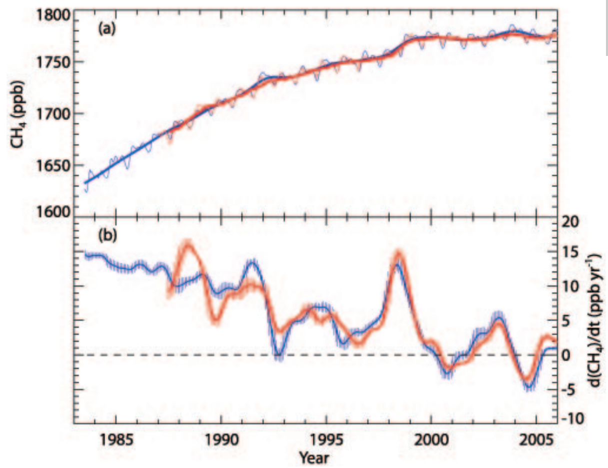
Satellite Measurements of Trace Gases or Air Pollutants

Orbits, measurement types, spectral regions, properties

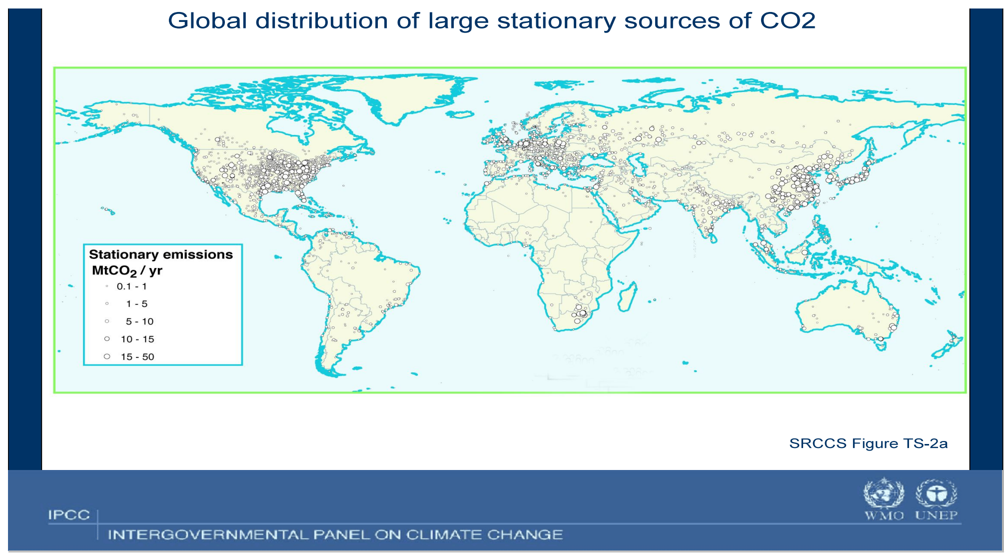
Satellite monitoring of the changing world - daily global coverage & longterm

Extreme Weather

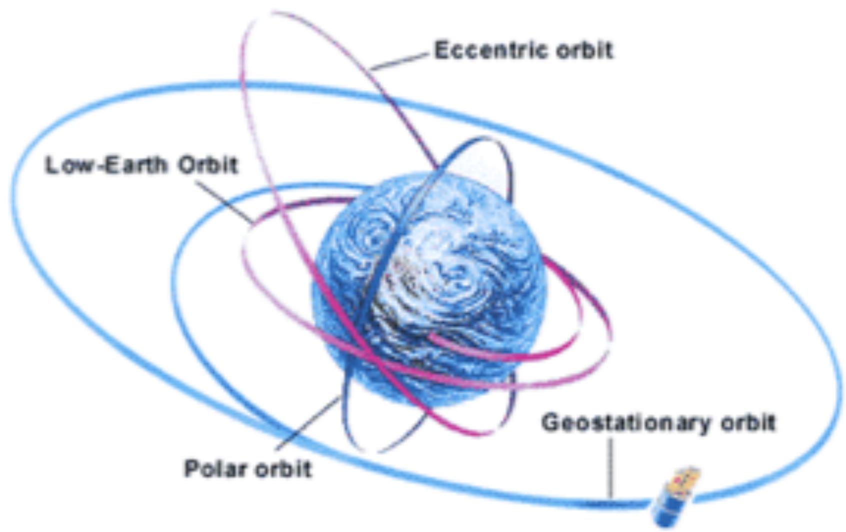
Climate Change



Inter-continental Transport of air pollution



Satellite Orbits



There are different types of orbits around the Earth of varying sizes and each is used for a particular objective:
http://www.wisedude.com/science_engineering/satellites.htm

- The Eccentric orbit holds a satellite that measures the Earth's magnetic and electric fields. This orbit is conducive for this purpose, since the satellite can obtain measurements at different distances from Earth.

- The Low Earth orbit is said to be the easiest to reach and is where the Russian space station and Hubble Space Telescope both orbit.

- The Polar orbit is, as its name suggests, concentrated around the Earth's poles. Weather satellites are placed here as readings of the entire Earth can be taken while the planet spins.

- The Geostationary orbit is about 35, 880 km above the Equator and holds communication satellites, especially television satellites. Both the Earth and the satellites complete their respective circles at the same time, meaning they move neck-to-neck.

Atmospheric Radiation Spectrum

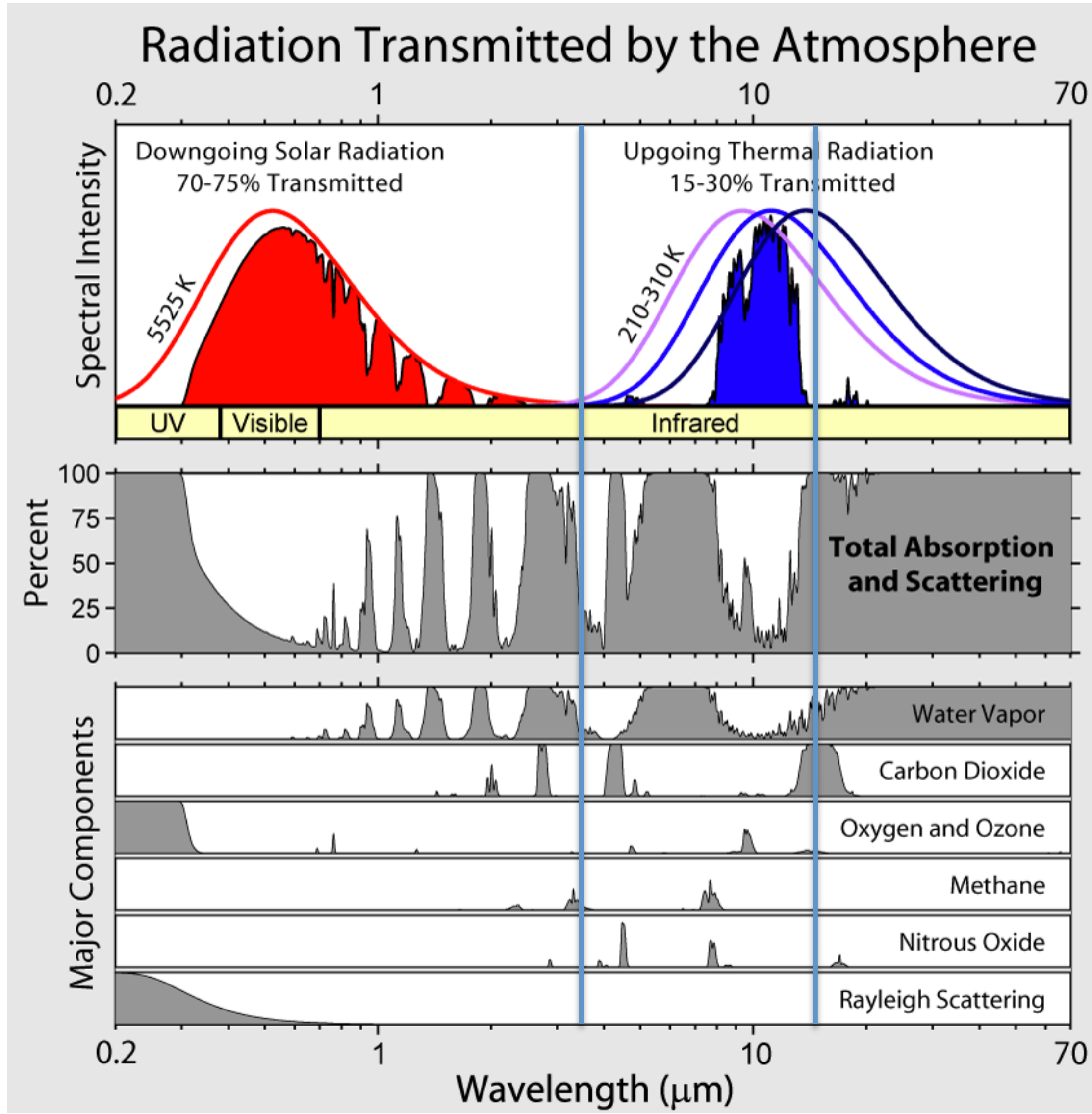
- Satellite remote sensing uses four spectral regions.
- Focus in IR region and species focus on atmospheric composition and greenhouse gases.

UV: some absorptions + profile information; aerosols

VIS: surface information: vegetation; some absorptions; aerosol information

IR: profile information: temperature information; cloud information; water / ice distinction; many absorptions / emissions from atmospheric composition

MW: no problems with clouds: ice / water contrast; surfaces; some emissions + profile information



ACTIVE VS. PASSIVE REMOTE SENSING

Passive Remote Sensing:

Natural sources of radiation, the attenuated, reflected, scattered, or emitted radiation is analysed

→ Usually UV, visible, IR

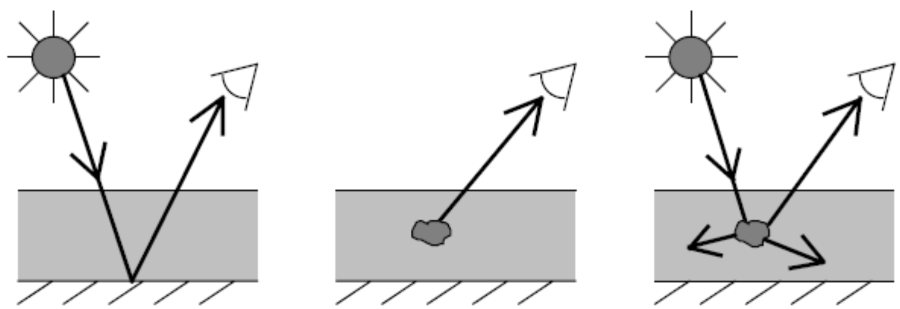
→ Sources include: sun, moon, Earth

Active Remote Sensing:

Artificial source of radiation, the reflected or scattered signal is analysed

→ Usually lasers (LIDAR) or RADAR

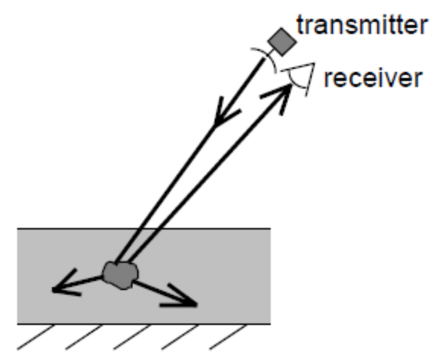
→ Active source, usually co-located with receiver



Extinction — radiation is absorbed or scattered out of the beam

Emission — radiation is emitted by the object (the atmosphere)

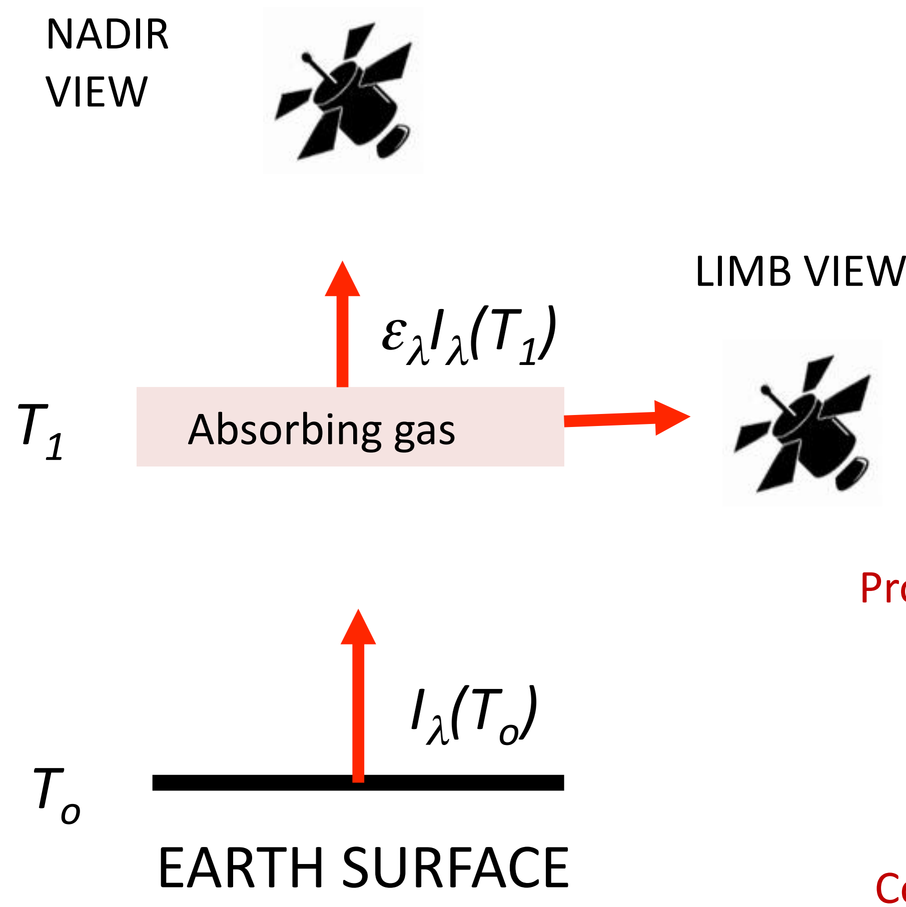
Scattering — natural radiation is scattered towards the satellite



Backscattering — artificial radiation is backscattered towards the satellite

Thermal Emission Measurements (IR, microwave)

Examples: AIRS, IASI, MLS, IMG, MOPITT, MIPAS, TES, HIRDLS



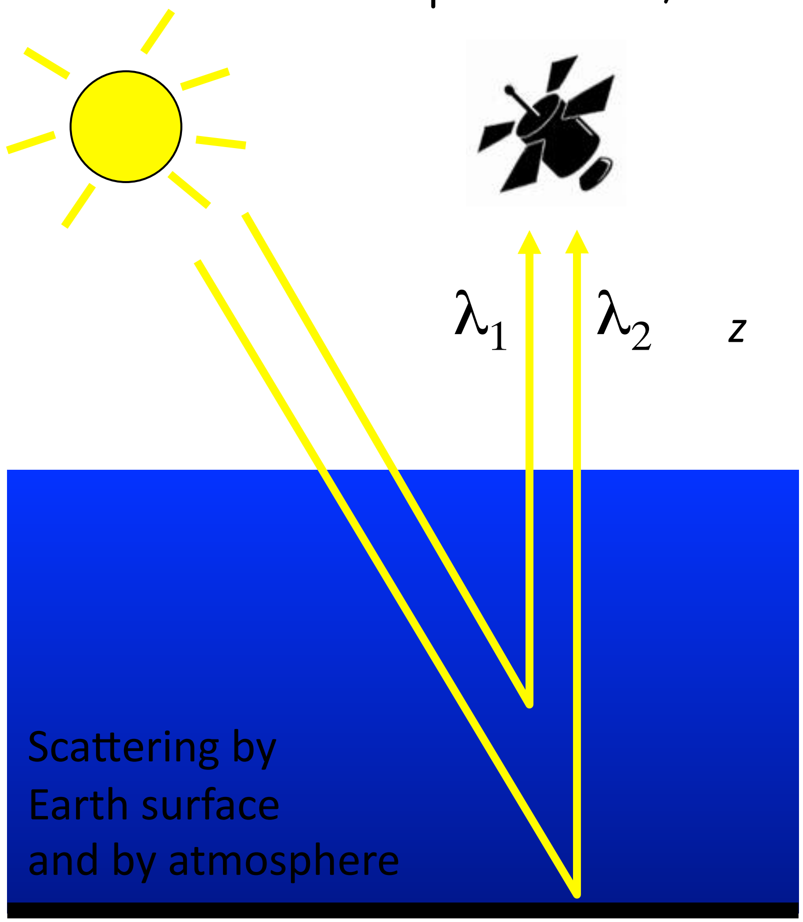
Pros:
- versatility (many species)
- small field of view (nadir)
- vertical profiling

Cons:
- low S/N in lower troposphere
- H_2O and other interferences

http://www.atmos.colostate.edu

Solar Backscatter Measurements

Examples: TOMS, GOME, SCIAMACHY, MODIS, MISR, OMI, OCO



Pros:
- sensitivity to lower troposphere
- small field of view (nadir)

Cons:
- Daytime only
- Column only
- Interference from stratosphere

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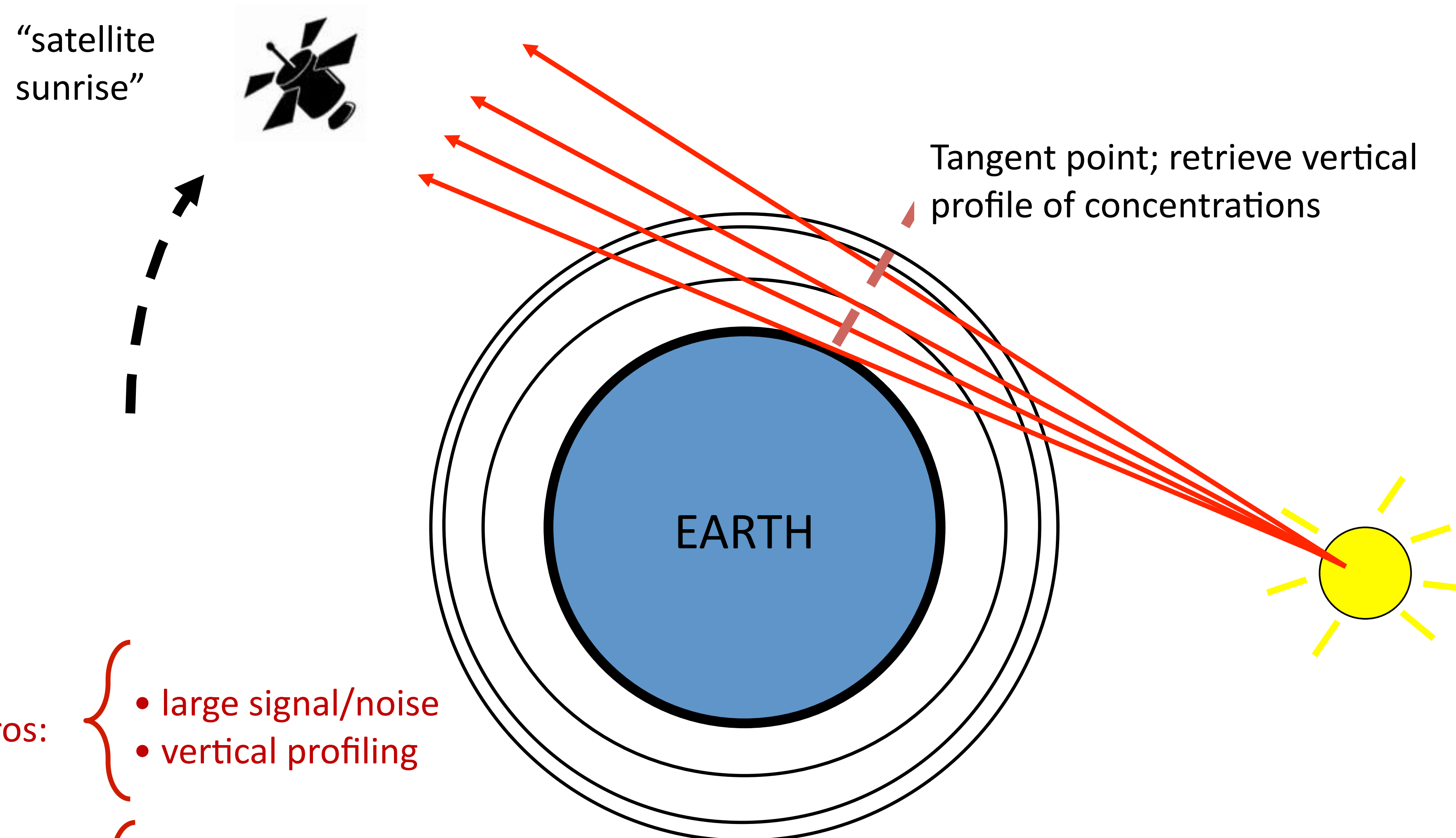
OCCULTATION MEASUREMENTS

Examples: SAGE, POAM, GOMOS



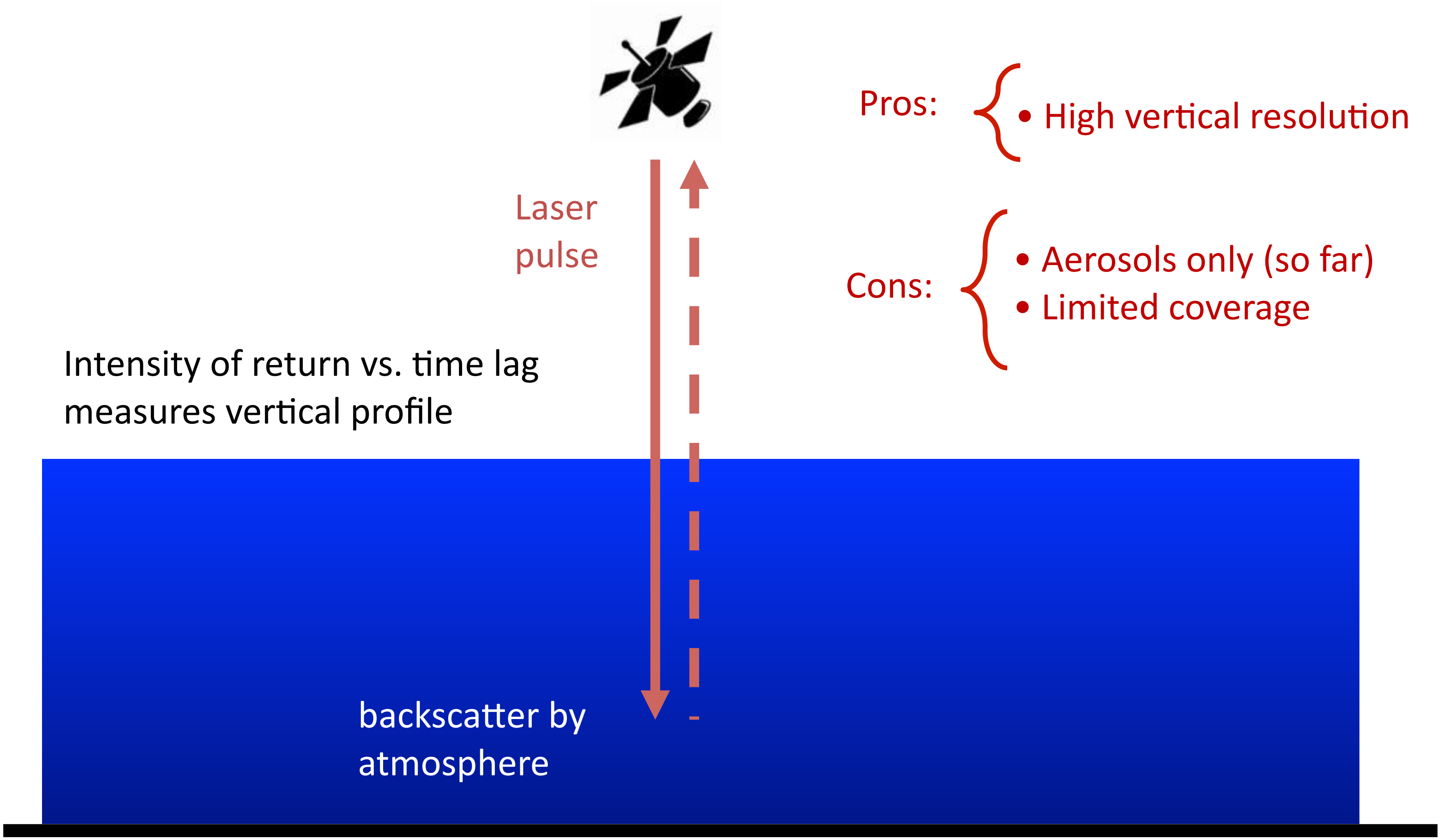
Pros:
- large signal/noise
- vertical profiling

Cons:
- sparse data, limited coverage
- upper troposphere only
- low horizontal resolution

http://www.atmos.colostate.edu

LIDAR MEASUREMENTS (UV to near-IR)

Examples: LITE, GLAS, CALIPSO



Pros:
- High vertical resolution

Cons:
- Aerosols only (so far)
- Limited coverage

Intensity of return vs. time lag measures vertical profile

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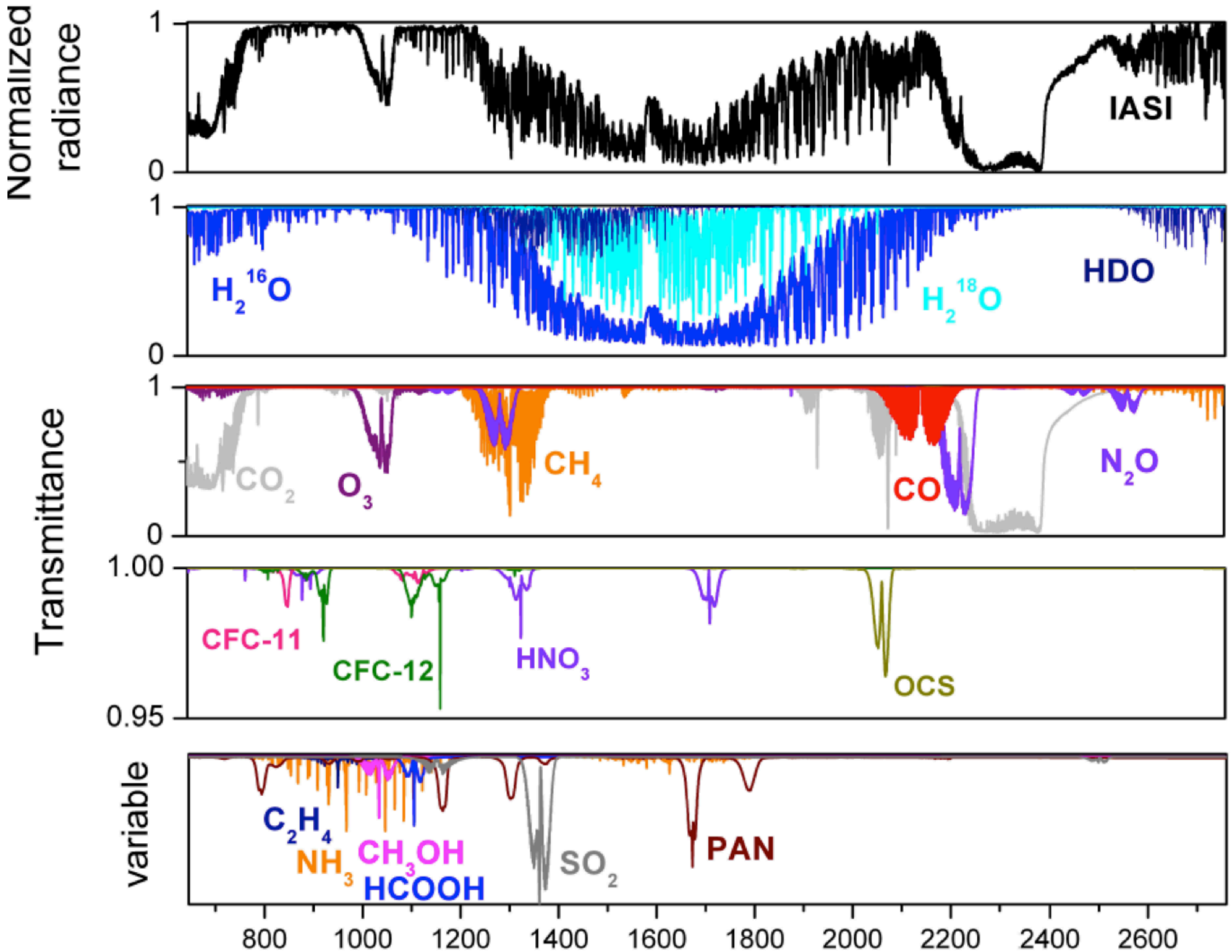
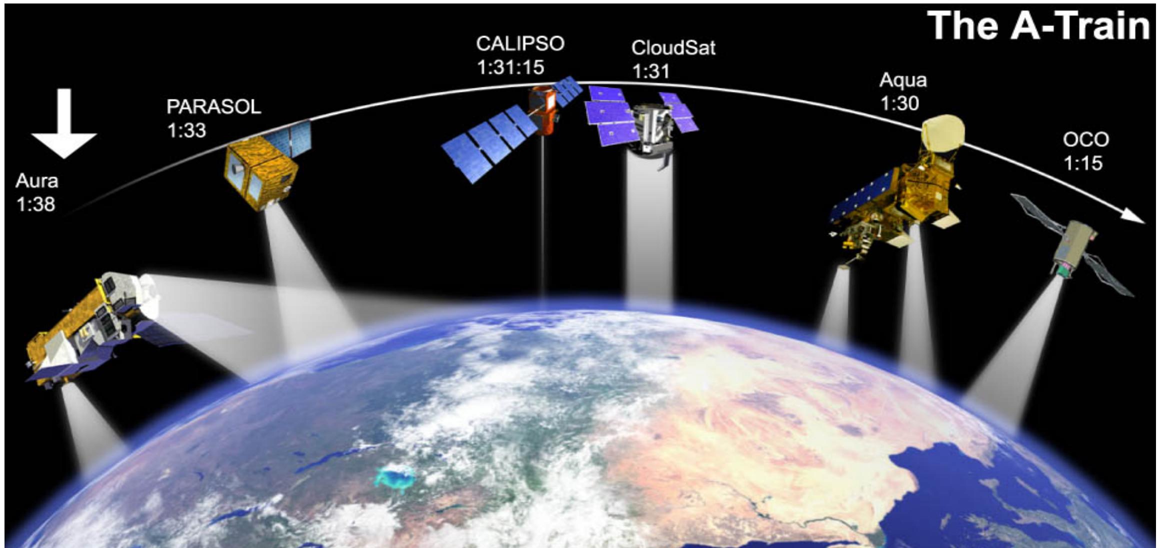
Numerous Species from IR



[Clerbaux et al., ACP 2009]

A-Train Satellites



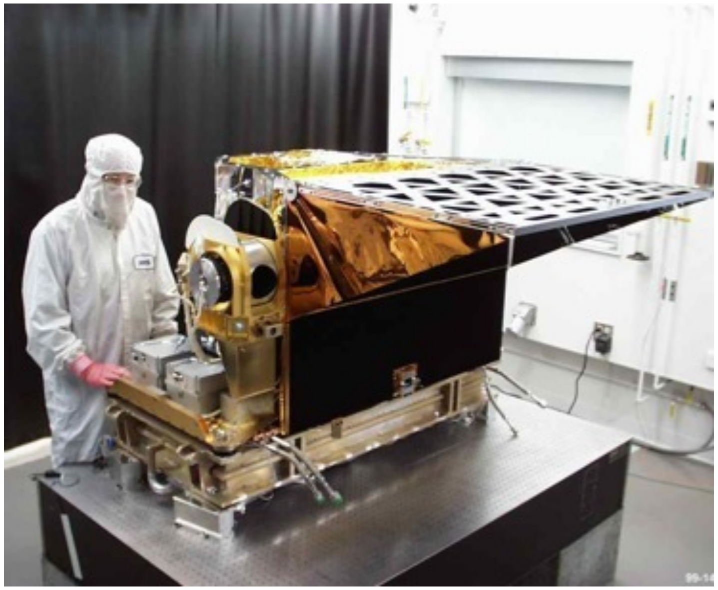
multiple		ERS-2	Adeos	Terra		EnviSat		Aqua	Space sta.	SCISAT -1	Aura					MetOp –A&B	NPP	
TOMS	AVHRR/ SeaWIFS	GOME	IMG	MOPITT	MODIS /MISR	SCIA-MACHY	MIPAS *	AIRS/ MODIS	SAGE-3	ACE-FTS*	TES	OMI	MLS*	HIRDLS *	CALIPSO /Cloud Sat	IASI	CrIS/ VIIRS/ OMPS	OCO-2
1979		1995	1996	1999	1999	2002	2002	2002	2004	2003	2004	2004	2004	2004	2004	2007	2011	2014

Besides traditional temperatures, water vapor, etc.:

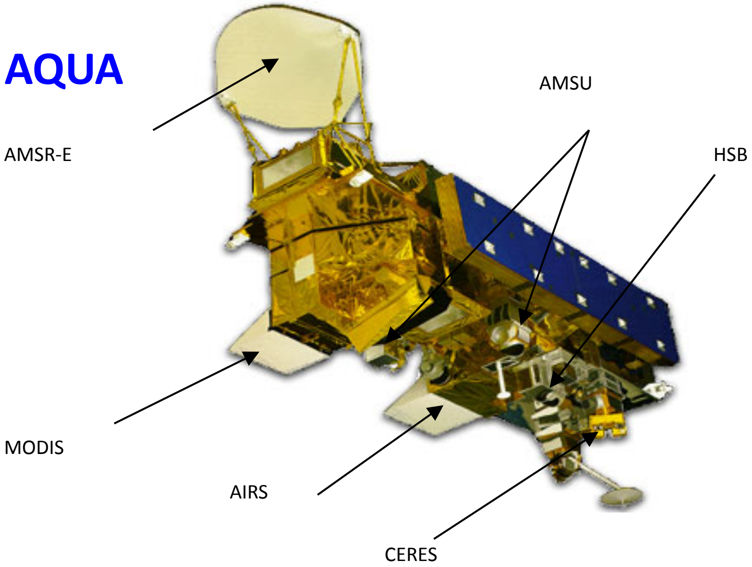
O_3, CO, CO_2, NO, NO_2, HNO_3, CH_4, HCHO, CHOCHO, SO_2, BrO, CH_3CN, HCOOH, CH_3OH, NH_3, HDO, Aerosols, Clouds

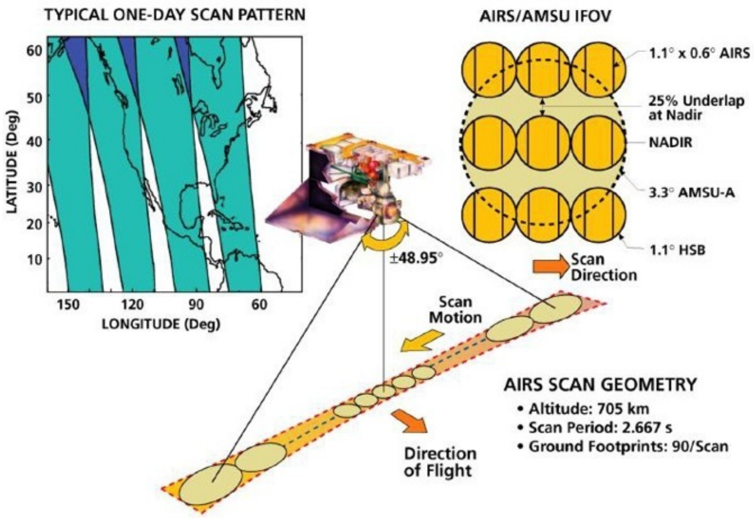
Atmospheric Infrared Sounder

Launched May 2002

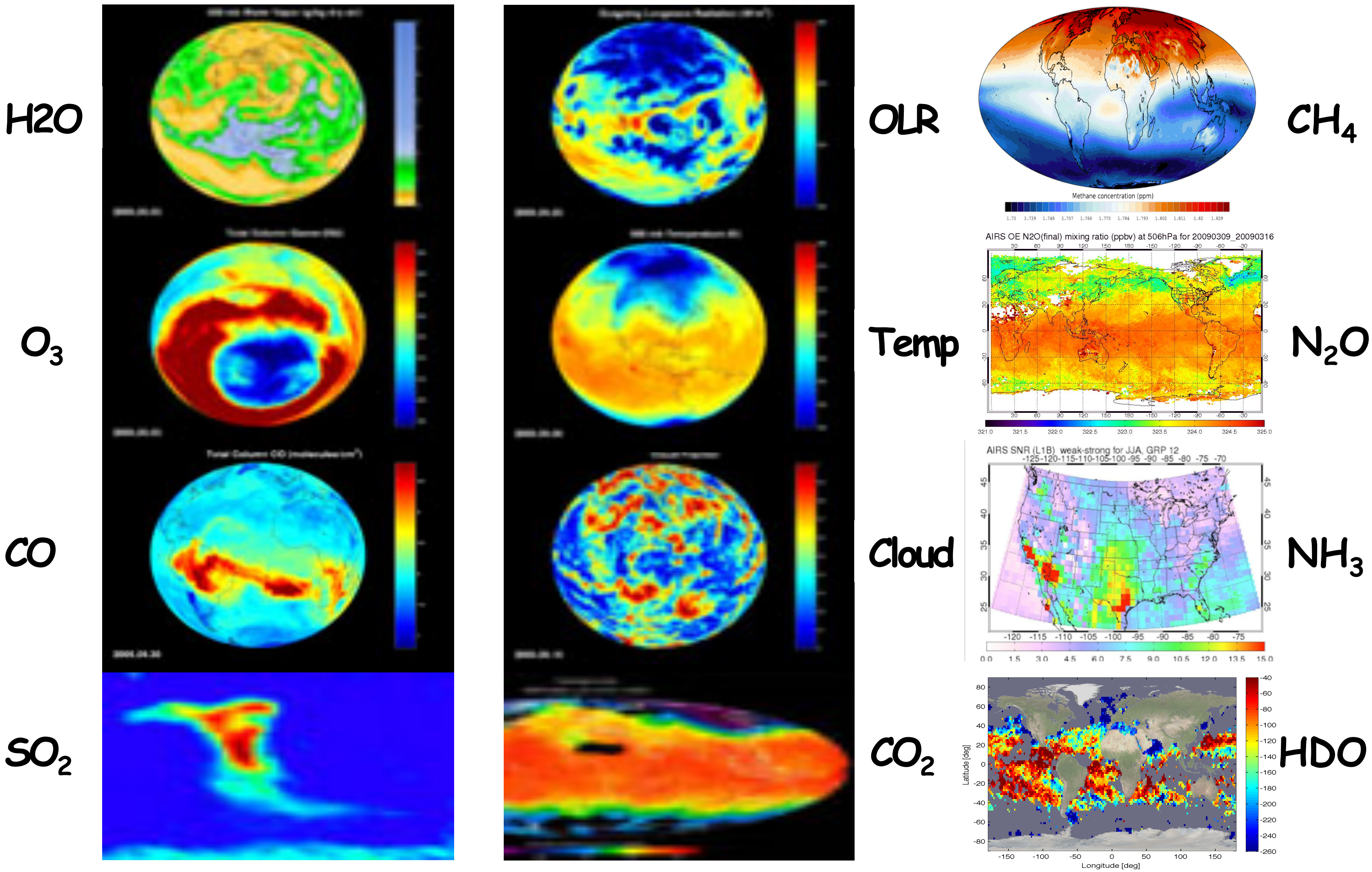


- A grating spectrometer originally designed to improve weather forecast and now also used for climate and air quality studies.
- Spectral resolution at $\nu/1200$ (~ 0.5 cm^{-1})
- Covers 650-2665 in three bands with a total of 2378 channels
- Spatial resolution 13.5 km^2 (with retrievals at ~45 km^2)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

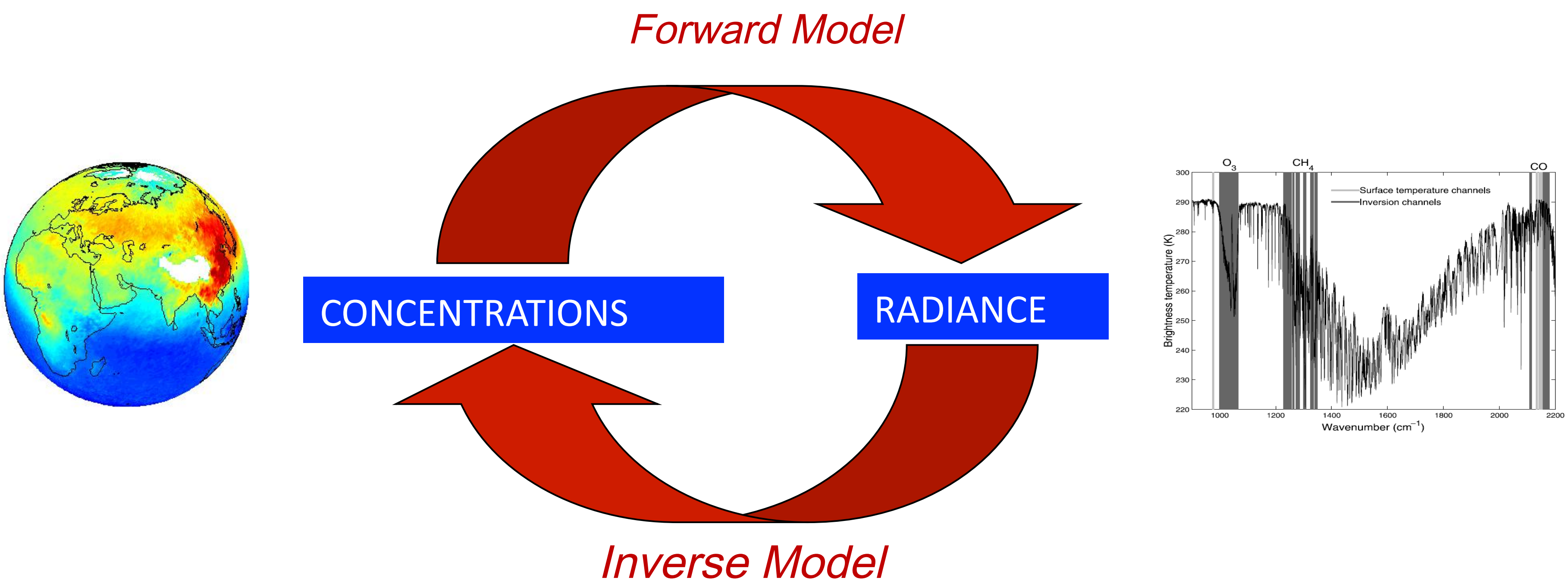




Atmospheric Infrared Sounder



Inverse Methods



$$y = F(x, b) + \varepsilon$$

y	- vector of wavelength-dependent radiances (radiance spectrum);
x	- state variable of concentrations;
F(x, b)	- forward model using Radiative Transfer Equations (RTE);
b	- other properties, besides x, needed to model the atmosphere.

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Retrieval Difficulty

– Use Prior Knowledge in Retrievals

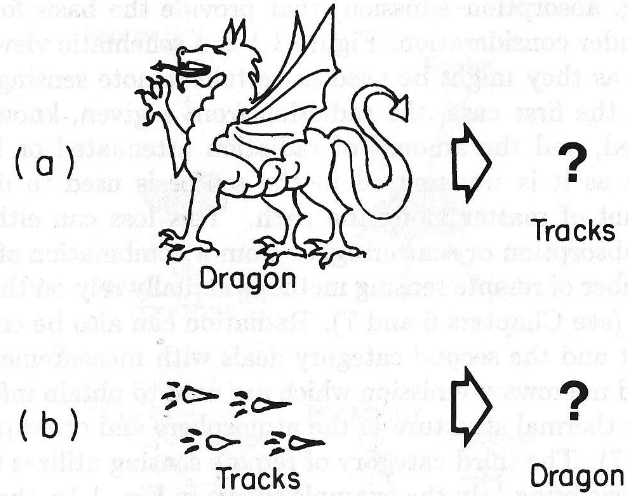


Figure 1.2 (a) The direct problem: Describe the tracks of a dragon. (b) The inverse problem: Describe a dragon from its tracks (from Bohren and Huffman, 1983.)

from Stephens, G. L., “Remote Sensing of the Lower Atmosphere: An Introduction”

Problems:

1. Non-uniqueness of solution (need to apply *a priori* information)
2. Discreteness of measurements of a smoothly varying function
3. Instability of the solution due to errors in the observations

FORWARD MODEL

$$\mathbf{y} = \mathbf{F}(\mathbf{x}, \mathbf{b}) + \varepsilon$$

- Observations (e.g. radiation)
- State of interest (e.g. concentrations)
- Complementary parameters
- Errors

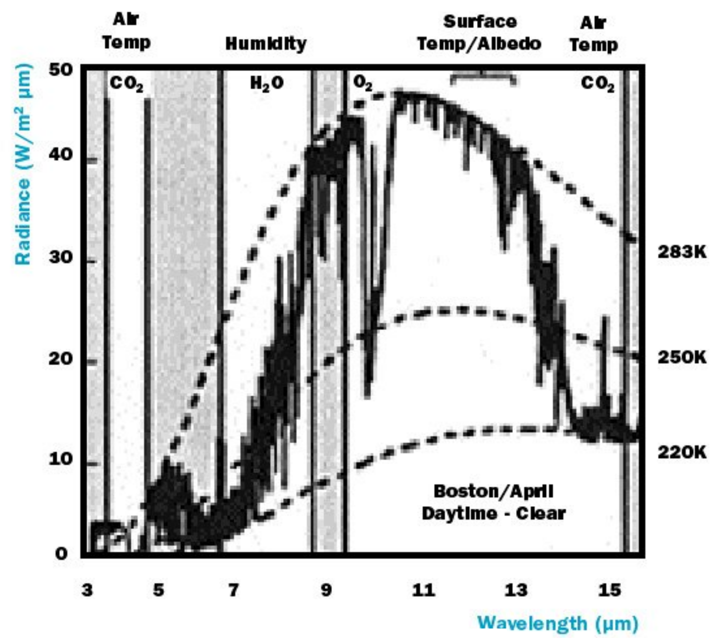
If linear (or linearize the forward model about some reference state X_0):

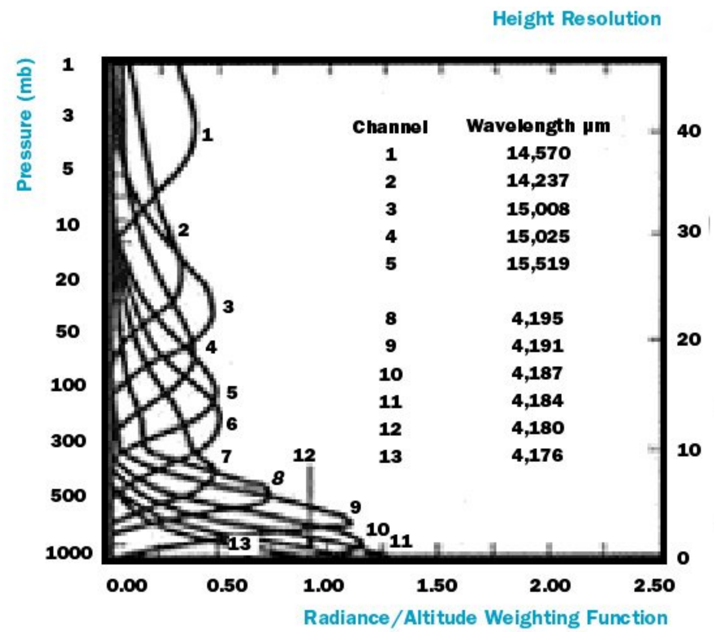
$$y - F(x_0) = \frac{\partial F(x)}{\partial x}(x - x_0) + \varepsilon = K(x - x_0) + \varepsilon$$

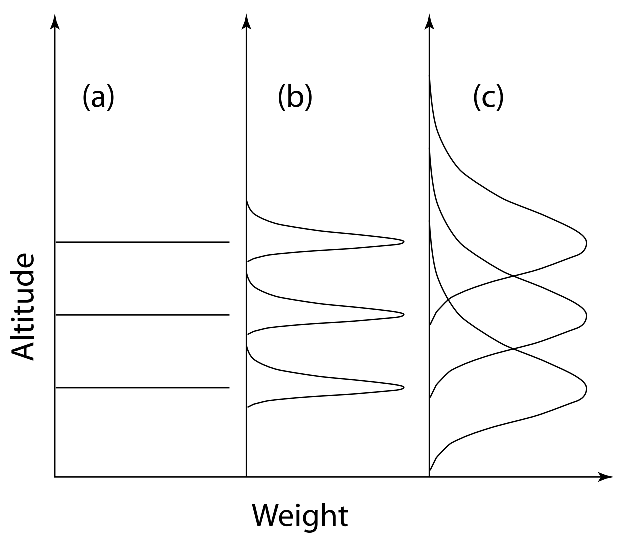
Where $K = \left(\frac{\partial F(x)}{\partial x}\right)$ is the weighting functions or Jacobians.

This problem is ill-posed because K (mxn) is not square (generally m < n, i.e., less measurements than unknowns).

Weighting Functions



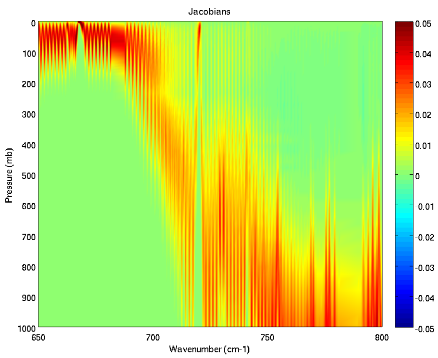




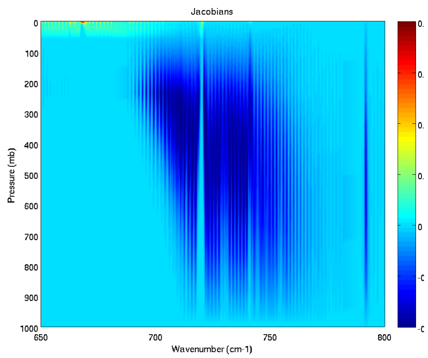
- Ideally the channel weighting functions are δ functions ie emission detected by a channel comes from a single altitude
- Realistically the weighting functions have finite width
- And in hyperspectral instruments, the functions overlap

Courtesy of Dr. DeSouza-Machado, UMBC

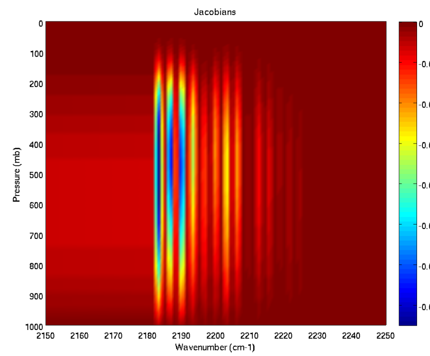
Jacobians-measurement sensitivity for a specie in a spectral band



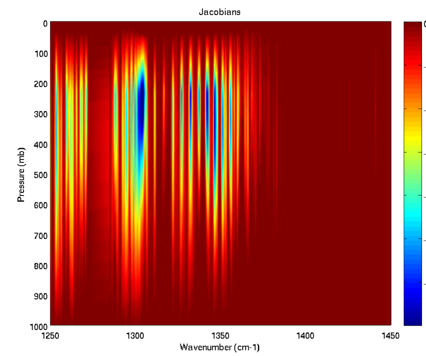
Temperature



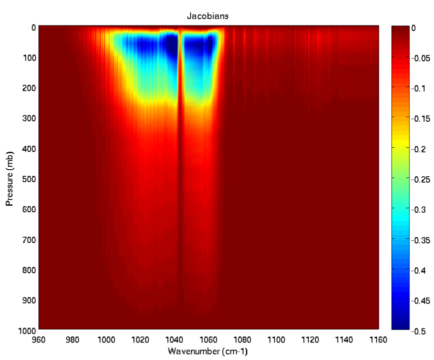
CO2



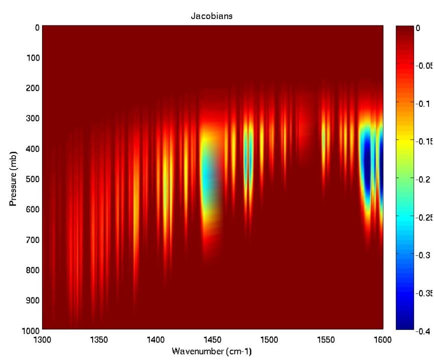
CO



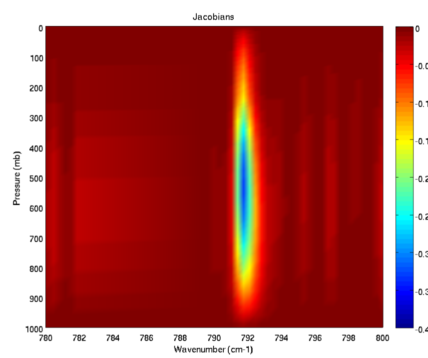
CH4



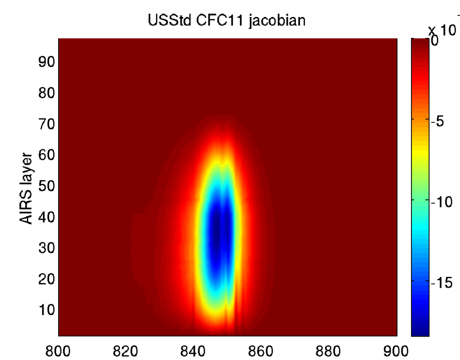
O3



WV

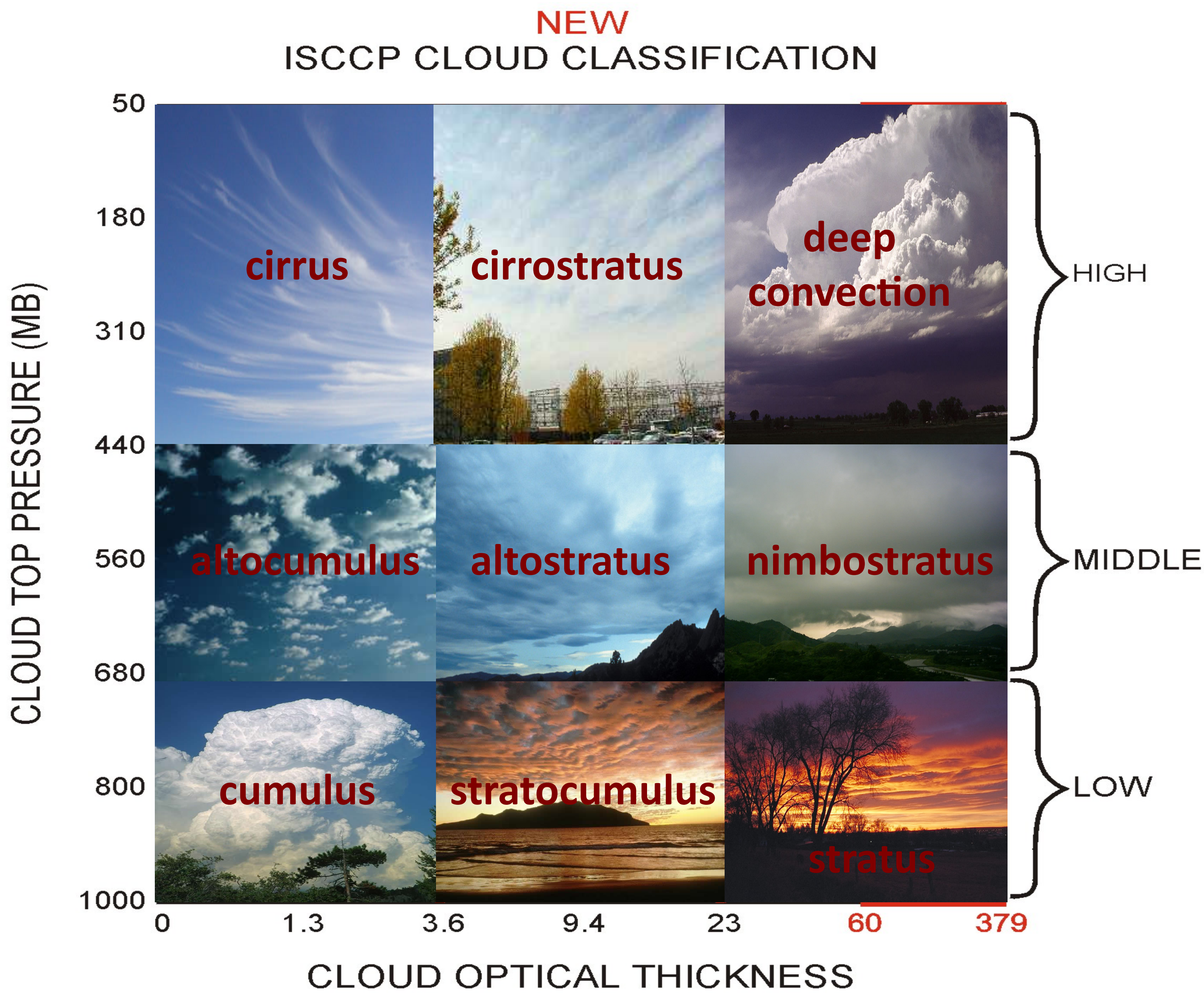


791 cm^{-1} CO_2



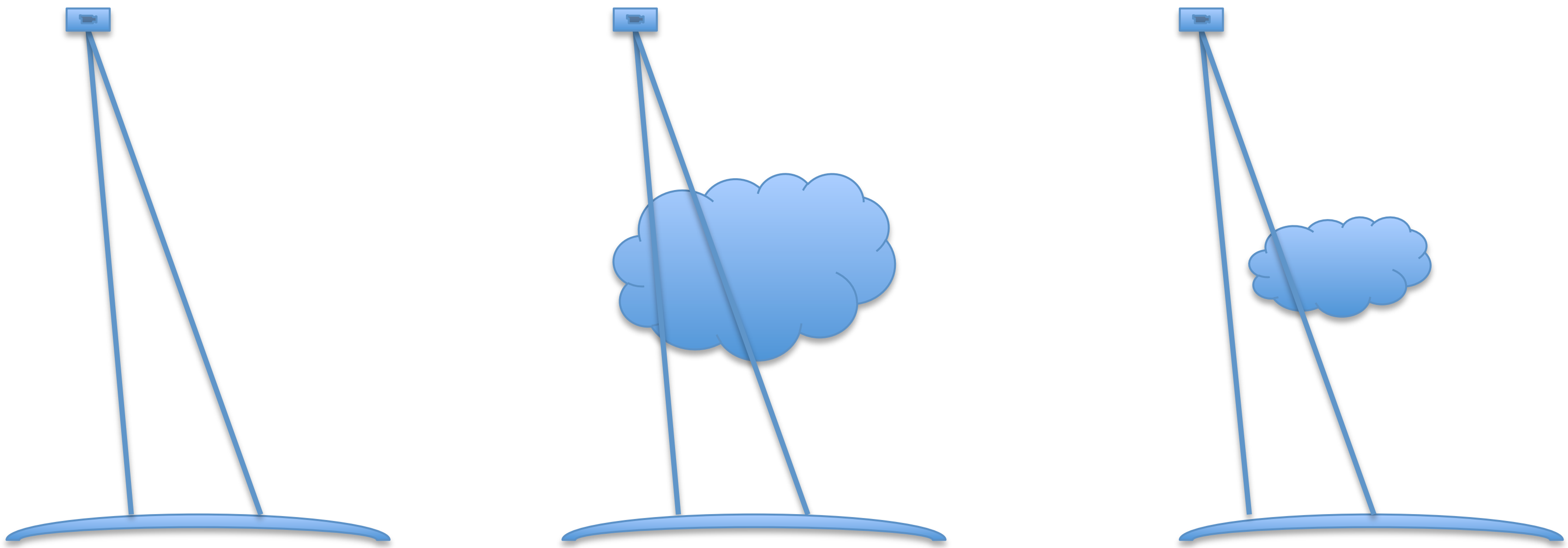
CFC11

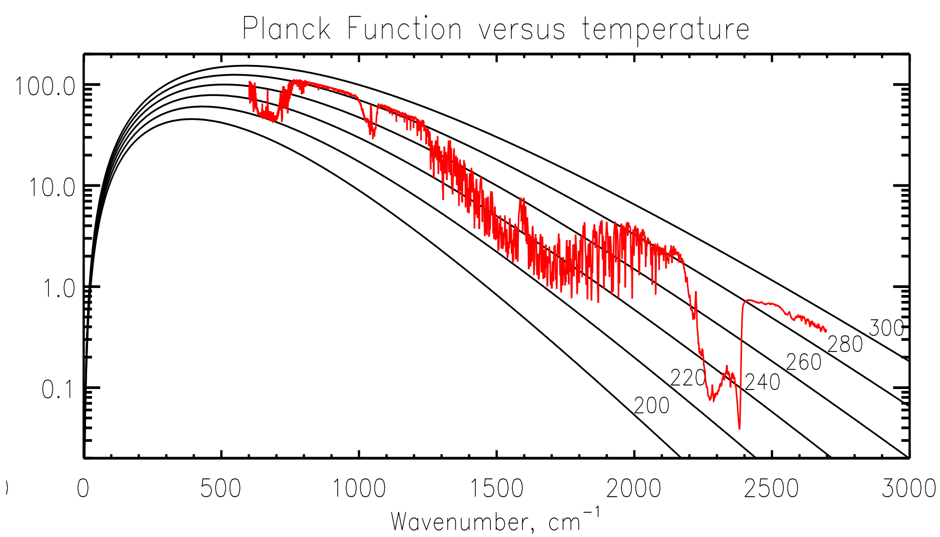
Courtesy of Dr. DeSouza-Machado, UMBC

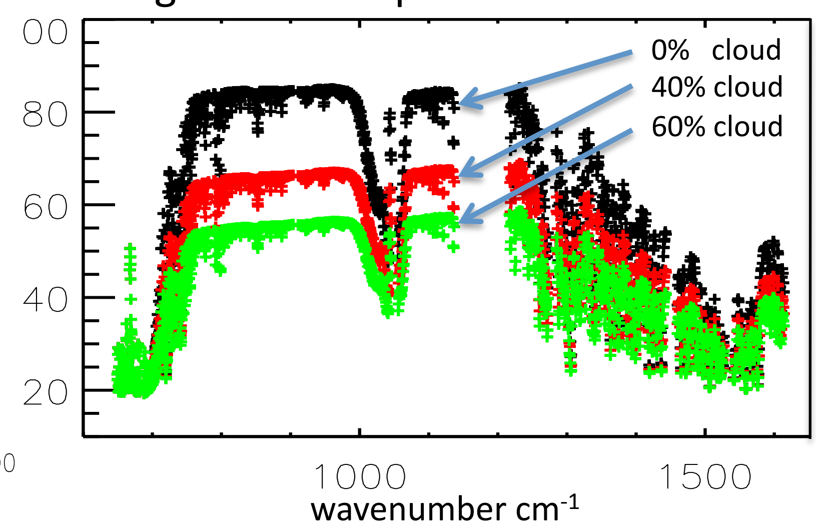

NEW
ISCCP CLOUD CLASSIFICATION
CLOUD TOP PRESSURE (MB)
50
180
310
440
560
680
800
1000
cirrus
cirrostratus
deep convection
altocumulus
altostratus
nimbostratus
cumulus
stratocumulus
stratus
HIGH
MIDDLE
LOW
0
1.3
3.6
9.4
23
60
379
CLOUD OPTICAL THICKNESS

Cloud Detection Principle

- Using atmospheric window regions, colder for clouds

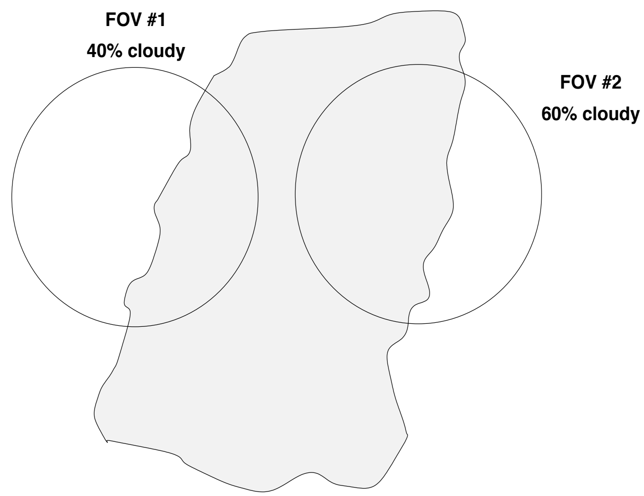






Treatment of clouds

- Cloud Clearing



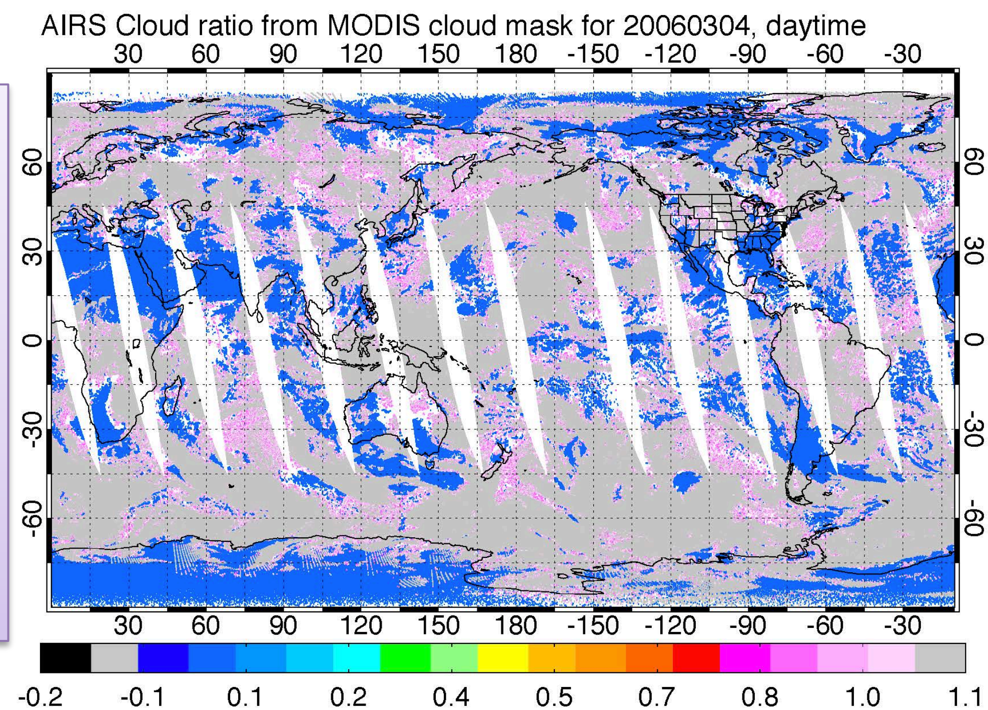
- Derive the clear column radiances that would have been there if there were no clouds
- Assuming the two scenes only differ by the cloud coverage.
- Works for broken or transparent clouds
- Improve coverage from ~15% to 50-70%!

$$R_{obs} = \alpha R_{cld} + (1-\alpha) R_{clr}$$

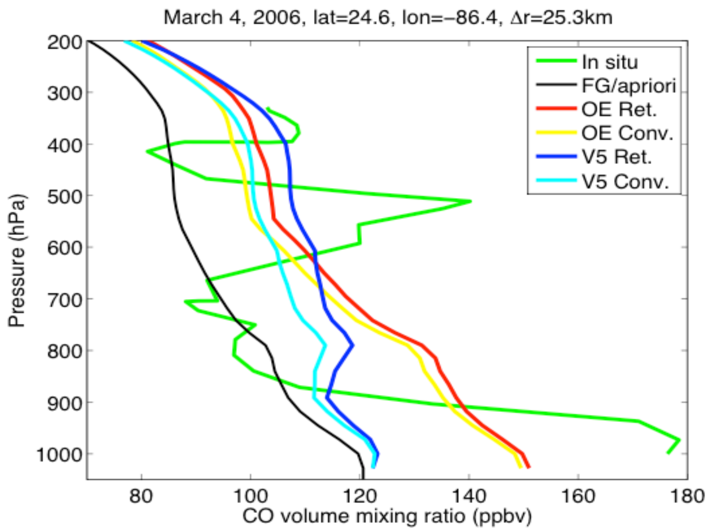
$$N^* \equiv \alpha_1/\alpha_2 = (R_1 - R_{clr})/(R_2 - R_{clr})$$

$$R_{clr} = (R_1 - N^* R_2)/(1 - N^*)$$

McMillin, L.M. and C. Dean 1982. Evaluation of a new operational technique for producing clear radiances. J. Appl. Meteor. 21 p.1005-1014.
Smith, W.L. 1968. An improved method for calculating tropospheric temperature and moisture from satellite radiometer measurements. Monthly Weather Review 96 p.387-396.



Validation



INTEX-B DC-8 spiral profiles on Mar. 4, 2006, over west of Birmingham, AL near the fires, with AIRS V5 CO (blue and cyan lines) and AIRS OE CO (red and orange lines).

Observations used for the Validations

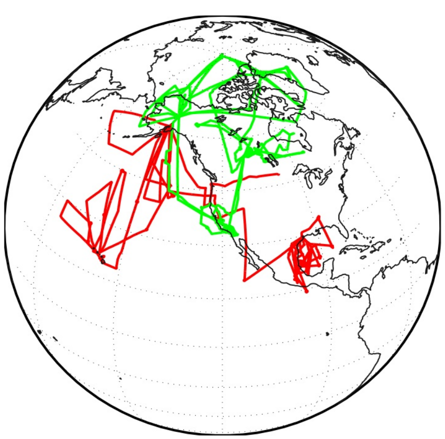
Field Campaigns:
- INTEX-A (DC-8)
- MILAGRO/ INTEX-B (DC-8, C130)
- ARCTAS (DC-8, P3)
- HIPPO

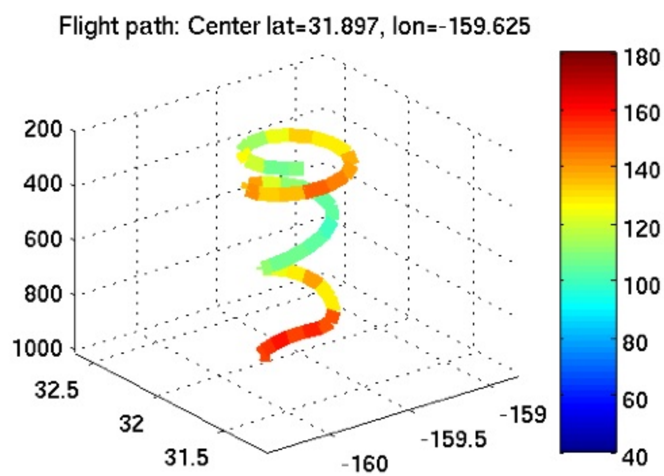
Ground Measurements:
- GMD
- NDACC

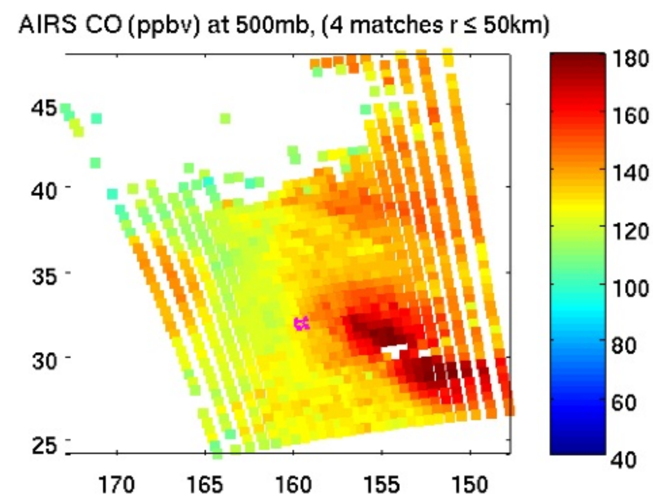
Ground Balloon Sondes:

Temperature, water vapor, and ozone

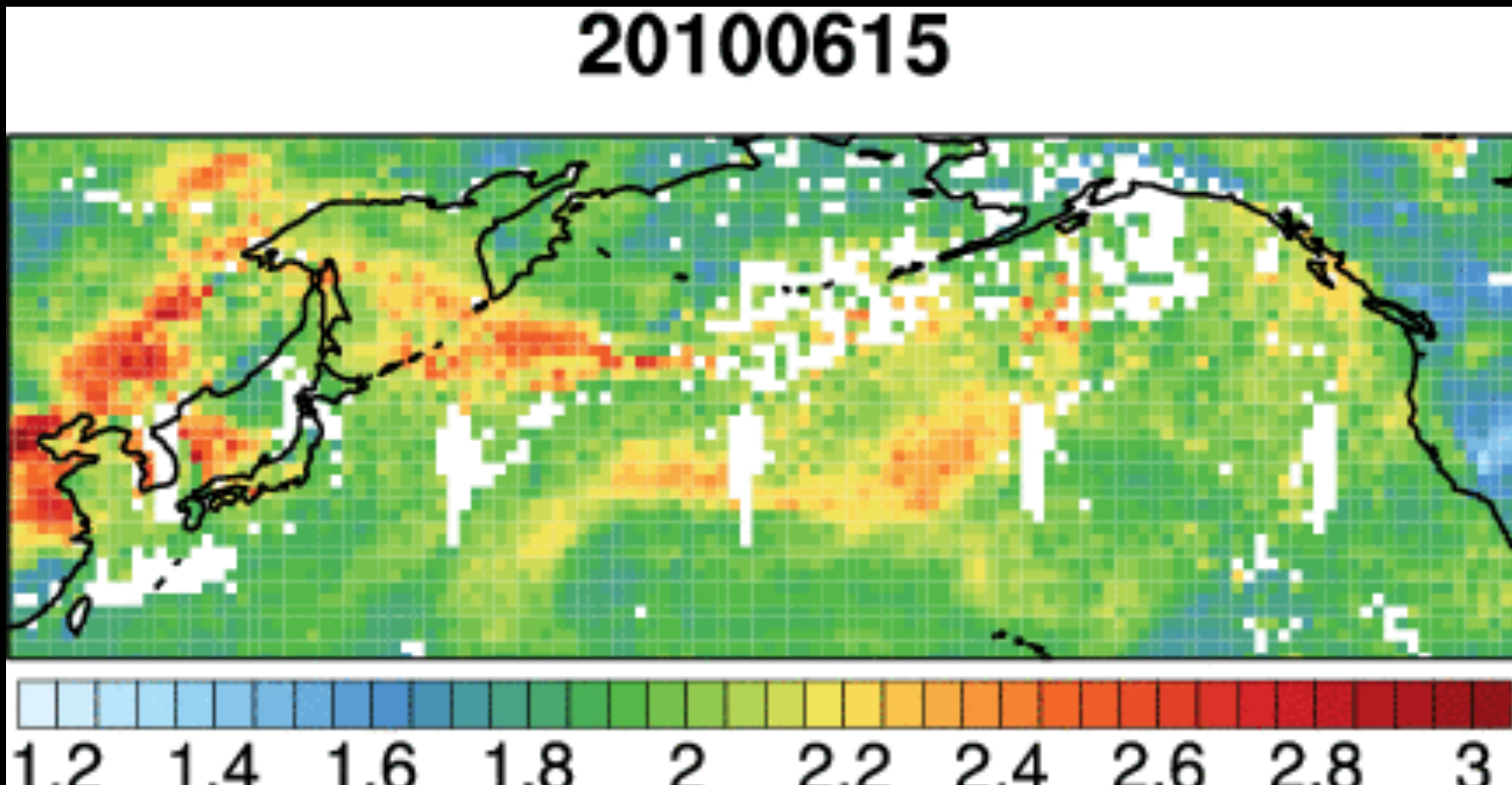
Airliners:
- MOZAIC
- Japanese Airliner





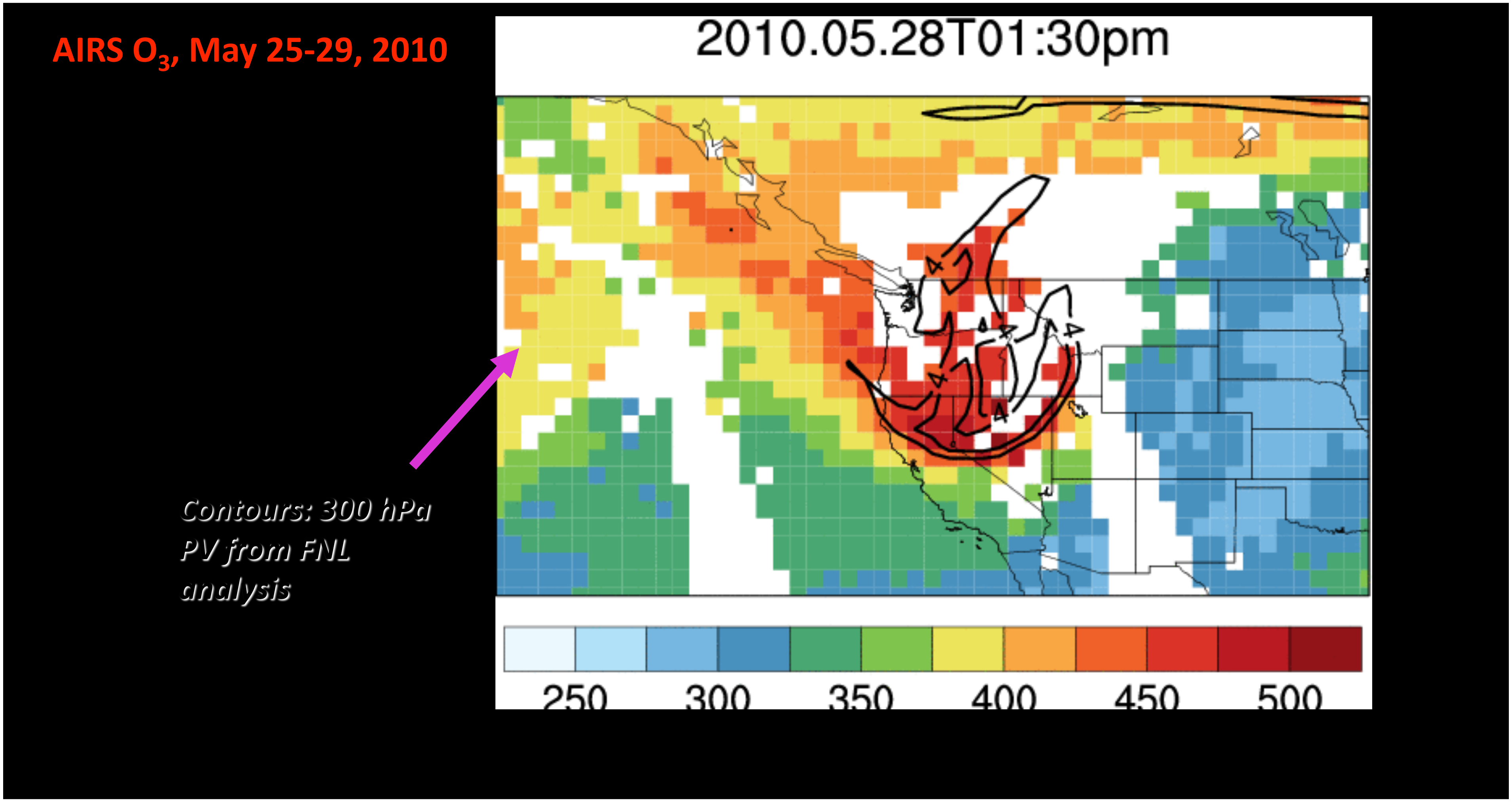


Transpacific Asian pollution plumes: the view from AIRS CO



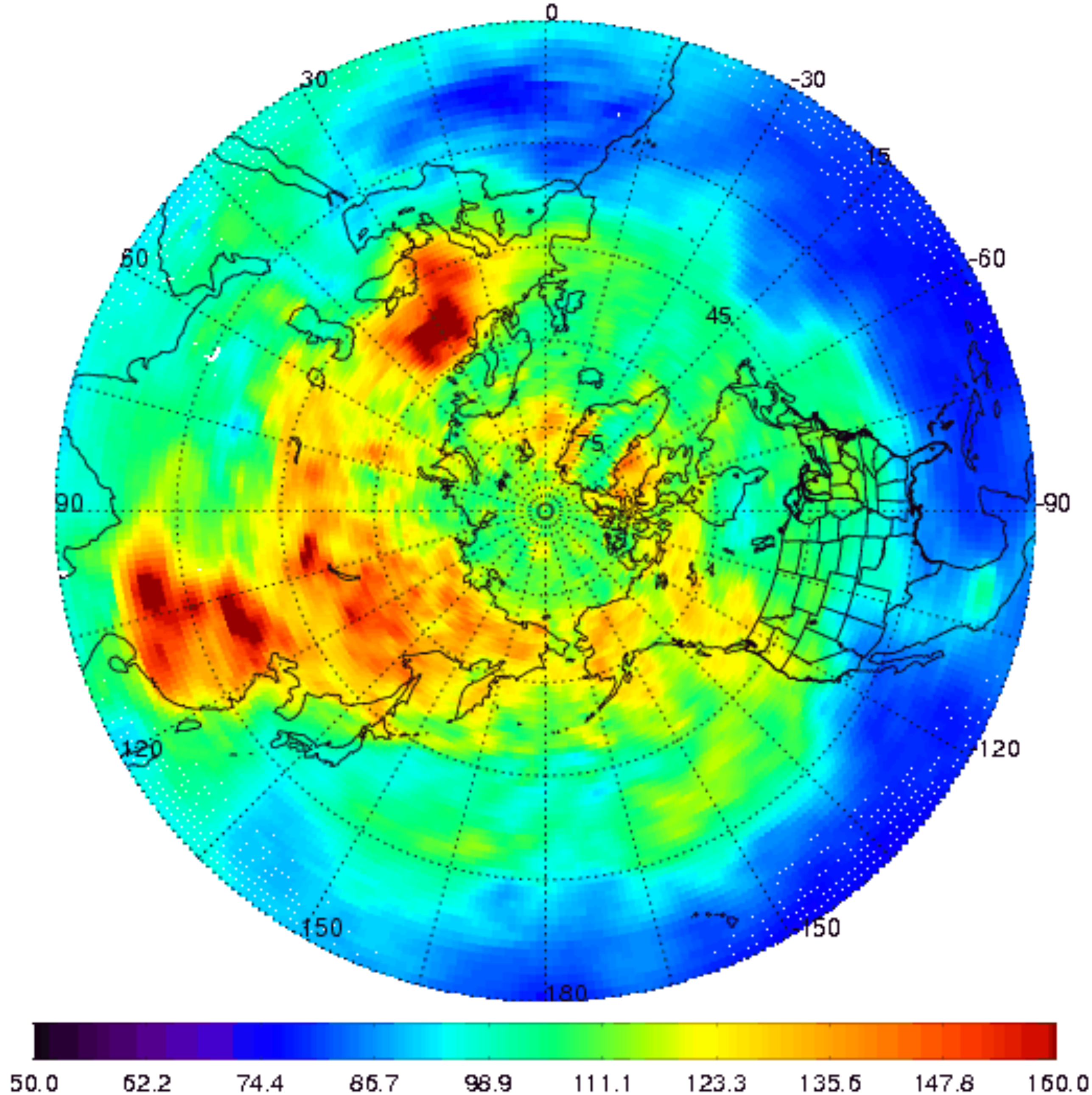
Lin, M., et al.: (2012a): Transport of Asian ozone pollution into surface air over the western United States in spring, *Journal of Geophysical Research*,117, D00V07, doi:10.1029/2011JD016961

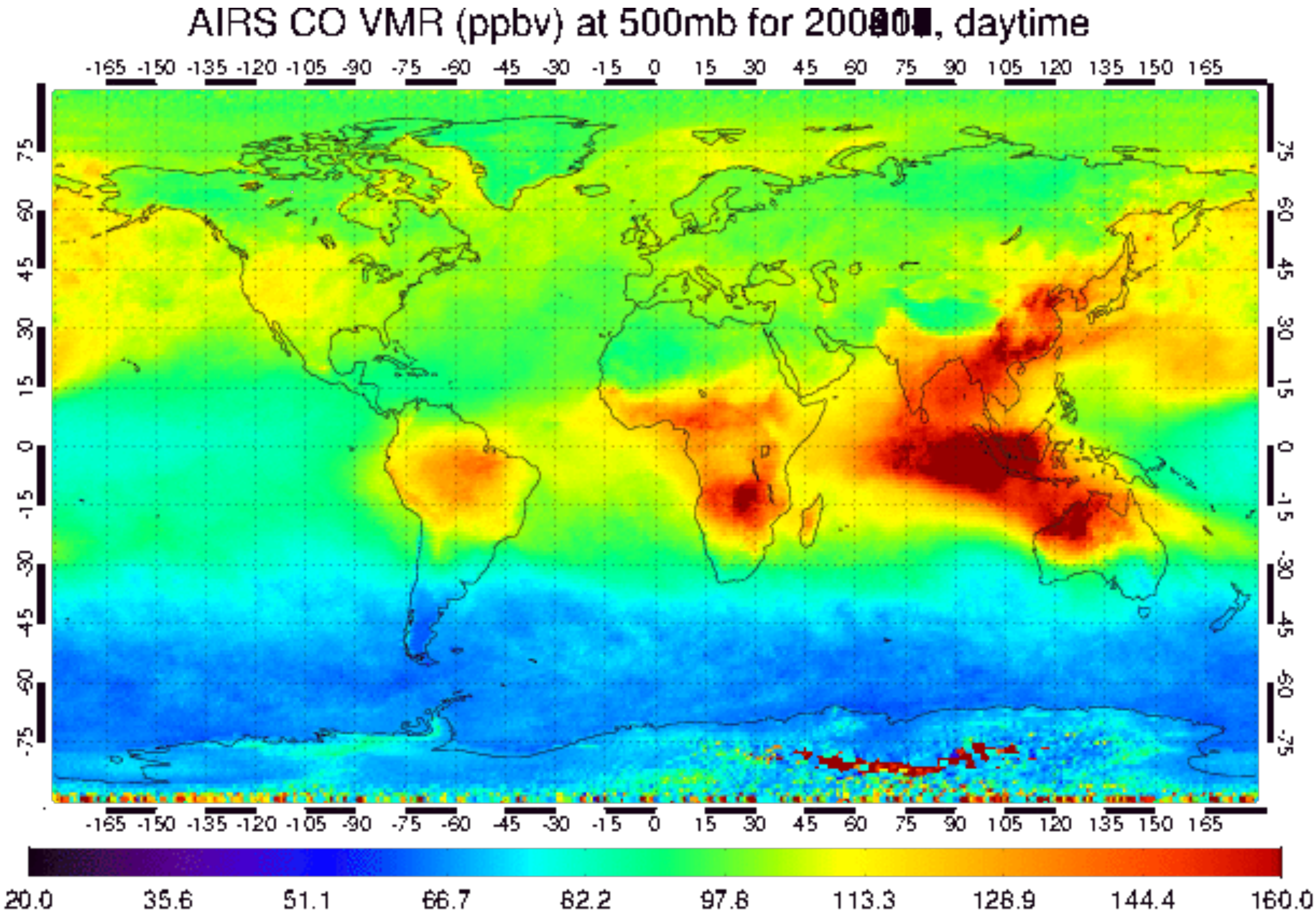
AIRS O_3 retrievals capture upper dynamics conducive to deep stratospheric intrusions over the western U.S.



Lin M *et al.* (2012b): Springtime high surface ozone events over the western United States: Quantifying the role of stratospheric intrusions, *Journal of Geophysical Research*, 117, D00V22, doi:10.1029/2012JD018151

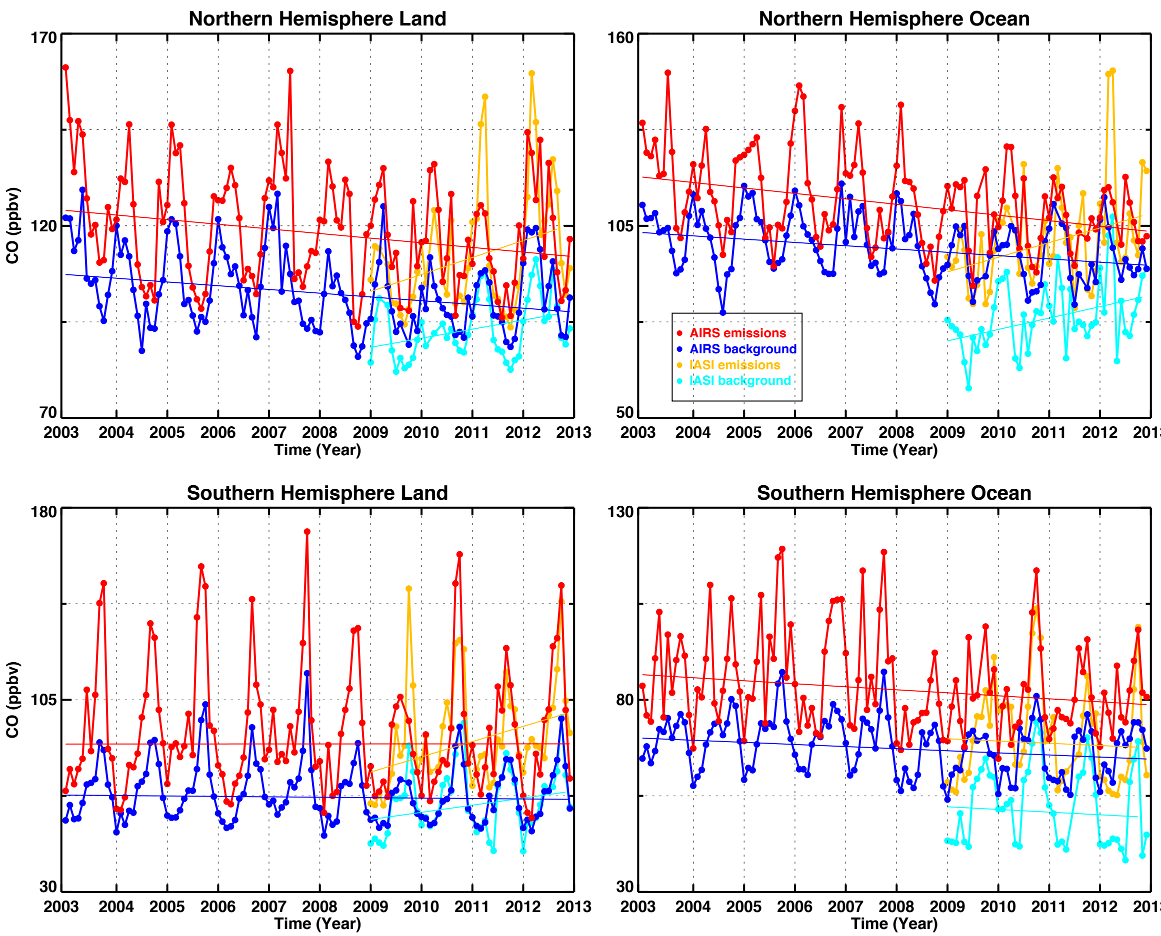
AIRS CO ppbv at 500hPa 20020901~20020908




AIRS CO VMR (ppbv) at 500mb for 200[redacted], daytime
-165 -150 -135 -120 -105 -90 -75 -60 -45 -30 -15 0 15 30 45 60 75 90 105 120 135 150 165
75 60 45 30 15 0 -15 -30 -45 -60 -75
20.0 35.6 51.1 66.7 82.2 97.8 113.3 128.9 144.4 160.0

AIRS V5 and NOAA IASI at 500 hPa CO trends

- recent emission (right Gaussian: red-AIRS and yellow-IASI) and
- background (left Gaussian: blue-AIRS and cyan-IASI)

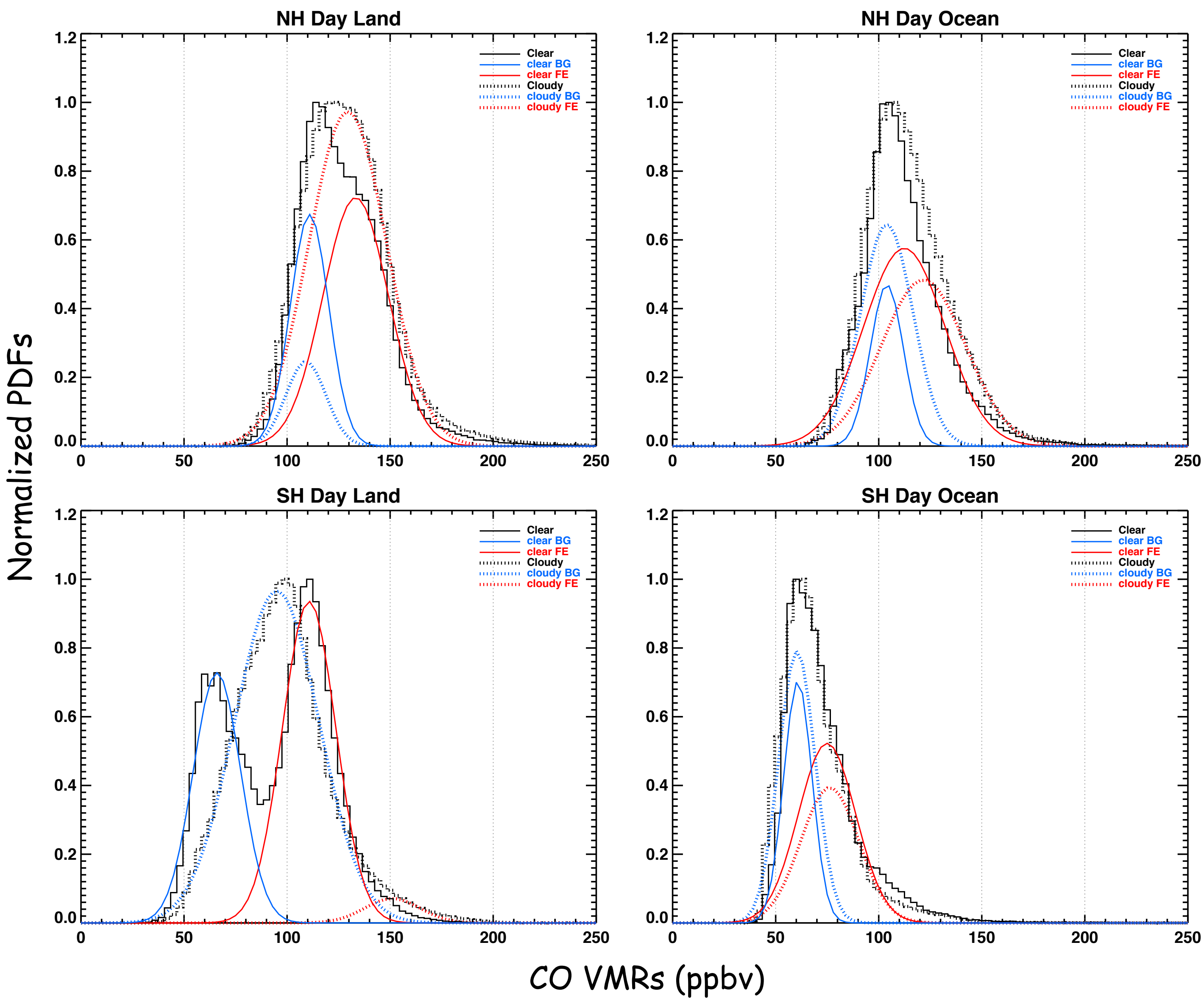


•Worden, H. M., Deeter, M. N., Frankenberg, C., George, M., Nichitiu, F., Worden, J., Aben, I., Bowman, K., Clerbaux, C., Coheur, P.F., de Laat, A.T., Detweiler, J. R., Drummond, J.R., Edwards, D., Gille, J., Hurtmans, D., Luo, M., Martínez-Alonso, S., Massie1, S., Pfister1, G., Sweeney, C., Warner, J.X., 2013, Decadal Record of Satellite Carbon Monoxide Observations, Atmos. Chem. Phys., 13, 837-850, doi:10.5194/acp-13-837-2013.

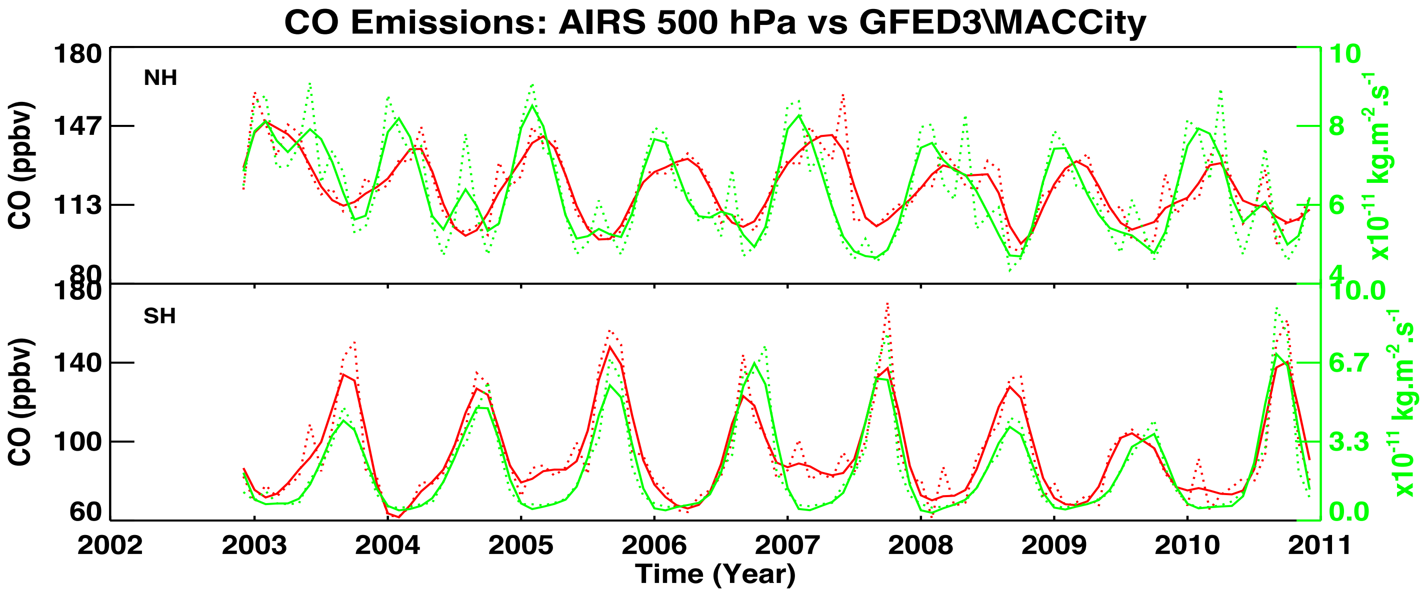
•He, H., Stehr, J. W., Hains, J. C., Krask, D. J., Doddridge, B. G., Vinnikov, K. Y., Canty, T. P., Hosley, K. M., Salawitch, R. J., Worden, H. M., and Dickerson, R. R. (2013), Trends in emissions and concentrations of air pollutants in the lower troposphere in the Baltimore/Washington airshed from 1997 to 2011, Atmos. Chem. Phys., 13, 7859-7874, doi:10.5194/acpd-13-3135-2013.

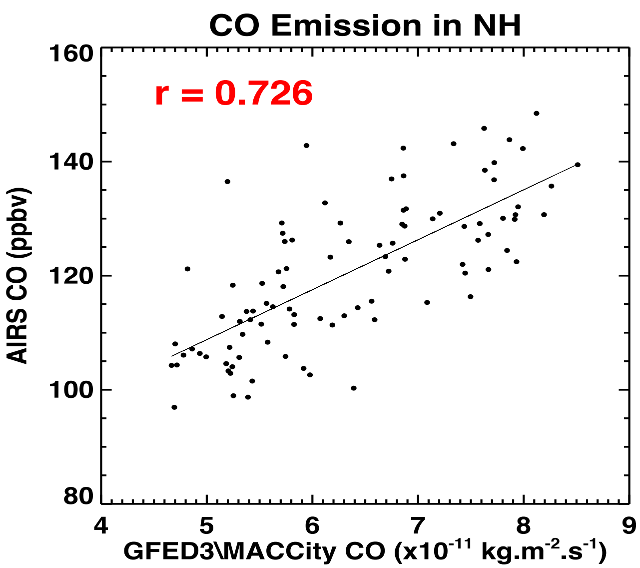
•Warner, J., Carminati, F., Wei, Z., Lahoz, W., and Attié, J.-L.: Tropospheric carbon monoxide variability from AIRS under clear and cloudy conditions, Atmos. Chem. Phys., 13, 12469-12479, doi:10.5194/acp-13-12469-2013, 2013.

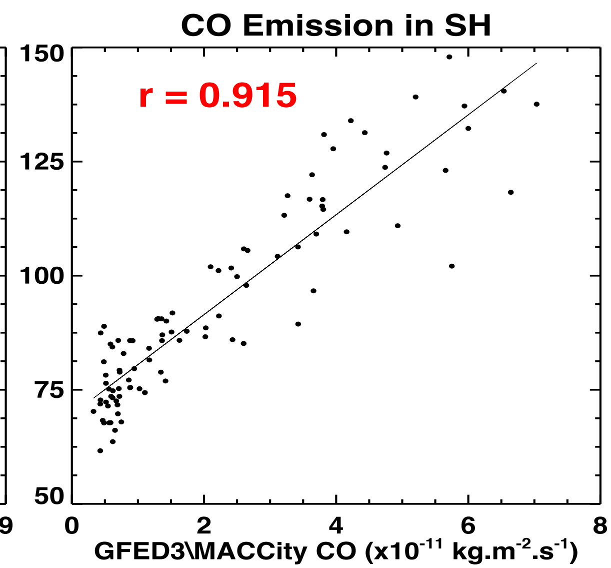
Separating CO fresh emissions from background - PDF distribution and two Gaussian Fits



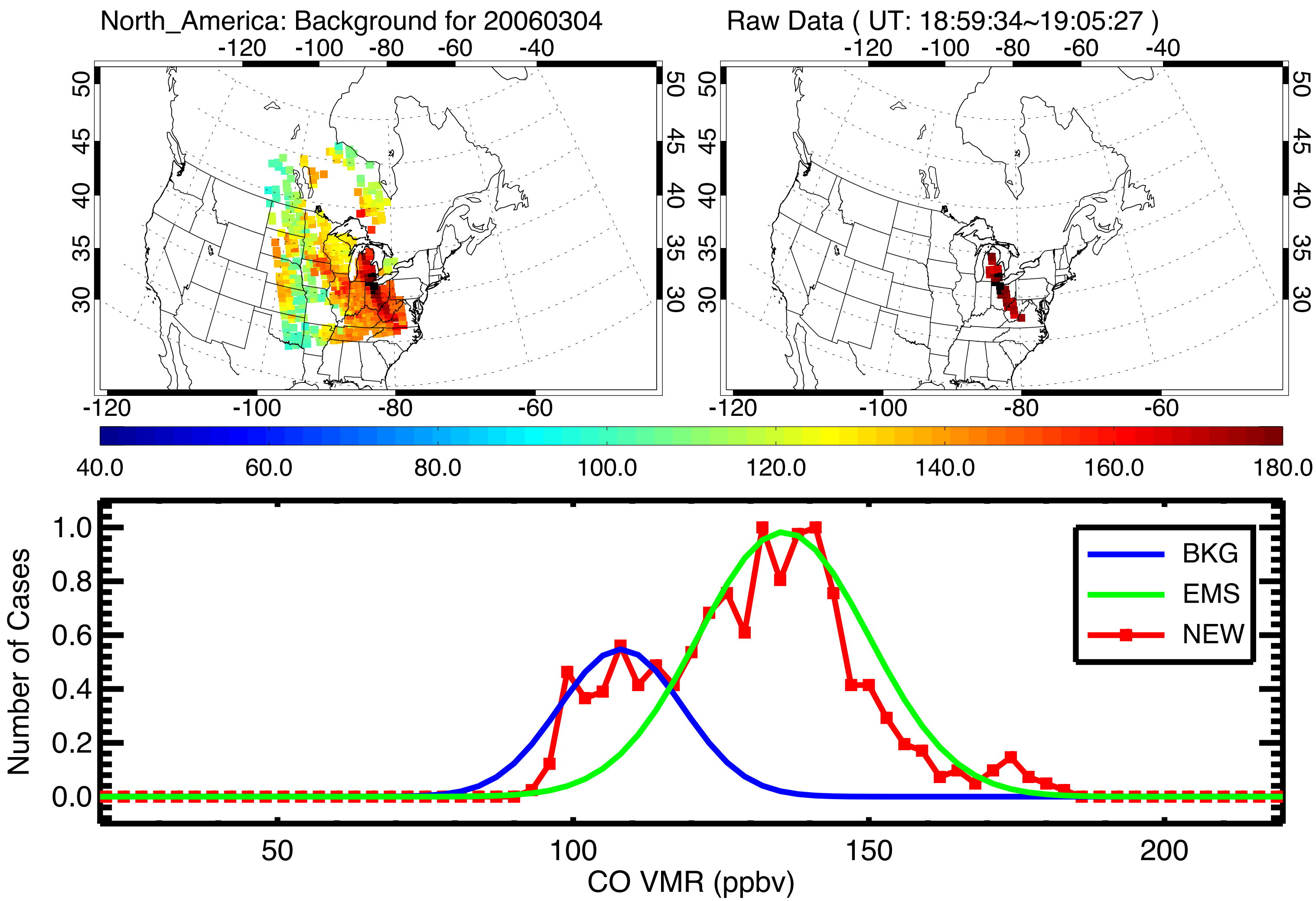
Recent emission from AIRS correlated with routine emission inventories





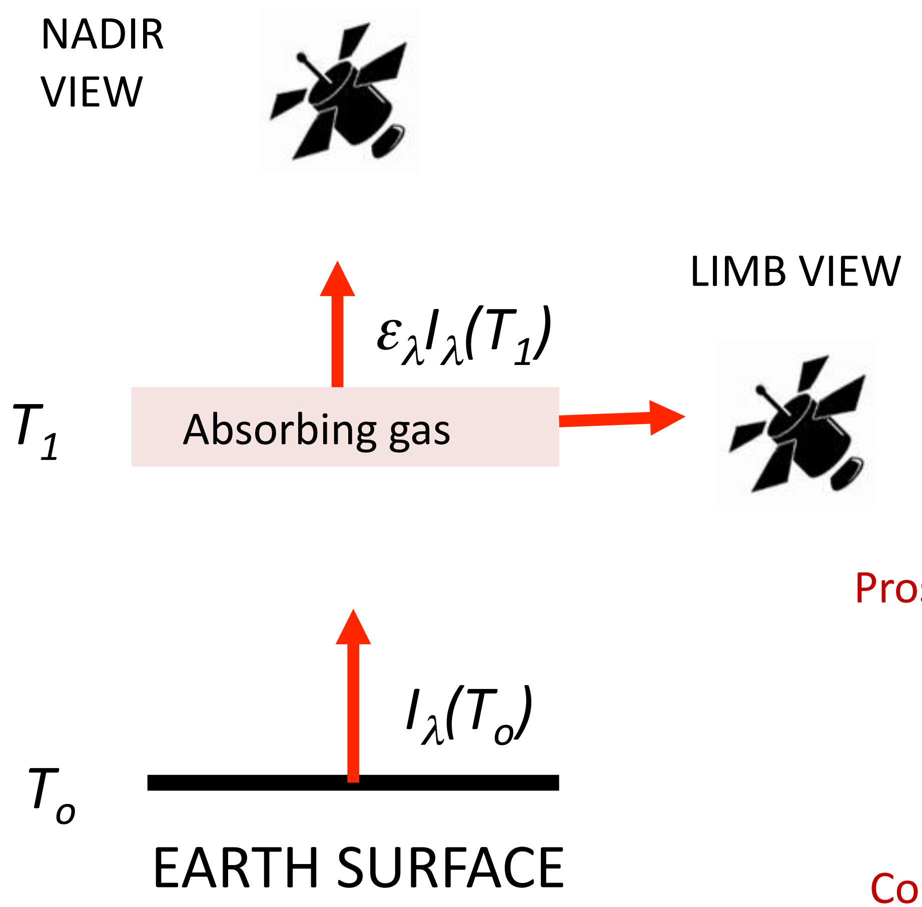


Implications of separating fresh emissions from the background



Thermal Emission Measurements (IR, microwave)

Examples: AIRS, IASI, MLS, IMG, MOPITT, MIPAS, TES, HIRDLS

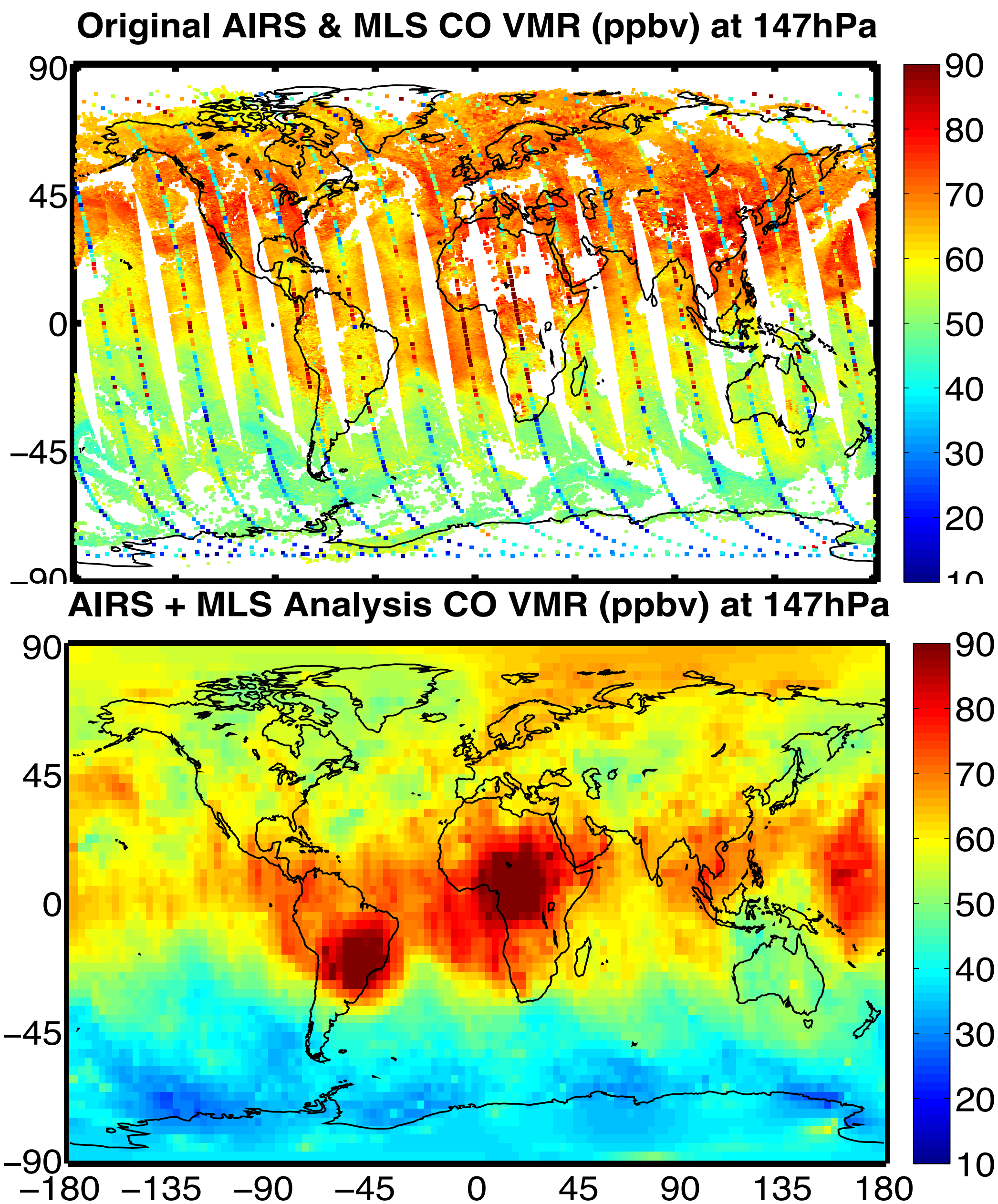


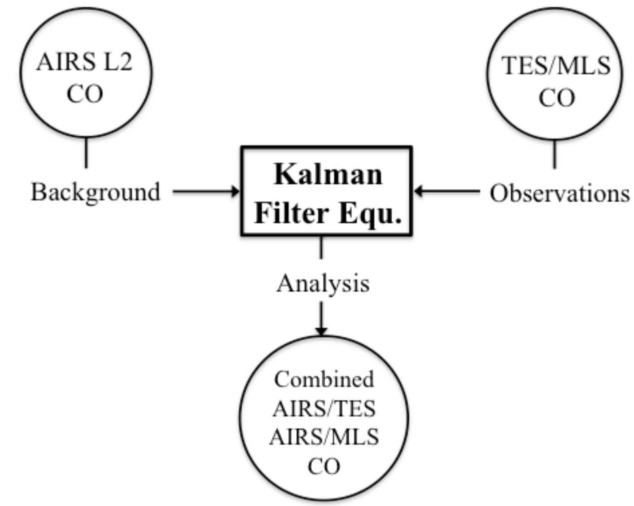
Pros:
- versatility (many species)
- small field of view (nadir)
- vertical profiling

Cons:
- low S/N in lower troposphere
- H_2O and other interferences

http://www.atmos.colostate.edu

Data Fusion using AIRS and MLS





- AIRS nadir with broad coverage
- MLS limb with high vertical resolution, but narrow coverage

Warner, J. X., Yang, R., Wei, Z., Carminati, F., Tangborn, A., Sun, Z., Lahoz, W., Attié, J.-L., El Amraoui, L., and Duncan, B.: Global carbon monoxide products from combined AIRS, TES and MLS measurements on A-train satellites, Atmos. Chem. Phys., 14, 103-114, doi:10.5194/acp-14-103-2014, 2014.