Trace Gas Products from High Resolution Infrared Instruments.

Chris Barnet & Mitch Goldberg

STAR Science Forum

Oct. 21, 2005

Walter Wolf: Near Real Time Processing & Gridding System
Lihang Zhou: Regression Retrieval & Near Real Time Web Page
Eric Maddy: CO_2 retrieval, tuning, verticality
Xiaozhen Xiong: CH_4 retrieval
Xingpin Liu: Re-processing, Statistics, Trace gas web-page
Fengying Sun: RTA upgrade installation & checkout
Jennifer Wei: START ozone experiment laison with NCAR

Outline of Presentation

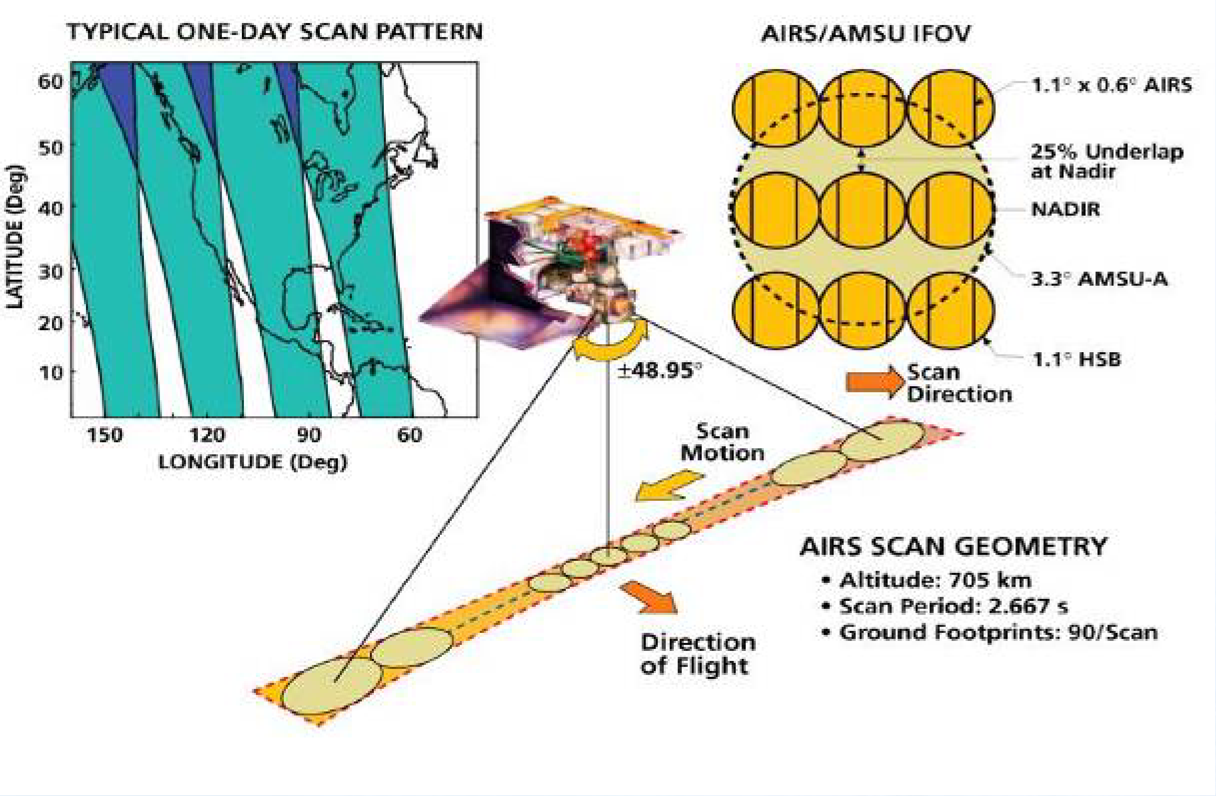
- Overview of the high spectral resolution instruments and products.
- Advantages of high spectral resolution, multi-spectral observations.
- Overview of trace gas products
  - Ozone
  - Carbon monoxide
  - Methane
  - Carbon dioxide
- Overview of product web page

Acronyms

- AIRS - Atmospheric Infrared Sounder
- IASI - Infrared Atmospheric Sounding Interferometer
- CrIS - Cross-track Infrared Sounder
- AMSU - Advanced Microwave Sounder Unit
- NDE – NPOESS Data Exploitation
- NPP - NPOESS Preparatory Project
- NPOESS - National Polar-orbiting Operational Environmental Satellite System

Thermal & Microwave Can be Used to Sound in Cloudy 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.

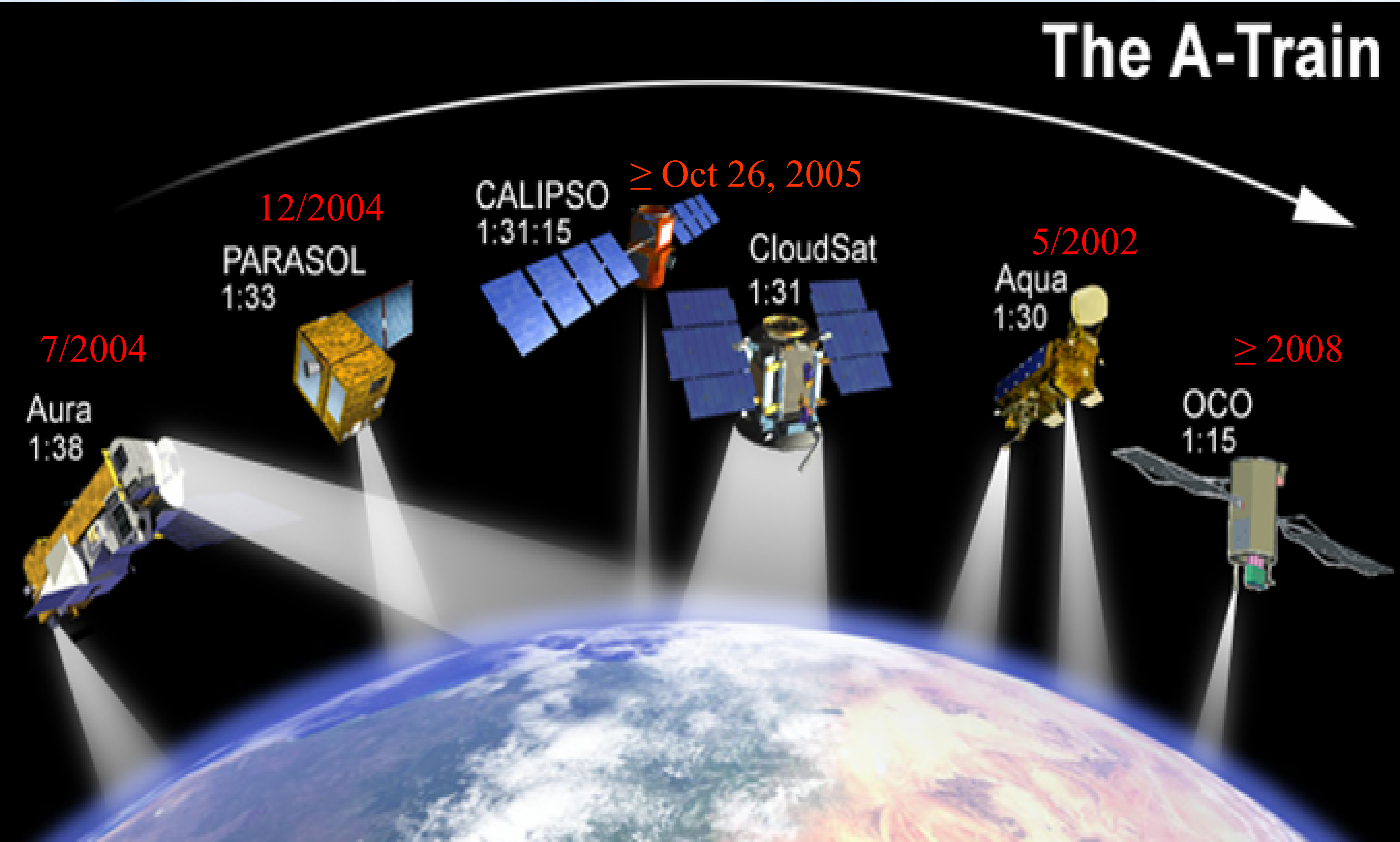


AIRS, IASI, and CrIS all acquire 324,000 FOR's per day

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

- Cloud Cleared Radiance
- Temperature, 1K/ 1km
- Moisture, 5%
- Ozone, 5%
- Land/Sea Surface Temperature
- Surface Spectral Emissivity
- Surface Reflectivity
- Cloud Top Pressure
- Cloud Liquid Water (AMSU product)
- Cloud Fraction (per 15 km footprint).
- Carbon Monoxide, 15%
- Carbon Dioxide, 1%
- Methane, 1%
- Nitric Acid, 20%(?)
- Cirrus Cloud Optical Depth and Particle Size

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

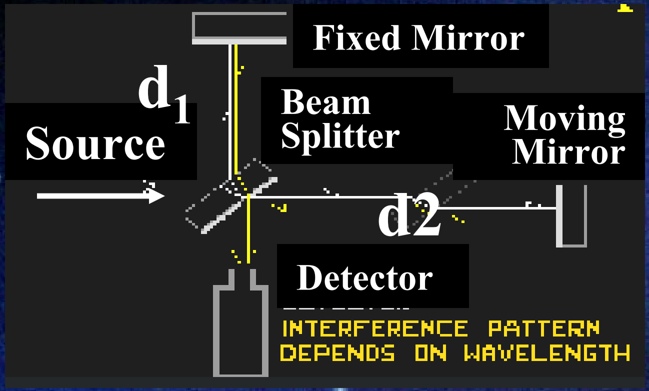


NOAA/NESDIS Strategy

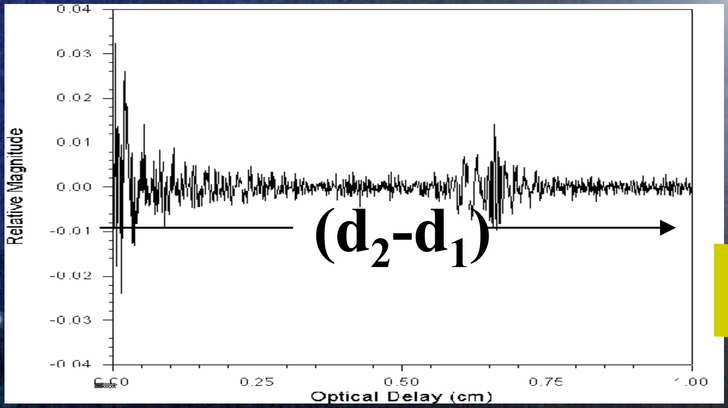
- Now: Develop and test atmospheric carbon algorithms using the Aqua AIRS/AMSU/MODIS Instruments
  - AIRS has excellent radiometric accuracy and stability
  - The A-train complement of instruments can be used to study effects of clouds, etc.
- 2006: Migrate the AIRS/AMSU/MODIS algorithm into operations with METOP/IASI/AVHRR
  - 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 & NPOESS 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
- The polar instruments can provide 324,000 soundings in cloudy conditions per day for the next 20+ years

Interferometer Measurements to Soundings

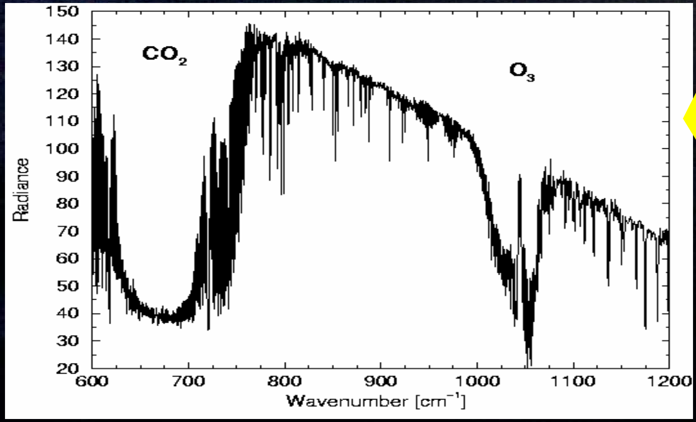
Michelson Interferometer (FTS)



Interferogram

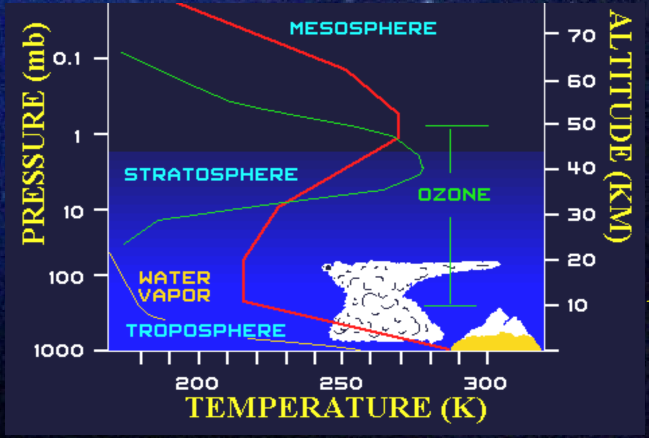


Fourier Transformation



Radiance Spectrum

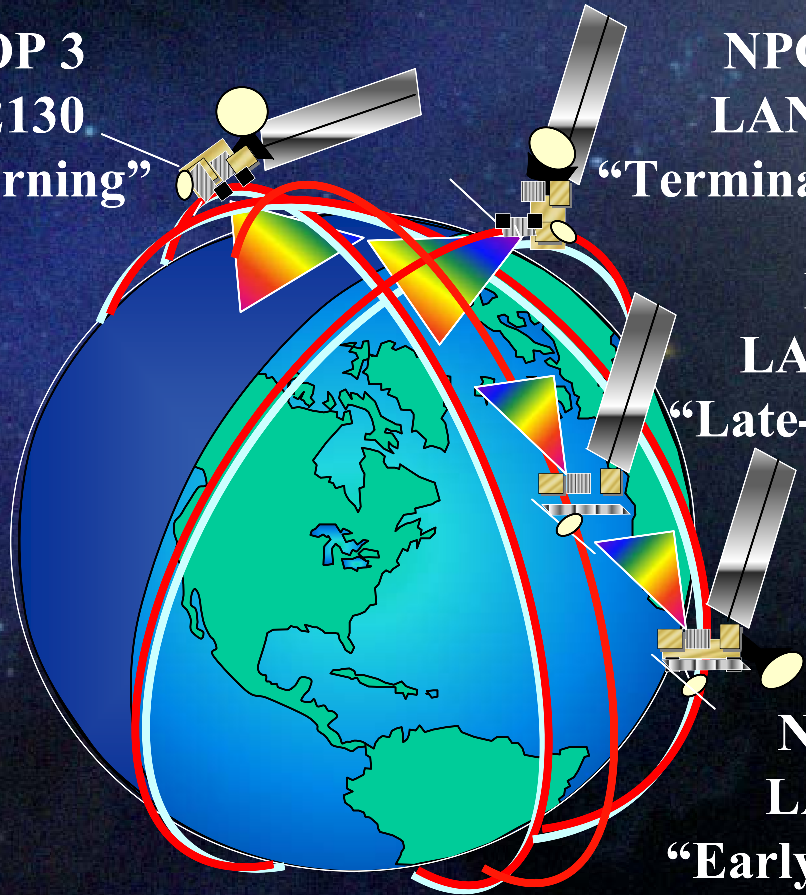
Numerical Inversion



Vertical Sounding

Thanks to Steve Mango for this slide and next 2 slides.

Agreement with NPP - Notional Concept

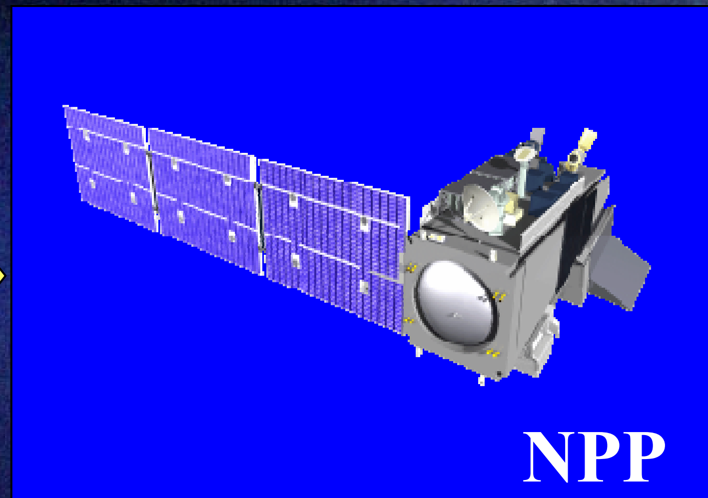


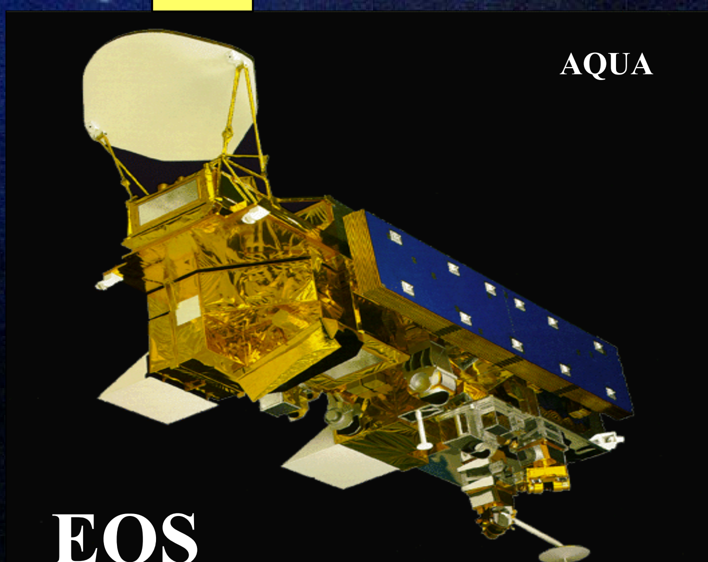
NPP
~2008-2013

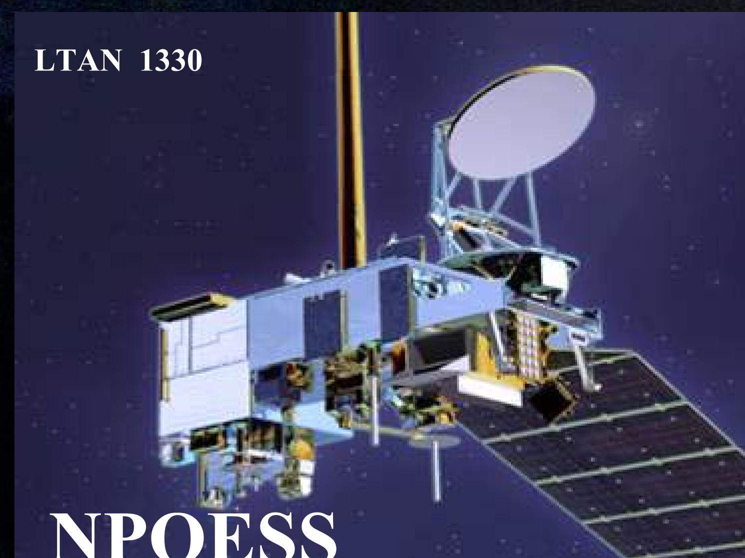
	Launches	Lifetime	Ozone Sensors	Atmos Sounders
METOP [2130]	~2006, 2011, 2016	5 yr	GOME-2/IASI	IASI/AMSU/MHS
NPP [2230]	~2008	5 yr	OMPS/CrIS	CrIS/ATMS
NPOESS [1330]	~ 2010, 2016	7 yr	OMPS/CrIS	CrIS/ATMS/CMIS
NPOESS [1730]	~2013, 2019	7 yr	CrIS	CrIS/ATMS/CMIS

NPOESS Preparatory Project [NPP]
"Bridge from EOS to NPOESS"

"Bridges EOS & NPOESS Climate Measurement Missions"



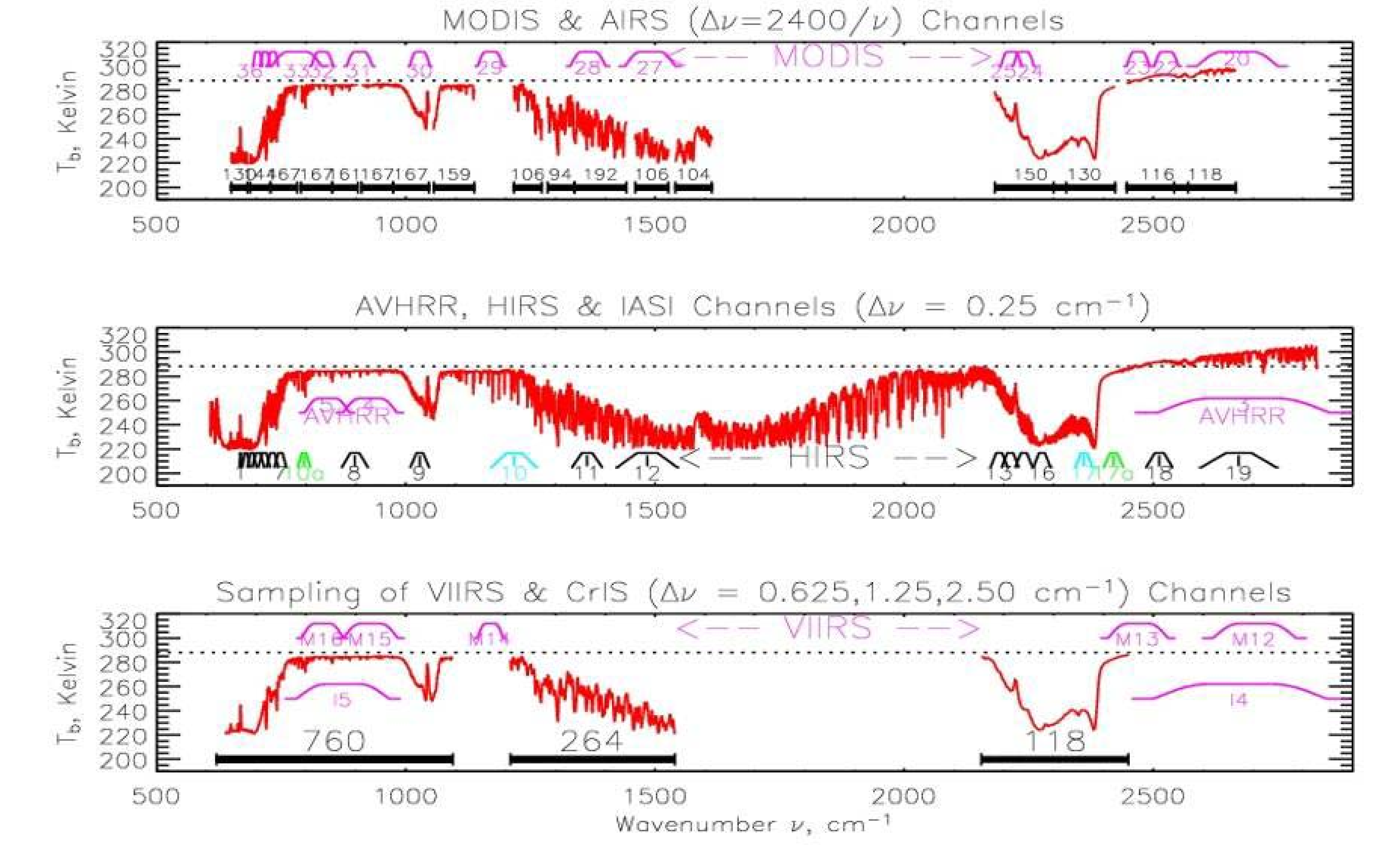




Retrieval of Atmospheric Trace Gases Requires Unprecedented Instrument Specifications

- 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.
  - For channel subsets, apodization of interferogram (IASI & CrIS) improves spectral purity.
- Need Excellent Instrument Noise & Instrument Stability
  - Low NEΔT is required.
  - Apodization of interferograms (IASI & CrIS) creates a spectrally local correlated noise; however, information content is unaltered.

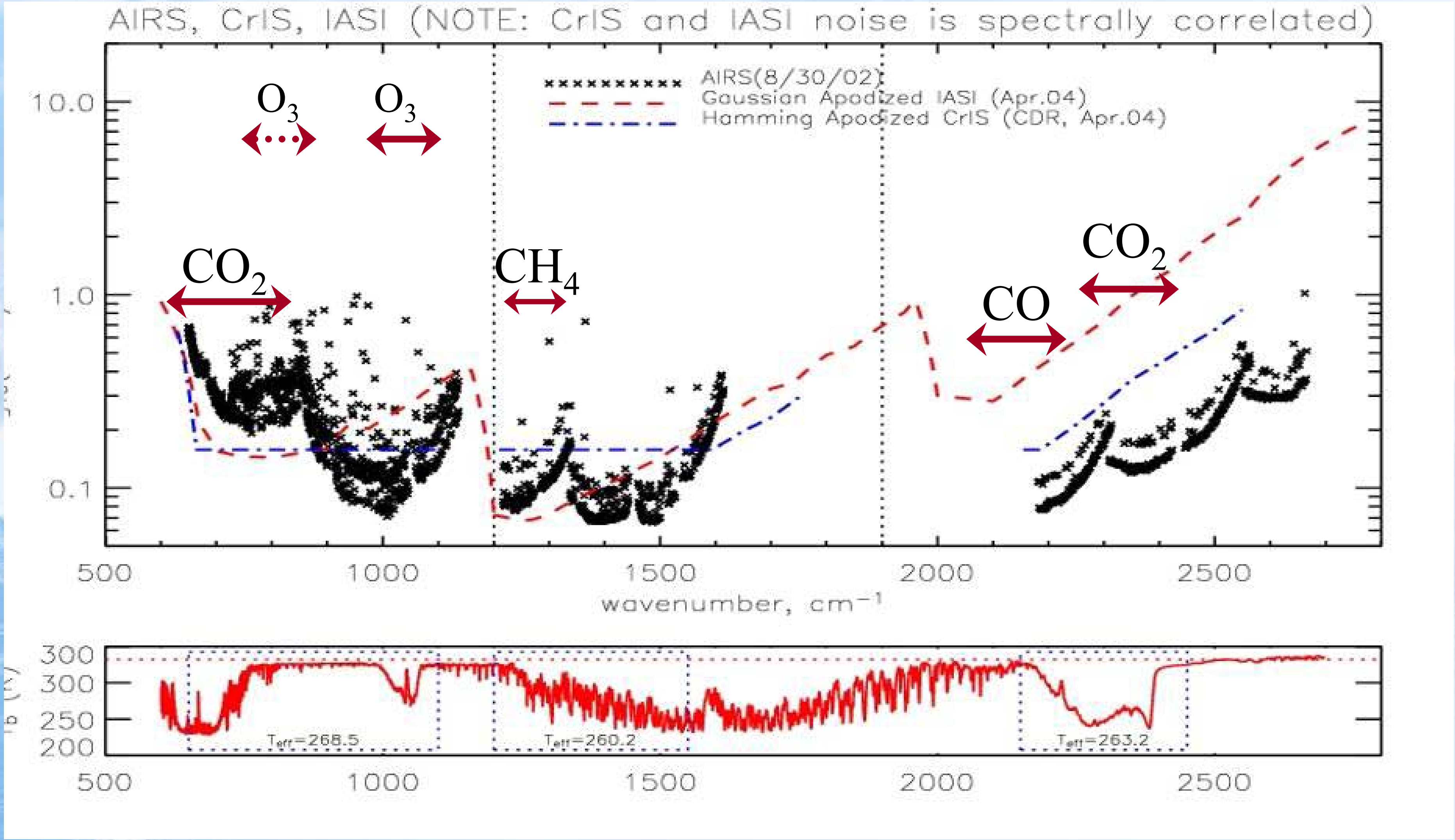
Spectral Coverage of AIRS, IASI, and CrIS



Spectral Resolution in Trace Gas Bands for AIRS, IASI, CrIS

gas	Wave Number	AIRS v/1200	IASI L=2 cm (apodized)	CrIS L=.8,.4,.2 (apodized)
CO_2	735 cm^{-1}	0.61	0.5	1.13
CO_2	791 cm^{-1}	0.66	0.5	1.13
O_3	1045 cm^{-1}	0.88	0.5	1.13
CH_4	1306 cm^{-1}	1.09	0.5	2.25
CO	2142 cm^{-1}	1.79	0.5	4.50
CO_2	2385 cm^{-1}	1.99	0.5	4.50

Instrument Noise, NEΔT at 250 K (Interferometers are Apodized)

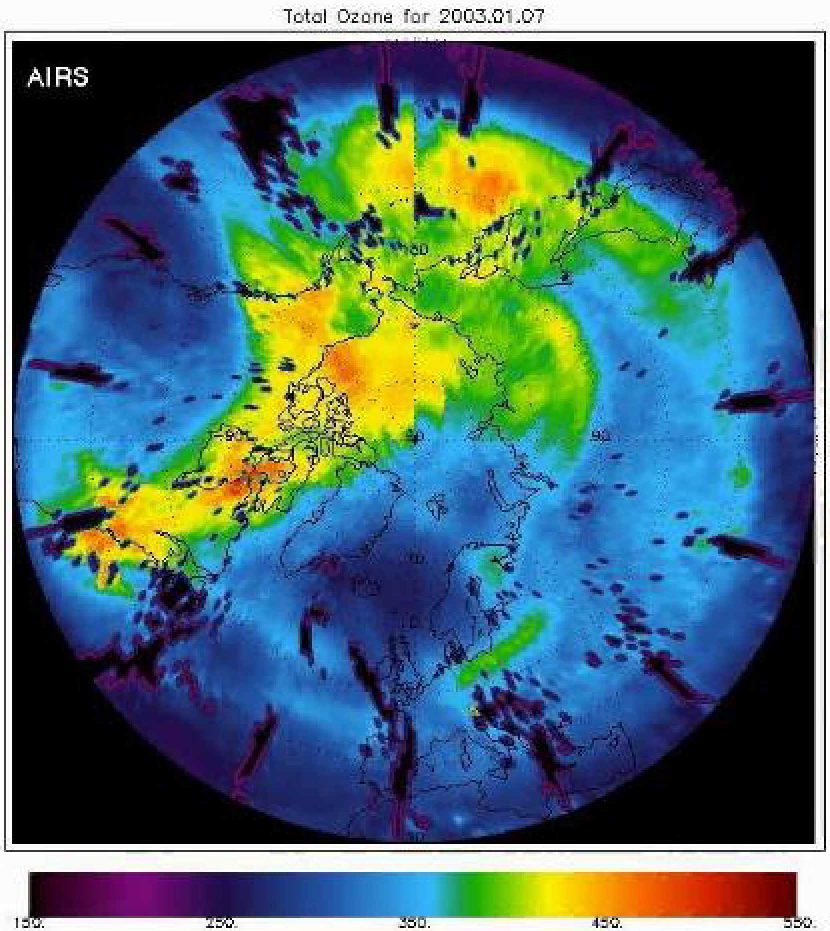


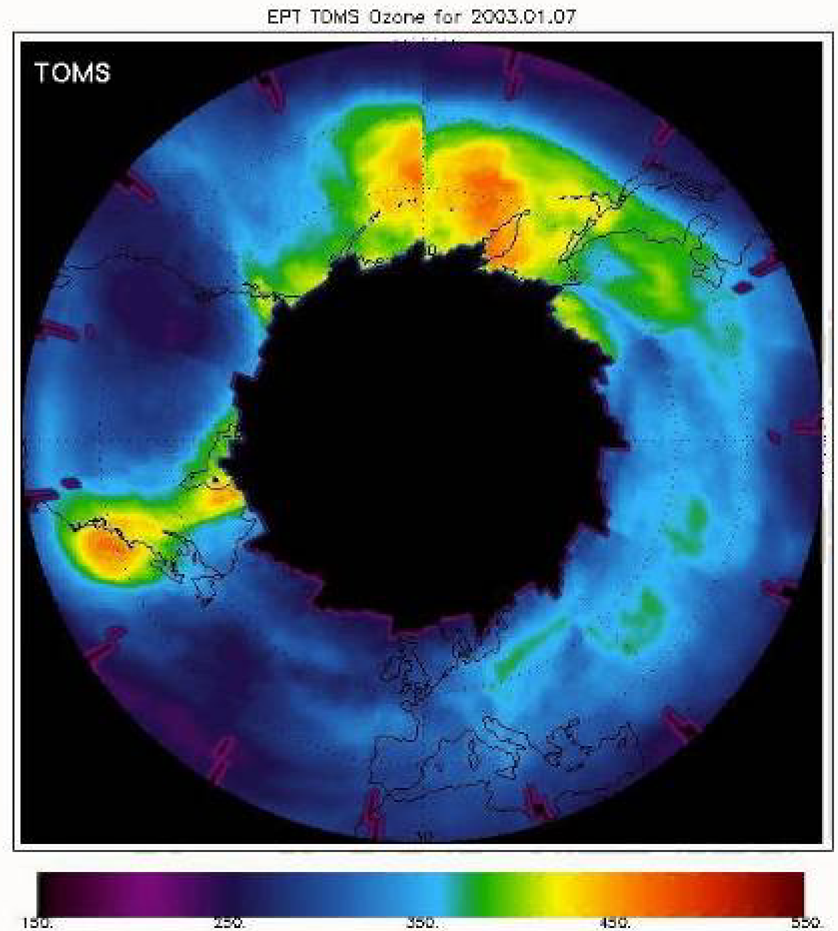
Ozone

- AIRS observes Ozone in daytime and nighttime using the 9.8 μm band.
- Validation campaign includes
  – dedicated ozone sondes
  – Comparisons w/ TOMS and Aura/OMI
  – In-situ measurements (INTEX-A, START)
- 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 regression to ECMWF & damping of physical retrieval)
  – V5.0 should be considerably better.

AIRS and TOMS Polar Night

Mike Newchurch (UAH), Bill Irion (JPL)





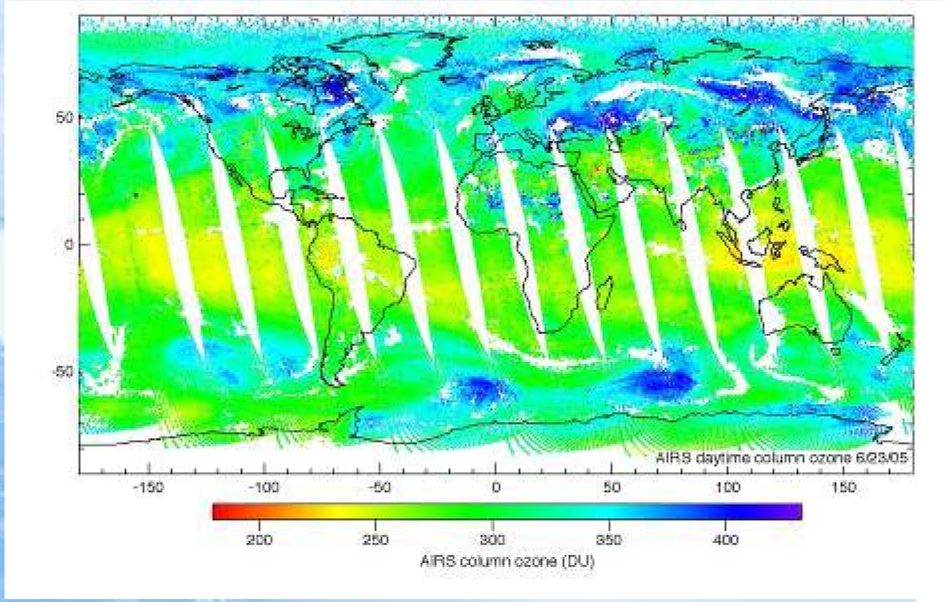
Jan. 7, 2003

AIRS and Aura/OMI comparisons

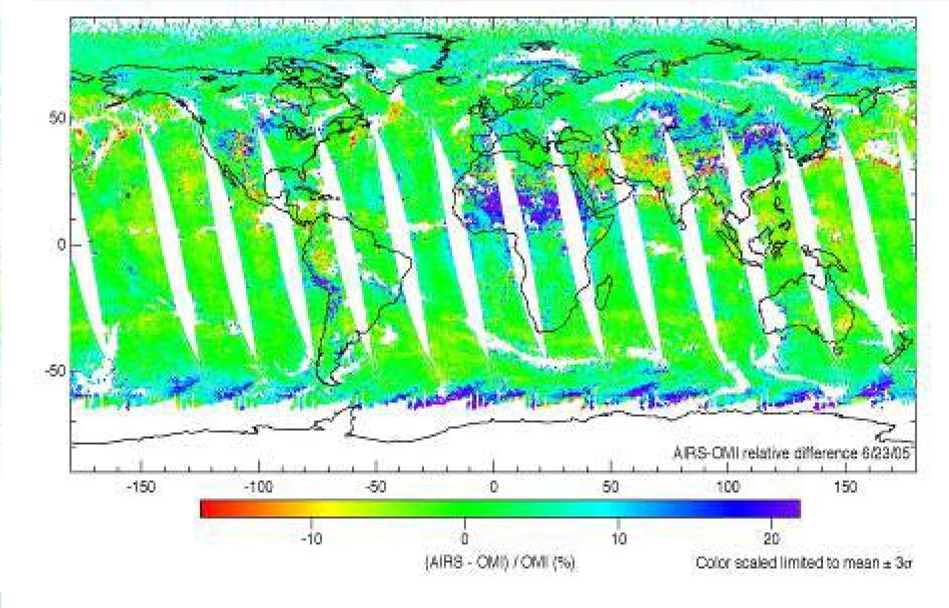
Mike Newchurch (UAH), Bill Irion (JPL)

AIRS daytime ozone 6/23/05

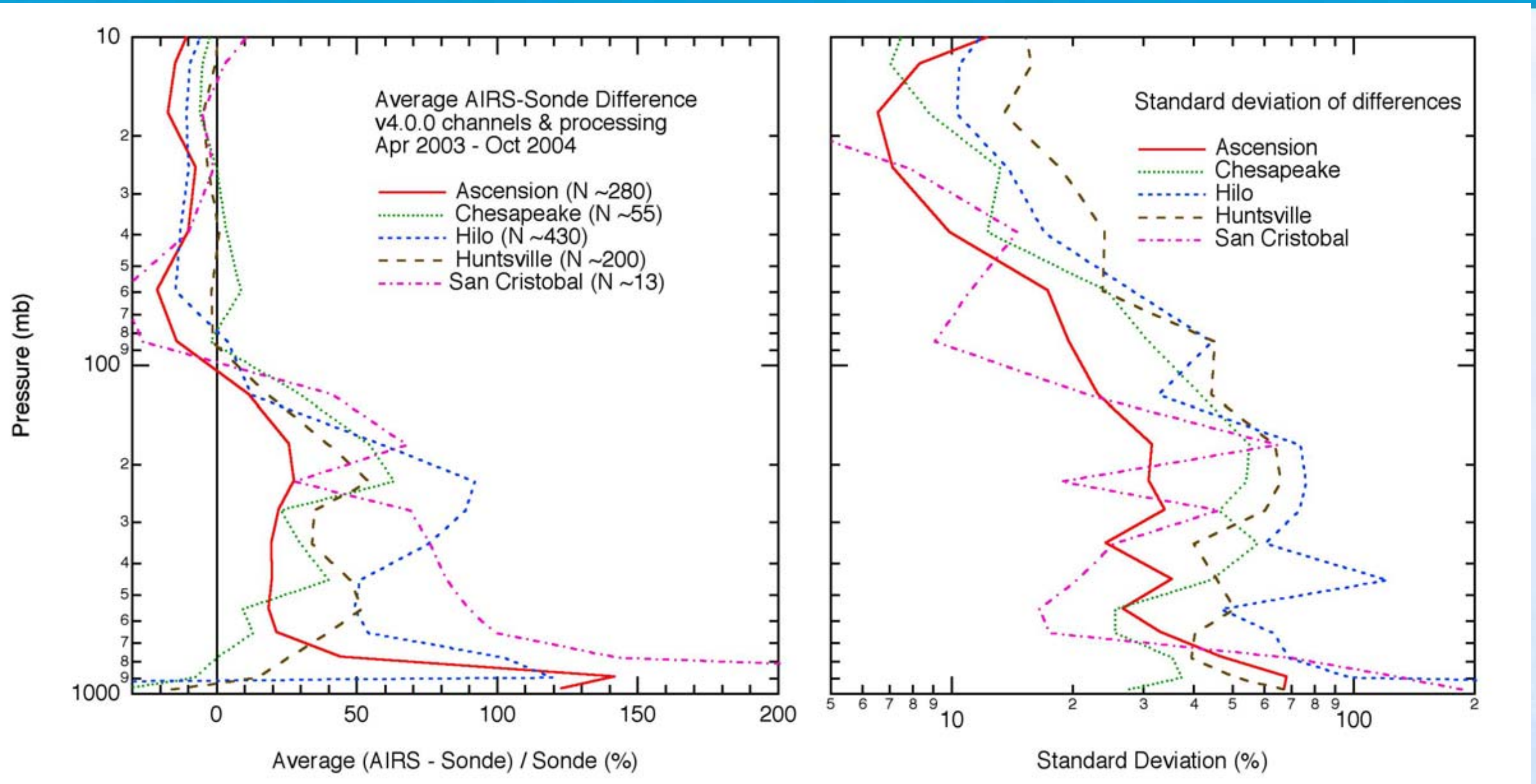
AIRS column



(AIRS - OMI) / OMI

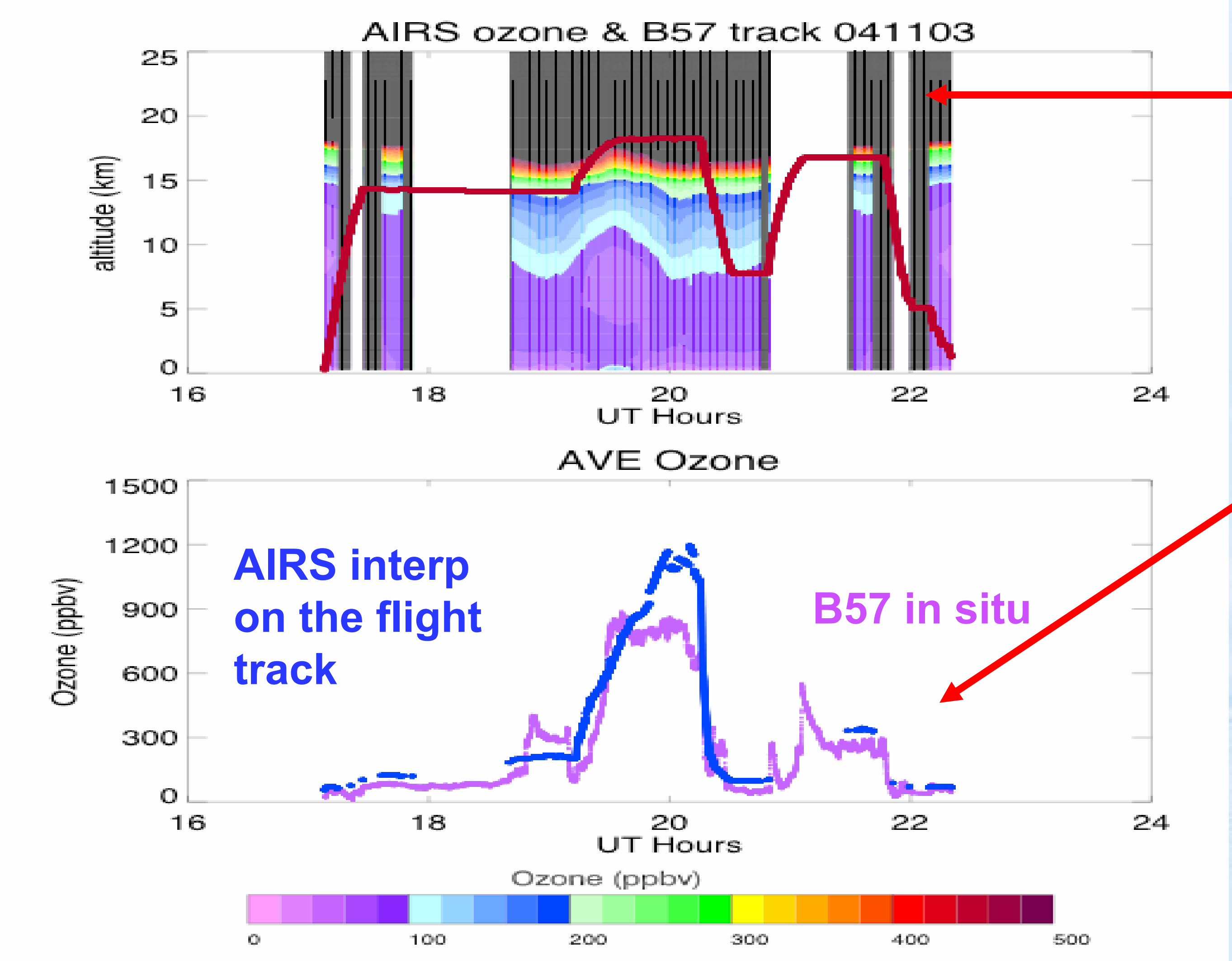


AIRS/Sonde comparison
Mike Newchurch (UAH), Bill Irion (JPL)



Average (AIRS - Sonde) / Sonde profiles for V4.0.0 (left panel) and standard deviations (right panel). "N" refers to the number of AIRS retrievals. Several AIRS observations may be matched up to a single ozonesonde. AIRS observations are made with 2 hours and 100 km of ozonesonde launch.

Example of Laura Pan's in-situ comparisons in dynamic regions



ignore the black columns - poor handling of missing data

"Good agreement between AIRS and in situ between 50-500 ppb"

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 will support this experiment with near real time AIRS L1b & L2 products, including v4.x ozone and carbon monoxide.
- Jennifer Wei will be our liason to START team.

Carbon Monoxide

- Varies between 50 to 200 ppbv
- Lifetime is a few months
- Sources (Lelieveld, 1998):
  - Fossil fuel combustion (*e.g.*, catalytic converter on automobiles) ≈ 550 Tg/yr
  - Forest Fires & Biomass Burning ≈ 400 Tg/yr
  - Methane Oxidation ≈ 850 Tg/yr

Jacobians are Useful for Inter-comparison of Instruments

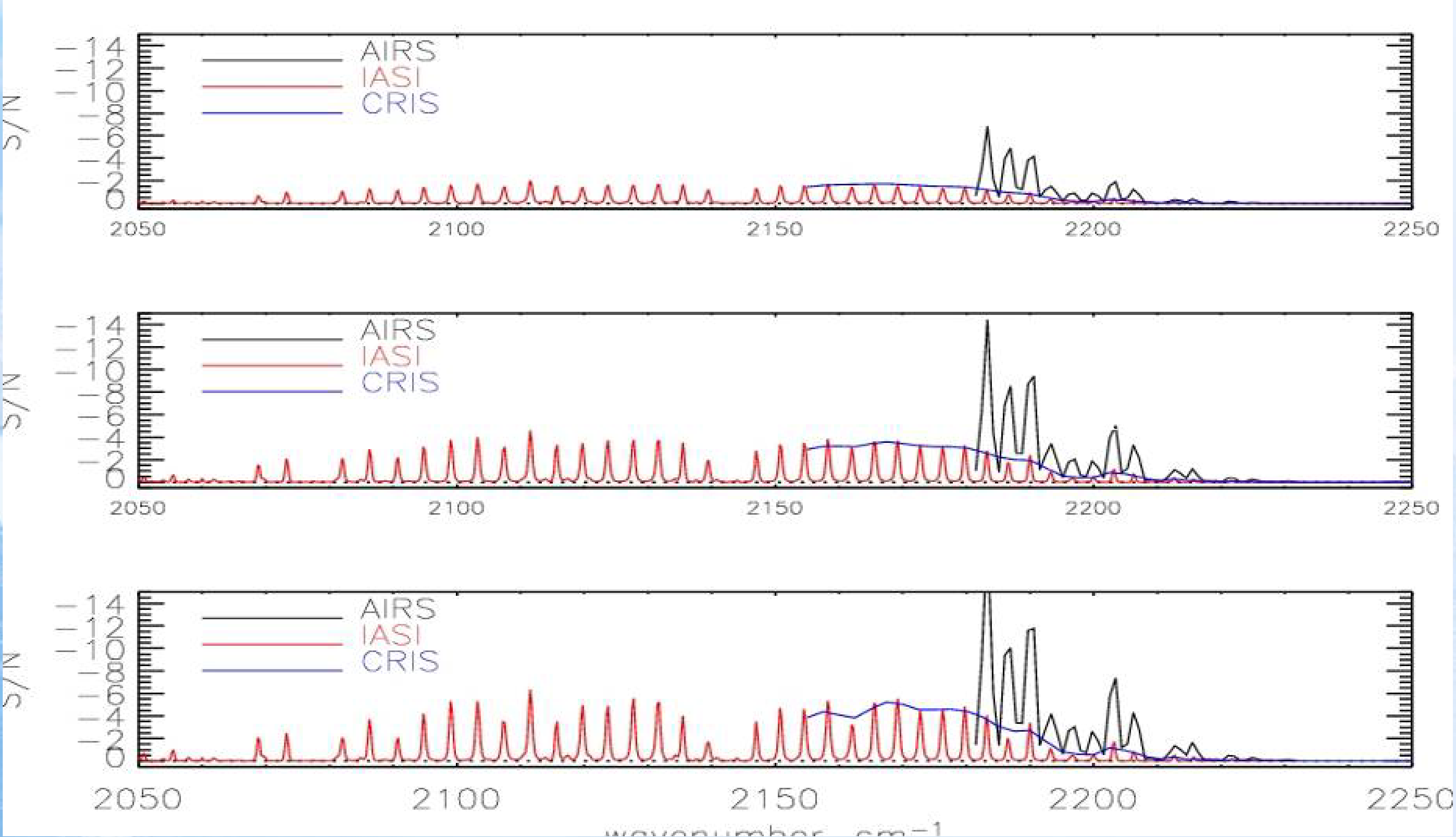
- Observed minus Calculated Radiances Can be Represented by a Taylor Expansion about perturbations

$$O - C = \frac{\partial R}{\partial X}\Delta X + \frac{\partial R}{\partial T}\Delta T + \frac{\partial R}{\partial q}\Delta q + \frac{\partial R}{\partial O3}\Delta O3 + \varepsilon$$

- **The signal to noise (S/N) of a channel is given by the ratio of the sensitivity to perturbations in gas X to the RSS of the instrument error and interference signals.**

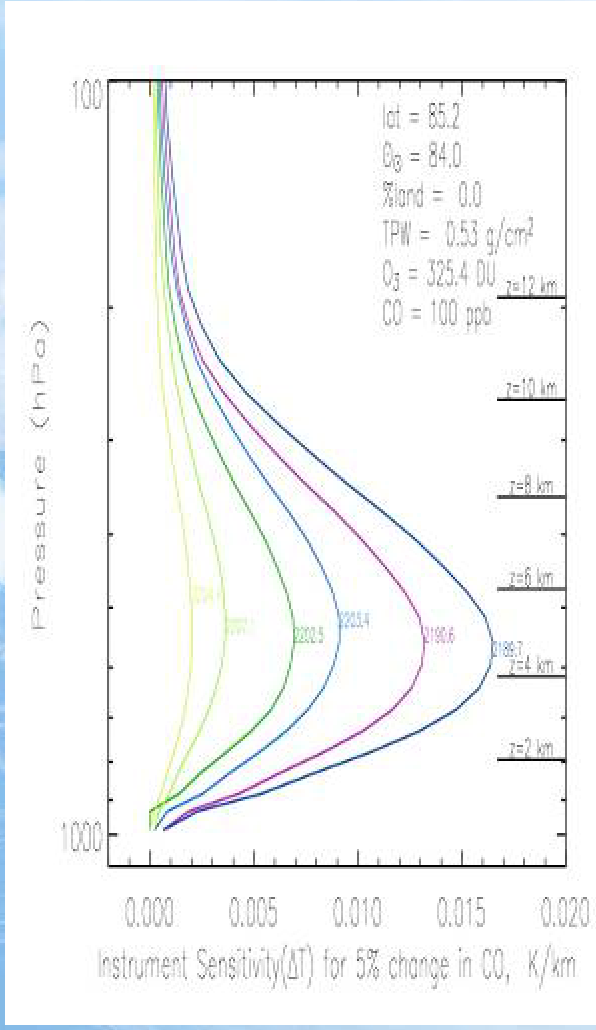
$$\frac{S}{N} = \frac{\frac{\partial R}{\partial X}\Delta X}{\sqrt{\left(\frac{\partial R}{\partial T}\Delta T\right)^2 + \left(\frac{\partial R}{\partial q}\Delta q\right)^2 + \left(\frac{\partial R}{\partial O3}\Delta O3\right)^2 + NE\Delta N^2}}$$

Carbon Monoxide S/N for a 10% (10 ppb) Perturbation

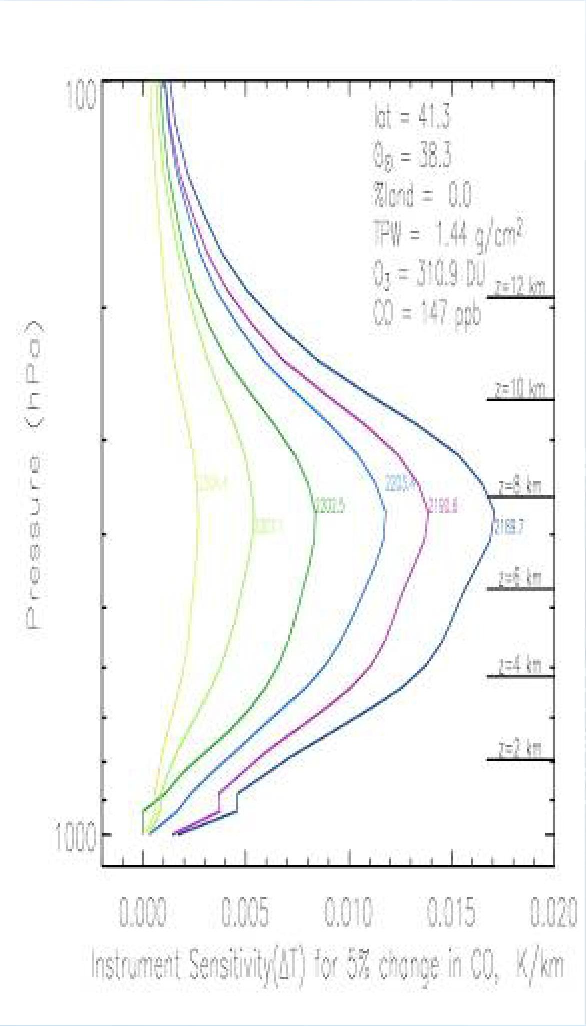


AIRS CO Kernel Functions are Sensitive to $H_2O(p)$, $T(p)$ & $CO(p)$.

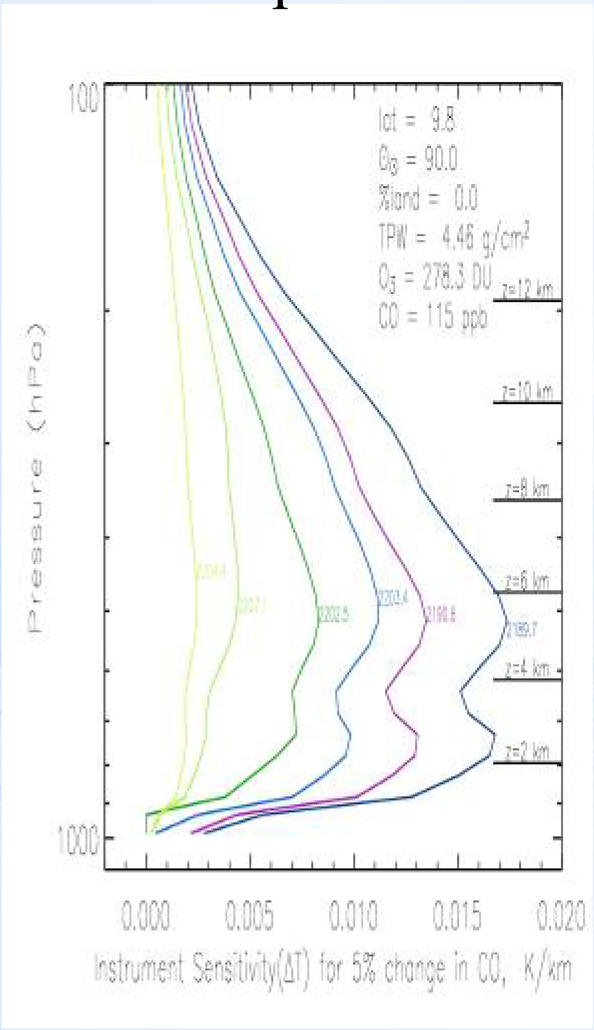
Polar



Mid-Latitude



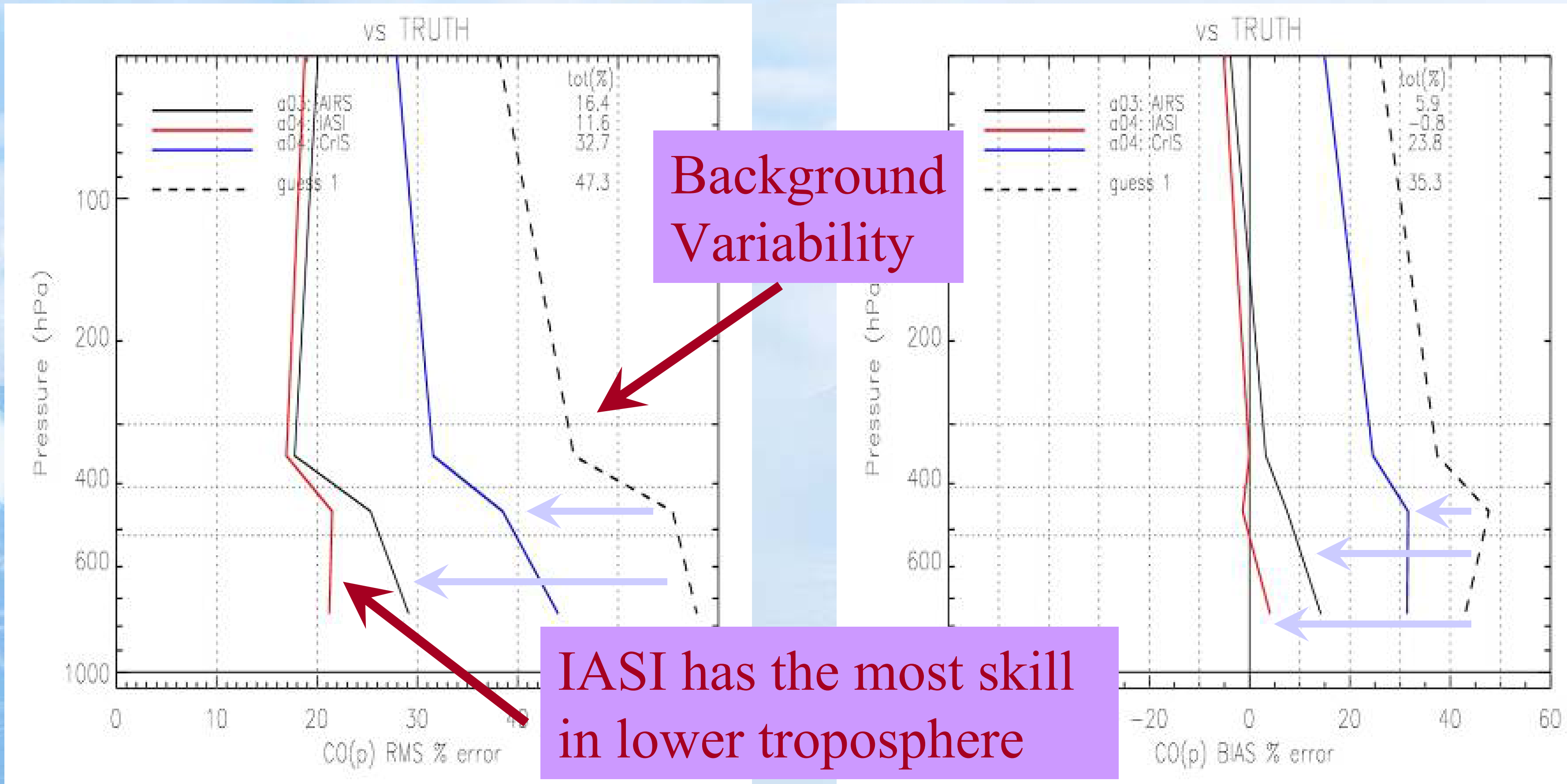
Tropical



Statistics of CO Retrieval for AIRS, IASI, and CrIS Simulated CLEAR Scenes

RMS

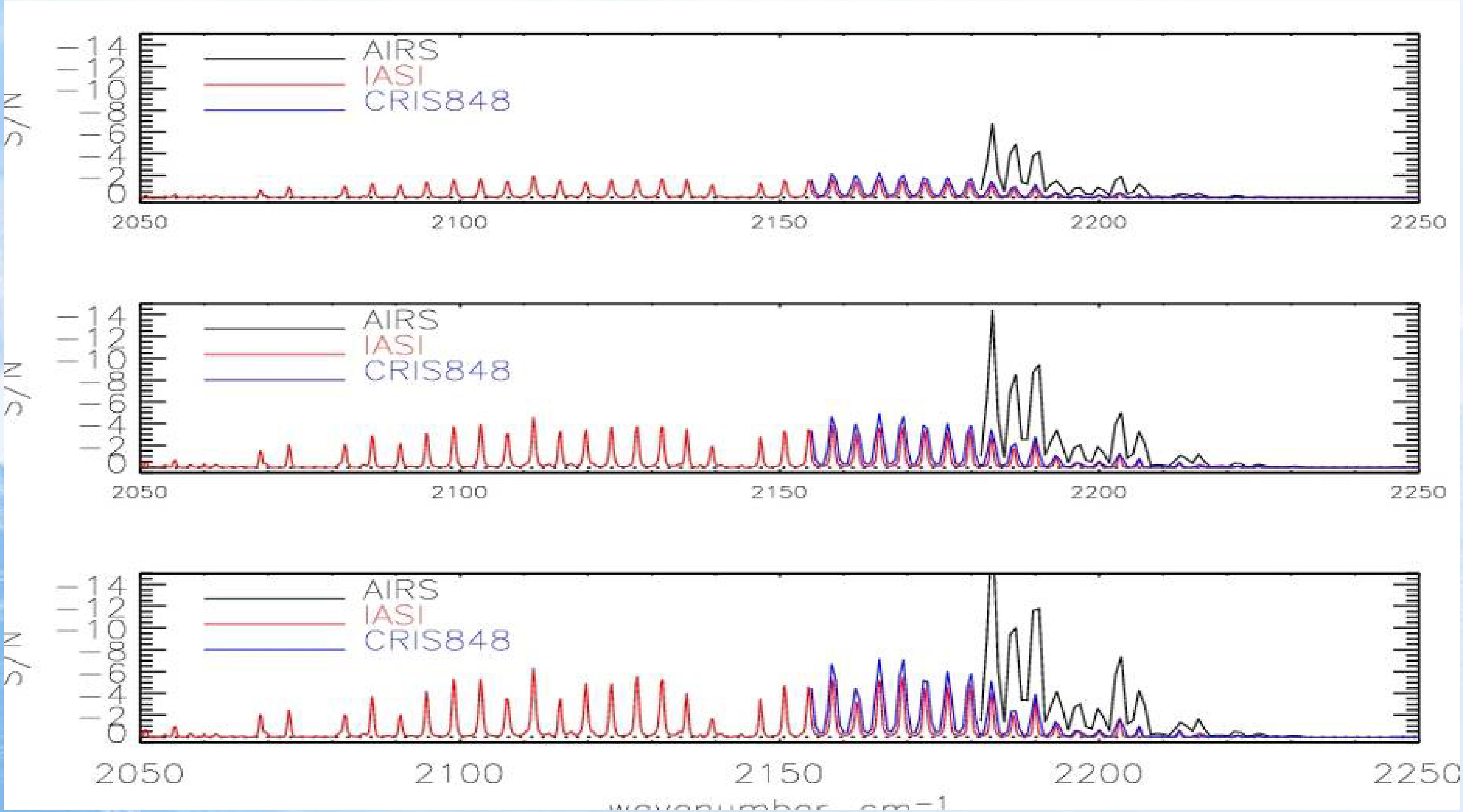
BIAS



CrIS CO Can be Improved

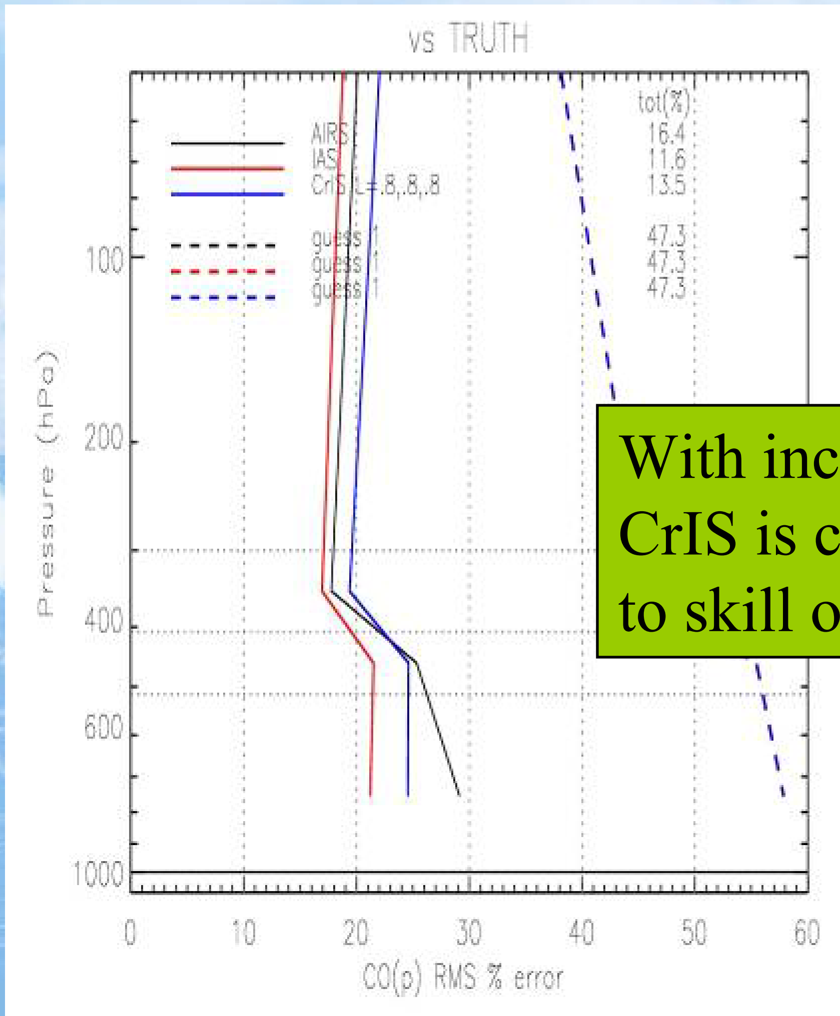
- CrIS OPD is 0.8 cm in all bands; however, the interferogram is not sampled beyond 0.2 cm in the SW band.
- Increasing sampling to OPD=0.4 or OPD=0.8 is technically feasible, but
  - Schedule impact for NPP makes modification unlikely.
  - Self-apodization issues complicates radiometric calibration.
- Information content is not affected unless new “resonances” are captured in the interferogram.
  - CO resonance occurs at 0.26 cm and is captured by OPD=0.4 cm.
  - CH_4 resonance at 0.18 cm is captured in MW w/ OPD=0.4 cm.
  - CO_2 resonance at 0.64 cm is captured in LW w/ OPD=0.8 cm.
- Retrievals based on resolved lines are not improved.
  - Number of samples per wavelength interval is proportional to OPD.
  - Noise per Nyquist sample increases by SQRT(OPD).
  - Noise/resolving element = SQRT(OPD)/SQRT(OPD) = 1

Carbon Monoxide S/N for a 10% (10 ppb) Perturbation if CrIS SWIR Band is OPD=0.8 cm



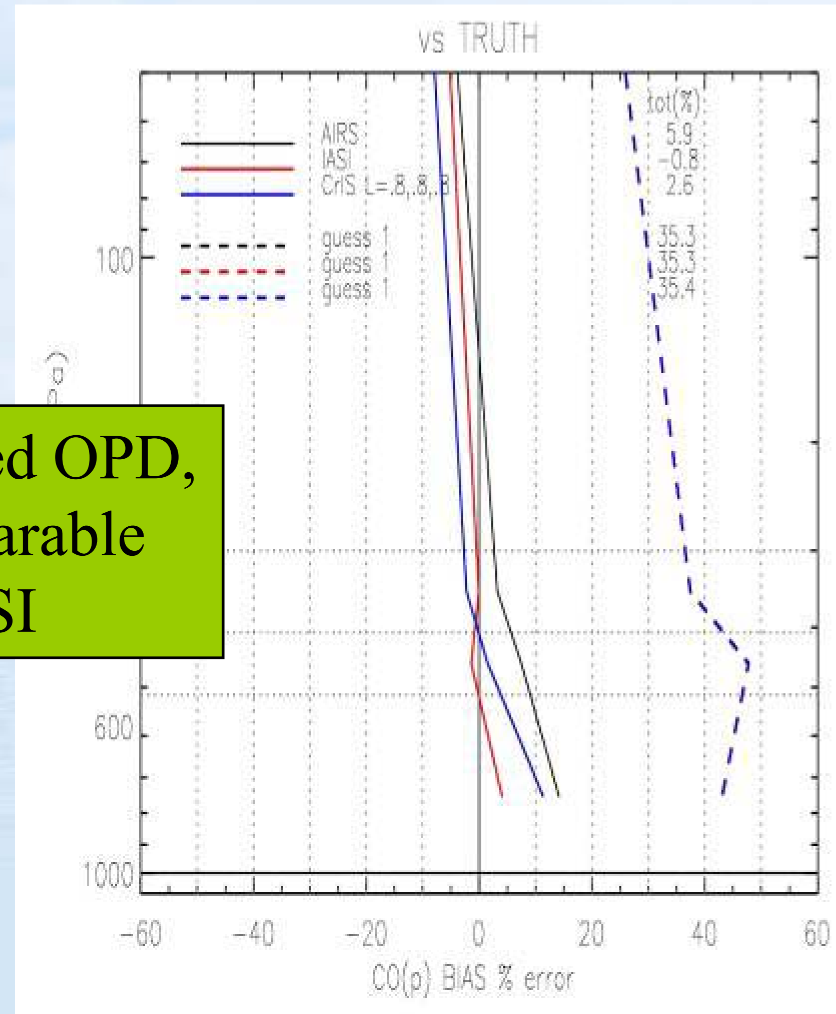
Statistics of CO Retrieval for Full Resolution CrIS & AIRS, IASI

RMS

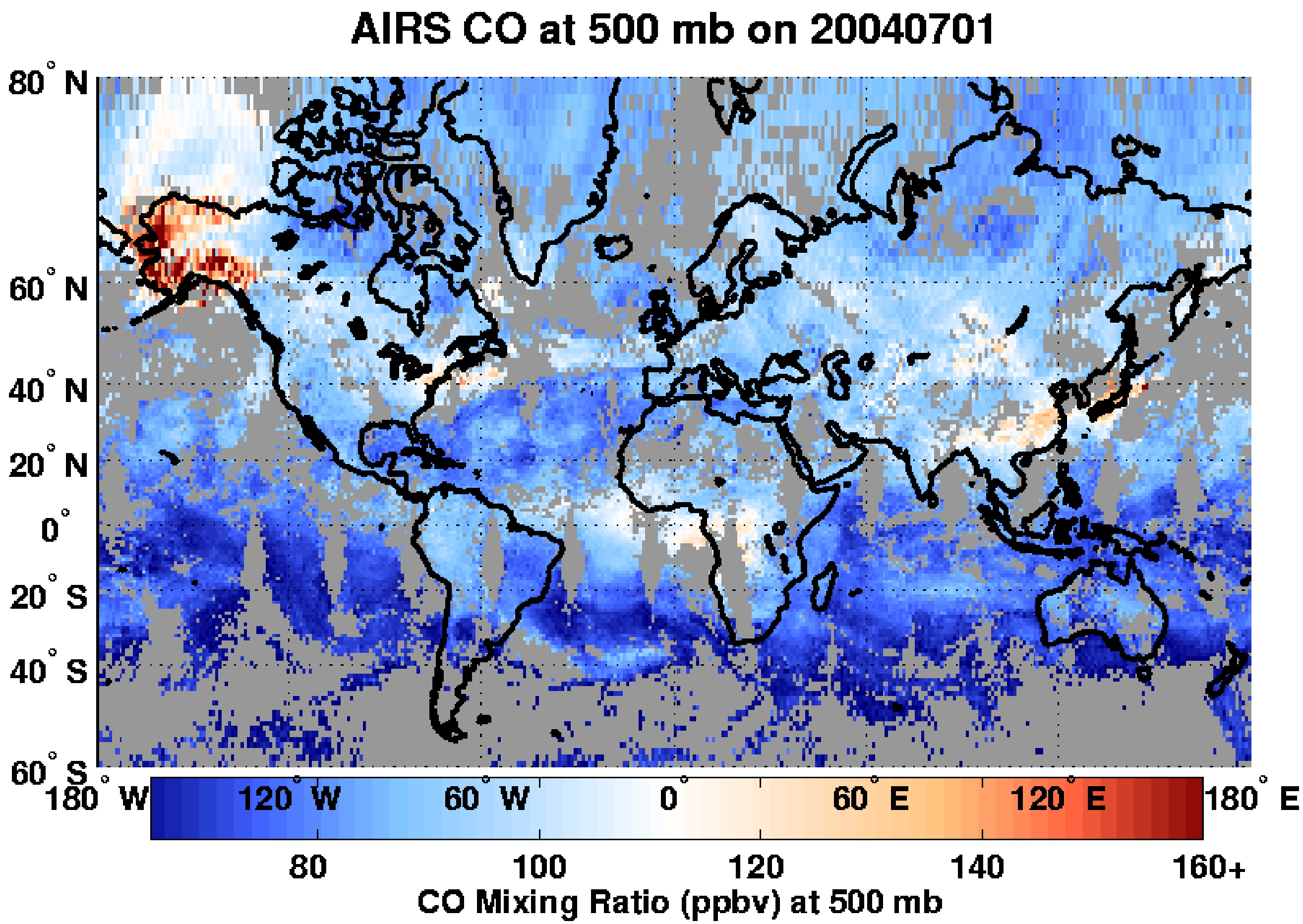


With increased OPD, CrIS is comparable to skill of IASI

BIAS



July 2004
AIRS Daily Global CO

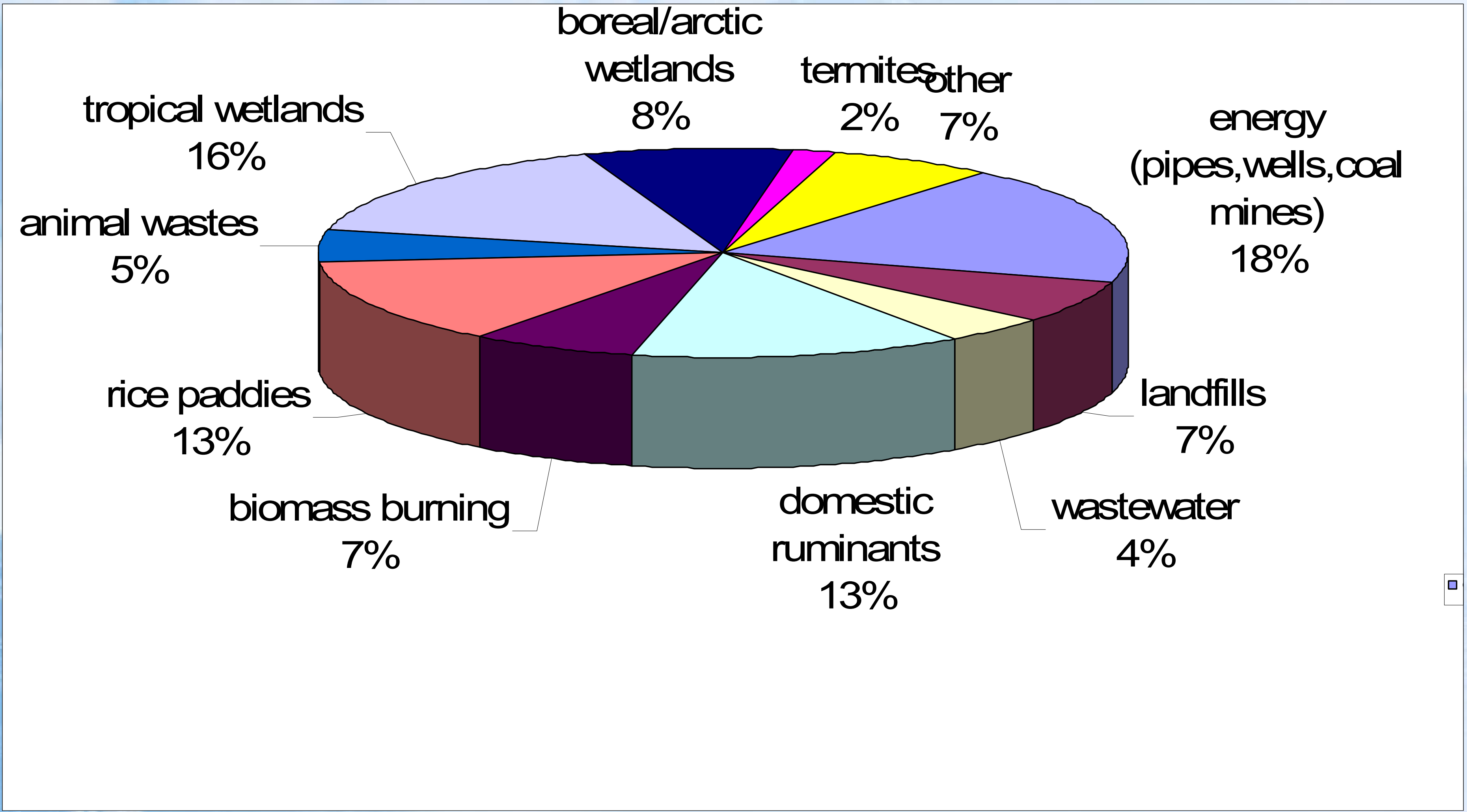


Analysis of NOAA products by Wallace McMillan, Juying Warner, & Michele McCourt

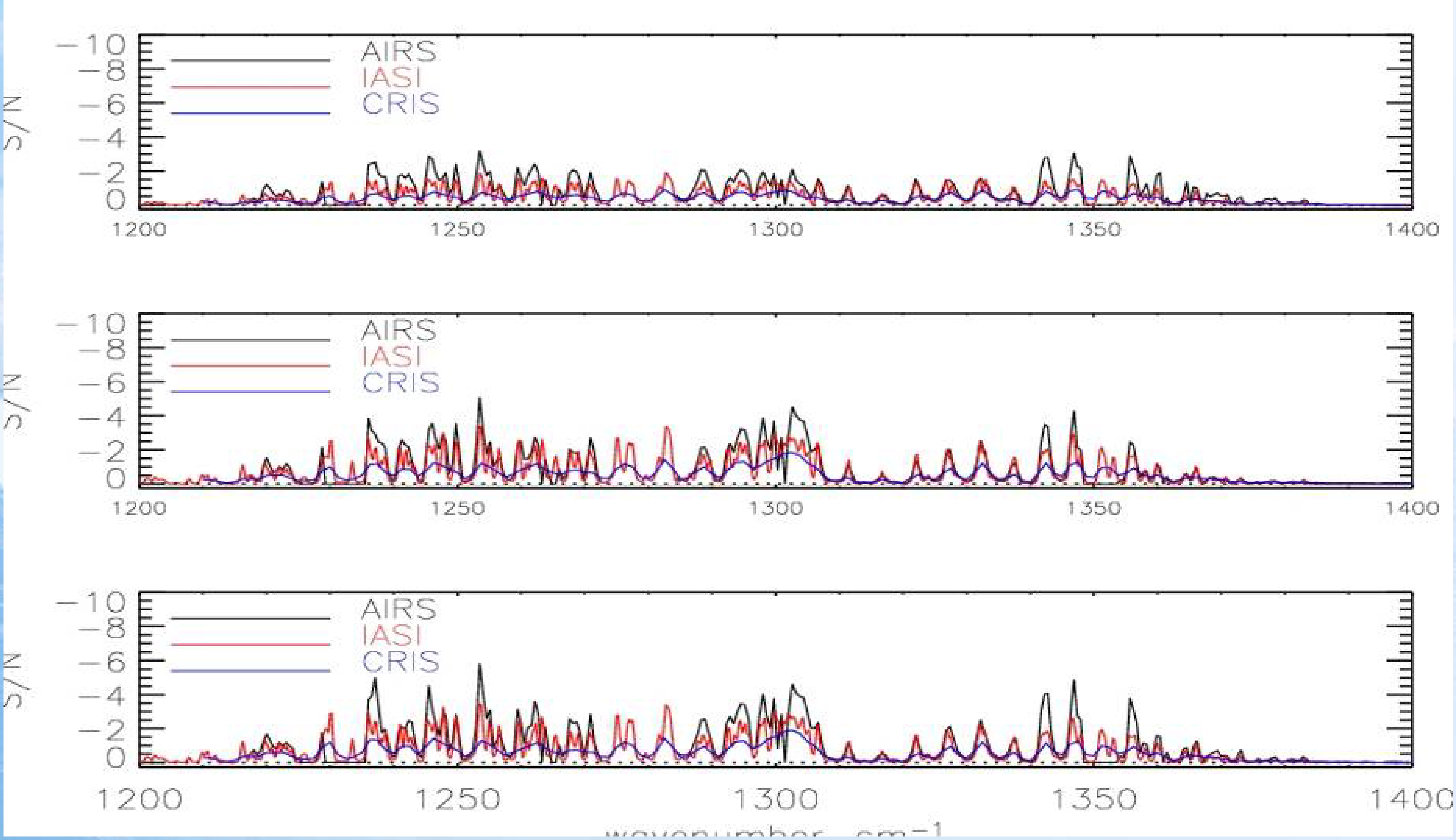
Methane

- Lifetime is on the order of 12 years
- Methane hydrate ($4CH_4+23H_2O$) is more abundant than all the world's oil, gas, and coal combined.
- Significant sink is CH_4-OH-CO coupling (Thompson, 1985)
  - $CH_4 + OH \rightarrow CO + H_2O$
  - $CO + OH \rightarrow CO_2 + H$
  - $O_3 + h\nu \rightarrow O(^1D) + O_2$
  - $O(^1D) + H_2O \rightarrow 2OH$

Methane Sources

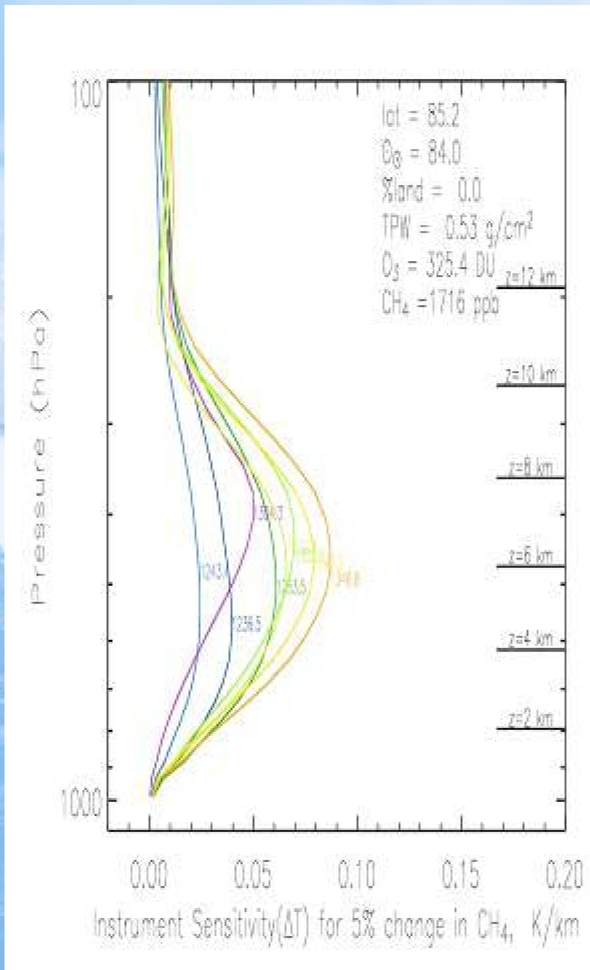


Methane S/N for a 2% (36 ppb) Perturbation

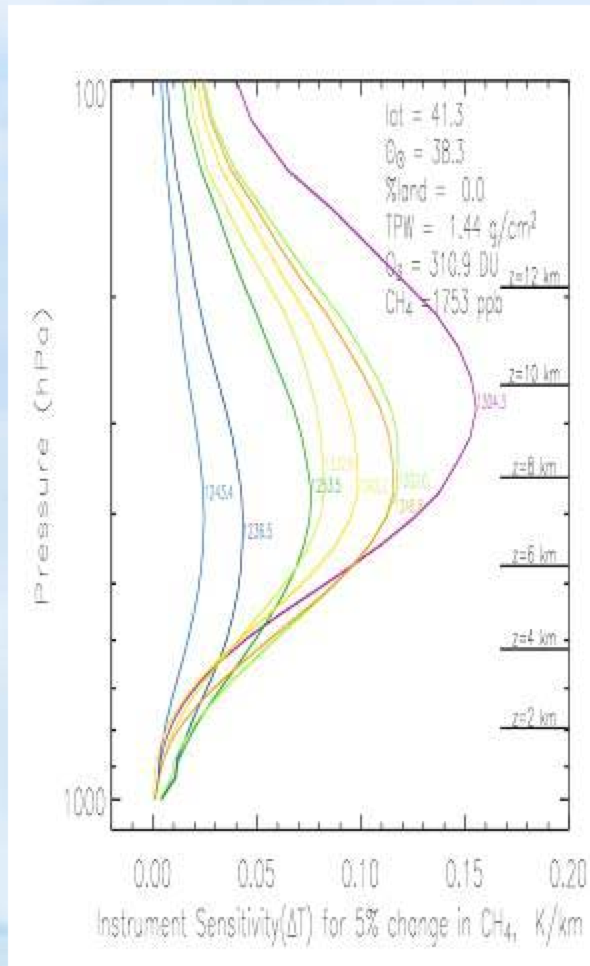


AIRS CH_4 Kernel Functions are Sensitive to $H_2O(p)$ & $T(p)$

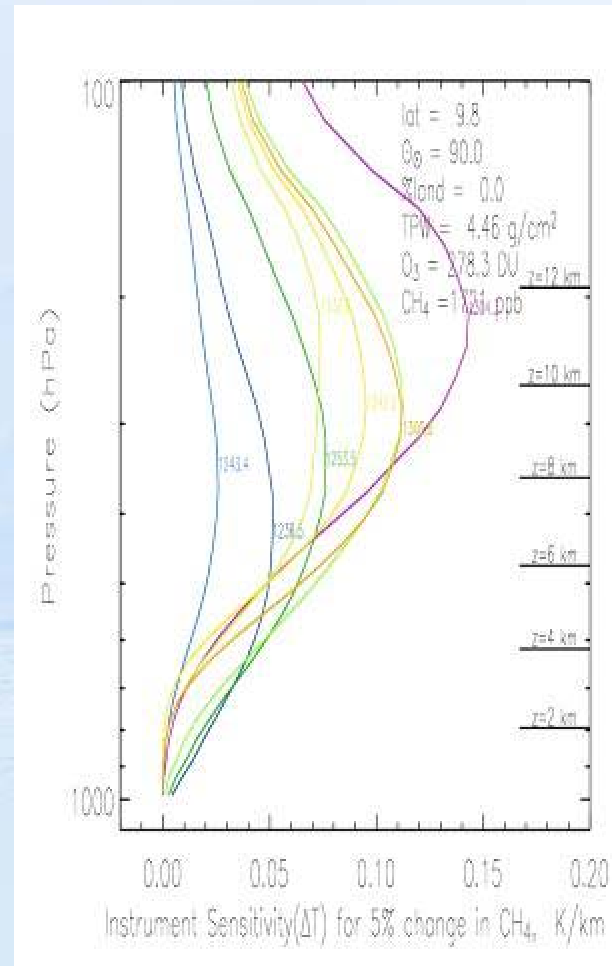
Polar



Mid-Latitude

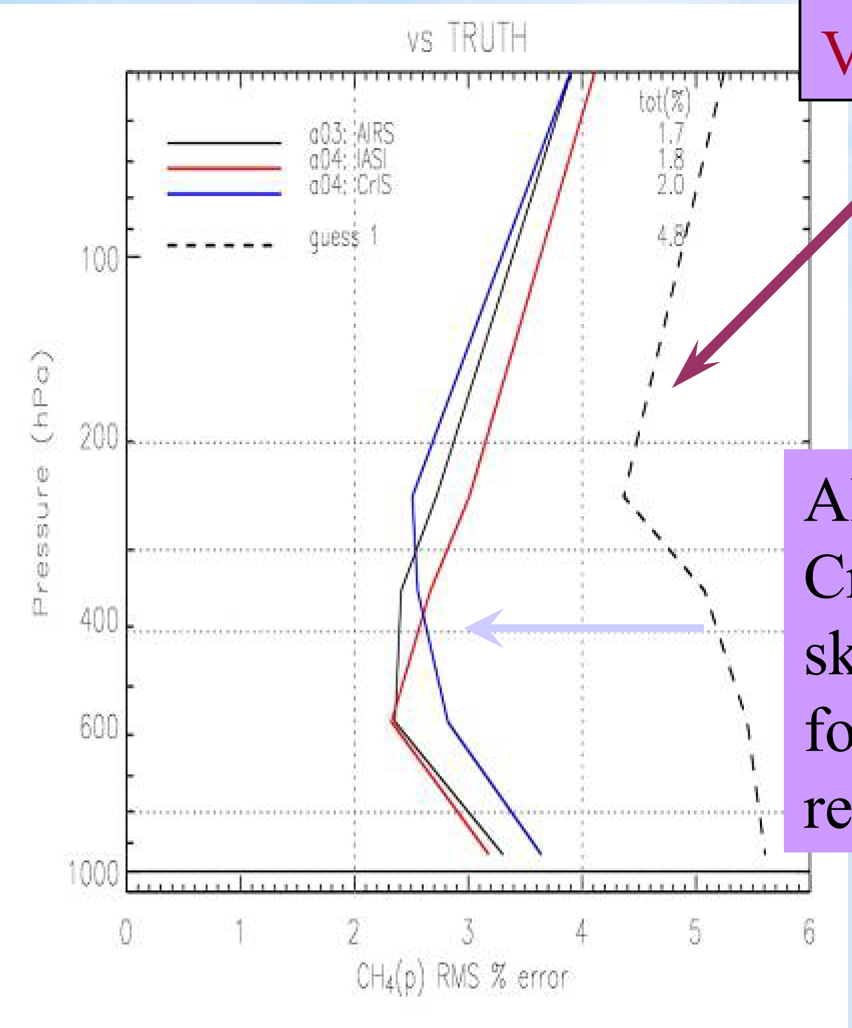


Tropical

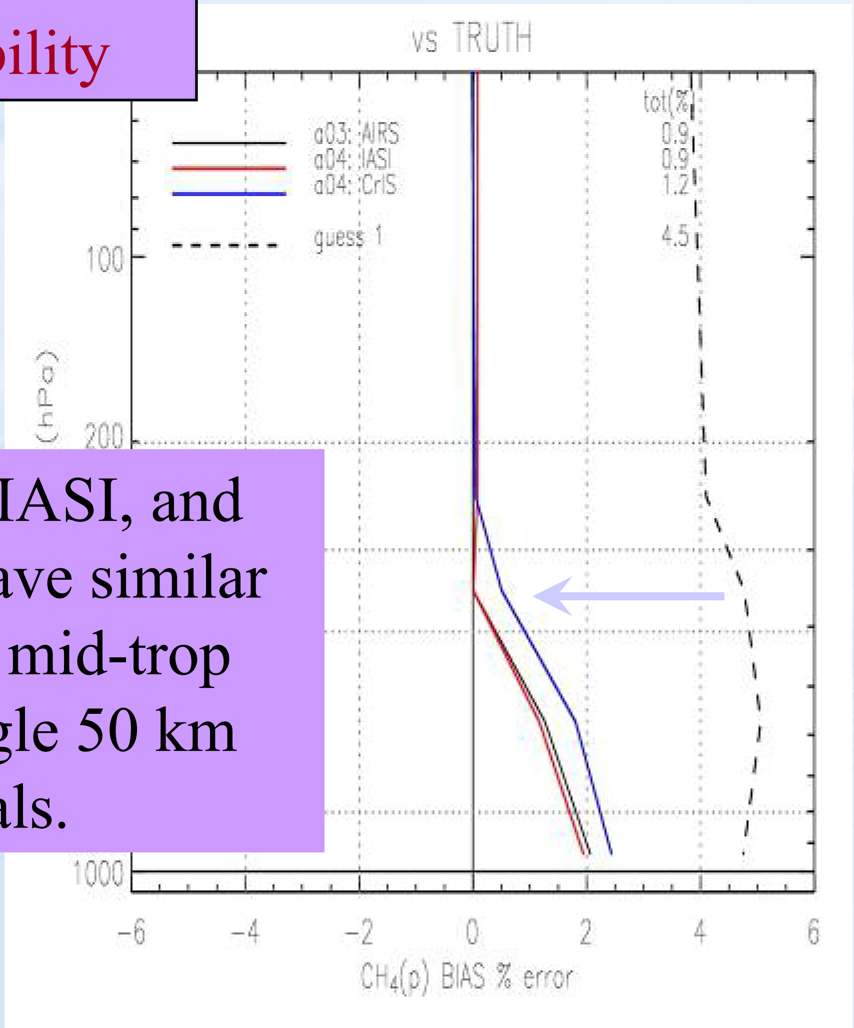


Statistics of a Methane Retrieval for AIRS, IASI, and CrIS Simulated CLEAR Scenes.

RMS



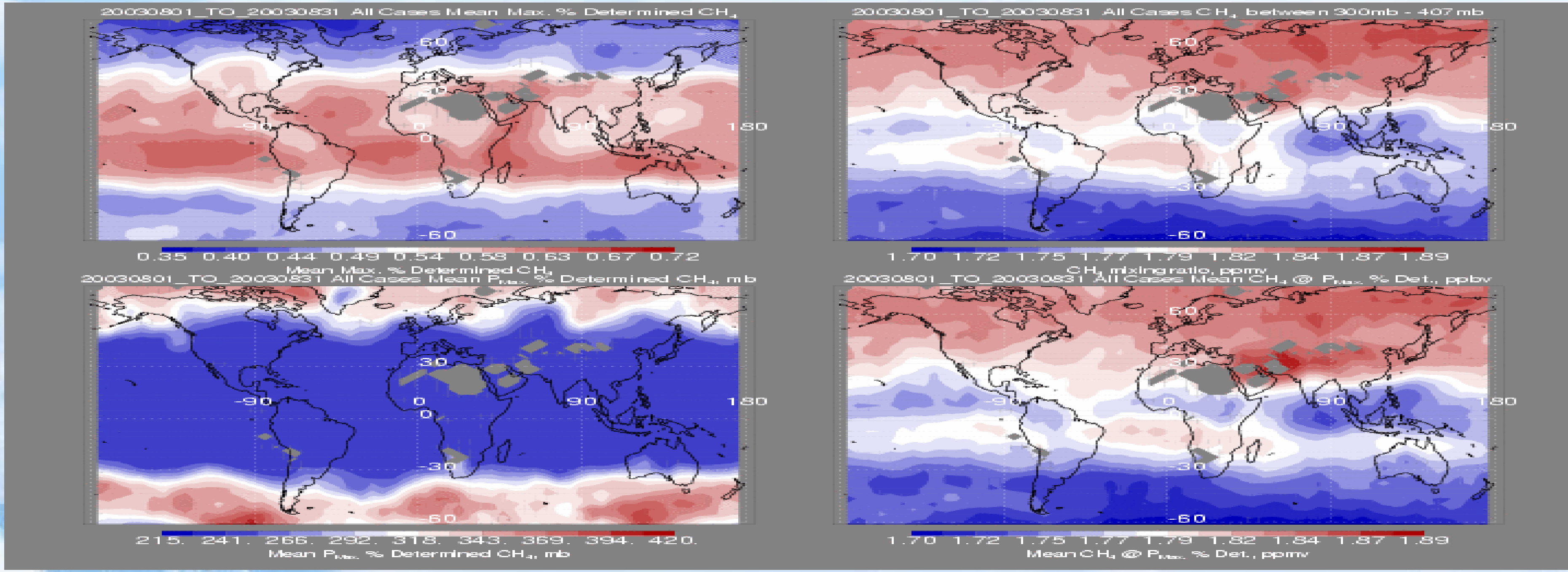
BIAS



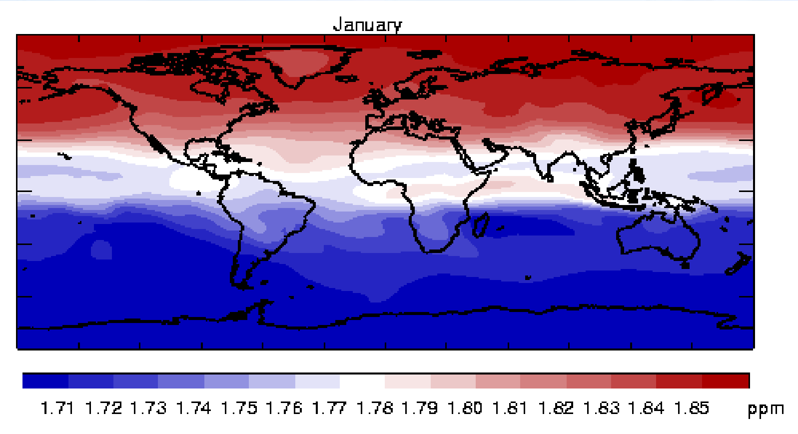
Background Variability

AIRS, IASI, and CrIS have similar skill in mid-trop for single 50 km retrievals.

Representing the vertical information content to compare CH4 product with models



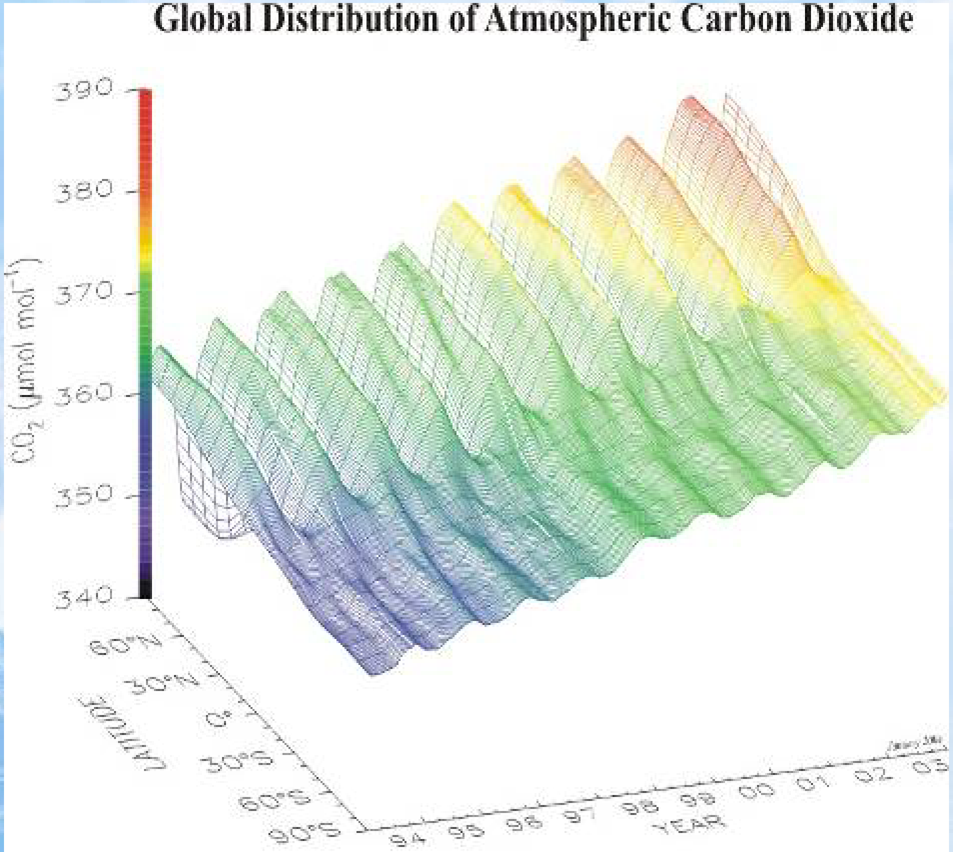
CH4 model from Sander Houweling (SRON)



Carbon Dioxide

- Lifetime is 100 years
  - conversion to limestone ($CaCO_2$) is main sink.
- +5.5 GT/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 GT/yr from biomass burning
- Atmospheric concentration is well measured (Charles Keeling, Scripts) + 1.5 ppmv/yr = 3.3 GT-C/yr
- Huge Terrestrial Annual Exchange (photosynthesis/respiration), 90 GT/yr
- Huge Ocean Exchange (phytoplanckton life cycle), 90 GT/yr, NET -2 GT/yr

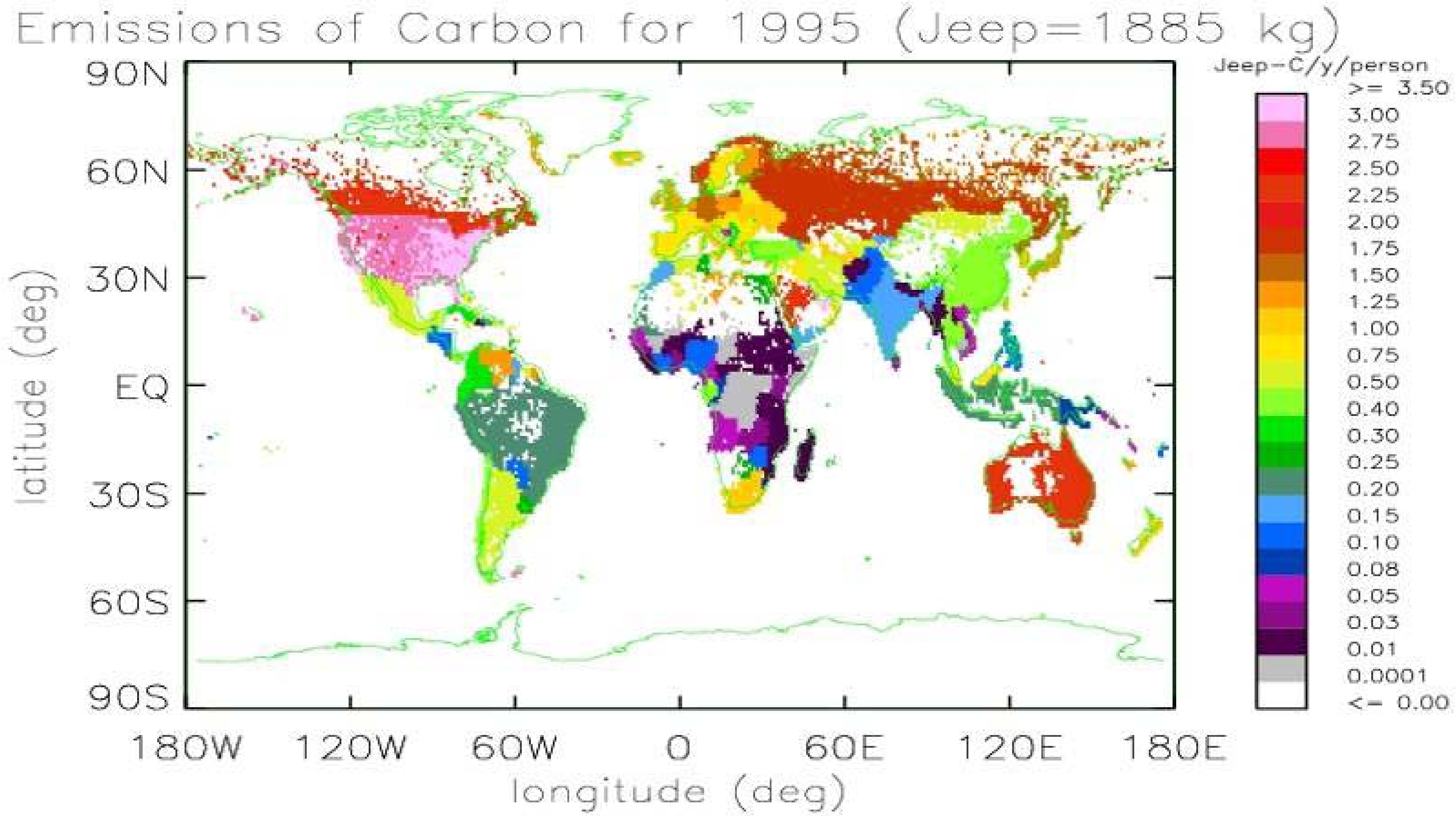
The NOAA/CMDL Flask Network Monitors Seasonal Cycle and Inter-annual trends



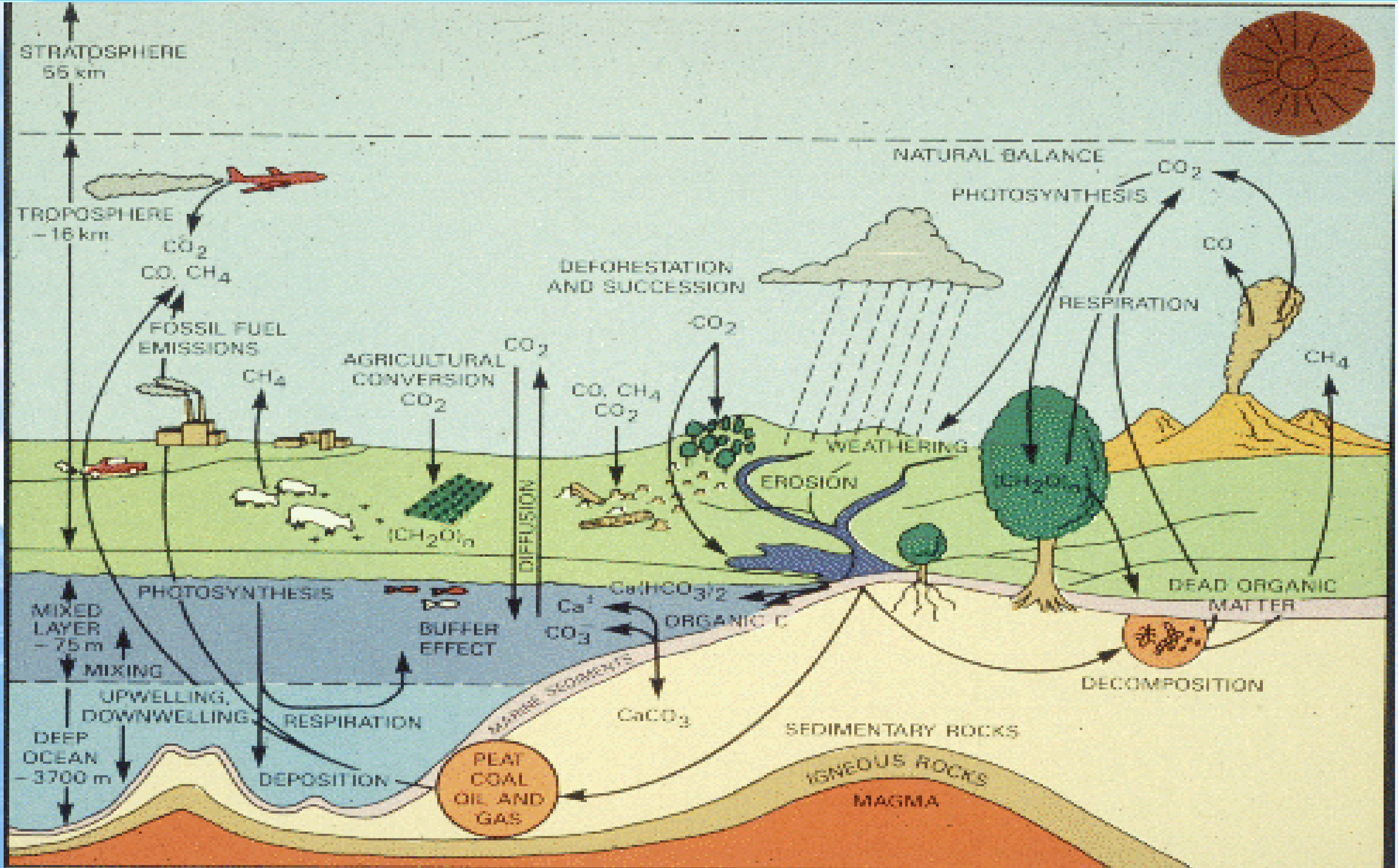
Three dimensional representation of the latitudinal distribution of atmospheric carbon dioxide in the marine boundary layer. Data from the NOAA CMDL cooperative air sampling network were used. The surface represents data smoothed in time and latitude. Principal investigators: Pieter Tans and Thomas Conway, NOAA CMDL Carbon Cycle Greenhouse Gases, Boulder, Colorado, (303) 497-6678 (pieter.tans@noaa.gov, http://www.cmdl.noaa.gov/ccgg).

- Flask network of ≈50 sites measures the surface concentration of CO_2 in mostly background locations.
- CMDL measurements show a large seasonal fluctuation of CO_2 (positive values occur in winter, negative values in summer).
- The seasonal cycle is significantly stronger in northern latitudes (± 7 ppm).
- An average increase of 1.5 ppm/yr is seen → 3.3 GT-C/yr

Fossil Fuel Emissions
Jeeps of Carbon/capita/year



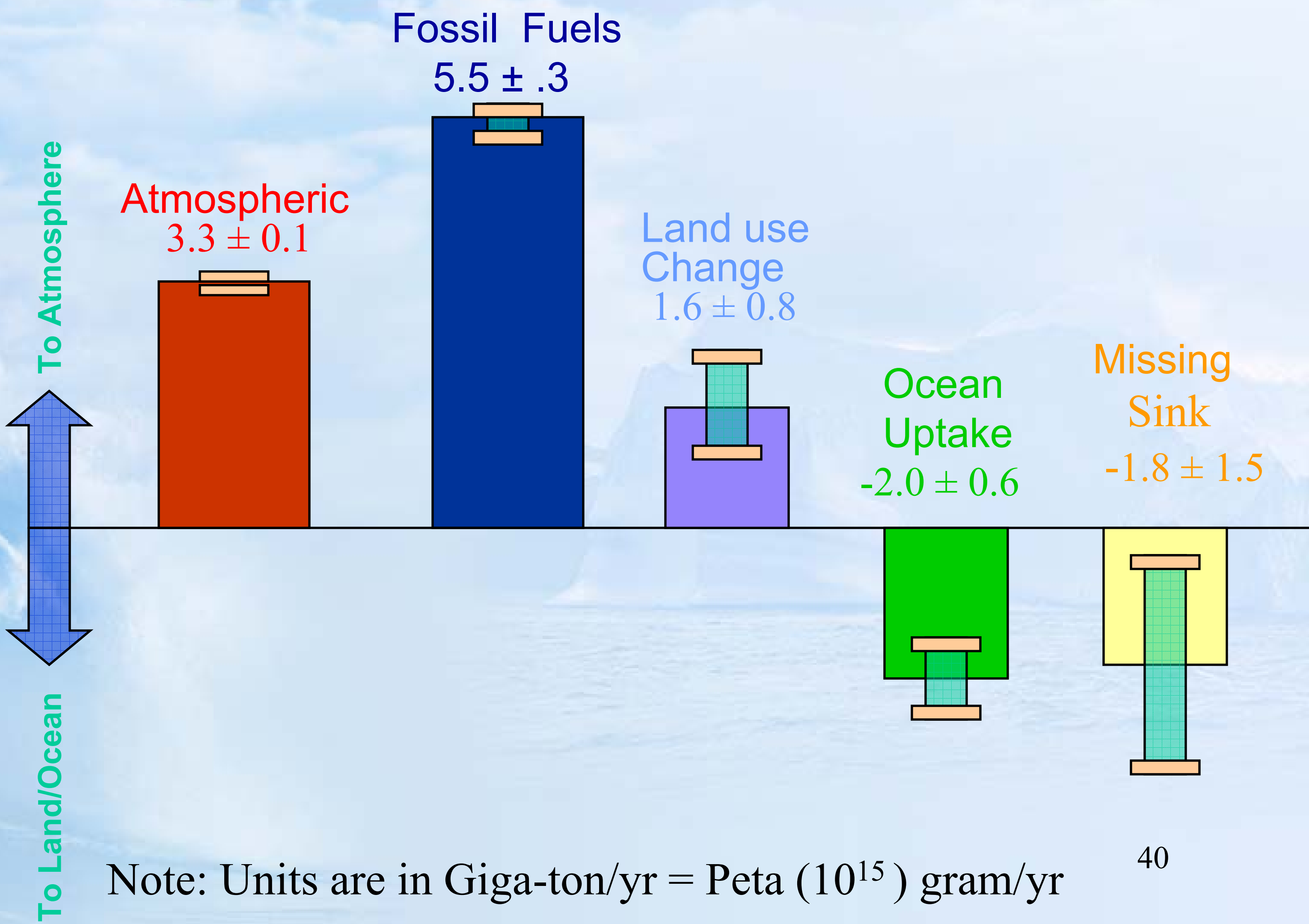
Carbon Cycle is complex with many time & spatial scales



Uncertainties in Carbon Budget Are Large

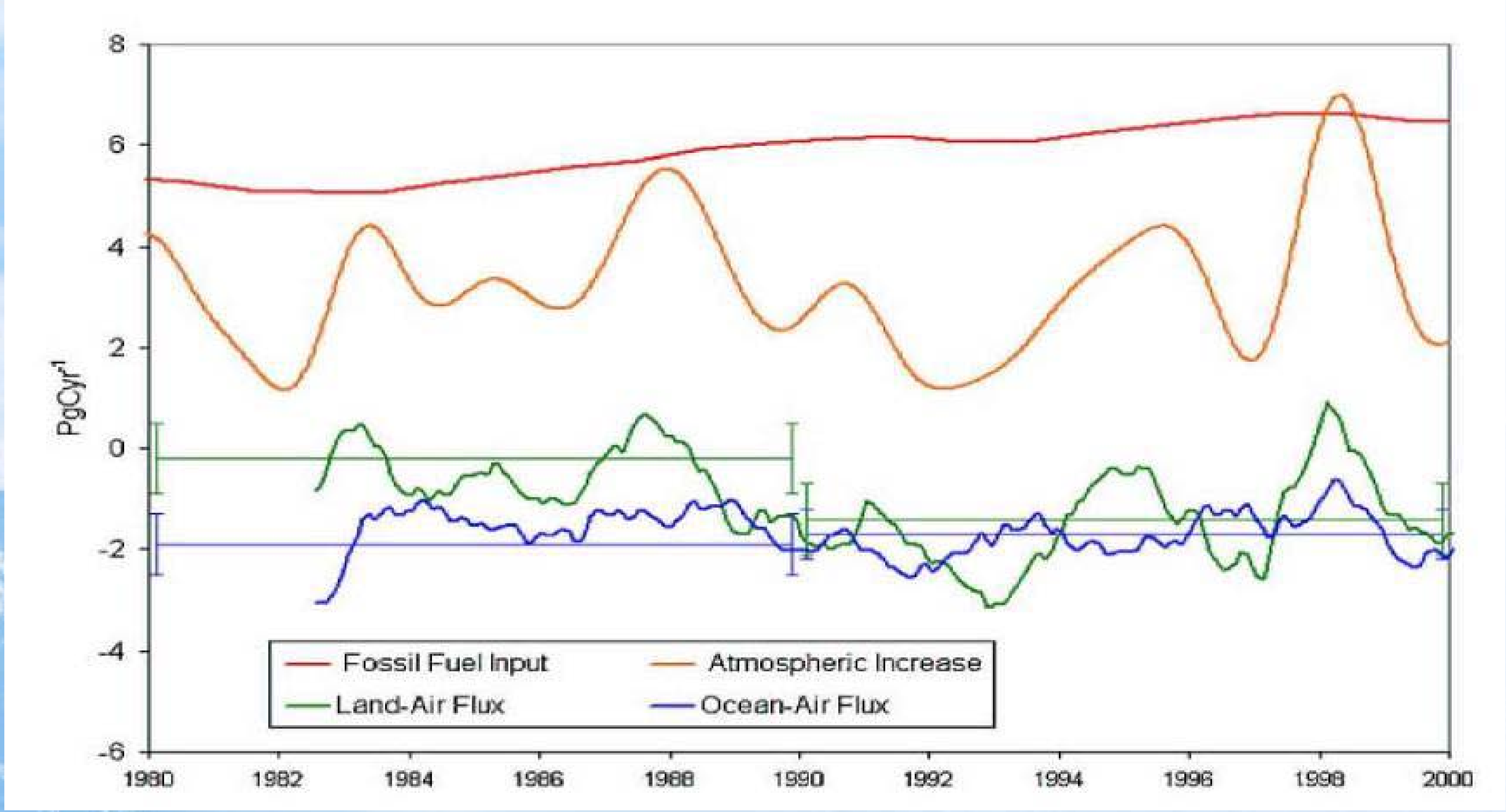
Current source and sink strengths are uncertain.

Prediction of future climate forcing is, therefore, uncertain as well.



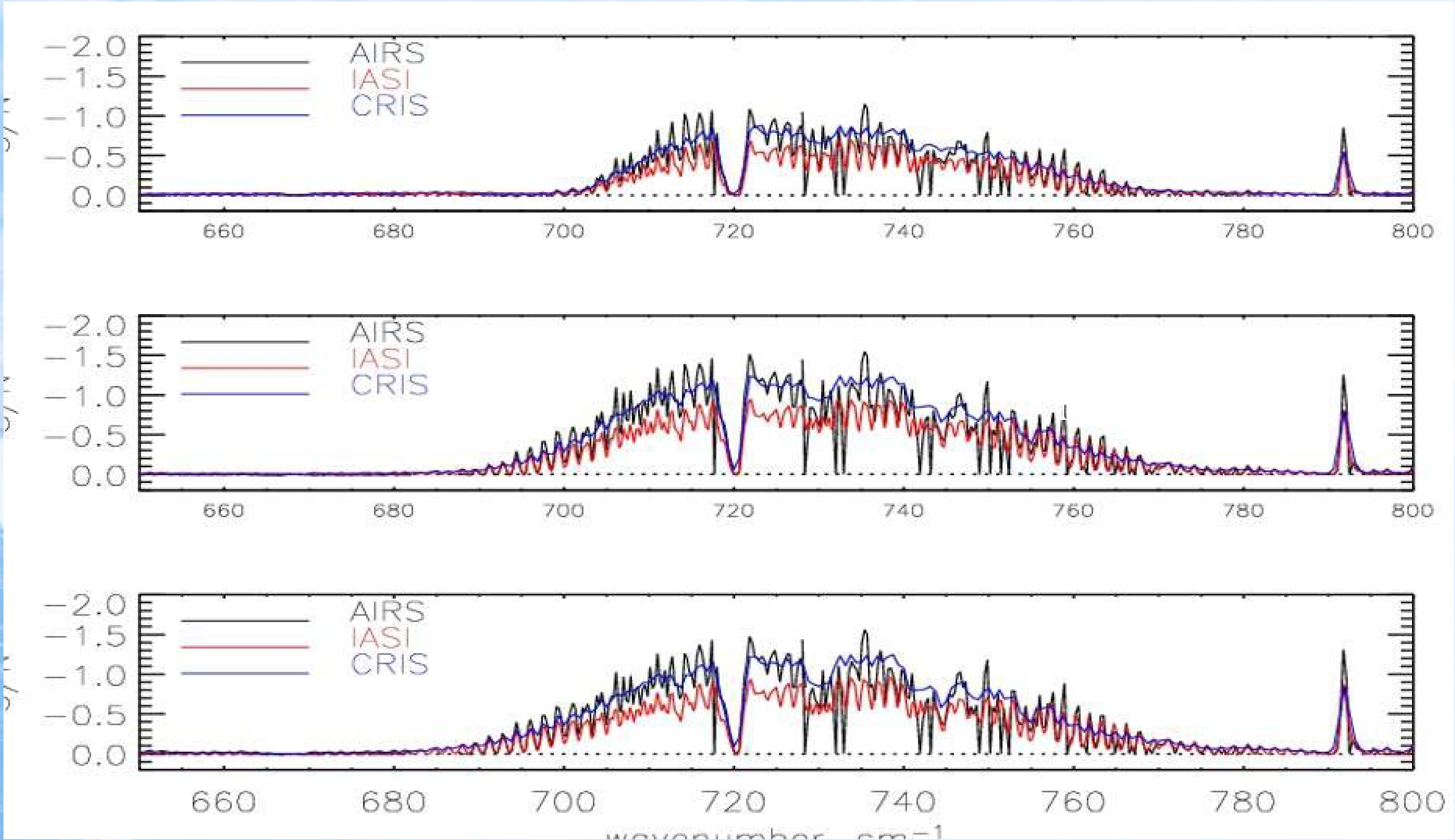
Note: Units are in Giga-ton/yr = Peta (10^{15}) gram/yr

Partition and evolution of terrestrial and oceanic uptake is the critical issue.



Lisa Dilling, 2003

CO_2 S/N for a 1% (3.7 ppm) Perturbation



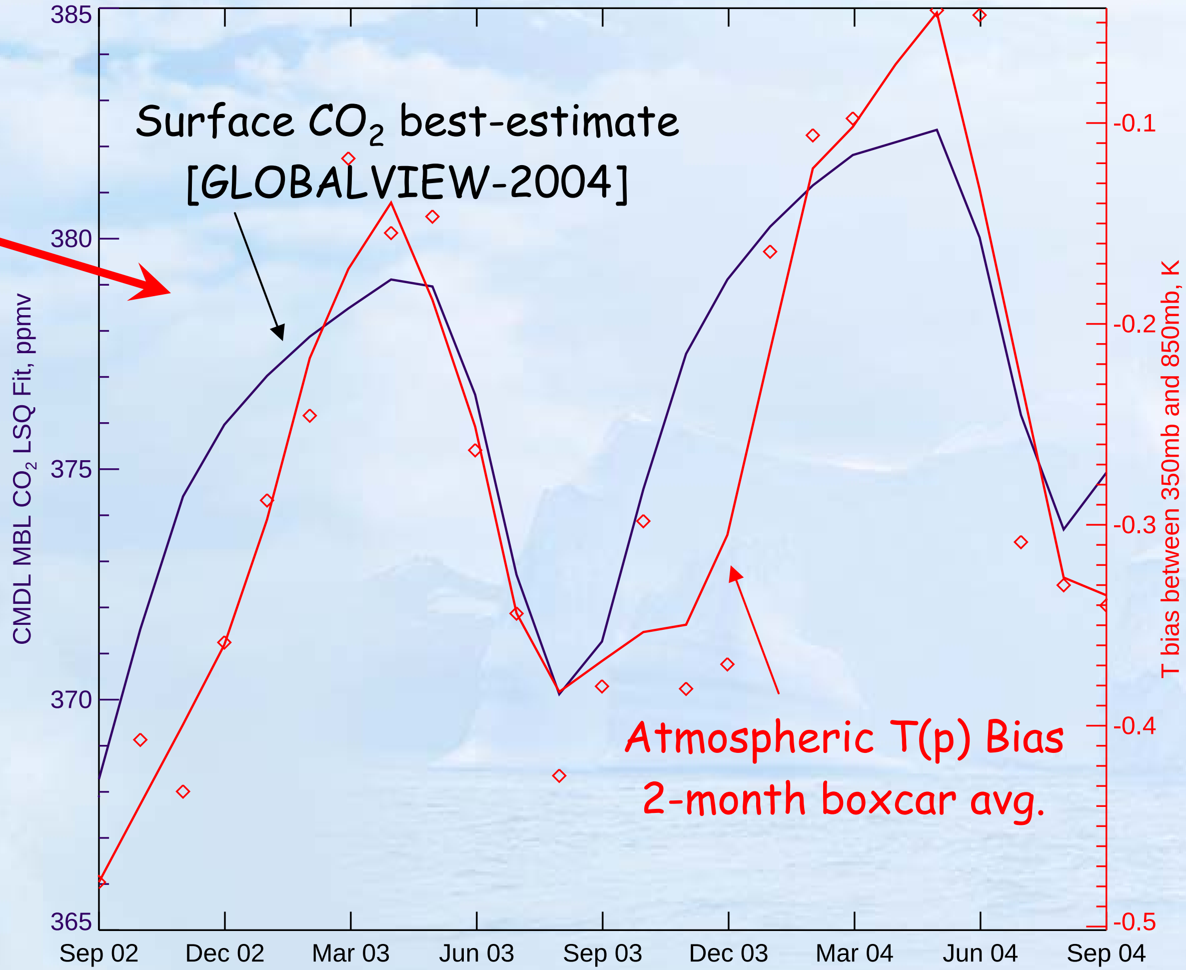
What if you ignore CO_2 and use infrared information

AIRS T(p) Retrieval Biases vs. RAOBS Correlate with Surface CO2: 90S_90N

Apparent:

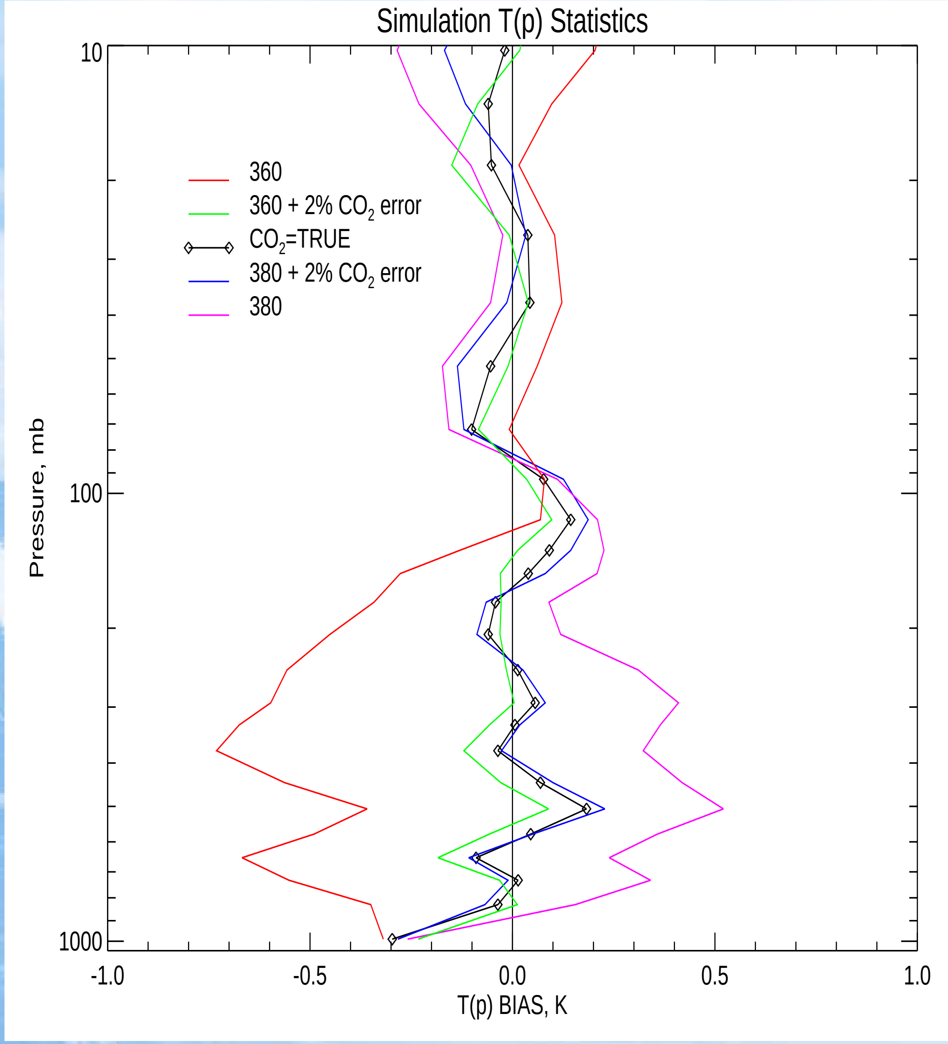
- Phase shift and amplitude reduction of seasonal cycle:
  0.1434K +/- 0.01K ->
  2.9ppmv +/- 0.2ppmv

- Annual increase:
  0.063K +/- 0.03K ->
  1.26ppmv +/- 0.6ppmv



[Maddy, *et al. OSA HISE-FTS*, 2005.]

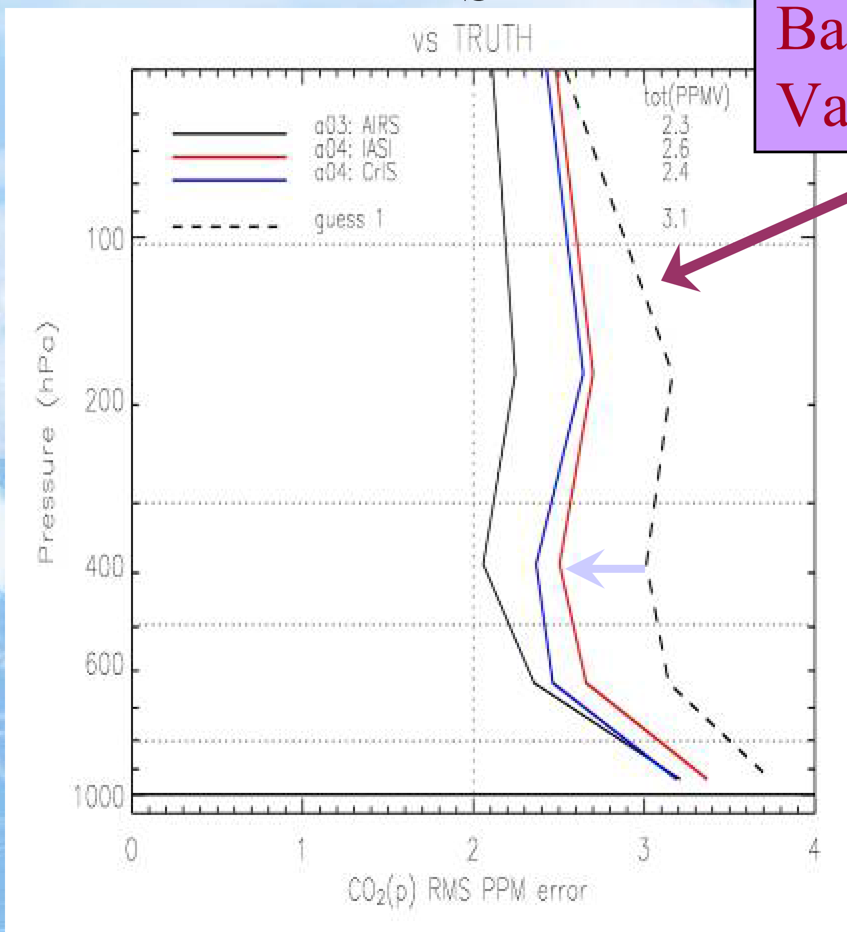
CO_2 Interference can be removed from T(p) biases



- Simulation of temperature biases resulting from CO_2 FG error.
  - With 2% CO_2 error in T(p) NCV (**green**, **blue**)
  - Without CO_2 in T(p) NCV (**red**, **purple**)
- We are investigating this further with RAOB matchups.

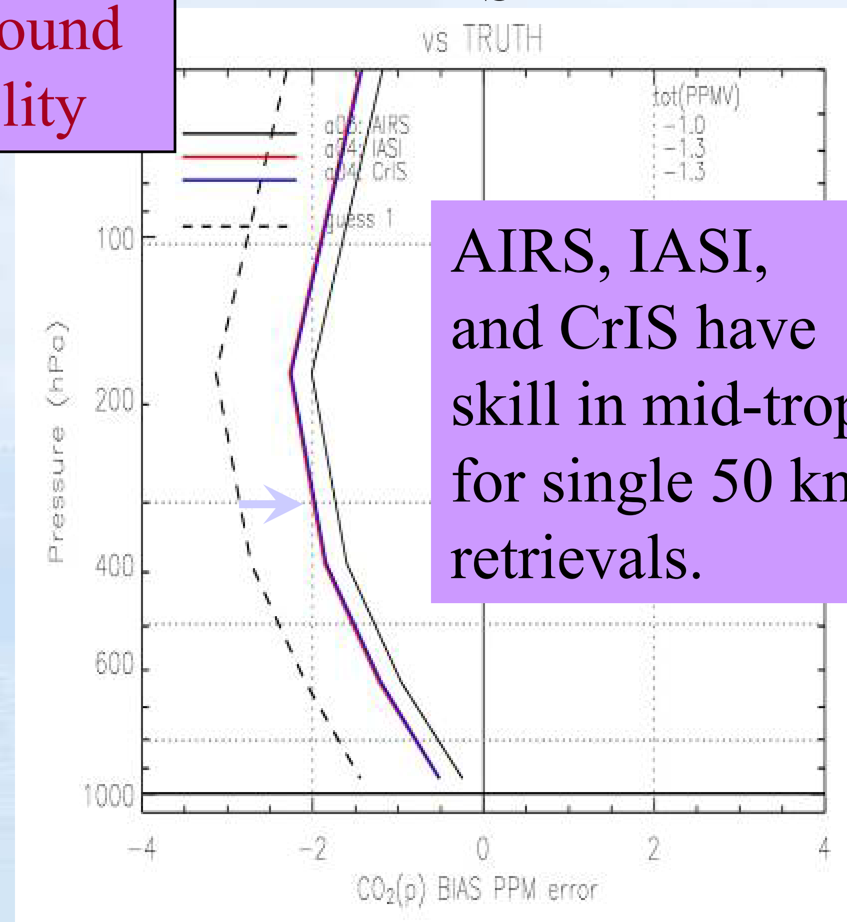
Statistics of a CO_2 Retrieval for AIRS, IASI, and CrIS Simulated CLEAR Scenes

RMS



Background Variability

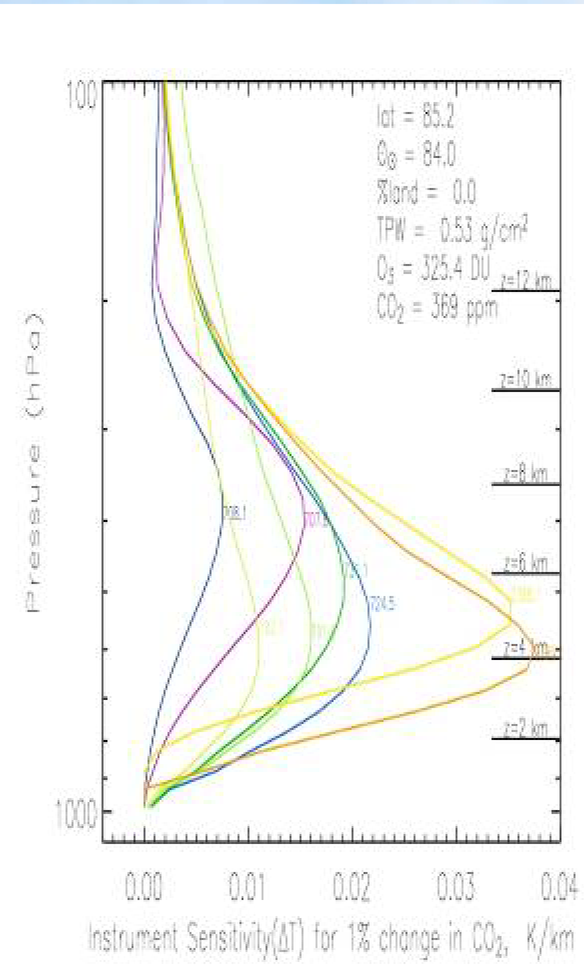
BIAS



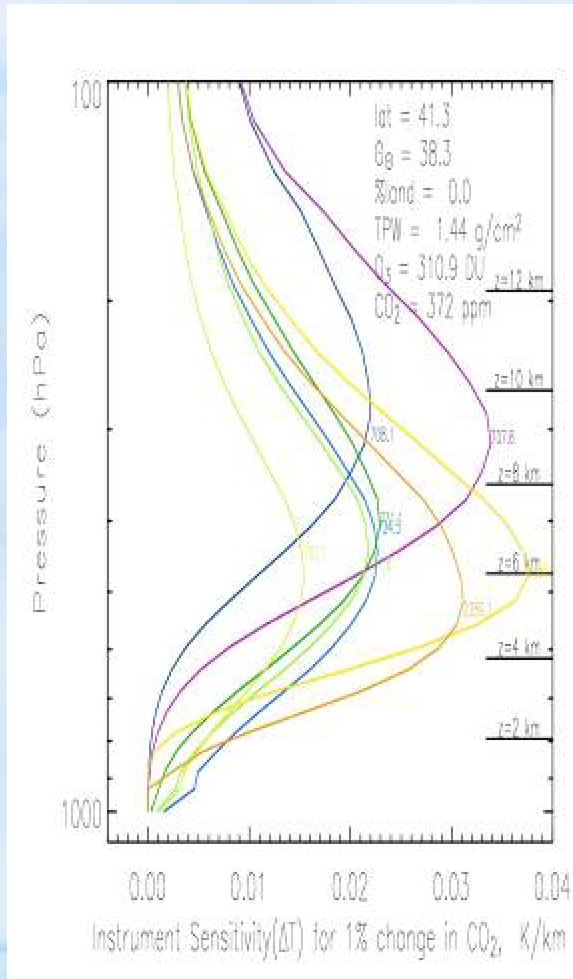
AIRS, IASI, and CrIS have skill in mid-trop for single 50 km retrievals.

AIRS 15μm CO_2 Kernel Functions are also Sensitive to H_2O, T(p), & O_3(p).

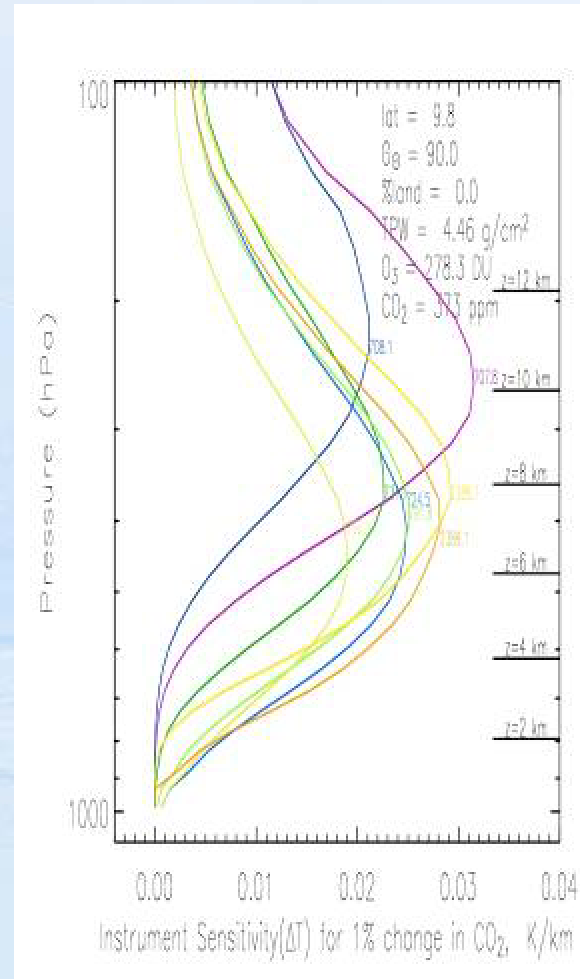
Polar



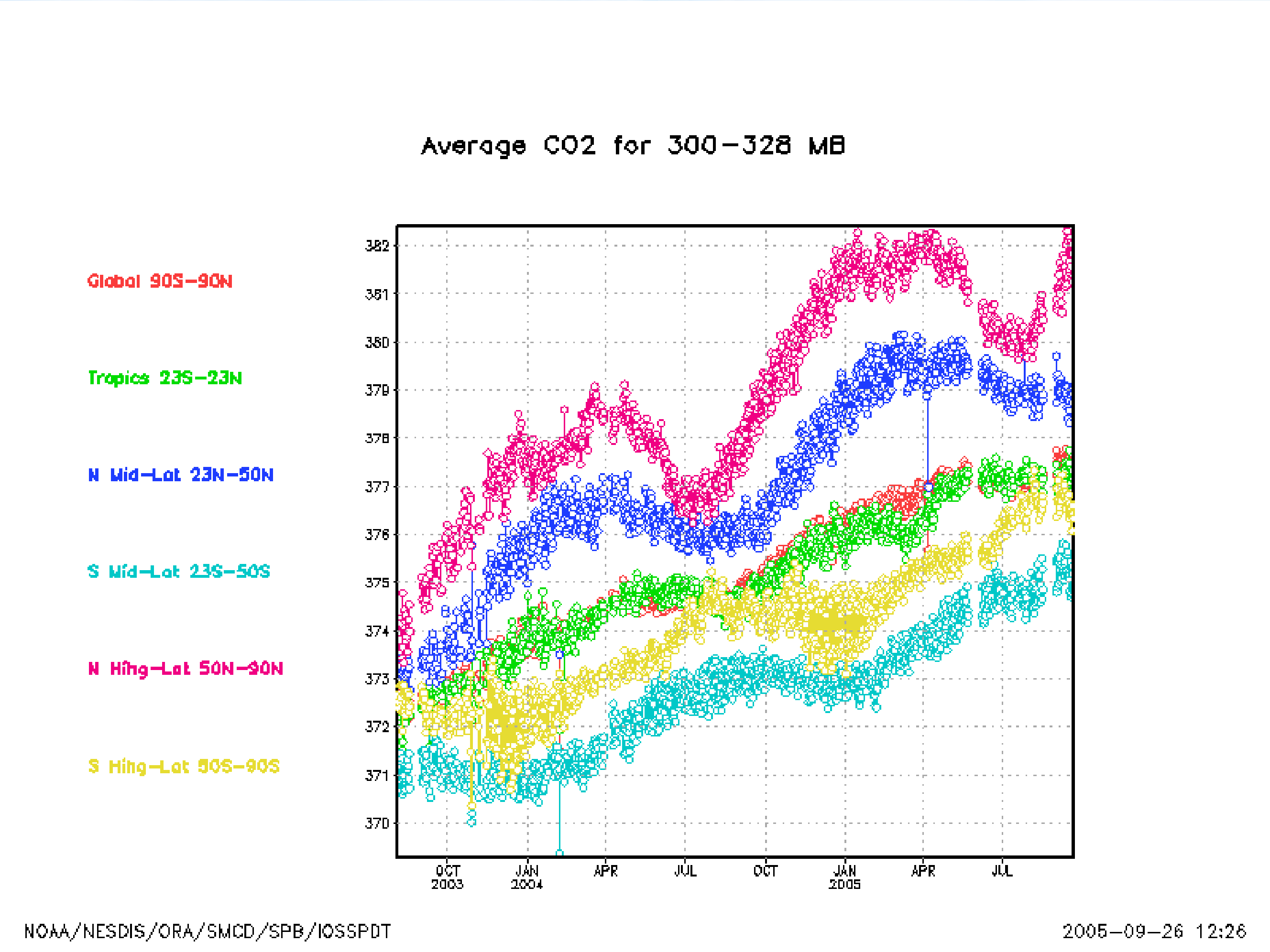
Mid-Latitude



Tropical



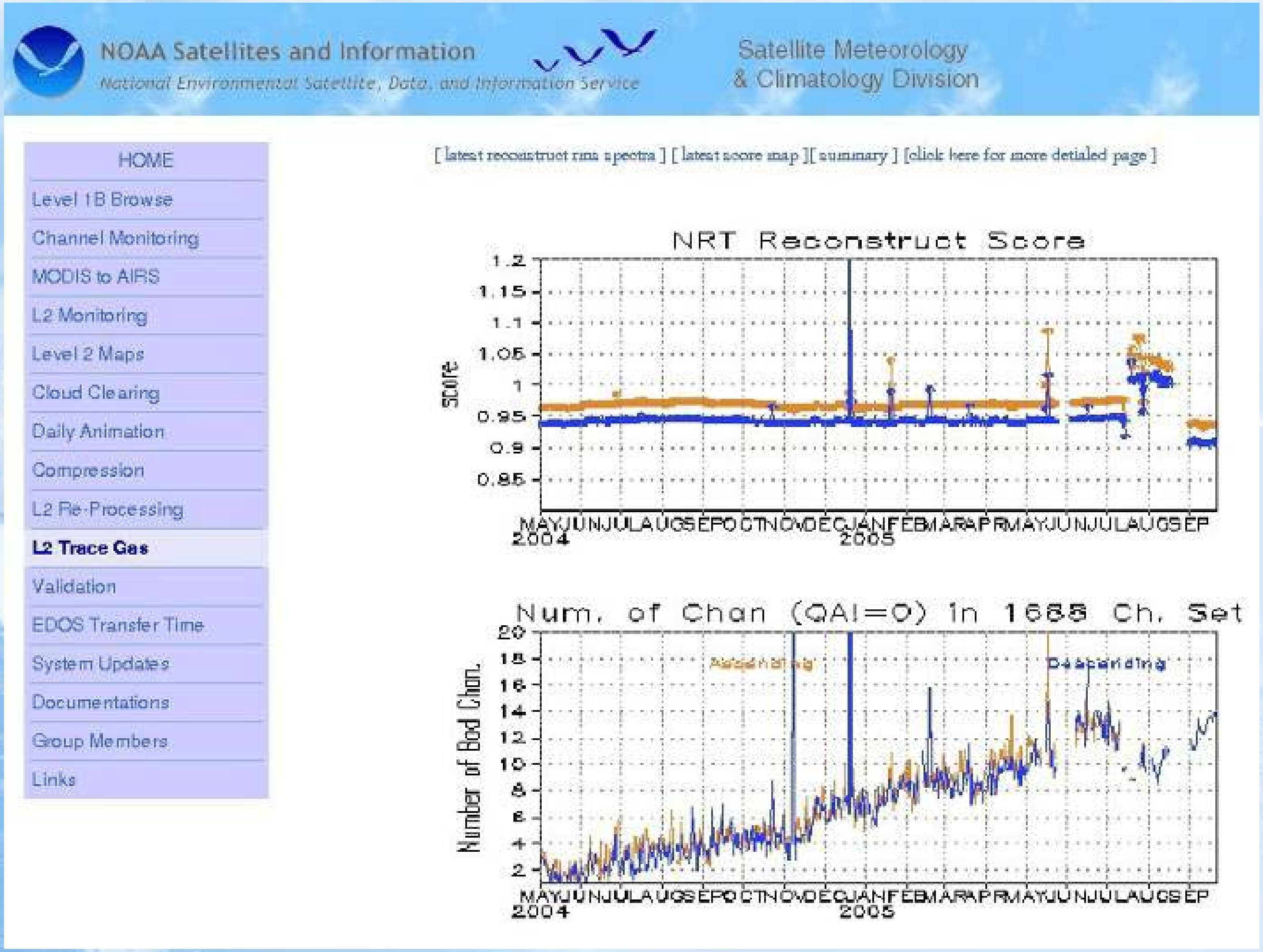
AIRS product is the first climatology of CO_2 in the mid-troposphere



AIRS CO_2 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 remove the CO_2 signal.
  - Errors in moisture of ±10% is equivalent to ±0.7 ppmv errors in CO_2.
  - Errors in surface pressure of ±5 mb induce ±1.8 ppmv errors in CO_2.
  - AMSU side-lobe errors prohibit using 57 GHZ O_2 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.
  - Having simultaneous O_3, CO, CH_4, and CO_2 products may be the unique contribution that thermal sounders can make.

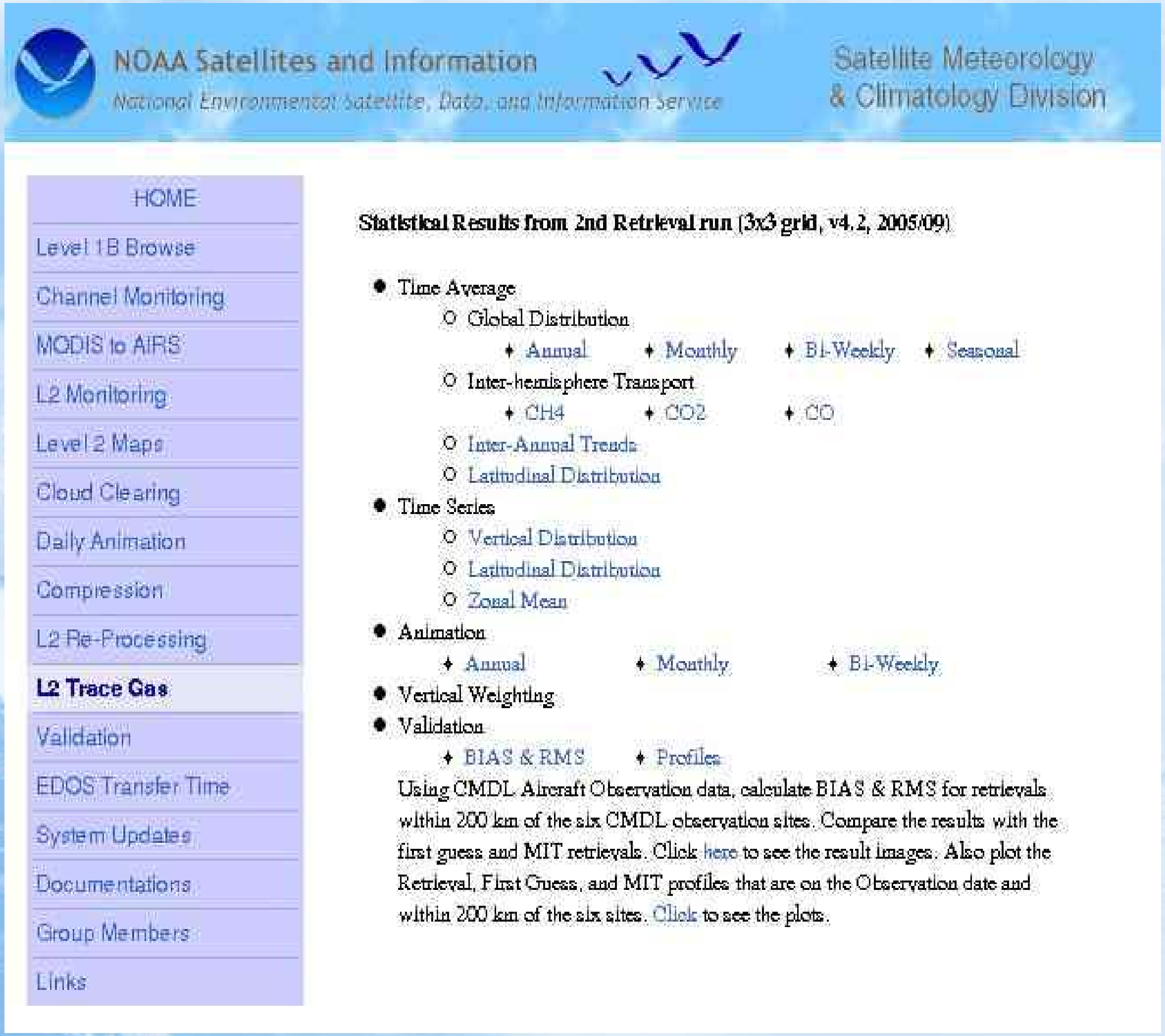
NOAA/NESDIS near-real time AIRS page



Example, of channel monitoring using PC scores.

http://www.orbit.nesdis.noaa.gov/smcd/spb/airs/index.html

Trace Gas Main Page



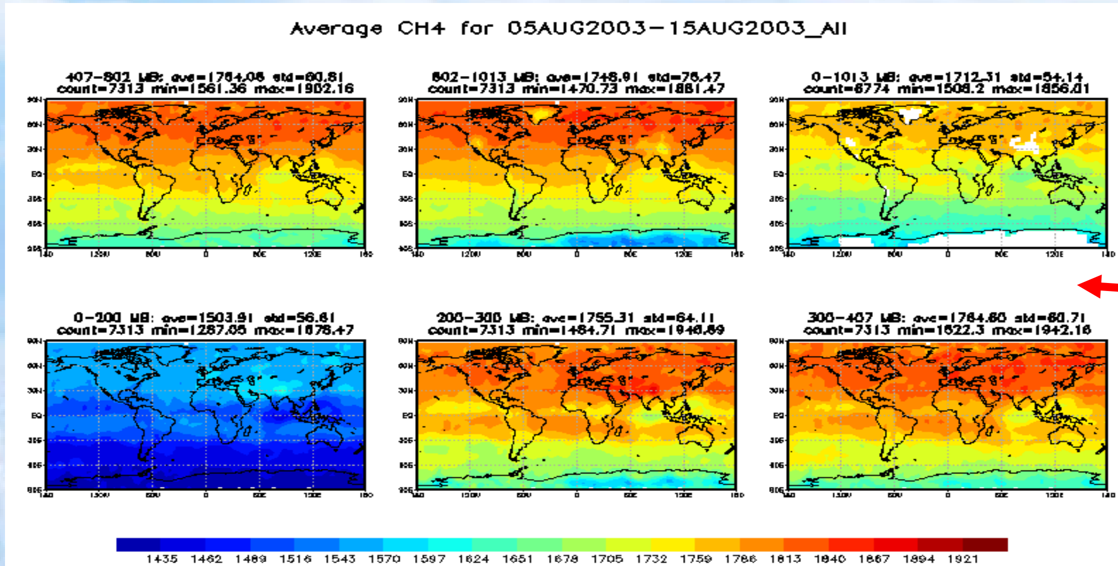
- Trace GAS paper allows quick look at the trace gas products as a function of geography, time, and w.r.t. to in-situ datasets.
- Will Use CH4 products as an example of some of the web-page capabilities

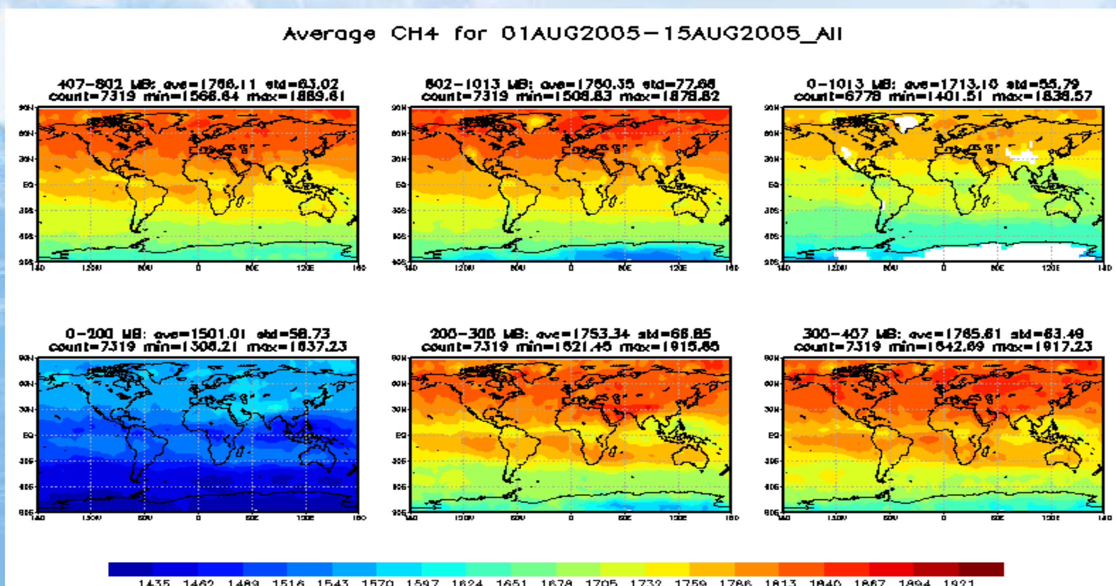
USERID & PASSWORD

Request via e-mail:

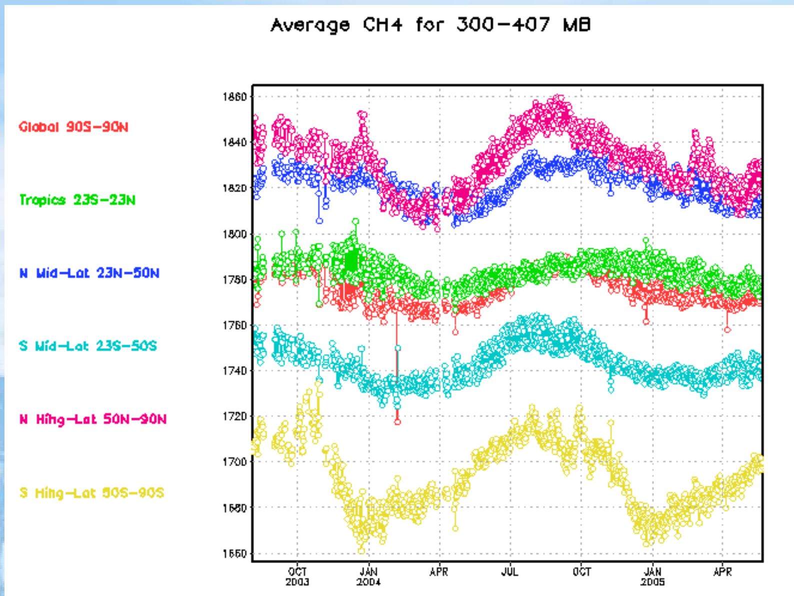
chris.barnet@noaa.gov

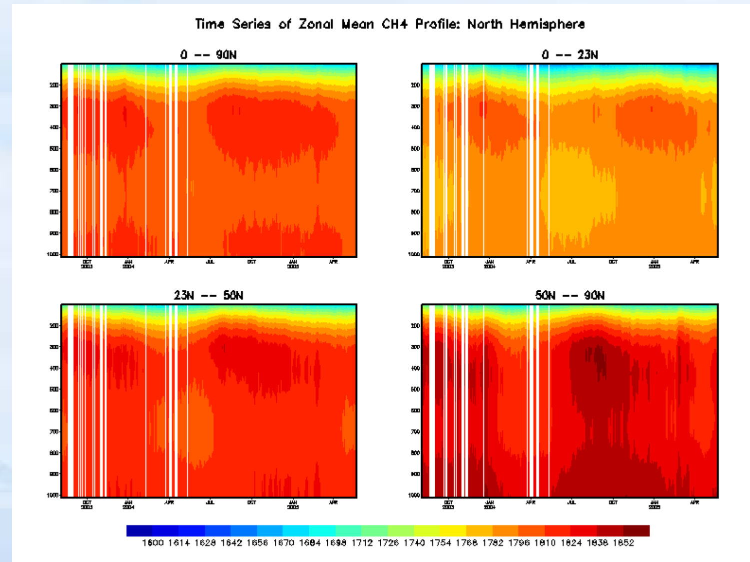
Monthly, Weekly, and Bi-weekly maps of products exist:

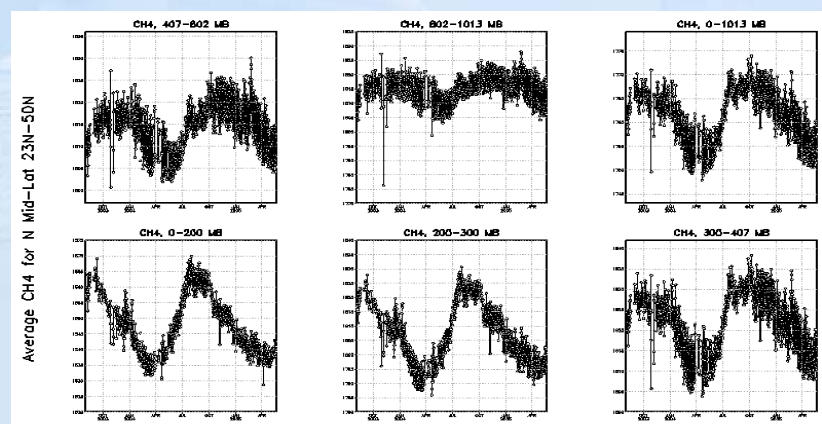




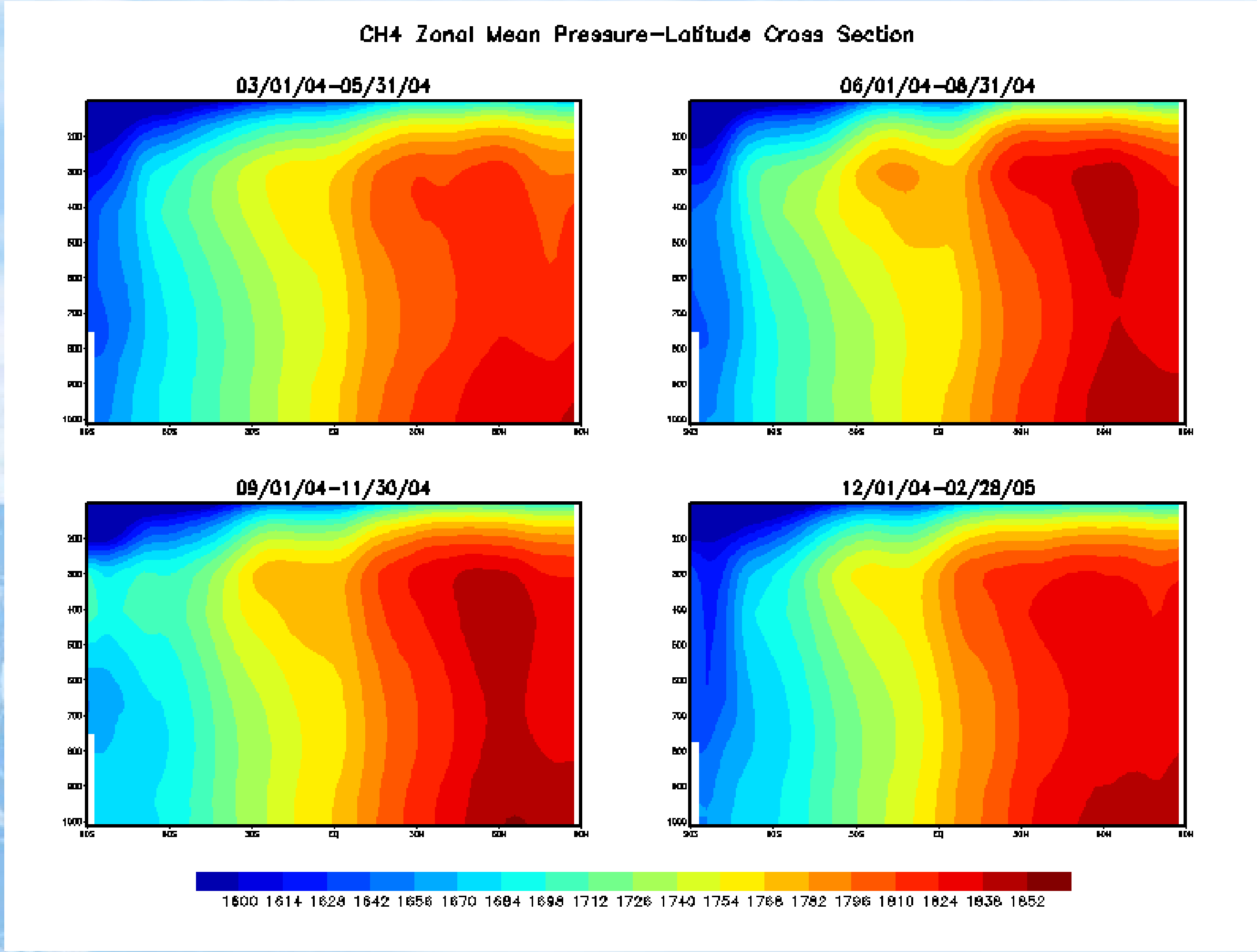
Many Options Exist for Time-Series Analysis







And inter-hemispheric transport



Acknowledgements

- Larrabee Strow & Scott Hannon, UMBC, for provided the rapid transmittance algorithms for AIRS, IASI, and CrIS including the OPD=0.4 and OPD=0.8 CrIS.
- Daniel Mooney and Mike Kelly, MIT LL, for information on CrIS noise and self-apodization issues.
- Dequi Gu, NGST, for CrIS noise models.
- Peter Schlüssel, EUMETSAT, for IASI noise models.

Conclusions and Summary

- High spectral resolution operational thermal sounders have the capability of measuring global atmospheric carbon for the next 20+ years.
- CO product is robust and validation experiments are underway (e.g., INTEX, W. McMillan, UMBC)
  - CO from CrIS can be significantly improved if SW band is operated at L=0.4 or L=0.8 cm.
- CH4 is difficult: preliminary analysis appears promising.
- CO_2 is significantly more difficult and many algorithms are being inter-compared. Beginning to re-process 2 years of acquired AIRS radiances.
- AIRS, IASI, and CrIS may contribute to source/sink determination by simultanously measuring T(p), q(p), O3(p), CO, CH4, & CO2 globally.