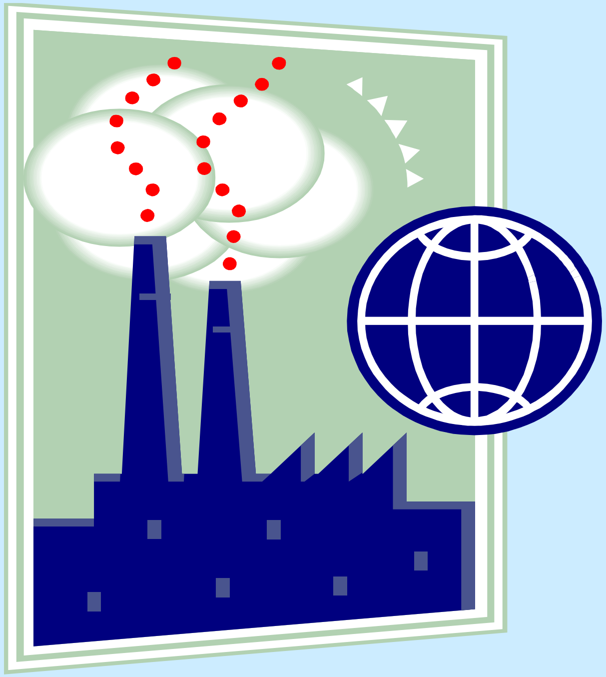


# Atmospheric Methane Distribution and Trends:

# Impacts on Climate and Ozone Air Quality


**Arlene M. Fiore**

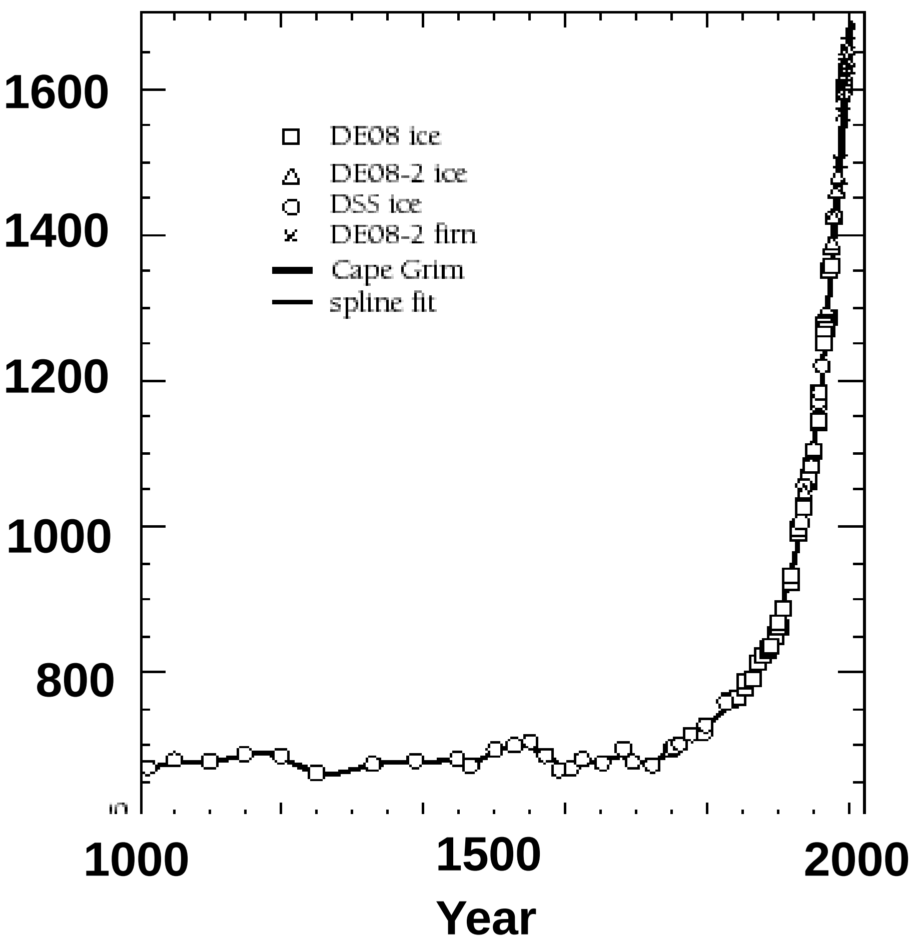
Larry Horowitz (NOAA/GFDL)
Jason West (Princeton)
Ed Dlugokencky (NOAA/GMD)


Geophysical Fluid Dynamics Laboratory
GFDL
NOAA

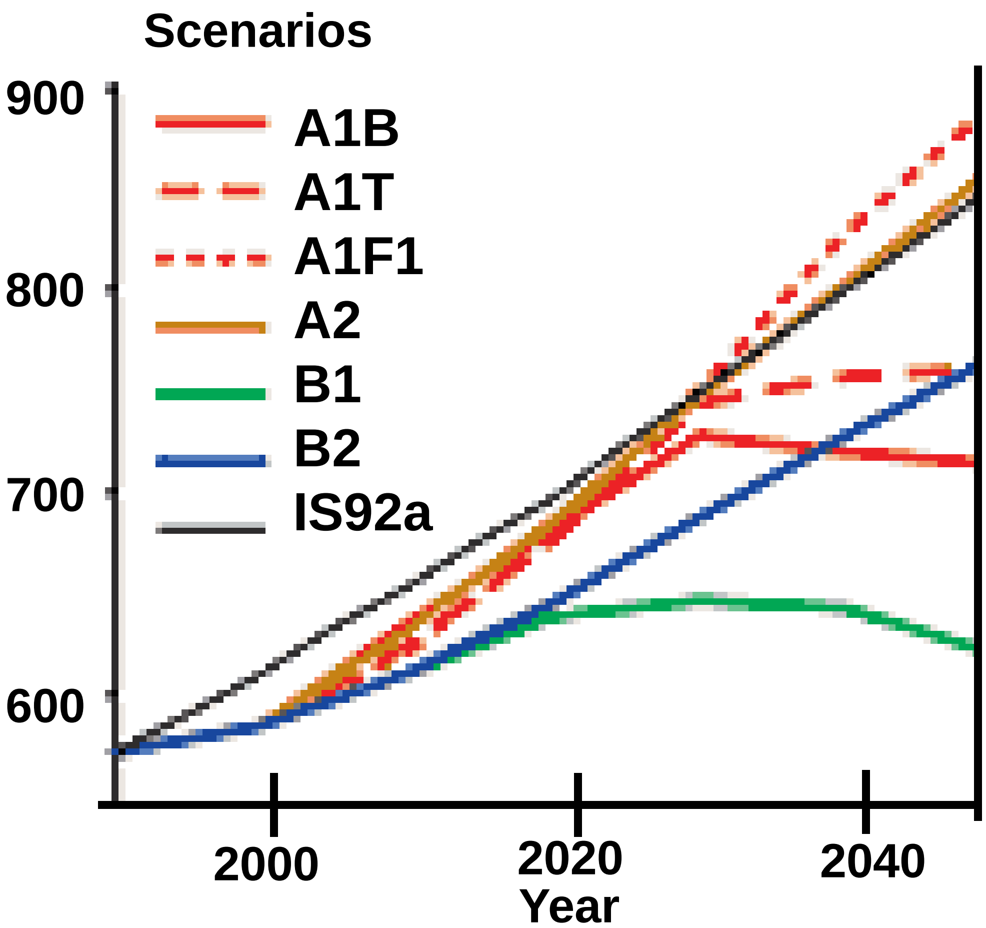
**Earth, Atmospheric, and Planetary Sciences Department Seminar**
**Massachusetts Institute of Technology**
**December 16, 2005**

# Atmospheric $CH_4$: Past Trends, Future Predictions

Variations of $CH_4$ Concentration (ppb) Over the Past 1000 years [*Etheridge et al.*, 1998]

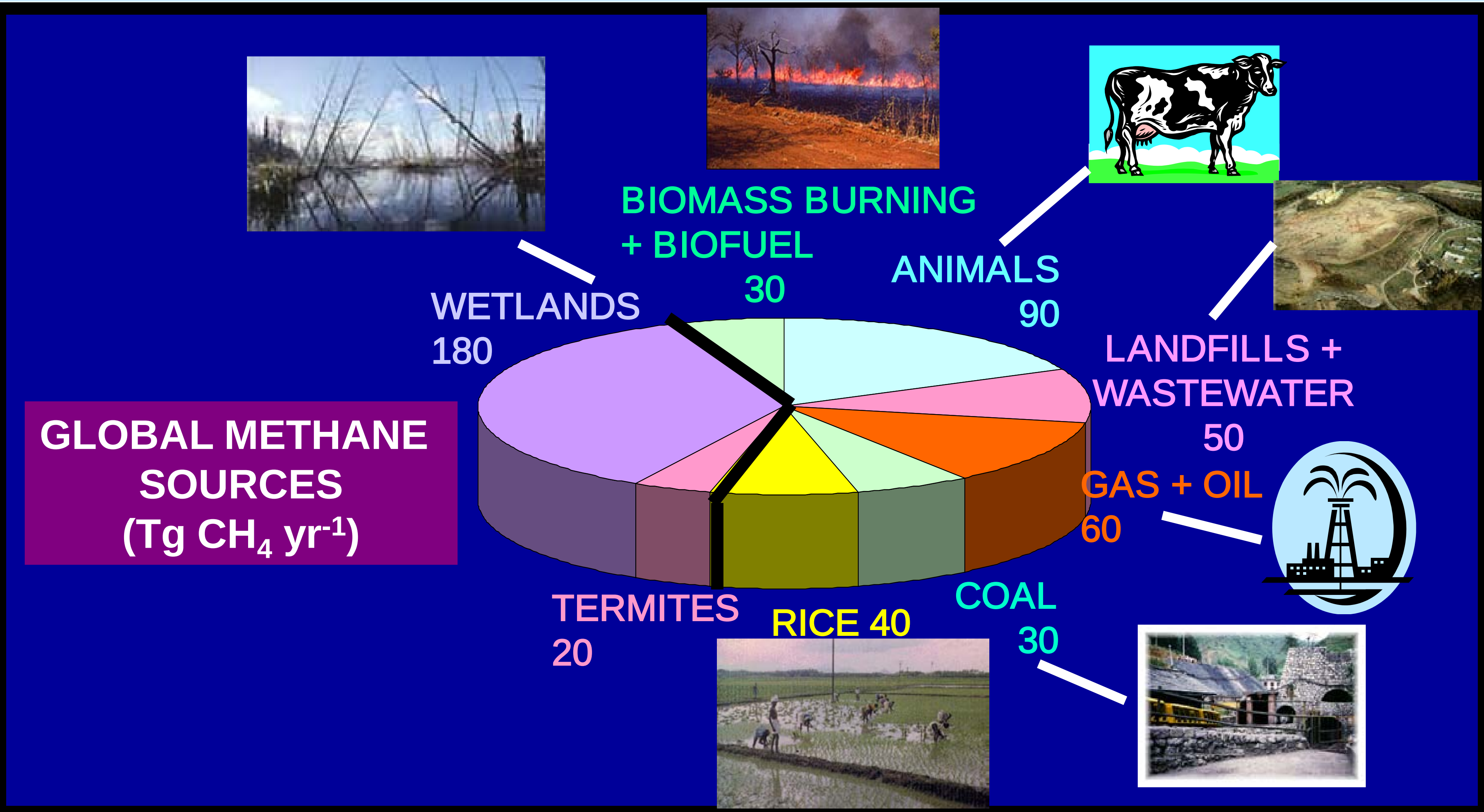



*IPCC* [2001] Projections of Future $CH_4$ Emissions (Tg $CH_4$) to 2050



# More than half of global methane emissions are influenced by human activities

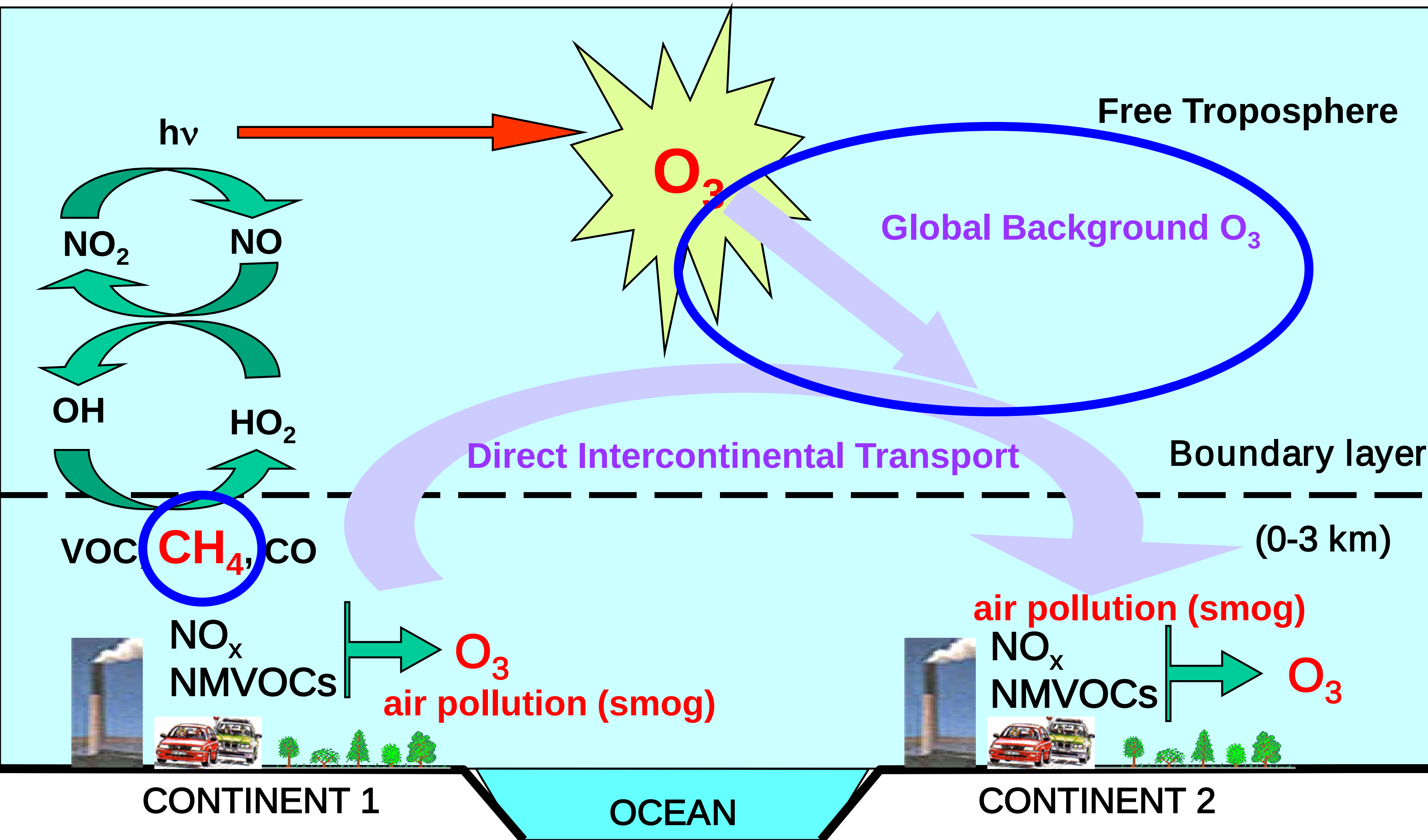
~300 Tg $CH_4$ $yr^{-1}$ Anthropogenic [EDGAR 3.2 Fast-Track 2000; *Olivier et al.*, 2005]
~200 Tg $CH_4$ $yr^{-1}$ Biogenic sources [*Wang et al.*, 2004]



# Air quality-Climate Linkage:

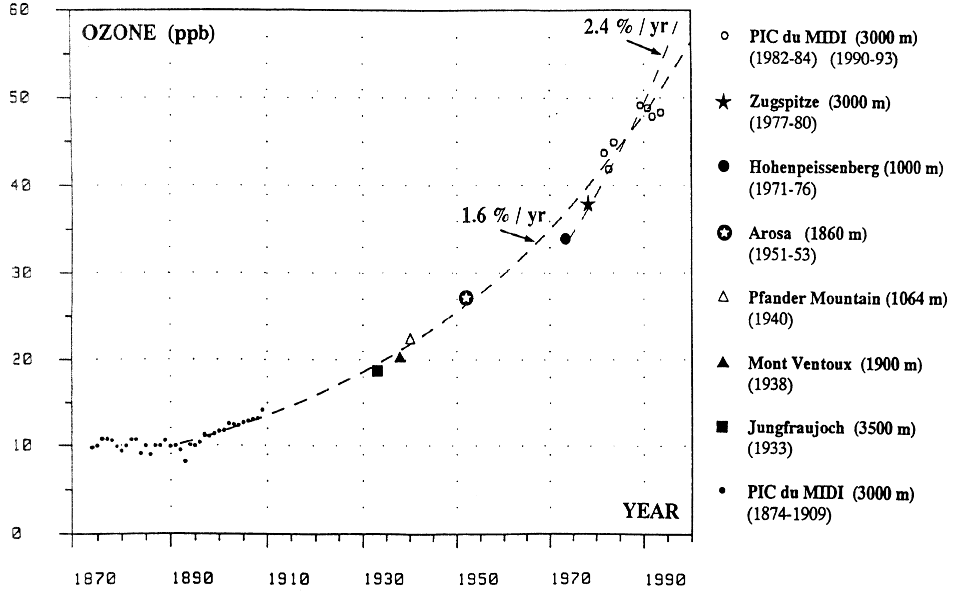
## $CH_4$, $O_3$ are important greenhouse gases

## $CH_4$ contributes to background $O_3$ in surface air

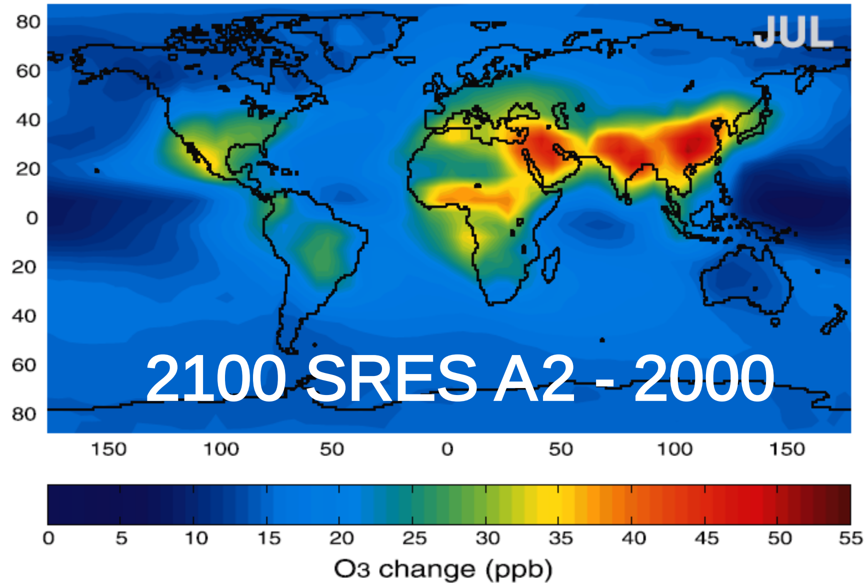


# Observations indicate historical increase in background ozone; IPCC scenarios project future growth

Ozone at European mountain sites 1870-1990 [*Marenco et al*., 1994].



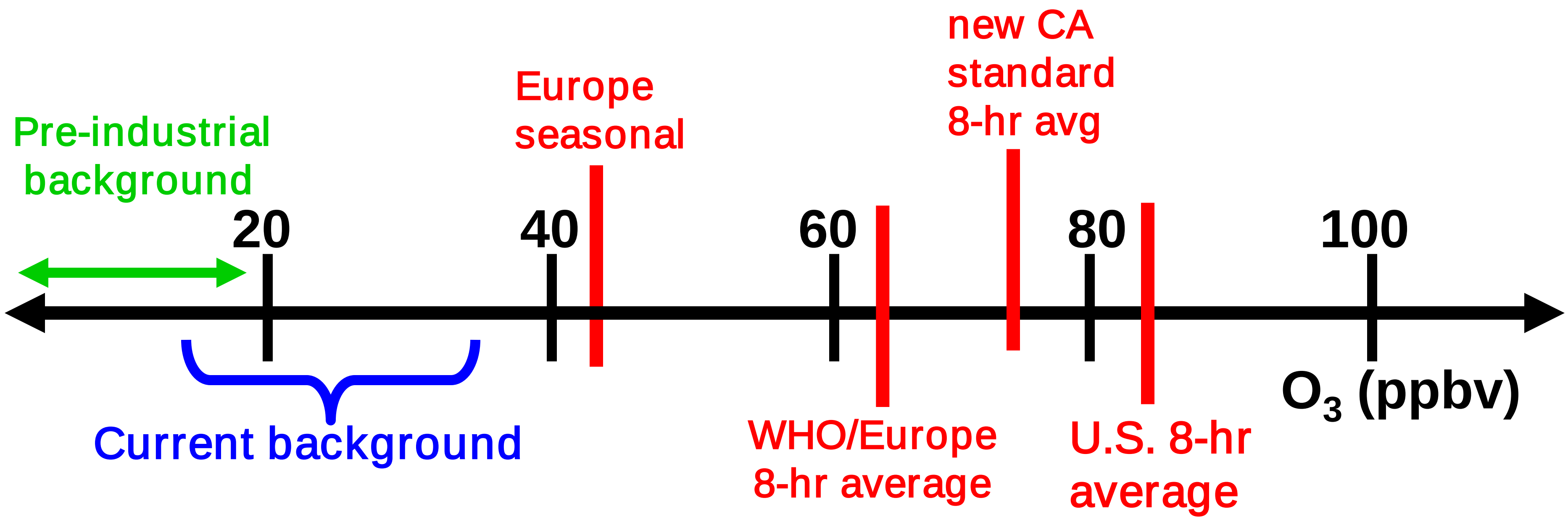

Change in 10-model mean July surface $O_3$ [*Prather et al*., 2003]




Attributed mainly to increases in methane and $NO_x$ [*Wang et al*., 1998; *Prather et al*., 2003]

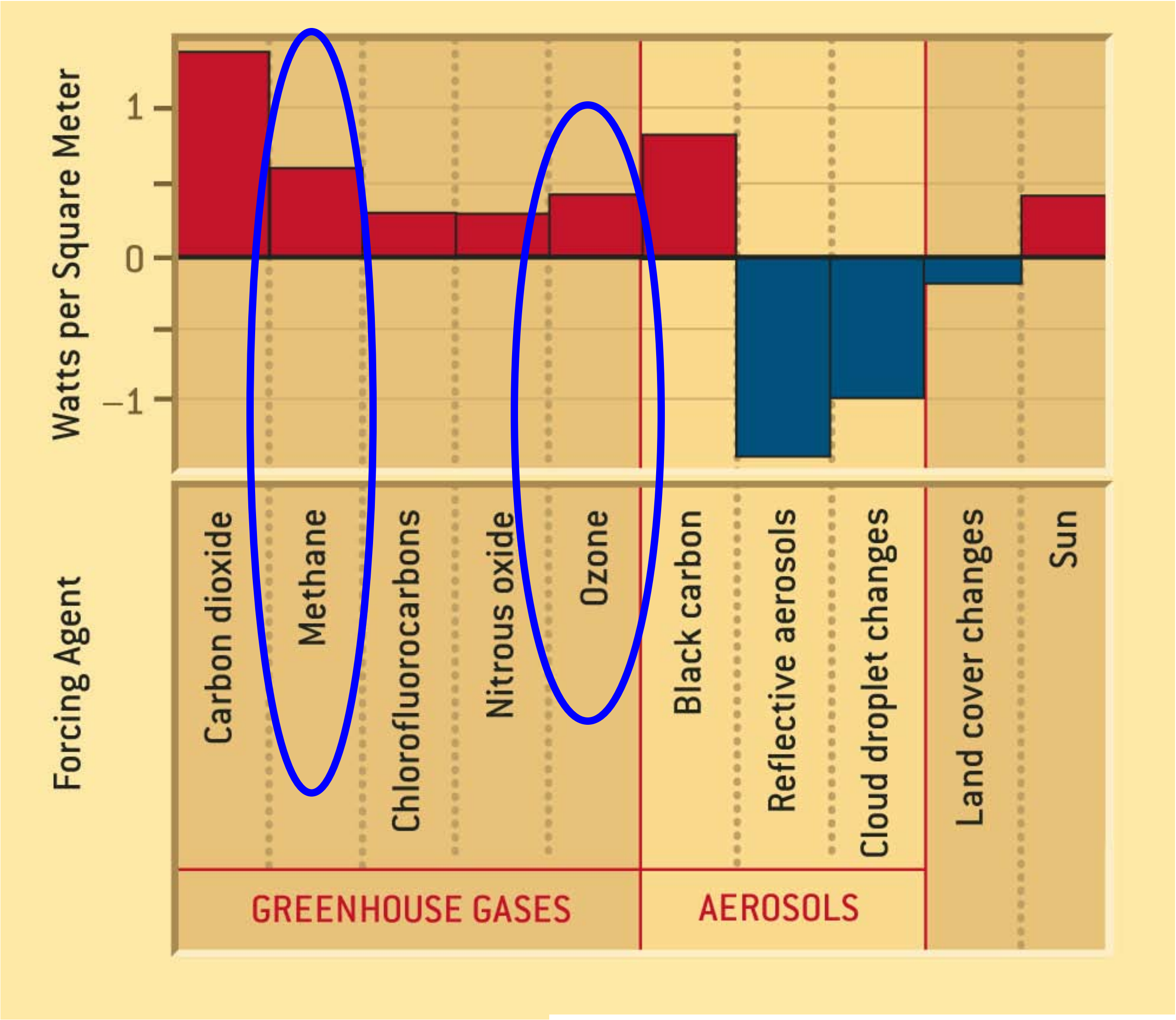
Adapted from J. West

# Rising background $O_3$ at northern mid-latitudes has implications for attaining air quality standards




Analyses of surface $O_3$ from North American and European monitoring sites indicate increasing background [*Lin et al*., 2000; *Jaffe et al*., 2003,2005; *Vingarzen et al*., 2004; *EMEP/CCC-Report 1/2005*]

## Radiative Forcing of Climate from Preindustrial to Present: Important Contributions from Methane and Ozone




*Hansen, Scientific American*, 2004

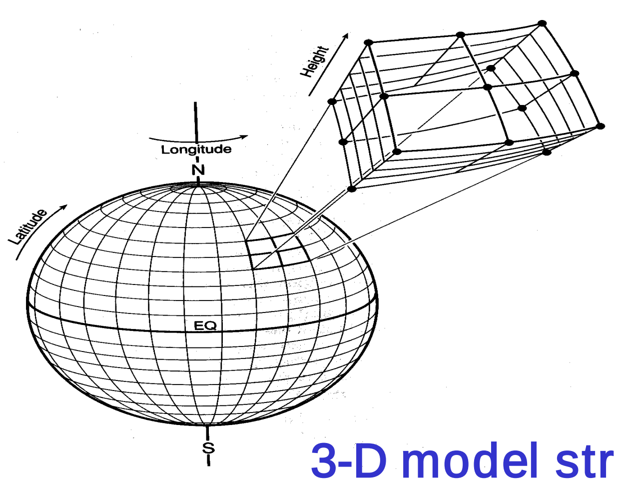
# Approach: Use 3-D Models of Atmospheric Chemistry to examine climate and air quality response to emission changes

## GEOS-CHEM
[*Bey et al*., 2001]

- GEOS GMAO meteorology
- 4°x5°; 20 $\sigma$-levels
- GEIA/Harvard emissions
- Uniform, fixed $CH_4$

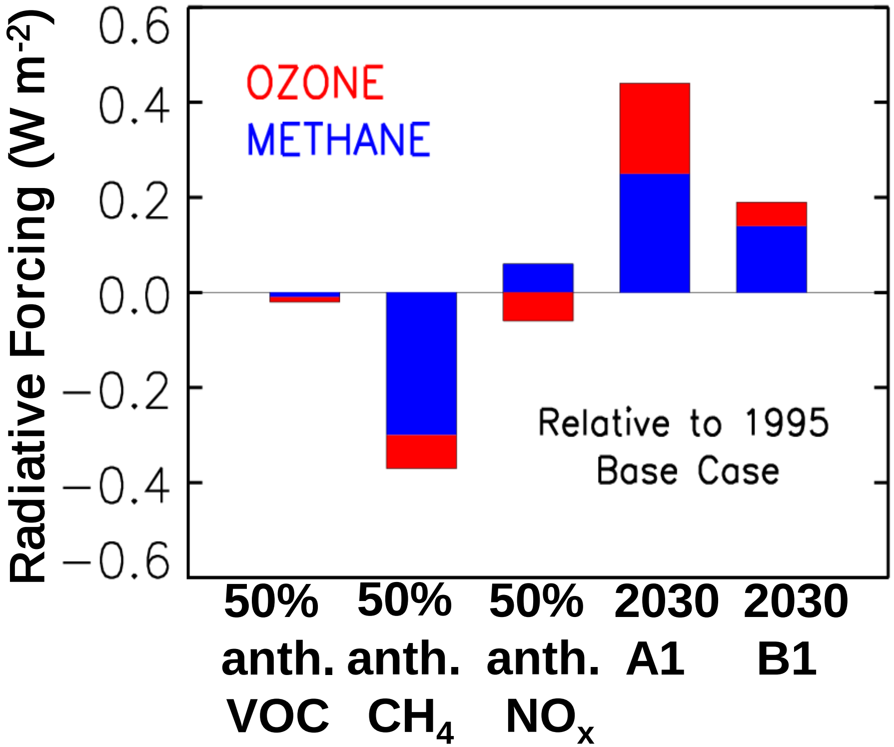
## MOZART-2
[*Horowitz et al*., 2003]

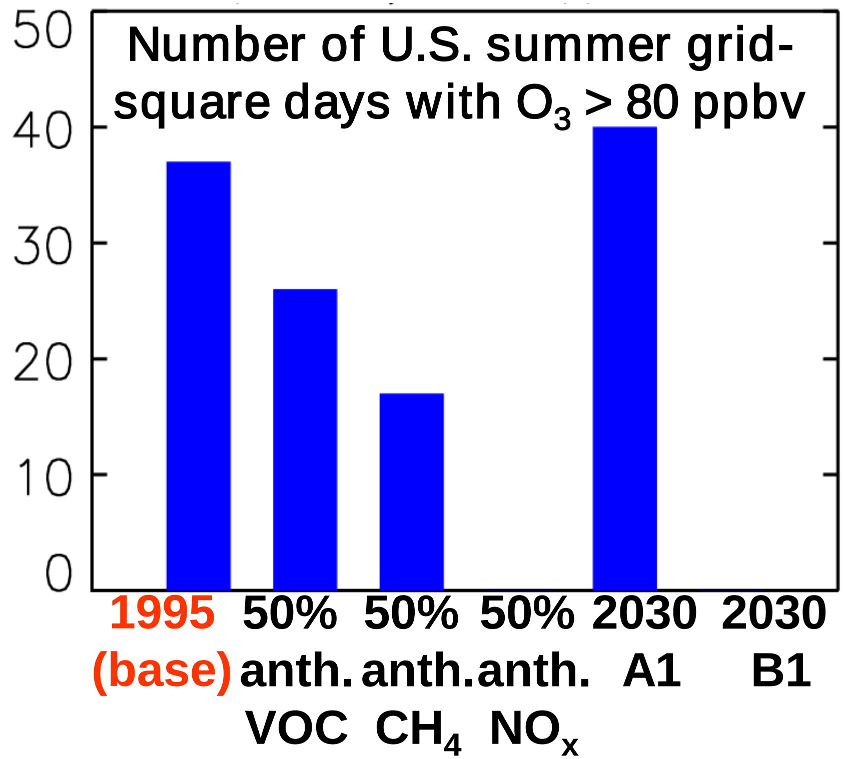
- NCEP meteorology
- 1.9°x1.9°; 28 $\sigma$-levels
- EDGAR v. 2.0 emissions
- $CH_4$ EDGAR emissions for 1990s




3-D model structure

# Double dividend of Methane Controls: Decreased greenhouse warming and improved air quality



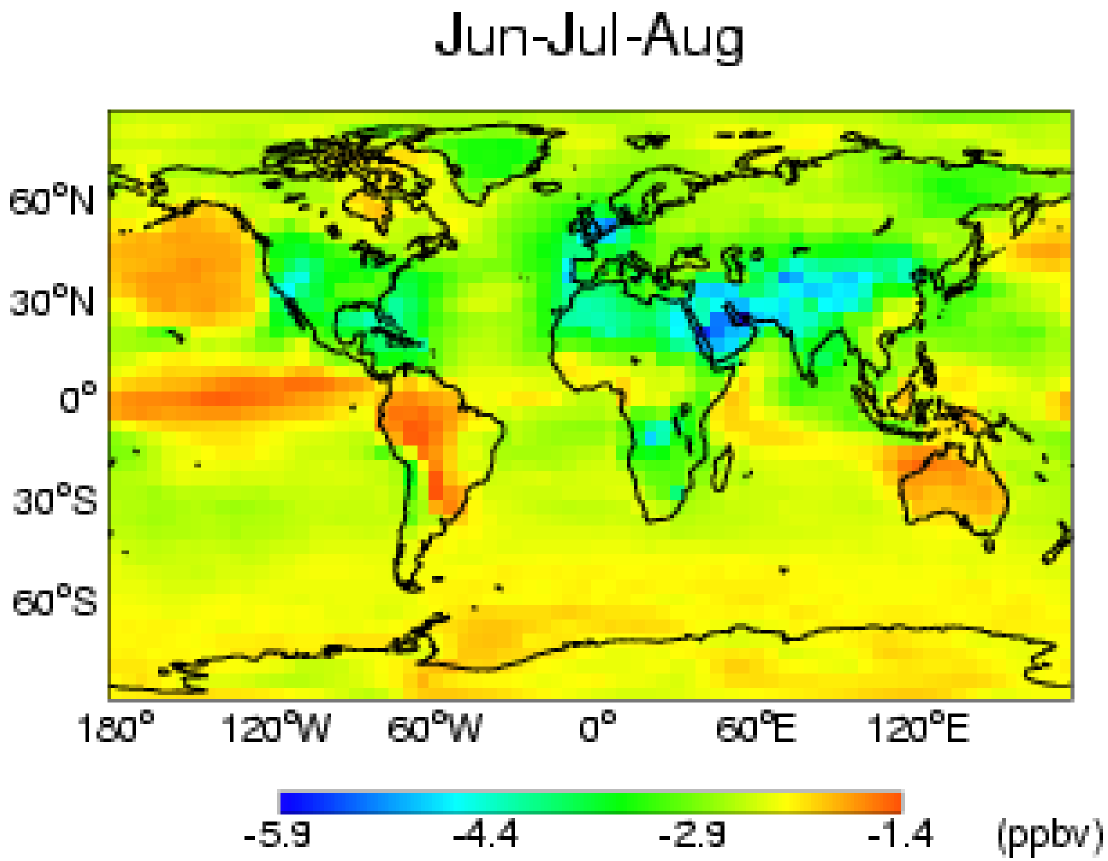

GEOS-Chem Model Simulations (4°x5°)

| IPCC scenario | Anthrop. $NO_x$ emissions (2030 vs. present) Global | U.S. | Methane emissions (2030 vs. present) |
|---|---|---|---|
| A1 | +80% | -20% | +30% |
| B1 | -5% | -50% | +12% |

**$CH_4$ links air quality & climate via background $O_3$**

*Fiore et al., GRL, 2002*

## Response of Global Surface Ozone to 50% decrease in global methane emissions (actually changing uniform concentration from 1700 to 1000 ppbv)

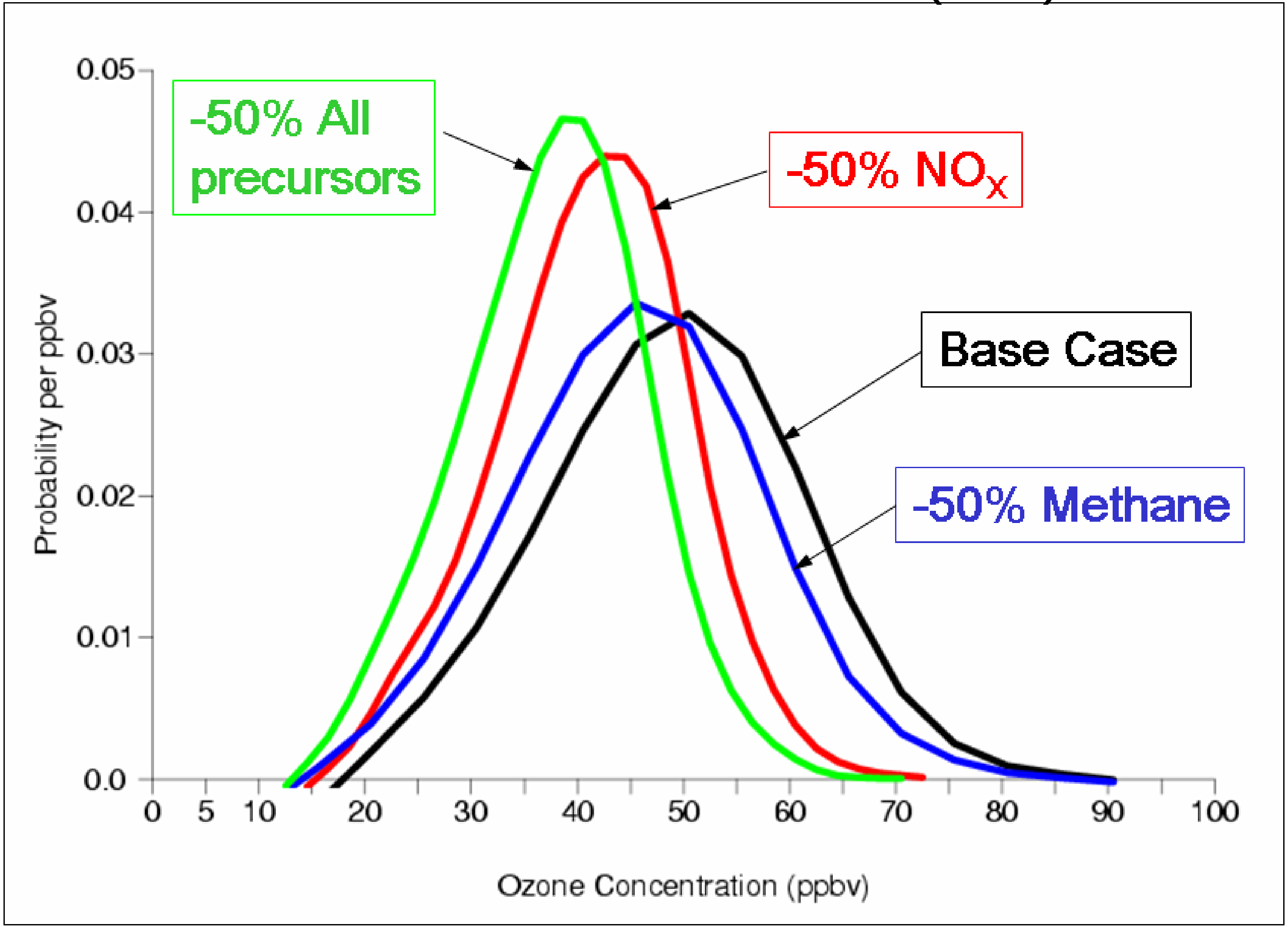



- Ozone decreases by 1-6 ppb
- ~3 ppb over land in US summer

** ~60% of reduction in 10 yr; ~80% in 20 yr.

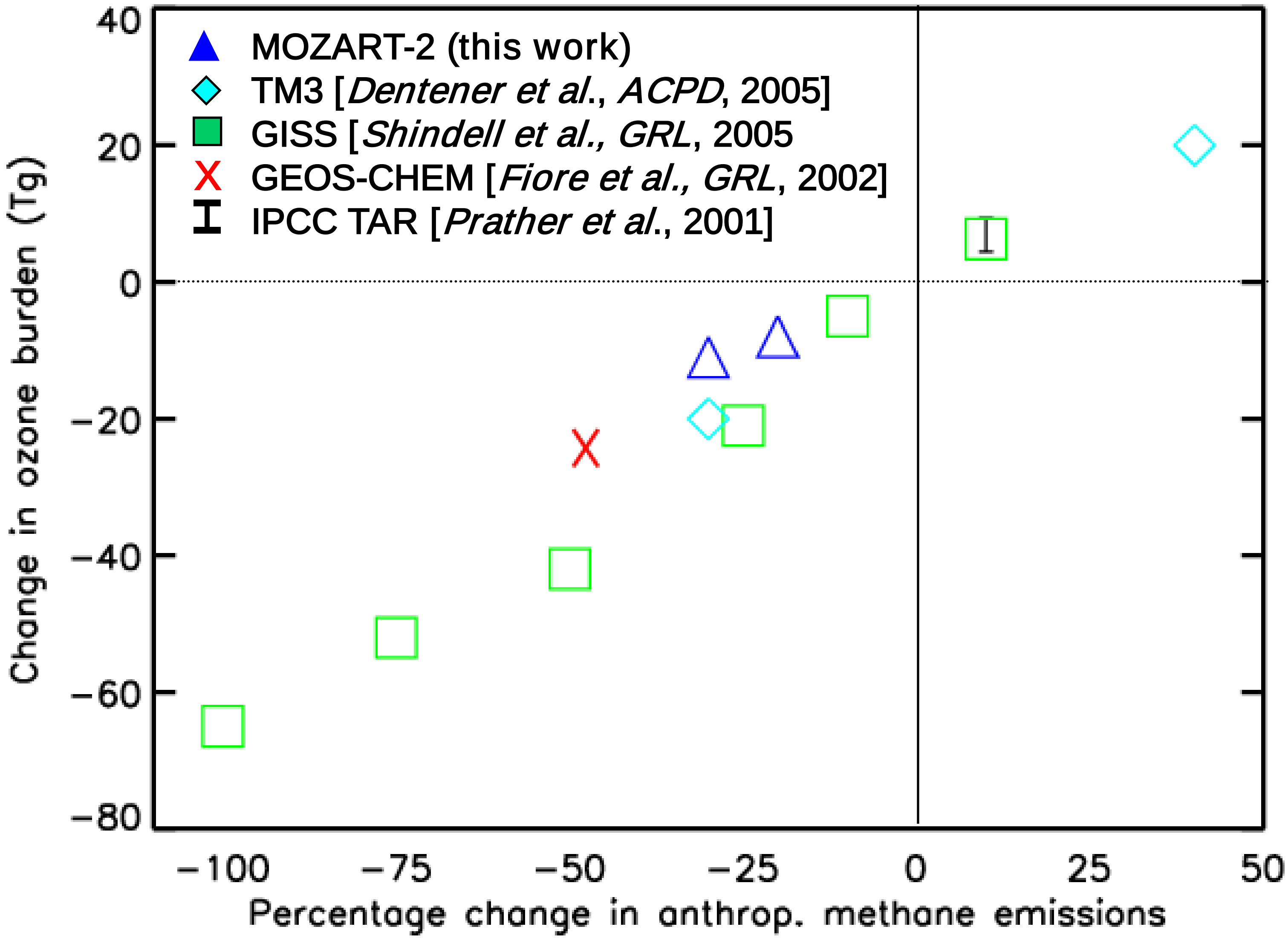
# Impacts of $O_3$ Precursor Reductions on U.S. Summer Afternoon Surface $O_3$ Frequency Distributions

GEOS-Chem Model Simulations (4°x5°)

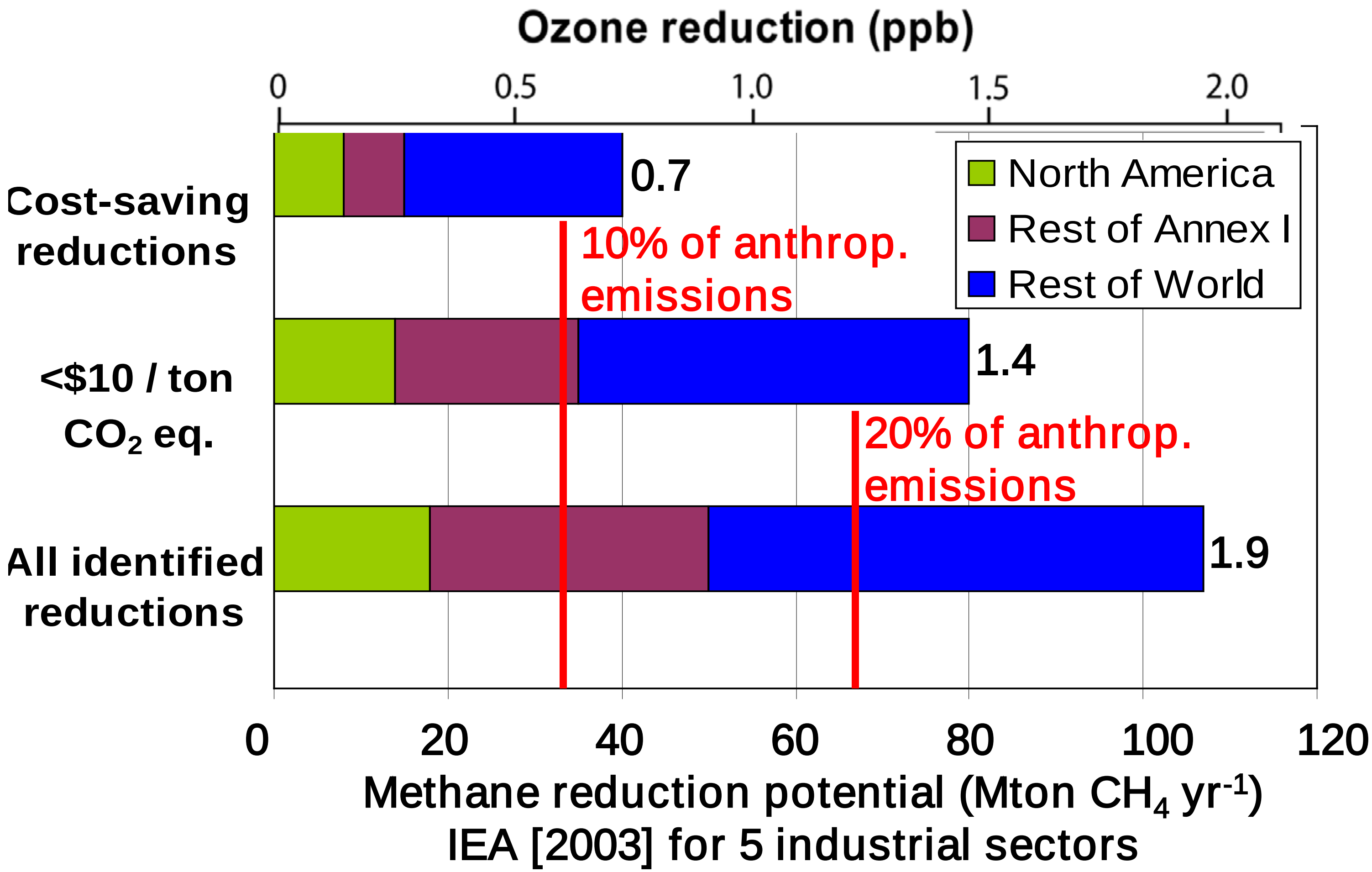



*West & Fiore, ES&T, 2005*

# Tropospheric ozone response to anthropogenic methane emission changes is fairly linear



# How Much Methane Can Be Reduced?




Comparison: Clean Air Interstate Rule (proposed $NO_x$ control) reduces 0.86 ppb over the eastern US, at \$0.88 billion $yr^{-1}$

*West & Fiore, ES&T, 2005*

# Ozone Abatement Strategies Evolve as our Understanding of the Ozone Problem Advances

$O_3$ smog recognized as an URBAN problem: Los Angeles, Haagen-Smit identifies chemical mechanism

Smog considered REGIONAL problem; role of biogenic VOCs discovered

A GLOBAL perspective: role of intercontinental transport, background

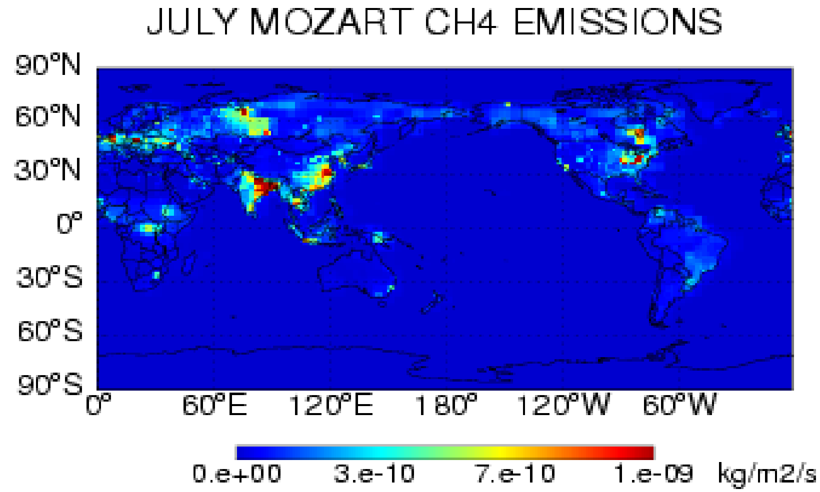
**1950s** → **1980s** → **Present**

Abatement Strategy:

NMVOCs + $NO_x$ + $CH_4$??

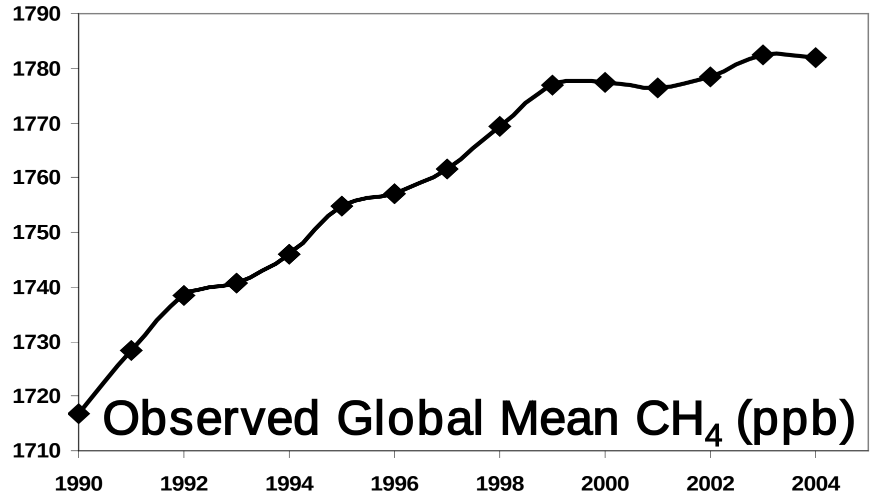
# Addressing the $CH_4$-$O_3$ air quality-climate linkage

Methane controls are receiving attention as a means to simultaneously address climate and global air pollution [*EMEP/CCC report 1/2005*]

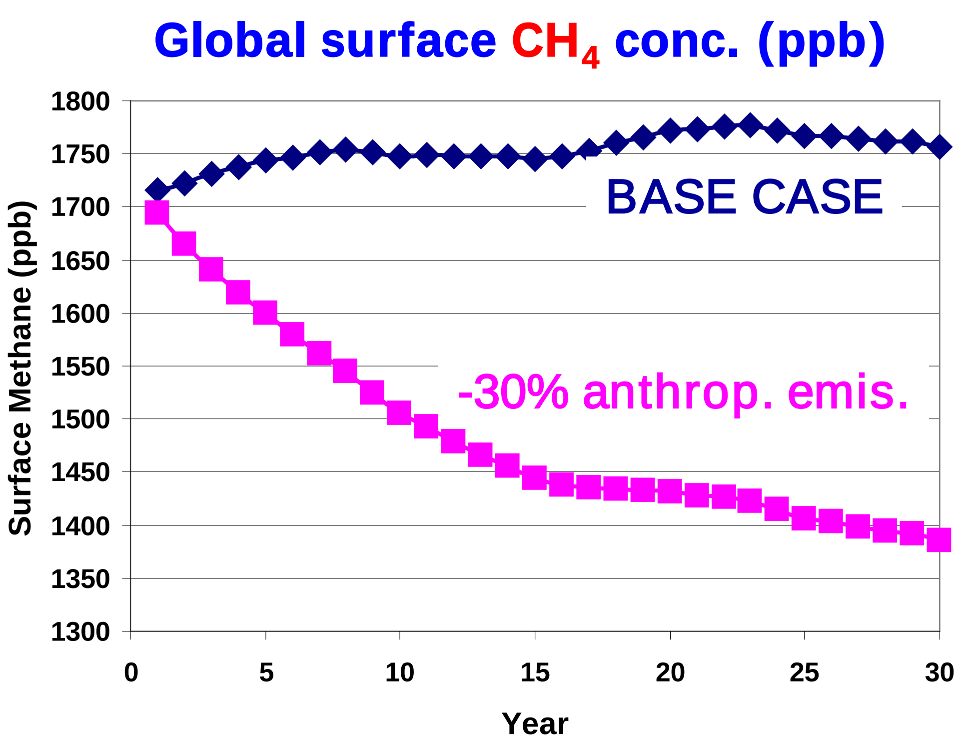


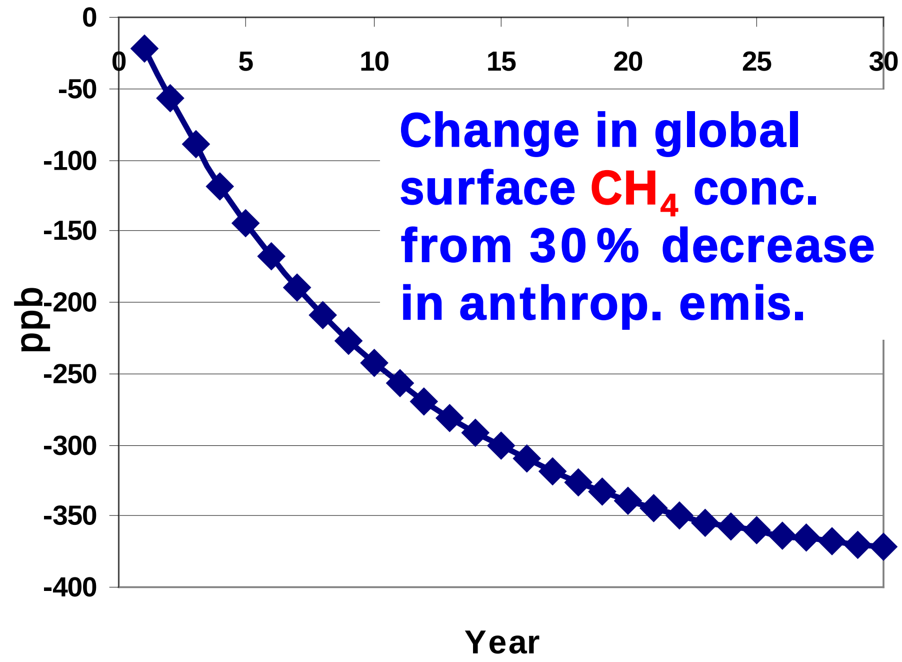

1. Does $CH_4$ source location influence the $O_3$ response?

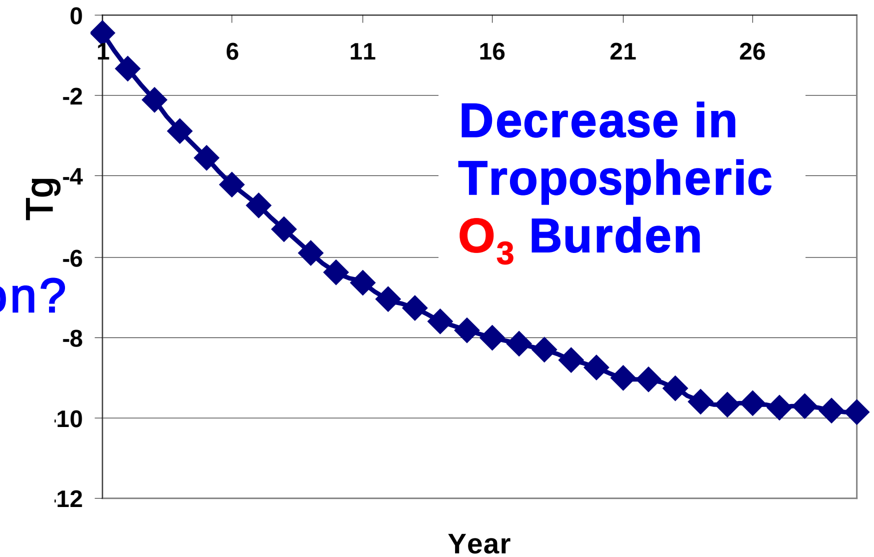
2. What is driving recent trends in atmospheric $CH_4$?
   → Sources?
   → Sinks?



# Methane Control Simulations in MOZART-2: 30% Decrease in Global Anthropogenic $CH_4$ Emissions




→ Approaching steady-state after 30 years

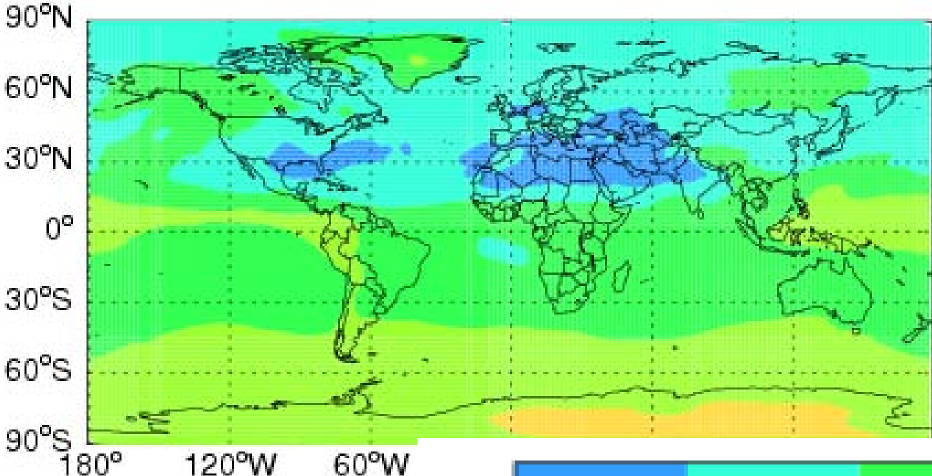
→ Does $O_3$ impact depend on source location?

(1) global -30% anthrop. emissions

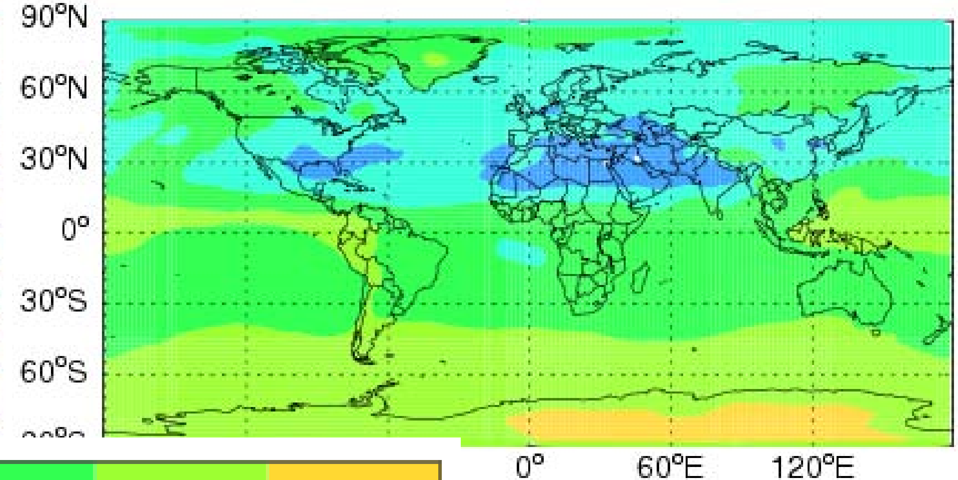
(2) zero Asian emissions (=30% global)

# CLIMATE IMPACTS: Change in July 2000 Trop. $O_3$ Columns (to 200 hPa)

**30% decrease in global anthrop. $CH_4$ emissions**

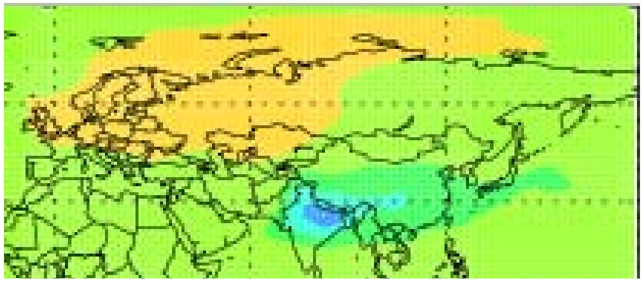


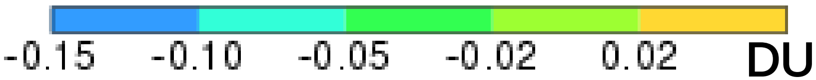

**Zero $CH_4$ emissions from Asia (= 30% decrease in global anthrop.)**





**No Asia – (30% global decrease)**





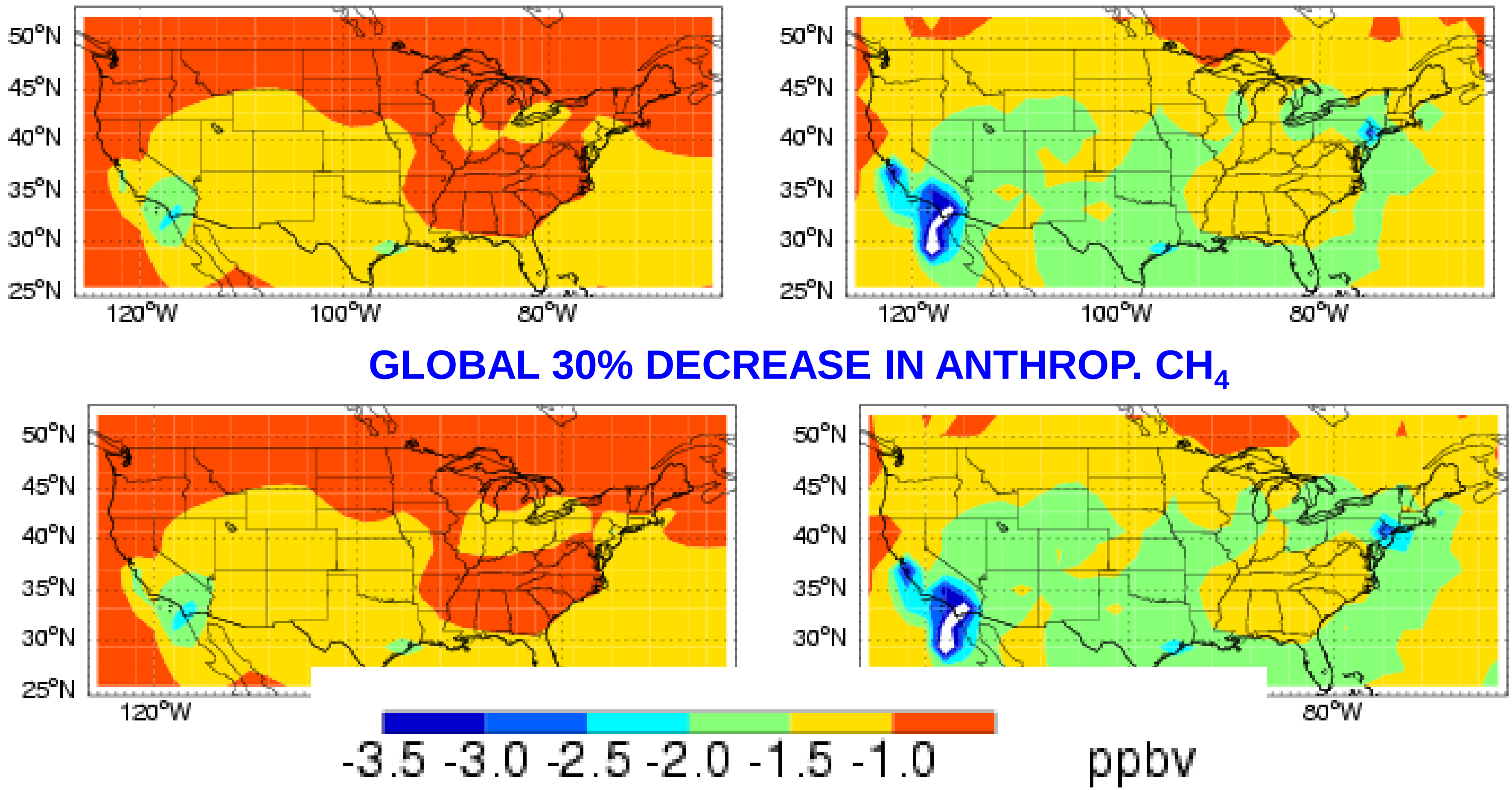

**Tropospheric $O_3$ column response is independent of $CH_4$ emission location except for small (~10%) local changes**

# U.S. Surface Afternoon Ozone Response in Summer also independent of methane emission location

**MEAN DIFFERENCE**

**MAX DIFFERENCE (Composite max daily afternoon mean JJA)**

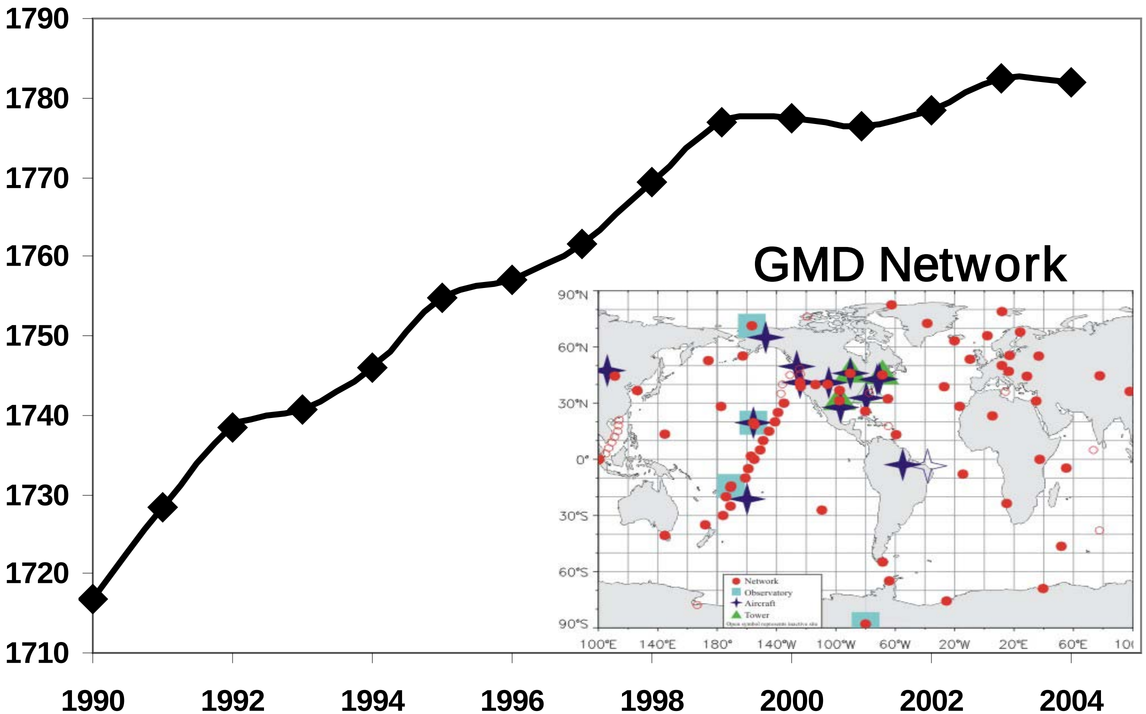
**NO ASIAN ANTHROP. $CH_4$**




**→Stronger sensitivity in $NO_x$-saturated regions (Los Angeles), partially due to local ozone production from methane**

# Observed trend in Surface $CH_4$ (ppb) 1990-2004

Global Mean $CH_4$ (ppb)




Data from 42 GMD stations with 8-yr minimum record is area-weighted, after averaging in bands 60-90N, 30-60N, 0-30N, 0-30S, 30-90S

Hypotheses for leveling off discussed in the literature:

1. Approach to steady-state

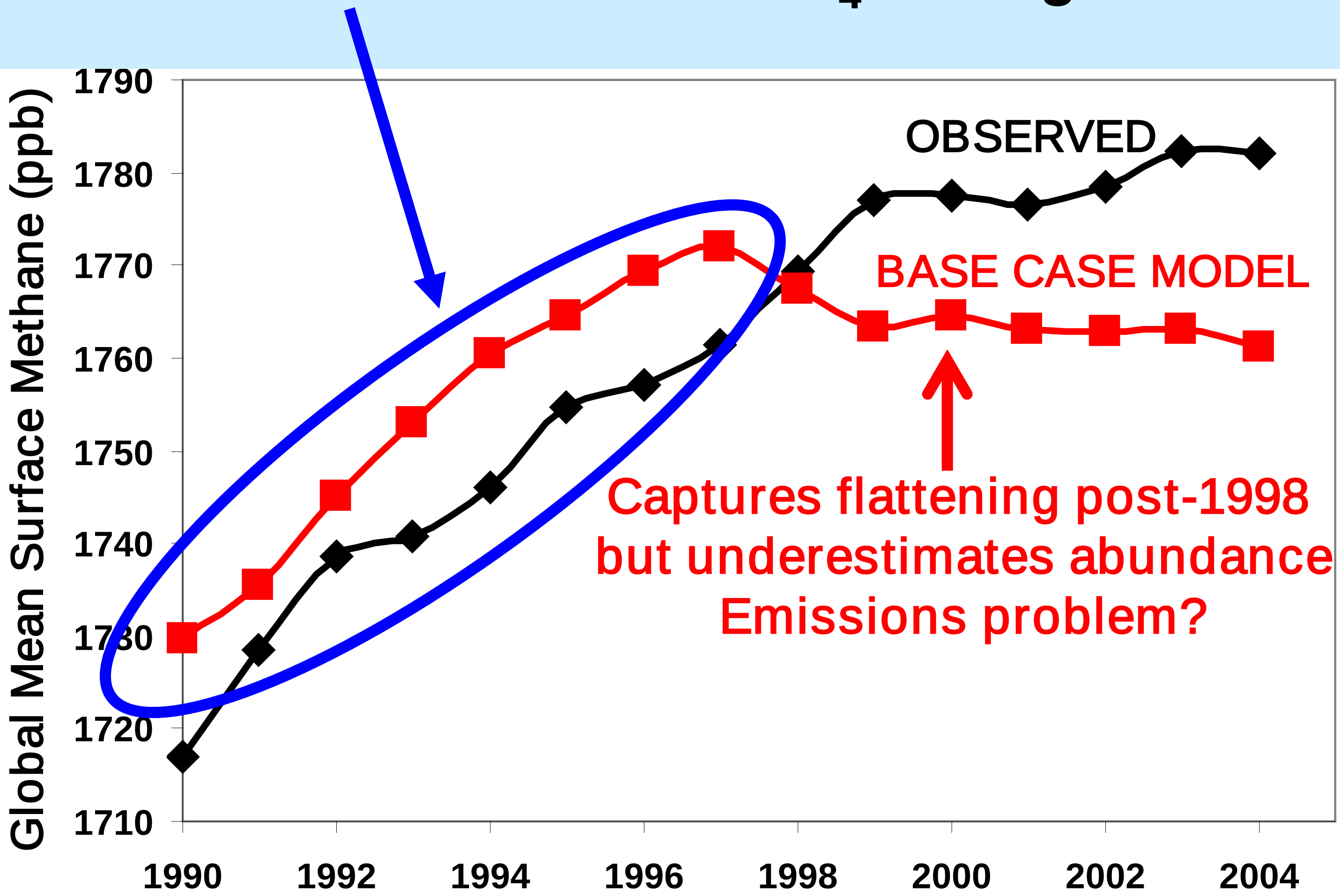
2. Source Changes
   - Anthropogenic
   - Wetlands
   - Biomass burning

3. Transport

4. Sink (OH)
   - Humidity
   - Temperature
   - OH precursor emissions
   - overhead $O_3$ columns

How does BASE CASE Model compare with GMD observations?

# Model with constant emissions largely captures observed trend in $CH_4$ during the 1990s




**Possible explanations for observed behavior:**

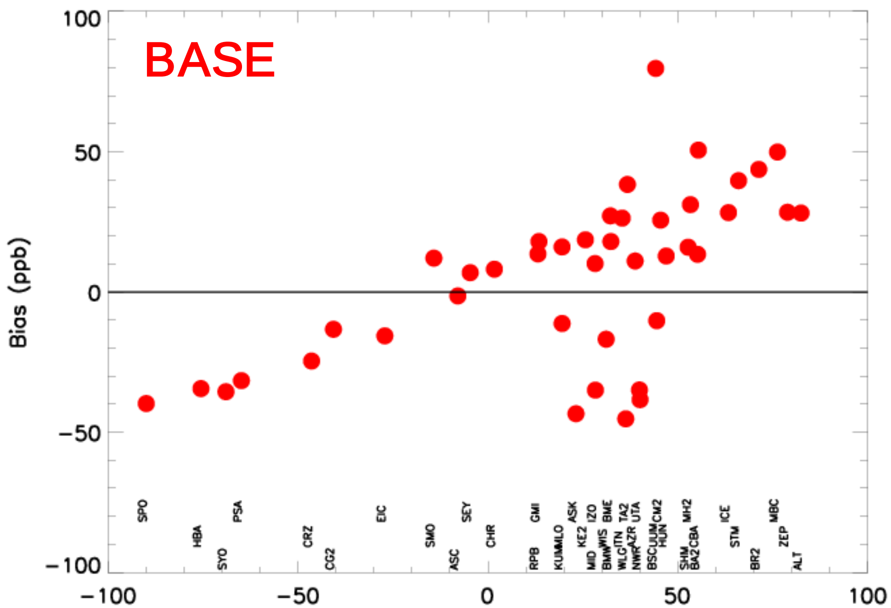
**(1) Source changes**

**(2) Meteorologically-driven changes in $CH_4$ lifetime**

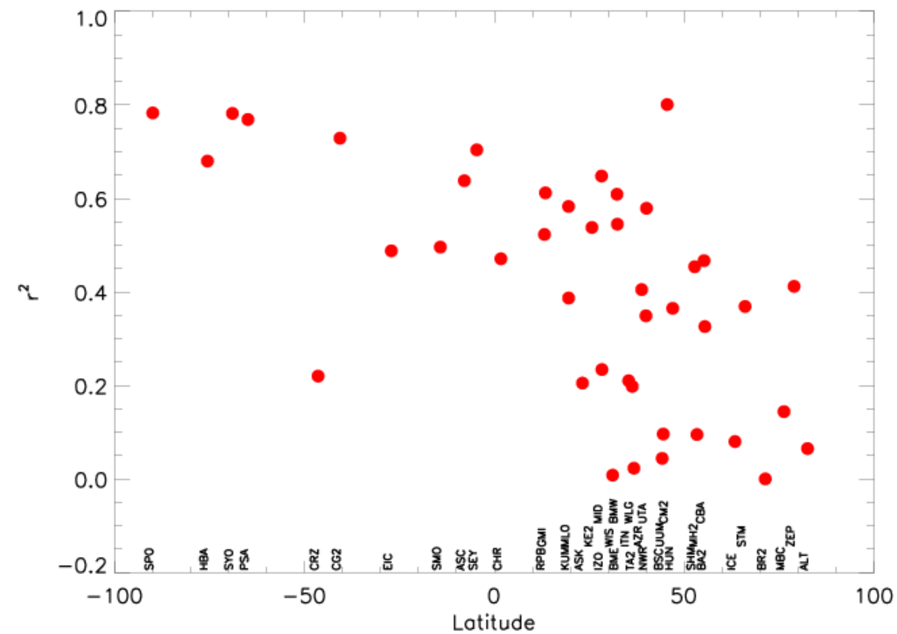
**(3) Approach to steady-state with constant lifetime**

# Bias and Correlation vs. GMD Surface $CH_4$: 1990-2004

Mean Bias (ppb)

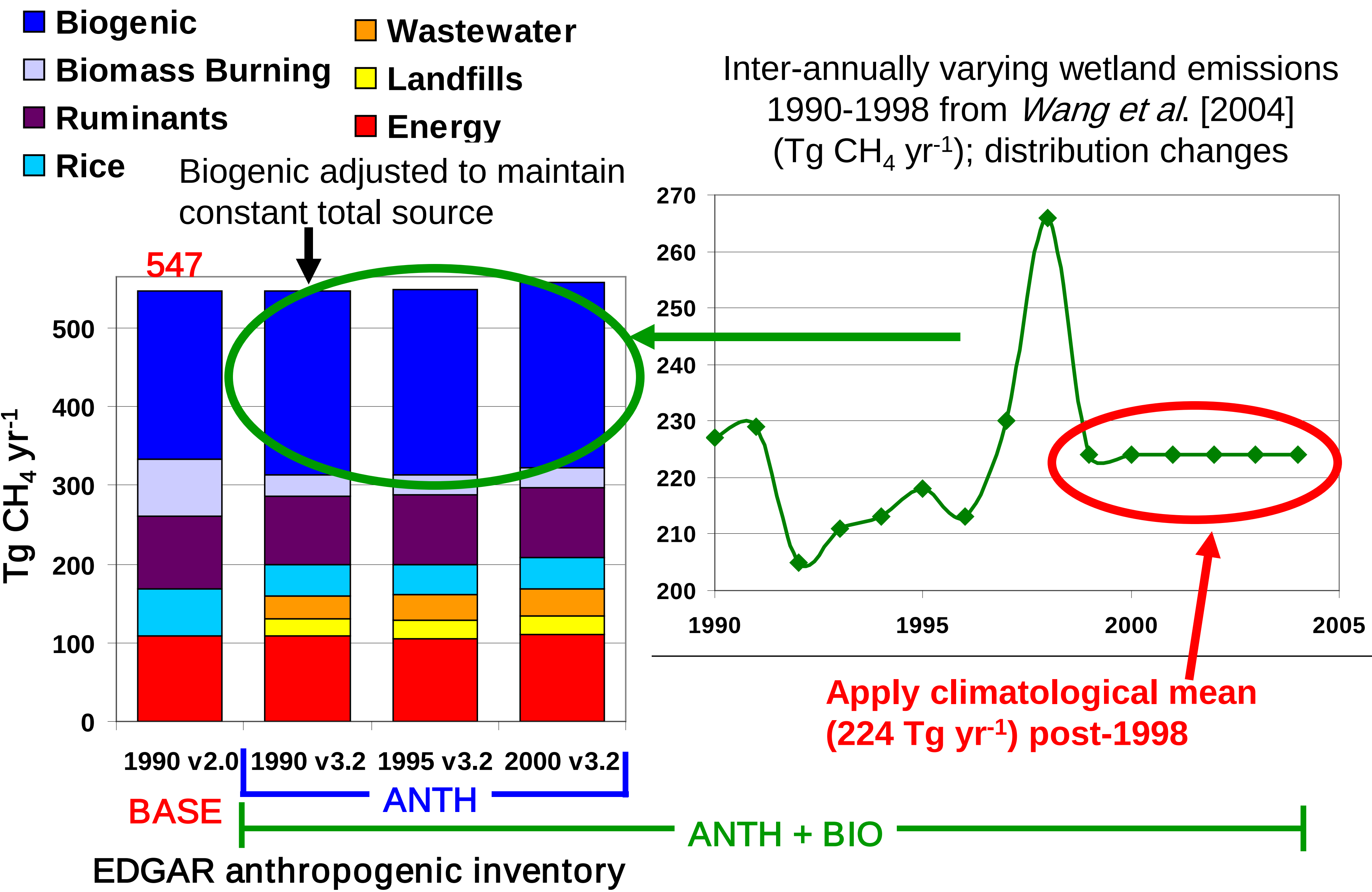



$r^2$

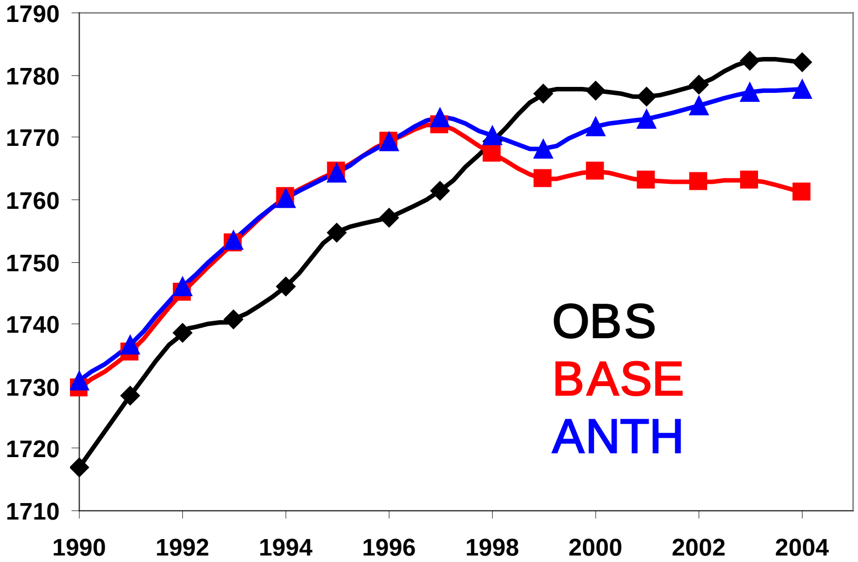


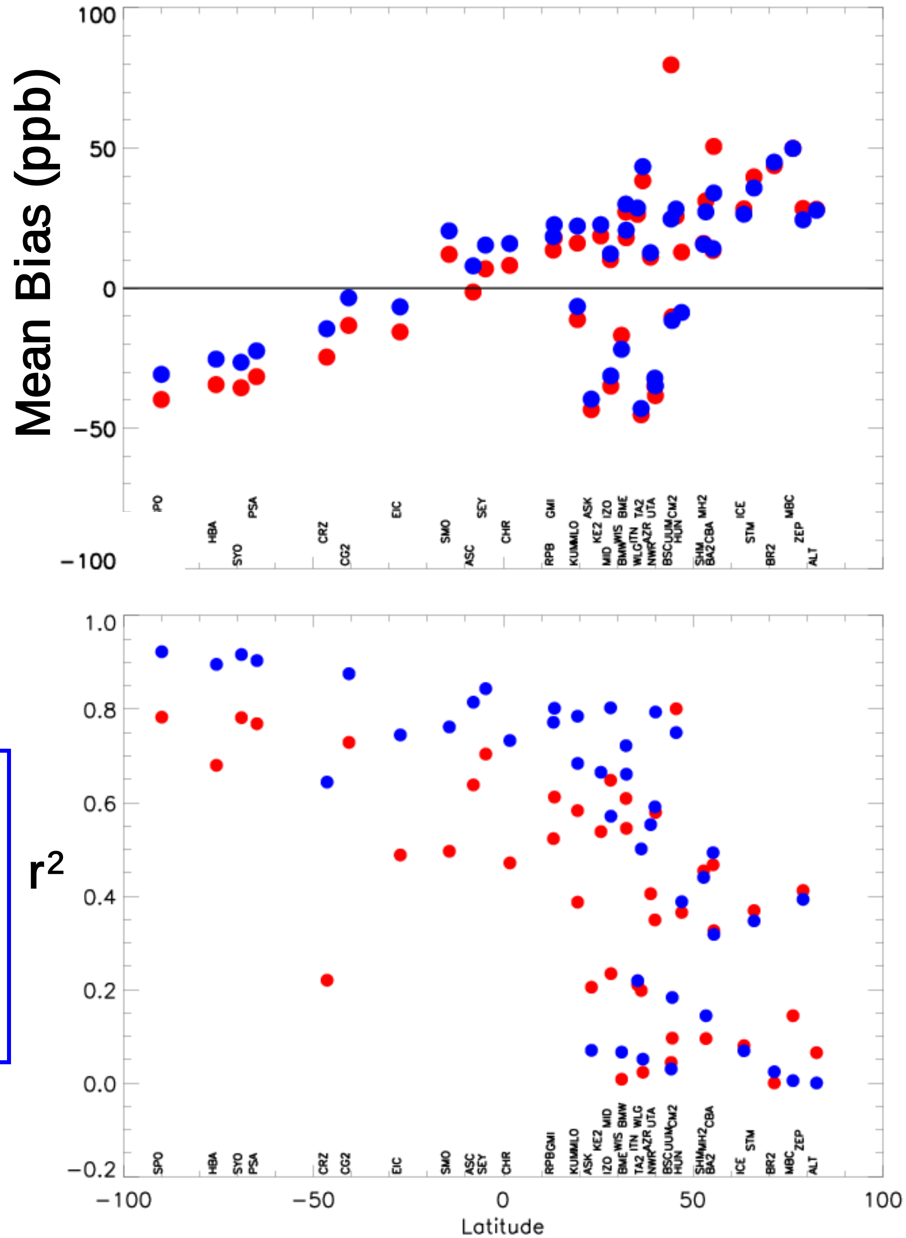

**BASE simulation with constant emissions:**
**→ Overestimates interhemispheric gradient**
**→ Correlates poorly at high northern latitudes**

# Estimates for Changing Methane Sources in the 1990s



# Bias & Correlation vs. GMD $CH_4$ observations: 1990-2004



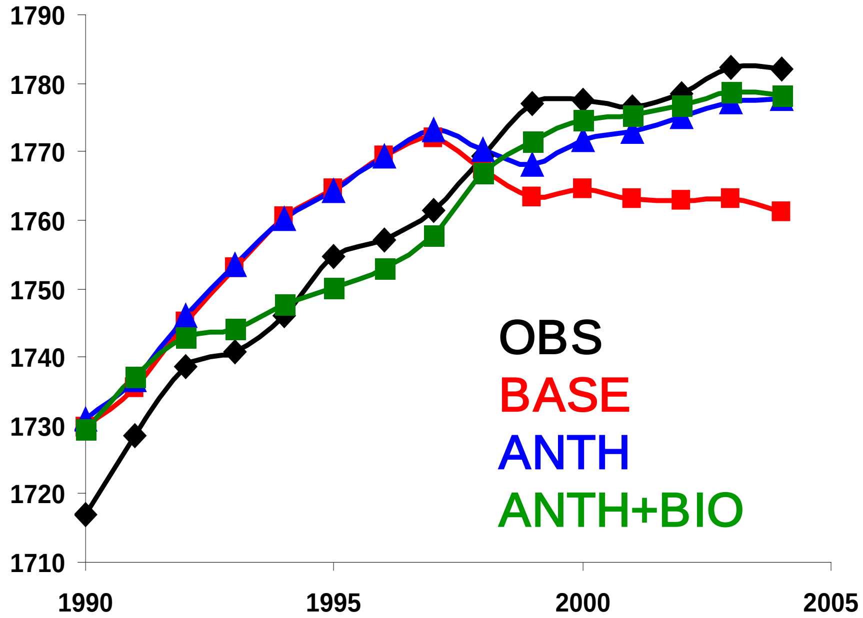

**ANTH simulation with time-varying EDGAR 3.2 emissions:**

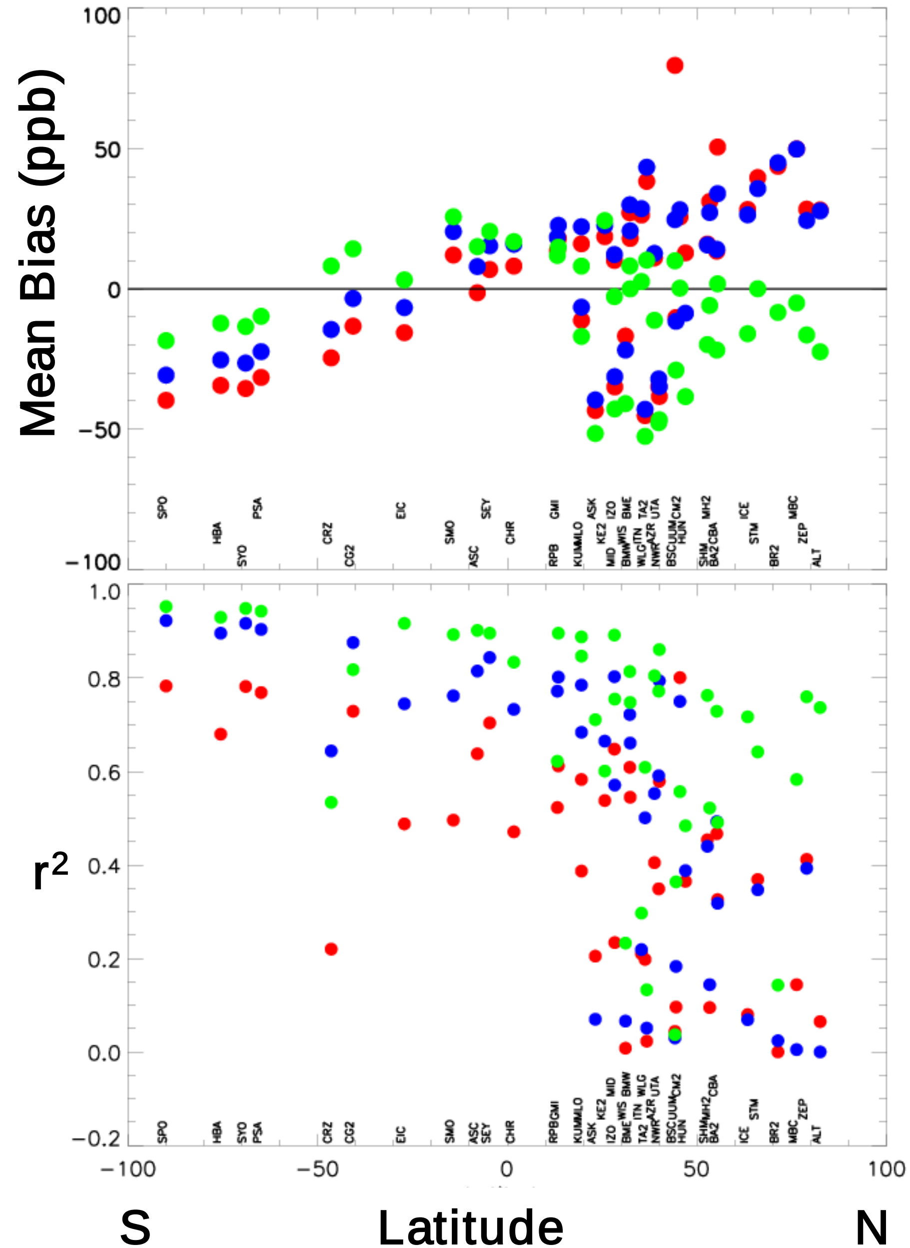
**→ Improves abundance post-1998**

**→ Interhemispheric gradient too high**

**→ Poor correlation at high N latitudes**

# Bias & Correlation vs. GMD $CH_4$ observations: 1990-2004



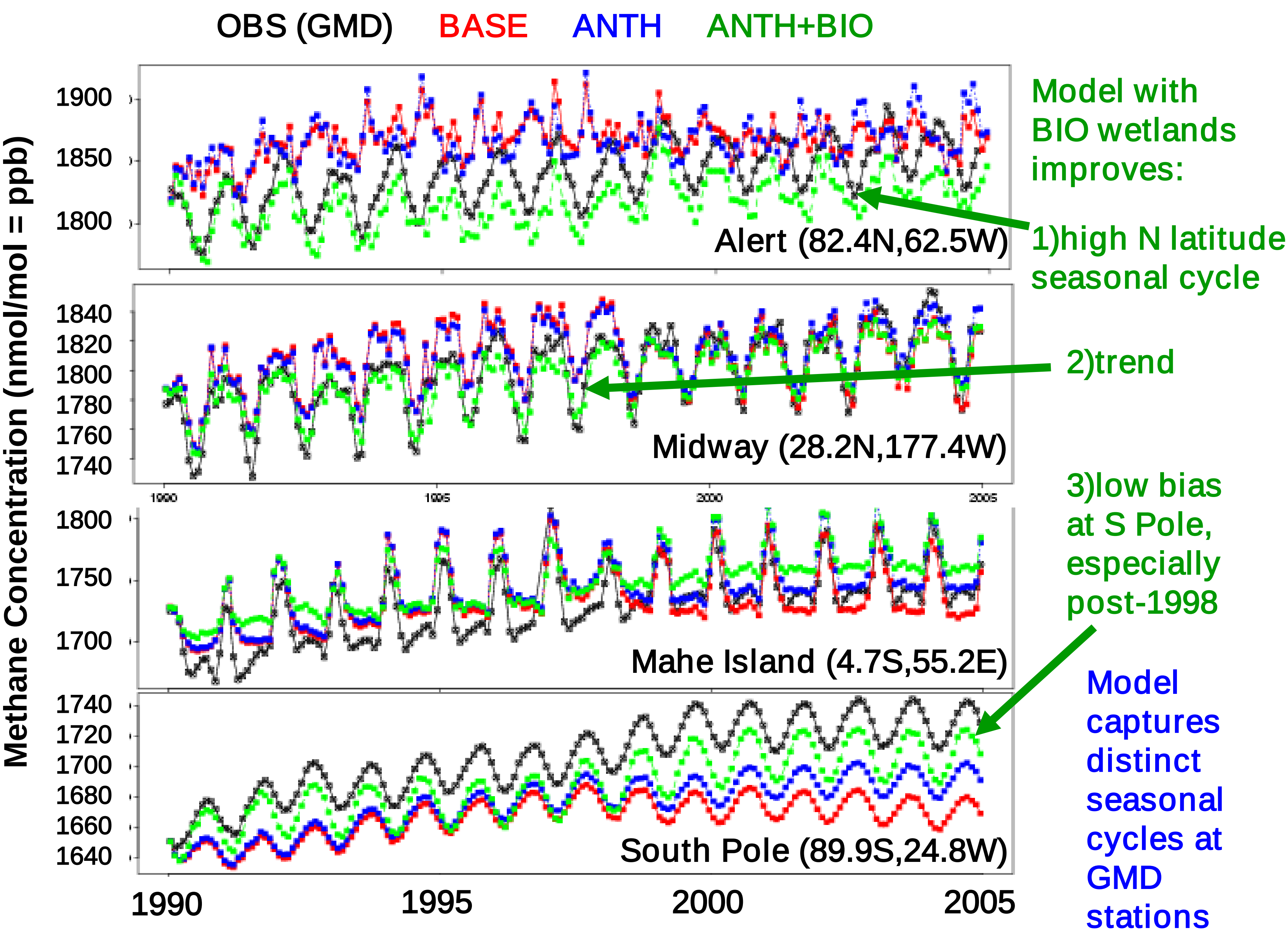




**ANTH+BIO simulation with time-varying EDGAR 3.2 + wetland emissions improves:**

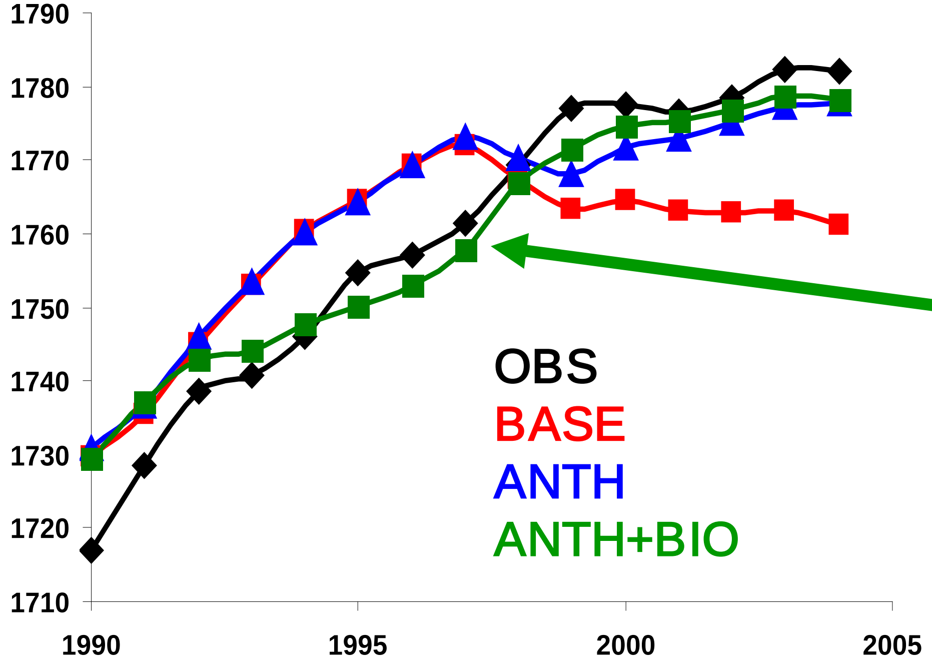
**→ Global mean surface conc.**

**→ Interhemispheric gradient**

**→ Correlation at high N latitudes**


OBS (GMD) BASE ANTH ANTH+BIO
Methane Concentration (nmol/mol = ppb)
1900
1850
1800
Alert (82.4N,62.5W)
1840
1820
1800
1780
1760
1740
Midway (28.2N,177.4W)
1800
1750
1700
Mahe Island (4.7S,55.2E)
1740
1720
1700
1680
1660
1640
South Pole (89.9S,24.8W)
1990
1995
2000
2005
Model with BIO wetlands improves:
1)high N latitude seasonal cycle
2)trend
3)low bias at S Pole, especially post-1998
Model captures distinct seasonal cycles at GMD stations

# Time-Varying Emissions:  Summary




Annual mean $CH_4$ in the "time-varying ANTH+BIO" simulation best captures observed distribution

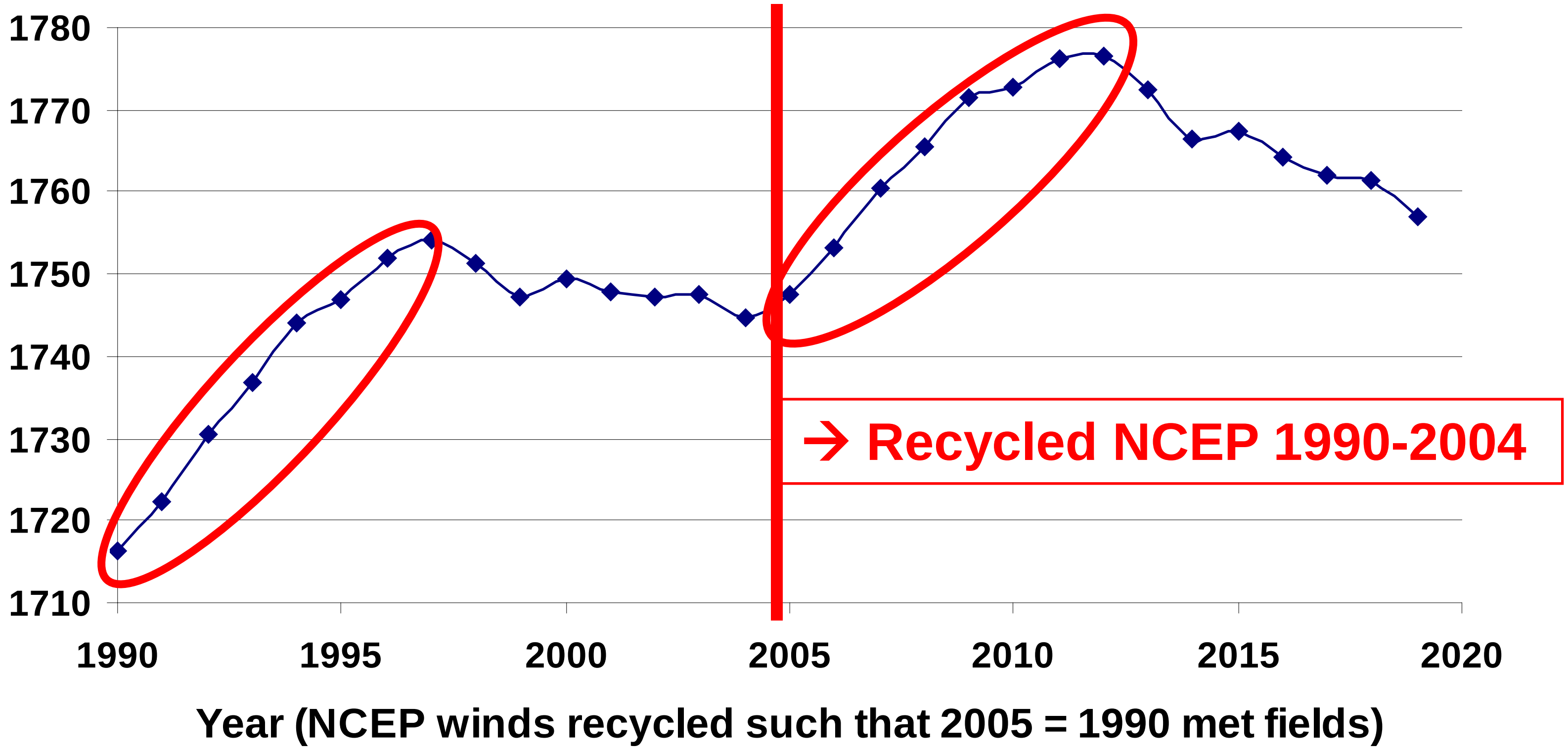
**Next: Focus on Sinks**

**-- Examine with BASE model (constant emissions)**

**-- Recycle NCEP winds from 2004 "steady-state"**

# Methane rises again when 1990-1997 winds are applied to "steady-state" 2004 concentrations

Area-weighted global mean $CH_4$ concentrations in BASE simulation (constant emissions)

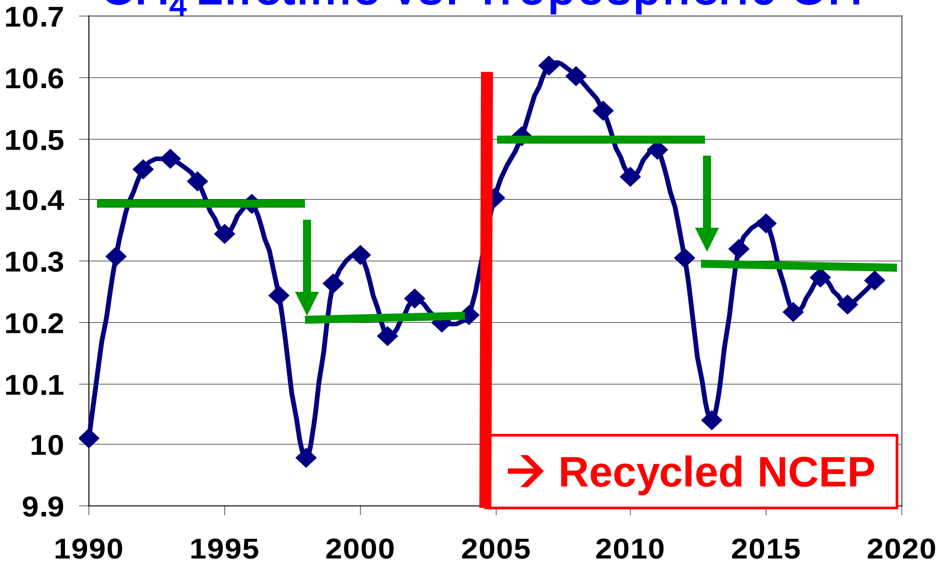



→ Meteorological drivers for observed trend

→ Not just simple approach to steady-state

# How does meteorology affect the $CH_4$ lifetime?

$CH_4$ Lifetime vs. Tropospheric OH




**Candidate Processes:**

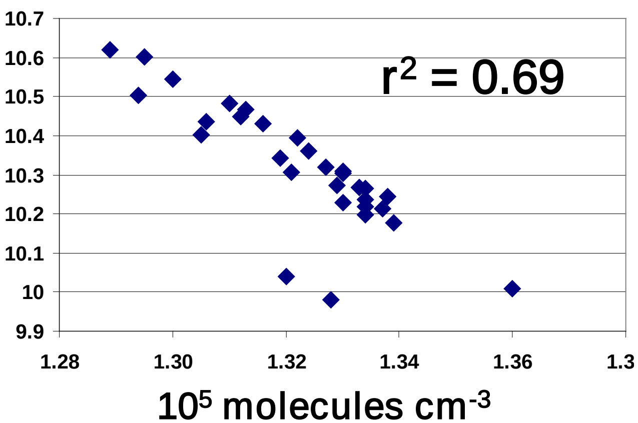
**Rapid transport to sink regions**

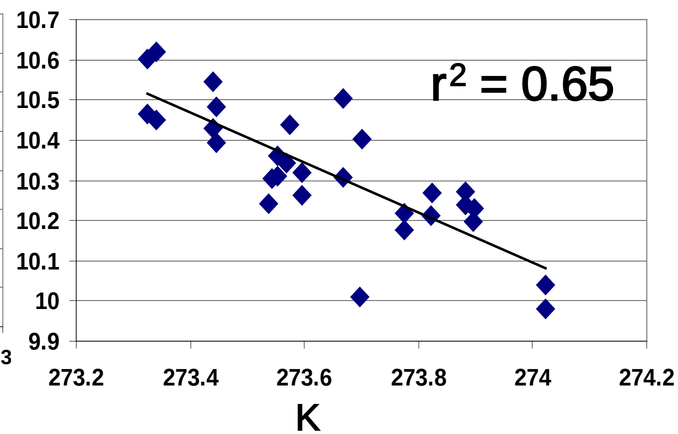
$$\tau = \frac{[CH_4]}{k[OH][CH_4]}$$

**Temperature**

**Humidity**
**Lightning $NO_x$**
**Photolysis**

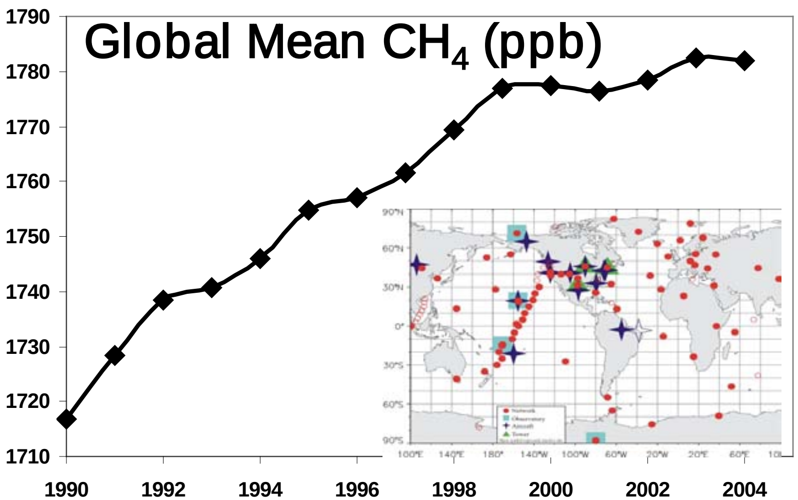
**Lifetime Correlates Strongly With Lower Tropospheric OH and Temperature**



# Methane Distribution and Trends: Climate and Air Quality Impacts

- **20% anthrop. $CH_4$ emissions can be reduced at low cost**
- **Ozone response largely independent of $CH_4$ source location**
- **30% decreases in anthrop. $CH_4$ reduces radiative forcing by 0.2 $Wm^{-2}$ and JJA U.S. surface $O_3$ by 1-4 ppbv**




Hypotheses for leveling off:

1. Approach to steady-state
   → not the whole story
2. Source Changes
   → improve simulated abundances but not driving trend
3. Transport
4. Sink (OH)

} Meteorology major driver; further work needed to isolate cause

⇒ **Potential for strong climate feedbacks**

Q: How will future global change influence atmospheric $CH_4$?

→Potential for complex biosphere-atmosphere interactions