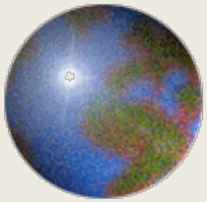


Tropospheric Emission Spectrometer: An Earth System Sounder

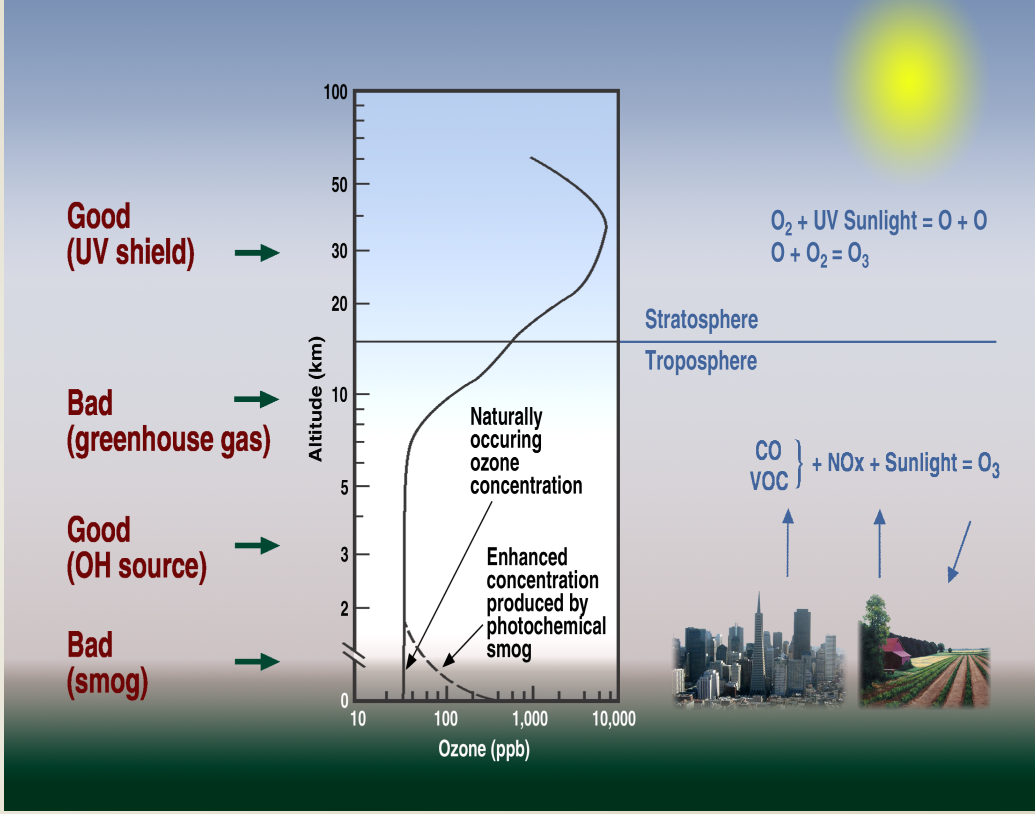
Kevin Bowman, John Worden

Jet Propulsion Laboratory-California Institute of Technology

Ozone: at the nexus of air quality and climate

Marion E. Lent makes her way to work as smog dims City Hall in this 1953 photo. (Los Angeles Times), courtesy P. Wennberg-Caltech

Characterization of the vertical distribution of ozone is critical to understanding its role in atmospheric chemistry and climate



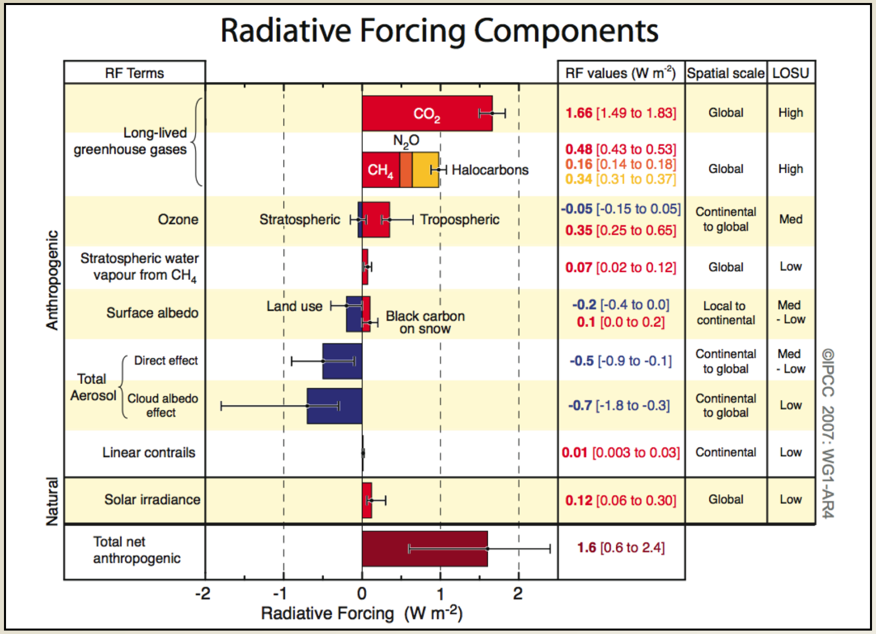
What is an air pollutant?

"Because greenhouse gases fit well within the Clean Air Act's capacious definition of "air pollutant," we hold that EPA has the statutory authority to regulate the emission of such gases from new motor vehicles."

MASSACHUSETTS *v. EPA*
Opinion of the Court, April 2nd, 2007
Justice Stevens

- Air pollutants now include Greenhouse Gases (GHG)
- Air quality constituents, e.g., ozone and black carbon, are also GHGs

Radiative forcing from atmospheric composition



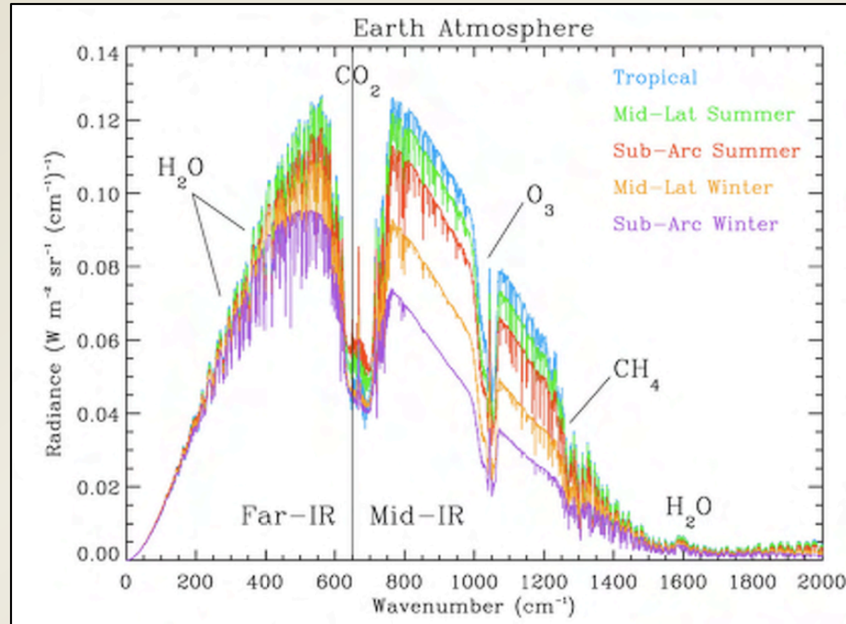
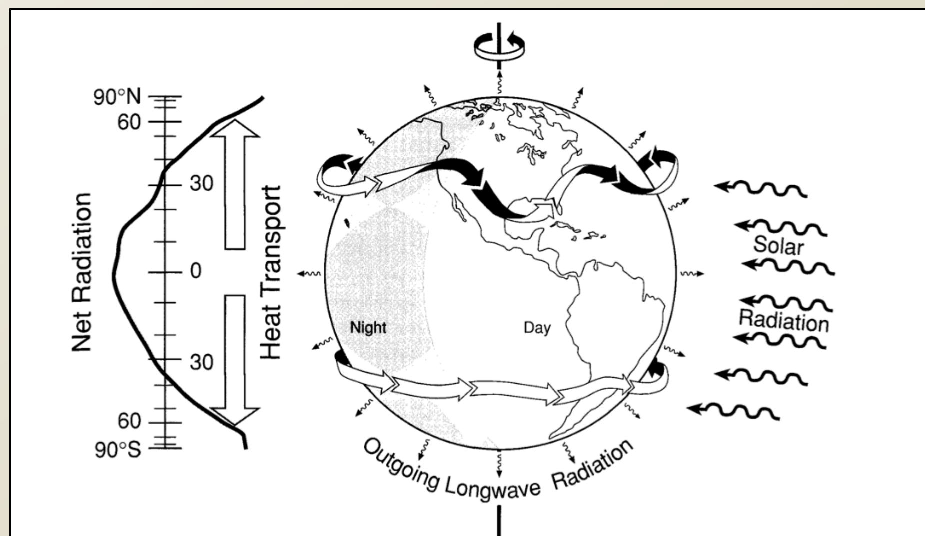


Fig. courtesy M. Mlynzcack (LaRC)

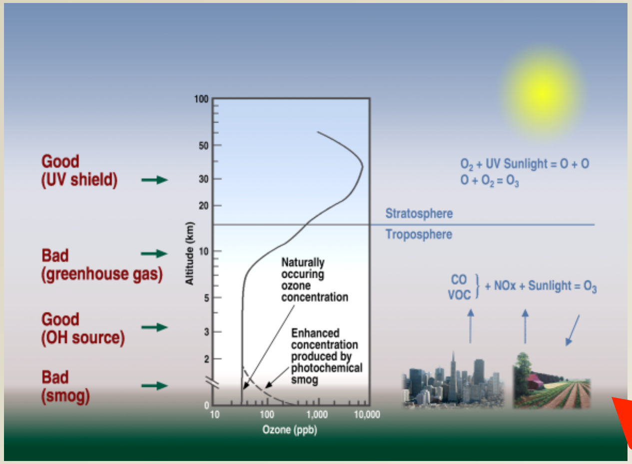


The 3 most important greenhouse gases since the preindustrial are carbon dioxide, methane, and ozone

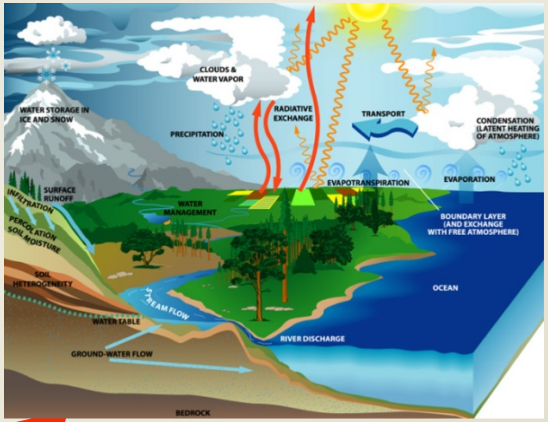
Anthropogenic perturbation to atmospheric composition have led to a radiative imbalance at the top of the atmosphere

Earth System sensitivity and response

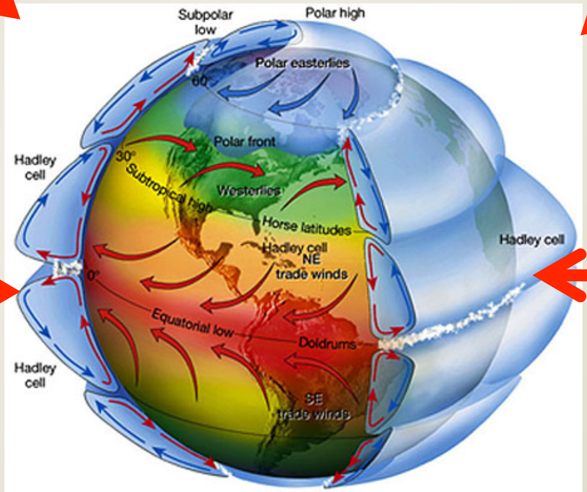
Chemistry



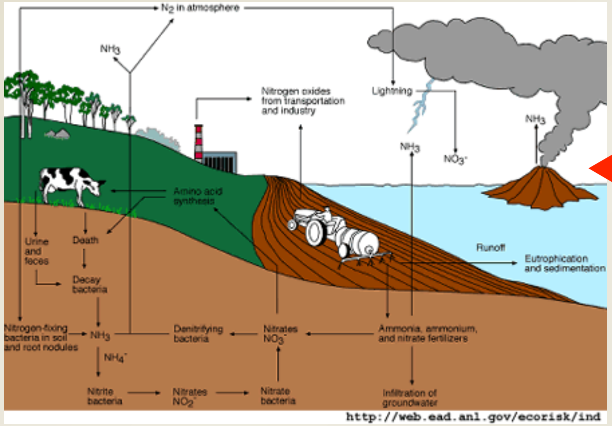
Net anthropogenic forcing, climate sensitivity, and response are driven by the Earth system and the coupling between its components



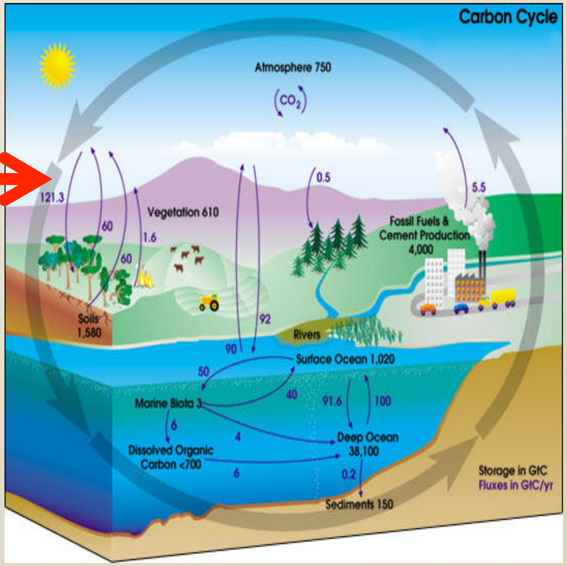
Atmosphere



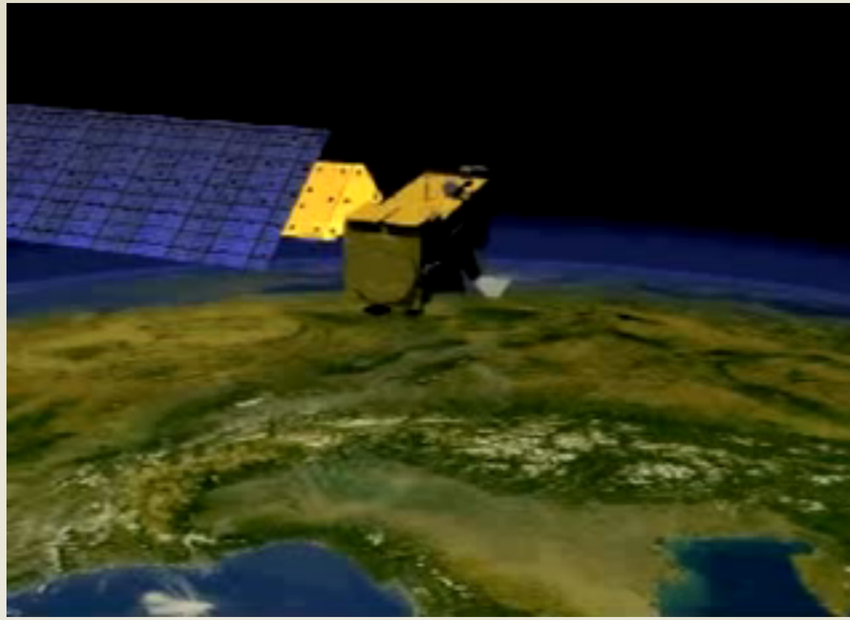
Nitrogen Cycle



Carbon Cycle

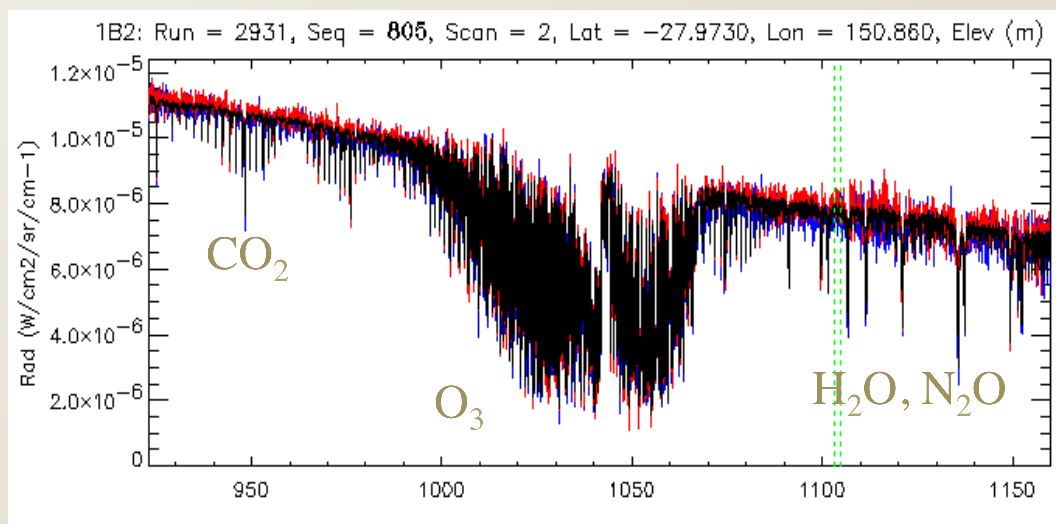


Tropospheric Emission Spectrometer



TES, launched aboard the Aura spacecraft in 2004, is a Fourier Transform Spectrometer measures infrared spectral radiances from 3.2 to 15.4 microns.

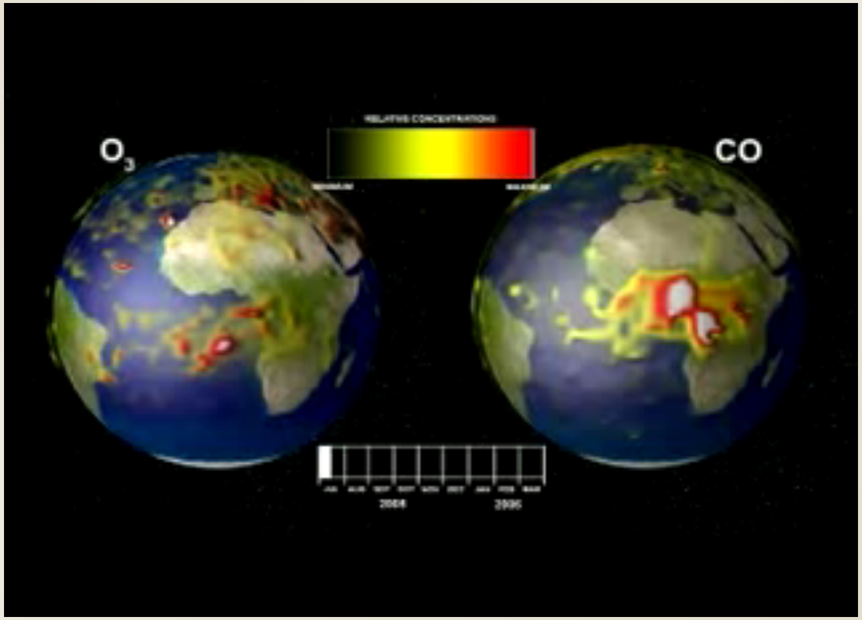
Spectral Resolution (unapodized)	0.06 cm^{-1} (nadir) 0.015 cm^{-1} (hi-res)
Spectral Coverage	650 to 3050 cm^{-1} (3.2 to 15.4 microns)
Global survey coverage	72 observations/orbit 16 orbits/day
Spatial Resolution	0.5 x 5 km (nadir) 2.3 x 23 km (limb)
Nadir NEDT @290K (Noise Equivalent Delta Temperature)	2B1: 1.08 K 1B2: 0.36 K 2A1: 0.36 K 1A1: 2.07 K



What can TES observe?

TES observations
Are sensitive to

- Ozone
- Carbon monoxide
- Temperature
- Water vapor
- HDO
- Emissivity
- Effective cloud parameters
    - Cloud optical depth
    - Cloud height
- Nitric acid
- Sulfur dioxide
- …and more

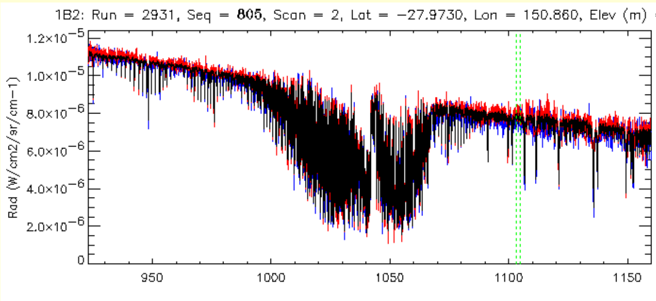


Fundamentally, TES observes *any* atmospheric or surface quantity that emits thermal radiation to space

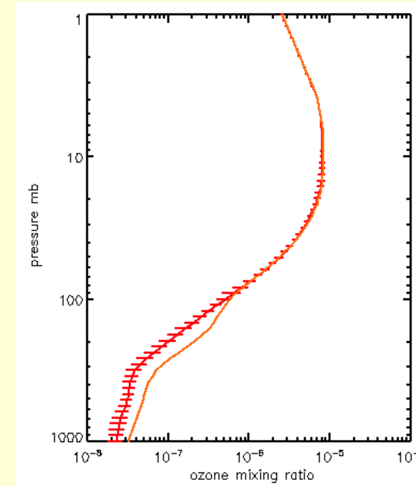
However, information about these quantities is a function of their spectral sensitivities and natural variability

TES observation operator:

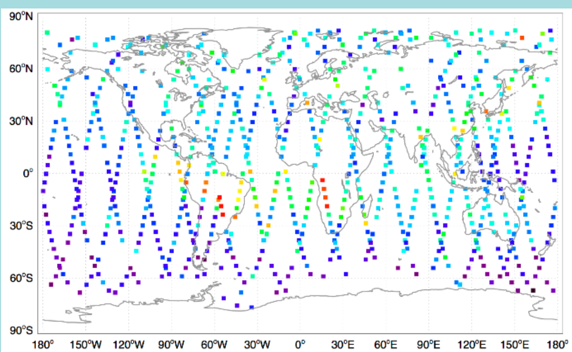
connecting measurements to assimilation



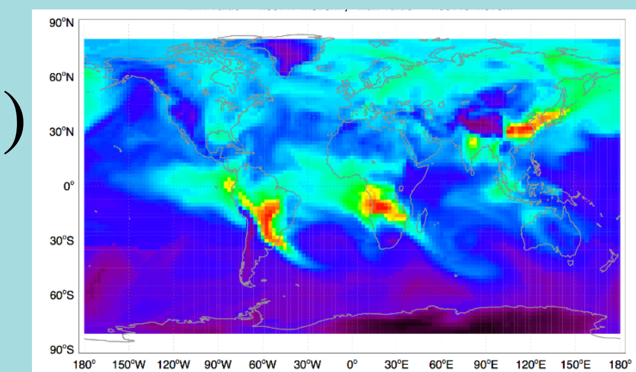
$$\|\mathbf{y}-\mathbf{F}(\mathbf{x}_a)\|^2_{\mathbf{S}_n^{-1}} + \|\mathbf{x}-\mathbf{x}_a\|^2_{\mathbf{S}_a^{-1}}$$



$$\hat{\mathbf{x}} = \mathbf{x}_a + \mathbf{A}(\mathbf{x}-\mathbf{x}_a) + \mathbf{G}\mathbf{n}$$

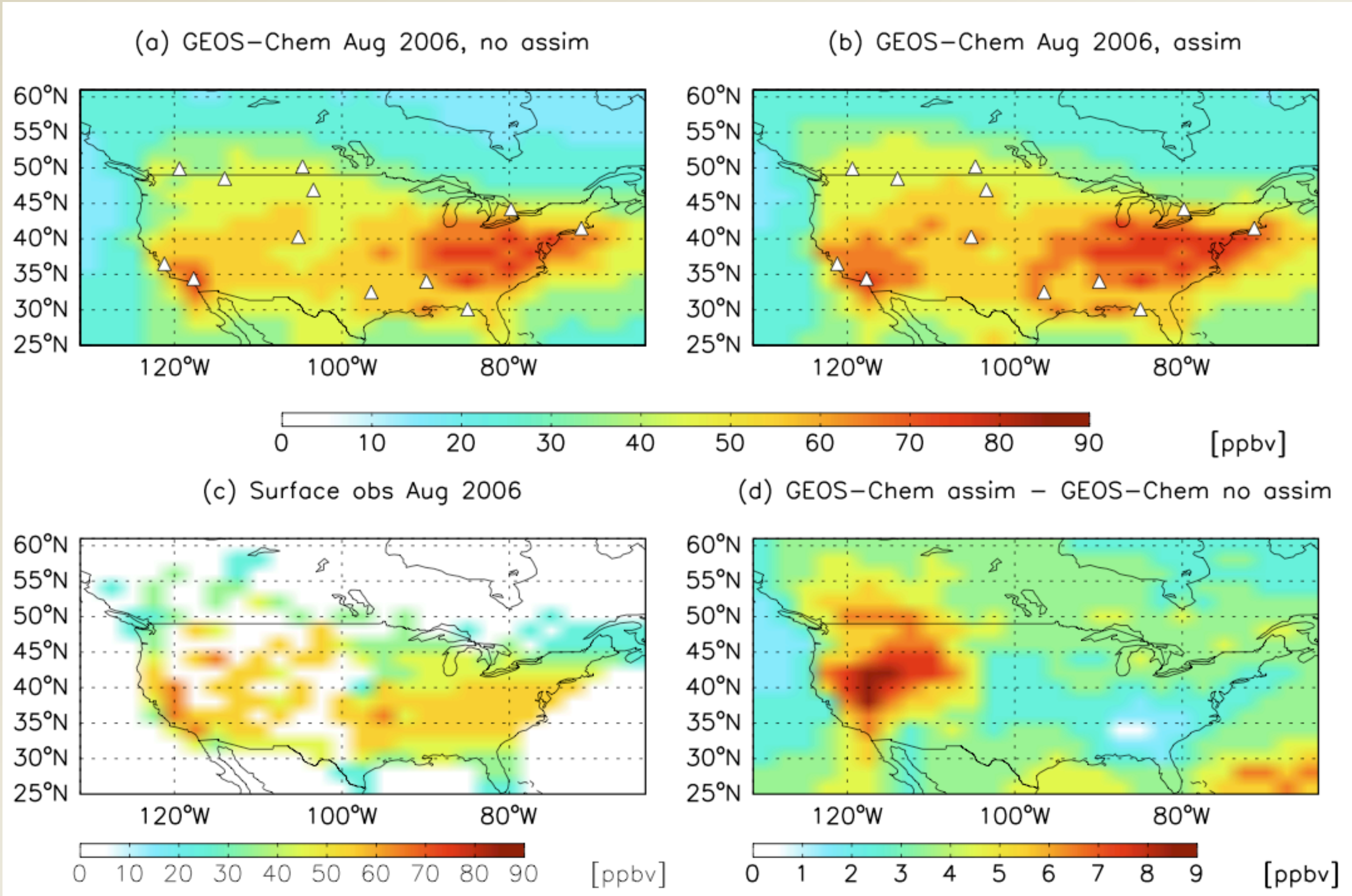


$$\mathbf{H}_i(\bullet) = \mathbf{x}_a + \mathbf{A}_i(\bullet - \mathbf{x}_a)$$



$$\sum_i \|\hat{\mathbf{x}}_i - \mathbf{H}_i(\mathbf{x})\|^2_{(\mathbf{G}_i\mathbf{S}_n^i\mathbf{G}_i^T)^{-1}} + \|\mathbf{x}_0 - \mathbf{x}_B\|^2_{\mathbf{B}^{-1}}$$

Impact of distance sources on local ozone



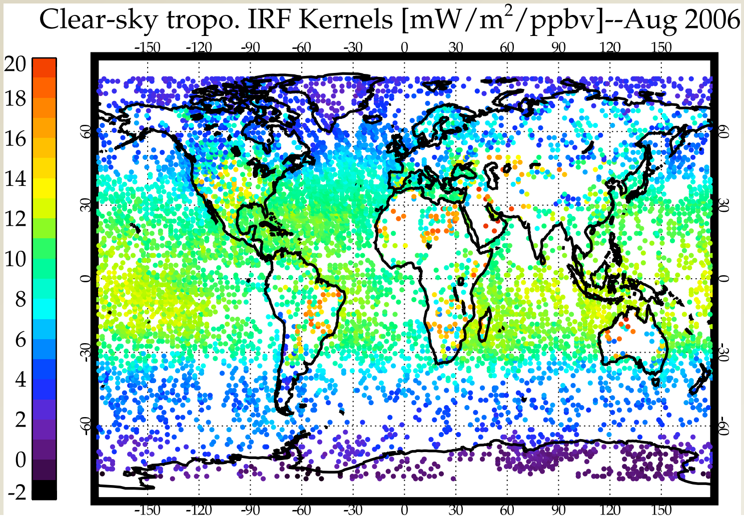
Parrington *et al*, 2009, GRL

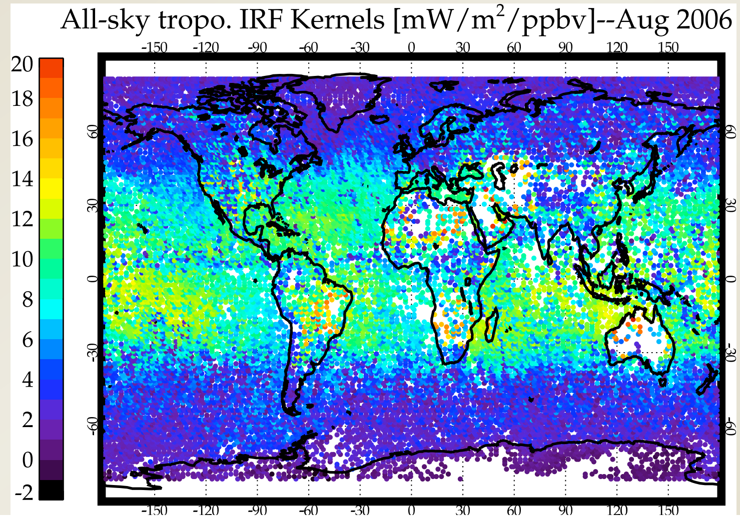
Assimilating TES ozone into the GEOS-Chem model increased surface ozone concentrations by up to 9ppb and free tropospheric concentrations by up to 40%.

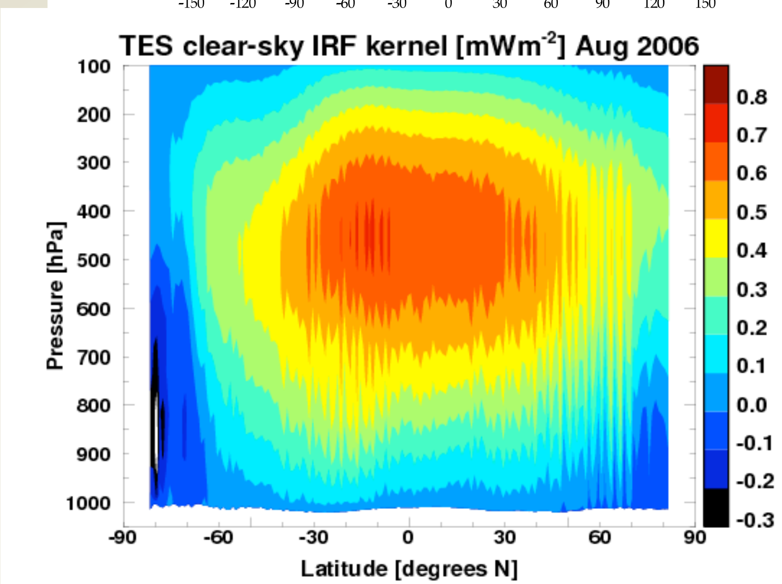
Assimilated GEOS-Chem fields showed improved agreement with both ozone sonde measurements and western surface ozone sites

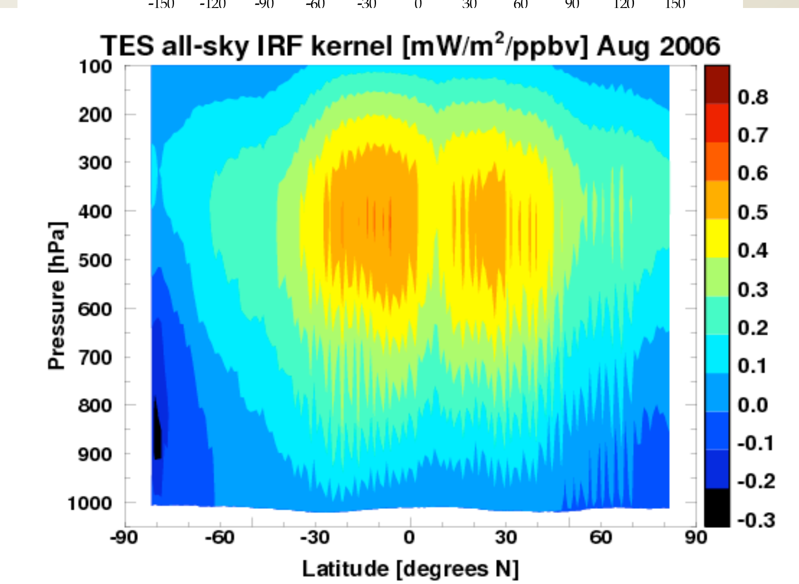
TES instantaneous longwave radiative kernels

Clear sky	Total sky









Worden *et al*, in review, JGR

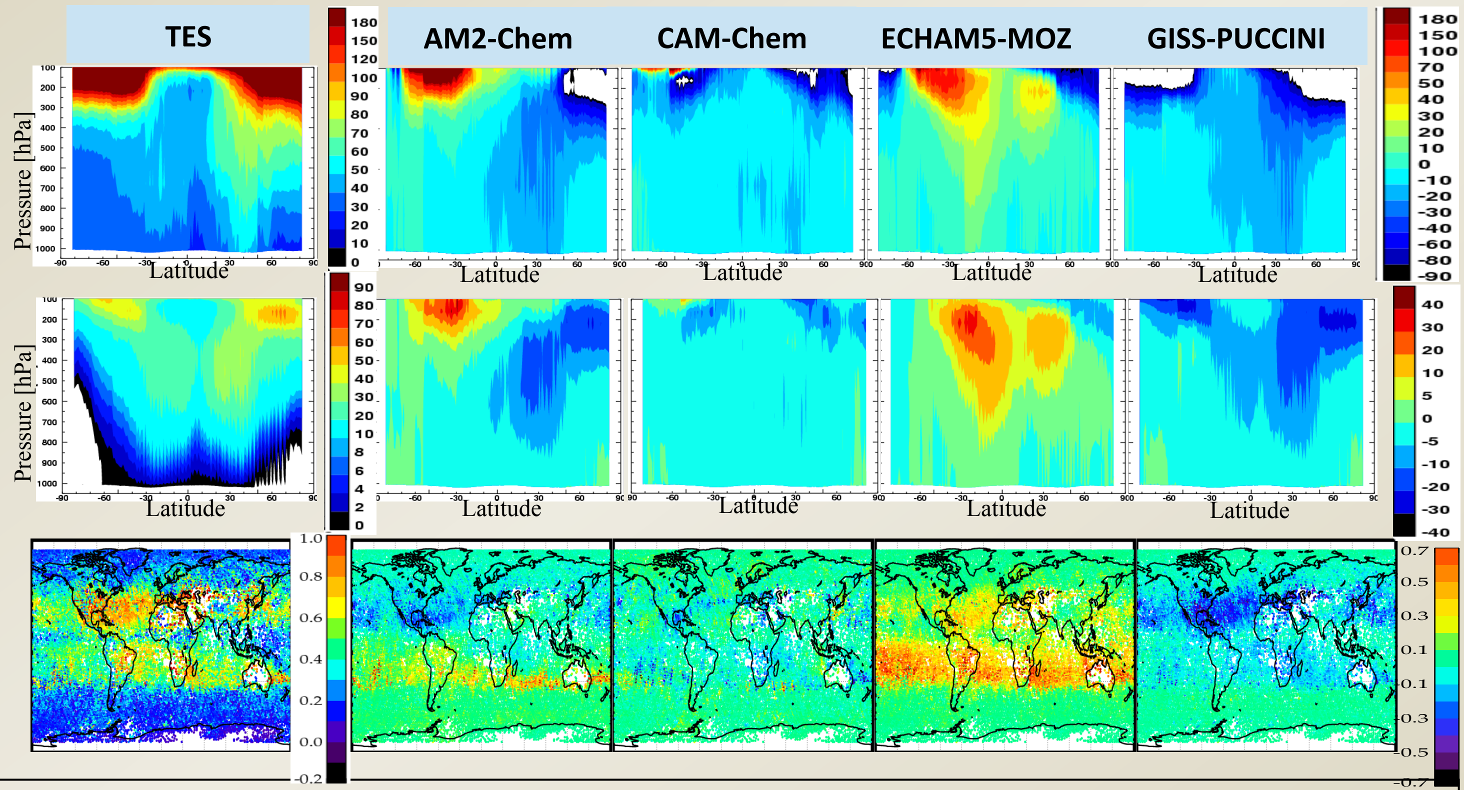
Direction observational constraints on ozone radiative forcing

Aghedo *et al*, 2010

Zonal-mean ozone and models' bias [ppbv]

All-sky zonal mean instanteneous radiative forcing and models' bias [milli-Watts/m^2]

All-sky instantaneous radiative forcing and models' bias [Watts/m^2]

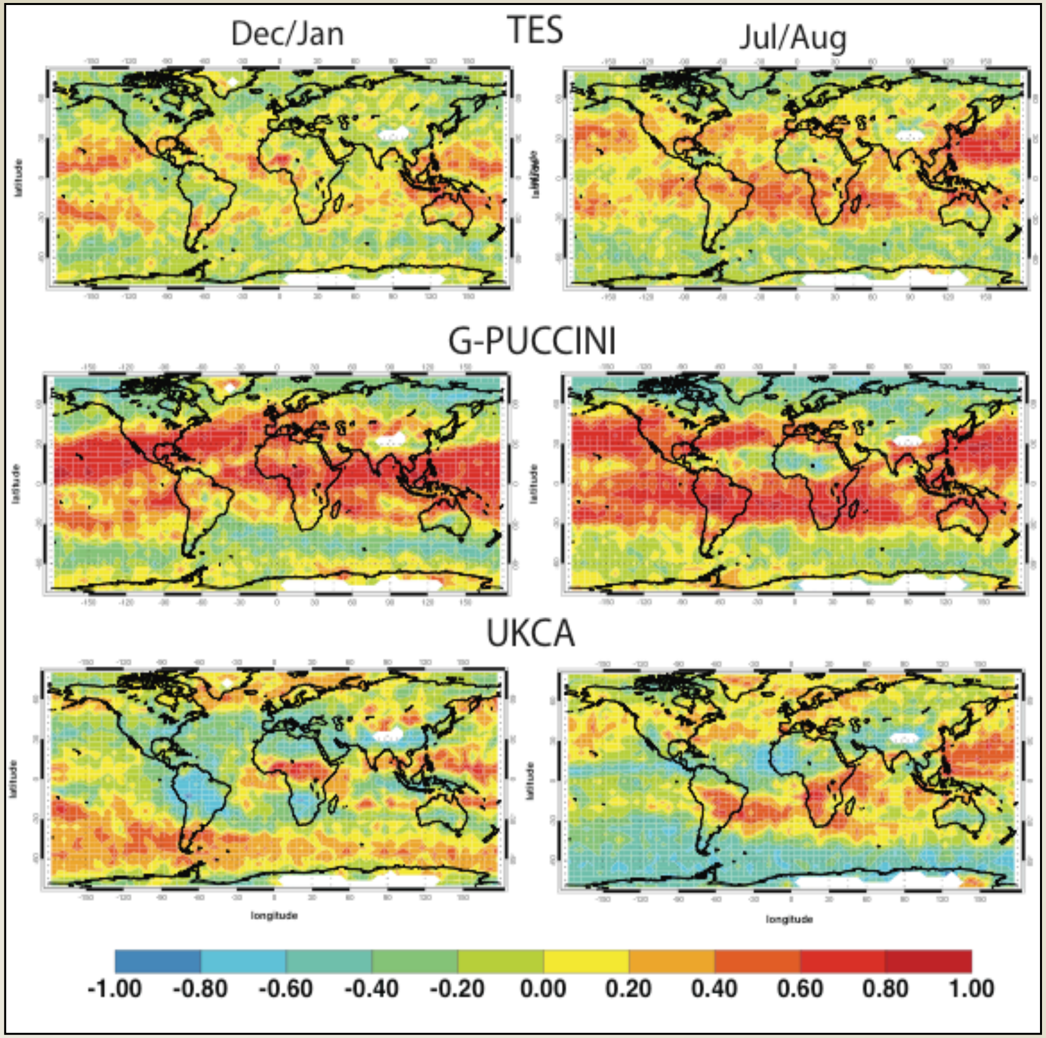


Problem: Tropospheric ozone is the third most important gas in terms of climate radiative forcing and this radiative forcing is highly uncertain because the vertical and horizontal distribution of ozone has significant uncertainties.

Results: For August 2006, TES data quantifies a zonal-average bias of about -30 to +40 mWatts/m^2 and the regional bias of about -40 mW/m^2 to 70 mW/m^2 in the radiative effect of tropospheric ozone predicted by four state-of-the-art chemistry models.

Significance: Uncertainty in the radiative forcing of tropospheric ozone is largest in the tropical and extra-tropical middle-to-upper troposphere.

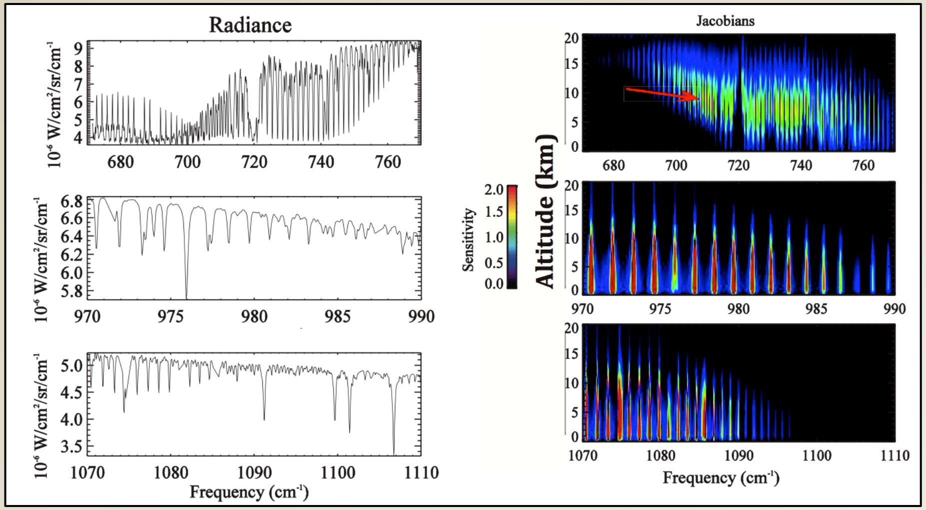
CO-Ozone constraints on chemistry-climate models

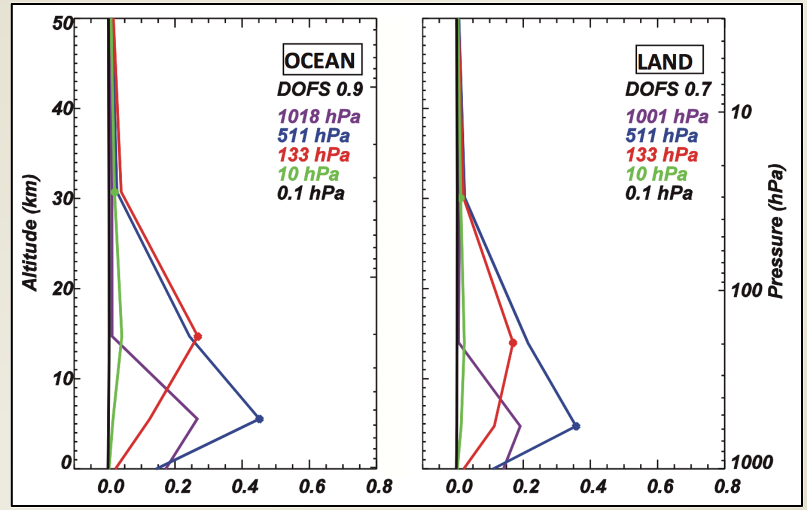


Voulgarakis *et al*, ACP, submitted

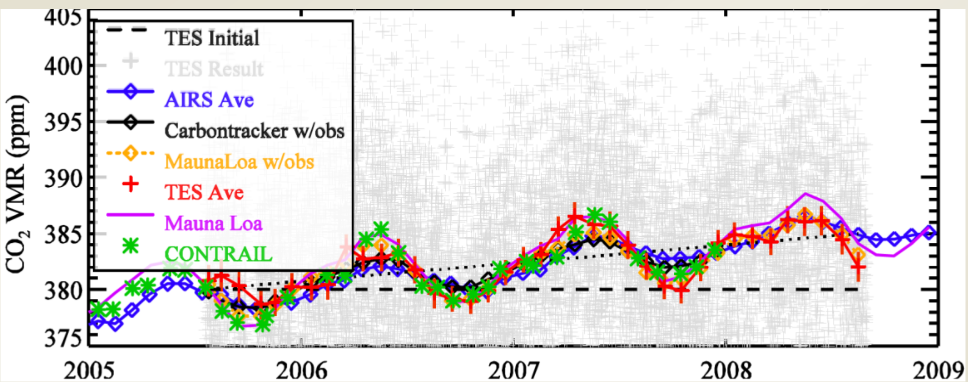
- The correlation of ozone and CO is an important tool to distinguish between combustion and background ozone.
- TES CO:O_3 correlations (2005-2009) have been compared to two state-of-the-art chemistry climate models:
  - NASA GISS-PUCCINI
  - UK Chemistry Aerosol Model (UKCA)
- Correlation patterns remarkably different between TES, G-PUCCINI and UKCA
  - Suggest relative balance of model natural and anthropogenic sources need to be re-examined.

TES tropospheric CO_2





Use of radiances around 10µm provide lower tropospheric sensitivity

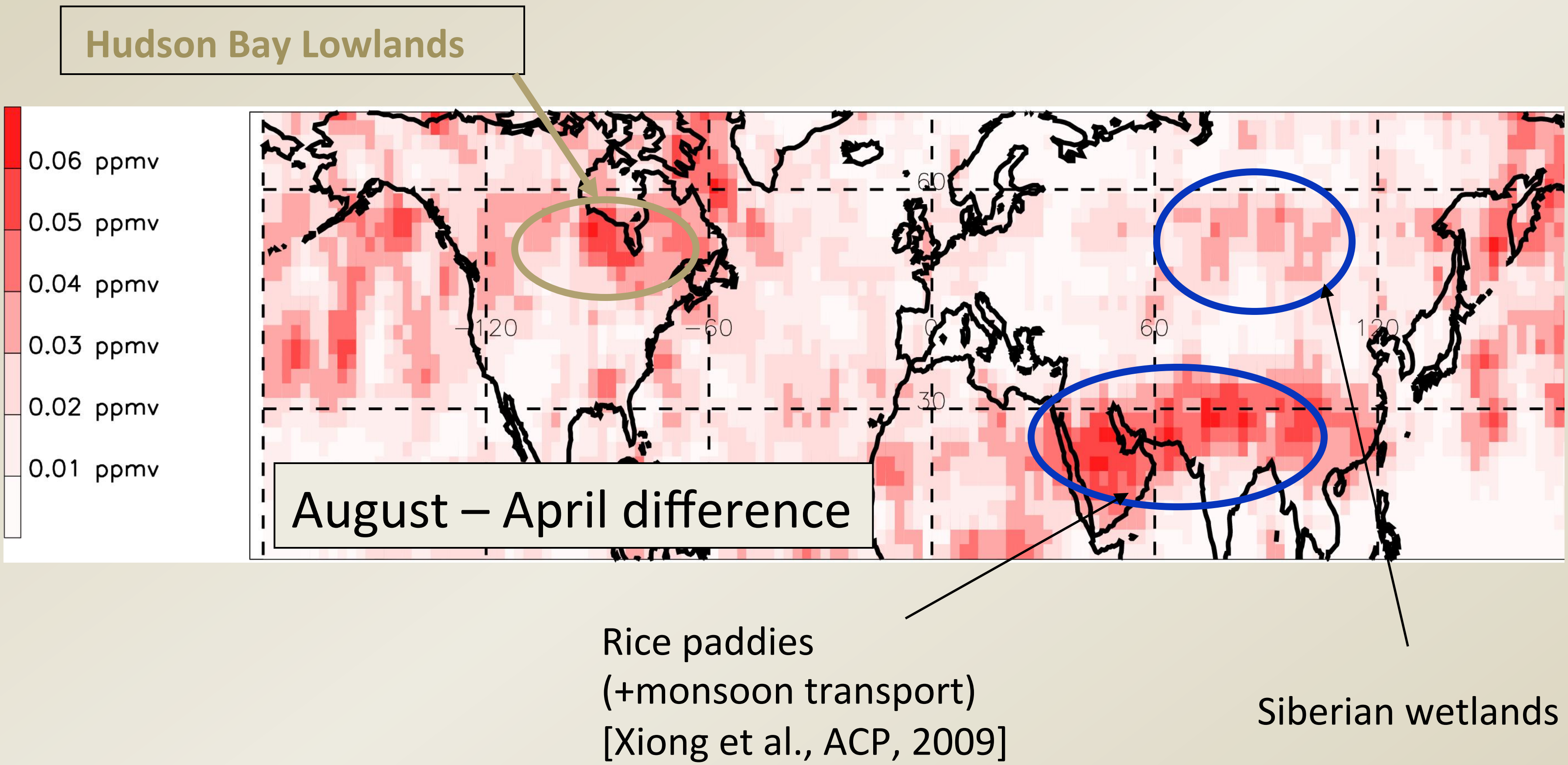


Kulawik *et al*, 2010, ACP

Comparisons with the HIPPO aircraft show bias from -0.6 to 0.2 ppm and correlations between 0.5 to 0.8

R. Nassar will discuss application of TES CO2 to global emissions estimates

Seasonal Differences in TES CH_4 (2005-2008 averages)



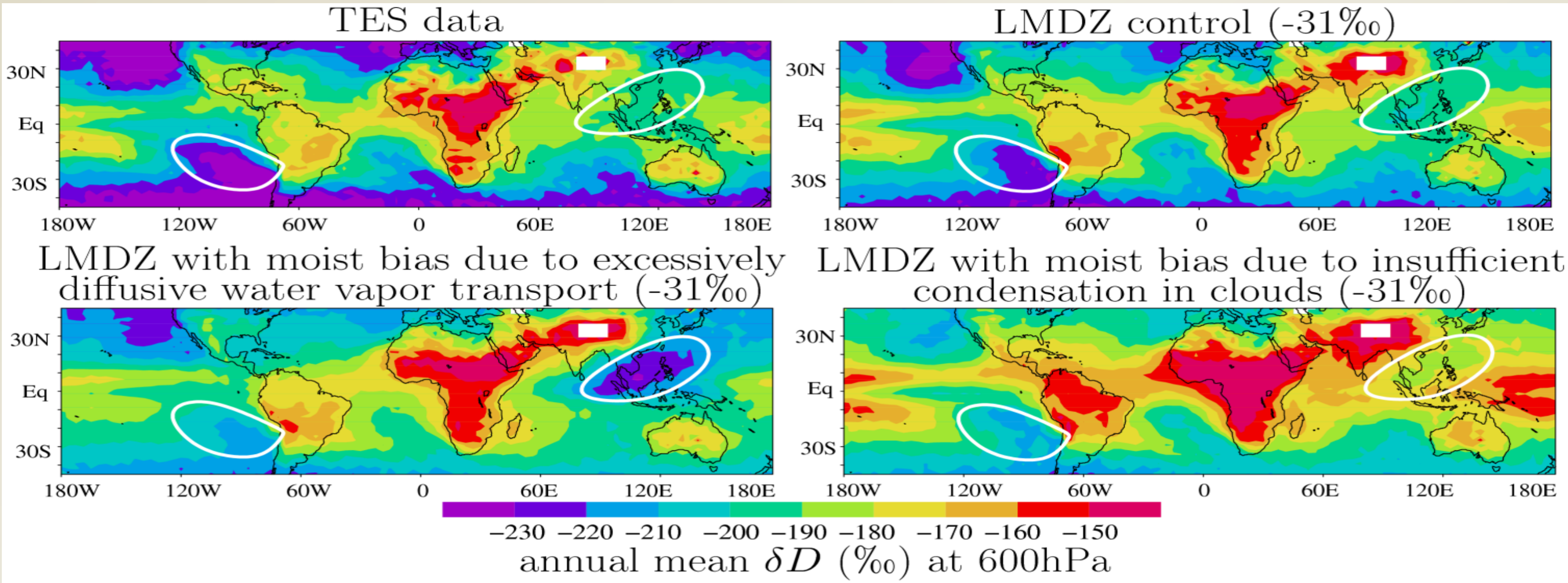
Emissions contribute to the seasonal signal.
Application of TES CH4 to flux estimates is underway.

Payne *et al*, in preparation

Evaluating the representation of moist processes in climate models using water vapor isotope measurements

Most climate models present a moist bias in the mid and upper troposphere: what are the processes whose representation needs improvement?

Approach: sensitivity tests with the LMDZ atmospheric model, model-data comparisons

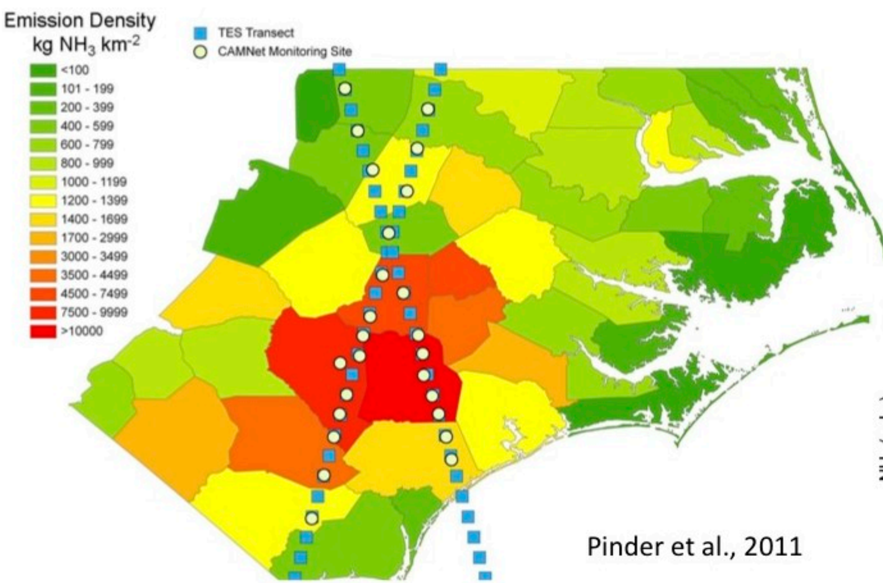


Result: Each reason for a moist bias has a distinct isotopic signature

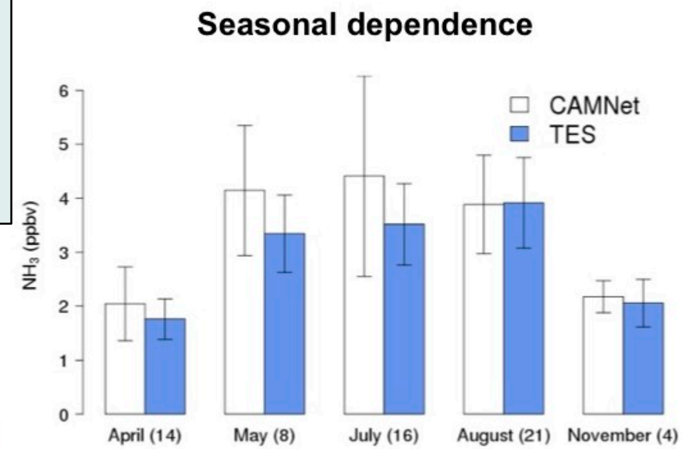
Conclusion: Water vapor isotope measurements can be used as observable diagnostics to understand the reason for the moist bias in atmospheric models.
Applying such diagnostics to 7 atmospheric models shows that excessively diffusive water vapor transport is the most frequent reason for the moist bias.

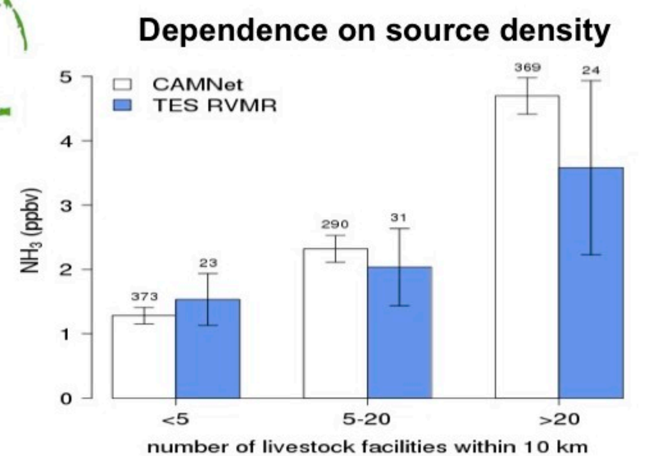
Observational constraints on ammonia sources

EPA ammonia surface network constructed along TES track in North Carolina show correlations in seasonal dependence and source density between satellite and ground measurements



Pinder et al., 2011





Conclusions

- The TES instrument, launched aboard Aura in 2004, continues to take observations of atmospheric constituents that enable a greater understanding of atmospheric chemistry and its interactions with climate
- However, the suite of measurements possible from IR hyperspectral sounders such as TES provide insight into parts of the Earth System and their coupling.
- Future hyperspectral sounders should be designed to be the pillars of the modern Earth Observing System and the glue that connects other observations together.