AIRS Contribution to Climate and Air Quality Studies – a Focus on Algorithm Refinement and Validation

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and

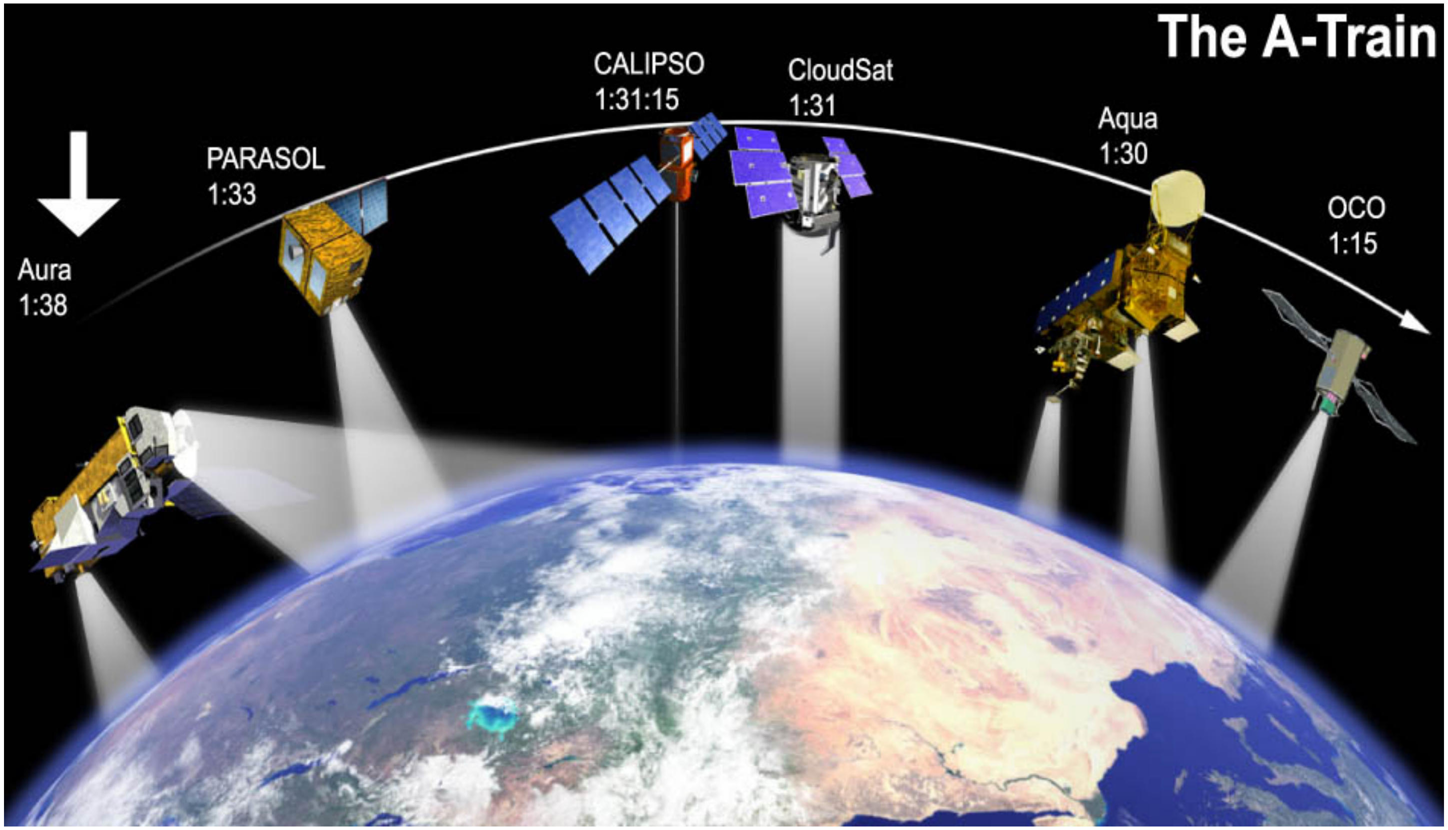
AIRS, TES, MODIS, INTEX-B, and ARCTAS science teams

- Supported through ROSES by:
    - the Atmospheric Composition,
    - the Tropospheric Chemistry Program,
    - the Science of Terra and Aqua,
    - the Climate Record Uncertainty Analysis Program
- Sub-contract by NASA JPL AIRS team

Topics

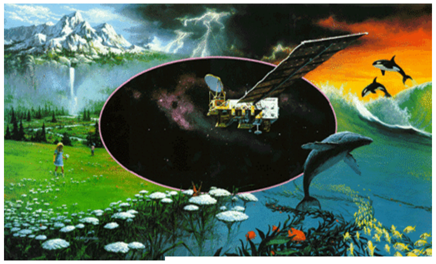
- Refine retrieval algorithms to best use measured signals and prior information based on the understanding of the retrieval quality from satellite measurements through validation and intercomparison - AIRS, MOPITT, and TES CO;
- Impact of cloud on the tropospheric CO variability from AIRS;
- Development of new products: AIRS Ammonia (NH_3) and HDO, and IASI CO.

A-Train

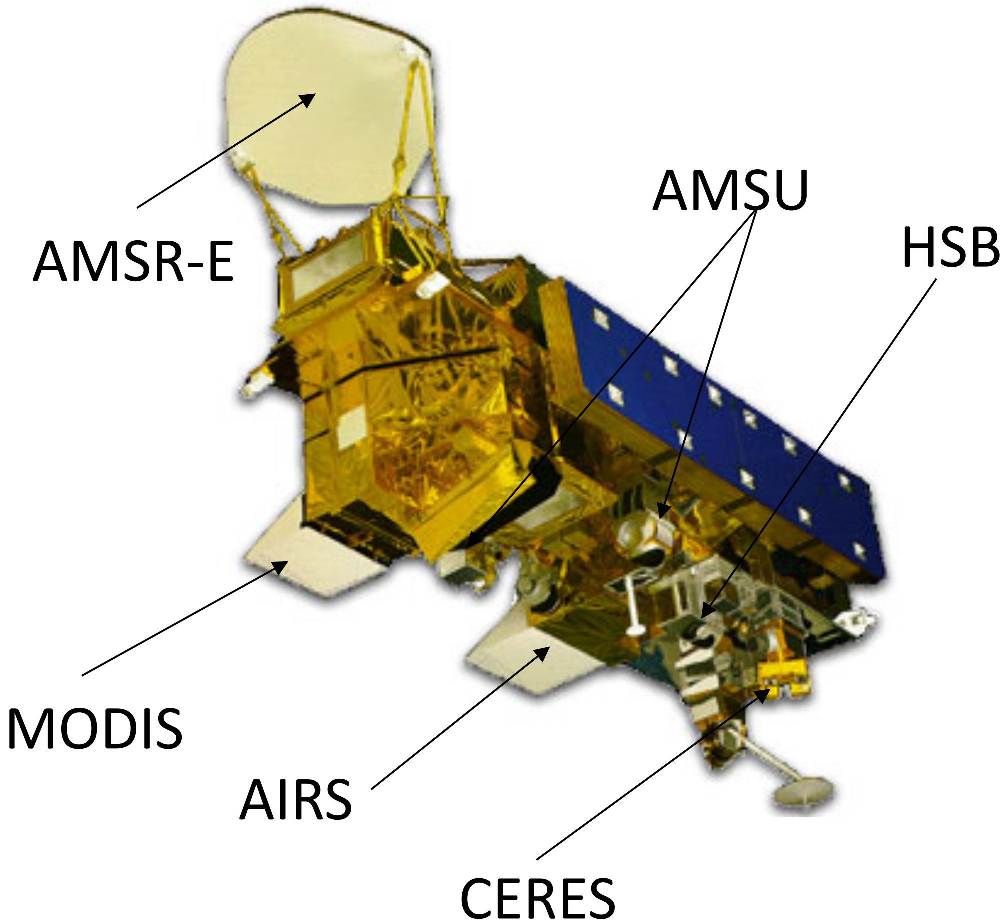


Benefited from near simultaneous measurements:

- AIRS/Aqua and TES/Aura make measurements within 15 minutes.
- MODIS/Aqua cloud mask helps AIRS cloud related studies.



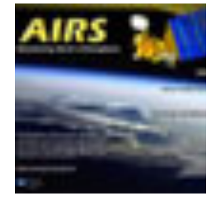
Earth Observing System
Aqua Satellite



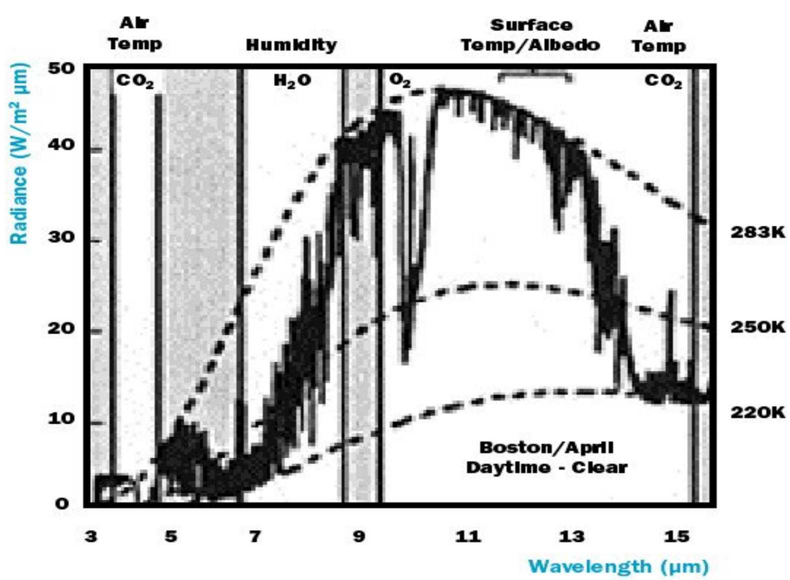
- AMSU used for AIRS cloud-clearing and T and H2O retrievals in addition to AIRS thermal channels.
- MODIS AOD and fire counts used jointly with AIRS for transport and biomass burning studies.
- MODIS cloud mask helps us to study AIRS cloud related products.

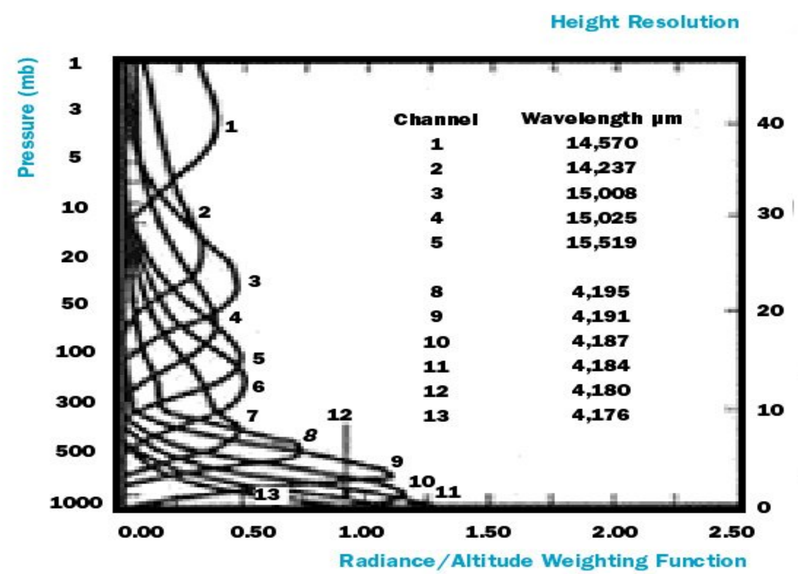
Launch date: May 4, 2002, 2:55 PDT
Earth view door open date: June 25, 2002

Atmospheric Infrared Sounder



- A grating spectrometer originally designed to improve weather forecast and now also used for climate and air quality studies.
- Spectral resolution at ν/1200 (~ 0.5 cm^{-1})
- Covers 650-2665 cm^{-1} in three bands with a total of 2378 channels
- Spatial resolution 13.5 km^2 (with retrievals at ~45 km^2)
- Wide swaths (1650km) and cloud clearing provide daily global coverage
- Very high Signal-to-Noise accuracies of 1K over 1 km-layer.





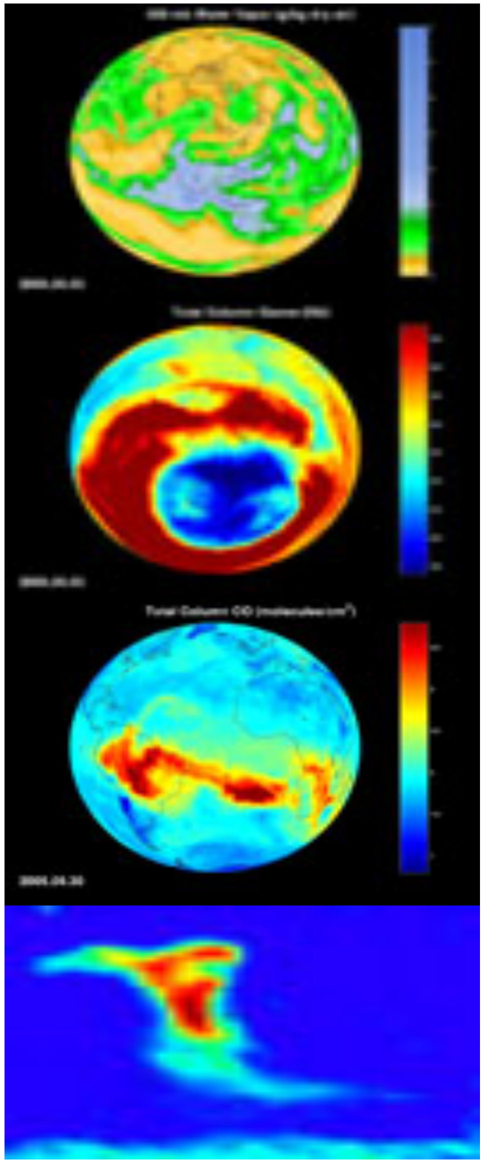
Atmospheric Infrared Sounder

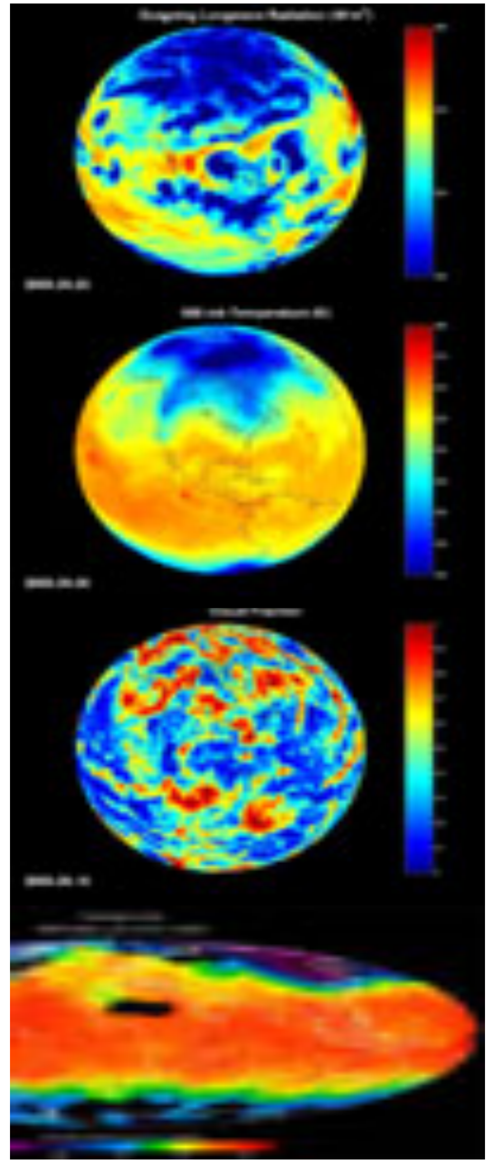
H2O

O_3

CO

SO_2 and dust





OLR

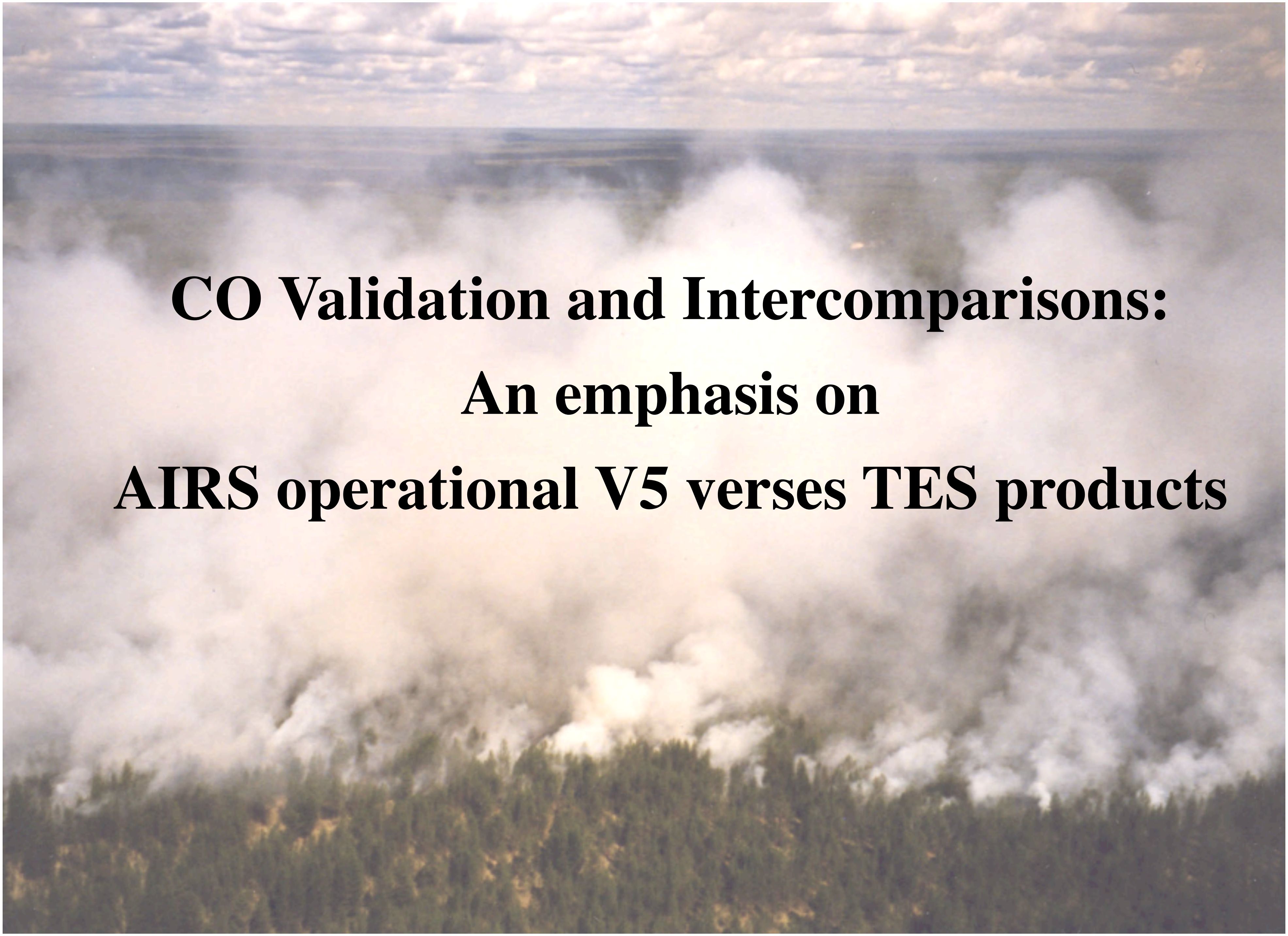
Temperatures

Cloud Fraction

CO_2

WHY Carbon Monoxide (CO) in Climate and Air Quality Studies

- CO directly impact the concentration of the OH radical through the atmospheric oxidation of CO, and hence, affects the rate at which many natural occurring and anthropogenic trace species are removed from the atmosphere.
- Oxidation of CO in the presence of NOx is a major contribution to tropospheric ozone production.
- CO a good tracer for studying transport in the atmosphere since the tropospheric CO is emitted by surface sources that include biomass burning, industrial pollution, etc., and it has a lifetime of approximately 2 months.
- Pollutants transport between continents such that local emissions affect global distribution and the transported global pollution affects air quality in local scales.

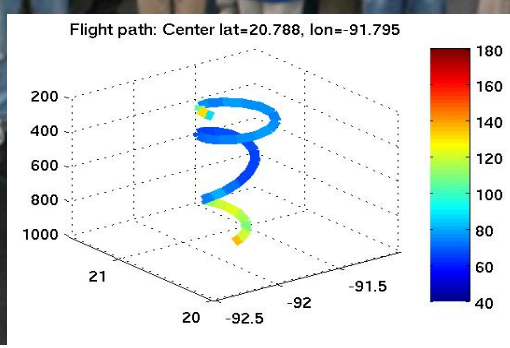

CO Validation and Intercomparisons:
An emphasis on
AIRS operational V5 verses TES products

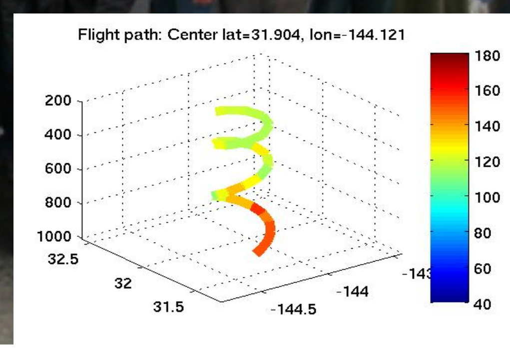
Thermal Sensor Characteristics for Tropospheric CO Between MOPITT, AIRS, TES, and IASI

Sensor/platform	Platform/orbit/sensor type	Spectral/spatial/radiomatric precision/ (NeDT@280K)
IASI/MetOp **October 2006**	817 km 09:30, descending FTS, 8461 channels OPD 2 cm	645 to 2760 12 km diam×4 pixels, swath 2200 km 0.5 cm−1 (apodized) 0.25 K
AIRS/AQUA **September 2002**	705 km 13:30, ascending Grating spectrometer, 2378 channels, resolving power $\lambda/\Delta\lambda$ = 1200	650–1136, 1216–1613, 2170–2674 13.5×13.5 km×9 pixels, swath 1650 km ~1.8 cm−1 (2170–2200 cm−1) 0.14 K
MOPITT/TERRA **December 1999**	705 km 10:30, descending Gas correlation radiometer, 3 bands 8 channels	2140–2192, 4265–4305 22×22 km, swath 640 km 0.04 cm−1 (effective) 0.05 K
TES/AURA **July 2004**	705 km 10:45, ascending FTS, 40540 channels OPD 8.45 cm	652–919, 923–1160, 1090– 1339 and 1891–2251 0.53×8.3 km×16 pixels 0.10 cm−1 (apodized) 1.5 K (@300 K)

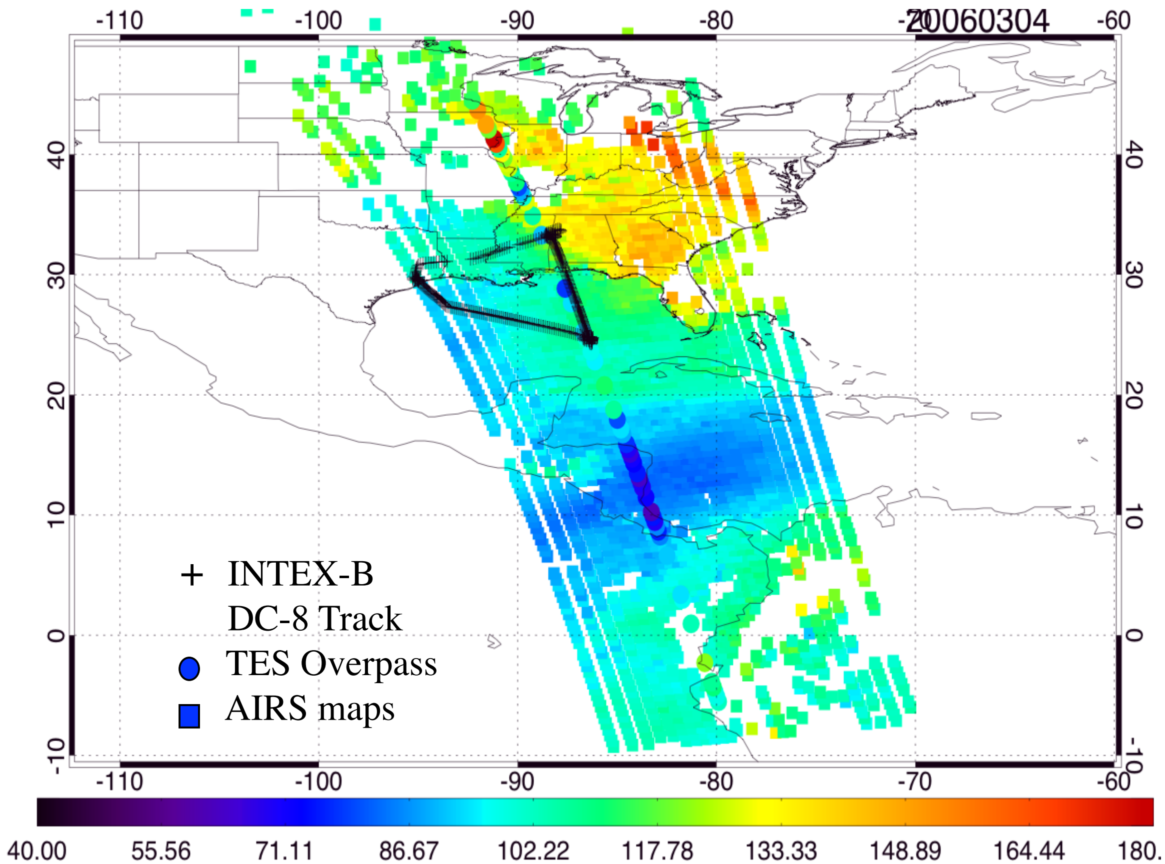
- MOPITT independent information at two vertical locations by using cell correlation
- AIRS great coverage, high signal-to-noise
- TES high spectral resolution (higher than all listed here), low coverage
- IASI high coverage and high spectral resolution, not as high signal-to-noise as AIRS
- MOPITT and IASI morning local time overpass, AIRS and TES are afternoon overpass

NASA Tropospheric Chemistry Field Campaigns INTEX-NA, INTEX-B, ARCTAS as Primary Validation Sources



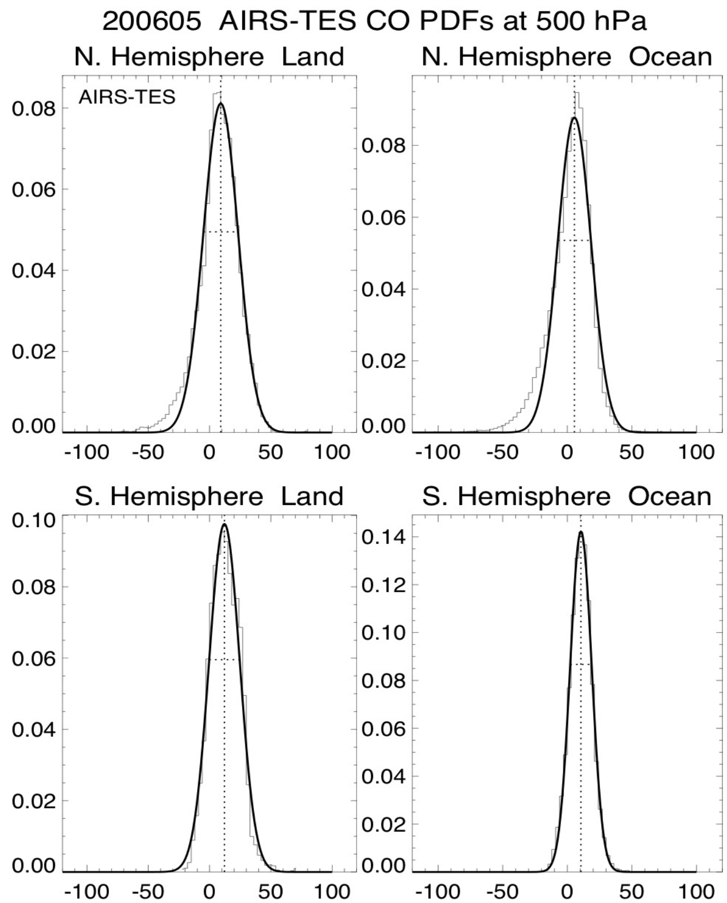


CO Profile Comparisons Between AIRS V5 and TES Operational Products at 500 hPa

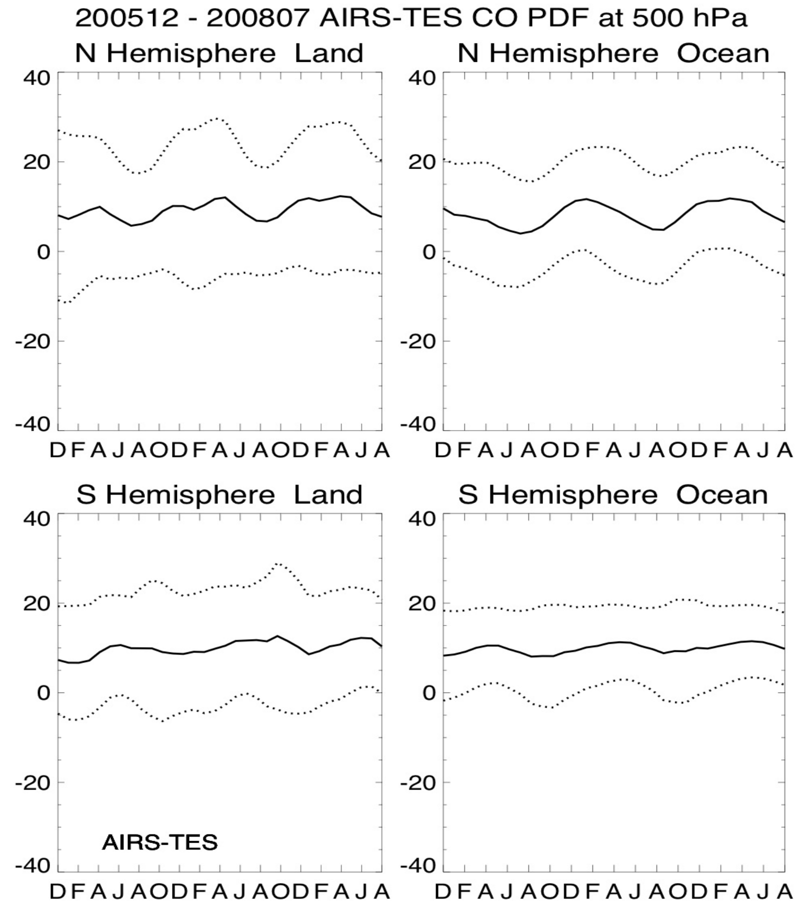


- Data used are from Dec. 2005 to July 2008.
- All pixels are collocated TES and AIRS that are measured within 15min.
- Day and night time data are used.
- Only data with TES cloud optical depth less than 1 are used.
- Various sampling sizes are used (5x8km for TES, 45X45km for AIRS).

AIRS - TES CO Normalized PDFs For March, 2006 at 500hPa

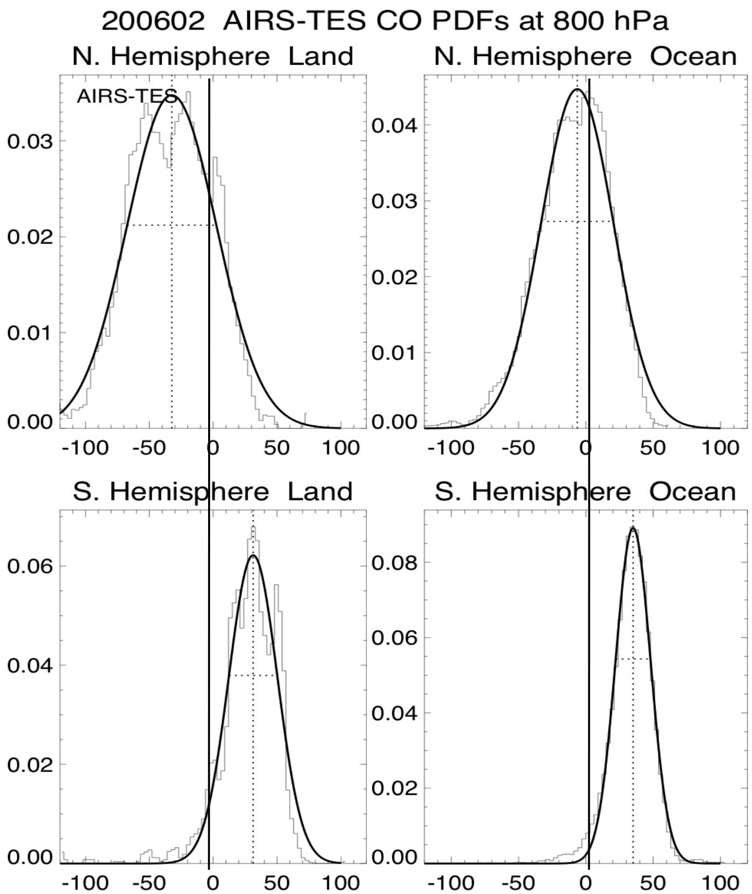


AIRS & TES 500hPa CO (ppbv) Biases and Variability For Dec. 2005 to July 2008

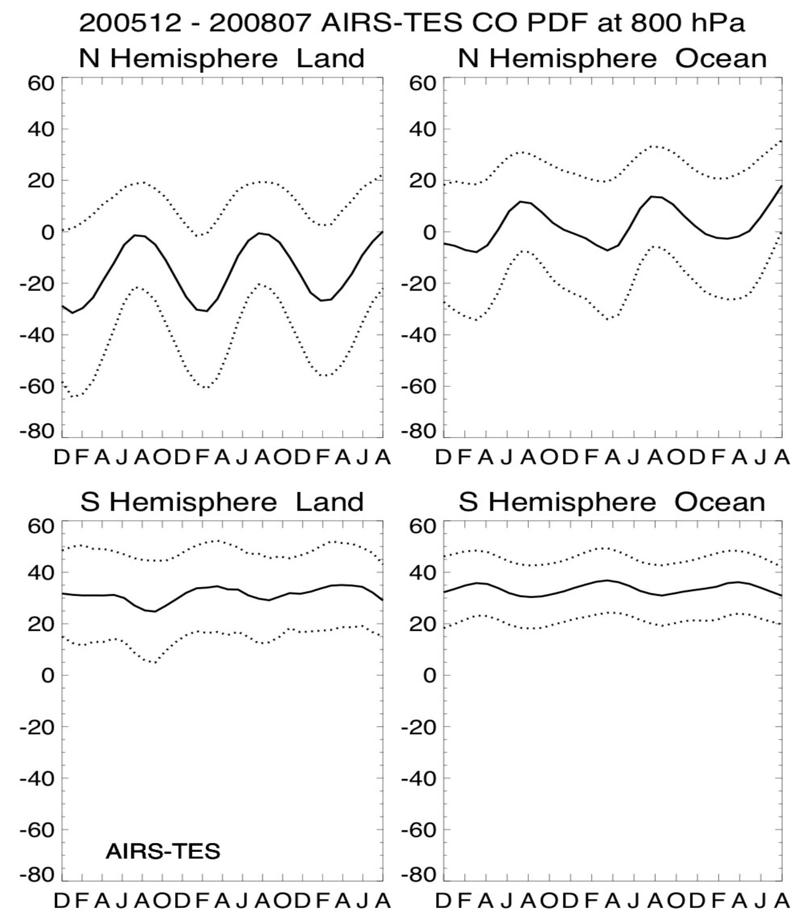


- Monthly Gaussian Functions are fitted from the PDF distributions of matched AIRS-TES at 500hPa for NH and SH over land and ocean.
- Modes (biases) and FWHM (SDVs) are plotted from Dec. 2005 to July 2008.

AIRS - TES CO Normalized PDFs For March, 2006 at 800hPa

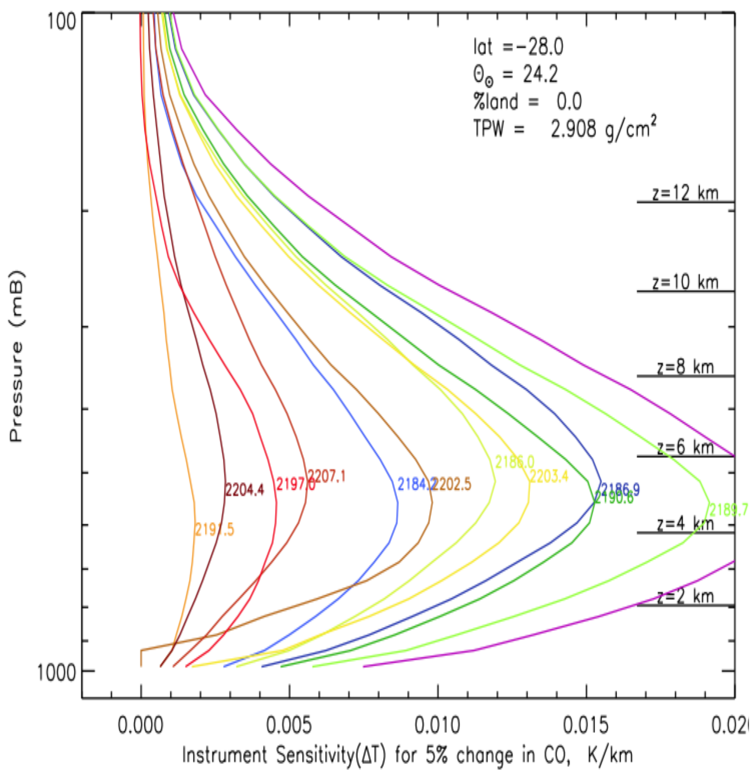


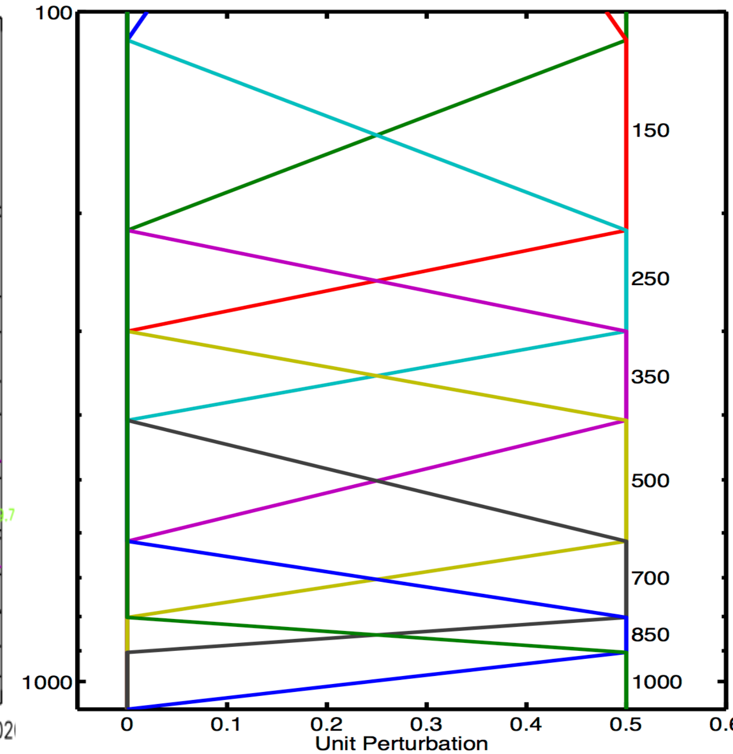
AIRS & TES 800hPa CO (ppbv) Biases and Variability For Dec. 2005 to July 2008



- AIRS and TES biases show higher daily and seasonal variability at 800hPa indicating different product sensitivities at this level than at 500hPa.
- Biases are significantly higher at 800hPa in the SH with AIRS higher than TES.

AIRS V5 CO Products





- Retrieval algorithms seek to minimize the weighted differences between the observed and calculated radiances by varying the geophysical states.
- AIRS uses an eigenvector decomposition technique with damping (Susskind et al., 2003), as oppose to Rodgers' Optimal Estimation (OE) method used by MOPITT and TES.
- Retrieval layers used 9 trapezoidal functions for perturbation.
- Damping parameters Bmax=1.75 to stabilize the solutions.
- MOPITT *apriori* single profile is used as the first guess.

AIRS CO retrievals using Optimal Estimation (OE) and the comparisons with V5 operational CO

- Tropospheric CO products from different space sensors (AIRS, MOPITT, TES, MLS, SCIAMACHY, and IASI, etc.) can be used jointly to provide greater temporal and spatial coverage and with higher information content due to more spectral bands or higher spectral resolution.

- Evaluating biases of the retrieved products between sensors

- Providing algorithms that minimize differences between retrieval products

Motivation

- Inter-calibrated products can be used jointly to increase the spectral, spatial, and temporal coverage.
- Provide users the retrieval output of AKs, error covariance matrix, DOFS, as defined similarly by other sensors

Optimal Estimation Retrievals

- Equations:

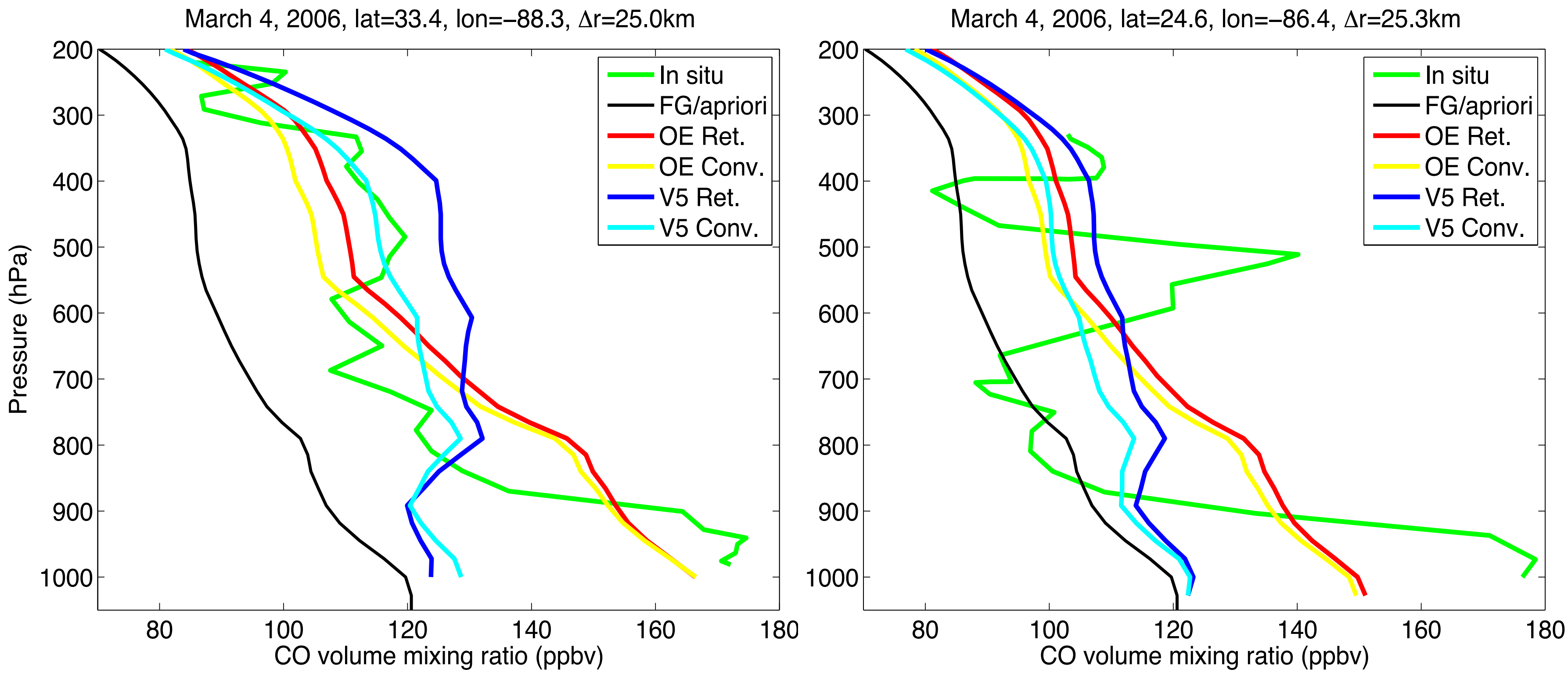
$$\boldsymbol{y} = f\,(\boldsymbol{x}, \boldsymbol{b}) + \boldsymbol{n}_{\varepsilon},$$

$$\boldsymbol{x}_{n+1} = \boldsymbol{x}_a + \mathbf{C}_a\mathbf{K}_n^{\mathrm{T}}(\mathbf{K}_n\mathbf{C}_a\mathbf{K}_n^{\mathrm{T}} + \mathbf{C}_{\varepsilon})^{-1}[\boldsymbol{y} - \boldsymbol{y}_n - \mathbf{K}_n(\boldsymbol{x}_a - \boldsymbol{x}_n)]$$

- MOPITT *a priori* fixed globally (equivalent to MOPITT V3), mean profile is similar to V5 1^{st} guess.
- Developed basing on AIRS V5 off-line codes.
- All other properties are the same as V5 except the minimization scheme for CO to benefit the comparison between the two algorithms.

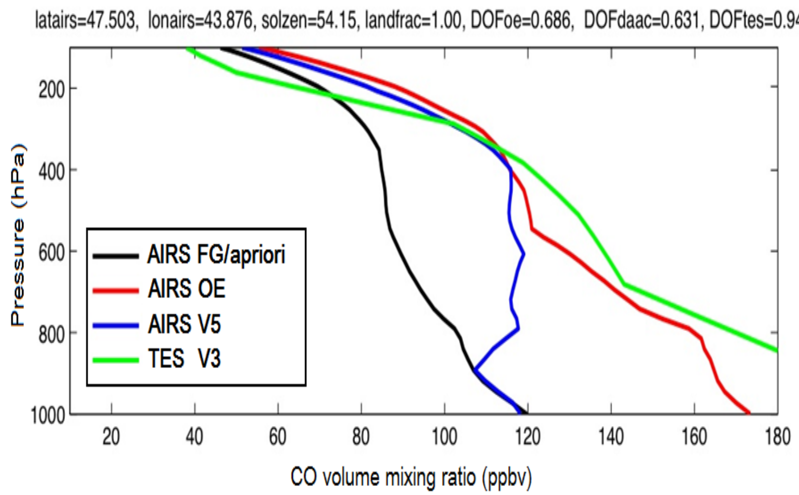
NH profiles during INTEX-B Mar. 4, 06

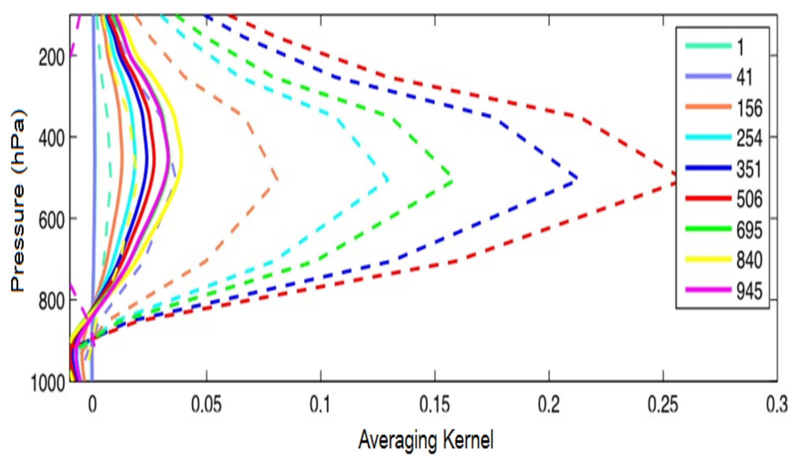
near the Southeast US agricultural fires



- In situ profiles show high CO concentration in the boundary layer due to an agricultural fires in the SE US.
- AIRS V5 and OE CO agree very well in the mid-trop. where the measurement signals are strong, very different in the lower trop. depending on how apriori is constrained.
- CO profiles are very different between AIRS V5 and OE although convolved *in situ* profiles agree with the retrievals very well in both cases.

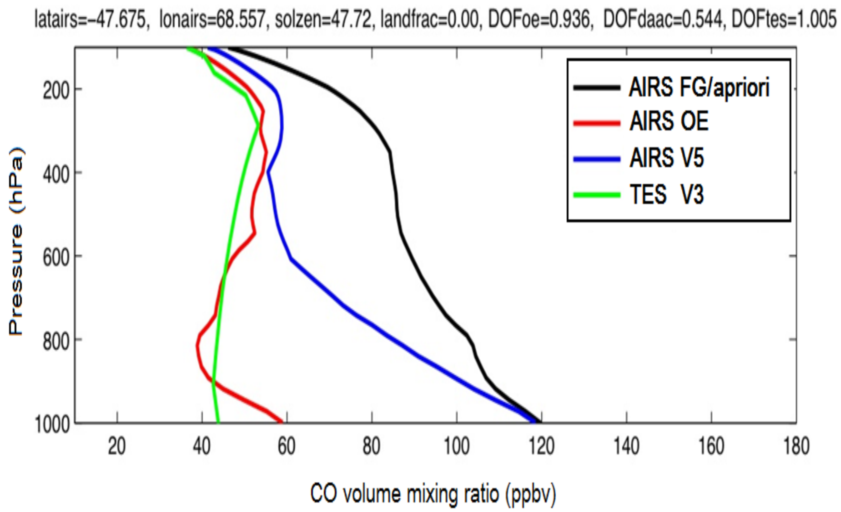
A typical NH CO profile over land

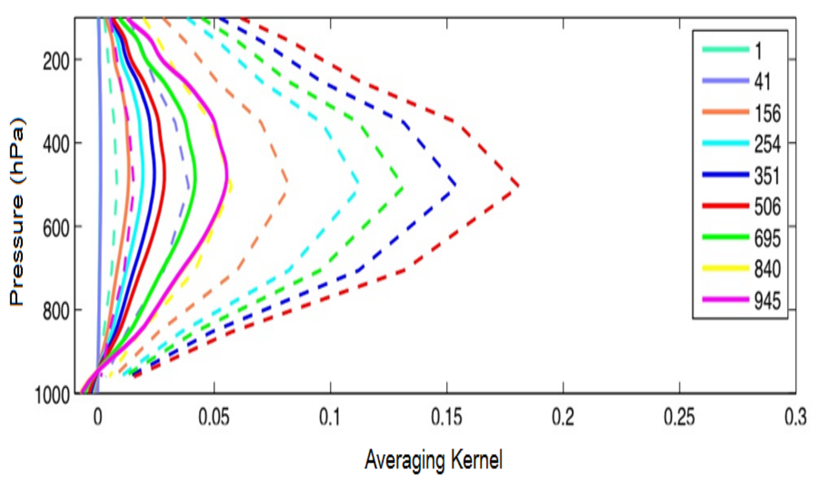




- AIRS V5 CO converge towards the 1st guess in the lower troposphere.
- The *a priori* constrain leads to higher CO in the lower troposphere for both AIRS OE and TES CO.
- AIRS OE averaging kernels indicates most sensitivity at 500mb where AIRS V5 is accurate.

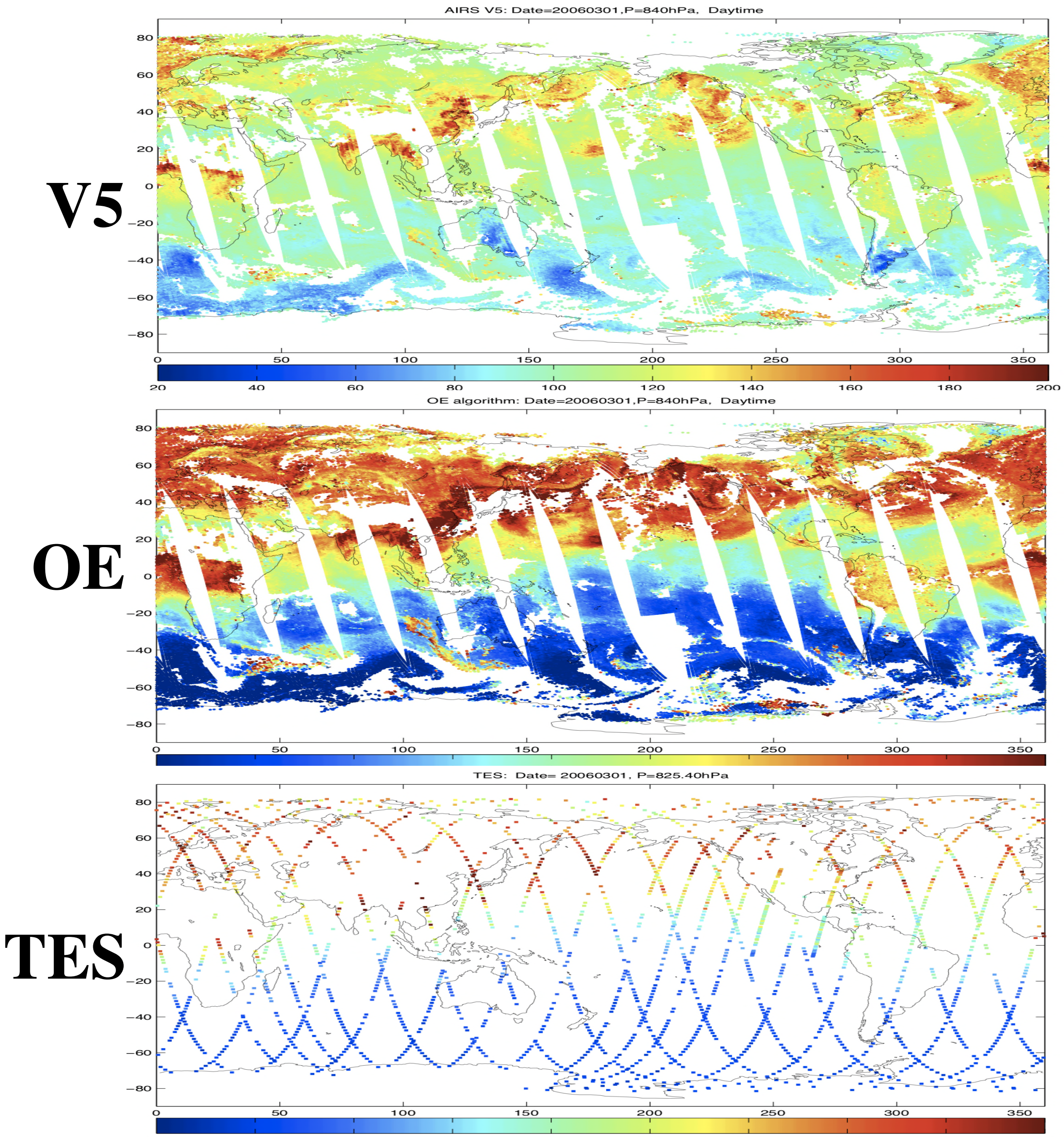
A typical SH CO profile over Ocean





- AIRS V5 CO converge towards the 1st guess in the lower troposphere.
- AIRS OE can capture very low CO in the clean region over SH oceans.
- Agreements between AIRS CO using OE and TES CO agree very well over this region.

Tropospheric CO at 840hPa on 20060301

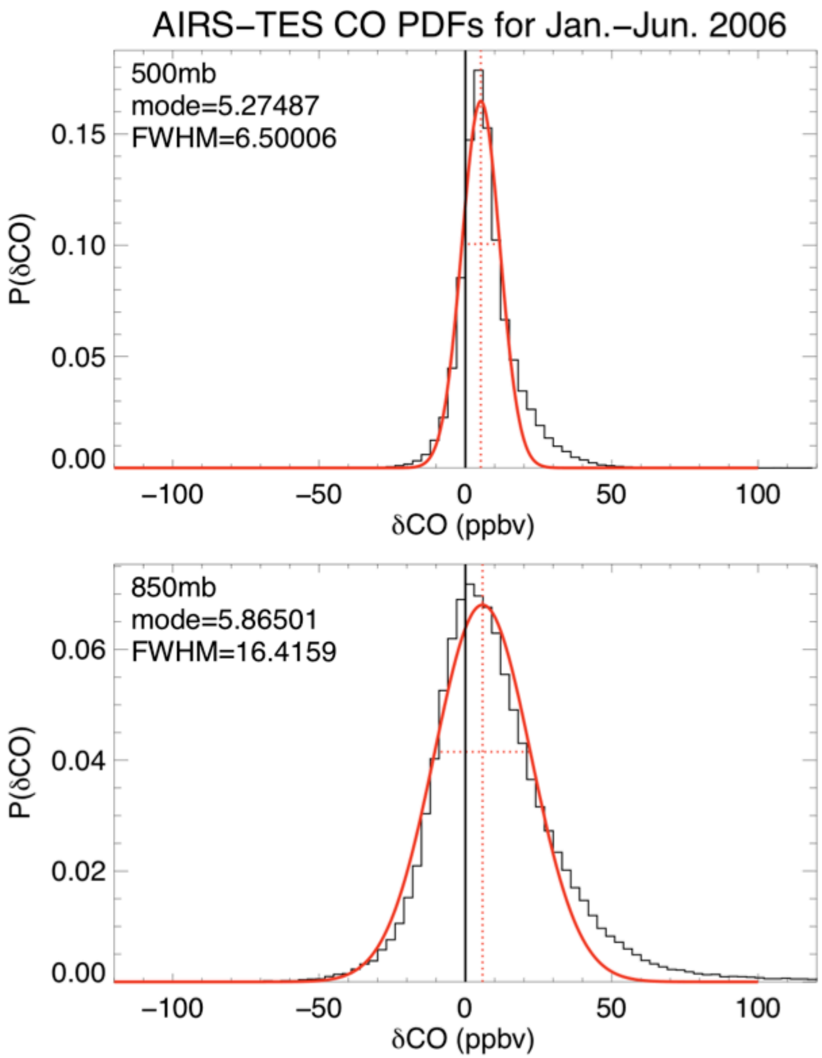


- AIRS V5 CO (top panel) in the lower troposphere exhibits reduced data range due to the lack of vertical correlation from the mid-troposhere and the use of one global 1st guess/apriori profile.

- Properly constrained CO profiles (middle panel with AIRS OE and lower panel for TES) provide more realistic CO in the lower troposphere.

- The algorithm is ready to produce CO for all available AIRS data record and generic enough for other trace gases!!

AIRS OE – $TES_{convolved\_AIRS}$ CO PDFs



- Biases between AIRS OE and TES are ~5ppbv at both 500 and 800hPa.

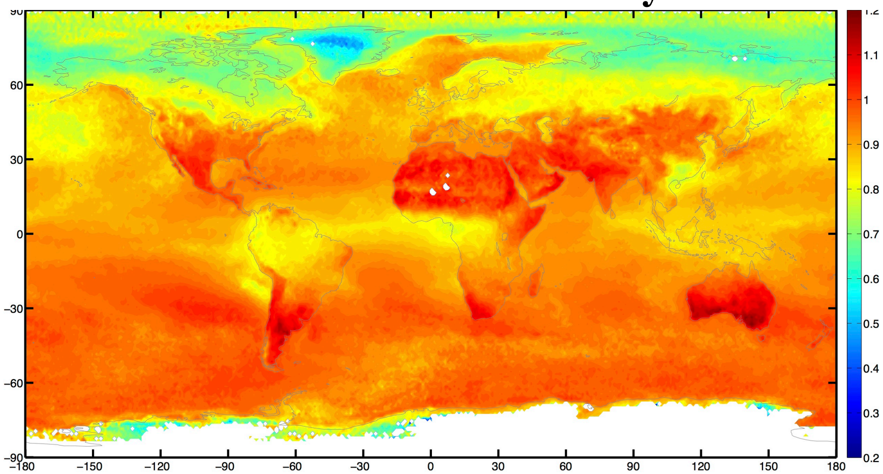
- Smaller than the SDVs.

- The SDVs at 800hPa are larger than at 500hPa.

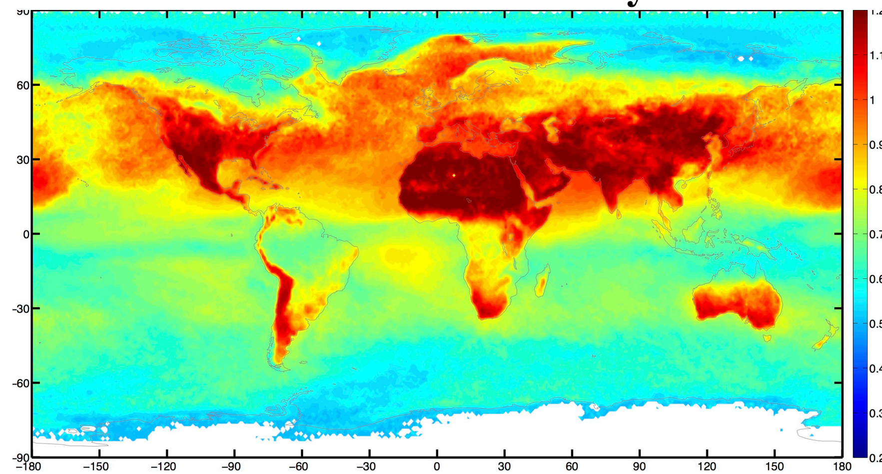
- The differences between AIRS and TES are mainly due to the algorithm not the sensor characteristics.

AIRS CO DOFS Analysis between the two algorithms for March 2006

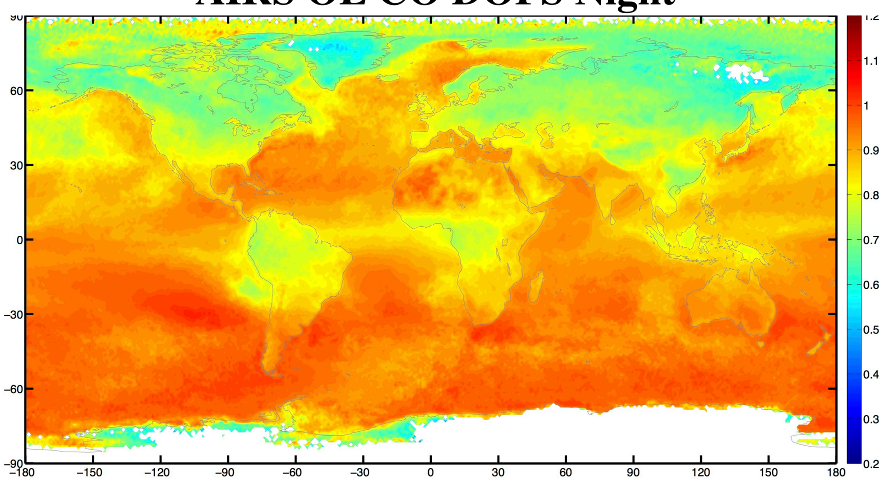
AIRS OE CO DOFS Day



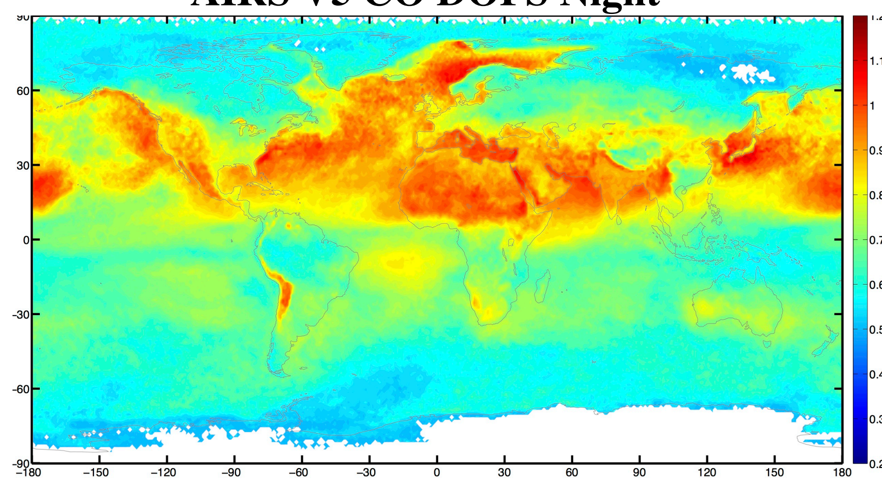
AIRS V5 CO DOFS Day



AIRS OE CO DOFS Night



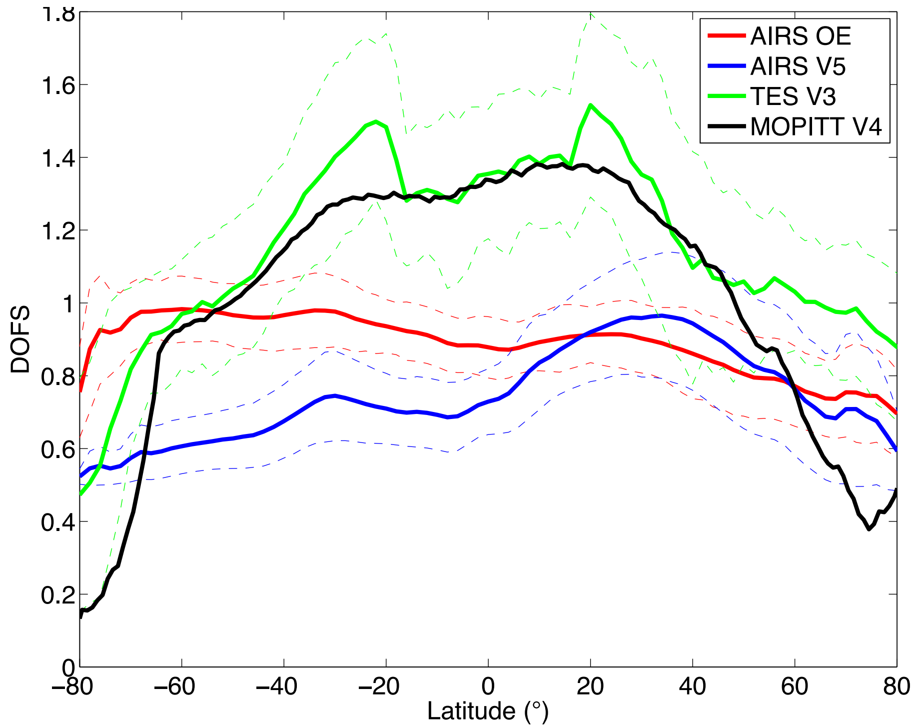
AIRS V5 CO DOFS Night



- AIRS V5 DOFS are computed differently from the OE method. Should not be compared directly with other sensors.
- AIRS OE CO DOFS average between 0.8 to 1.
- Note day/night differences due to the change of surface thermal contrasts.

CO DOFS Analysis Between AIRS, MOPITT, and TES for March 2006

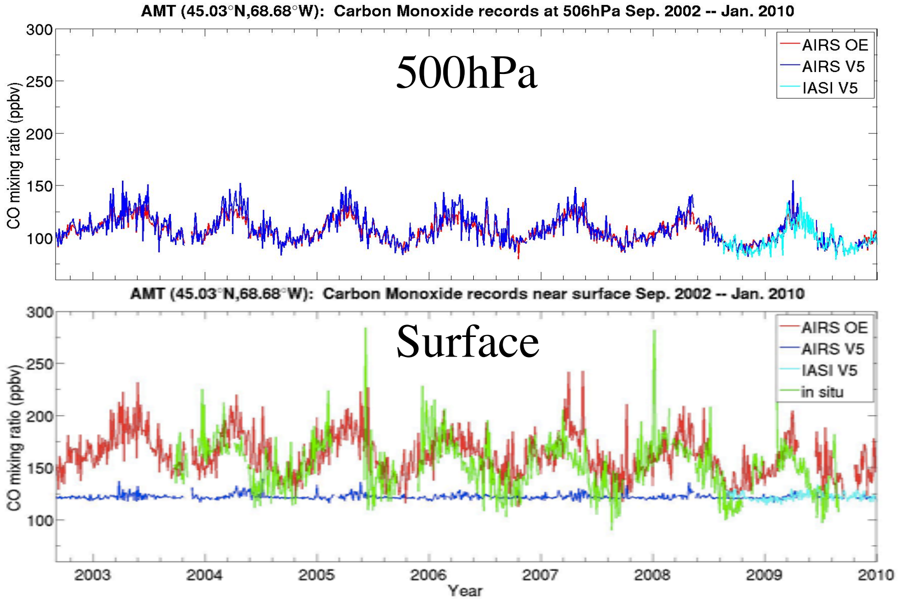
AIRS V5 CO (blue), AIRS OE CO (red), TES CO (green), and MOPITT (black)



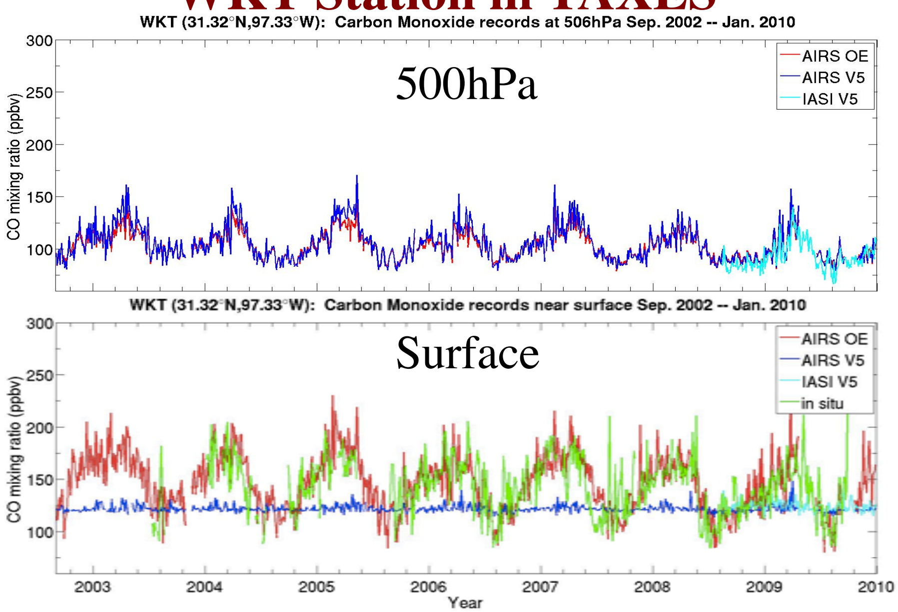
- AIRS OE CO DOFS average between 0.8 to 1.
- TES CO DOFS are higher than 1. at mid- and low-latitudes.
- MOPITT and TES CO DOFS are comparable at mid- and low-latitudes.

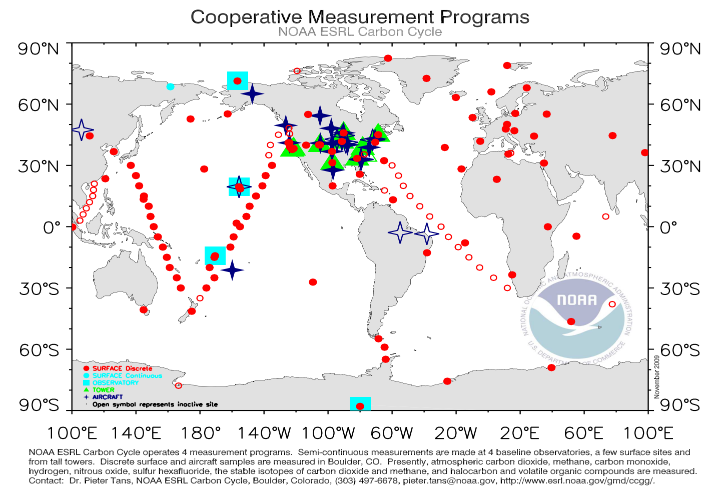
OE CO Applications

AMT Station in MAINE



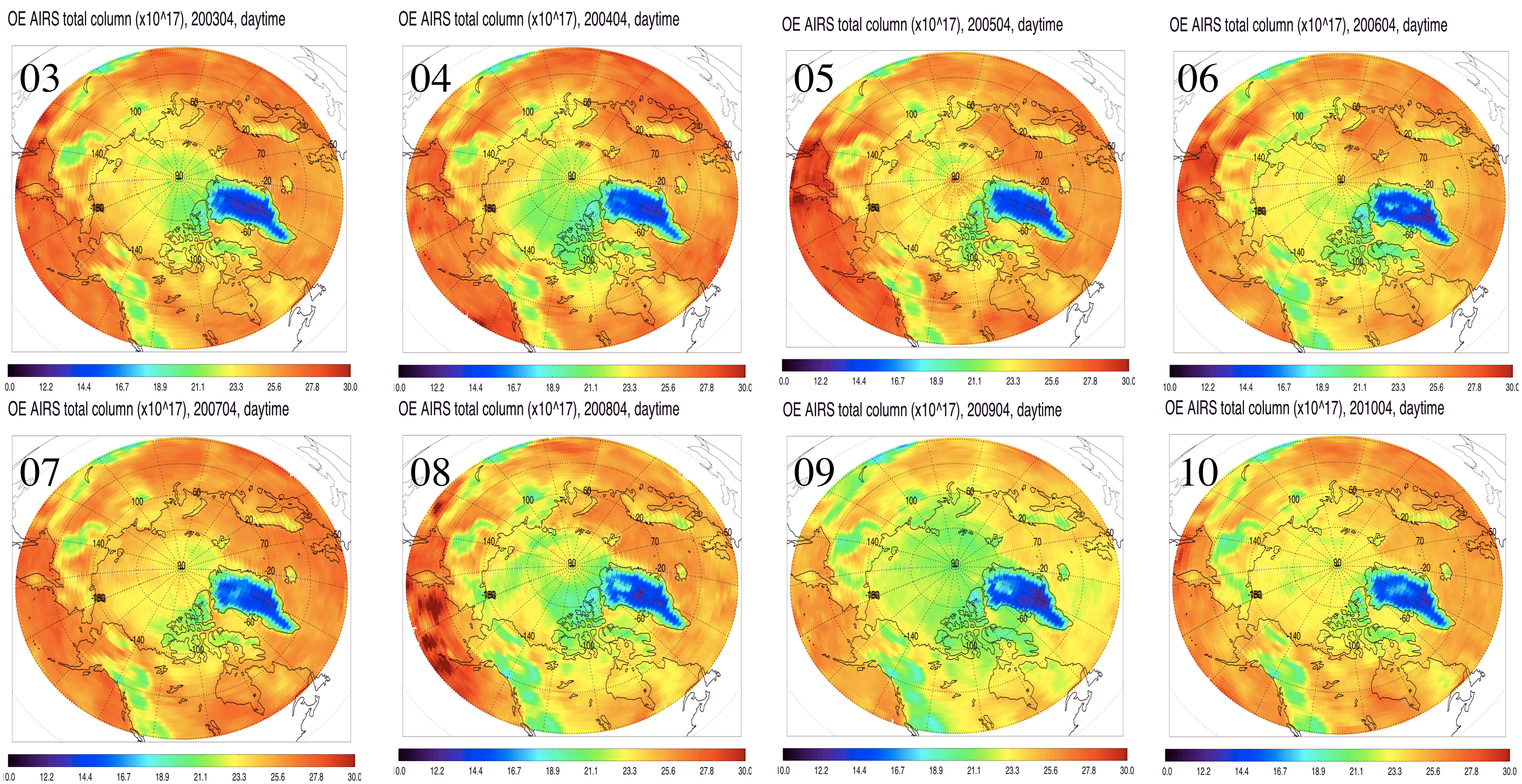
WKT Station in TAXES





- OE Retrievals can be used to study CO variability and trends!
- Capture the comparable magnitude of seasonal variations.
- OE and V5 agree very well at 500hPa, vary significantly in the lower troposphere.
- Satellite sensor drift.

AIRS CO Total Column ($\times 10^{17}$ molecules/cm^2) Using Optimal Estimation Retrievals for April 2003 - 2010



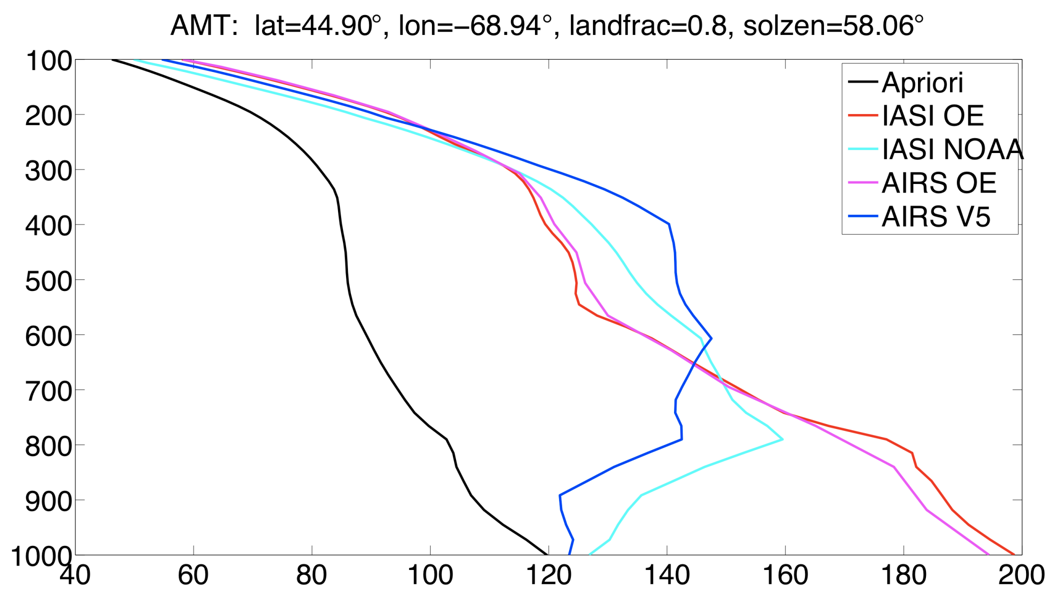
- New CO retrievals using optimal estimation, which differ from the operational products, reduce retrieval biases in the Arctic, and show more visible transport patterns.
- Transport pathways clearly shown primarily from Asia and Europe.
- Reduced pollutions in 2009 and 2010 are evident, partly due to the economic slowdown.

What's next in AIRS OE CO Algorithm

- Processing AIRS OE CO for the available data record and distributing the datasets on our ftp site as soon as available: (ftp://stratus.umbc.edu/pub/warner/AIRS_OE)
- Continued validation with new measurements and AIRS new version V6.
- Carrying through thorough error analysis.
- Development of IASI OE CO products.

Continue with IASI CO Quick-look Retrievals Using OE Algorithm

- Funded by NASA's Climate Data Record Uncertainty Analysis



- IASI on MetOp similar to AIRS in spectral and spatial coverage will operate for a planned 15-year/3-sensor mission
- IASI CO products will be similarly produced as for AIRS CO
- Based on NOAA IASI L2 meteorological products and CCRs
- Using estimated errors for IASI

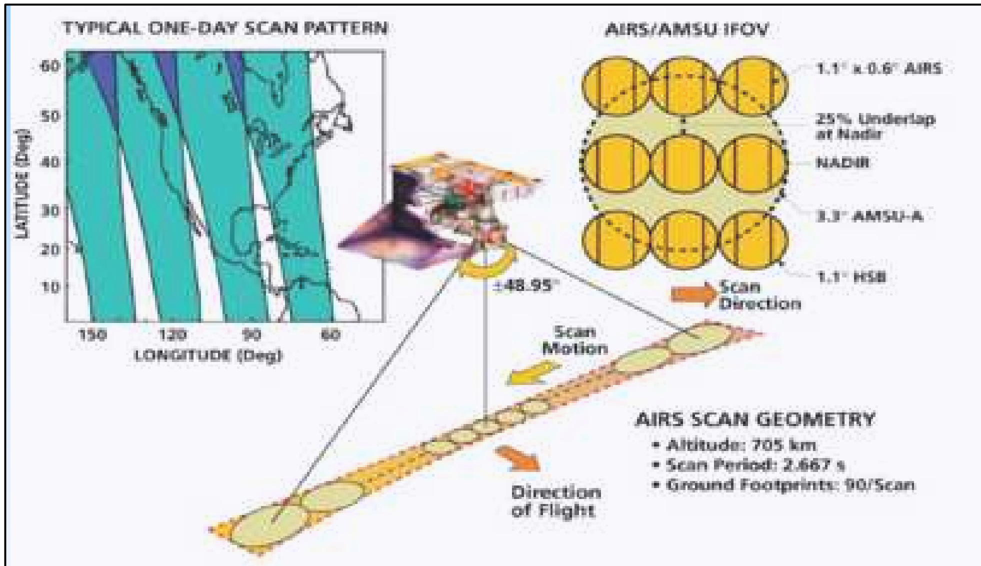
Impact of Clouds on AIRS Tropospheric CO Variability

- How cloud treatment affects AIRS retrieval.

- Understand sources of CO due to well-mixed background concentrations, fresh emissions, and contamination, etc.

- Potential Single FOV ($13.5km^2$) retrievals for AIRS without using AMSU.

Impact of Cloud on AIRS Tropospheric CO Variability



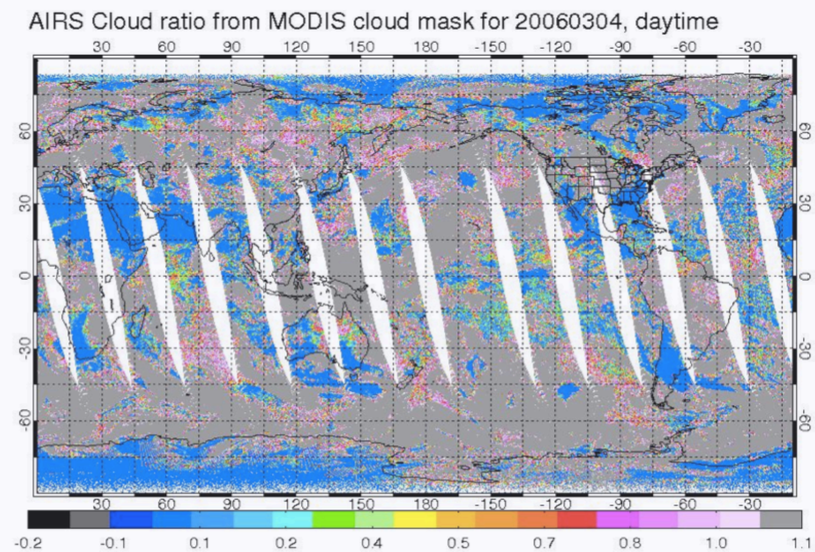
AIRS Cloud-Clearing

(re-construct clear column radiances)

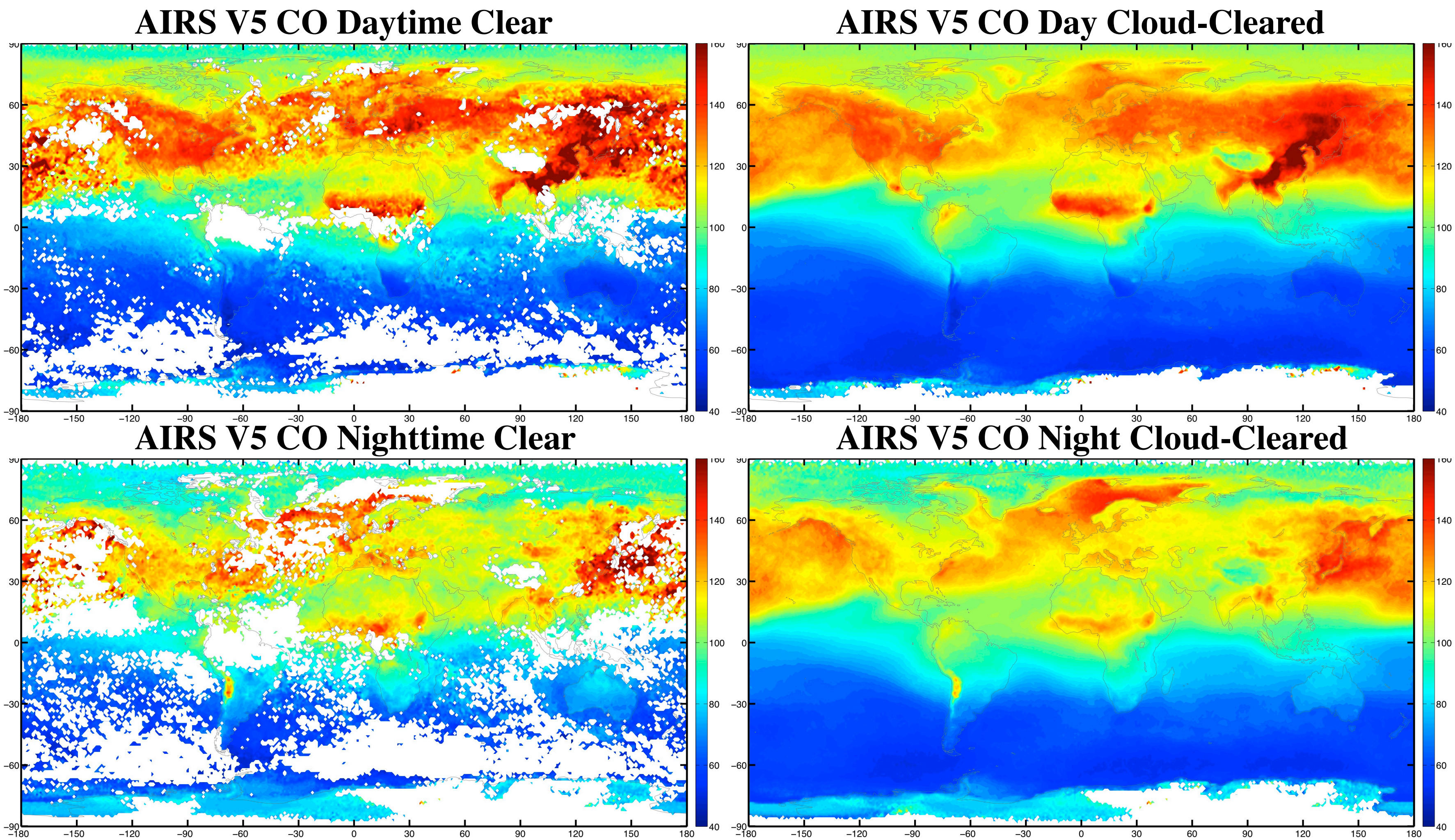
- Sounding is performed on 50 km field of regard (FOR).
- FOR is currently defined by the size of the microwave sounder footprint.
- AIRS/AMSU & CrIS/ATMS have 9 IR FOV''s per FOR.
- Yield more than 50% of coverage.

AIRS Clear Pixels Determined By MODIS Cloud Mask

- AIRS and MODIS are both on Aqua.
- AIRS single-view pixels are used to collocate with MODIS 1x1km^2 pixels.
- AIRS clear coverage by MODIS cloud mask (blue) is ~10%.

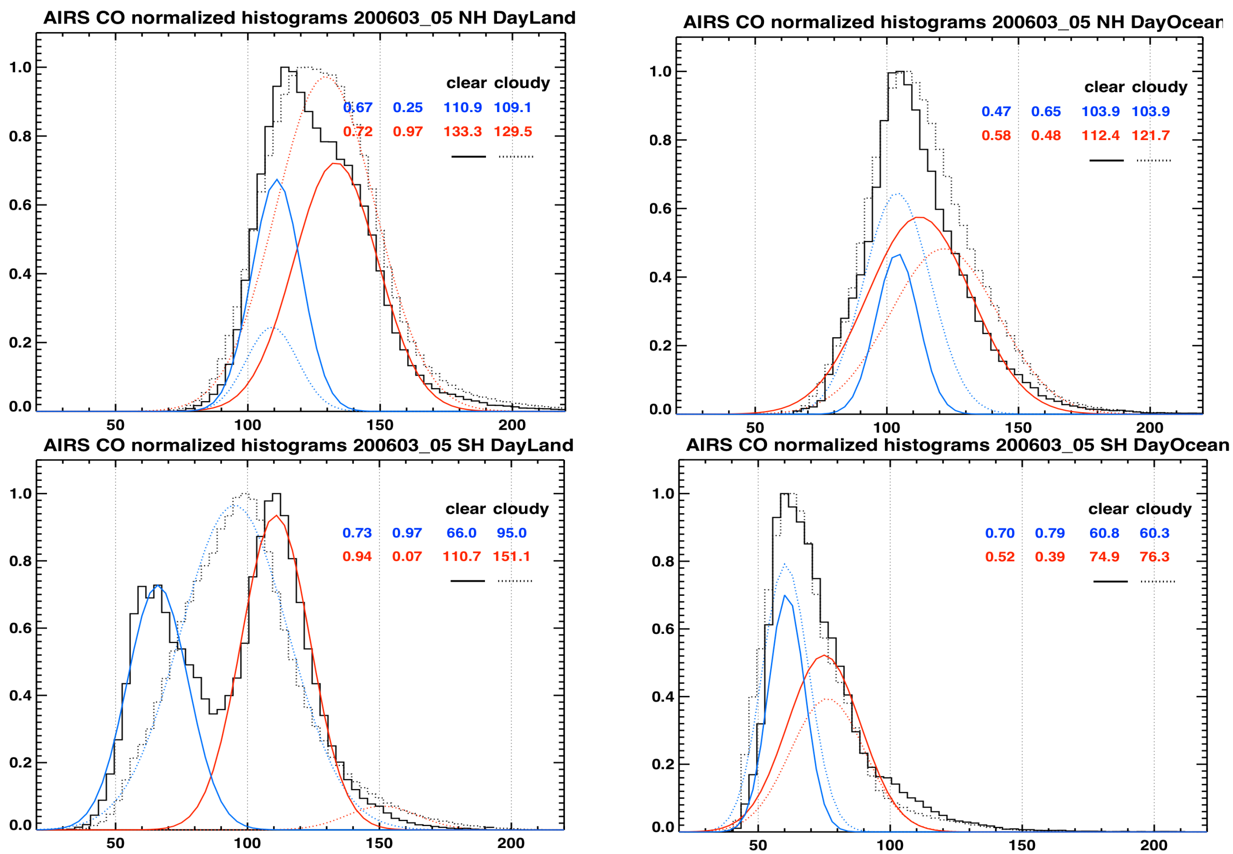


AIRS V5 CO Analysis between Cloud-cleared and Clear for Mar-May 2006



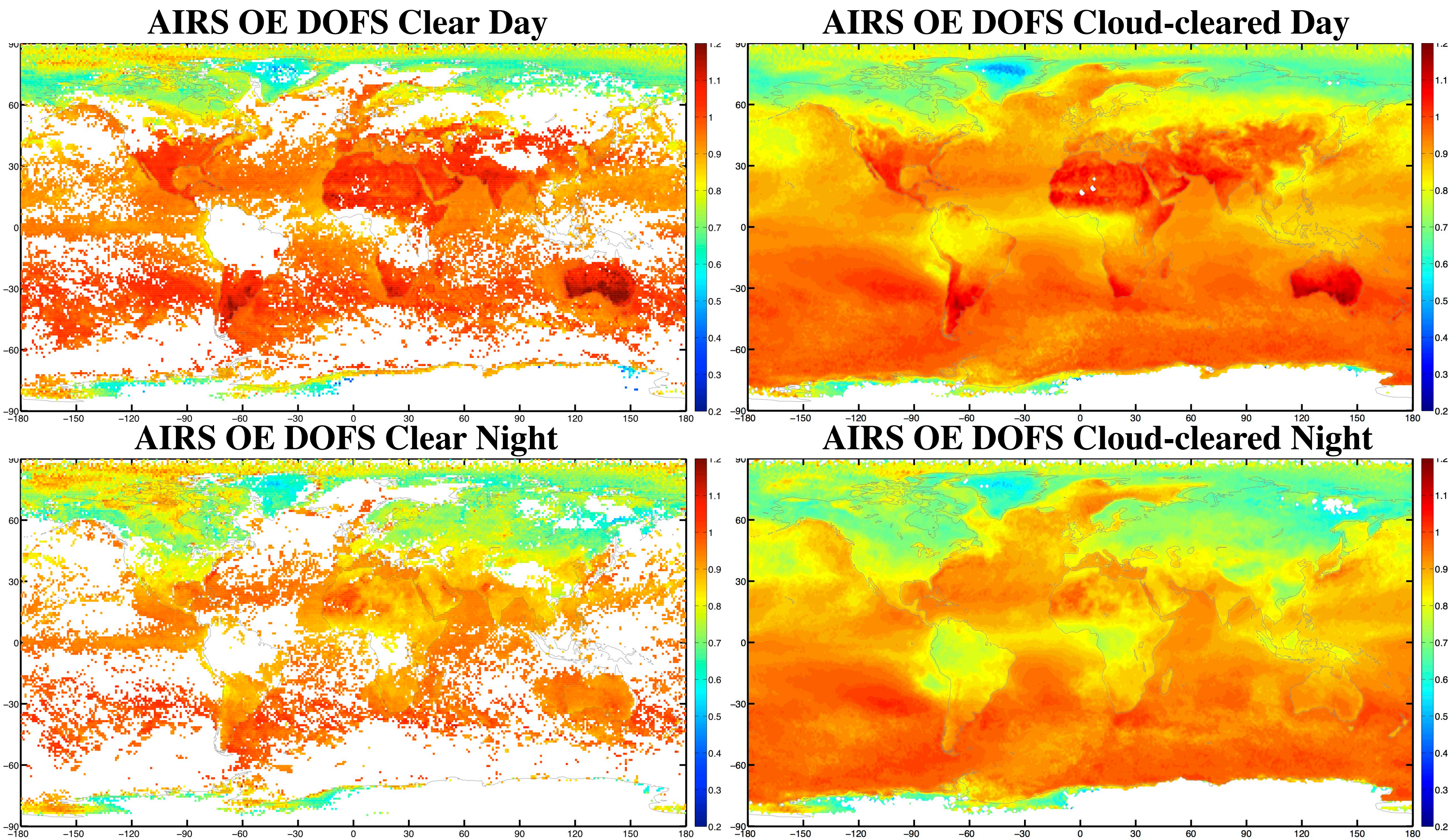
- Clear cases are chosen where more than 99% of MODIS pixels in an AIRS pixel are believed to be clear.
- CO distributions are very similar in general using cloud-cleared radiances.

Impact of Cloud on AIRS Tropospheric CO Variability



- Histograms for clear condition (solid) and cloud-cleared (dashed) are fitted by two Gaussian functions.
- Left Gaussian fits (blue) represent background CO while the right Gaussian fits (red) show fresh emissions.
- Cloud effects in the NH are correlated more with emissions, while background CO is less affected. Partly indications of convective transport of surface emissions.
- Cloud effects in the SH serve to mask the otherwise distinguished two populations.
- Separated background CO statistics can set the stage for near-real time emissions monitoring.

Cloud Effects to AIRS CO DOFS for March 2006



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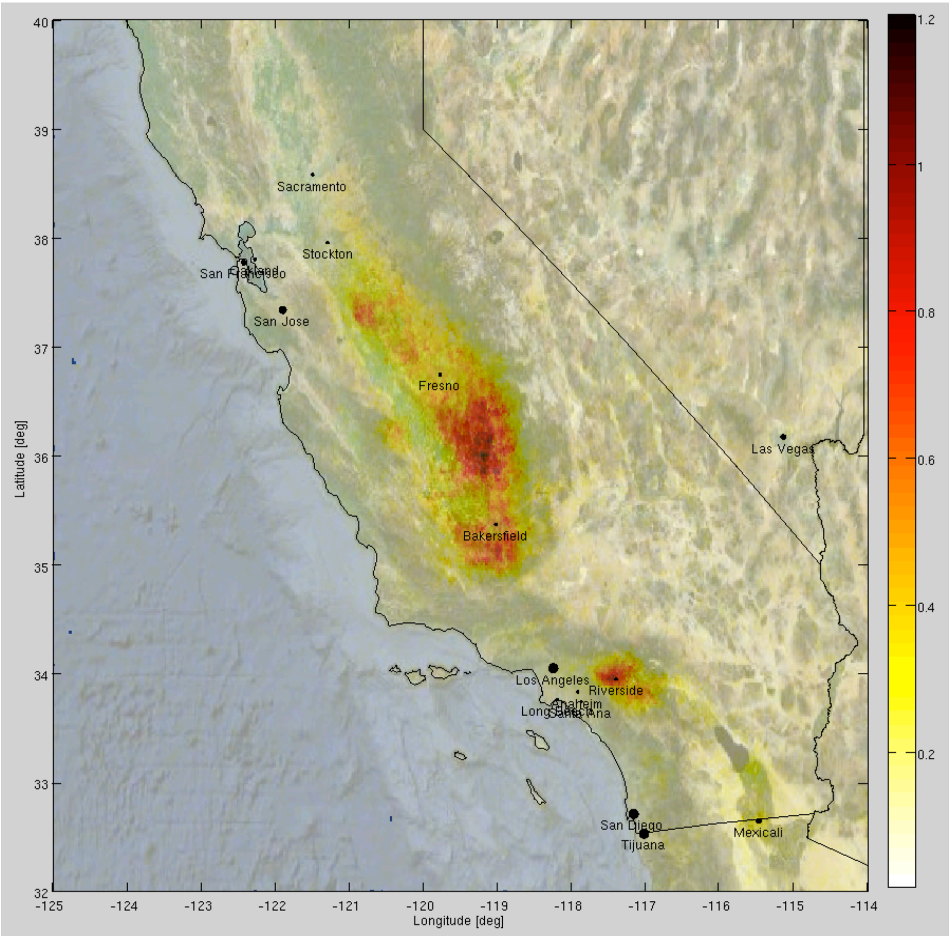
- Note day/night differences due to the change of surface thermal contrasts.

On-going:
Measurements of NH_3 with AIRS
- Funded by NASA's the Science of Terra and Aqua



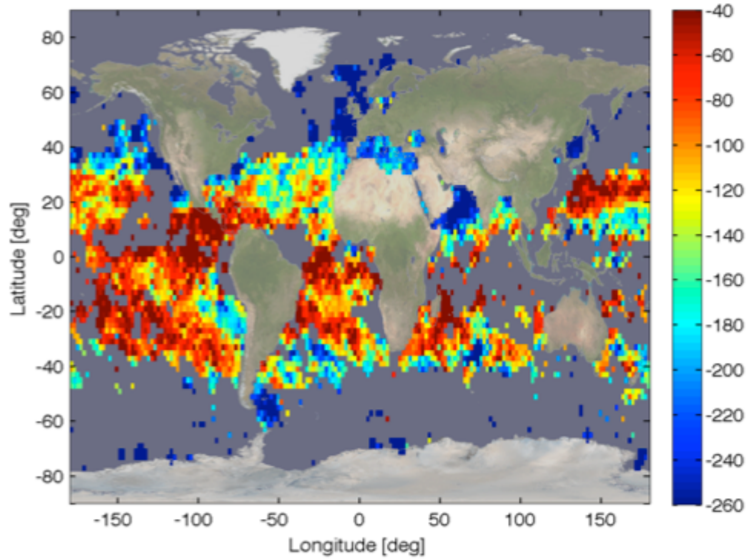
*Courtesy of L. L. Strow and group.

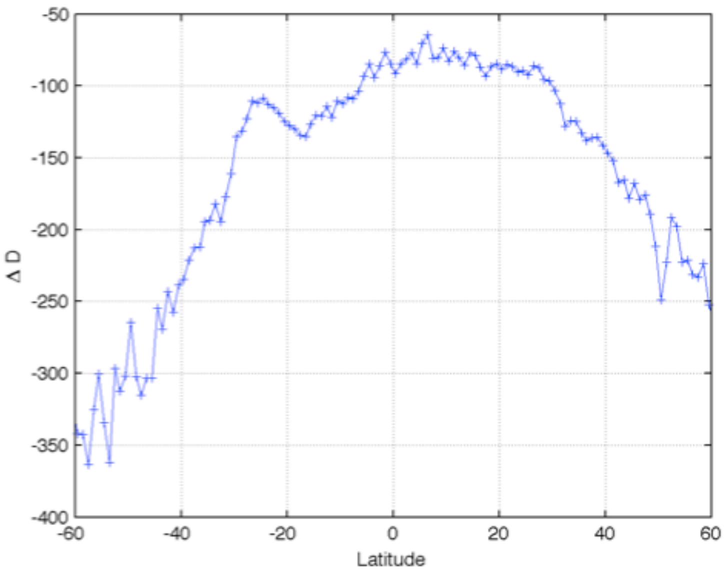
- NH3 major component of the global nitrogen cycle
- Global emissions primarily due to agriculture
- Environmental impact:
  - Deposition of reactive nitrogen in sensitive ecosystems
  - Enhanced creation of ammonium sulphate and ammonium nitrate aerosols.
- Lifetime less than *8* hours, daytime AIRS measurements are useful.
- First observed with TES (Beer, et. al. GRL 2008). Global measurements using IASI (Clarisse et. al. 2009).
- AIRS radiances show good sensitivity.
- AIRS is likely more sensitive to NH_3 than IASI due to the 1:30 pm versus 9:30 am overpass time.

On-going: with AIRS

Measurements of HDO (water isotope)

- Funded by NASA's the Science of Terra and Aqua





*Courtesy of L. L. Strow and group.

- H_2O preferentially evaporates while HDO preferentially condenses. The HDO/H_2O ratio gives information on water vapor sources, sinks.
- Positive feedback on global warming.
- The AIRS RTA uses a constant HDO/H_2O ratio. But, the H_2O retrieval uses a number of HDO lines! Consequently, the AIRS H_2O retrieval may have errors of 10-20+% in regions with a low HDO/H_2O ratio.
- Since AIRS has strong, well separated HDO spectra in the shortwave, an accurate HDO/H_2O ratio retrieval may be possible.

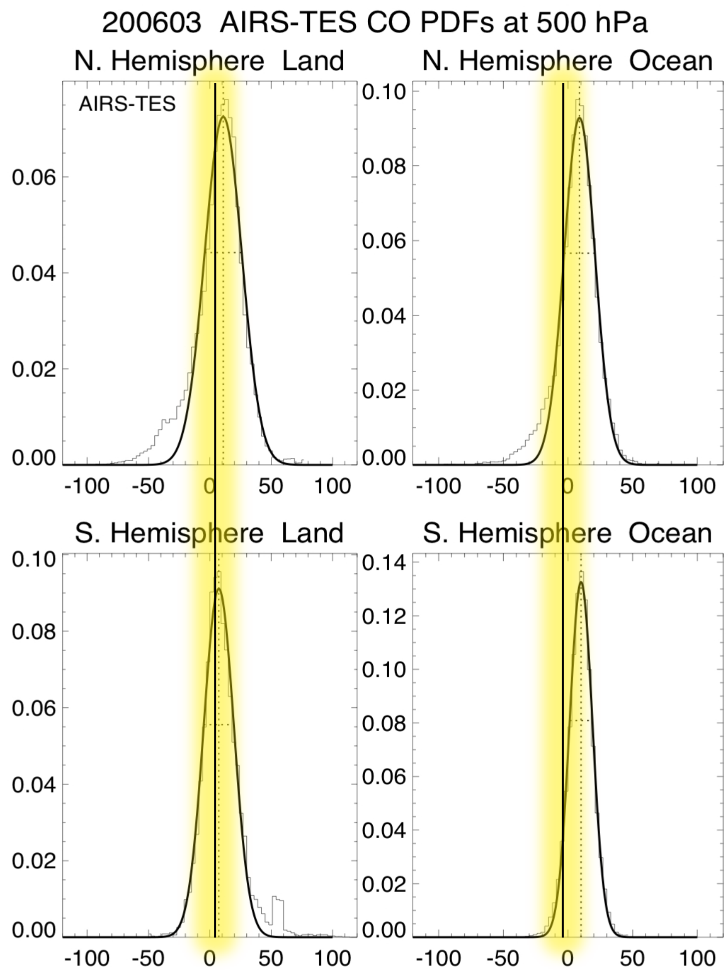
Summary and Future Work

- Differences between AIRS and TES CO mostly attribute to algorithm differences rather than sensor characteristics.
- Accuracies of AIRS CO using OE improved in the lower troposphere and SH compared to AIRS operational V5 CO based on validation results.
- CO using cloud-cleared radiances are correlated with higher CO values in the NH indicating in part the convective transport of pollution. Cloud-clearing tends to contaminate CO in the SH preventing the distinction between the background and new emission in the PDFs.
- CO populations can be distinguished as the background and fresh emissions by multiple Gaussian fits to the PDFs. This sets the stage for near-real time monitoring of pollution source, such as Biomass burning events.

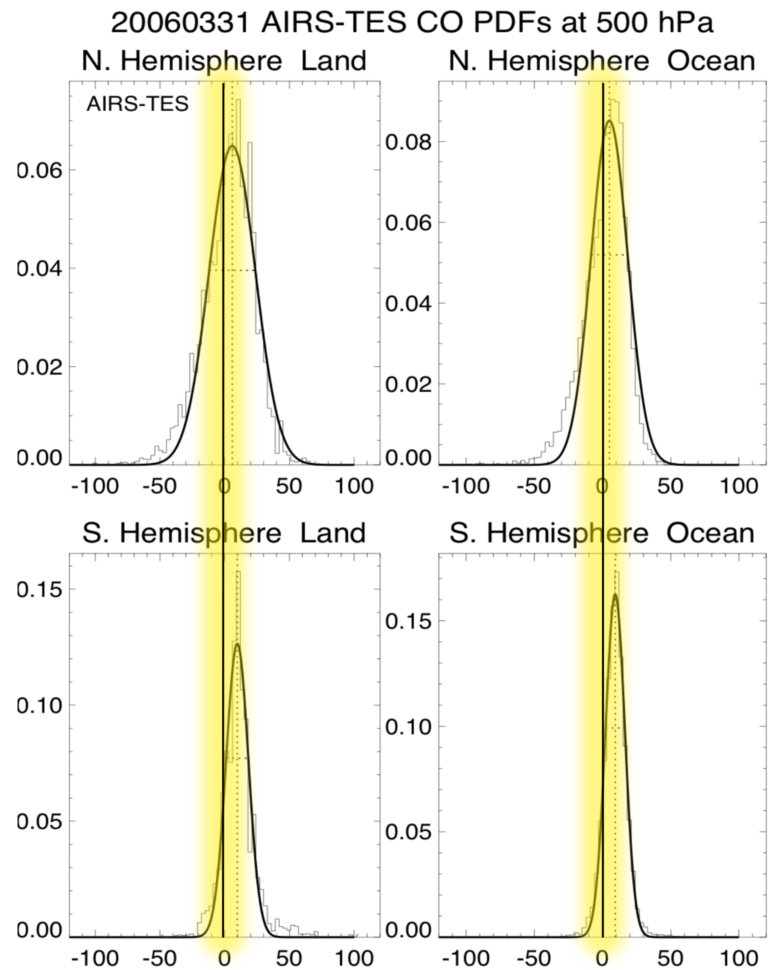
- Validating and studying CO variability, trends, and possible drifts in data records using ground measurements.
- Complete AIRS CO data records for the available observation period.
- Producing IASI CO using the same algorithms.
- Develop minor gases using AIRS measurements.

CO Differences are comparable at 500hPa

AIRS_V5-TES



AIRS_OE-TES

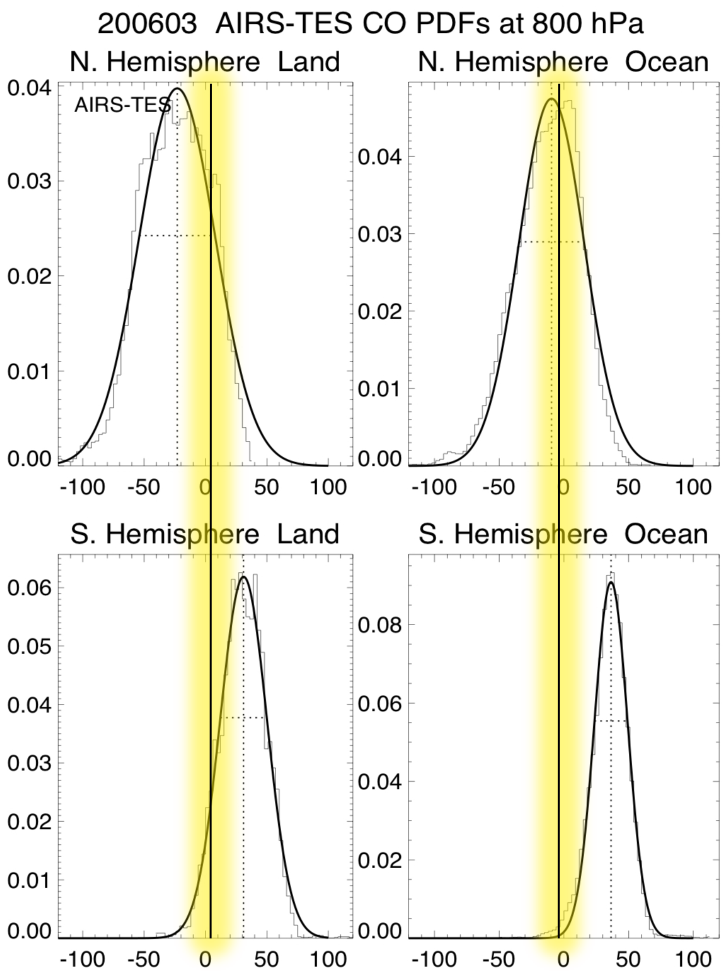


- CO retrievals at 500hPa from OE and V5 are similar
- AIRS CO biased higher compared with TES CO

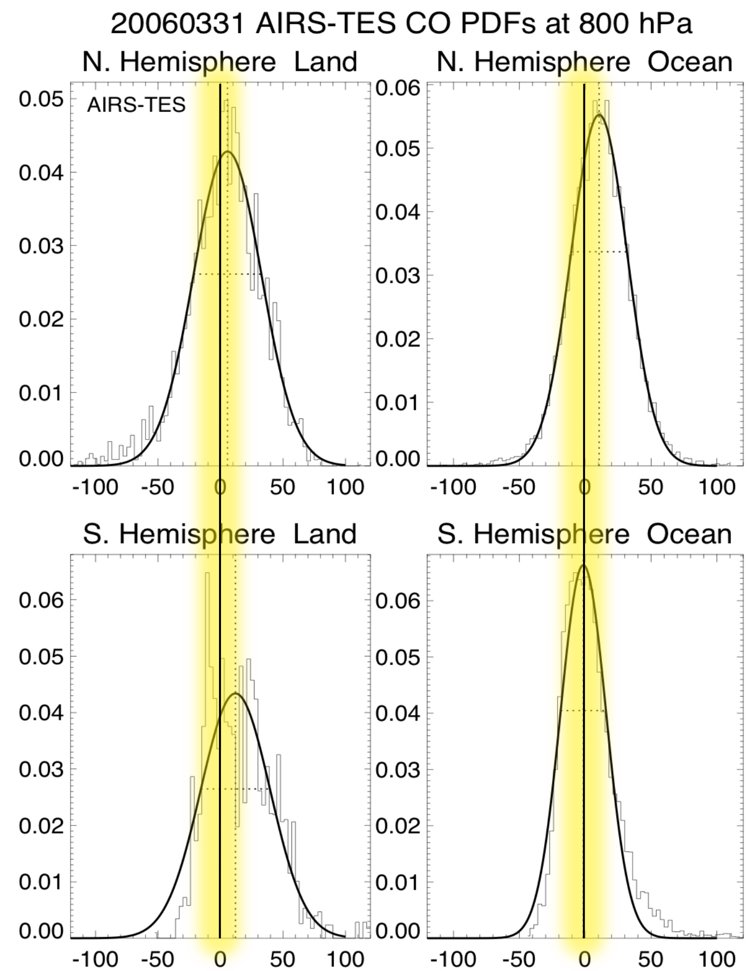
AIRS-TES Biases significantly reduced at 800hPa

by ~20 ppbv over NH land, and ~30 ppbv in the SH!!

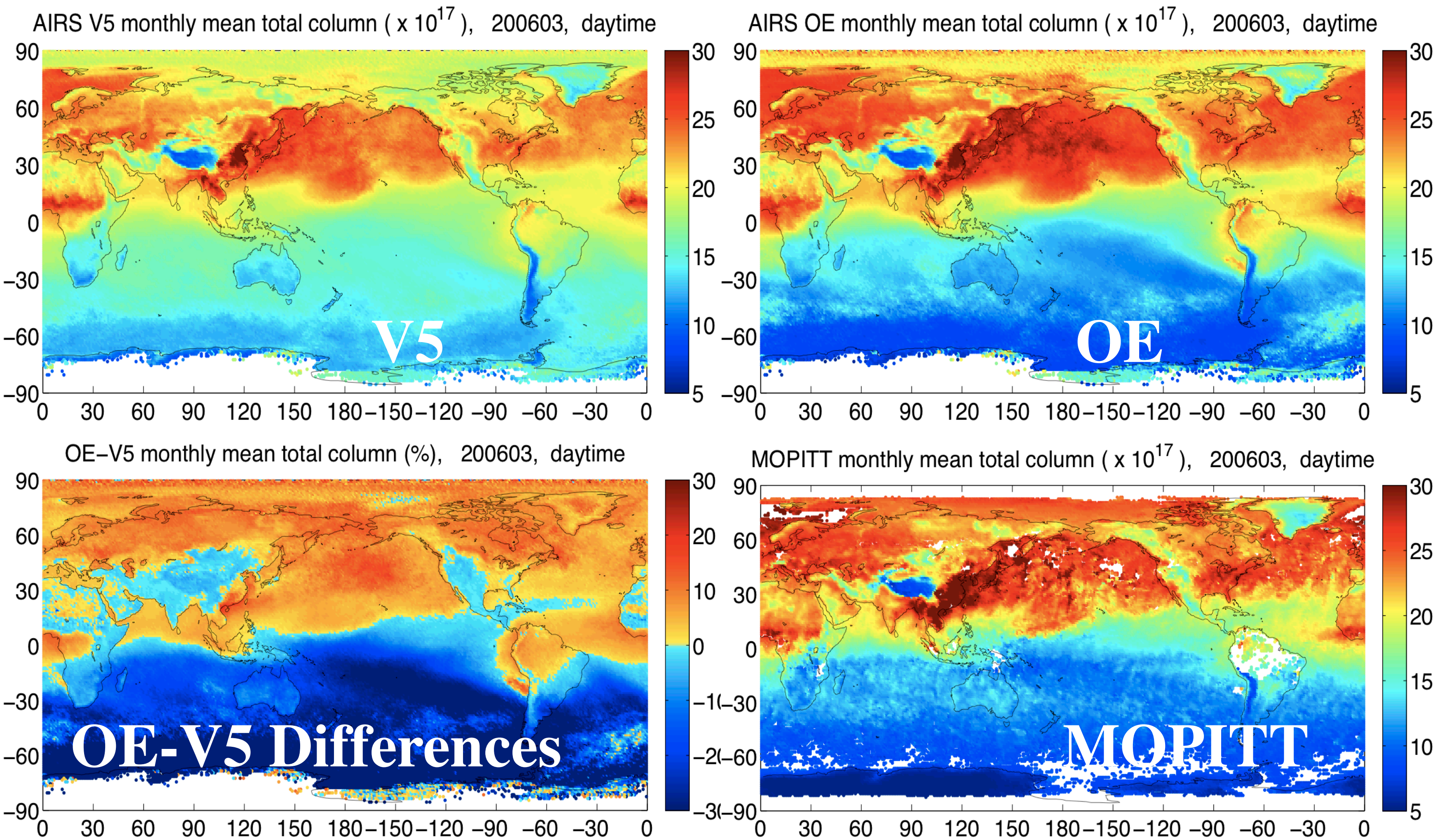
V5



OE



AIRS and MOPITT V4 CO TC Mar. 06



- OE CO total columns are higher in the NH and lower in the SH compared to V5 CO by 10-20% and as high as 30% in areas.
- Better agreement with MOPITT with main differences at the Polar regions.

The AIRS averaging kernel can be expressed as,

$$A = U \frac{\lambda}{\lambda + \Delta\lambda} U^T \quad (1)$$

where the matrix U are the eigenvectors from the unitary transformation, and λ are the eigenvalues of the eigenvectors damped by Δλ as described by Susskind *et al*., [2003].

The convolution of the DACOM *in situ* profiles discussed in section 3.2 uses the following formula:

$$x' = x_0 \left[1 + A \left(\frac{x - x_0}{x_0} \right) \right] \quad (2)$$

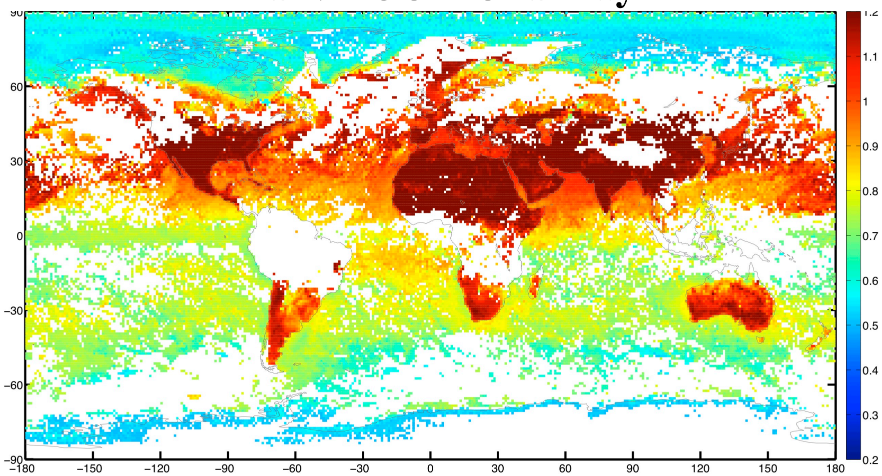
where x' represents the transformed *in situ* profile, x is the true profile, and x_0 is the *a priori* profile.

- To understand the sensors' measurement capabilities one needs to properly incorporate the retrieval sensitivity represented by the Averaging Kernels (Aks).

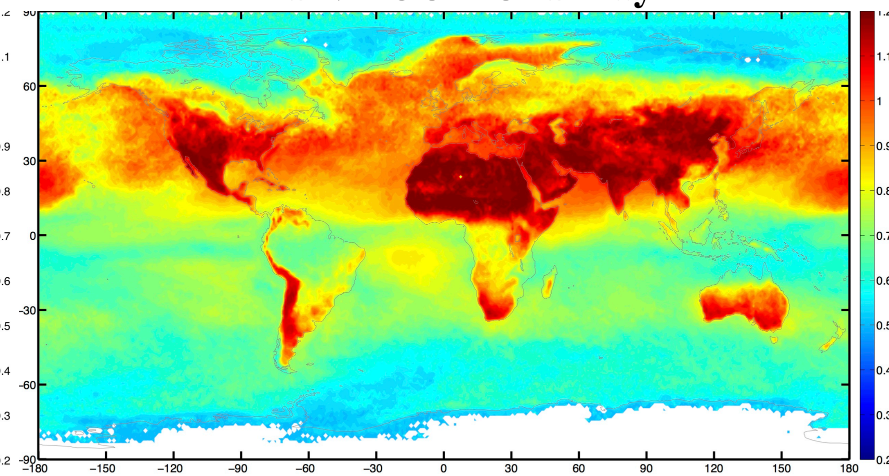
- Direct comparisons provides uncertainties in areas we need to improve.

AIRS CO DOFS Analysis between the two algorithms for March 2006

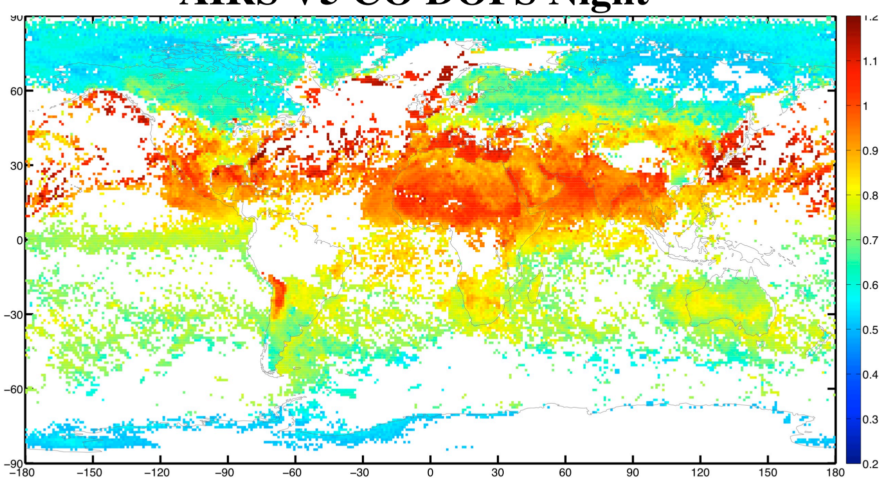
AIRS V5 CO DOFS Day



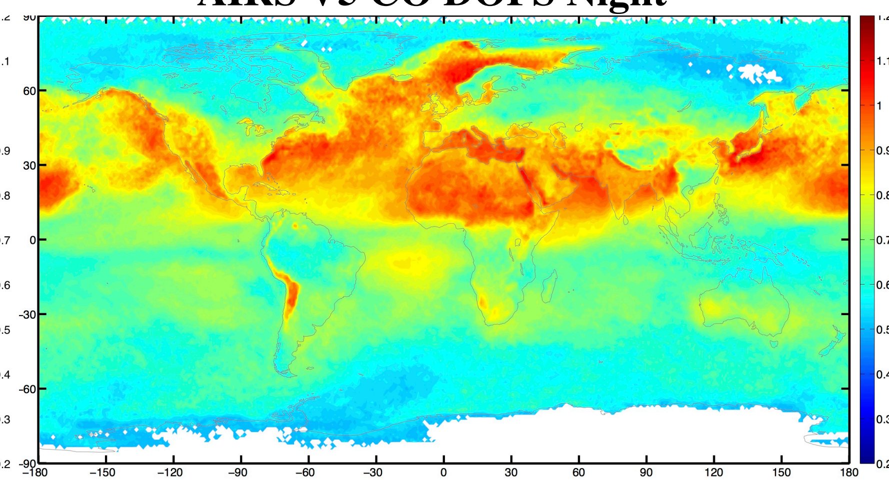
AIRS V5 CO DOFS Day



AIRS V5 CO DOFS Night



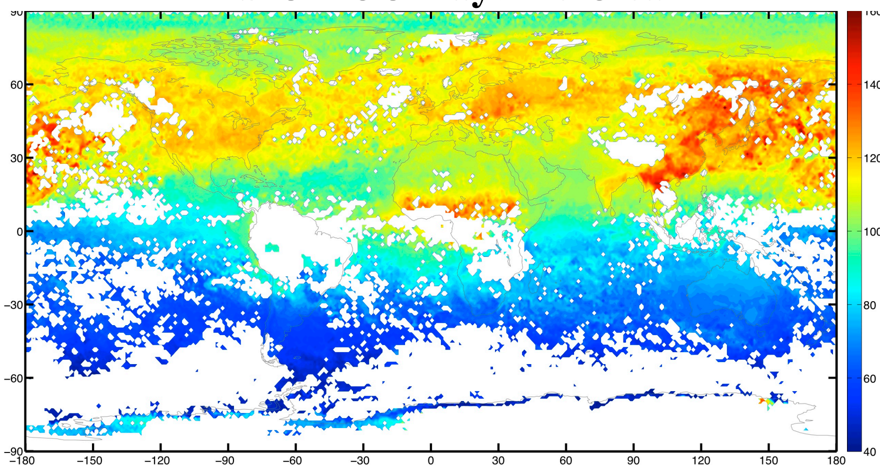
AIRS V5 CO DOFS Night



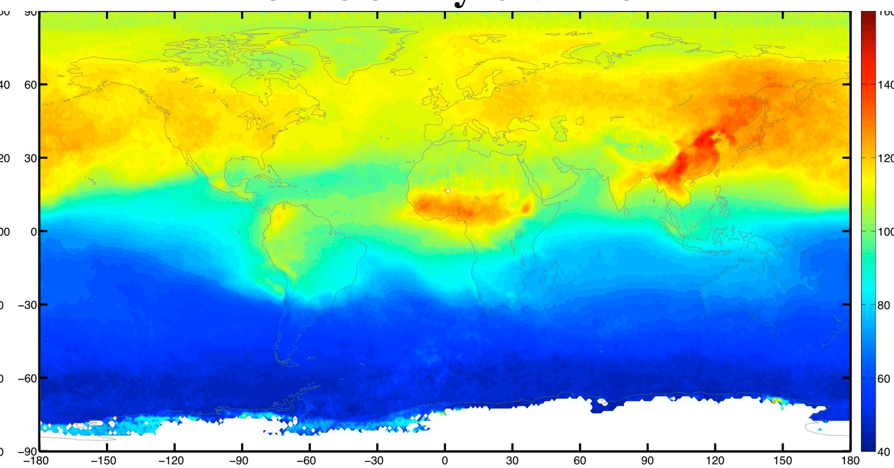
- Cloud effects tend to reduce AIRS V5 DOFS.
- Biomass Burning coverage screened out by MODIS cloud mask by mistaken the smoke with cloud.

AIRS OE CO Analysis between Cloud-cleared and Clear for Mar-May 2006

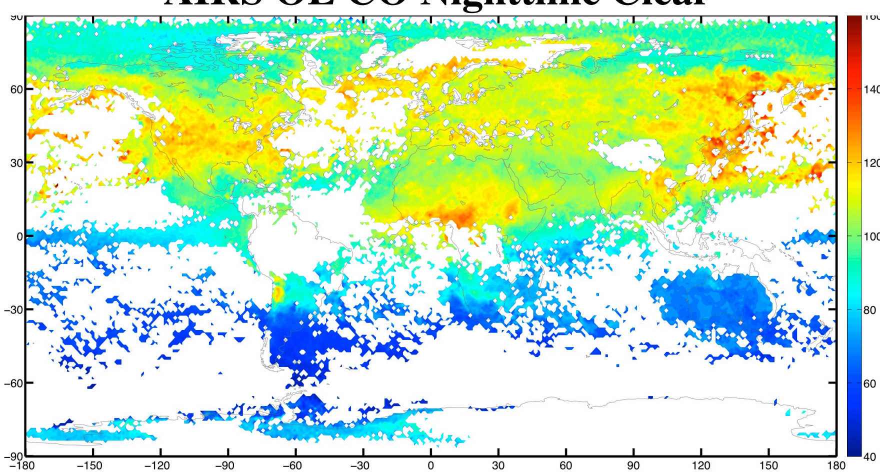
AIRS OE CO Daytime Clear



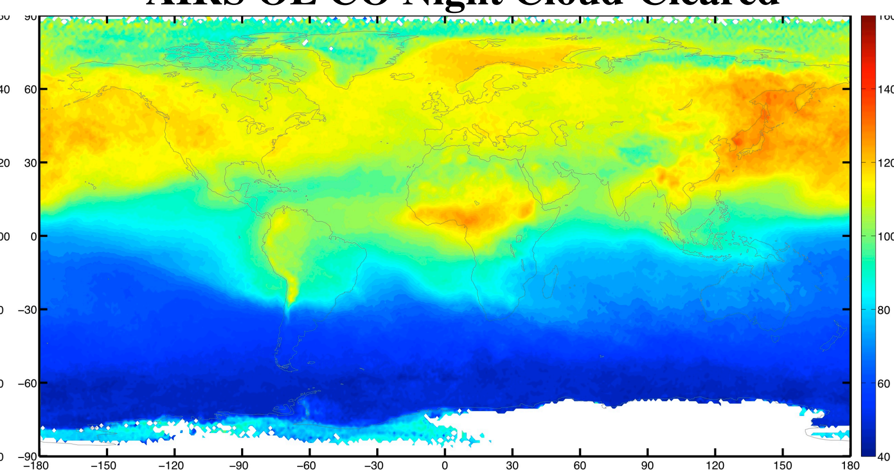
AIRS OE CO Day Cloud-Cleared



AIRS OE CO Nighttime Clear



AIRS OE CO Night Cloud-Cleared

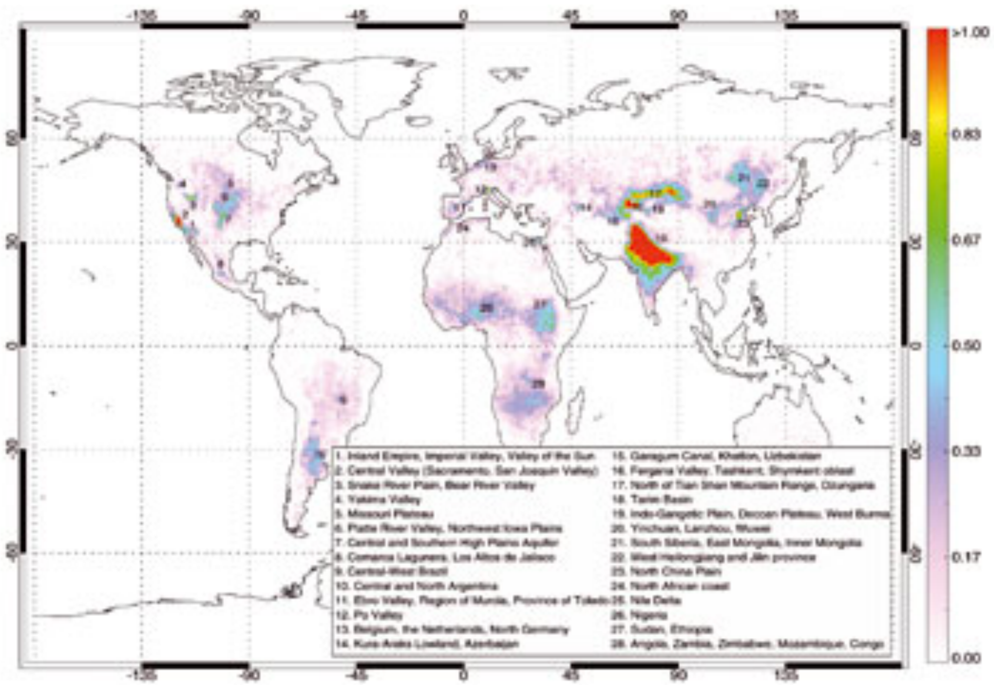


- AIRS V5 DOFS are computed differently from the OE method. Should not be compared directly with other sensors.
- AIRS OE CO DOFS average between 0.8 to 1.
- Note day/night differences due to the change of surface thermal contrasts.

On-going:

Measurements of NH_3 with AIRS

- Funded by NASA's the Science of Terra and Aqua



Global ammonia distribution derived from infrared satellite observations, Lieven Clarisse, et al., 2009

- NH3 major component of the global nitrogen cycle
- Global emissions primarily due to agriculture
- Environmental impact:
  - Deposition of reactive nitrogen in sensitive ecosystems
  - Enhanced creation of ammonium sulphate and ammonium nitrate aerosols (EPA PM2.5)
- Lifetime less than *8* hours, daytime AIRS measurements will be useful.

- First observed with TES (Beer, et. al. GRL 2008). Global measurements using IASI (Clarisse et. al. Nature Geoscience 2009).
- AIRS is likely more sensitive to NH3 than IASI due to the 1:30 pm versus 9:30 am overpass time.