Trace Gas Products from High Resolution Infrared Instruments

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Presentation given at the
Community Workshop on Air Quality Remote Sensing from Space
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- Mitch Golberg (NOAA/NESDIS/STAR)
- Mous Chahine (NASA/JPL)
- Eric Maddy, Xingpin Liu, Xiaozhen Ziong, Jennifer Wei, Lihang Zhou (QSS, Inc.)

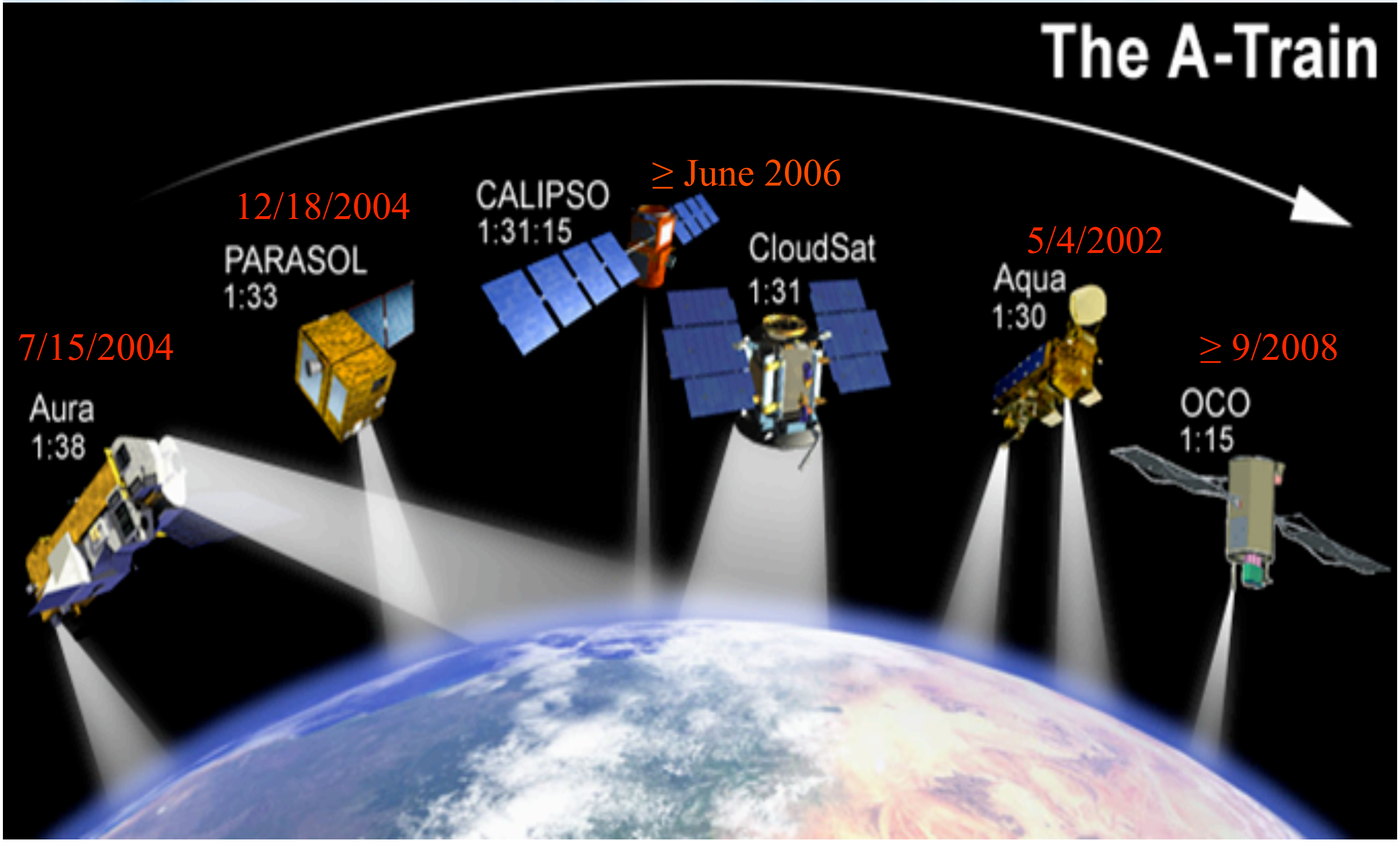
Outline of Presentation

- Overview of trace gases that can be monitored by operational thermal sounders.
- Product development plans at NOAA/NESIDS
- Overview and status of infrared trace gas products from AIRS
  - Ozone
  - Carbon monoxide
  - Methane
  - Carbon dioxide
  - SO2 volcanic event flag
- Summary & AIRS Science Team’s vision for future thermal sounders.

Collaborators

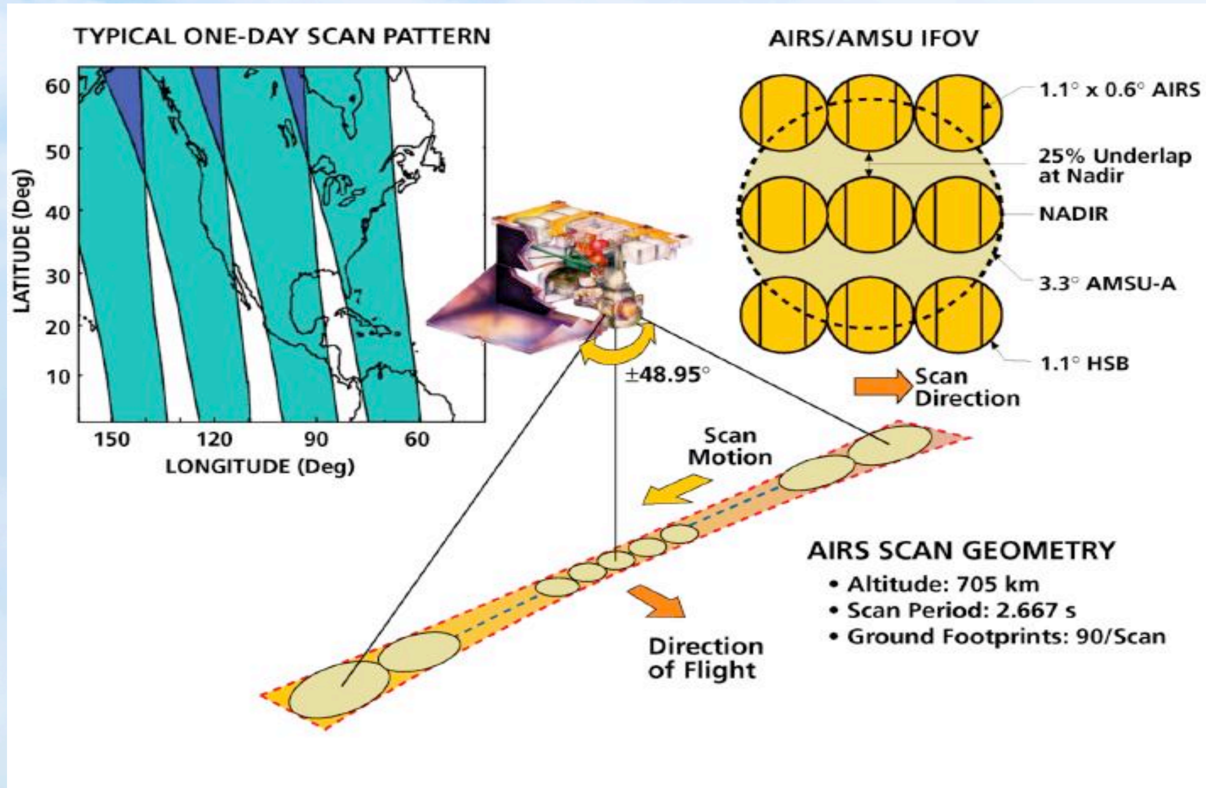
- Ozone Product:
  - Laura Pan
  - Bill Irion, Mike NewChurch
- CO Product:
  - Wallace McMillan, Juying Warner, Michele McCourt (UMBC)
- Real Time SO2 alert system
  - Walter Wolf, NOAA/NESDIS Star
  - JPL AIRS ST (Sung Yung Lee, Evan Manning)

AIRS, AMSU, & MODIS have a Unique Opportunity to Explore & Test New Algorithms for Future Operational Sounder Missions.



Thermal & Microwave Can be Used to Sound in Cloudy or Clear Scenes.

- Sounding is performed on a field of regard (FOR).
- FOR is currently defined by the size of the microwave footprint.
  - IASI has 4 FOV's per FOR
  - AIRS & CrIS have 9 FOV's per FOR.
- ATMS is spatially oversampled can emulates an AMSU FOR.



AIRS, IASI, and CrIS all acquire 324,000 FOR's per day

AIRS, IASI, and CrIS Products per 50 km field of regard (FOR)

- Cloud Cleared Radiance
- Temperature, 1K/ 1km
- Moisture, 15%/2km
- Ozone, 10% total column
- Land/Sea Surface Temperature, 1.0/0.5 K
- Surface Spectral Emissivity, 1%
- Surface Reflectivity, 5%
- Cloud Top Pressure, .5 km
- Cloud Liquid Water (AMSU product)

- Cloud Fraction, 5% (per 15 km footprint).
- Carbon Monoxide (CO), 15%
- Carbon Dioxide (CO_2), 1%
- Methane CH_4), 1%
- Sulfur Dioxide (SO_2), TBD
- Nitric Acid (HNO_3), TBD
- Nitrous Oxide (N_2O), TBD
- Cirrus Cloud Optical Depth and Particle Size, TBD

NOTE: AIRS Core products must be flawless before trace gas products are viable.

NOAA/NESDIS Strategy: Use existing operational sounders.

Polar orbiting instruments provide global soundings in cloudy or clear conditions for the next 20+ years.

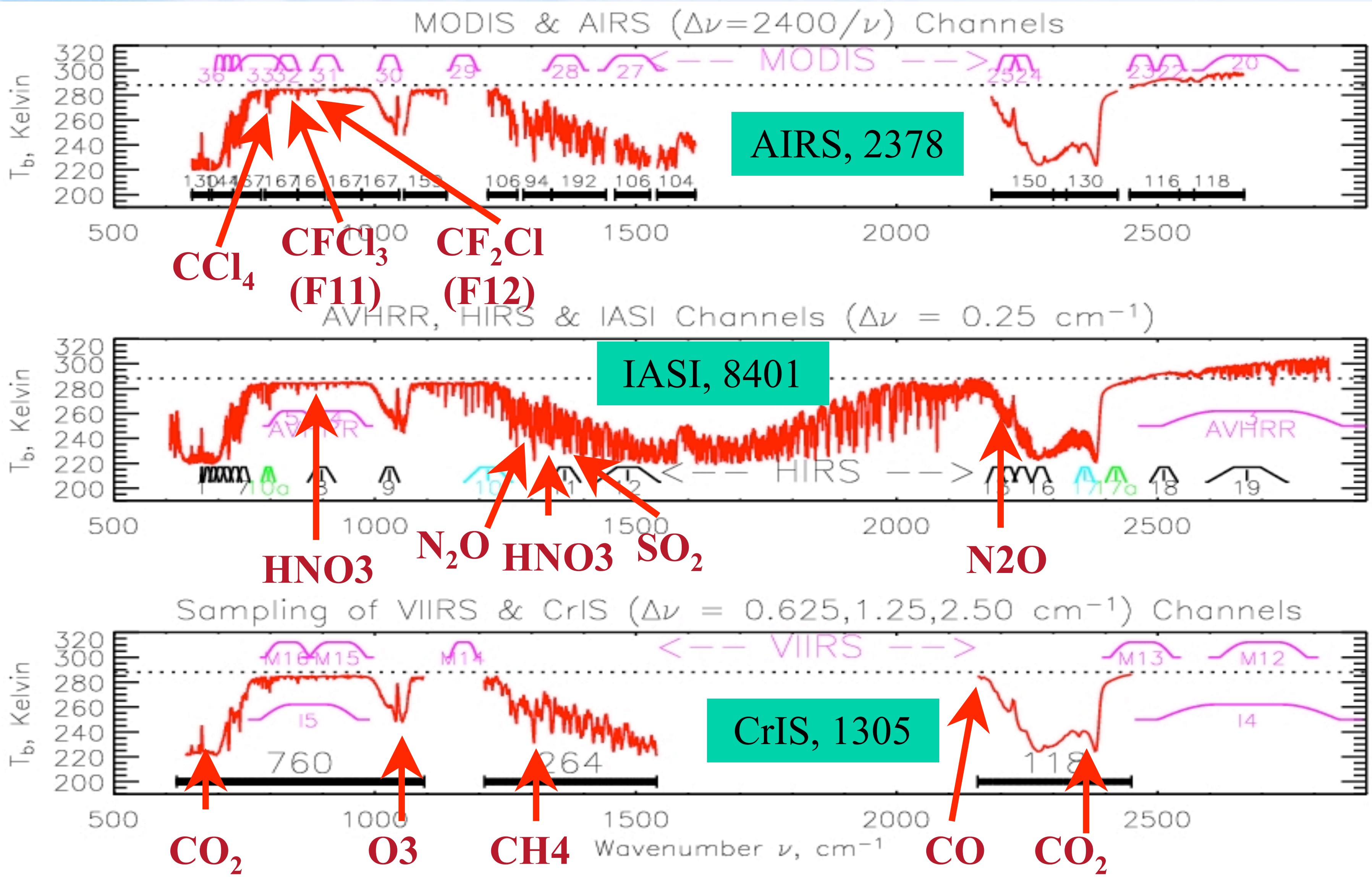
- Now: Develop core and test trace gas algorithms using the Aqua AIRS/AMSU/MODIS (May 4, 2002) Instruments
  - Compare products to *in-situ* (*e.g*., CMDL Aircraft, JAL, INTEX, etc.) to characterize error characteristics.
  - The A-train complement of instruments (*e.g*., MODIS, AMSR, Calipso) can be used to study effects of clouds, surface emissivity, etc.
- 2006: Migrate the AIRS/AMSU/MODIS algorithm into operations with METOP/IASI/AVHRR (2006,2011,2016)
  - Study the differences between grating and interferometric measurements, *e.g*., effects of scene and clouds on the instrument line-shape.
- 2008: Migrate the AIRS/IASI algorithm into operations for NPP (2008) & NPOESS (2012,2015) CrIS/ATMS/VIIRS. These are part of the "NOAA Unique Products" within the NOAA NPOESS Data Exploitation (NDE) program.
- 2012: Migrate AIRS/IASI/CrIS algorithm into GOES-R/HES/ABI

Trace Gas Product Potential from Operational Thermal Sounders

gas	Range (cm^{-1})	Precision	Interference	
O_3	1025-1050	5%	H2O,emissivity	
CO	2080-2200	15%	H2O,N2O	
CH_4	1250-1370	20 ppb	H2O,HNO3	Working
CO_2	680-795	2 ppm	H2O,O3	
	2375-2395	2 ppm		
SO_2	1340-1380	1000%	H2O,HNO3	
HNO_3	860-920	20%	emissivity	In Work
	1320-1330	25%	H2O,CH4	
N_2O	1250-1315	1%	H2O	
	2180-2250	1%	H2O,CO	
$CFCl_3$ (F11)	830-860	20%	emissivity	
CF_2Cl (F12)	900-940	20%	emissivity	Held Fixed
CCl_4	790-805	50%	emissivity	

Haskins, R.D. and L.D. Kaplan 1993

Spectral Coverage of AIRS, IASI, and CrIS

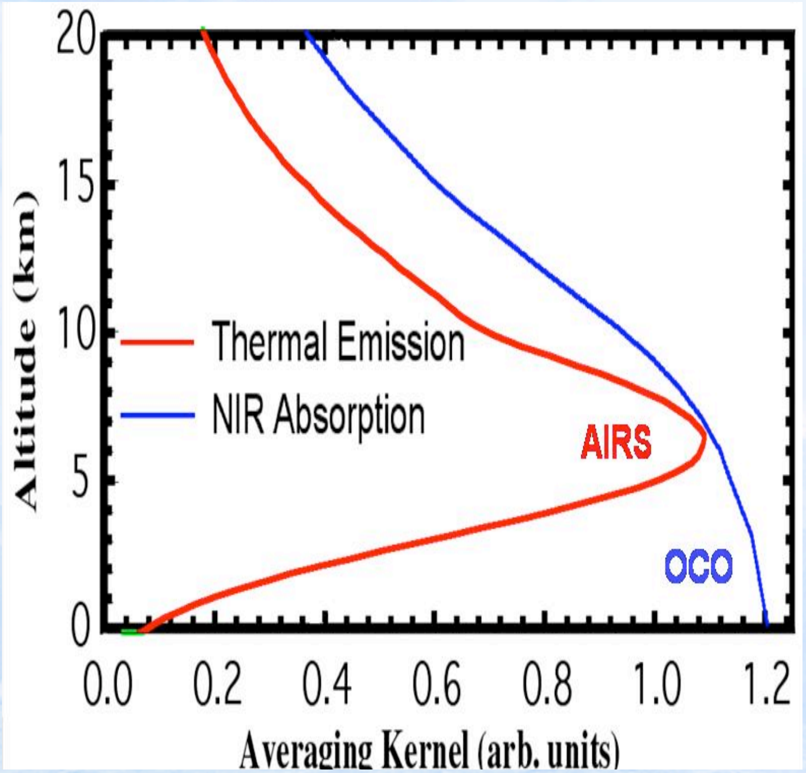


Retrieval of Atmospheric Trace Gases Requires Unprecedented Instrument Specifications

- **Need Large Spectral Coverage (multiple bands) & High Sampling**
  - Increases the number of unique pieces of information
    - Ability to remove cloud and aerosol effects.
    - Allow simultaneous retrievals of T(p), q(p), O_3(p).
- **Need High Spectral Resolution & Spectral Purity**
  - Ability to isolate spectral features → vertical resolution
  - Ability to minimize sensitivity to interference signals..
- **Need Excellent Instrument Noise & Instrument Stability**
  - Low NEΔT is required.
  - Minimal systematic effects (scan angle polarization, day/night orbital effects, etc.)

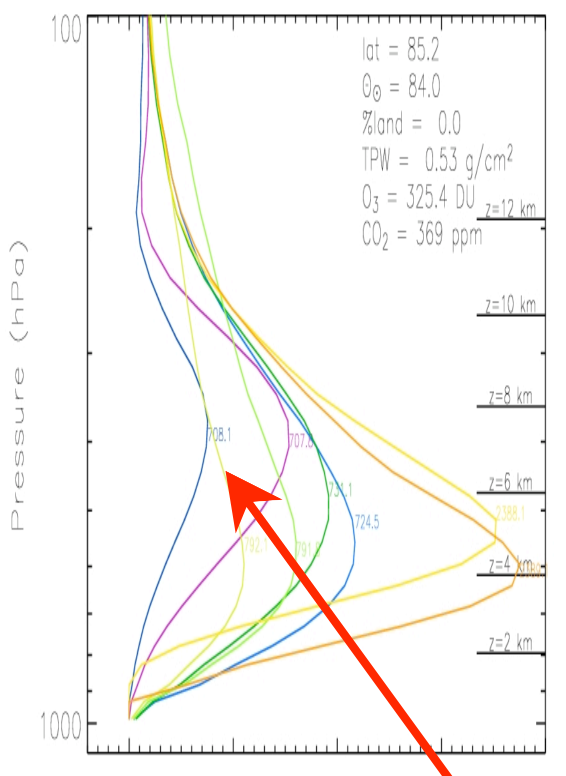
Deriving sources and sinks require knowledge of vertical averaging

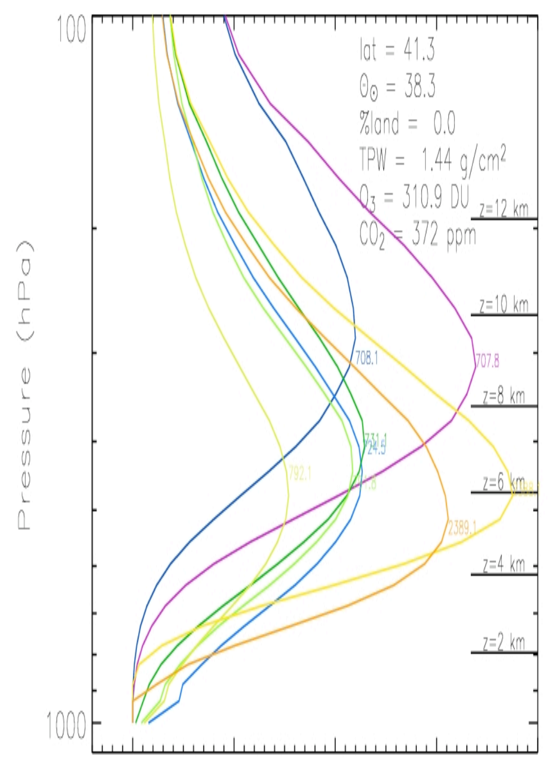
- Thermal instruments measure a mid-tropospheric column
  - Age of air is on the order of weeks or months.
  - Significant horizontal and vertical displacements of gases can occur from the sources.
  - Surface source/sink signals are attenuated.
- Vertical weighting function is a function of the temperature profile & composition of the atmosphere.
- Passive Solar (*e.g.*, SCIAMACHY & OCO) & LIDAR measure total column.

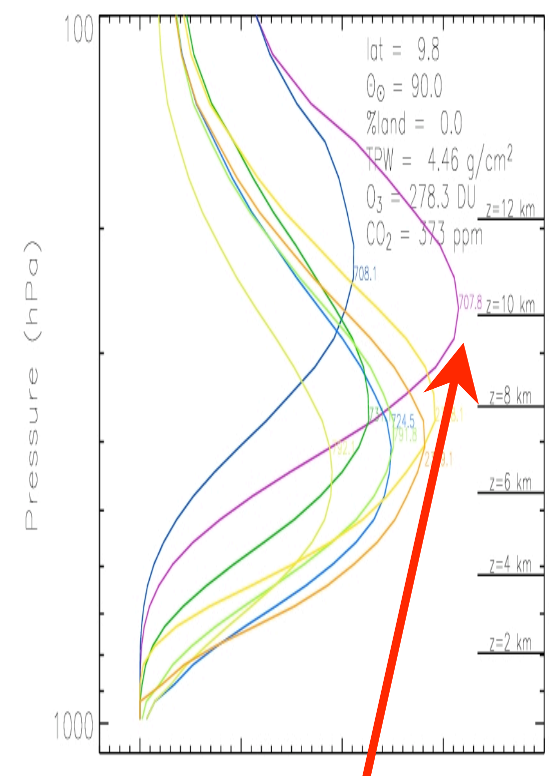


Thermal Trace Gas Kernel Functions are also Sensitive to H_2O, T(p), & O_3(p).

Polar	Mid-Latitude	Tropical
TPW = 0.5 cm	TPW = 1.4 cm	TPW = 2.5 cm







Isothermal vertical structure weakens sensitivity

moisture optical depth pushes peak sensitivity upwards.

Ozone

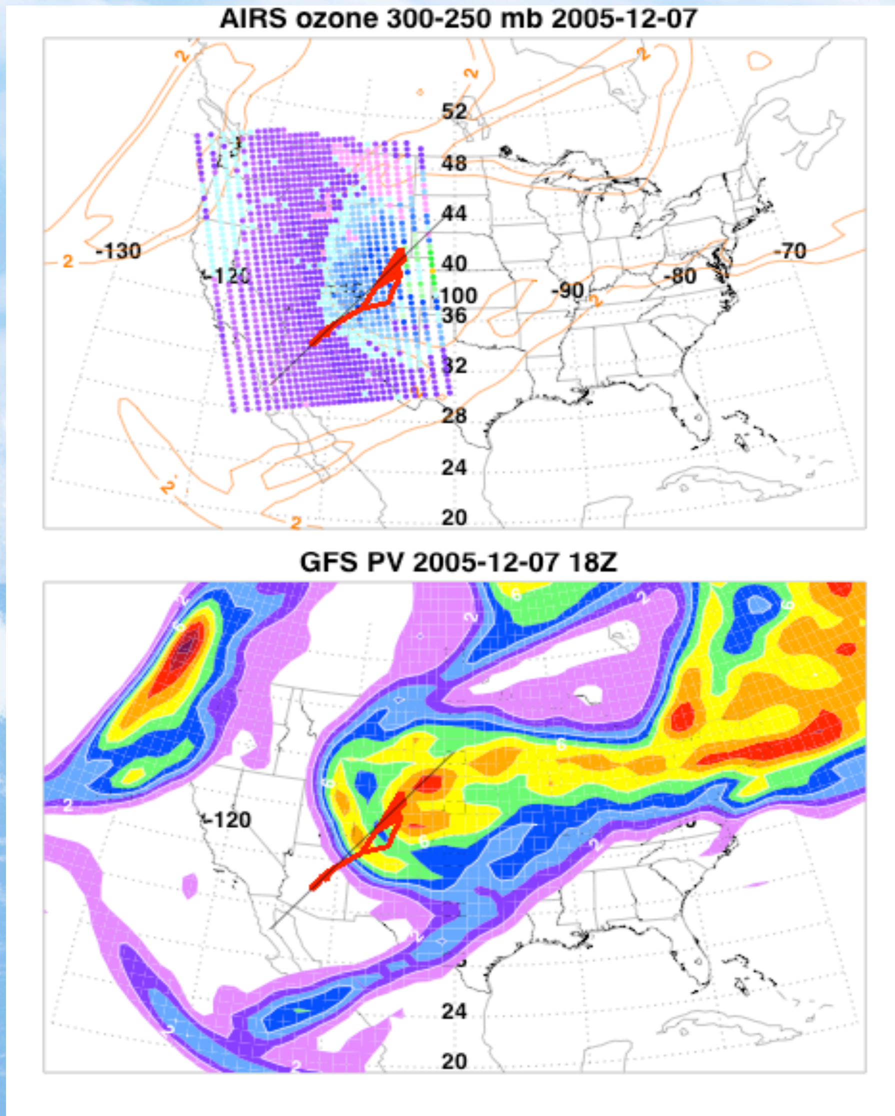
- AIRS observes Ozone in daytime and nighttime using the 9.8 μm band.
- Validation campaign includes
  - dedicated ozone sondes (Mike NewChurch, UAH)
  - Comparisons w/ TOMS and Aura/OMI (Bill Irion, JPL)
  - In-situ measurements: START (Laura Pan, NCAR)
- Total column product (derived from profile) looks good; however, at this time we have issues with biases in the profile product.
  - Spectroscopy issues
  - Retrieval algorithm issues:
    - Training of statistical regression with ECMWF
    - Damping of physical retrieval.

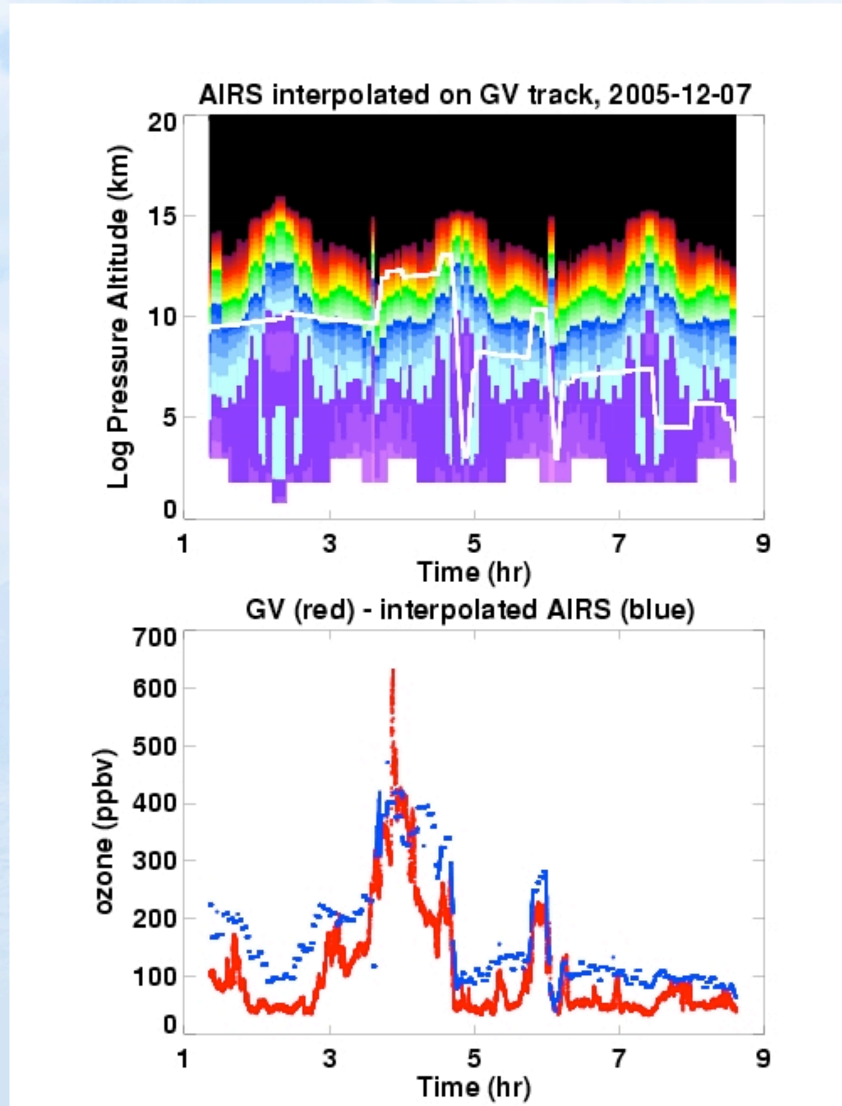
Stratospheric-Tropospheric Analysis of Regional Transport (START) Experiment

- Laura Pan is PI of START Ozone team
- Nov. 21 to Dec. 23, 2005, 48 flight hours using NCAR's new Golfstream V "HAIPER" aircraft.
- Ozone measured with NCAR's UV-abs spectrometer

- NOAA NESDIS supported this experiment with real time AIRS L1b & L2 products, including ozone and carbon monoxide.
- Jennifer Wei is the NOAA/NESDIS liason to START team.
  - 3 stratospheric fold events were measured during this campaign
  - analysis is in process.

Example START omparison for Dec. 7, 2005 (Courtesy of Laura Pan, NCAR)

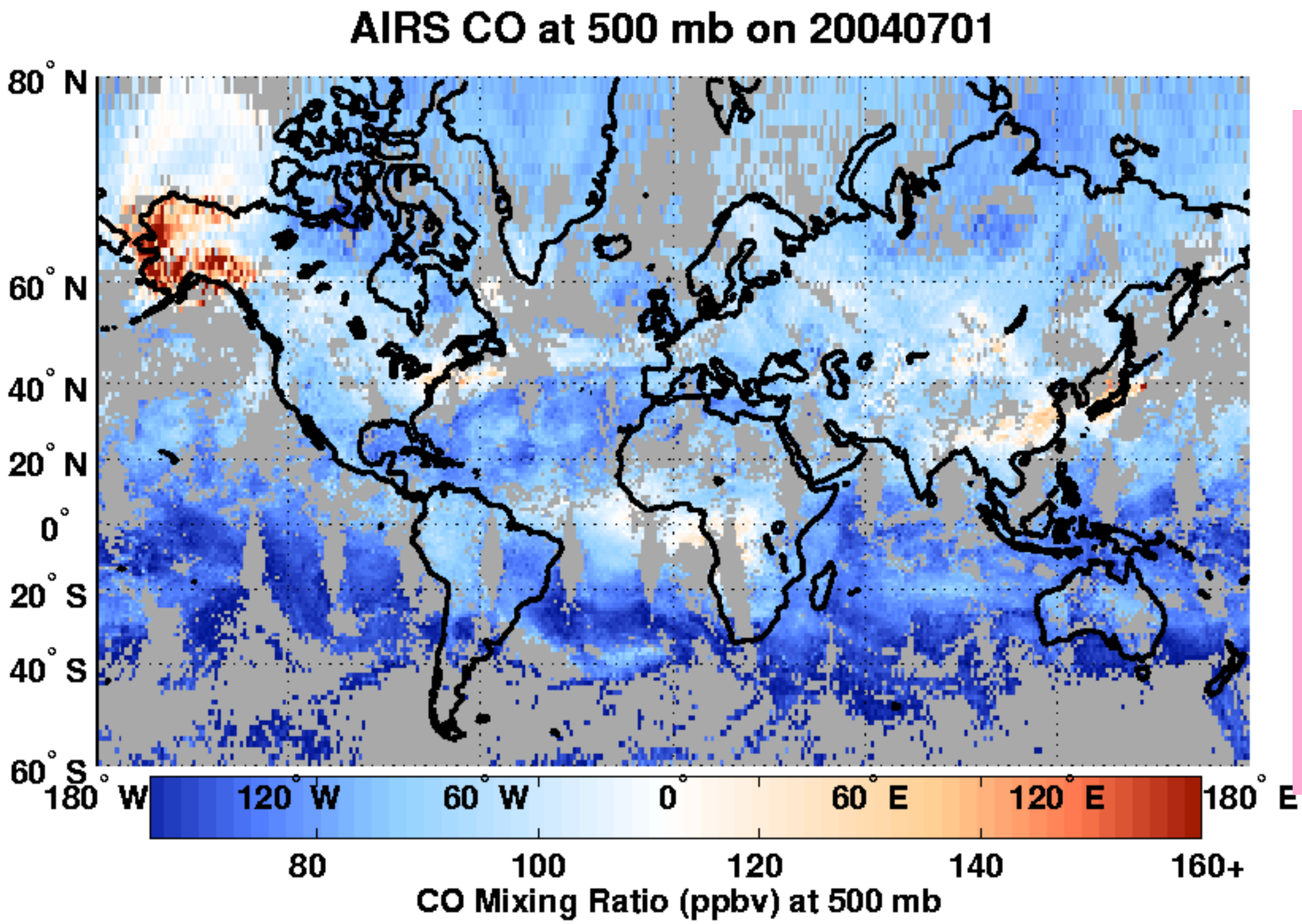




Carbon Monoxide

- Concentration varies between 50 to 200 ppbv
- Lifetime is a few months
- Sources (Lelieveld, 1998):
  - Fossil fuel combustion (one reason for catalytic converter on automobiles) ≈ 550 Tg/yr
  - Forest Fires & Biomass Burning ≈ 400 Tg/yr
  - Methane Oxidation ≈ 850 Tg/yr

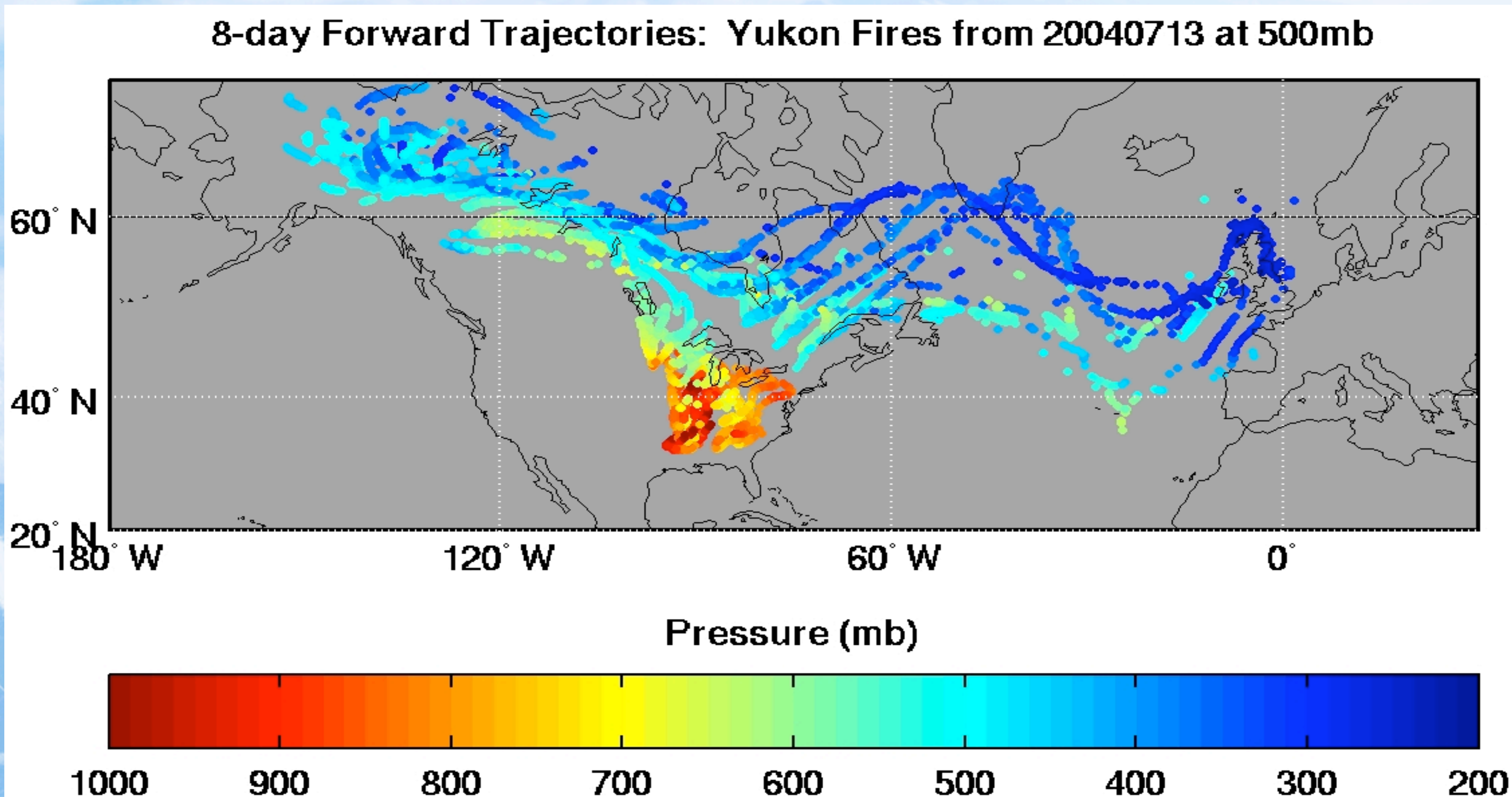
July 2004
AIRS Daily Global CO



Analysis of NOAA products by Wallace McMillan, Juying Warner, & Michele McCourt

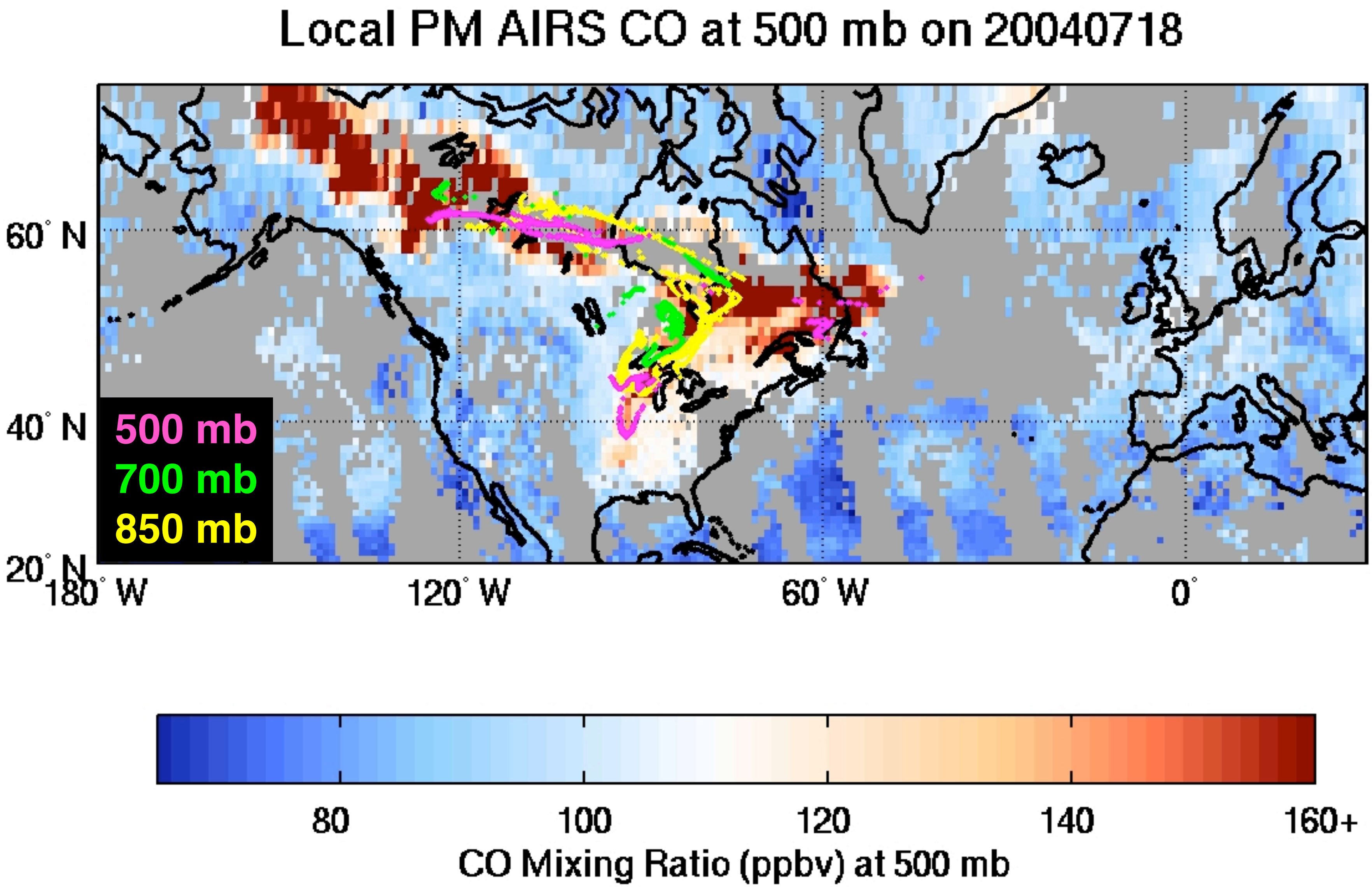
Univ. Maryland, Baltimore County (UMBC)

Trajectory models of transport of CO
Wallace McMillan, et al, UMBC

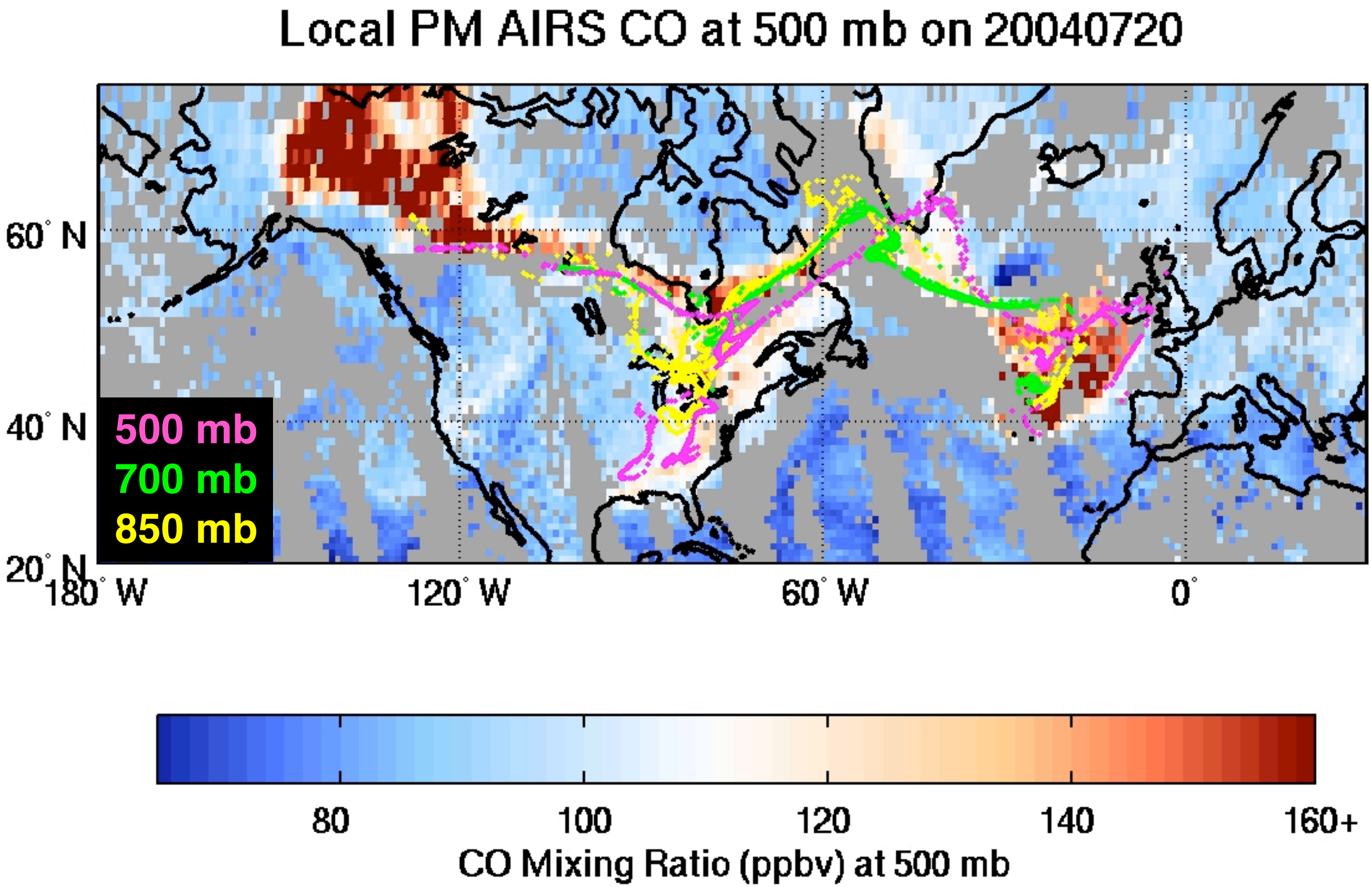


- NASA Goddard kinematic trajectory model with AVN winds
- Initialized at 500mb 1200 UTC 13 July 2004 from fires

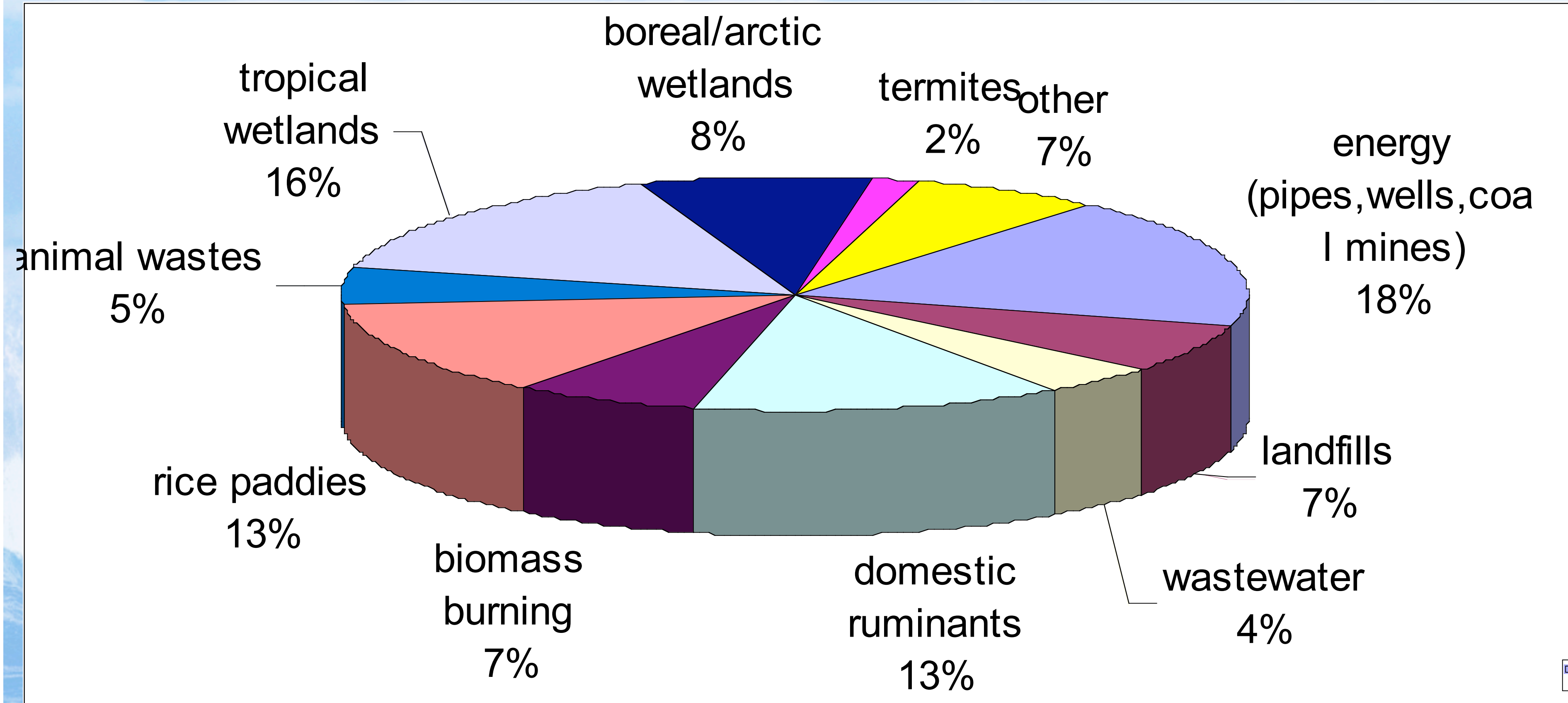
AIRS CO and Trajectories



AIRS CO and Trajectories



Methane Sources



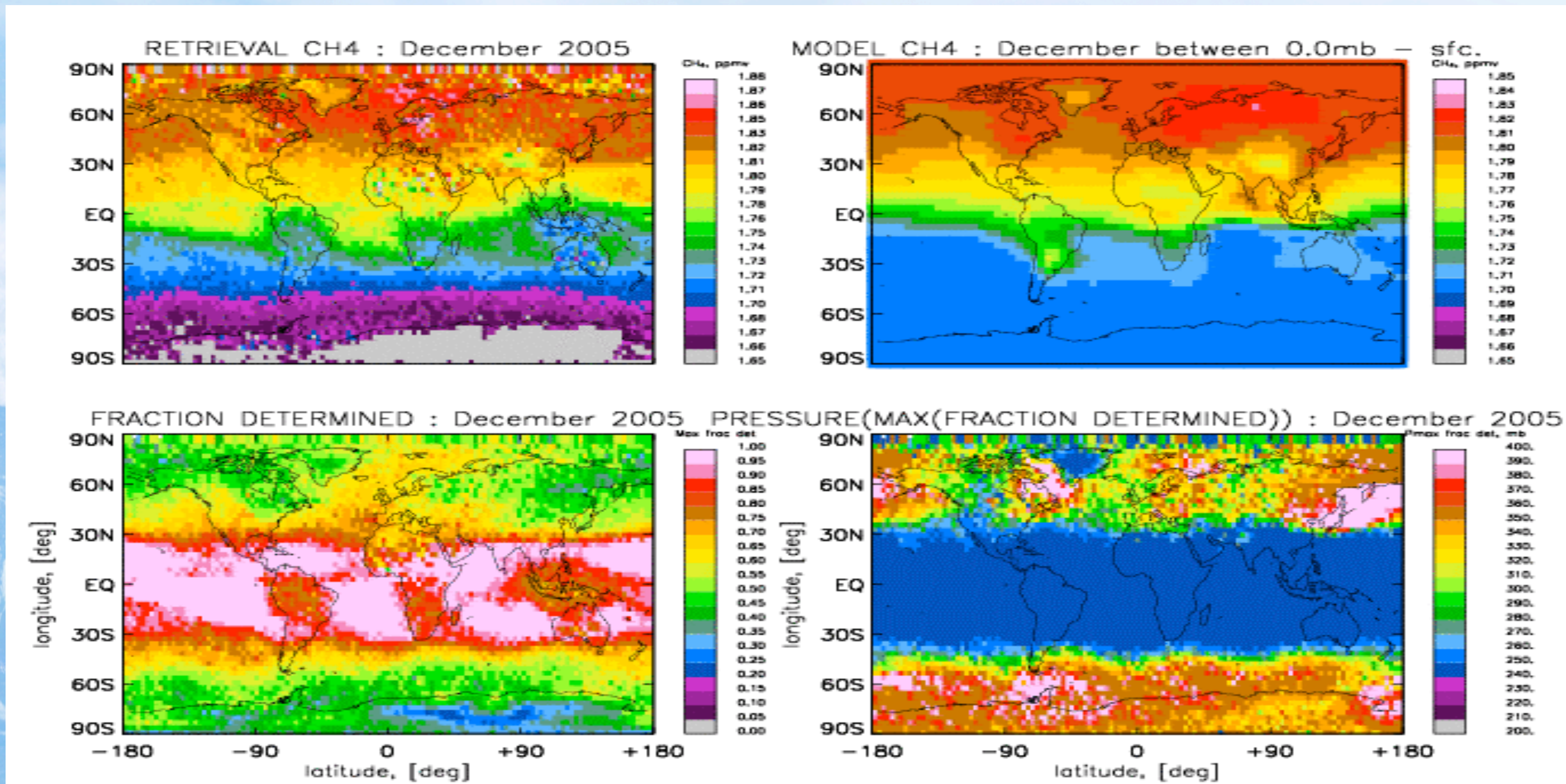
Ref.: Lelieveld, 1998 & Houwelling 2002 (600 Tg total)

Note: Trees (Keppler et al. 2005) may contribute 62-235 Tg (10-35%), mostly in tropics

Representing the vertical information content to compare CH4 product with models

AIRS mid-trop measurement column

CH4 total column f/ transport model (Sander Houweling, SRON)



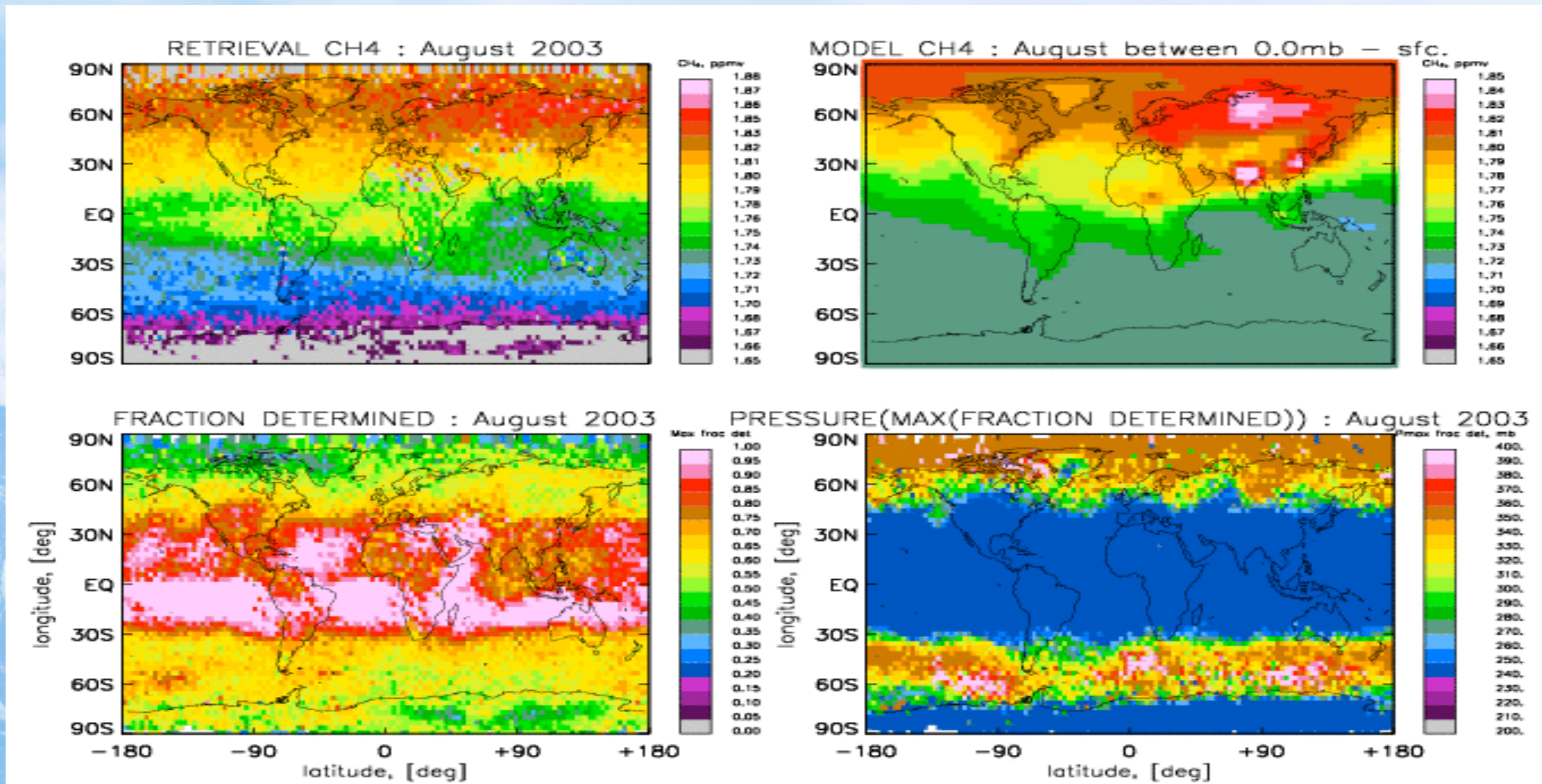
Fraction Determined from AIRS Radiances

Peak Pressure of AIRS Sensitivity

29 Months of AIRS Methane Product

AIRS mid-trop measurement column

CH4 total column f/ transport model (Sander Houweling, SRON)



Fraction Determined from AIRS Radiances

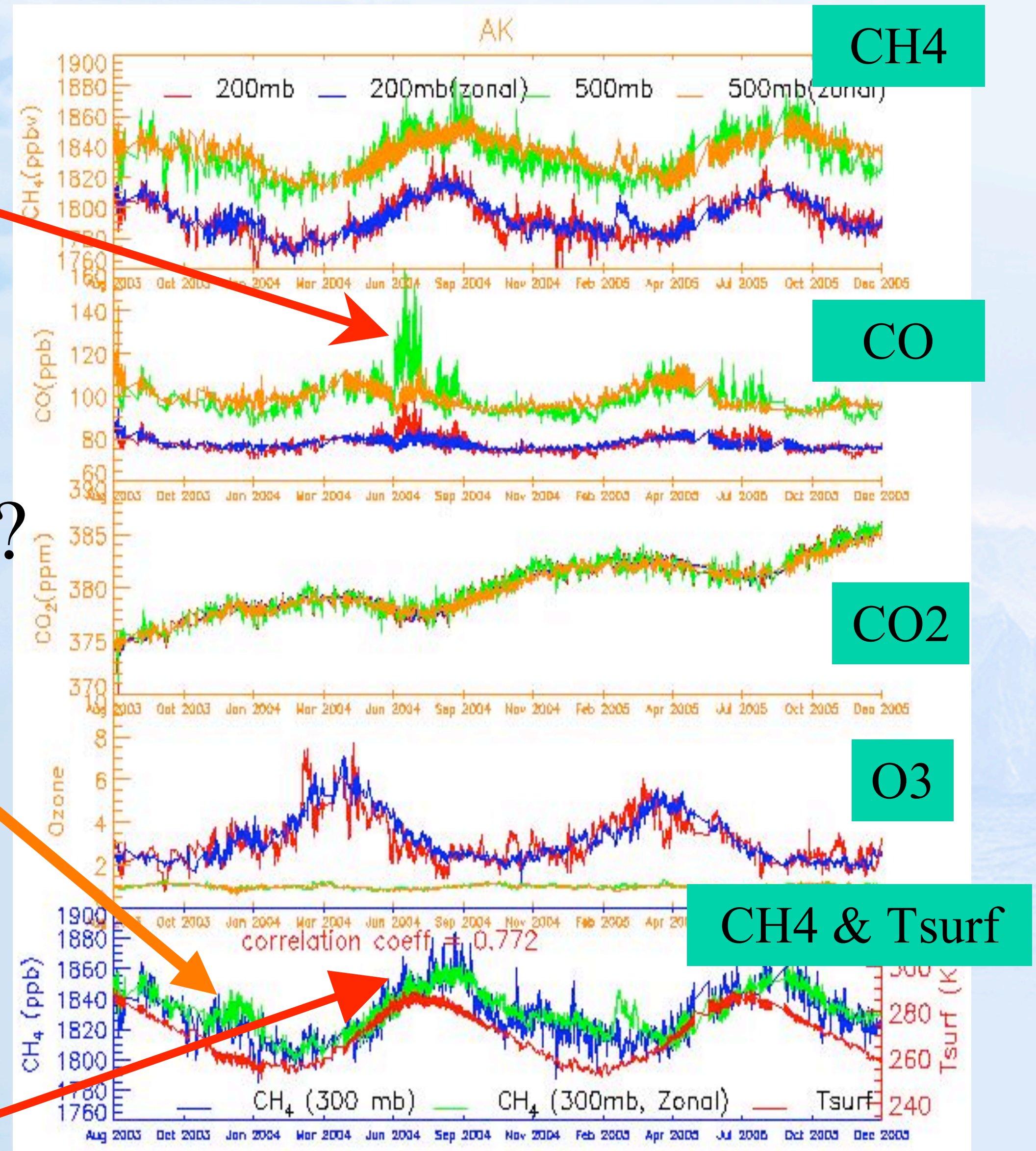
Peak Pressure of AIRS Sensitivity

29 month time-series of AIRS products
Alaska & Canada Zone (60-70 lat, -165 to-90 lng)

Fire
(7/04)

Gas Leak??

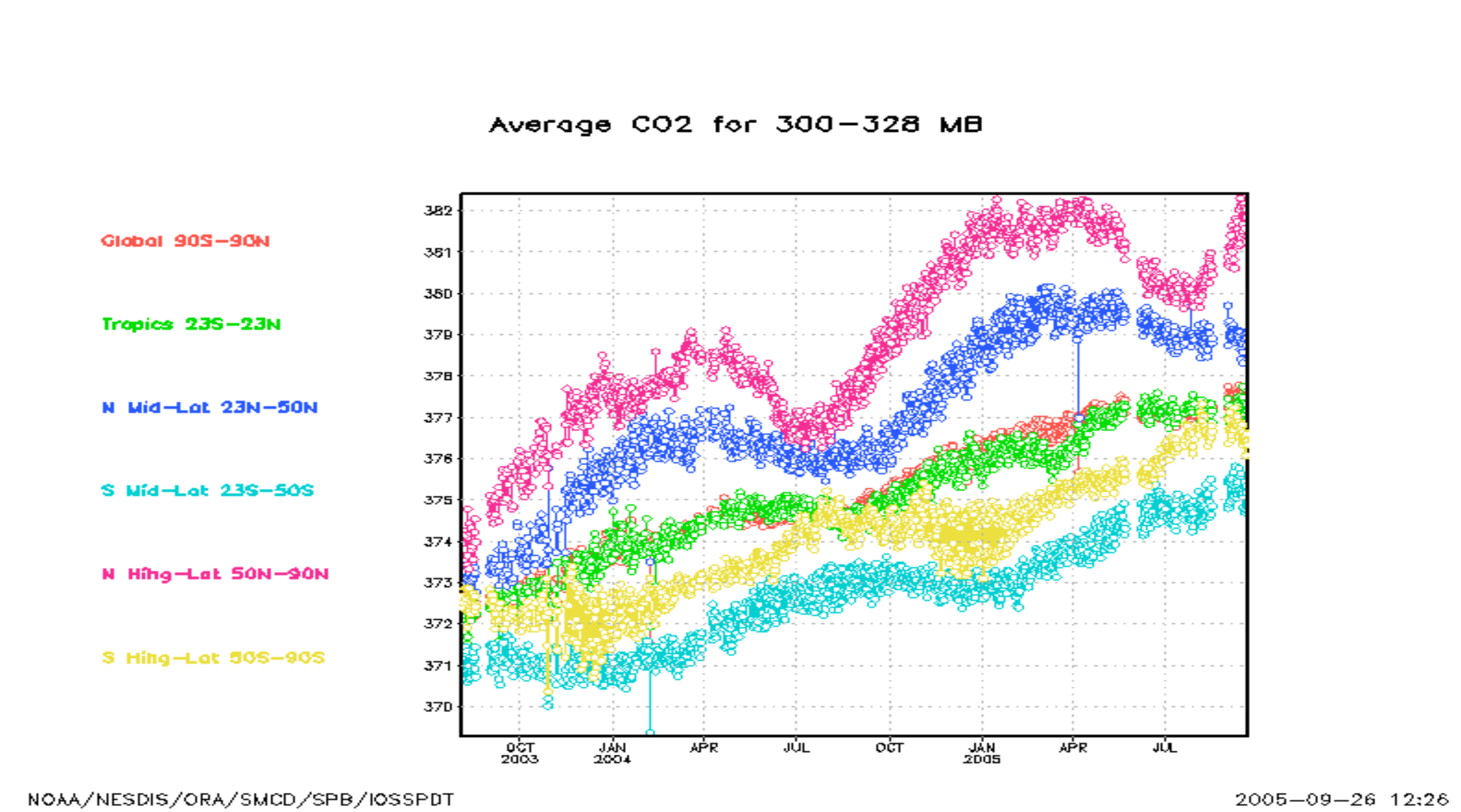
Wetlands?



Carbon Dioxide and the Carbon Budget

- Lifetime in atmosphere is $\approx$ 100 years
  - conversion to limestone ($CaCO_2$) is main sink.
- +5.5 ± .3 GT-C/yr from fossil fuel emissions
  - A car emits 5 lbs of C per gallon, at 25 m/g that is a charcoal briquette every ¼ mile (Gerry Stokes)
- +1.6 ± .8 GT/yr from biomass burning
- Atmospheric concentration is well measured (Charles Keeling, Scripts) + 1.5 ppmv-CO2/yr = 3.3 ± .1 GT-C/yr
- Huge Terrestrial Annual Exchange (photosynthesis/respiration), 90 GT-C/yr
- Huge Ocean Exchange (phytoplanckton life cycle),
  - 90 GT-C/yr exchange
  - NET sink of -2.0 ± .2 GT-C/yr
- -1.8 ± 0.9 GT-C/yr unknown sink
  - Most like terrestrial or unknown ocean process.

NOAA AIRS product is the first climatology of CO_2 in the mid-troposphere



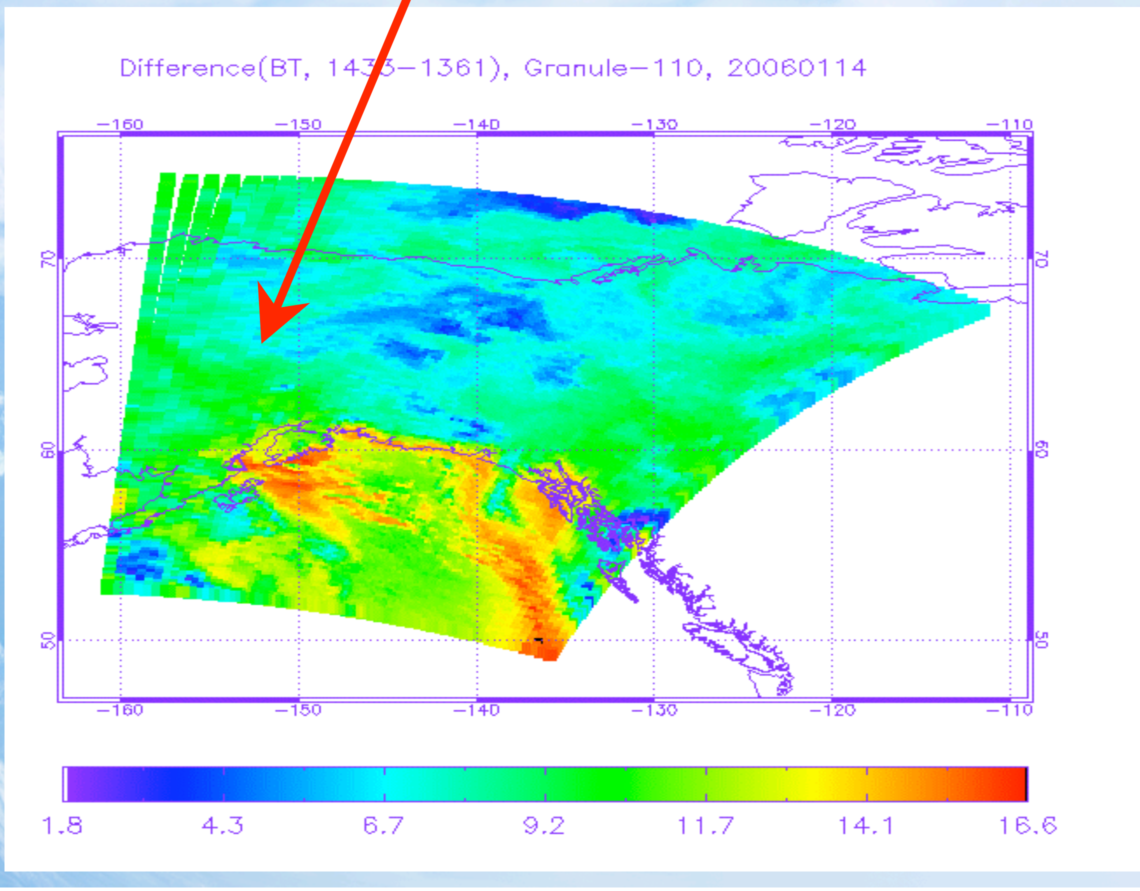
- Currently, using only LW we get reasonable seasonal & latitudinal structure
- Precision of ≈ 2 ppmv appears to be plausible on biweekly global maps.
- Recent work on spectroscopic corrects will allow use of LW & SW bands

NOAA AIRS CO2 Product is Still in Development

- Measuring a product to 0.5% is inherently difficult
  - Empirical bias correction (a.k.a. tuning) for AIRS is at the 0.1 K level and can interfere with the CO2 signal.
  - Errors in moisture of ±10% is equivalent to ±0.7 ppmv errors in CO2.
  - Errors in surface pressure of ±5 mb induce ±1.8 ppmv errors in CO2.
  - AMSU side-lobe errors prohibit using 57 GHZ O2 band as a T(p) reference point.
- We can characterize seasonal and latitudinal variability.
- The real questions is whether thermal sounders can contribute to the source/sink questions.
  - Requires accurate vertical & horizontal transport models
  - Having simultaneous O3, CO, CH4, and CO2 products may be the unique contribution that thermal sounders can make.

SO2 volcanic event flag is operational in real-time with e-mail alert system

Augustine Volcano [Alaska 59.37 N, 153.42 W]
summit elevation 1252 m
The volcano is located 290km SW of Anchorage.



SO2 flag (7.3 um) and automatic alert system is implemented at NOAA/NESDIS

Working on a collaboration with A .J. (Fred) Prata to develop near real-time SO2 product.

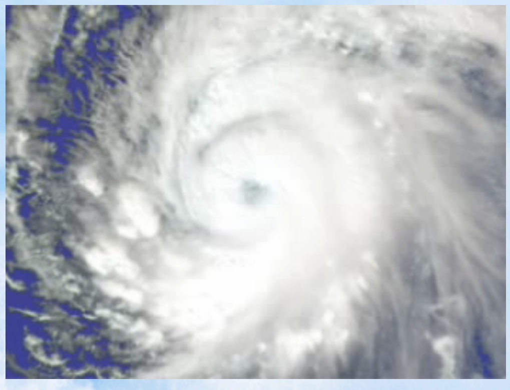
Conclusions and Summary

- High spectral resolution operational thermal sounders have the capability of measuring mid-tropospheric concentrations of atmospheric trace gases globally for the next 20+ years.
- CO product is robust and validation experiments are underway (e.g., INTEX, W. McMillan, UMBC)
  - Preliminary trajectory models explain transport of CO from fires.
- CH_4 is difficult: preliminary analysis appears promising.
- CO_2 is significantly more difficult and many algorithms are being inter-compared. Re-processing of acquired AIRS radiances (30 months, so far) to optimize algoirithm.
- AIRS, IASI, and CrIS may contribute to source/sink determination by simultanously measuring T(p), q(p), O_3(p), CO, CH_4, & CO2 globally.
- Other gases products (HNO_3, SO_2, N_2O) are in-work.

What is the Future Evolution of Thermal Sounders?
AIRS Science Team Concept: ARIES

Improved:
- **Cloud Clearing**
- **Surface Emissivity**
- **Retrievals over Land**

AIRS High Spectral



AIRS
- 13.5 km IR IFOV
- 3.7-15.4 μm IR
- 2378 IR Channels
- $\lambda/\Delta\lambda = 1200$
- NEdT = 0.05 - 0.3 K
- ± 50° FOV

High Spatial / High Spectral

ARIES
- 1 km IR IFOV
  250 x 250 km imaging
- 3.6-15.4 μm IR
- >2000 IR Channels
- $\lambda/\Delta\lambda > 1000$
- NEdT = 0.1 - 0.3 K
- ± 55° FOV

MODIS High Spatial

MODIS
- 1 km IR IFOV
- 3.7-14.2 μm IR
- 16 IR Channels
- $\lambda/\Delta\lambda = 20\text{-}50$
- NEdT = 0.05 - 0.3 K
- ± 55° FOV