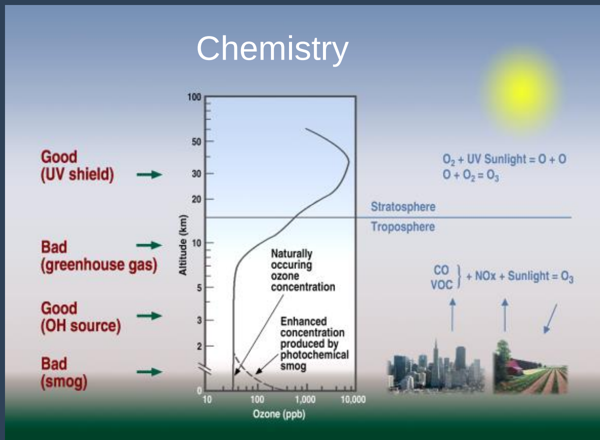
Jet Propulsion Laboratory
California Institute of Technology

# Role of IR Sounders in climate, air quality, and Earth System Science

Kevin W. Bowman and the TROPESS team

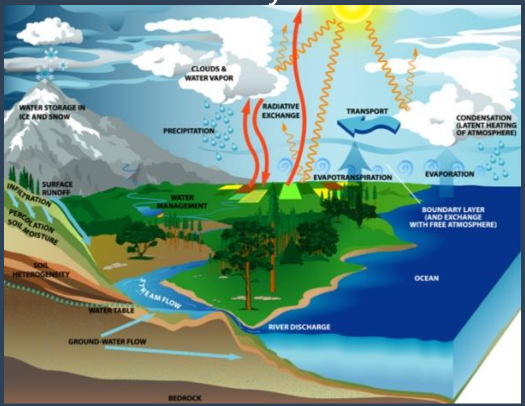
# IR Sounding provides a unique window into the Earth System

Chemistry

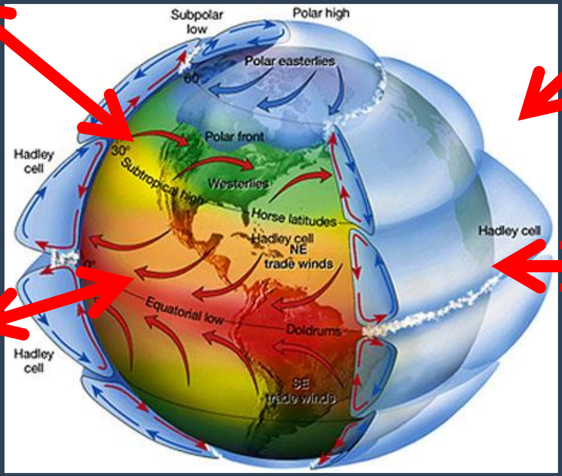



Atmospheric composition plays a critical mediating role in Earth System Cycles.

Water Cycle




Atmosphere, Climate

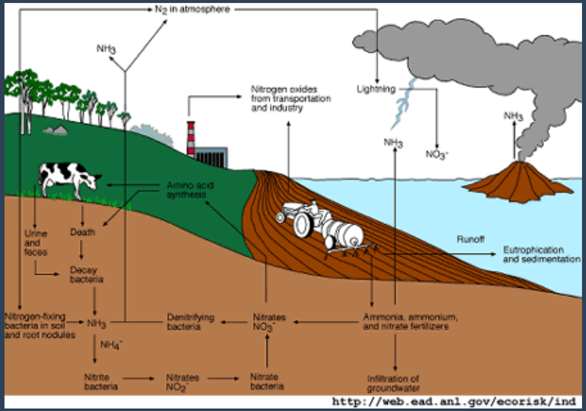



Ozone ($O_3$), Carbon Monoxide (CO), Methanol ($CH_3OH$), Formic Acid (HCOOH)

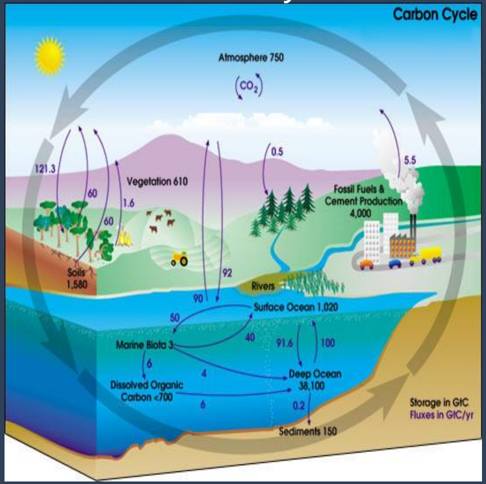
Water Vapor and Isotopes ($H_2O$ and HDO)

Carbon Cycle

Nitrogen Cycle




Carbon Cycle




Ammonia ($NH_3$), PAN ($CH_3COOONO_2$)

Radiative Kernels, Surface Temperature, Atmospheric Temperature, Cloud Optical, Depth and Pressure, Surface Emissivity

Carbon Dioxide ($CO_2$), Methane ($CH_4$), Carbonyl Sulfide (OCS)

# Tropospheric Emission Spectrometer: Pathfinder Earth System Sounder

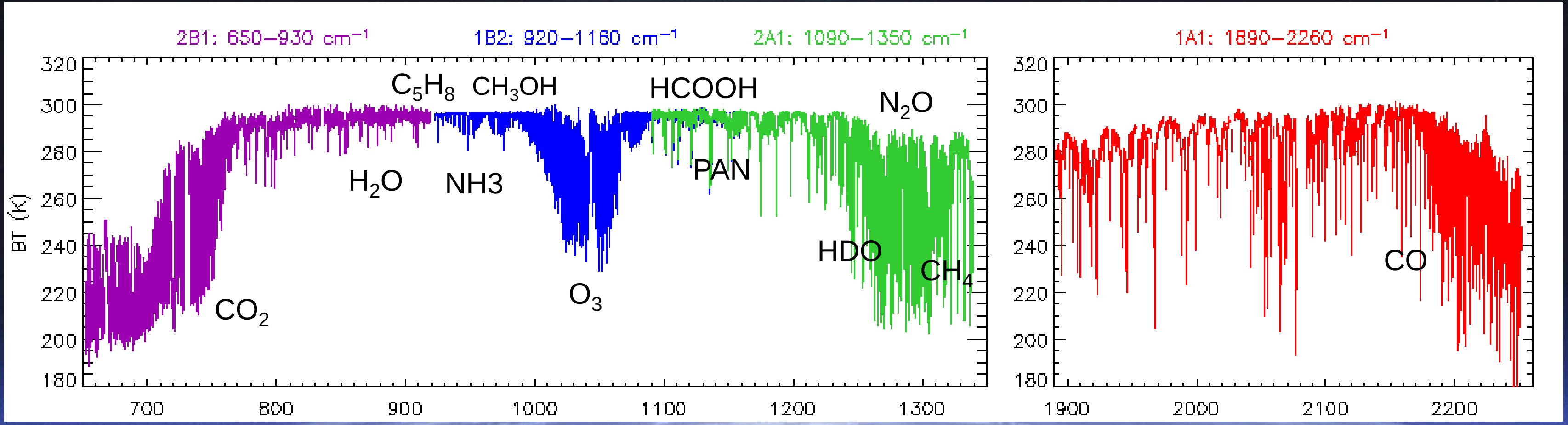
**TES Data Products**

Ozone ($O_3$)
Carbon Dioxide ($CO_2$)
Water Vapor and its Isotopes ($H_2O$ and HDO)
Carbon Monoxide (CO)
Methane ($CH_4$)
Surface Temperature
Atmospheric Temperature
Cloud Optical Depth and Pressure
Surface Emissivity

Ammonia ($NH_3$)
Methanol ($CH_3OH$)
PAN ($CH_3COOONO_2$)
Formic Acid (HCOOH)
Carbonyl Sulfide (OCS)
TES/OMI Ozone Profiles
TES/MLS CO Profiles

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

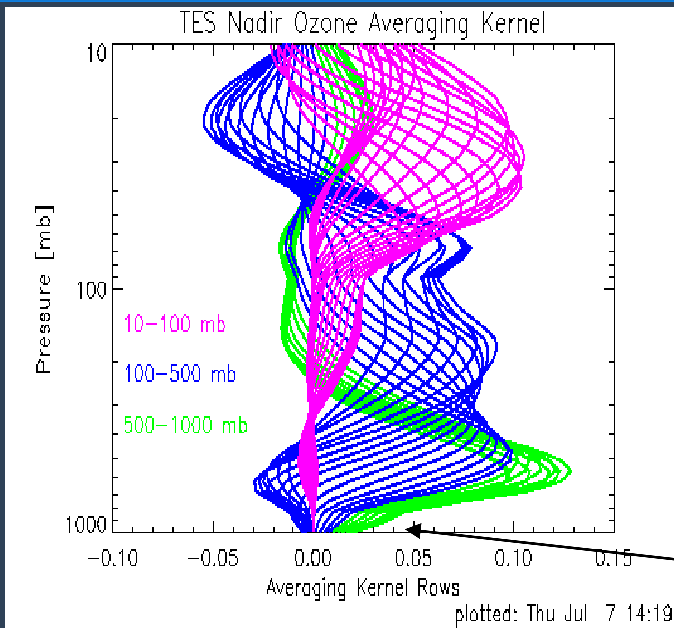
TES has 10x higher spectral resolution than CrIS




Frequency ($cm^{-1}$)

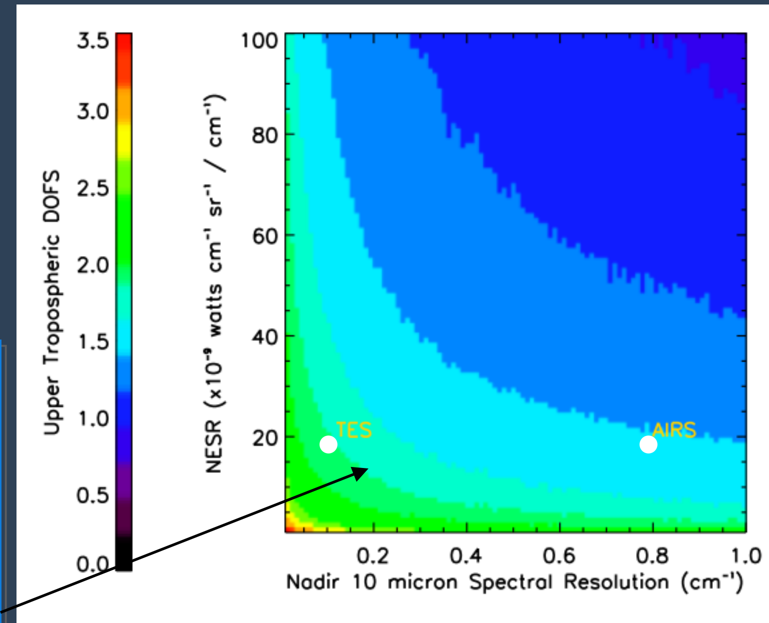
# The what and where of vertical resolution

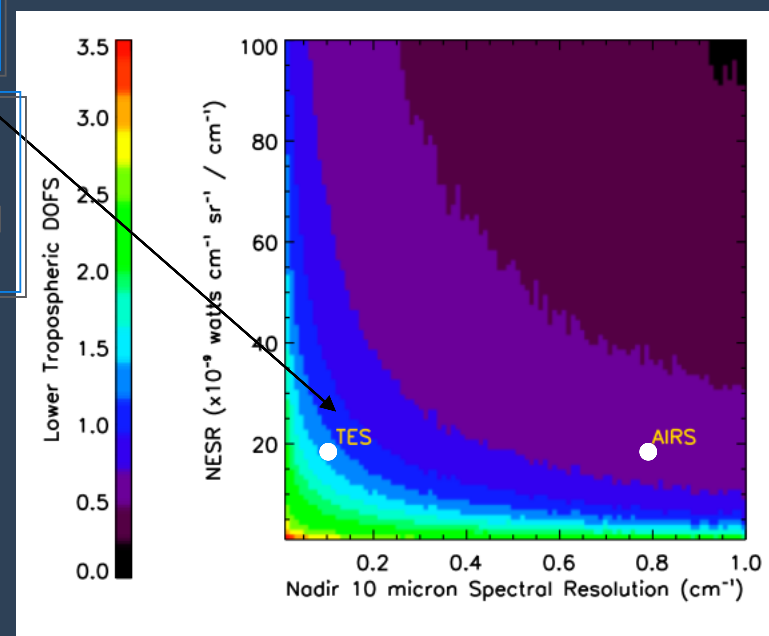
For the thermal infrared, spectral resolution and noise provide bounds for both *what* and *where* vertical resolution is obtainable




The difference in vertical sensitivity between TES and AIRS is much less in the upper troposphere than in lower troposphere

Sensitivity to boundary layer ozone dependant on thermal contrast



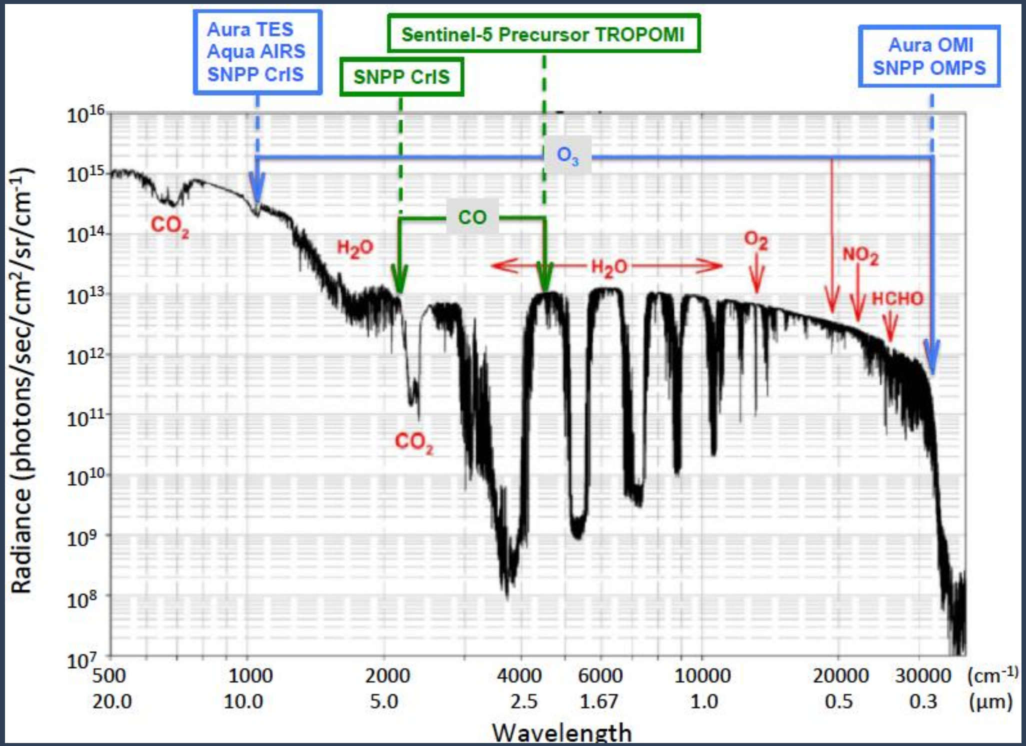




The averaging kernel characterizes the sensitivity of an ozone profile estimate to variations in the fine structure of the atmospheric state.

The peaks and widths of the kernel define the location and degree of vertical resolution

# More eyes are better than one: The panspectral approach

**IR-NIR**
TES
AIRS
IASI
CrIS
OCO-2
TROPOMI

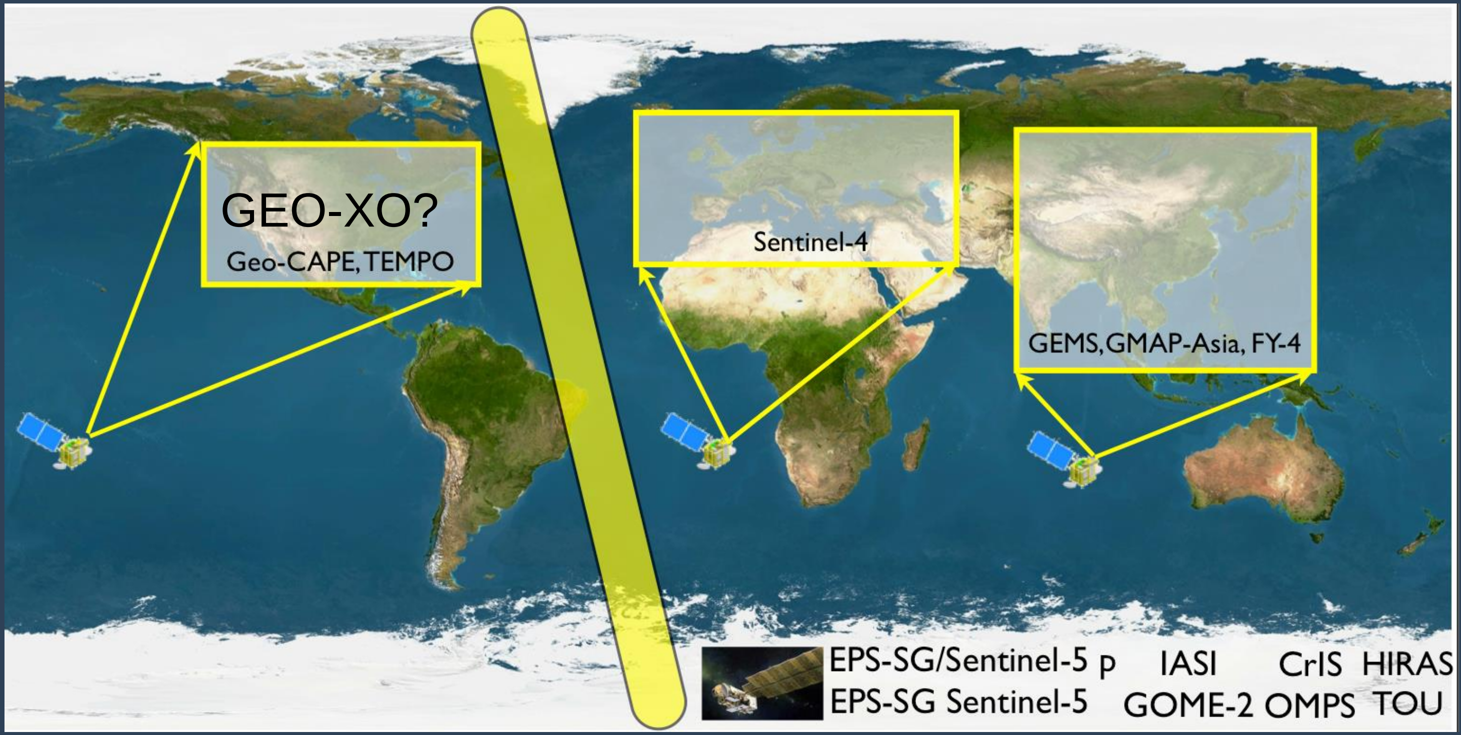



**UV-Vis**
SCIAMACHY
OMI
GOME
GOME-2
OMPS
TROPOMI

- Panspectral techniques provide better vertical sensitivities than individual bands → critical for relating concentrations to emissions
- Systematic errors between instruments and spectroscopy must be assessed.

TROPESS has considerable heritage in multi-spectral, multi-instrument retrieval algorithms for UV, IR,NIR, microwave (Worden et al, GRL, 2007, Luo et al, 2013, Fu et al, ACP, 2013, Kuai et al, 2013, Worden et al, 2015, Fu et al, 2016) for ozone, CO, CO2, and CH4.

# An IR Sounders are part of a composition constellation

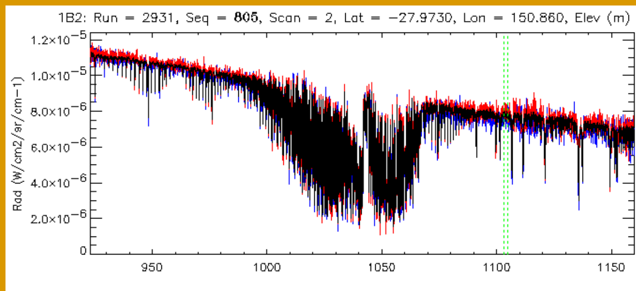



Bowman, *Atm. Env.* 2013

IR Sounders such as CrIS and IASI represent the backbone of a composition constellation (CEOS-AC-VC) for both US and international composition missions.

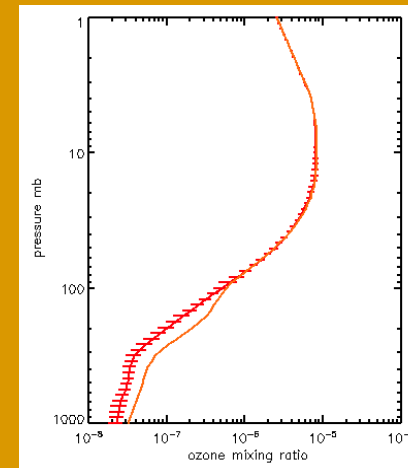
- Sustained observations for the next decade.
- Hyperspectral IR sounders are radiometrically stable.
- LEO observations to integrate GEO platforms

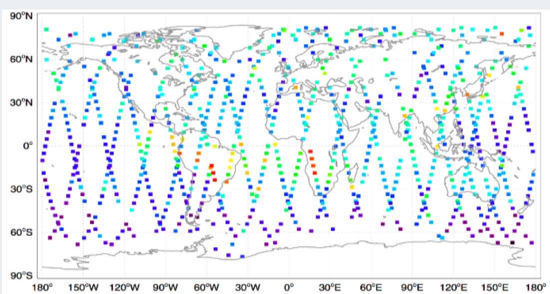
# Remote Sensing Science: retrievals and uncertainty



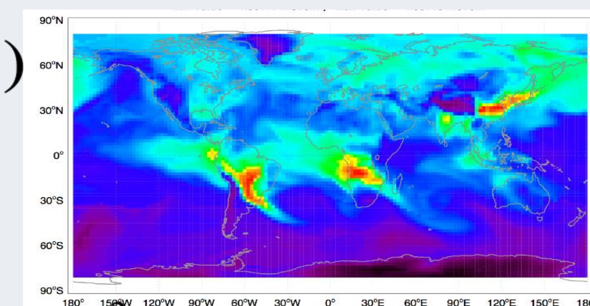

$$\|\mathbf{y}-\mathbf{F}(\mathbf{x}_a)\|^2_{\mathbf{S}_n^{-1}} + \|\mathbf{x}-\mathbf{x}_a\|^2_{\mathbf{S}_a^{-1}}$$

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




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




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

Optimal estimation (OE) techniques and error diagnostics (e.g., Bowman et al, 2002, 2006; Worden et al, 2004; Kulawik et al, 2006, 2008) provide instrument operators for evaluation against models and assimilation (Jones et al, 2003, Miyazaki et al, 2015).

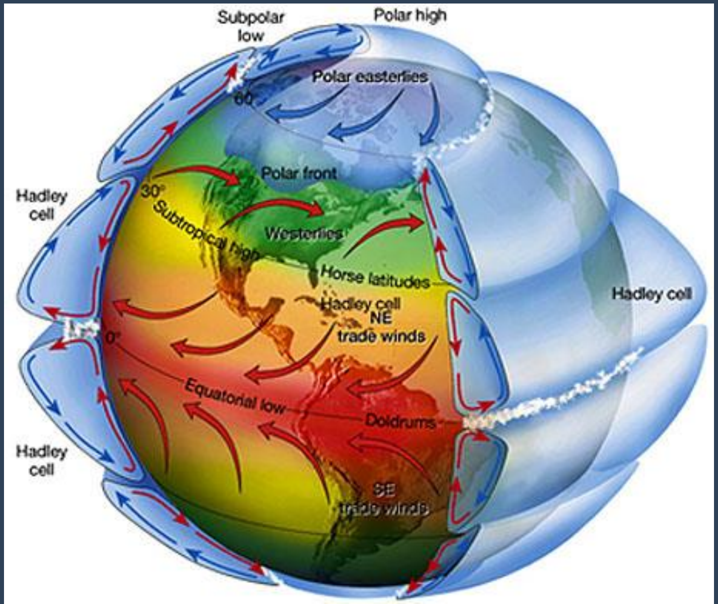
**The science community has come to expect these tools for rigorous science and assimilation of remote sensing data, e.g., Alvarado et al, 2015**

# Climate

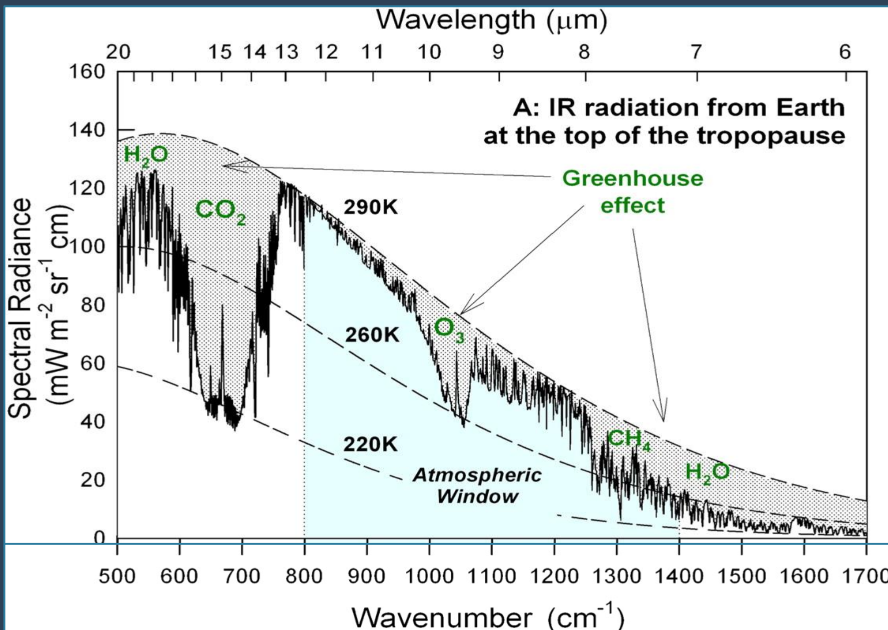
Changes in thermal absorption of radiatively active gases including $CO_2$, $CH_4$, and $O_3$ are the fundamental drivers of climate change.

$CH_4$, and $O_3$ are *short-lived climate pollutants* (SLCPs) that have emerged as important levels for climate mitigation.

IR sounders play a fundamental role in understanding chemistry-climate interactions

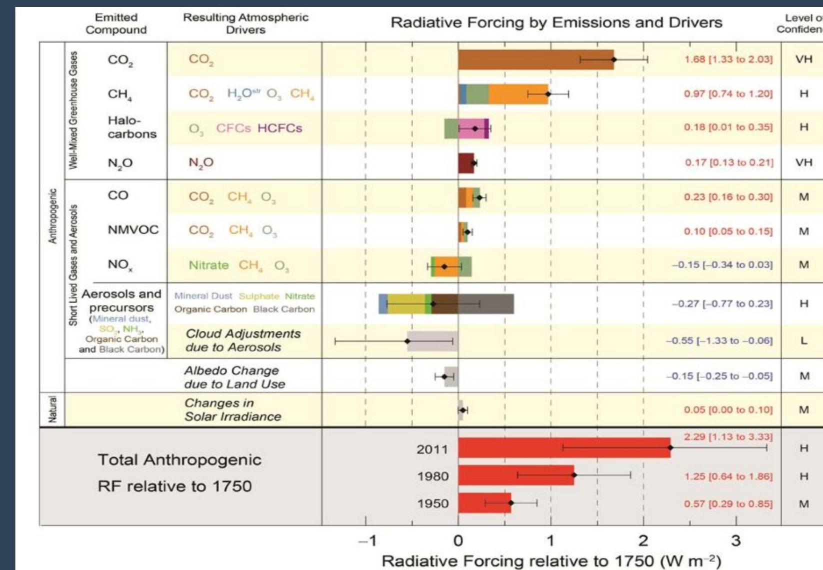


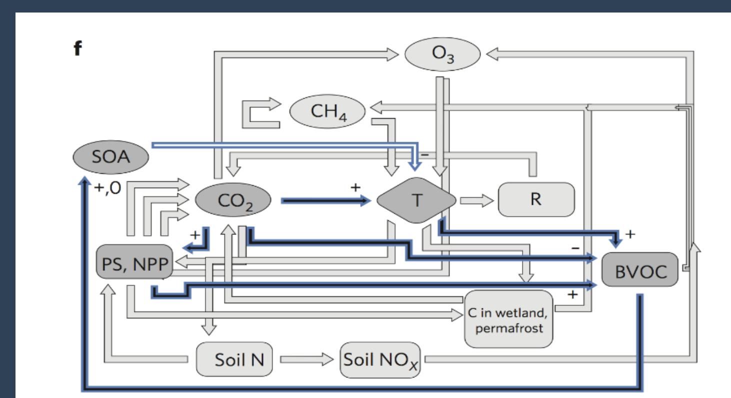

# Radiative forcing from atmospheric composition




Wallington T J et al. PNAS 2010;107:E178-E179

IPCC AR5



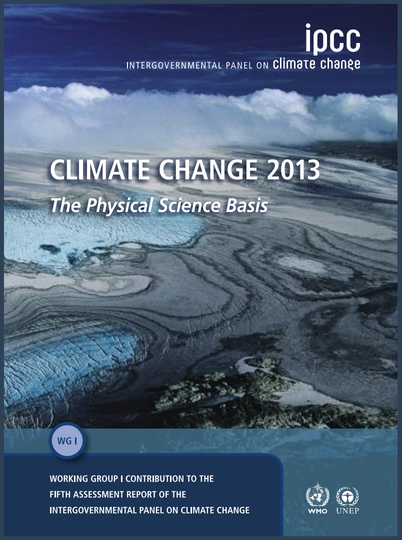

*Arneth et al, 2010, Nat. Geo. Sci.*

Carbon dioxide, methane, and ozone are the three most important greenhouse gases resulting from anthropogenic activities.

These gases are coupled through common sources and coupled within the Earth System.

# How has Tropospheric Ozone Changed Climate?

Air quality emissions can change tropospheric ozone, which in turn absorbs infrared radiation. But, it’s impact is spatially homogeneous



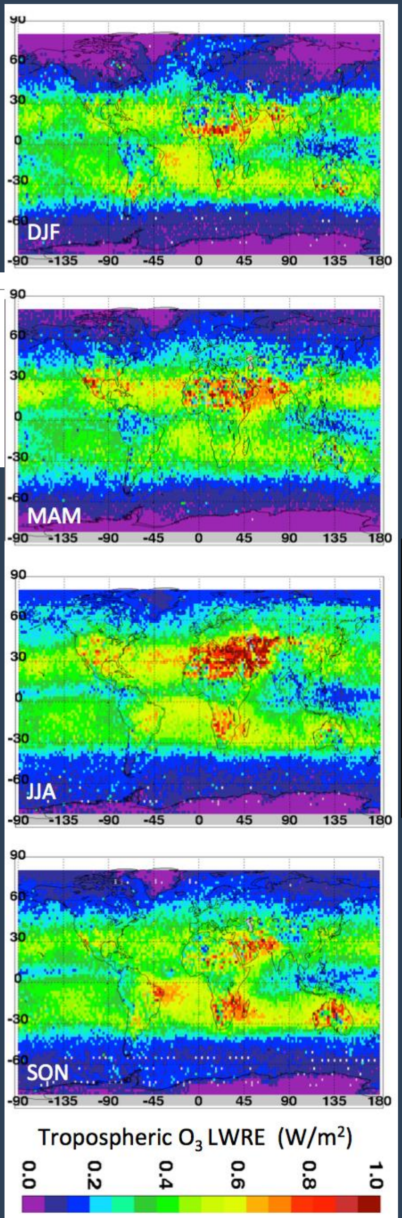

Satellite measurements of the clear-sky greenhouse effect from tropospheric ozone

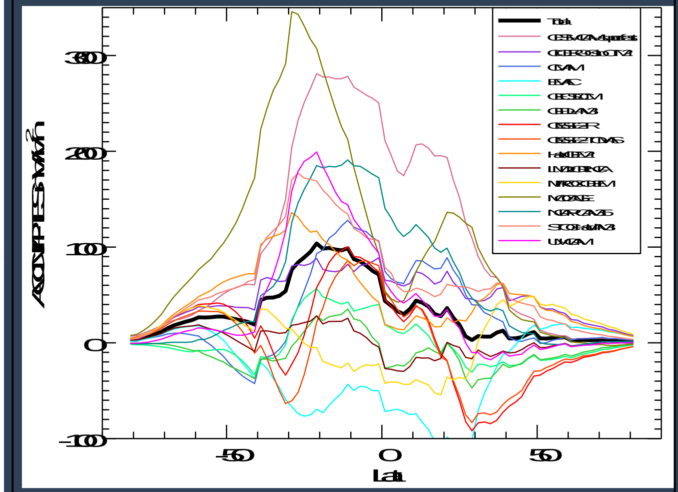

HELEN M. WORDEN[1]*, KEVIN W. BOWMAN*, JOHN R. WORDEN, ANNMARIE ELDERING AND REINHARD BEER

Science Division, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA
[1]Present Address: Atmospheric Chemistry Division, National Center for Atmospheric Research, PO Box 3000, Boulder, Colorado 80307, USA
*e-mail: hmw@ucar.edu; Kevin.Bowman@jpl.nasa.gov


*Nature Geosciences, 2008*

Instantaneous radiative kernel (IRK), which are the sensitivity of outgoing radiation to vertical distribution of ozone, have been calculated on TES, IASI, AIRS, and CrIS




In the tropics, discrepancies lead to over 300 mWm$^{-2}$ for individual models and up to 100 mWm$^{-2}$ for the ACCMIP ensemble. Mean NH bias is negligible.

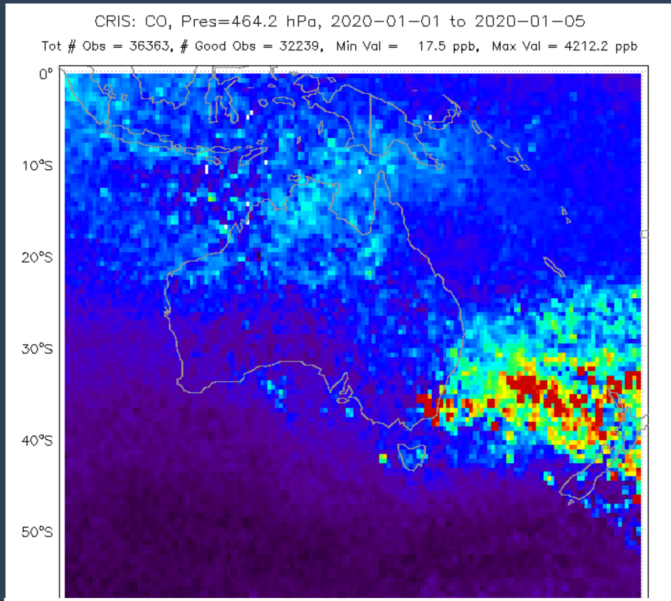
Bowman et al, 2013

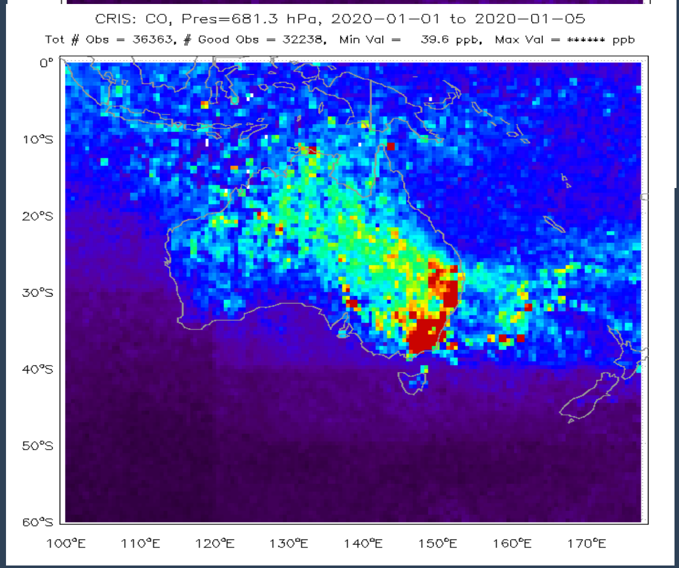
Climate models compute future changes in climate based upon atmospheric composition. Evaluation by IR sounders can help asses their fidelity.

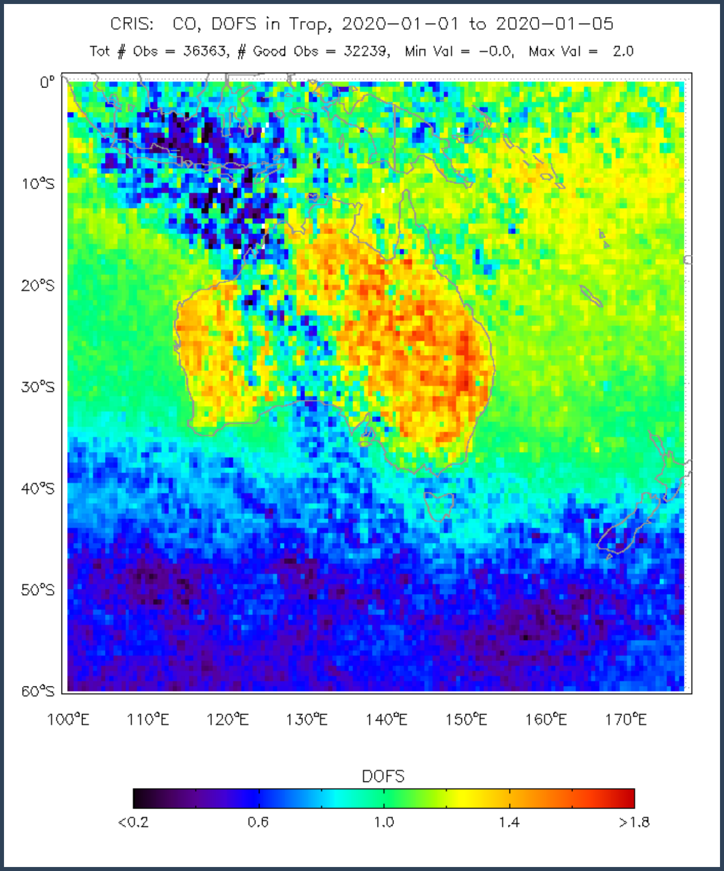
# Climate and Extreme Events

Australian Fires

# Composition Impacts

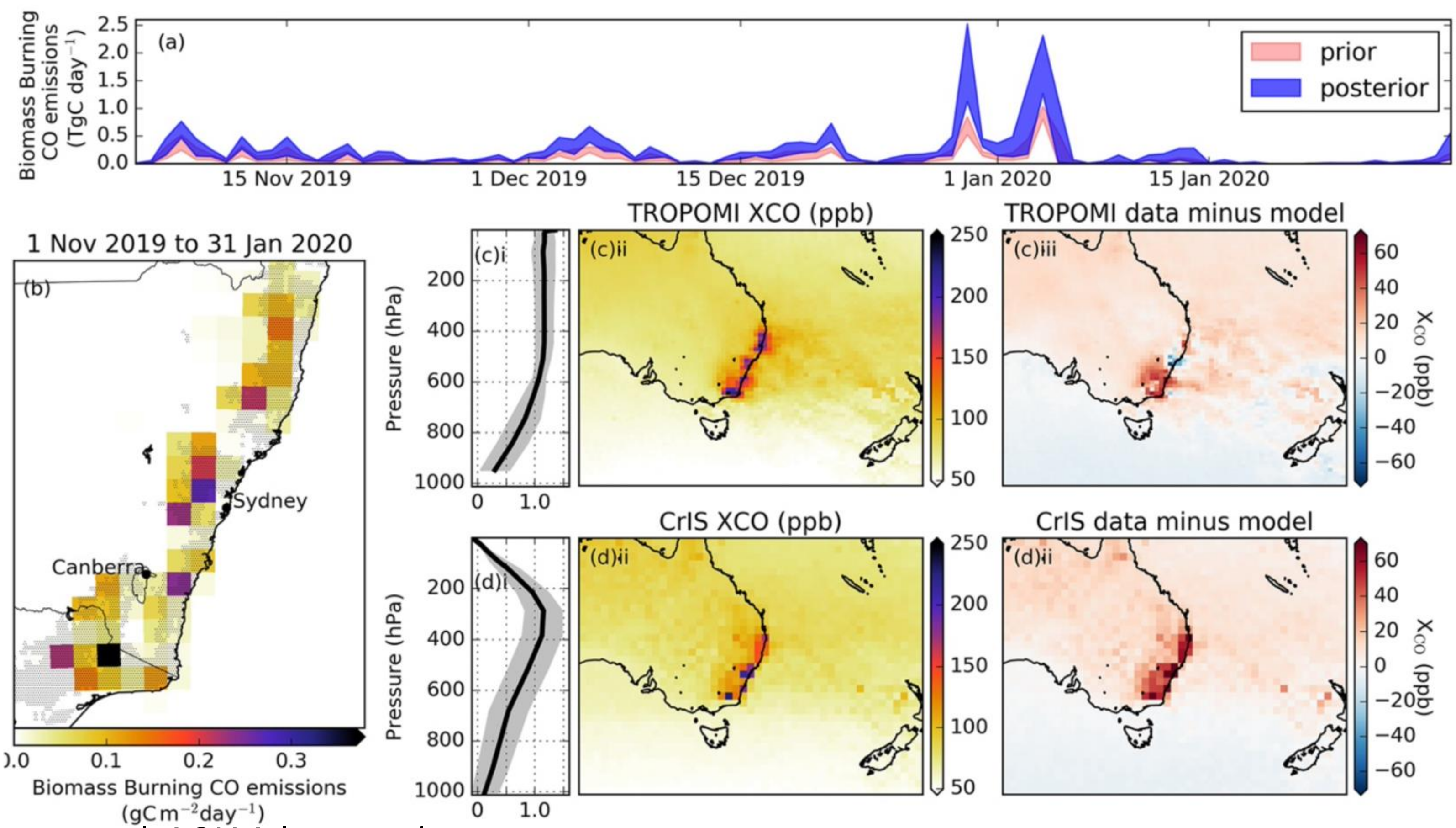



DOFS suggests up to 2 pieces of information. Beginning to distinguish mid and upper tropospheric circulation

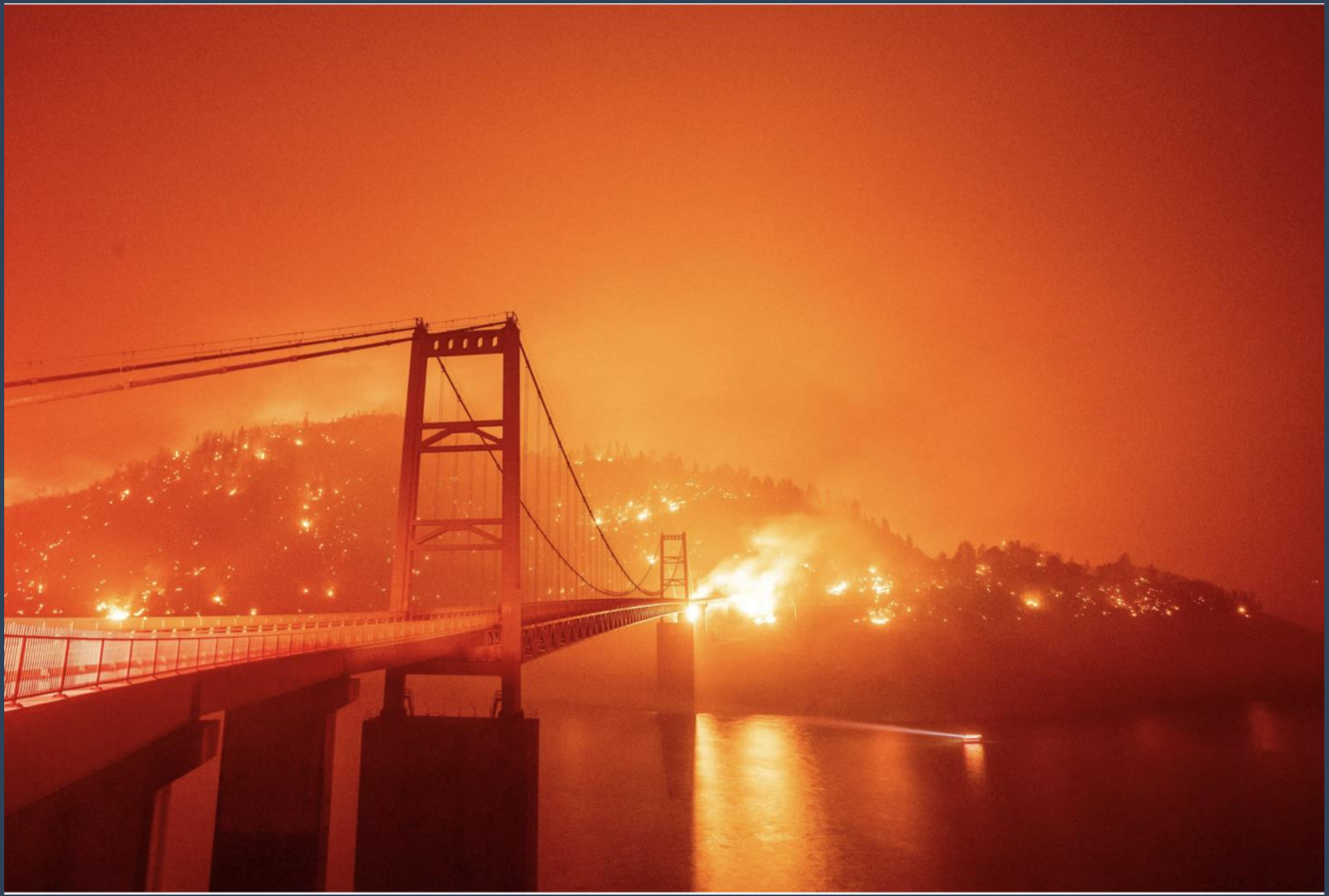
# CrIS and TROPOMI CO: Australian Fires




Byrne et al, AGU Advances, *in press*

- Found that 113–236 TgC of CO2 were released through biomass burning
- Larger than the total annual fossil fuel emissions in Australia

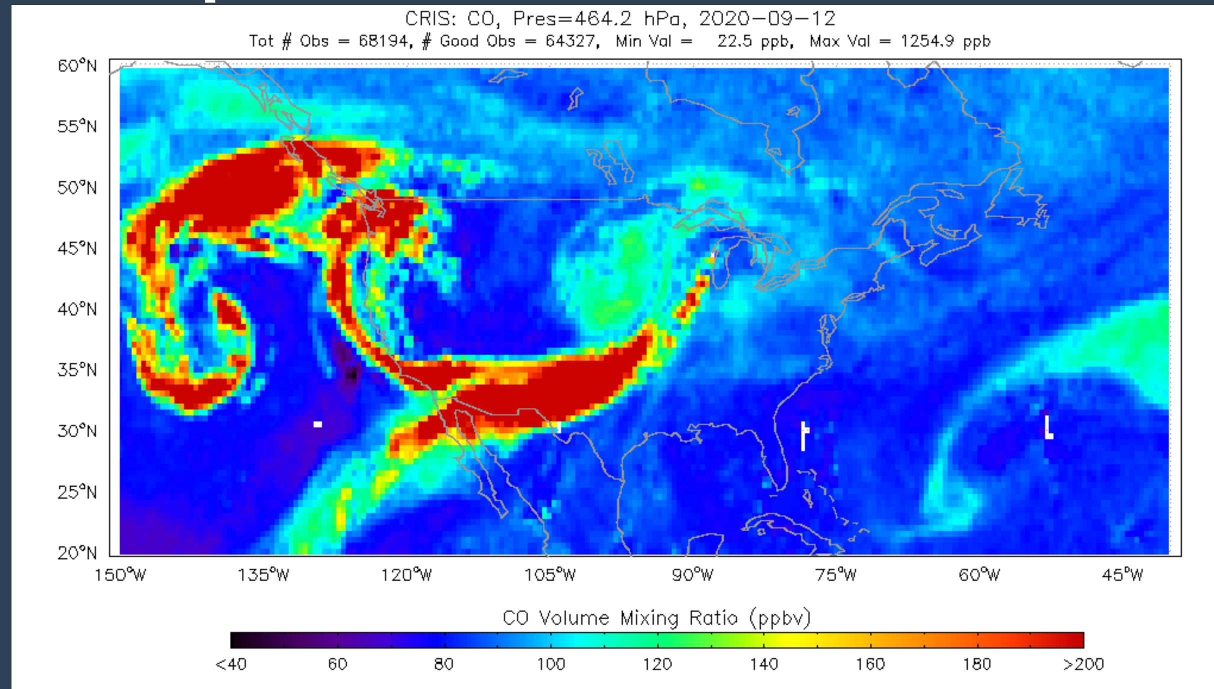
# Something wicked this way comes

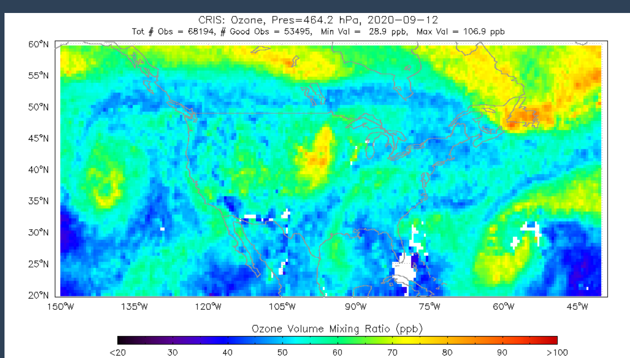


The fires in 2020 were the worst in California history—costing over 16 billion dollars in direct damages to structures and management costs.  That's 3x NOAA's budget. Of the 10 most destructive fires in US history, 8 occurred in the past 5 years

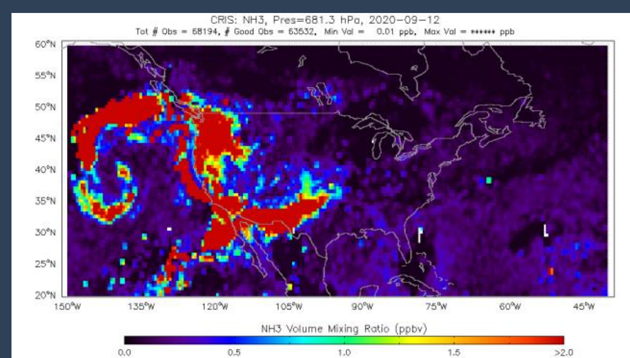
# West Coast Fires: Sept 12, 2020

The west coast fires had a dramatic impact on atmospheric composition that is seen in CO, O3, PAN, and NH3.

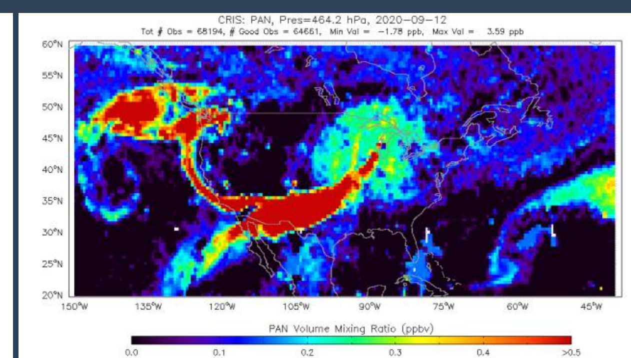



$O_3$



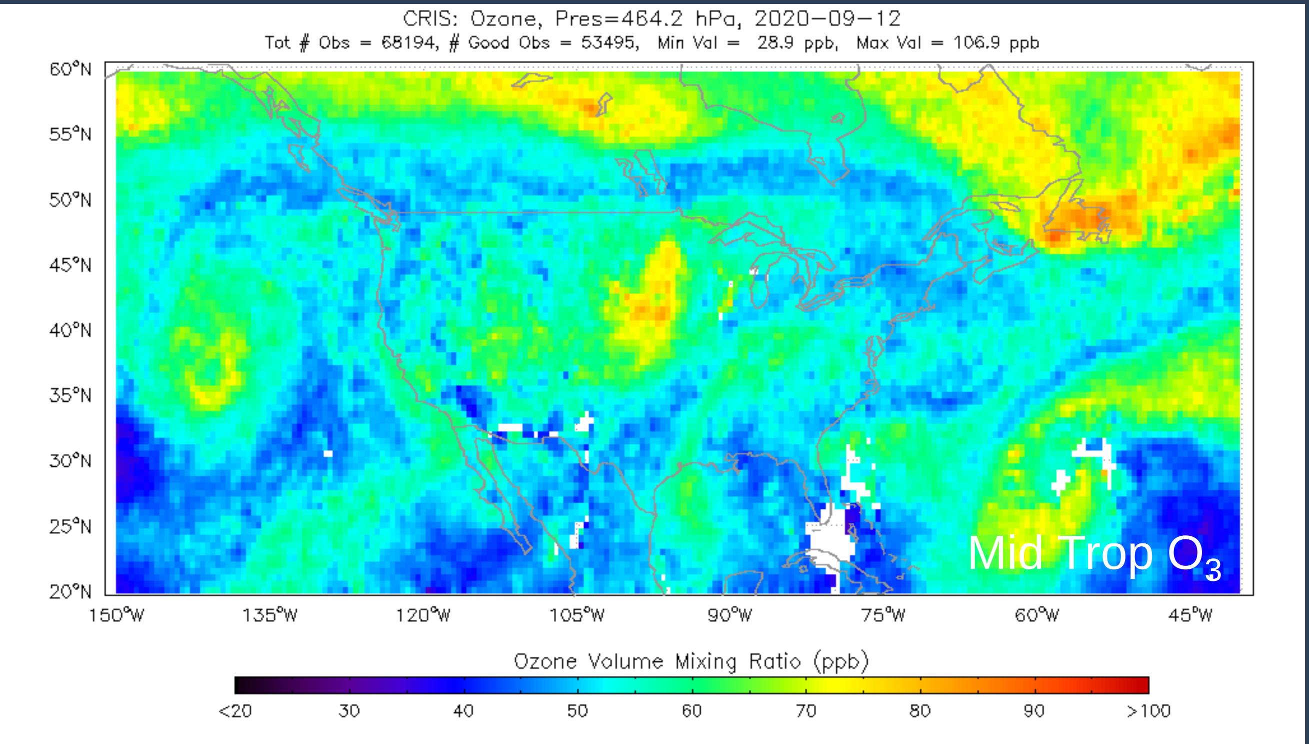

$NH_3$

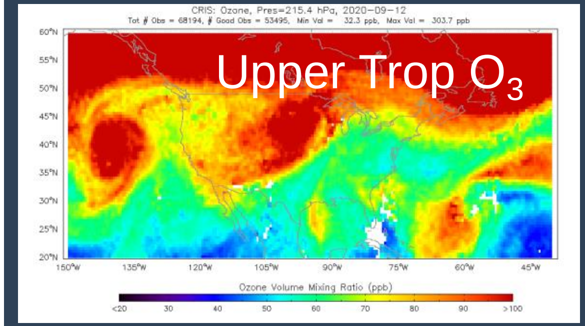


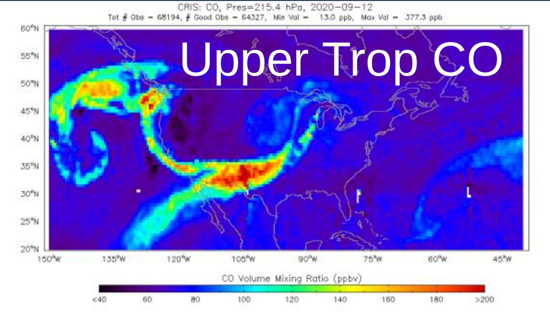

PAN

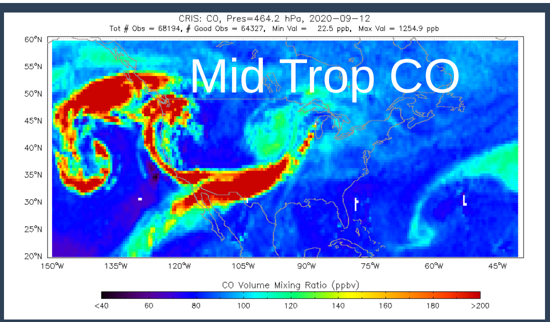
# Ozone Formation vs Stratospheric Transport

Ozone seen by CrIS is a mixture of both tropospheric and stratospheric processes.

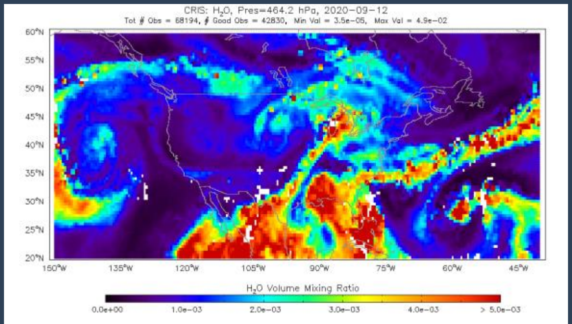


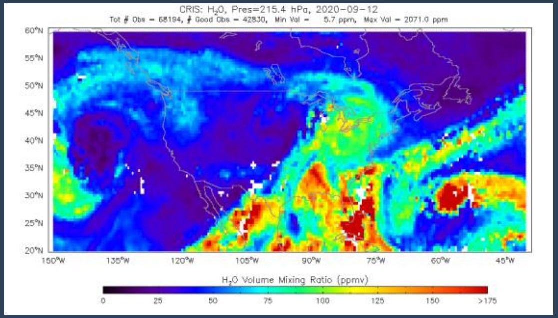



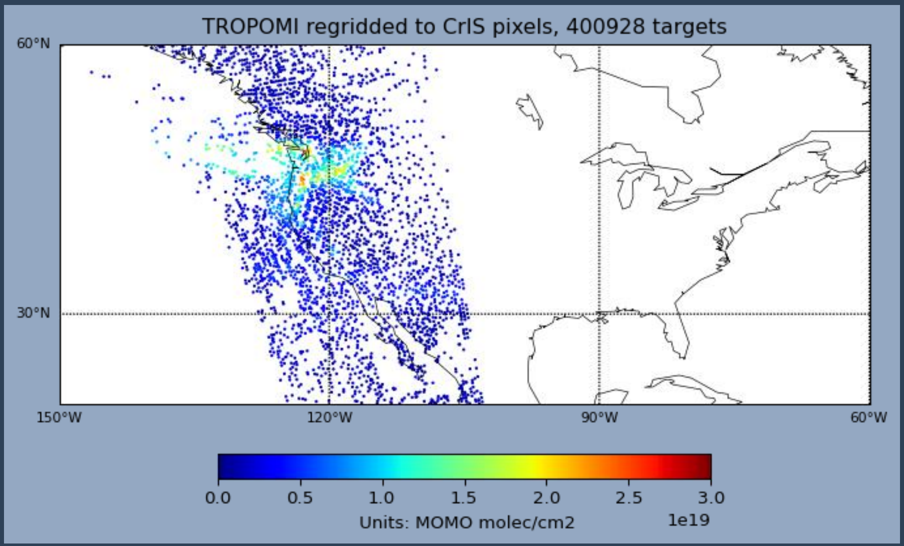



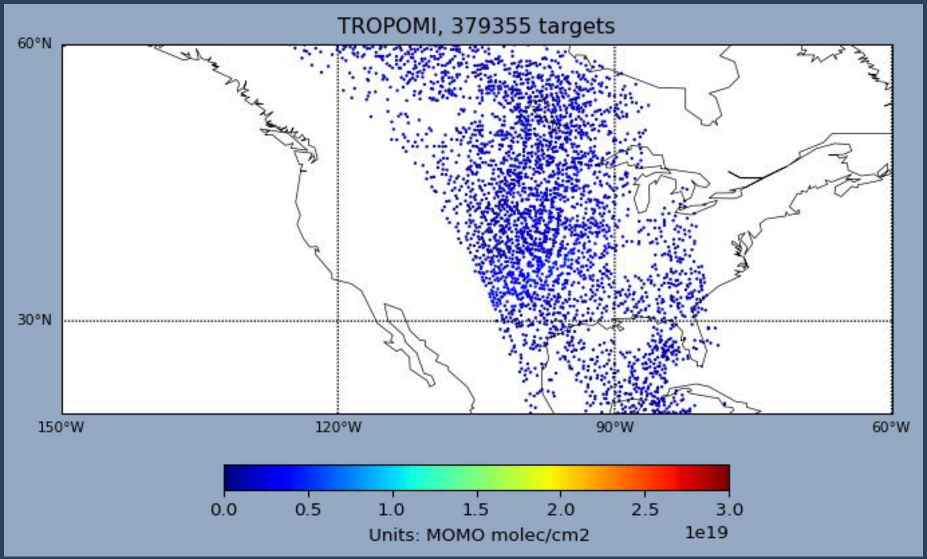

Mid (left) and upper (right) trop water vapor

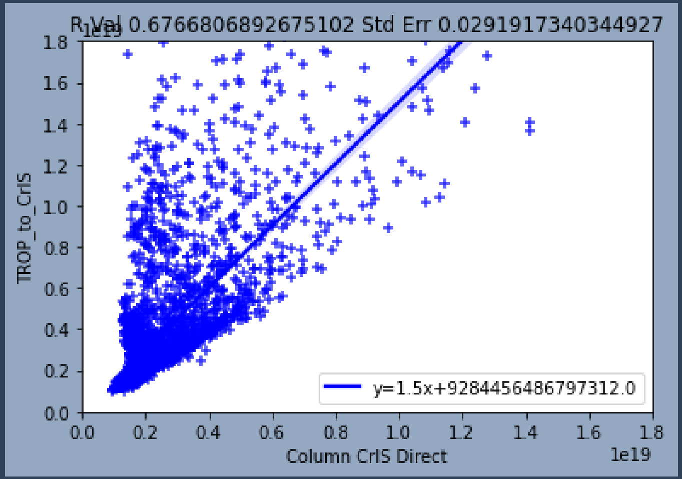


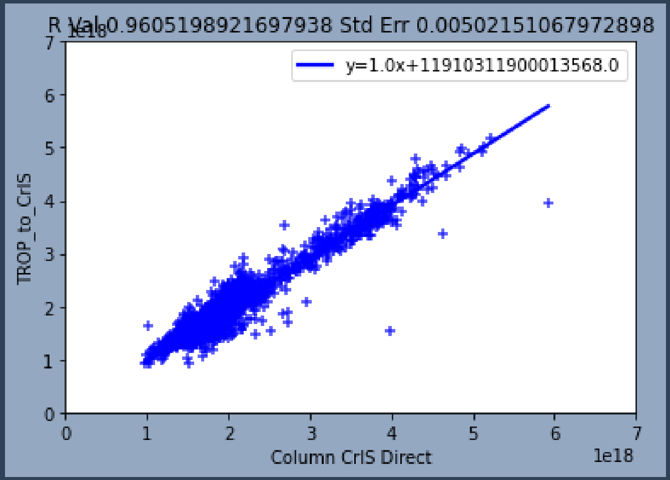



# CrIS and TROPOMI can disentangle vertical structure




Courtesy Saide and Neyra, UCLA

# Nitrogen Cycle

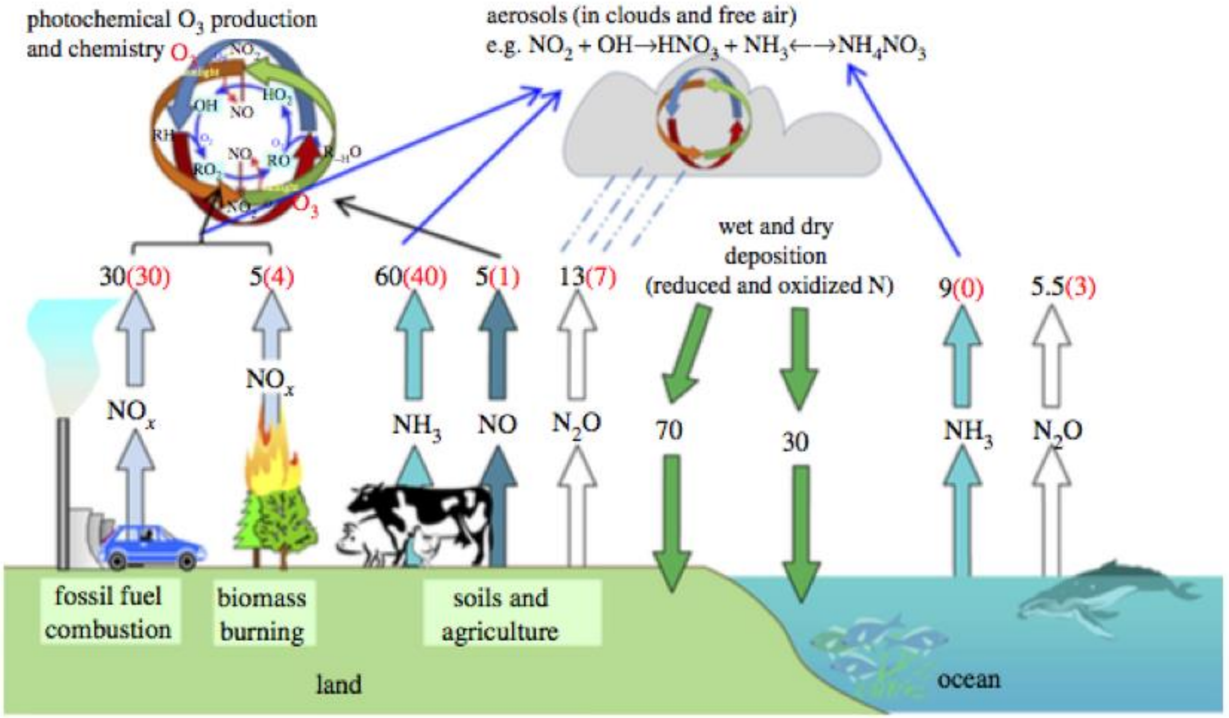



**Figure 3.** The global atmospheric processing of reactive nitrogen, illustrating the main sources, the main chemical pathways and products and the magnitudes of the fluxes (units Tg $yr^{-1}$). The emission flux values in black are the total fluxes while the red values indicate the anthropogenic contribution.

Fowler et al, 2013

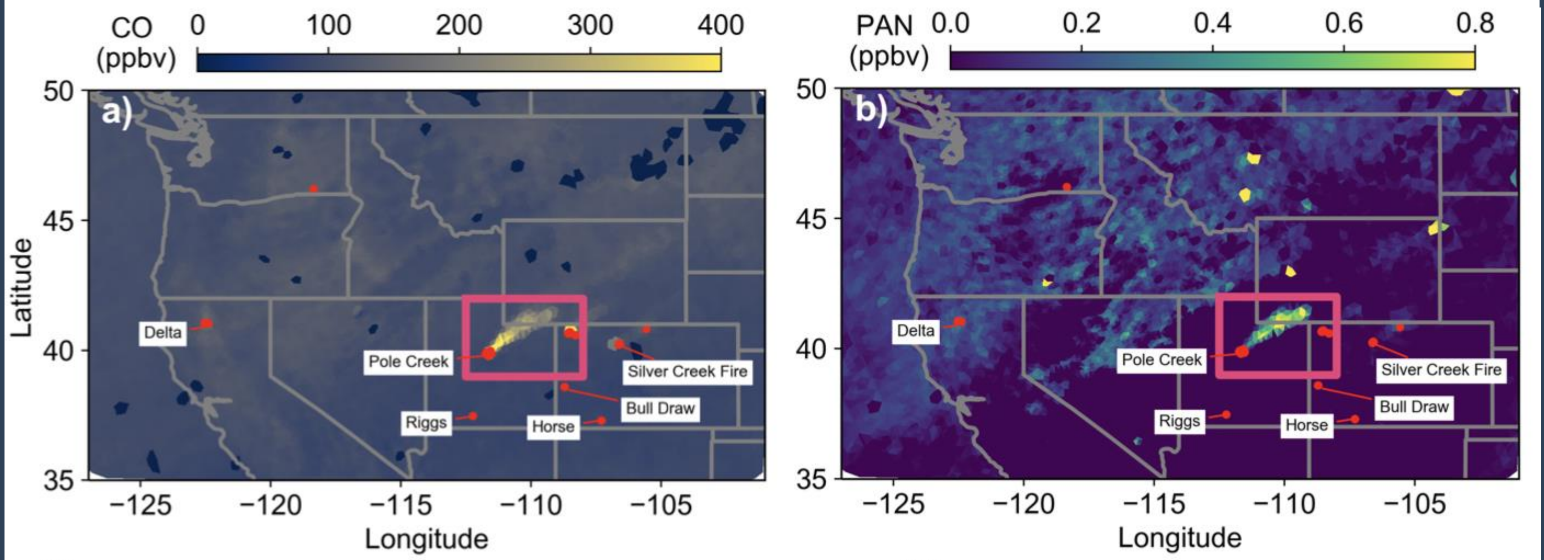
The nitrogen cycle is a biogeochemical cycle that plays a complex role in driving atmospheric chemistry, the carbon cycle, and marine life.

IR sounders make unique measurements of nitrogen containing gases.

# Combinations of CO and PAN help assess the transport and transformation of pollutants: Pole Creek Fire (Utah)

13

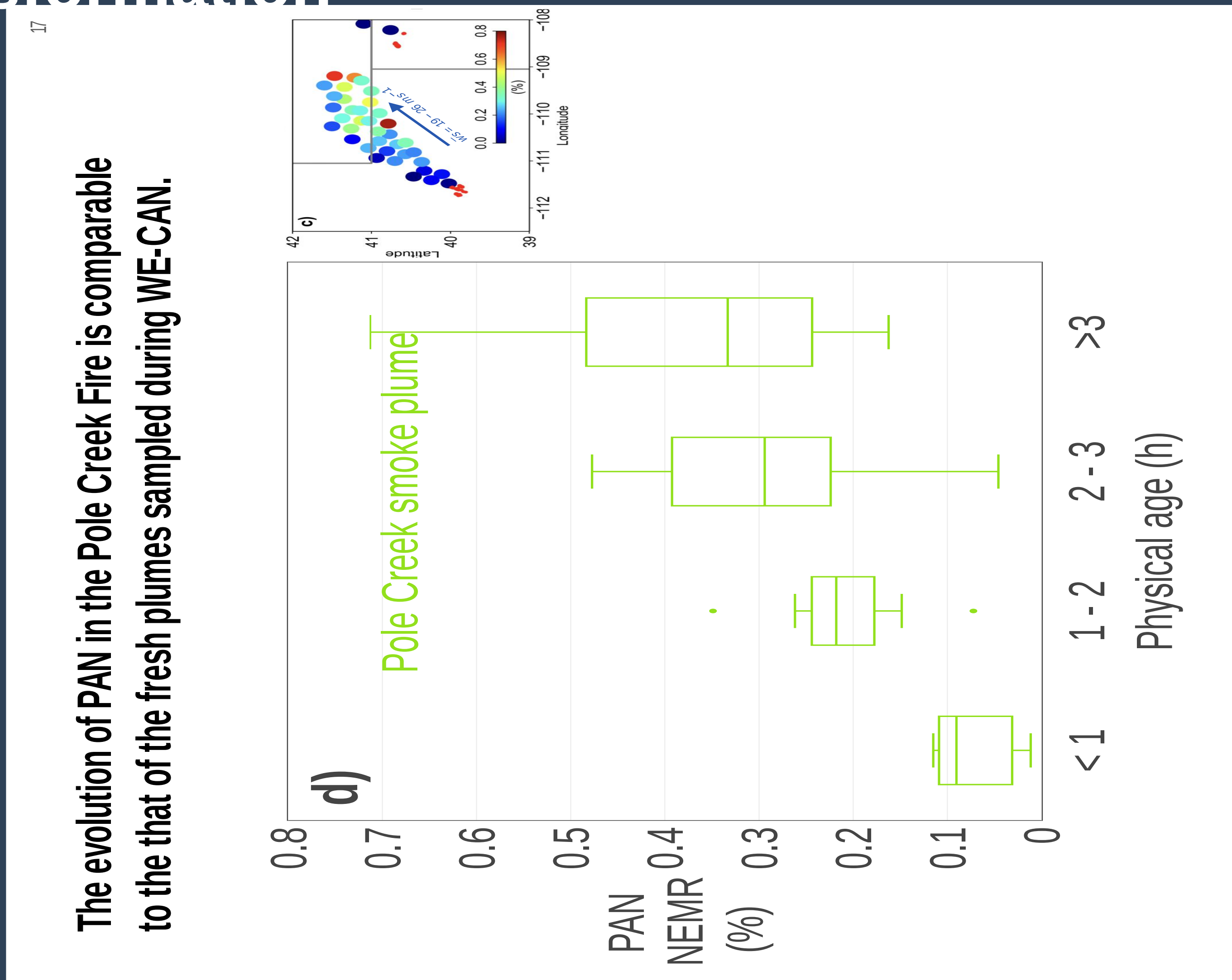
**CrIS detects CO and PAN from the Pole Creek smoke plume on September 13, 2018.**





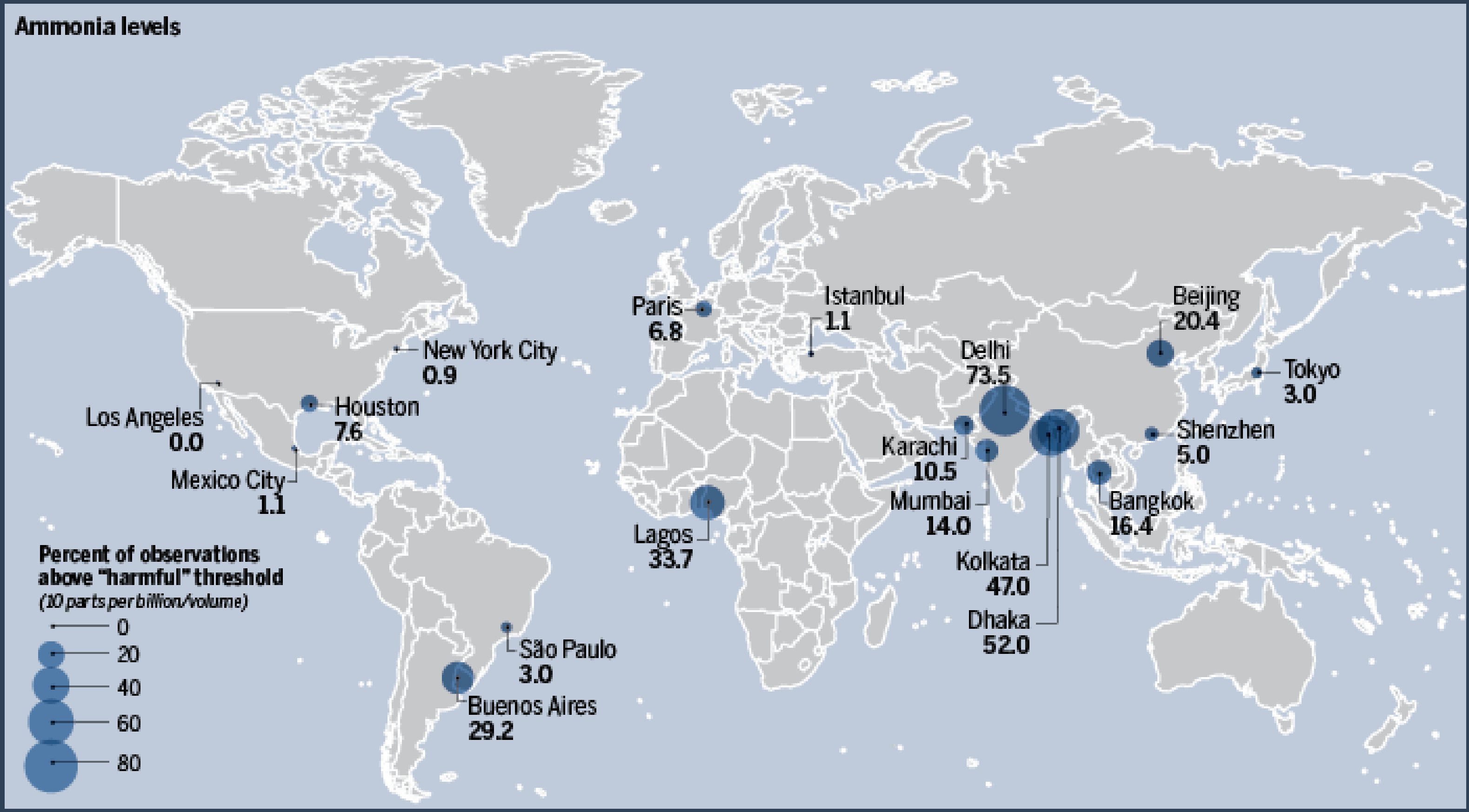

Calahorrano et al, in prep

# CrIS is revealing chemical transport and transformation




Calahorrano et al, *in press*

# New frontier in air quality: Ammonia



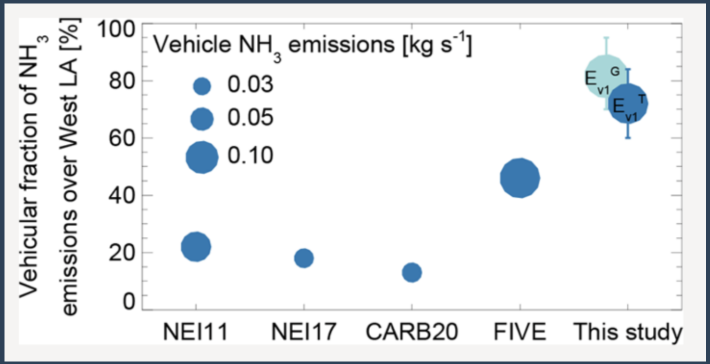

TES megacity observations show high ammonia in globally.

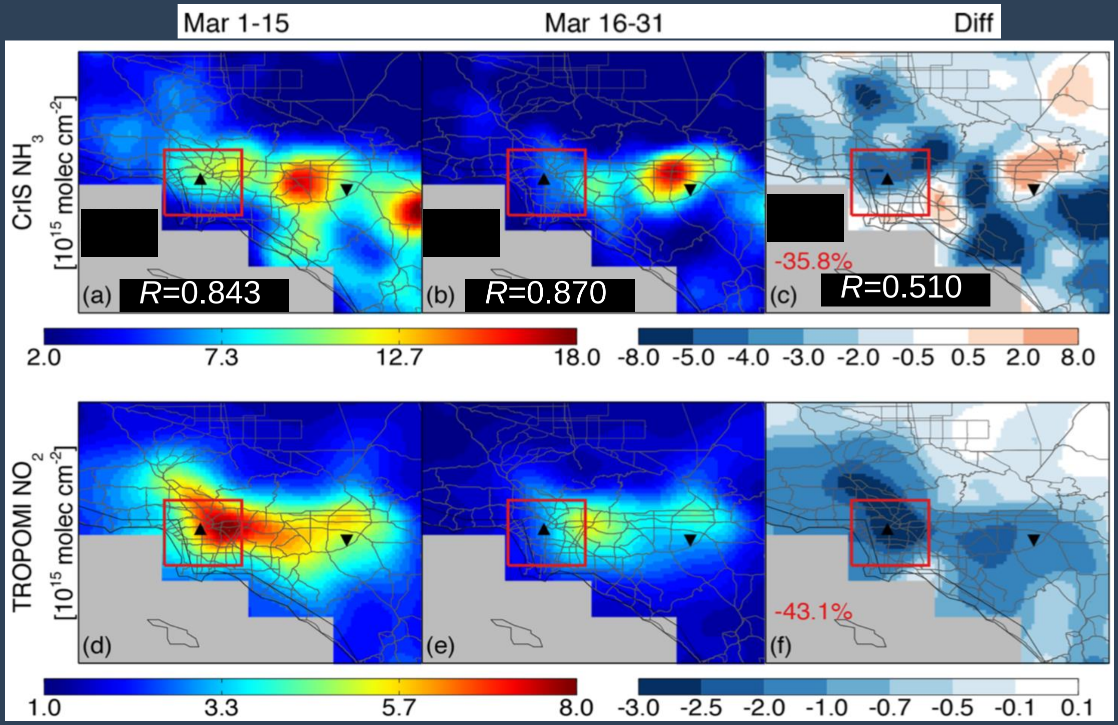
As Nox emission decrease, NH3 emissions will become increasingly important

(Graphic) G. Grullón/Science; (Data) JPL TES Science Team

# Ammonia emissions are unregulated but could become a dominant source of pollution

COVID-19 lockdowns provide a unique opportunity for making the first satellite-based constraints on vehicle NH3 emissions for an entire urban region (western Los Angeles), which was found to make up 60−95% of total NH3 emissions, substantially higher than the values of 13−22% in state and national inventories.





***Reference:*** *H. Cao, D. K. Henze, et al. (2021). COVID-19 lockdowns afford the first satellite-based confirmation that vehicles are an under-recognized source of urban $NH_3$ pollution in Los Angeles. Environmental Science & Technology Letters.* https://doi.org/10.1021/acs.estlett.1c00730

# Conclusions

- What is the ideal configuration for an IR sounder backbone?
  - Any IR sounder must be considered in the context of the CEOS Atmospheric Composition-Virtual Constellation (AC-VC)
  - Full exploitation of current and future sounders (IASI, IASI-NG, CrIS, CrIS+)
  - Morning and afternoon orbits better capture photochemical processes
- For IR, spectral resolution and range matter
  - The higher the resolution the closer we can measure where we breath.
  - Panspectral approaches: collocation with SWIR/NIR (O3, CO2, CO, CH4) are *essential* for near-surface resolution
  - SWIR/NIR are the backbone of carbon species (CO2,CO,CH4)
- For NH3 emissions, spatial resolution is important
  - Single pixel, field-of-view (rather than field of regard) at better resolution
- What additional IR measurements would be ideal to augment the backbone?
  - Climate change through disturbance (fires) and extreme events is a threat multiplier for human health
  - IR Geostationary sounders can capture the forcing/response relationships to climate extremes and the impact of fires as they develop
    - Potential for predictive skill and process understanding
- Which wavelengths are used/required in other applications?
  - Broad spectral range is needed to capture Earth System processes
- Observing System Simulation Experiments (OSSE) are recommended to quantify specific instrument requirements within the context of CEOS is highly recommended.

Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov