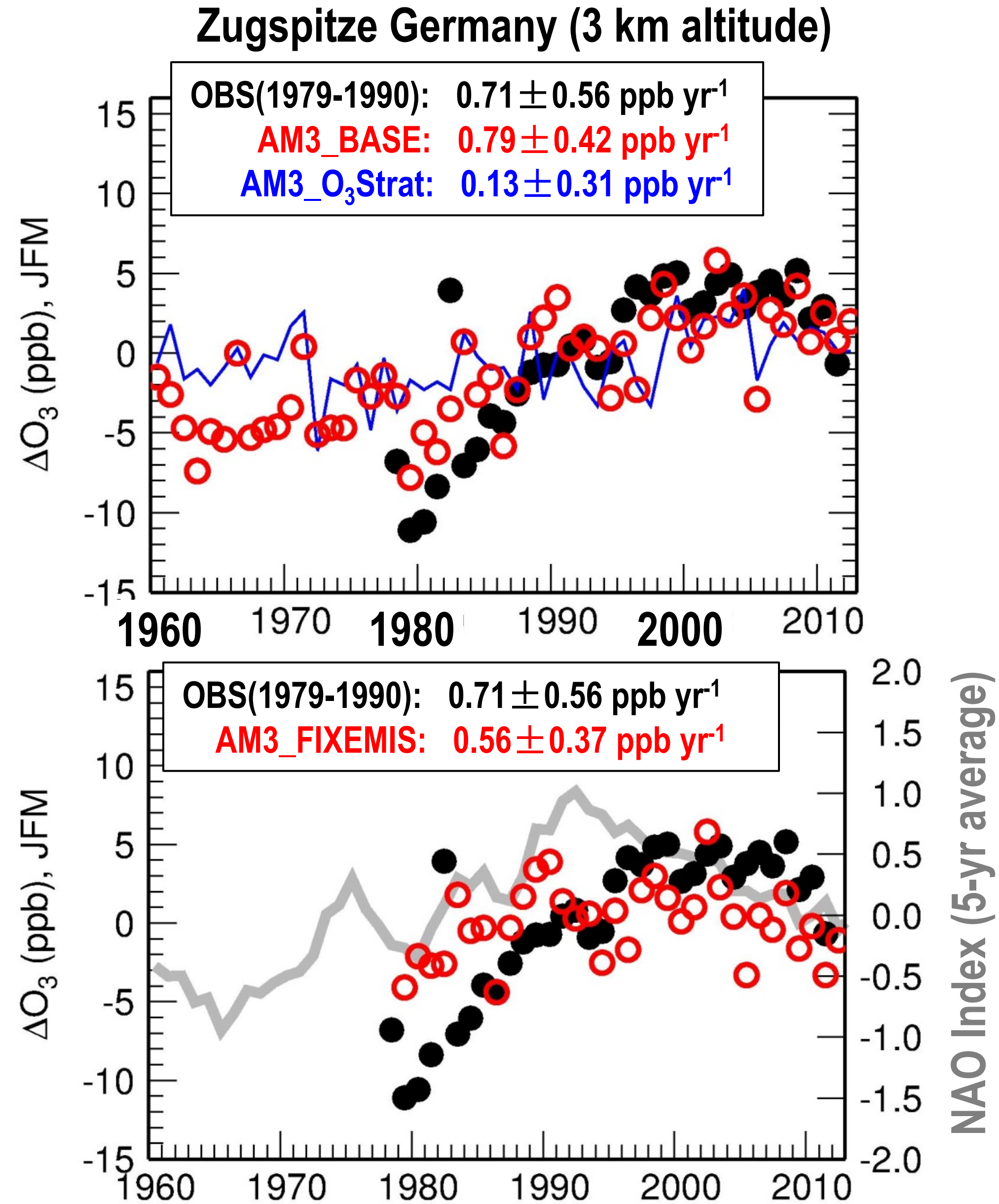



→ **Rising Asian emissions contributes to raising $O_3$ at Lassen by 0.2 ppb $yr^{-1}$ (65%).**

# Neither changes in $NO_x$ emissions nor STE can explain the observed winter $O_3$ increases over Europe in the 1980s

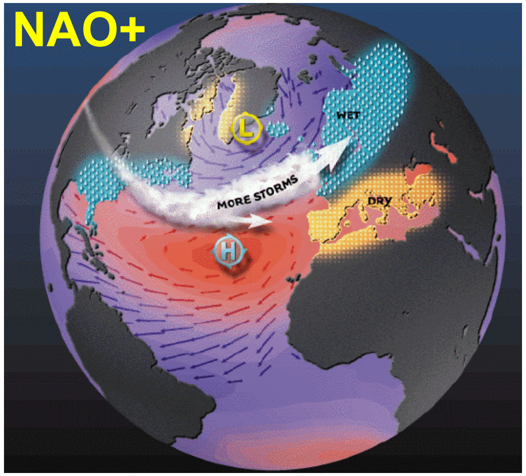


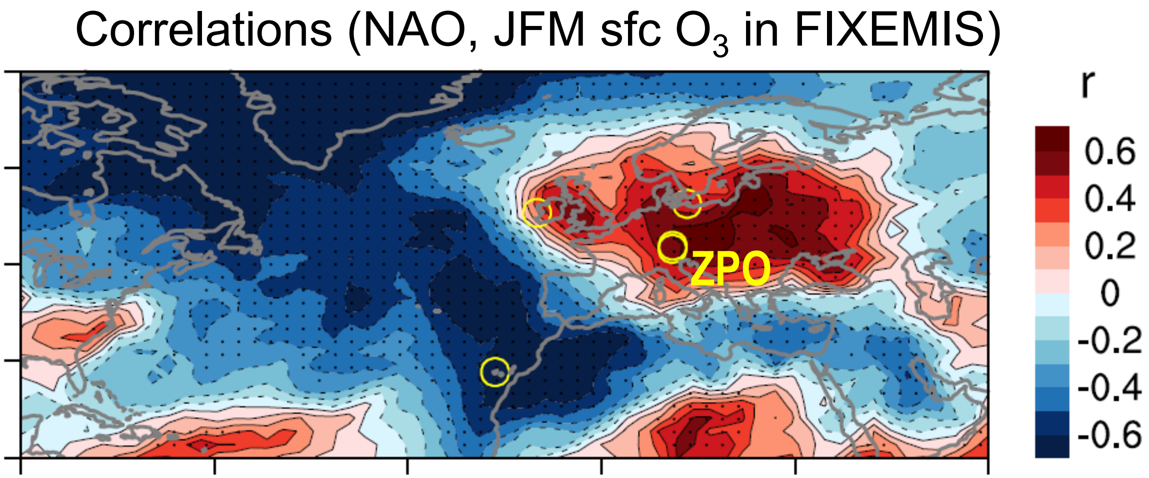



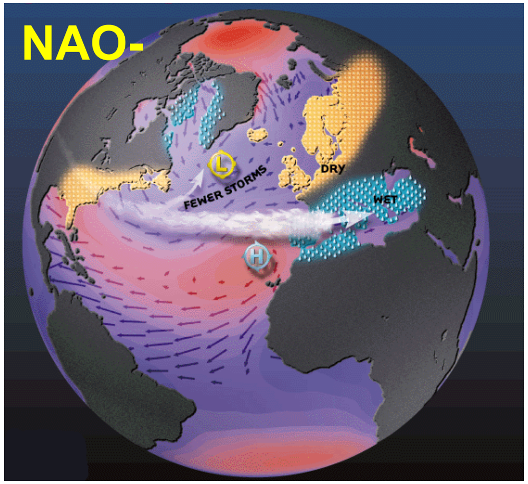

- Circulation shifts (NAO) can explain ~80% of the observed trend in the 1980s.

Lin, M. et al. (to be submitted to GRL, 2016)

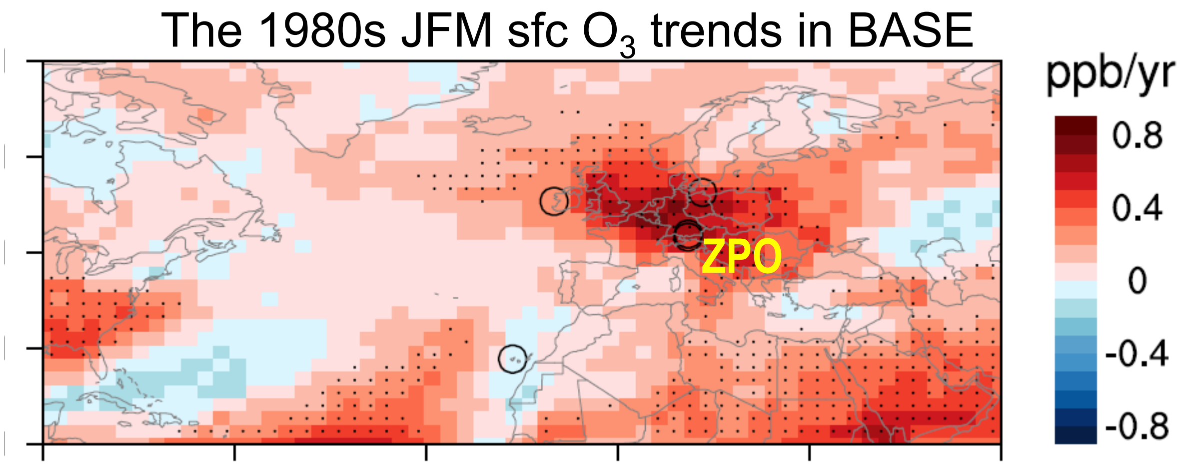
# Strengthened zonal pollution transport in the 1980s as a result of the positive NAO contributes to raising winter $O_3$ in Europe



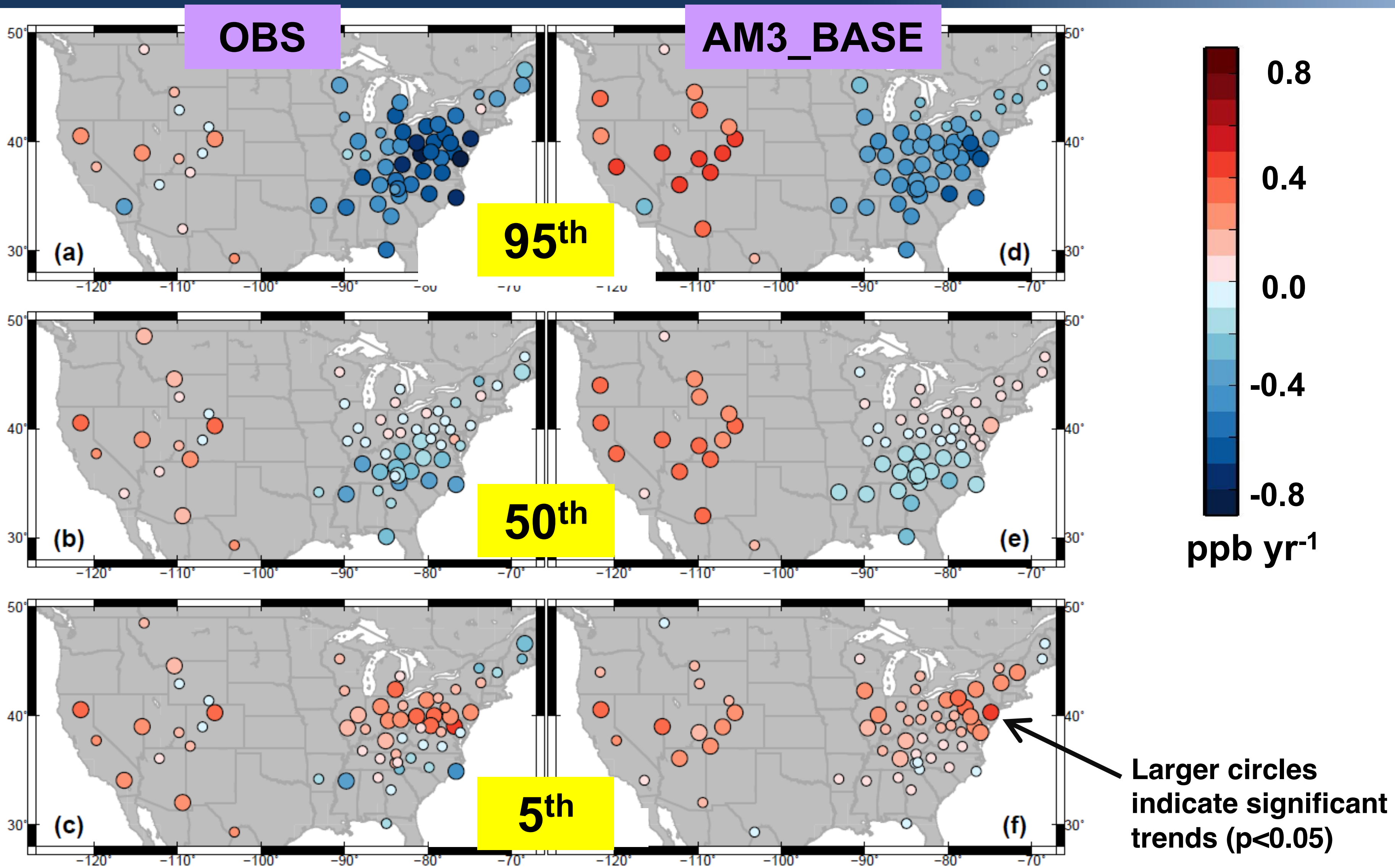

http://www.ldeo.columbia.edu/res/pi/NAO/




*Lin, M.Y. (to be submitted to GRL, 2017)*

# Part III: Regional $O_3$ trends and extremes across the US

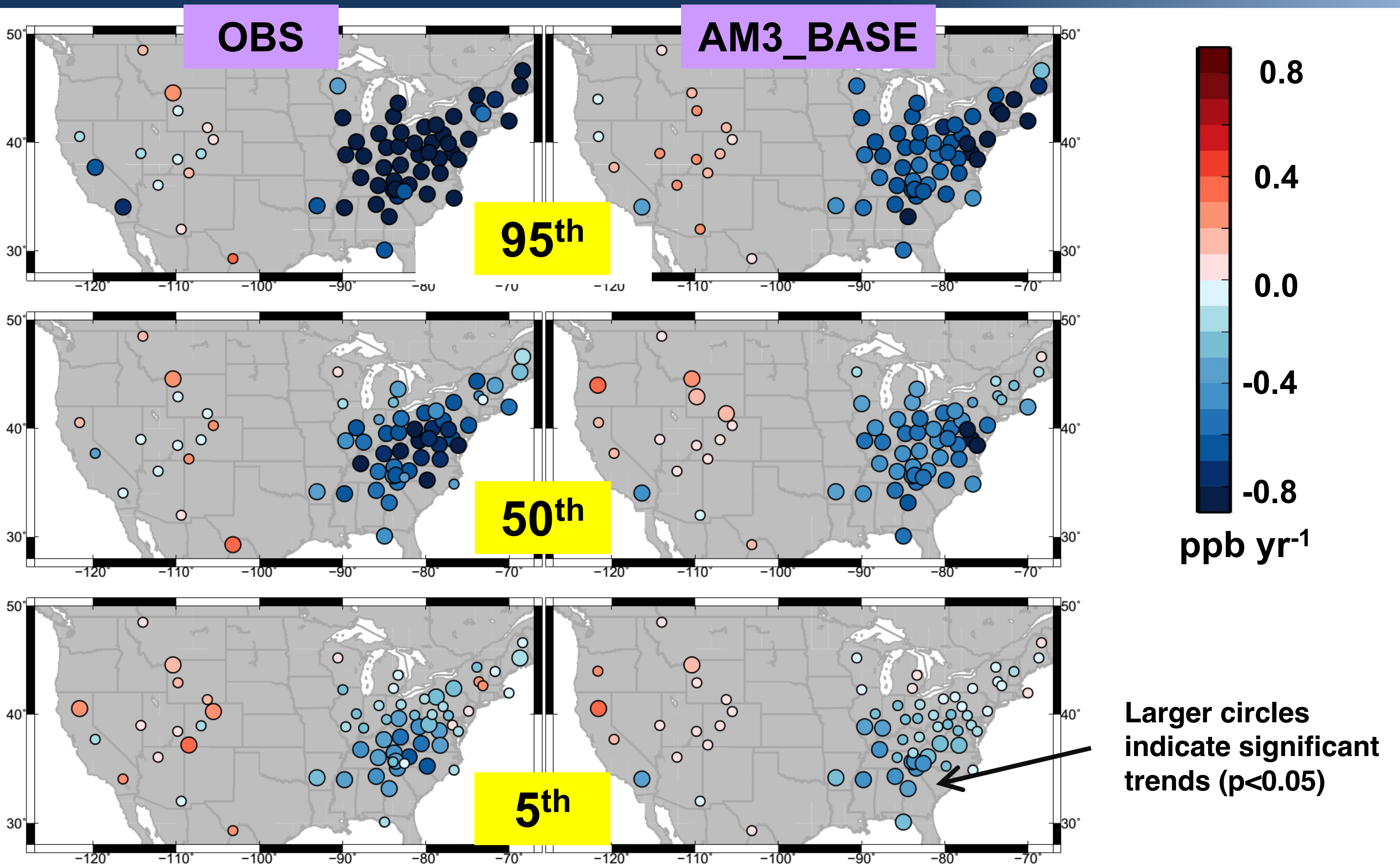
# SPRING US surface $O_3$ trends over 1988-2014




WUS: Model filtered for baseline conditions

*Lin, M.Y. et al.* [ACP, 2017]

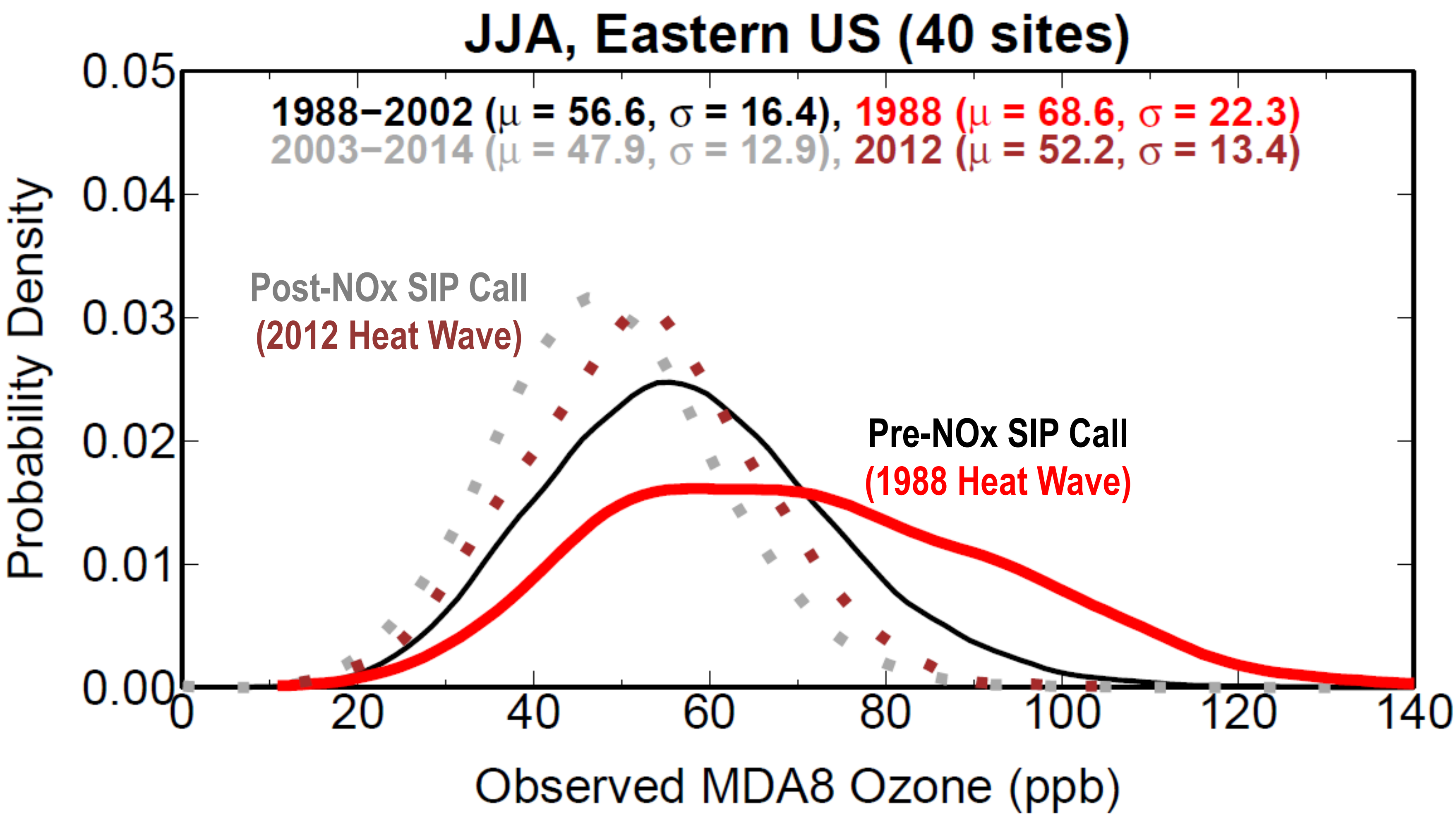
# **SUMMER** US surface $O_3$ trends over 1988-2014




WUS: Model filtered for baseline conditions

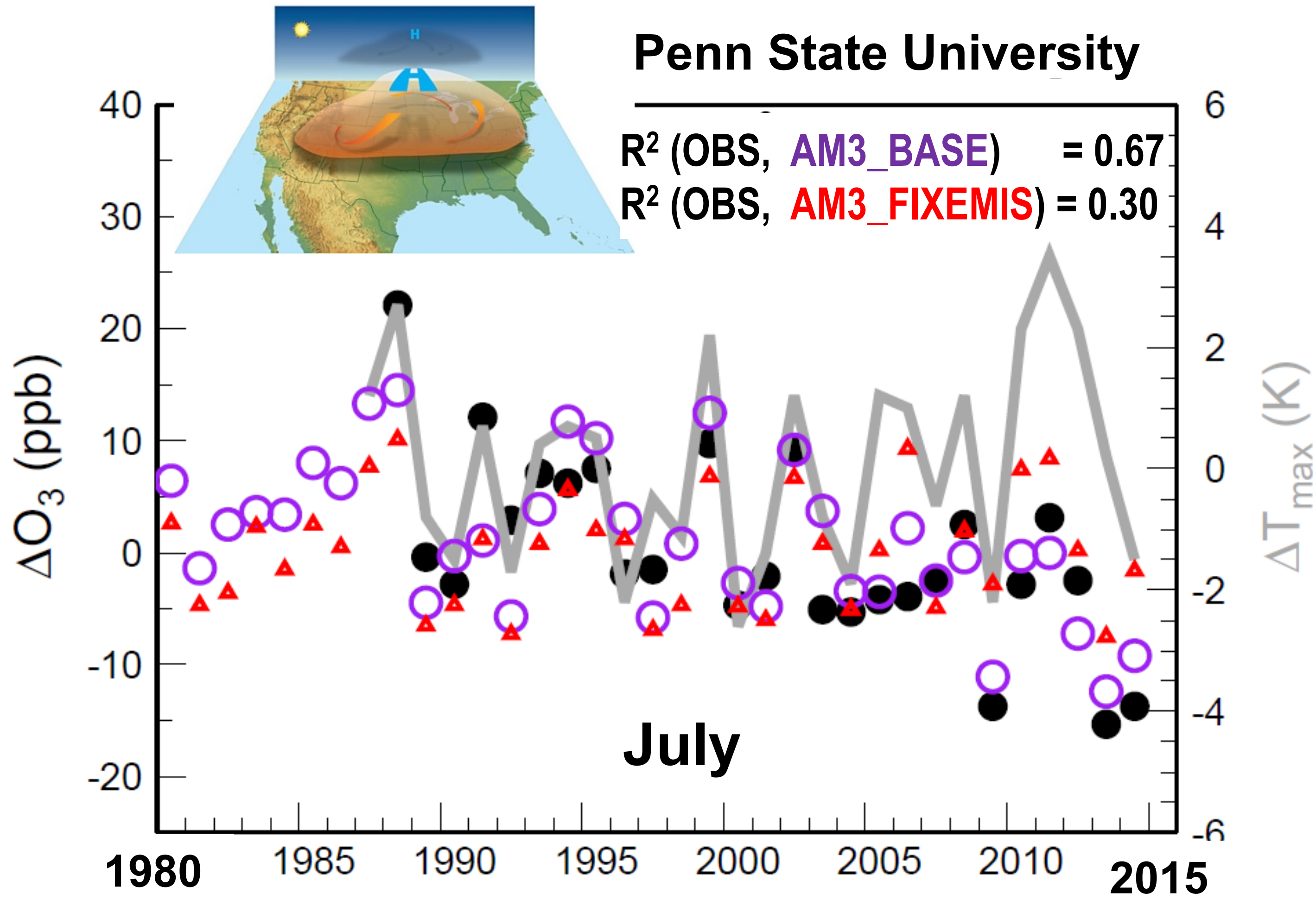
*Lin, M.Y. et al.* [ACP, 2017]

# Observed shifts in EUS summer surface $O_3$ distribution following $NO_x$ reductions




*Lin, M.Y. et al.* [ACP, 2017]

# Year-to-year variability of EUS summertime $O_3$ pollution




→ **Ongoing work for the dynamical causes of regional heat waves and associated pollution extremes**

*Lin, M.Y. et al.* [ACP, 2017]

# Some final thoughts on climate variability & surface $O_3$ connections

- **Attribution of observed tropospheric $O_3$ trends** requires consideration of internal climate variability, particularly in short length (e.g., TES/OMI/MLS)
- Recognizing links between air pollution and climate variability offers opportunities for **seasonal forecasts**.
- Projecting the response of regional air quality to **future climate change** requires large ensemble members.

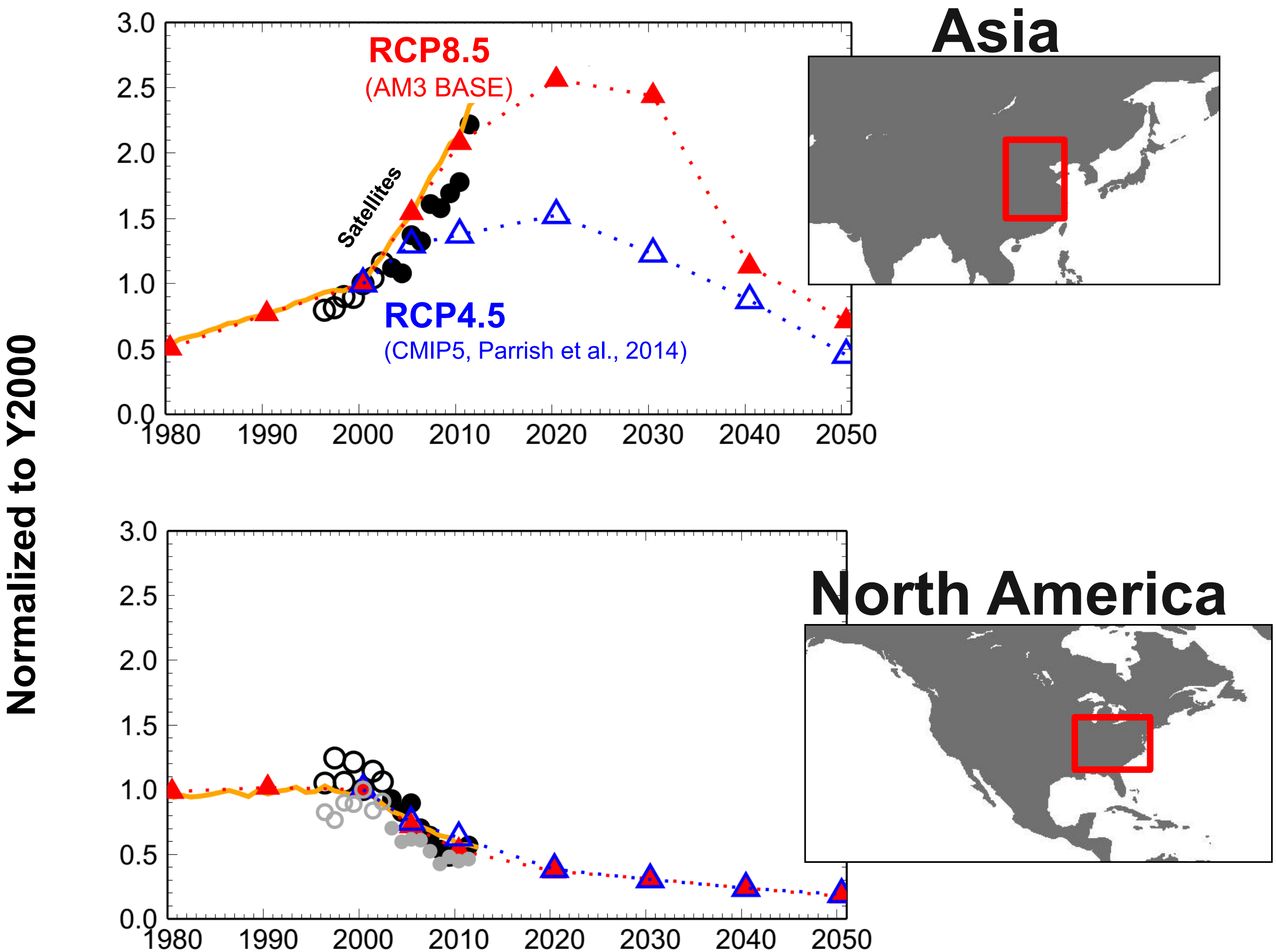
Cooperative Institute for Climate Science (2010-present)

**NNH13ZDA001N** (2014-2016)
**NNX14AR47G** (2014-2017)

**NNX12AF15G** (2011-2015)

# Additional Slides for Discussions

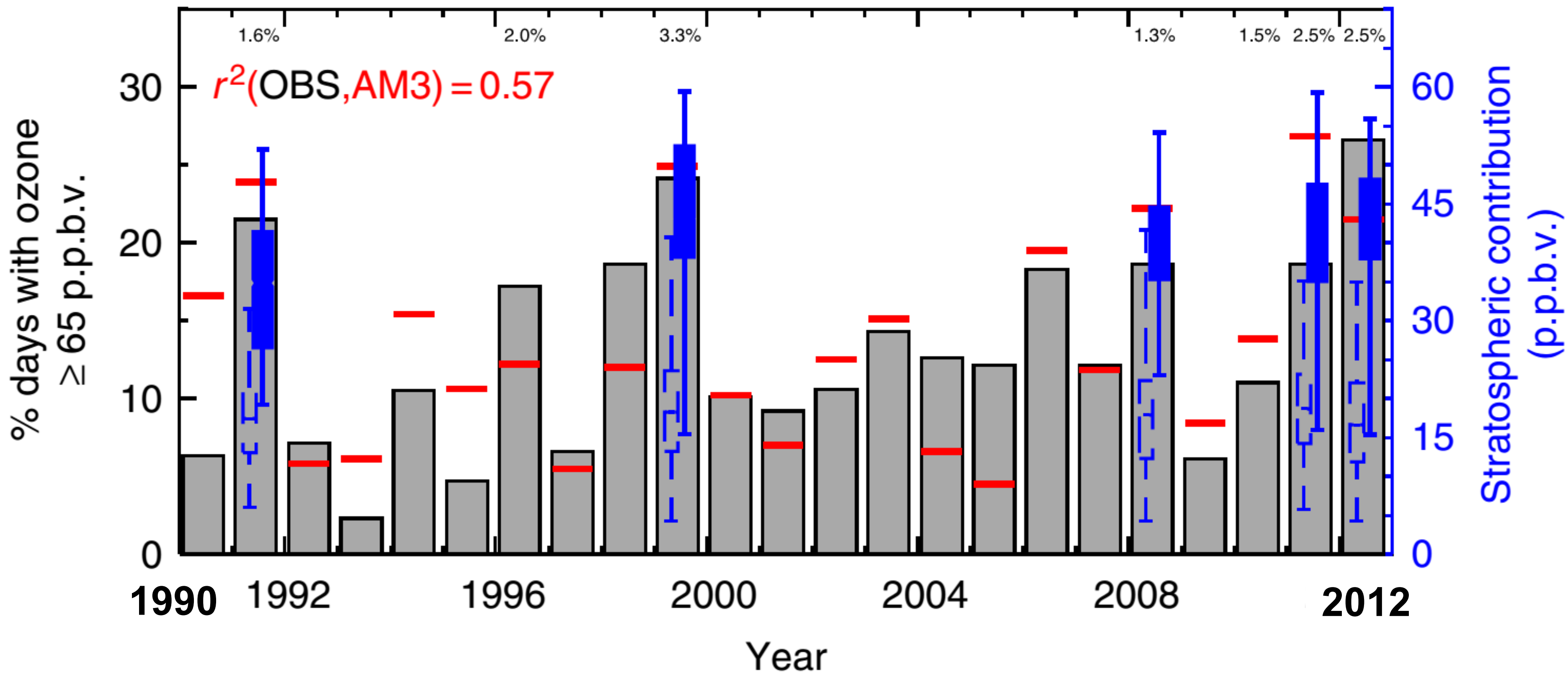
# Changes in anthropogenic $NO_x$ emissions





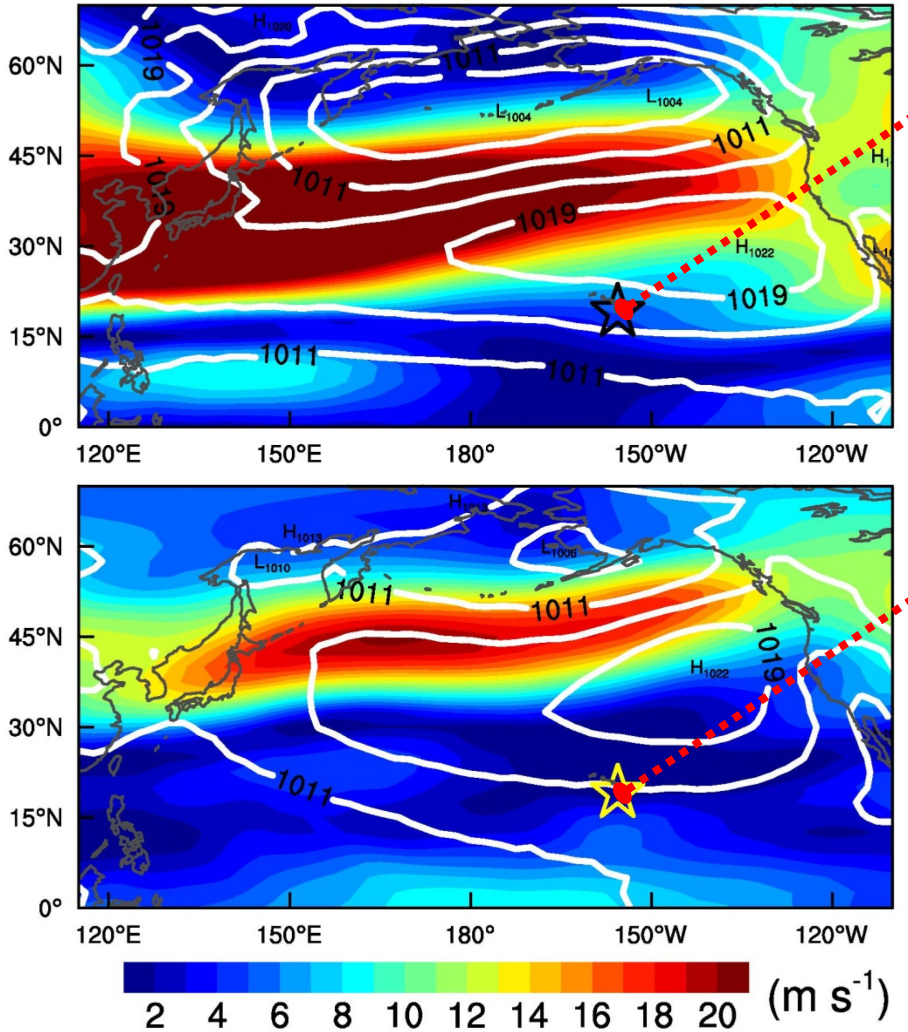

See also Richter et al. [2005], Zhang Q. et al. [2009]; Lin JT et al. (2011); Granier et al. (2011); Hilboll et al. [2013]

# Interannual variability in high-$O_3$ events
(WUS, April-May)




→ Stratospheric influence increases on days when total simulated ozone was above 70 ppbv ( ) versus below 60 ppbv ( )

# A climate perspective …




**NCEP 500 hPa wind**

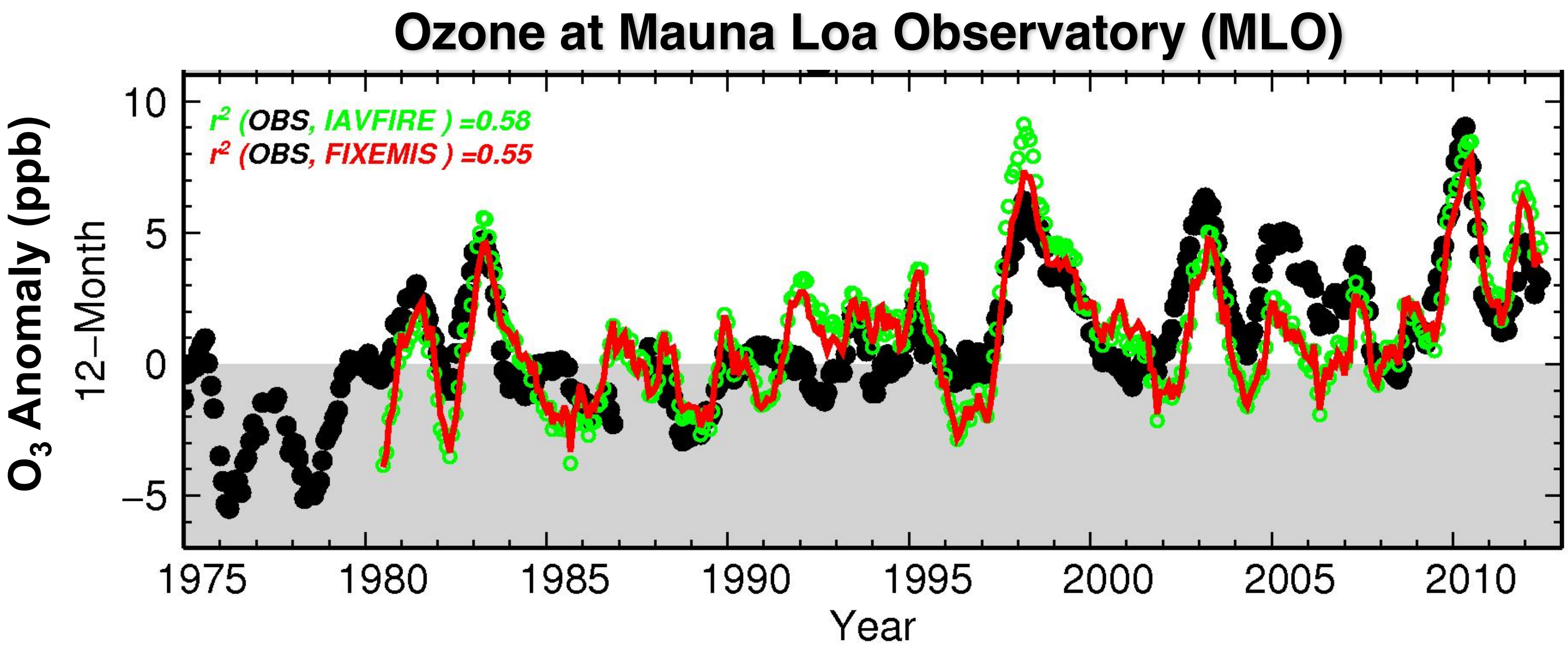
**Boreal Spring:**

**Sensitive to the subtropical jet location**
**→ ENSO**
**→ Pacific Decadal Oscillation (PDO)**
**→ The Hadley circulation**

**Boreal Fall:**

**Deep in the tropical belt**
**→Isentropic subsidence of mid-latitude pollution to Mauna Loa**
**→Pressure dipoles related to the Pacific North-American (PNA) pattern**

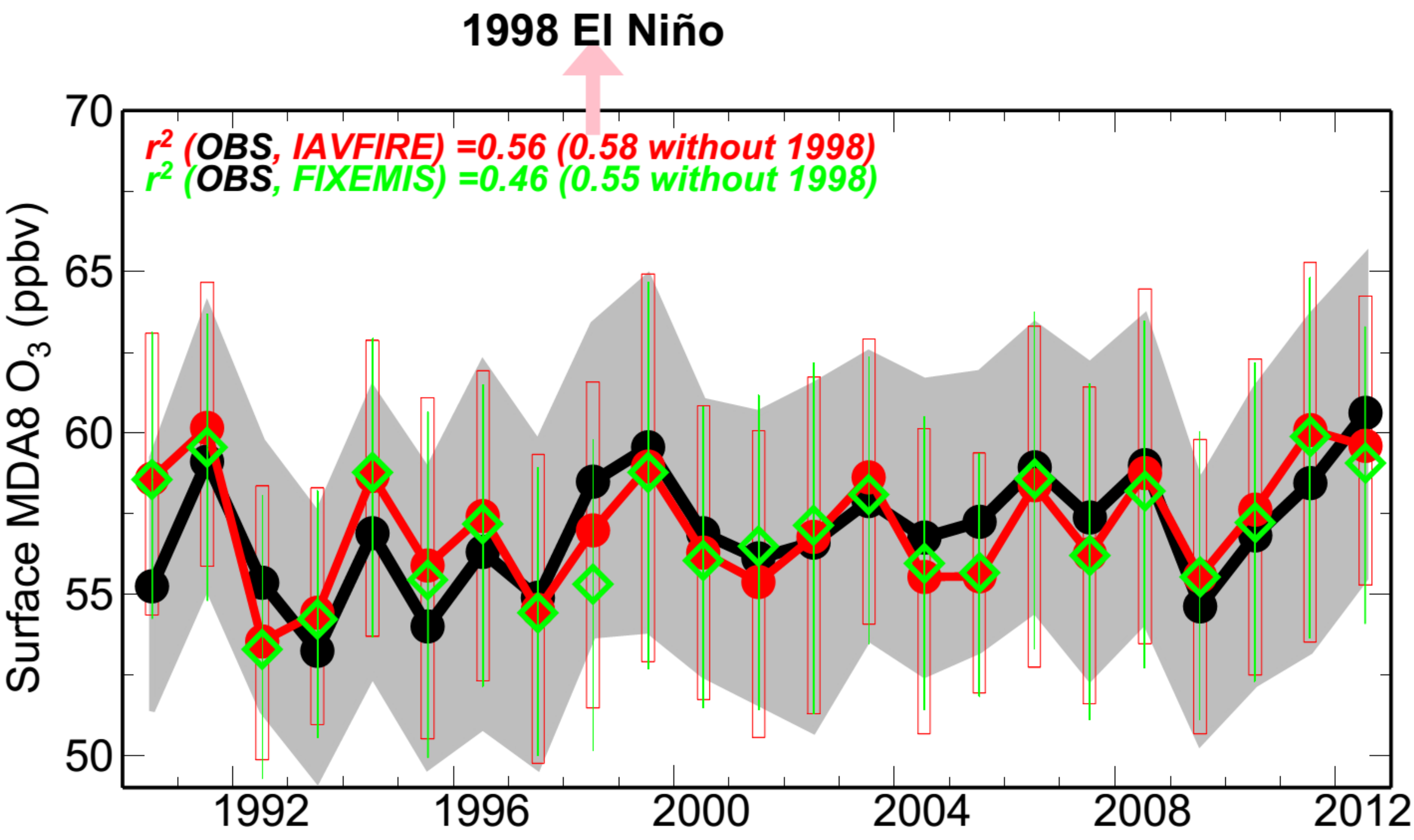
# Despite enhanced wildfire activity in equatorial Asia during El Niño, wildfire emissions are not the major driver of $O_3$ interannual variability at Mauna Loa



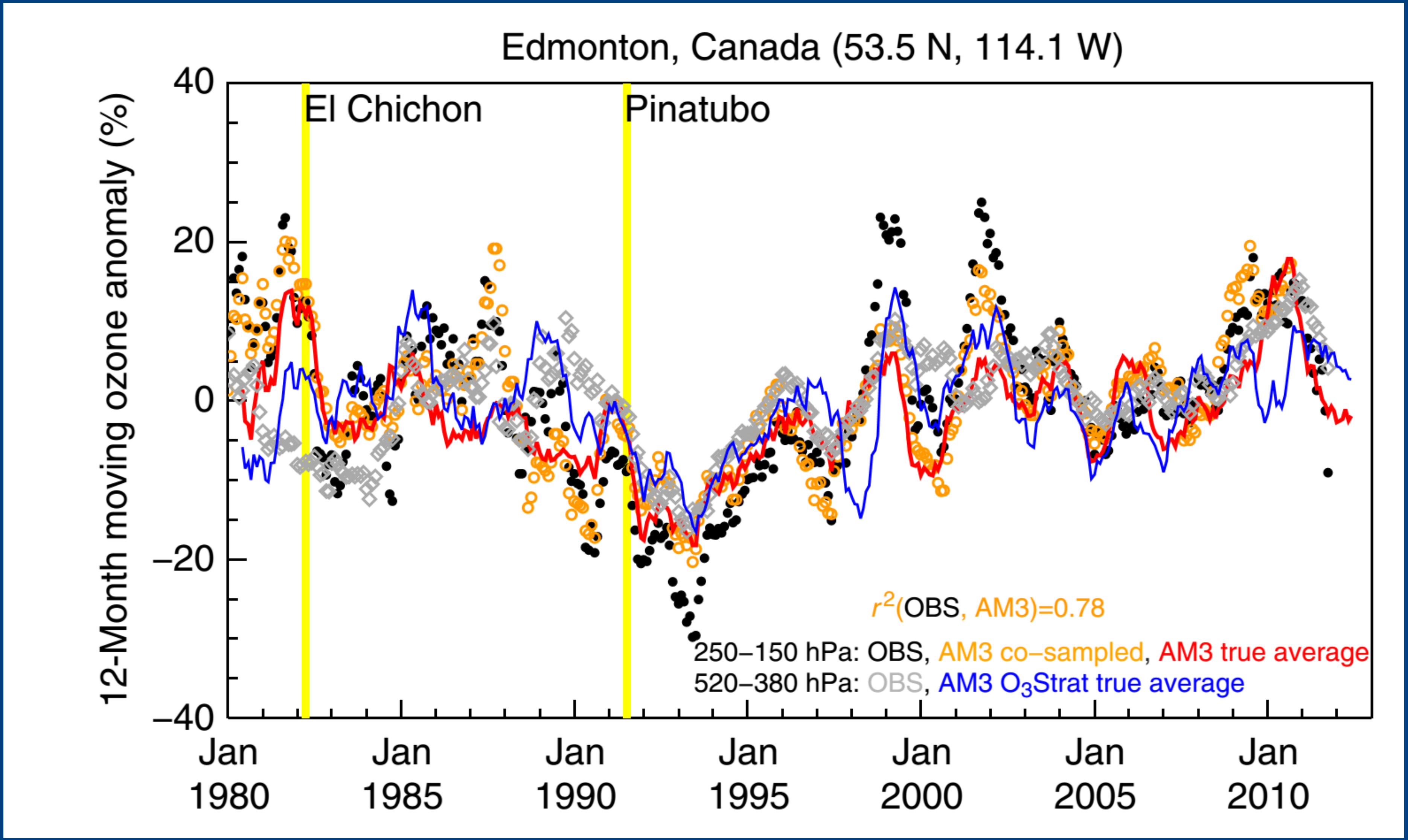

- **GFDL AM3 with fixed emissions (nudged) captures observed $O_3$ changes**
- **Negligible influence from El Niño-related wildfires in equatorial Asia**

*Lin M.Y. et al (Nature GeoSci., 2014)*

# Minor influence from wildfire emissions on inter-annual variability of springtime surface ozone over WUS




*Meiyun Lin et al (Nature Communications, 2015)*




*Lin M. et al., Nature Communications, 2015*

# The STT influence on WUS surface $O_3$ variability shows little correlations with mean $O_3$ burdens in the UTLS

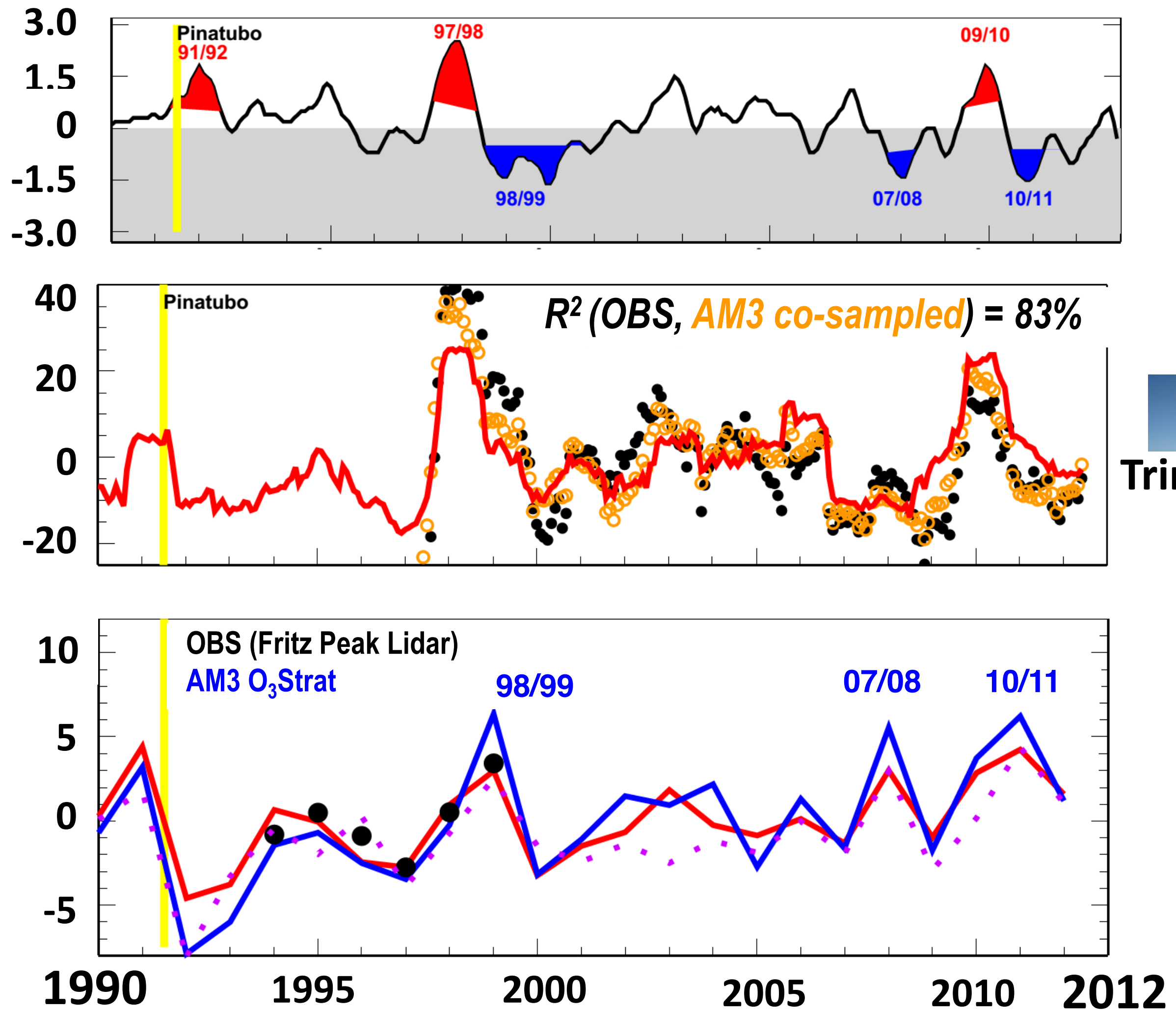
**Niño 3.4 Index**

**250-150hPa $O_3$ anomaly (%, 12-Mon moving)**

*$R^2$ (UTLS, Surface) = 7%*

**FreeTrop & Surface $O_3$ anomaly (ppb, Apr-May)**

*$R^2$ (FreeTrop, Surface) =74%*



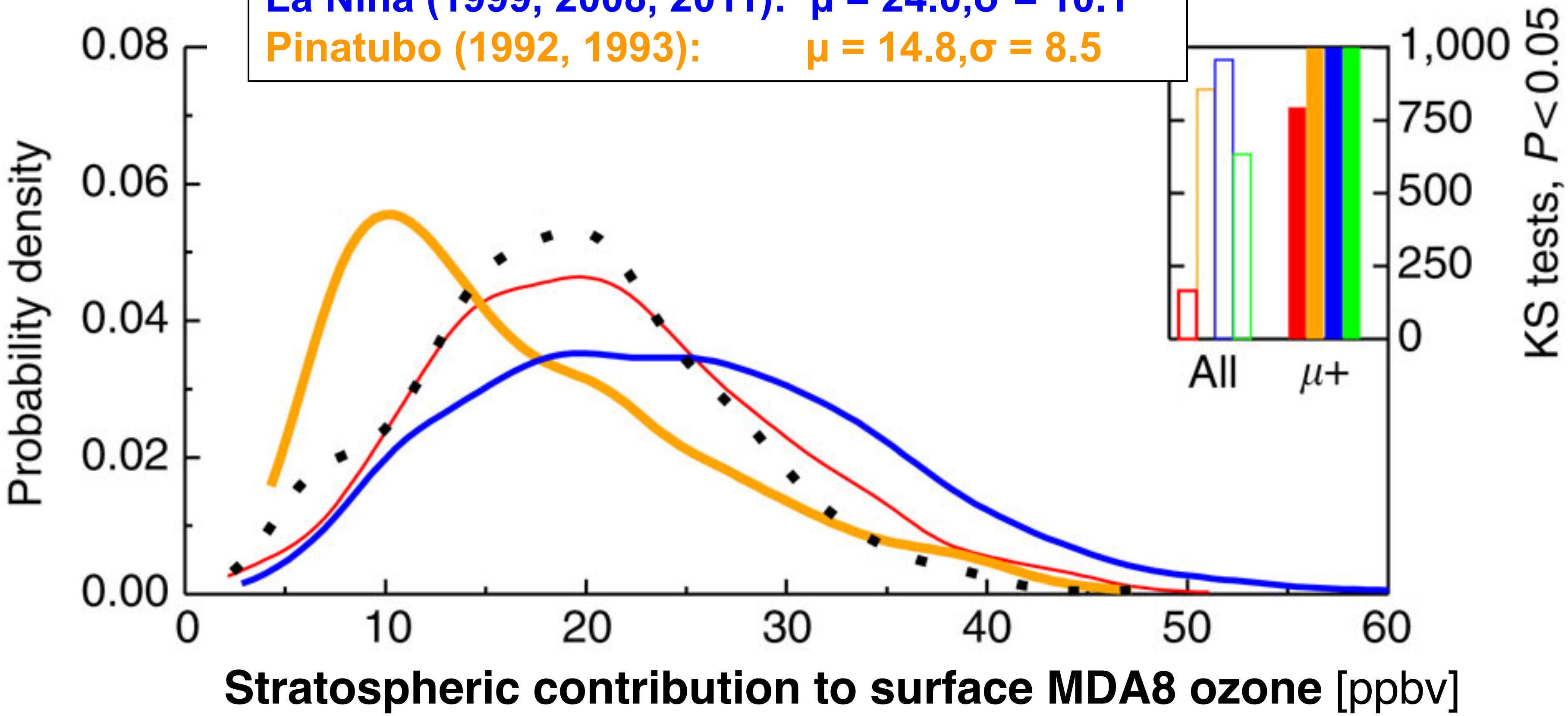


*Lin M. et al., Nature Communications, 2015*

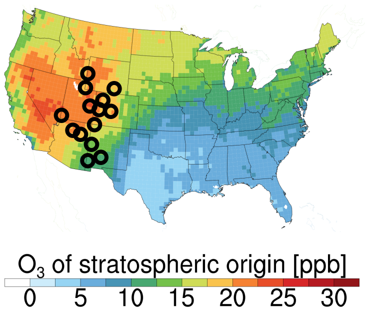
# Simulated stratospheric contribution
(WUS, April-May)

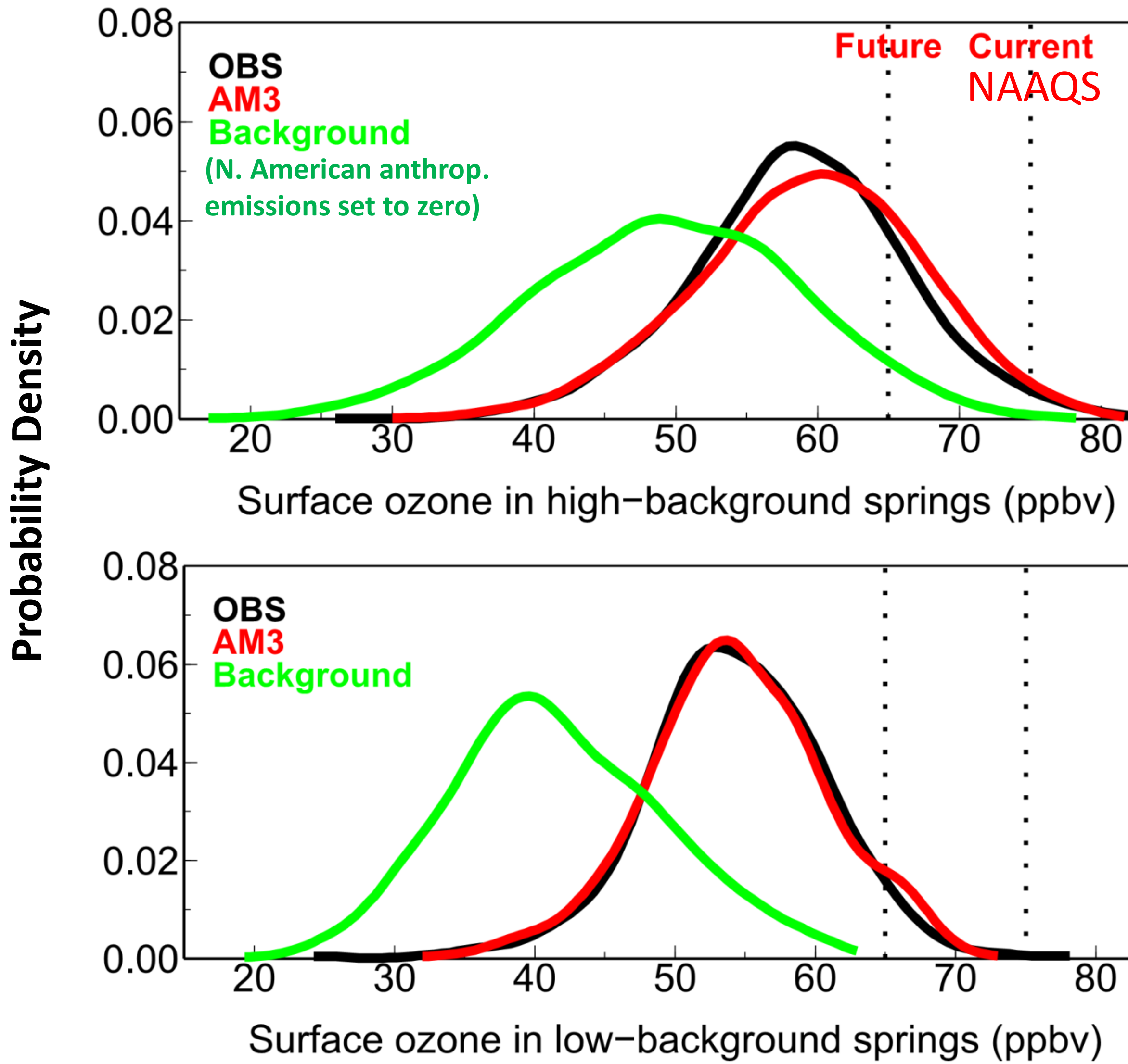
| | |
|---|---|
| **Neutral:** | **μ = 19.3,σ = 7.5** |
| **El Niño (1998, 2010):** | **μ = 20.5,σ = 8.2** |
| **La Niña (1999, 2008, 2011):** | **μ = 24.0,σ = 10.1** |
| **Pinatubo (1992, 1993):** | **μ = 14.8,σ = 8.5** |

**Statistical testing**



# Surface $O_3$ distribution in high vs low background springs




1991
1999
2008
2011
2012

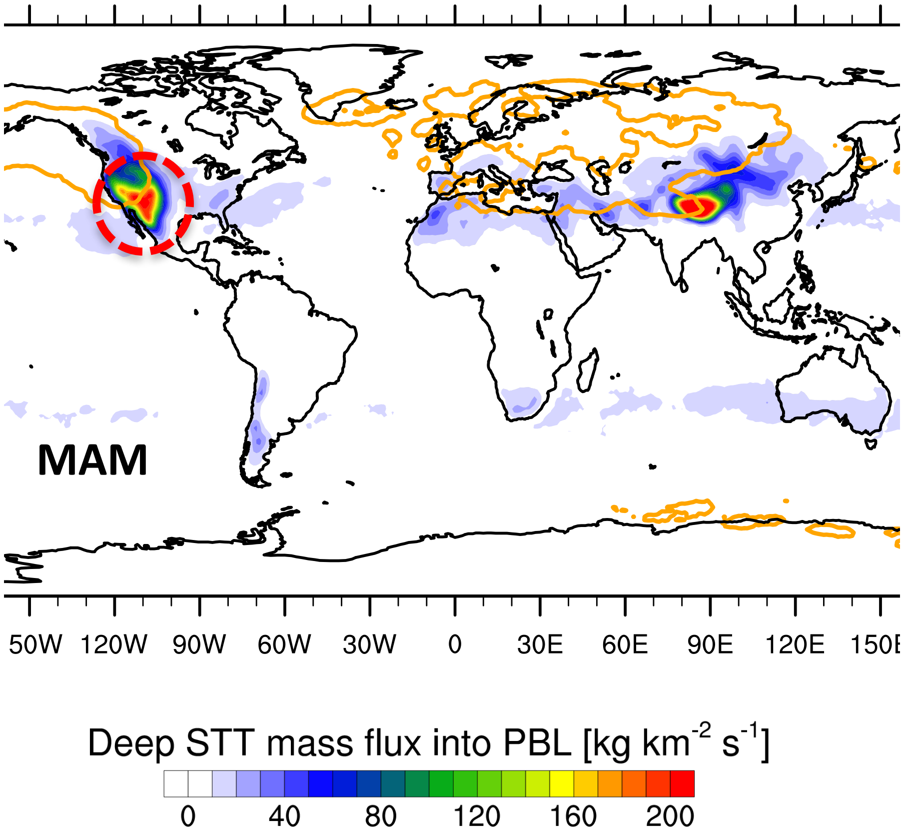
1992
1993



*Meiyun Lin et al. (Nature Communications, 2015)*

# Southwest US is global hotspot for *deep* STT

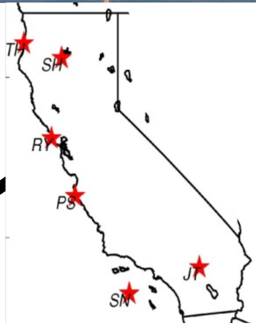
**Proximity to N. Pacific storm track exit and high average elevation**



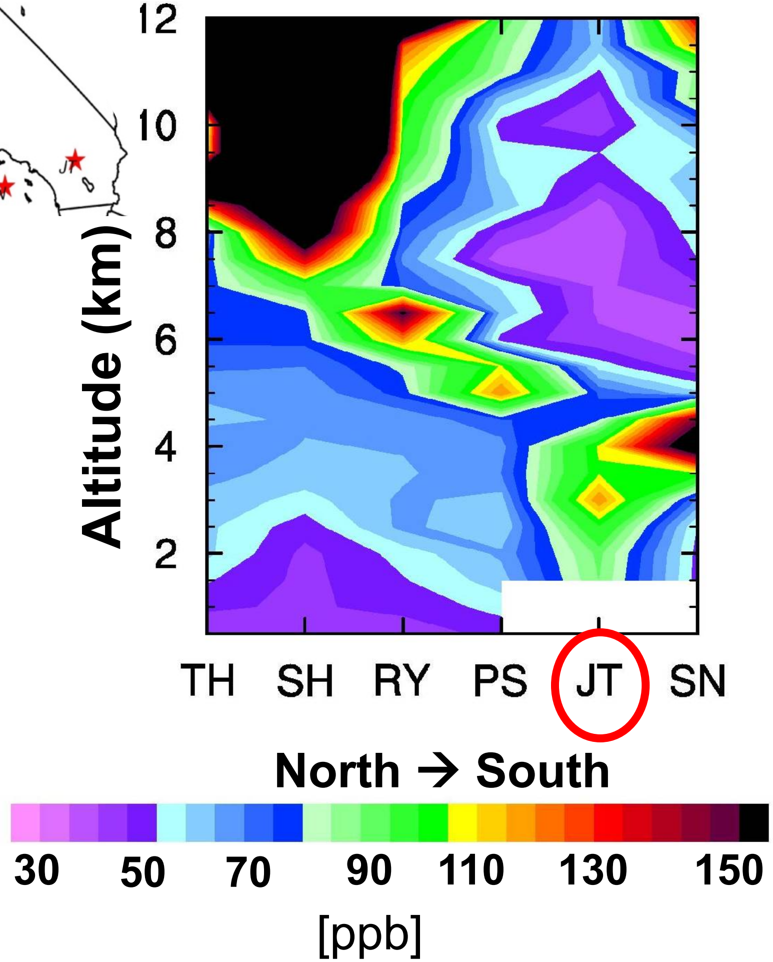

**A global climatology of stratosphere–troposphere exchange using the ERA-Interim data set from 1979 to 2011**

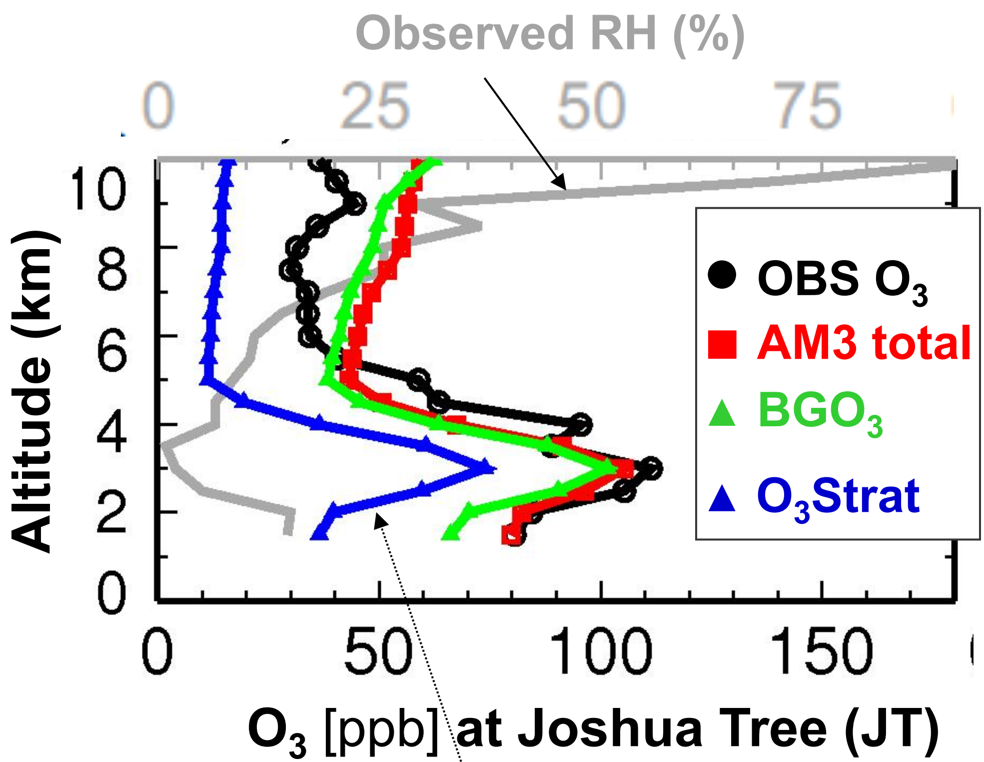
**B. Škerlak, M. Sprenger, and H. Wernli** ACP, 14, 913–937, 2014

# GFDL-AM3 model captures observed deep stratospheric intrusions over WUS




## Sondes over California

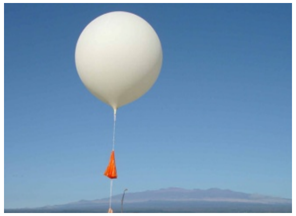


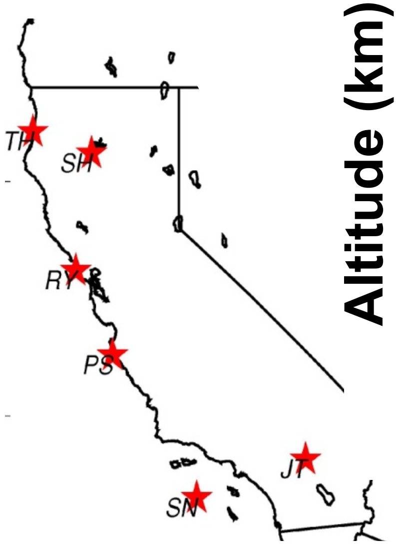



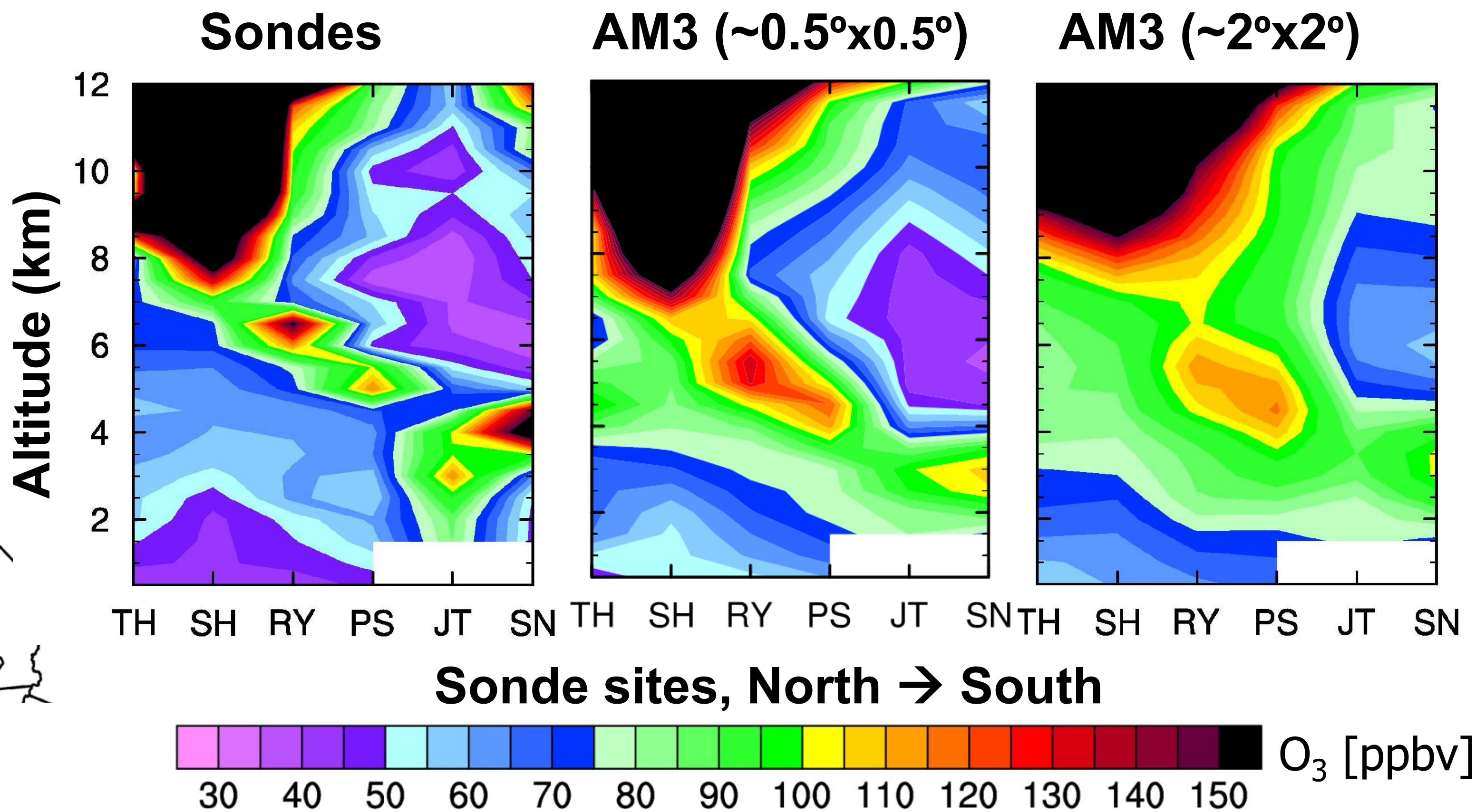

- Simulated enhancements of $O_3$Strat consistent with observed low RH

*Lin MY et al (JGR, 2012b), Springtime high surface ozone events over the WUS: Quantifying the role of stratospheric intrusions*

# Simulations of deep SI events in GFDL-AM3
(May 28, 2010 example)



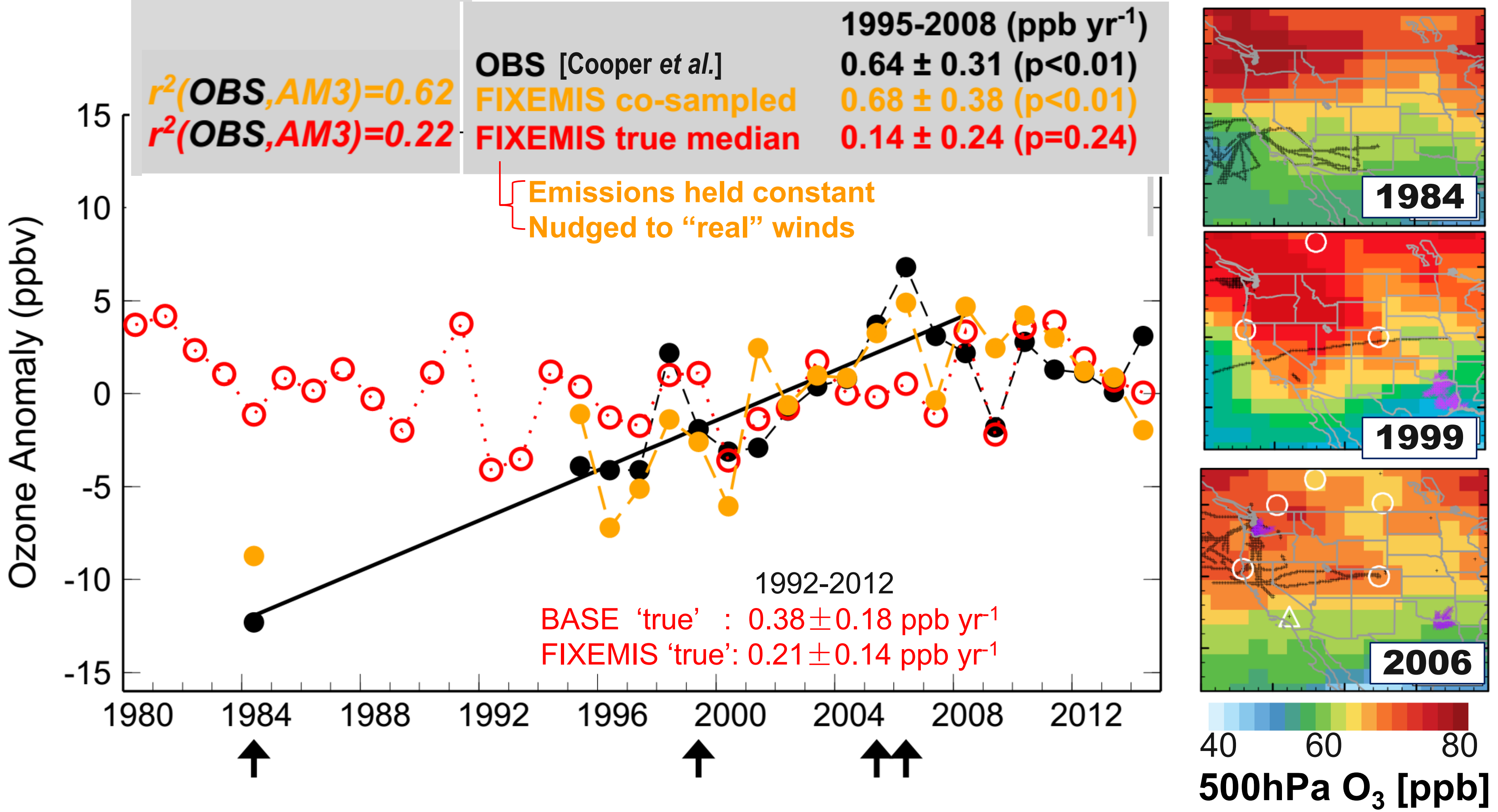



- 0.5º model better captures vertical structure
- 2º model reproduces the large-scale view

***Lin MY et al (JGR, 2012b):*** *Springtime high surface ozone events over the WUS …*

# Large internal climate variability and sparse in-situ sampling complicate $O_3$ trend estimates




→ Rising Asian emissions from 1980s to 2000s raises US background $O_3$ by 7 ppb
→ But 20-year trends driven by internal variability can be as large as emission-driven trends

*Lin, Meiyun; LW Horowitz; OR Cooper; D Tarasick et al.* [GRL, 2015]