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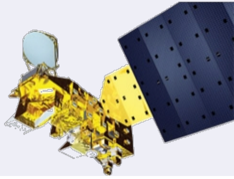

AIRS CO2 Science Highlights and Project Status

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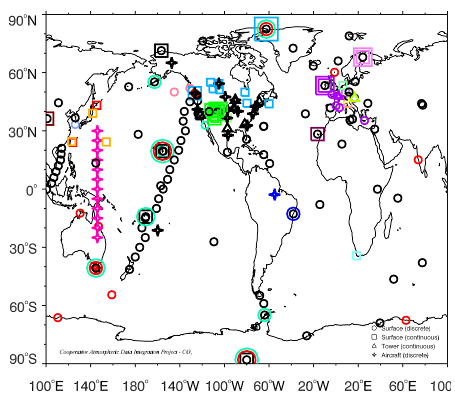
NASA Sounder Science Team Meeting
17-19 March 2014

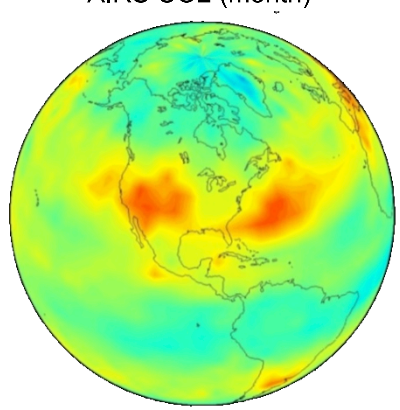
Introduction

- Why is the retrieval of free tropospheric CO_2 important?
  - Atmospheric CO_2 is the major agent for radiative forcing
    - Interannual increase due to human activity, and ~50% of anthropogenic CO_2 remains in atmosphere
  - The free troposphere is the pathway by which CO_2 produced at the surface by natural and anthropic processes is circulated around the globe to be deposited in the natural sinks
  - The free tropospheric (and stratospheric) CO_2 are the background which must be accounted for in the process of determining the surface carbon flux by remote sensing
    - SH, “the garbage dump for the NH CO_2 emissions”, very sparsely observed from ground/airborne
  - Modeling of atmospheric transport processes are yet not sufficiently developed
    - Vertical lofting
    - Inter-hemispherical transport
- Satellite retrievals provide the spatial and temporal coverage over the globe necessary to elucidate the transport of CO_2 and to ultimately identify the regional sources and sinks and net fluxes around the globe
(AIRS, GOSAT, SCIAMACHY, TES, and forthcoming OCO-2)

In situ CO2 observations



AIRS CO2 (month)



Aqua/AIRS Hyperspectral TIR Instrument

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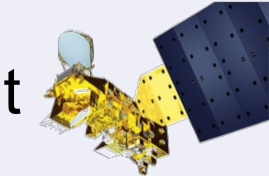
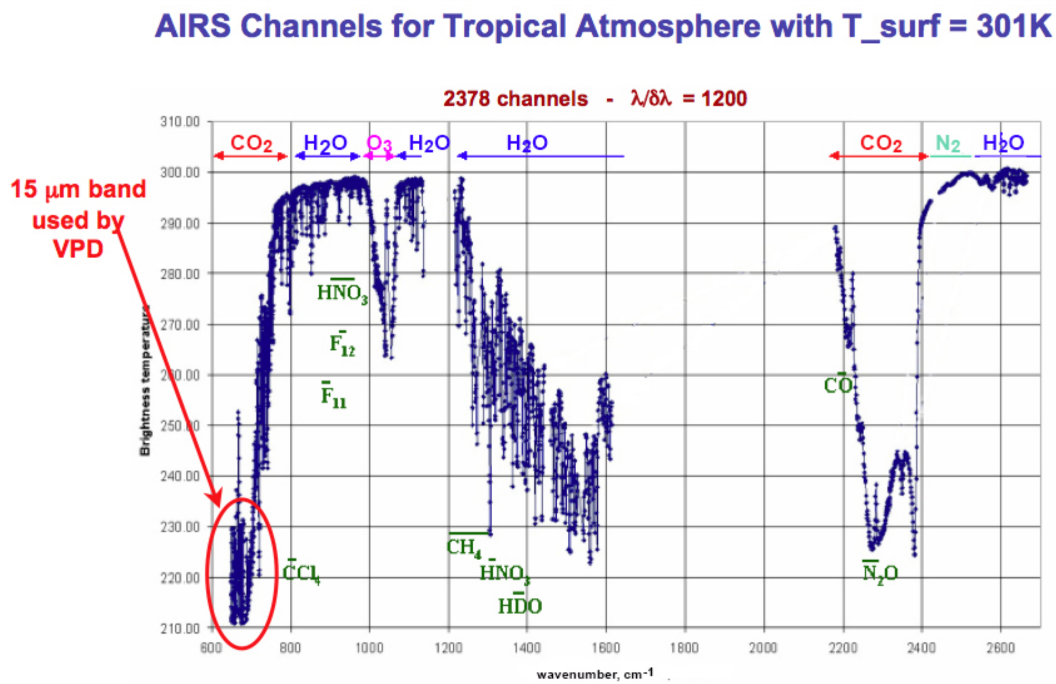


AIRS Hyperspectral Infrared Spectrum



AIRS Characteristics

- **Aqua Spacecraft**
  - **Launched: May 4, 2002**
- **Sun-Synchronous A-train Orbit: 705 km**
  - **1:30 pm Equatorial ascending crossing**
  - **1:30 am Equatorial descending crossing**
  - **98.14° orbital inclination**
  - **Global Daily Coverage**
- **2378 Channel Grating Spectrometer**
  - **IR IFOV : 1.1° x 0.6°**
  - **13.5 km spatial resolution at nadir**
  - **±48.95° Cross-track scan**
    - **90 IFOV per 2.667 sec**
  - **Spectral Range: 3.5-15.4 µm**
  - **L1B Radiances have Climate Quality Accuracy and Stability**

- AIRS CO2 retrieval algorithm employs method of Vanishing Partial Derivatives (VPD) ingesting AIRS L2 cloud cleared radiances and physical retrievals
  - Chahine, et al. (2005) "On the Determination of Atmospheric Minor Gases by the Method of Vanishing Partial Derivatives with Application to CO2", GRL, 32, L22803, doi:10.1029/2005GL024165.
- AIRS V5 Mid-Tropospheric CO2 data product from 9/2002-Present is available at:
  - http://disc.sci.gsfc.nasa.gov/AIRS/data-holdings

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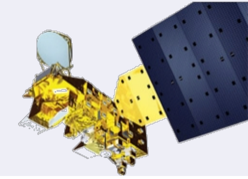
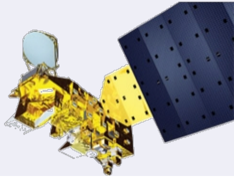
Published Studies Bearing on CO2 Transport Around the Globe

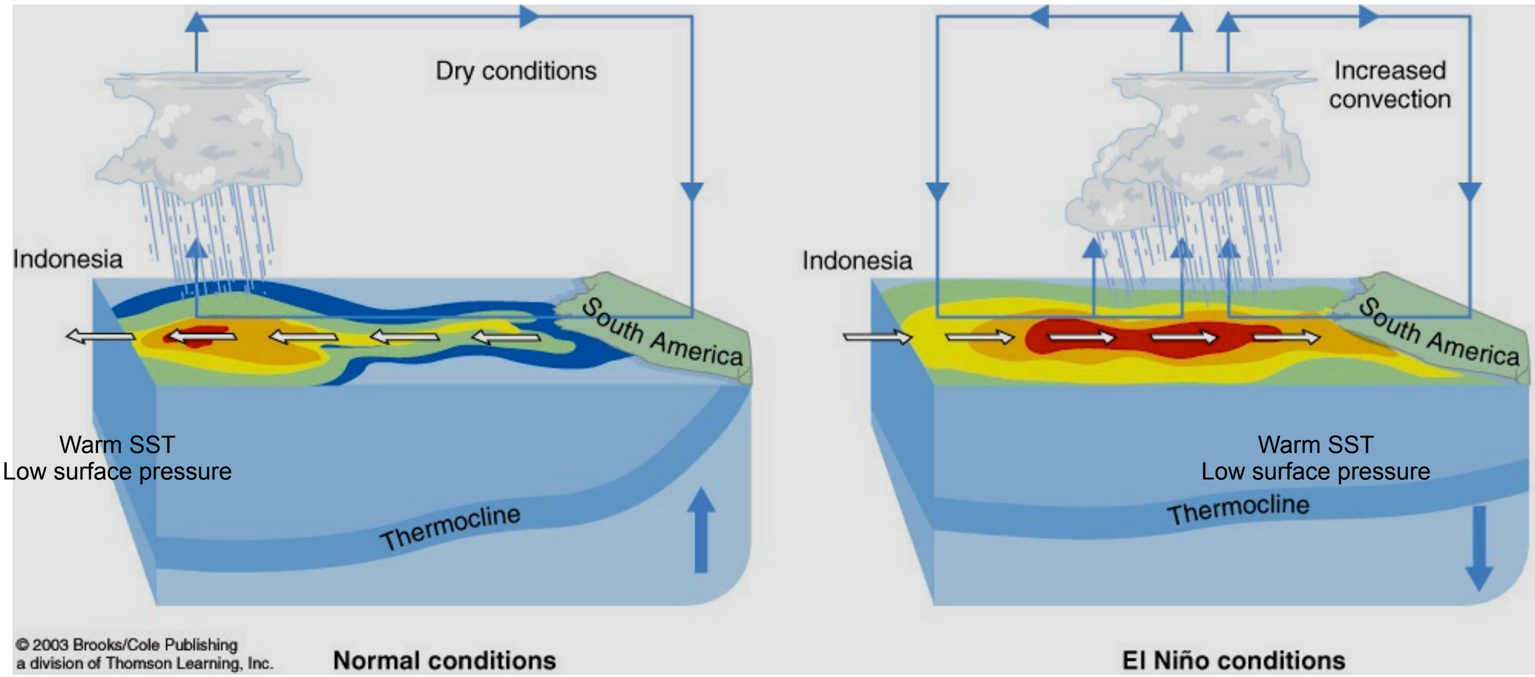


- Published studies demonstrate that the AIRS data contain signals arising from the large-scale circulation patterns in both the tropics and at high latitudes: ENSO, MJO, Walker Circulation,TBO, AO, and SSW in addition to the interannual growth of global CO2 and its annual seasonal cycle.
  - Jiang, X et al. (2010), "Interannual variability of mid-tropospheric CO2 from Atmospheric Infrared Sounder", GRL, 37, L13801, doi: 10.1029/2010GL042823
  - Li, KF et al. (2010), "Tropical mid-tropospheric CO2 variability driven by the Madden–Julian oscillation." *Proceedings of the National Academy of Sciences* 107, no. 45, 19171-19175.
  - Wang, J et al. (2011), The influence of tropospheric biennial oscillation on mid-tropospheric CO2, GRL, 38, L20805, doi:10.1029/2011GL049288
  - Feng, et al. (2011) "Evaluating a 3-D transport model of atmospheric CO2 using ground-based, aircraft, and space-borne data." Atmospheric Chemistry and Physics 11, no. 6, 2789-2803.
  - Liu, J et al. (2011), "CO2 transport uncertainties from the uncertainties in meteorological fields." *Geophysical Research Letters* 38, no. 12.
  - Pagano, T et al. (2011) "Monthly representations of mid-tropospheric carbon dioxide from the Atmospheric Infrared Sounder." In *SPIE Optical Engineering+ Applications*, pp. 81580C-81580C. International Society for Optics and Photonics.
  - Kang, J-S et al. (2012), Estimation of surface carbon fluxes with an advanced data assimilation methodology, J. Geophys. Res., 117, D24101, doi:10.1029/2012JD018259
  - Jiang, X et al. (2013) "Influence of El Niño on mid-tropospheric CO2 from Atmospheric Infrared Sounder and Model." *Journal of the Atmospheric Sciences* 70, no. 1.
  - Jiang, X et al. (2013) "Influence of Stratospheric Sudden Warming on AIRS Mid-tropospheric CO2." *Journal of the Atmospheric Sciences* 70, no. 8.
  - Pagano, T, et al. (2014) “Global variability of mid-tropospheric CO2 as measured by the Atmospheric Infrared Sounder”, Journal of Applied Remote Sensing (accepted for publication).

El Niño-Southern Oscillation (ENSO)



ENSO is an important interannual variability in the tropical region and impacts the spatial/ vertical distribution of tracers



El Niño condition - Eastward shift of warm sea surface temperature and low pressure and reversal of trade winds
Result – convection center also shifts eastward, thus there should be an impact upon the spatial distribution of concentration of CO_2 in the mid- to high troposphere.

Hypothesis: shift of large-scale vertical convection should be detected in AIRS CO_2

El Niño Signal in AIRS Retrieved CO2

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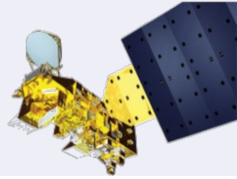
Jiang et al., (2012), "Influence of El Nino on mid-tropospheric CO2 from Atmospheric Infrared Sounder and model", JAS, doi:10.1175/JAS-D-11-0282.1

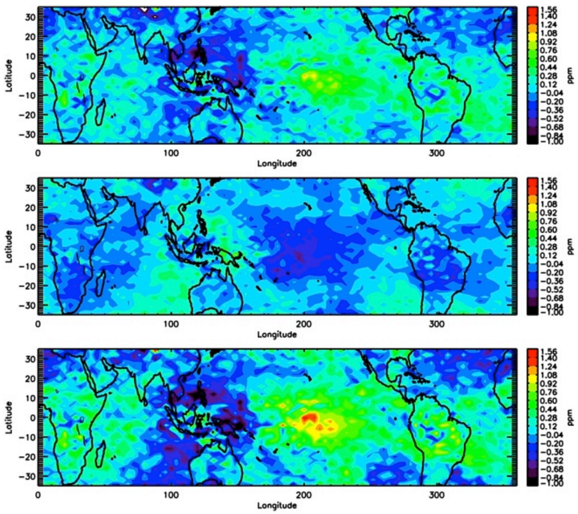


AIRS CO2

11 El Niño months

17 La Niña months

El Niño - La Niña

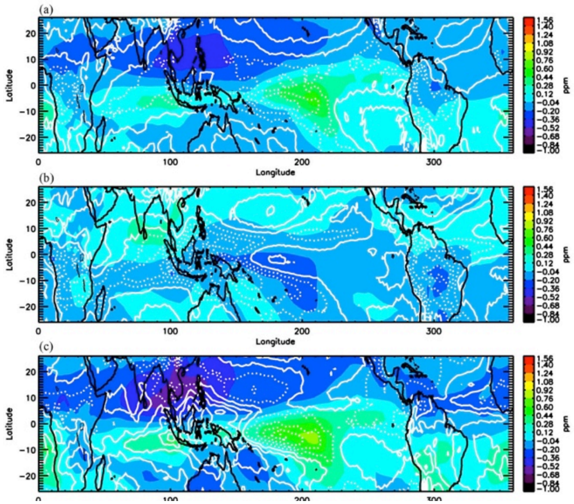


MOZART-2 CO2

El Niño

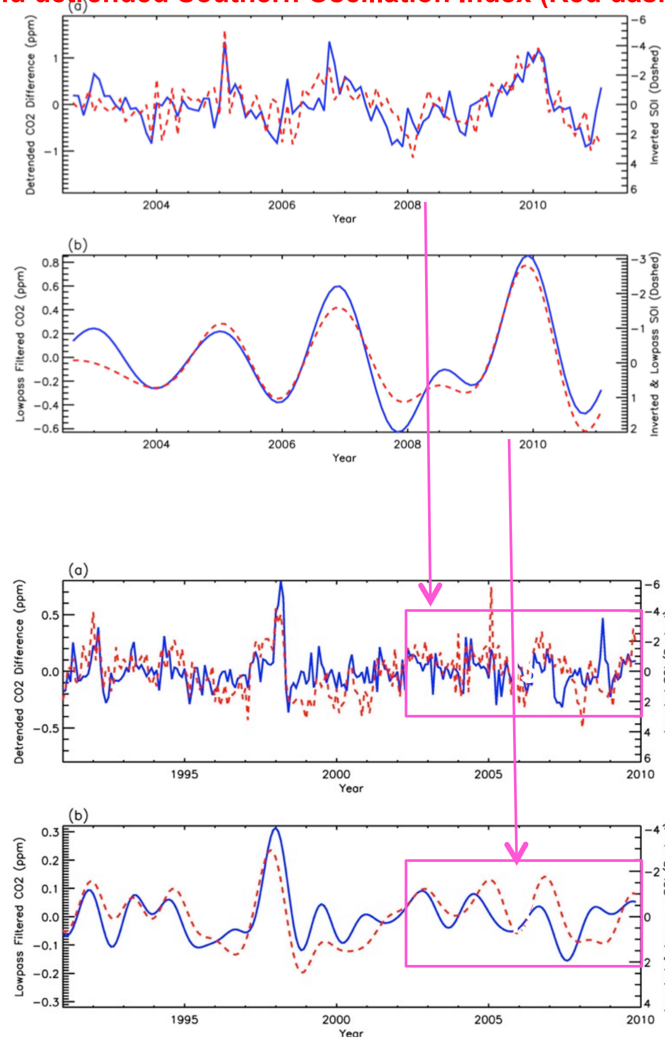
La Niña

El Niño - La Niña



CO2 difference between the Central Pacific (190°E-240°E; 18°S-18°N) and the Western Pacific (110°E-160°E, 18°S-18°N) (Blue solid line)

Inverted and detrended Southern Oscillation Index (Red dashed line)



Raw Data Correlation: 0.62

Low pass Correlation: 0.94

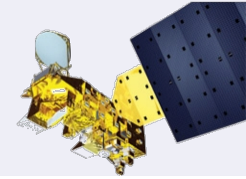
Raw Data Correlation: 0.48

Low pass Correlation: 0.65

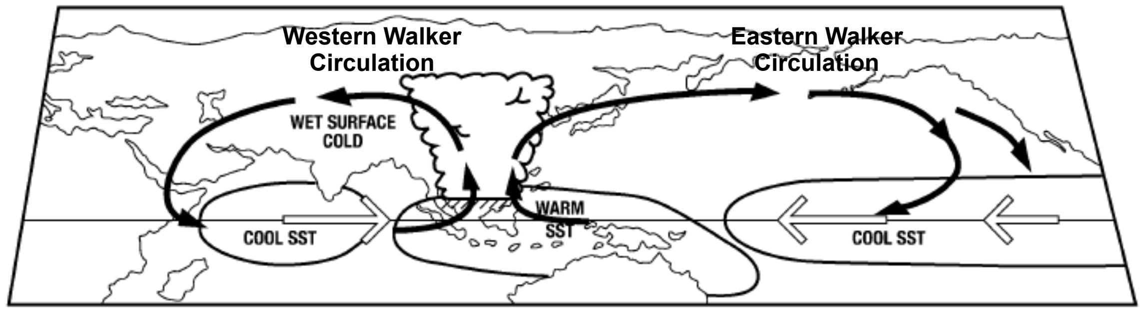
There is more (less) AIRS retrieved CO2 in the Central Pacific and less (more) AIRS retrieved CO2 in the Western Pacific during El Nino (La Niña) events.

Similar results are seen in MOZART-2 mid-tropospheric CO2, although the amplitude is reduced and spatial pattern less concentrated in the model compared to that in AIRS CO2 data.

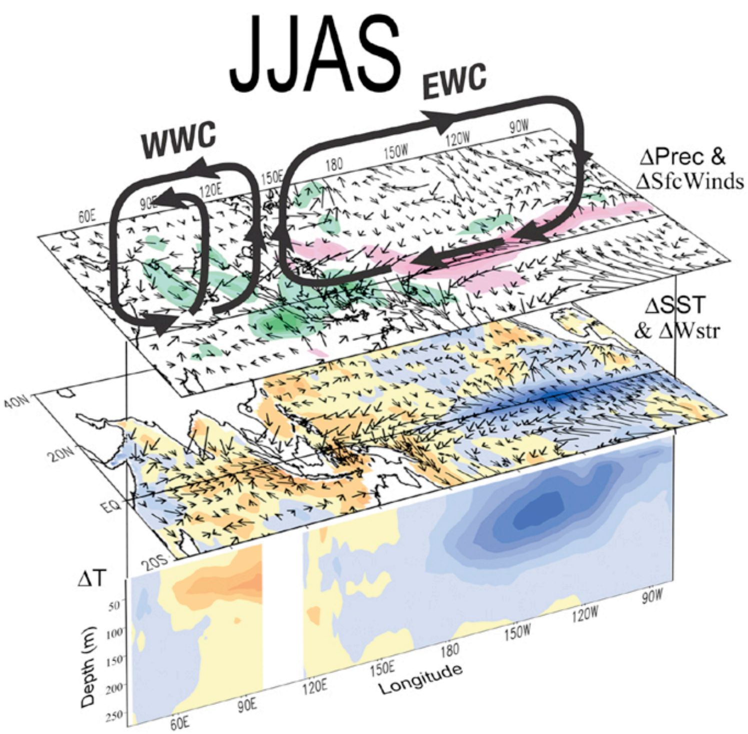
Tropospheric Biennial Oscillation (TBO)



The tropospheric biennial oscillation is the tendency for a relatively strong Asian monsoon to be followed by a relatively weak monsoon, and vice versa, with roughly a 2-3 year period. This variability in the tropical region also impacts the spatial/vertical distribution of tracers due to its effect on vertical transport.



[Meehl & Arblaster, 2002]



Strong Monsoon - Strong Western Walker Circulation

Weak Monsoon - Weak Western Walker Circulation

Hypothesis: variable strength of Western Walker Center vertical convection should impact AIRS CO2 product

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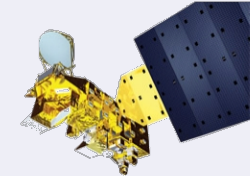
TBO Signal in AIRS Retrieved CO2

Wang et al. (2011), The influence of tropospheric biennial oscillation on mid-tropospheric CO2, GRL, 38, L20805, doi:10.1029/2011GL049288.

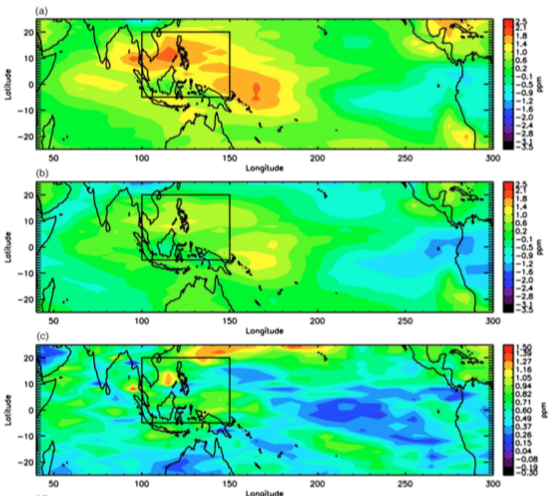


AIRS CO2

Strong Monsoon (JJAS) (2003, 2005, 2007, 2010)

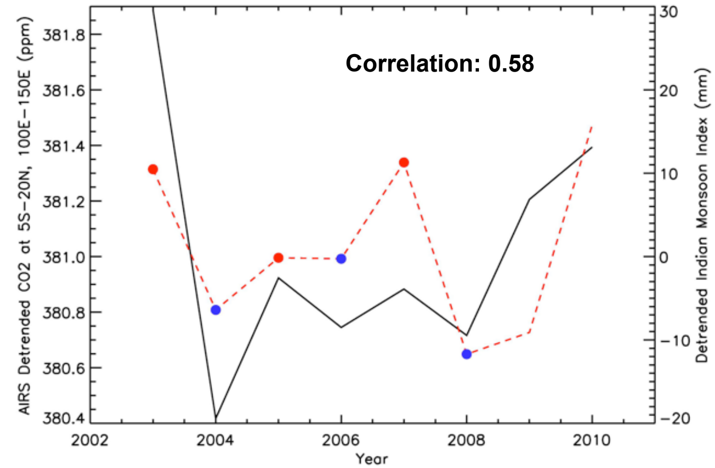
Weak Monsoon (JJAS) (2004, 2006, 2008)

Strong – Weak Monsoon



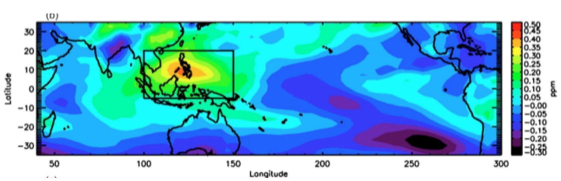
There is more (less) AIRS retrieved CO2 in the Central Pacific and less (more) AIRS retrieved CO2 in the Western Pacific during weak (strong) Asian monsoon events.

Black Line: AIRS detrended mid-trop CO2 at 5°S-20°N, 100°E-150°E
Red Dashed Line: Detrended Indian Monsoon Index Derived from TRMM Precipitation (red points strong monsoon; blue points weak monsoon)



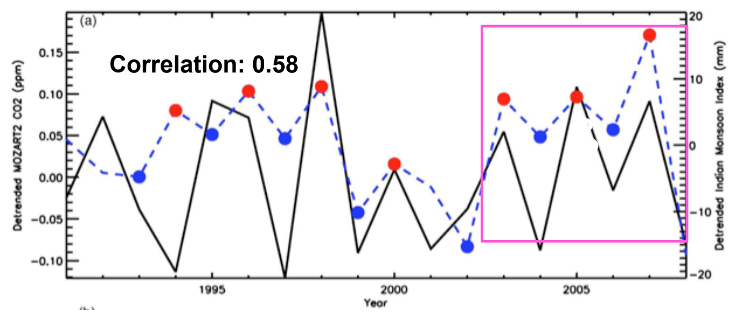
MOZART-2 CO2

Strong – Weak Monsoon



Spatial distribution more restricted than AIRS concentrations. Again, more (less) CO2 in the Central Pacific and less (more) CO2 in the Western Pacific during weak (strong) Asian monsoon events.

Black Line: MOZART-2 CO2 at 5°S-20°N, 100°E-150°E
Blue Dashed Line: GPCP Monsoon Index
(red points strong monsoon; blue points weak monsoon)



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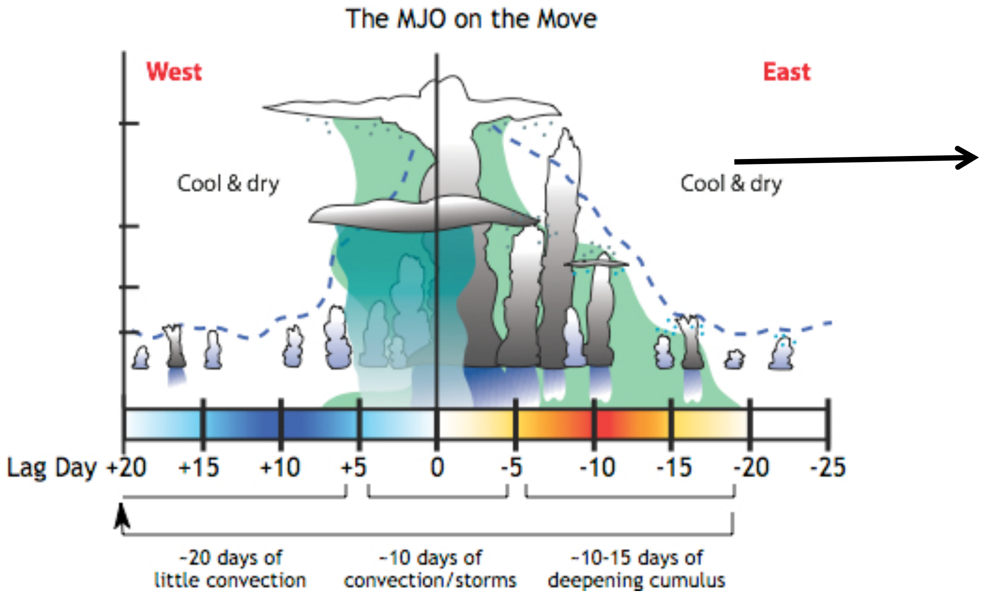
Madden-Julian Oscillation (MJO)

The Madden–Julian oscillation (MJO) is the dominant component of intraseasonal variability in the tropics and has a period of 40 to 60 days. In the troposphere, the MJO is an equatorial planetary-scale wave envelope of multi-scale convective processes. Rather than being a standing pattern (like ENSO) it is a traveling pattern, propagating eastwards at approximately 4 to 8 m/s, through the atmosphere above the warm parts of the Indian and Pacific oceans. This overall circulation pattern manifests most clearly as anomalous rainfall.

The MJO is characterized by an eastward progression of large regions of both enhanced and suppressed tropical rainfall, observed moving eastward from the western Indian Ocean through the central tropical Pacific Ocean. This pattern of tropical rainfall then generally becomes nondescript as it moves over the cooler ocean waters of the eastern Pacific (except over the region of warmer water off the west coast of Central America) but sometimes reappears at low amplitude over the tropical Atlantic and higher amplitude over the Indian Ocean. The wet phase of enhanced convection and precipitation is followed by a dry phase where thunderstorm activity is suppressed.

Hypothesis: This enhanced large-scale convection and its movement eastward should create a signal visible in the AIRS retrieved mid-tropospheric CO2 concentration.



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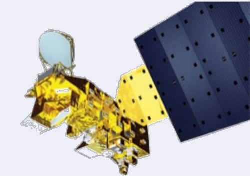
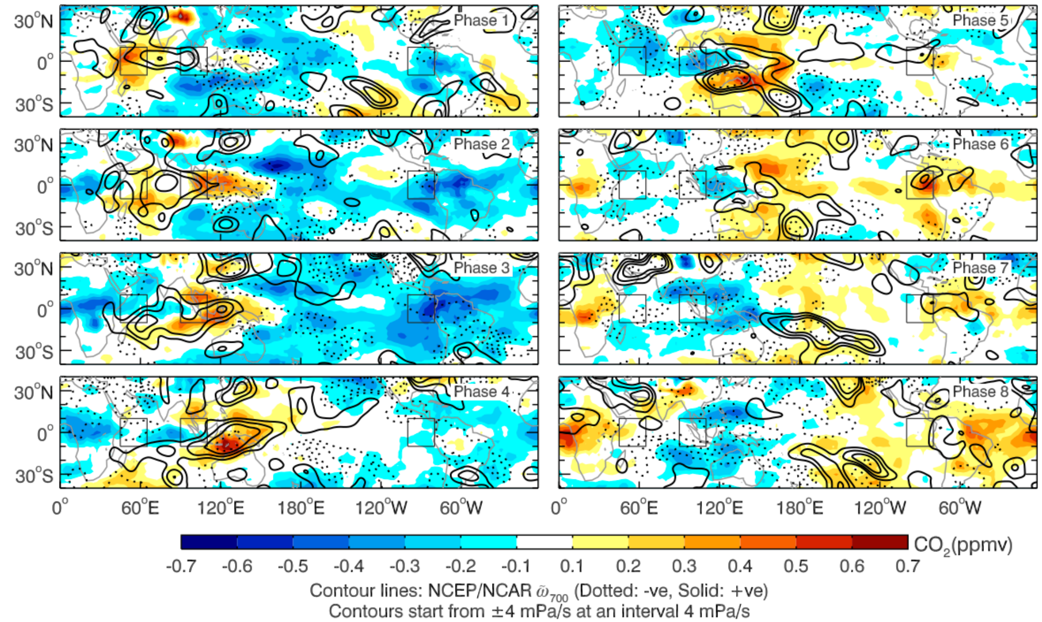
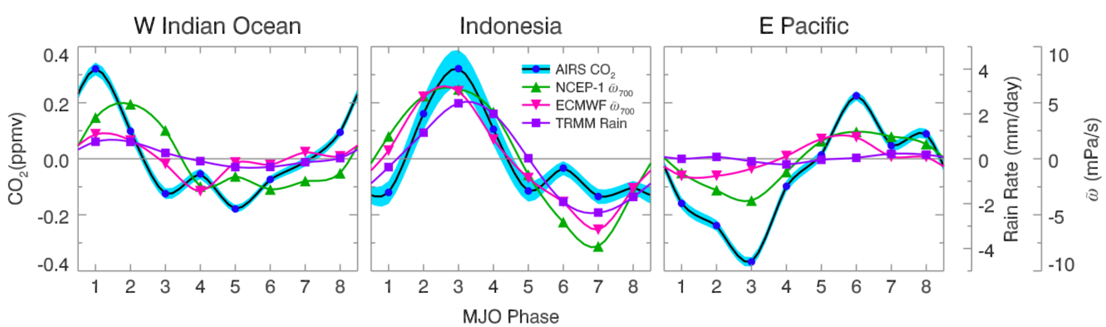
MJO Signal in AIRS Retrieved CO_2

Li et al. , (2010), "Tropical mid-tropospheric CO_2 variability driven by the Madden–Julian oscillation." *Proceedings of the National Academy of Sciences* 107, no. 45, 19171-19175.



MJO related AIRS CO_2 anomalies for 8 MJO 6-day phases. Data are for days with strong MJO activity, $(RMM_1)^2+(RMM_2)^2 \geq 1$, for boreal winters in period from Nov 2002 through February 2010. Eastward propagation shown by solid/dotted MJO-related rainfall anomaly outside of threshold ± 1 mm/dy.





Composite MJO time series of AIRS CO_2, reanalysis 700 hPa vertical velocity, and TRMM rainfall anomalies over the western Indian Ocean, Indonesia and the eastern Pacific Ocean enclosed by the square boxes in the upper figure. Over all three locations the CO_2 variation is positively correlated with ERA-interim ω700. Positive CO_2 anomaly over regions characterized by rising air and negative CO_2 anomaly over regions characterized by sinking air appears to be generally true for the entire tropics.

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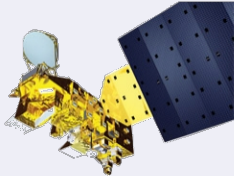
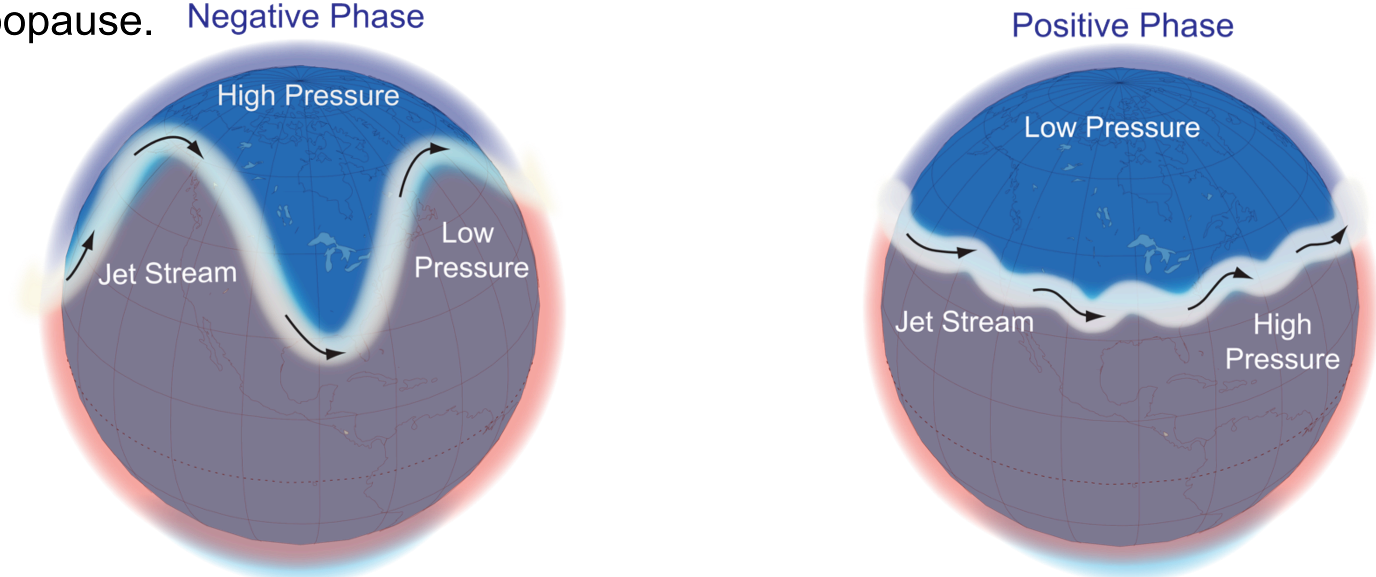


Northern Annular Mode/Arctic Oscillation (NAM/AO)

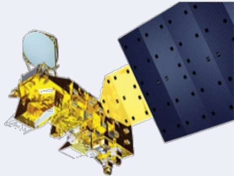
The Northern Annular Mode, or Arctic Oscillation, is characterized by pressure anomalies of one sign in the Arctic with the opposite anomalies centered about 37N-45N. These pressure patterns impact the middle latitude jet stream and thus the degree of isolation of the polar atmosphere from that of the middle latitudes and the height of the tropopause in the Arctic. Positive AO isolates the polar atmosphere and depresses the altitude of the tropopause.



Negative AO – weak zonal winds, polar air mixes with mid-latitudes, higher altitude tropopause over the Arctic, frigid weather outbreaks in the mid-latitudes

Positive AO – strong zonal winds, isolated polar air, lower altitude Arctic tropopause

Hypothesis: Isolation of interior of polar vortex and downward intrusion of stratospheric air should decrease AIRS retrieved CO2 over the Arctic.

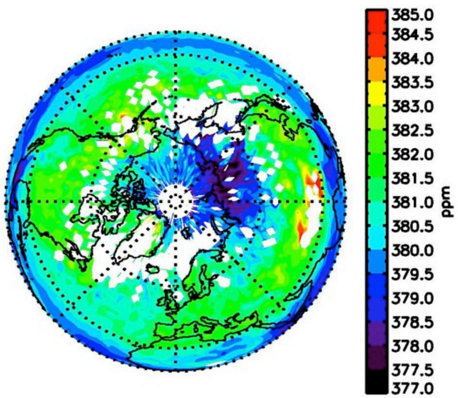


Influence of NAM/AO on AIRS Retrieved CO2

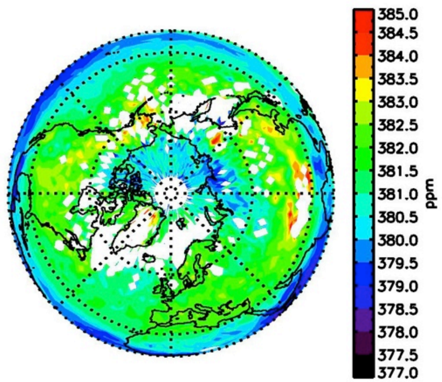
Jiang et al., (2010), "Interannual variability of mid-tropospheric CO2 from Atmospheric Infrared Sounder", GRL, 37, L13801, doi: 10.1029/2010GL042823 .

AIRS CO2

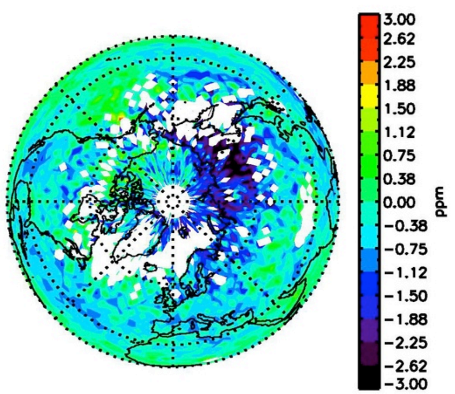
Strong Vortex - Positive AO Index (Nov-Apr) (2005, 2007)



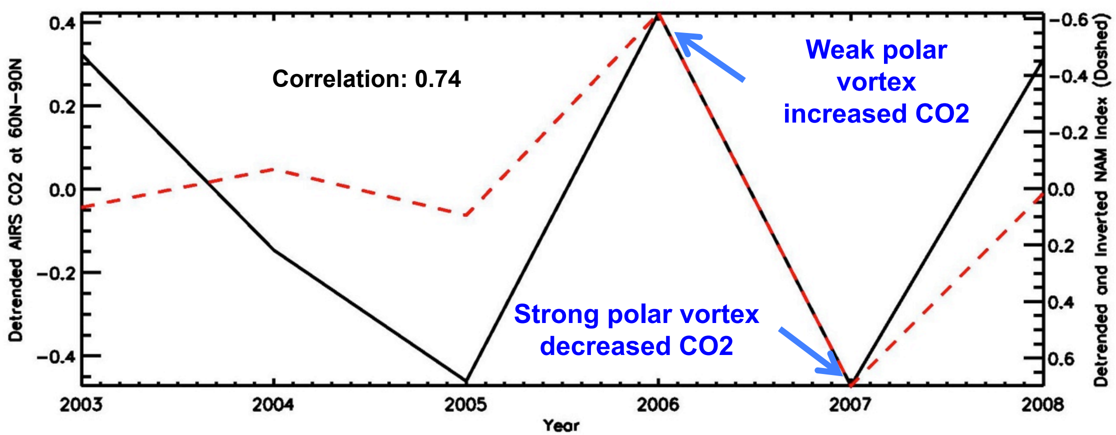
Weak Vortex - Negative AO Index (Nov-Apr) (2006, 2008)



Strong – Weak Vortex



Black Line: AIRS detrended mid-trop CO2 60N-90N (Nov-Apr)
Red Dashed Line: Detrended and inverted Arctic Oscillation Index (Nov-Apr)



Strong vortex isolates the polar regions from the mid-latitudes and the tropopause sinks.

AIRS retrieved CO2 over the Arctic is decreased due to isolation from CO2-richer mid-latitudes and intrusion of lower-CO2 stratosphere.

During a sudden stratospheric warming event, the process is rapidly reversed, and retrieved Arctic CO2 increases 2-3 ppm.

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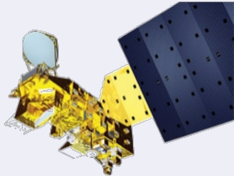
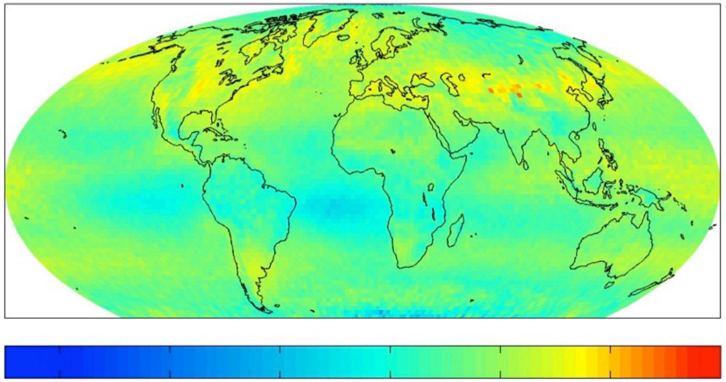


Persistent Depleted Region in of AIRS Mid-Tropospheric CO2 in South Atlantic Related to Eastern Walker Circulation

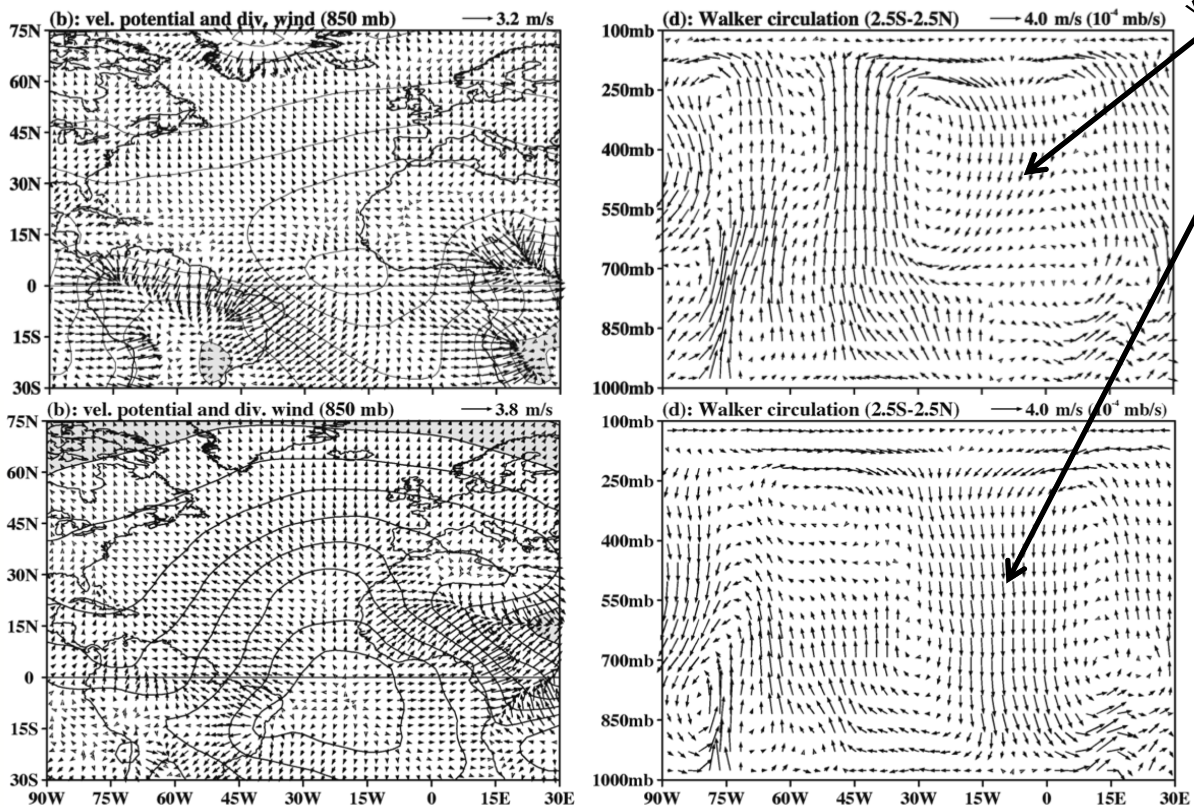
Annual Average
2003-2010
Detrended
AIRS Mid-Trop CO2



Downward Flow of Eastern Walker Circulation

January

July



Wang, Chunzai. "Atlantic climate variability and its associated atmospheric circulation cells." *Journal of Climate* 15, no. 13 (2002): 1516-1536.

Influence of Atlantic Walker Cell on AIRS Retrieved CO2

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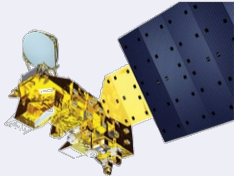
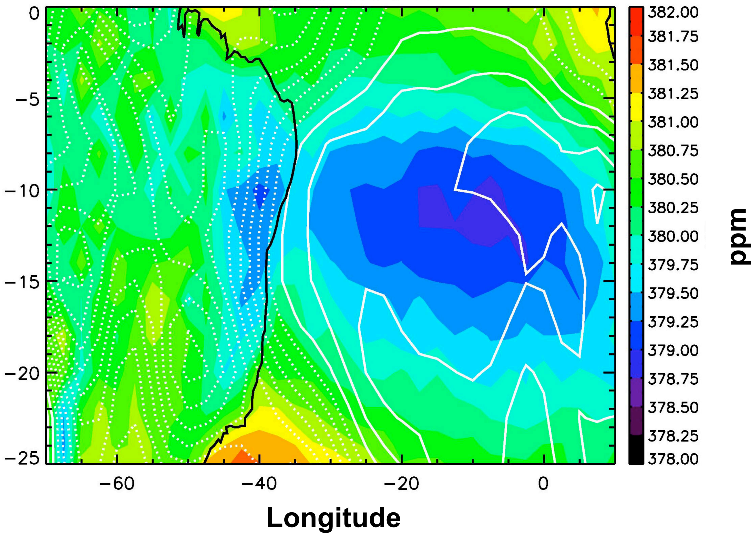


(Jiang et al. paper in preparation)

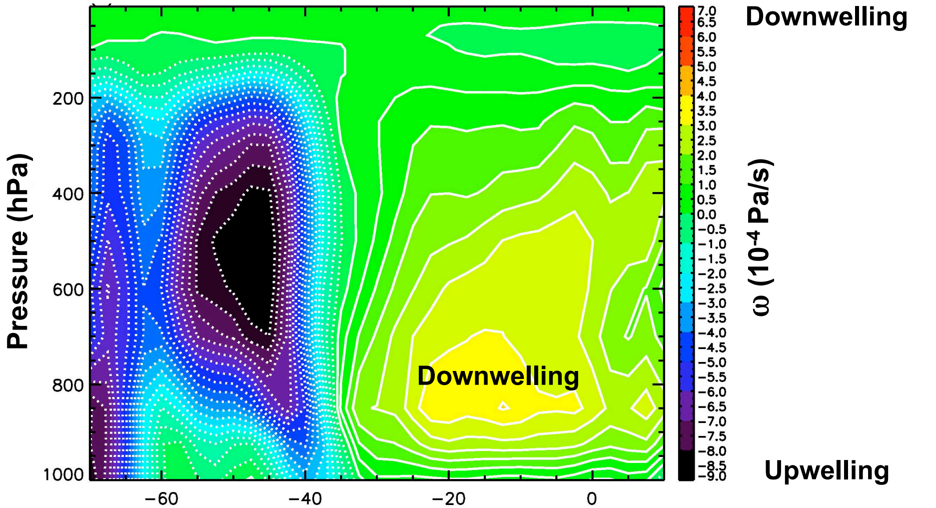
Sinking air in the descending branch of the Atlantic Walker Cell brings lower concentration of CO2 from the higher altitudes

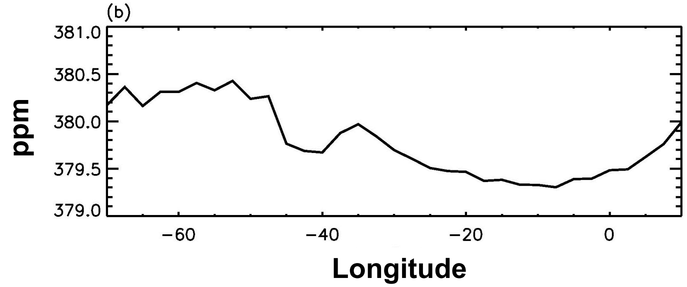
Average AIRS CO2 in 2003-2010 DJFM



White contours are the NCEP2 400 hPa vertical pressure velocity (dP/dt). Solid white contours refer to the sinking air. Dashed white contours refer to the rising air.

Omega (dP/dt) in 2003-2010 DJFM Averaged over 20°S – 5°S





Variation with longitude of AIRS CO2 averaged over 20°S-5°S in 2003-2010 DJFM.

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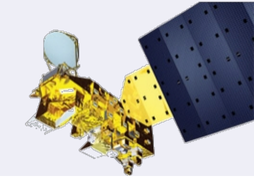
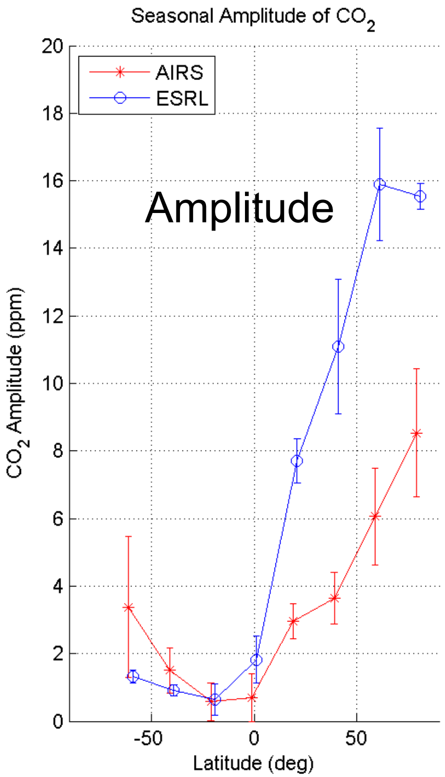
AIRS CO2 Shows Significant Influence of Surface CO2 Seasonal Variability

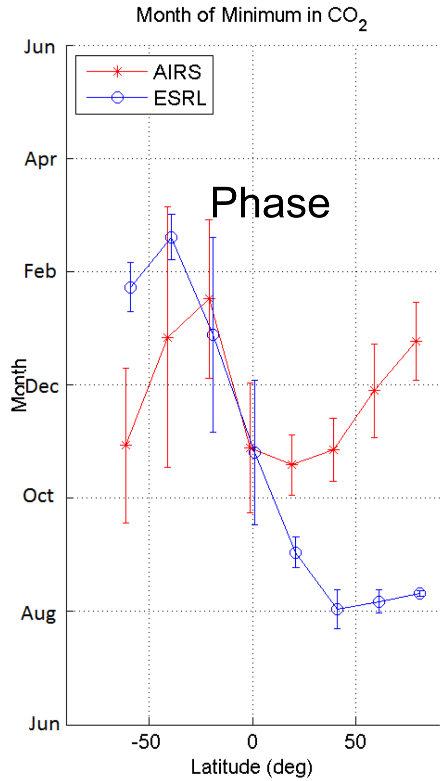
(Pagano et al. (2014) "Global variability of mid-tropospheric CO2 as measured by the Atmospheric Infrared Sounder", Journal of Applied Remote Sensing, (accepted).
)



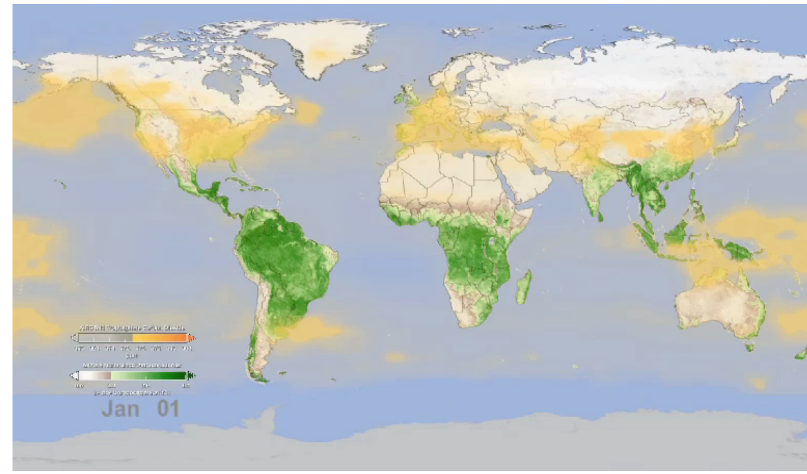
AIRS CO_2 Seasonal Cycle:

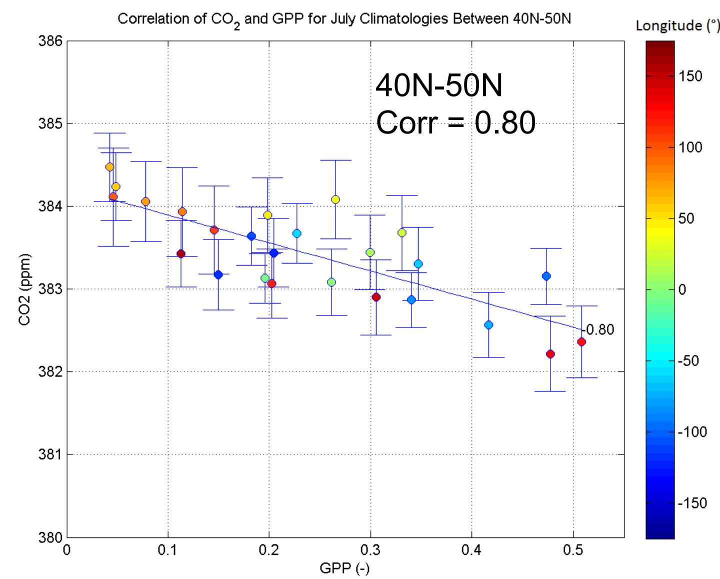
- Strong seasonal cycle present in mid-trop
- NH damped and delayed compared to surface CO2 concentration variation => vertical transport
- SH variation higher amplitude and precedes surface CO2 variation => Inter-hemispherical transport



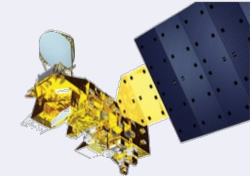


High Correlation of CO_2 and GPP for July in NH Boreal Forests





V6 CO2 Development



- V6 Prototype code
  - Code designed for rapid conversion to PGE
    - Execution options set via environmental variables
      - Channel lists, priors, SARTA version, QA filtering rules and thresholds
  - Capable of ingesting V5 and V6 AIRS L2 products
  - Capable of using three RTA versions (V107, V108 or V6)
  - Supports multiple channel sets for separate partial column retrievals
- V6 Prototype testing
  - V5 AIRS-Only CO2 product released while V6 in development
  - Retrievals using same channel set consistent with V5 for |lat| < 50°
    - V6 does not require V5 radiance bias correction
    - Expanding and optimizing QA
    - Validating against in situ profiles

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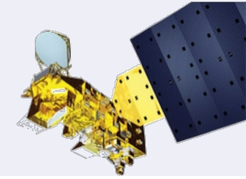
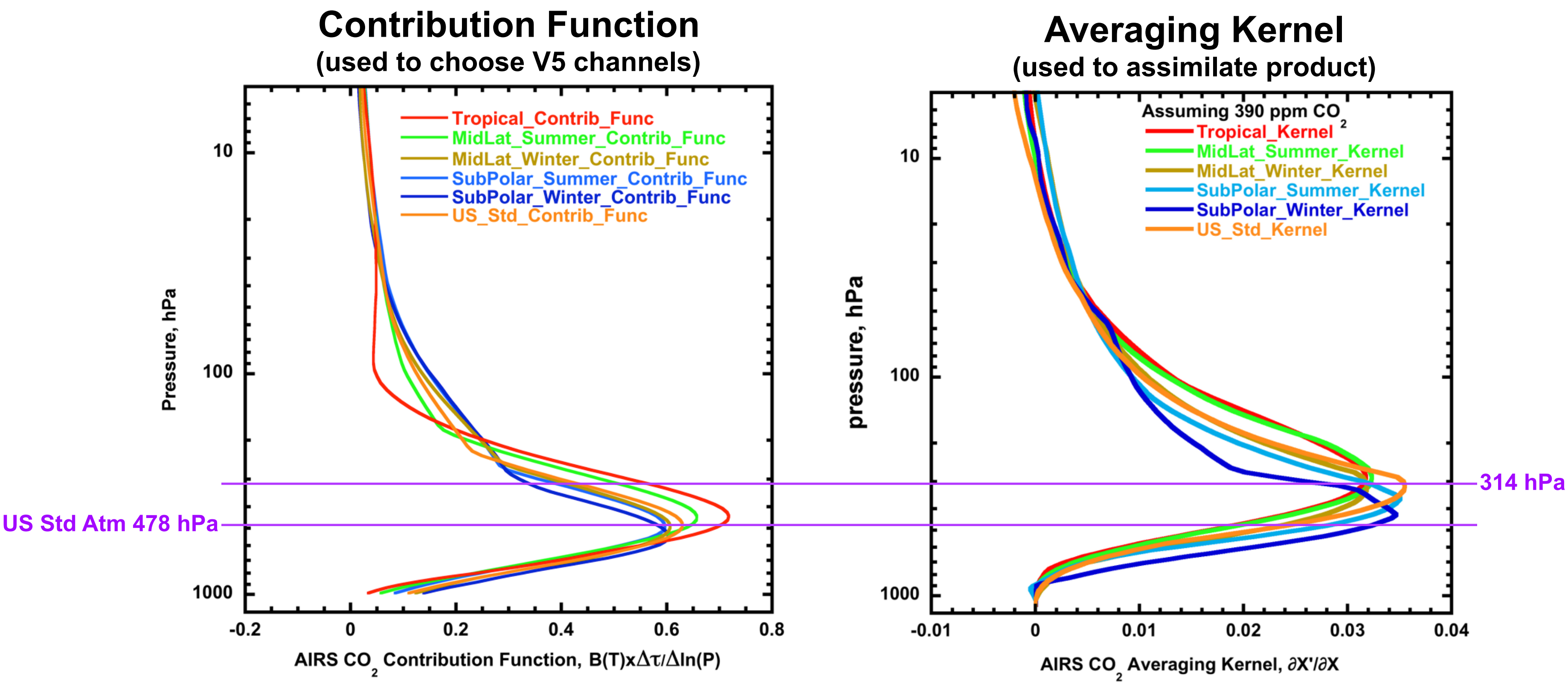
AIRS Mid-Tropospheric CO2 Product Contribution Function and Averaging Kernel





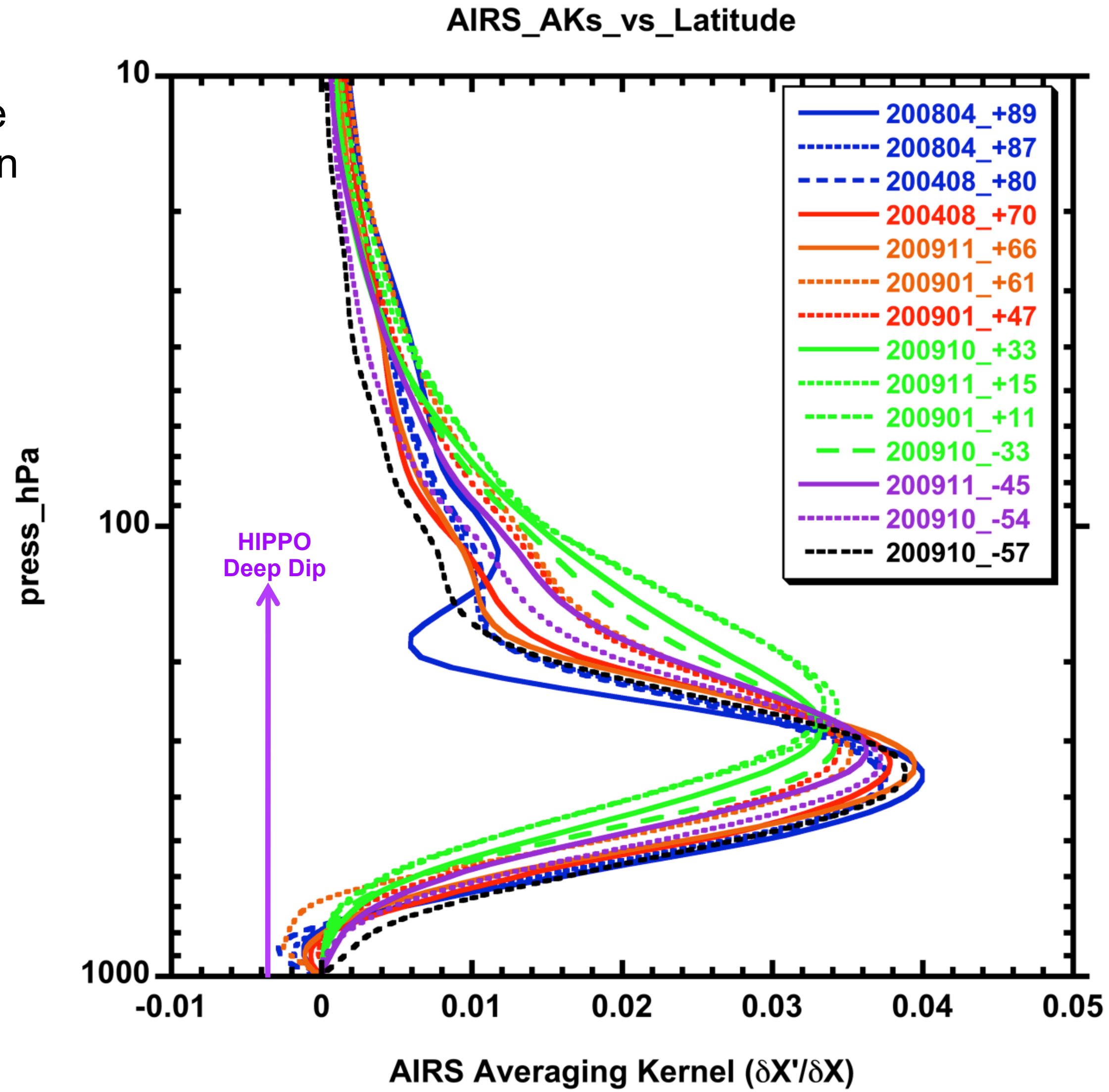
- **The AIRS Mid-Trop Contribution Function is a measure of the contribution of an atmospheric layer to the TOA radiance used in the AIRS CO_2 retrieval**

- **The AIRS Mid-Trop Averaging Kernel is a measure of the sensitivity of the AIRS CO_2 retrieval to a change in CO_2 concentration in an atmospheric layer**

Validation via In-Situ Profile Measurements

Airborne profile measurements are the best available data for validation

- Profiles must cover significant range of AIRS vertical sensitivity
- Convolve profiles with AIRS sensitivity function to arrive at a value to compare to collocated AIRS retrieved value
- HIPPO “Deep Dip” profiles cover sufficient vertical extent to allow validation to within 2 ppm with simple extension of profiles to higher altitudes



HIPPO Profile and AIRS Averaging Kernel

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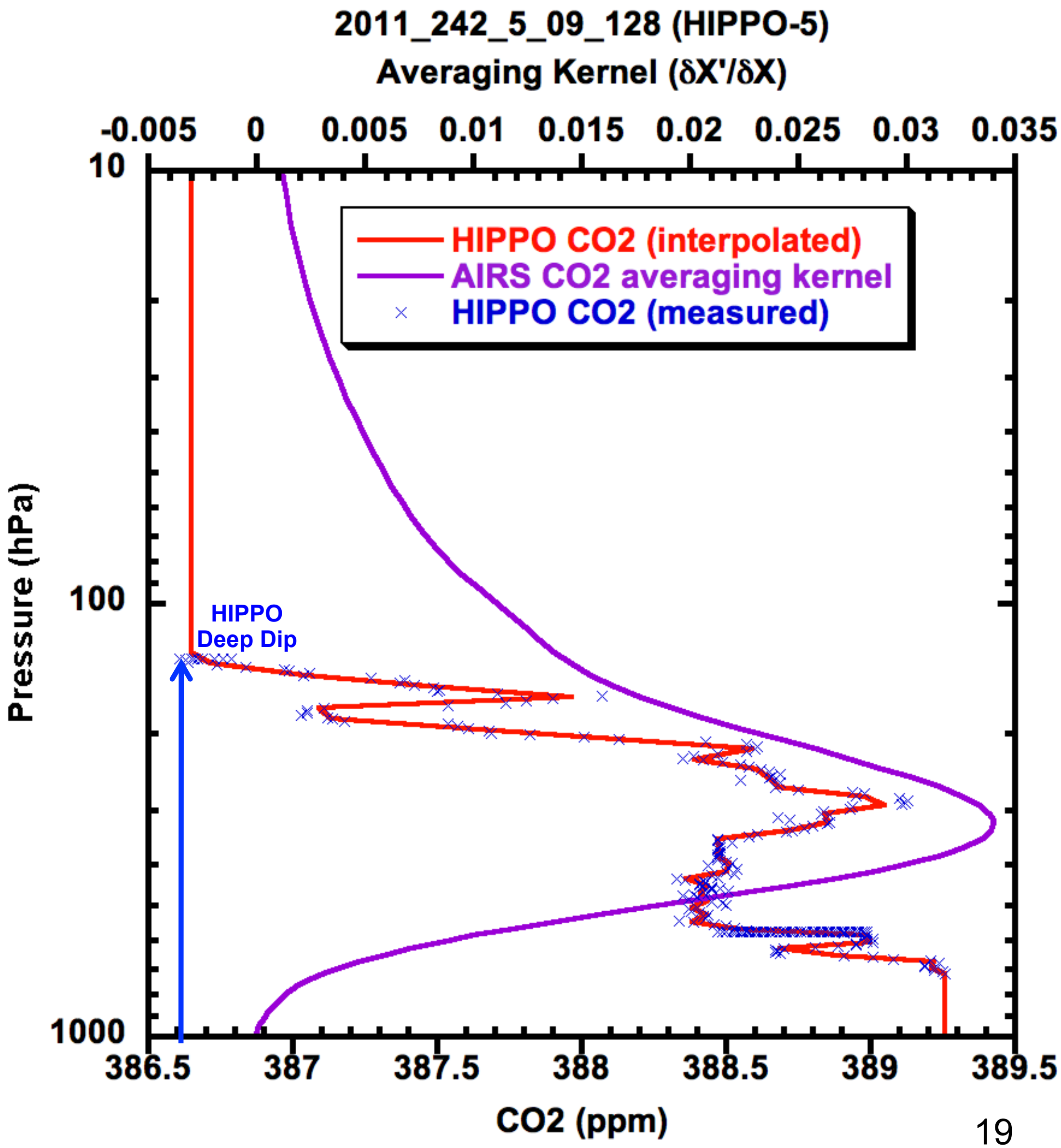
Example

- Interpolate HIPPO measurements over range of aircraft altitude to AIRS support pressure levels
- Extend highest altitude point
- Extend lowest altitude point
- Convolve profile with AIRS sensitivity function to arrive at a value to compare to collocated AIRS retrieved value
- Extension of HIPPO "Deep Dip" profile at high altitude results in overestimation error of less than 2 ppm
- More realistic extension including stratospheric fall-off in development



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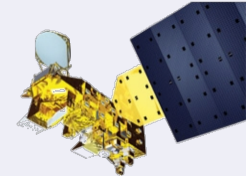
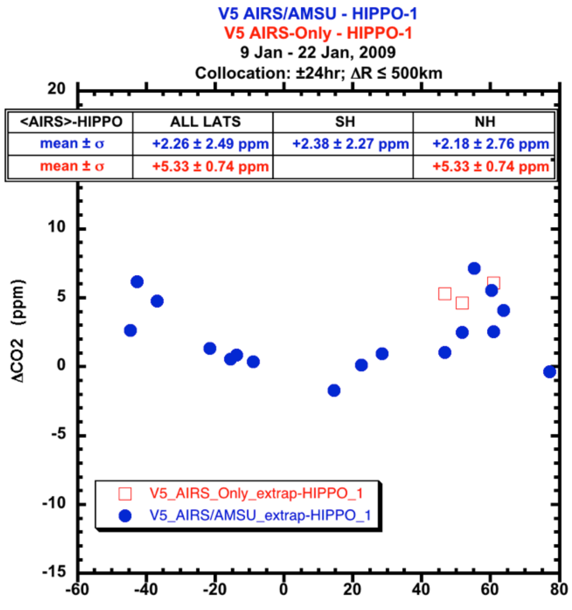
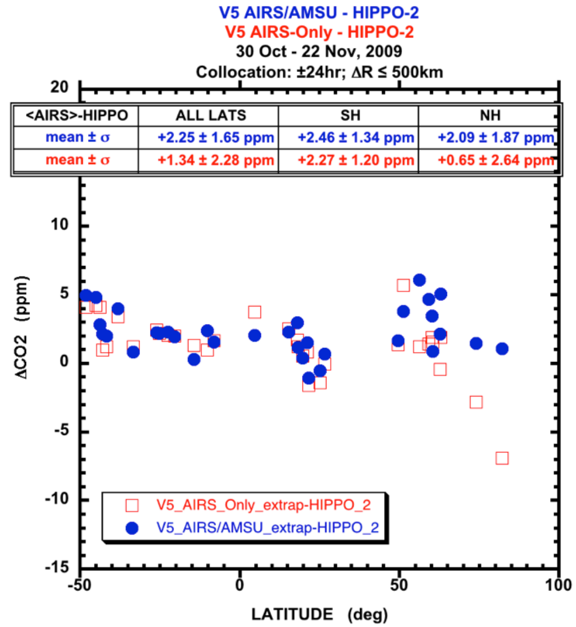
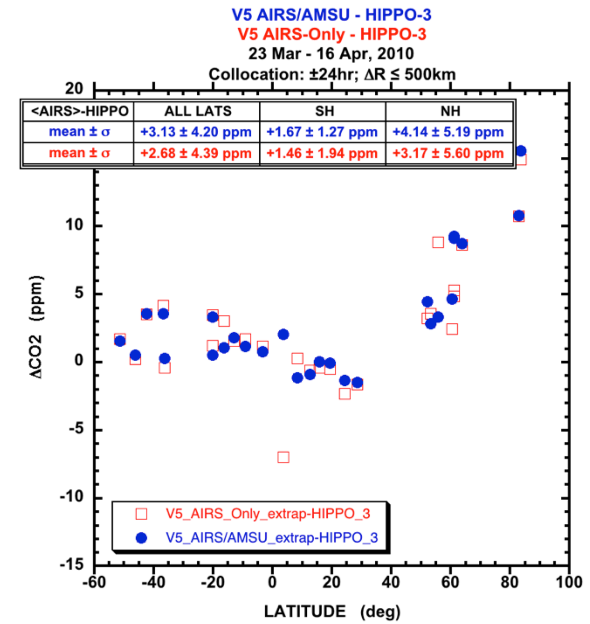
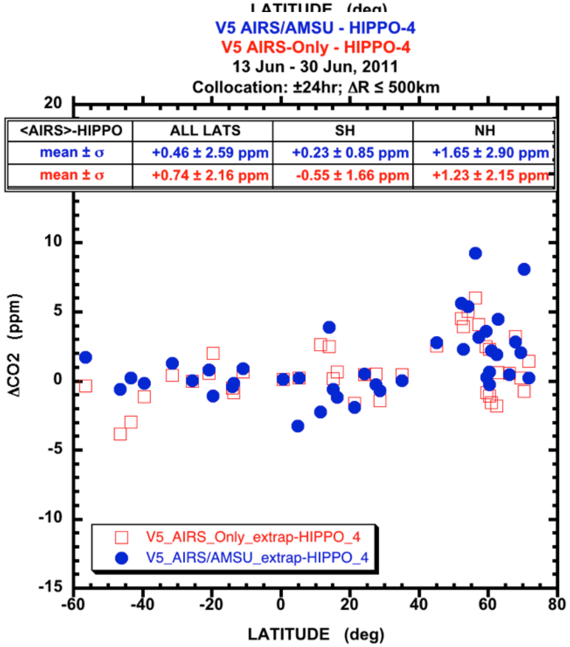
V5 AIRS/AMSU and AIRS-Only vs HIPPO

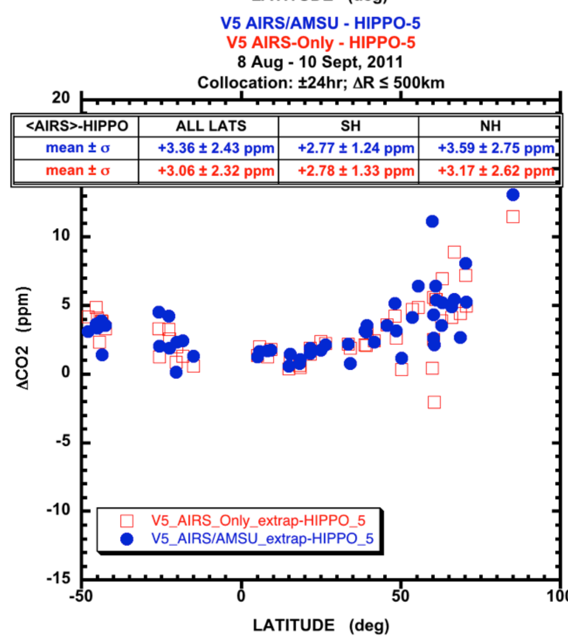


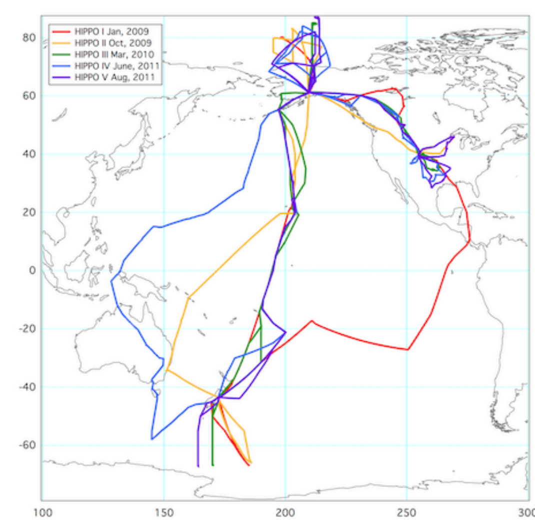












Proto-V6 AIRS and V5 AIRS vs HIPPO

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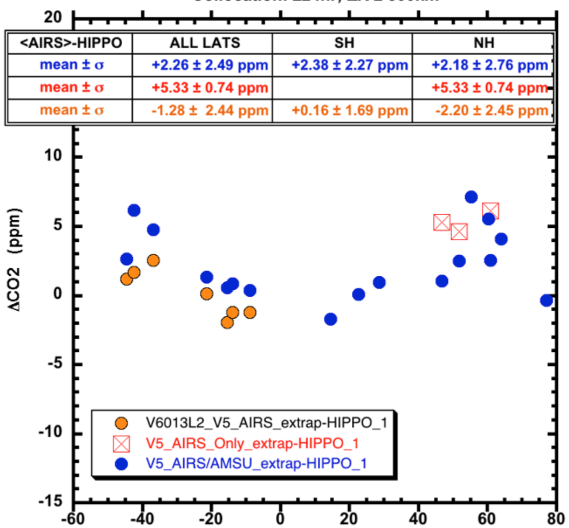
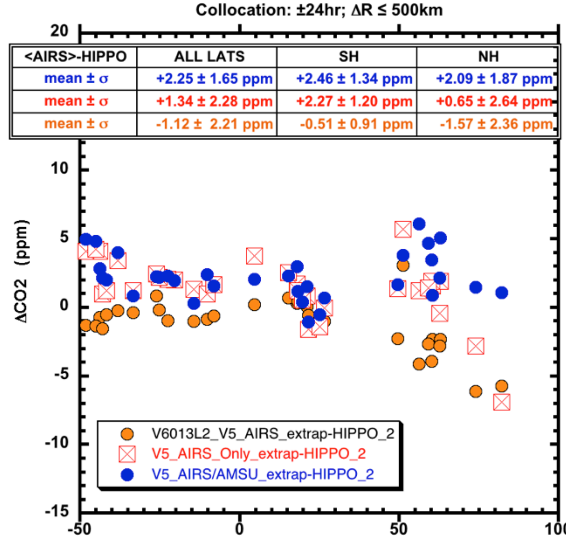
V5 AIRS/AMSU - HIPPO-1
V5 AIRS-Only - HIPPO-1
V6013L2_V5_AIRS/AMSU - HIPPO-1
9 Jan - 22 Jan, 2009
Collocation: ±24hr; ΔR ≤ 500km

<AIRS>-HIPPO	ALL LATS	SH	NH
mean ± σ	+2.26 ± 2.49 ppm	+2.38 ± 2.27 ppm	+2.18 ± 2.76 ppm
mean ± σ	+5.33 ± 0.74 ppm		+5.33 ± 0.74 ppm
mean ± σ	-1.28 ± 2.44 ppm	+0.16 ± 1.69 ppm	-2.20 ± 2.45 ppm



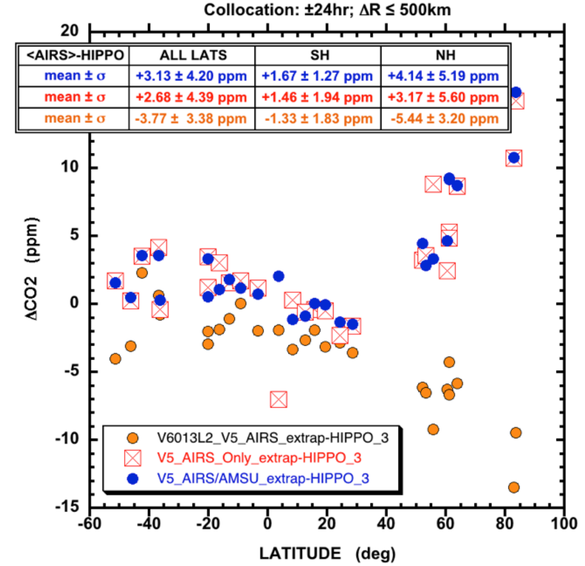
V5 AIRS/AMSU - HIPPO-2
V5 AIRS-Only - HIPPO-2
V6013L2_V5_AIRS/AMSU - HIPPO-2
30 Oct - 22 Nov, 2009
Collocation: ±24hr; ΔR ≤ 500km

<AIRS>-HIPPO	ALL LATS	SH	NH
mean ± σ	+2.25 ± 1.65 ppm	+2.46 ± 1.34 ppm	+2.09 ± 1.87 ppm
mean ± σ	+1.34 ± 2.28 ppm	+2.27 ± 1.20 ppm	+0.65 ± 2.64 ppm
mean ± σ	-1.12 ± 2.21 ppm	-0.51 ± 0.91 ppm	-1.57 ± 2.36 ppm



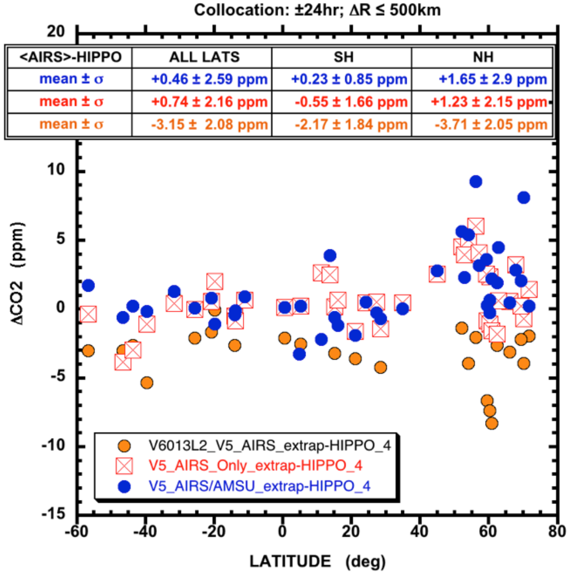
V5 AIRS/AMSU - HIPPO-3
V5 AIRS-Only - HIPPO-3
V6013L2_V5_AIRS/AMSU - HIPPO-3
23 Mar - 16 Apr, 2010
Collocation: ±24hr; ΔR ≤ 500km

<AIRS>-HIPPO	ALL LATS	SH	NH
mean ± σ	+3.13 ± 4.20 ppm	+1.67 ± 1.27 ppm	+4.14 ± 5.19 ppm
mean ± σ	+2.68 ± 4.39 ppm	+1.46 ± 1.94 ppm	+3.17 ± 5.60 ppm
mean ± σ	-3.77 ± 3.38 ppm	-1.33 ± 1.83 ppm	-5.44 ± 3.20 ppm



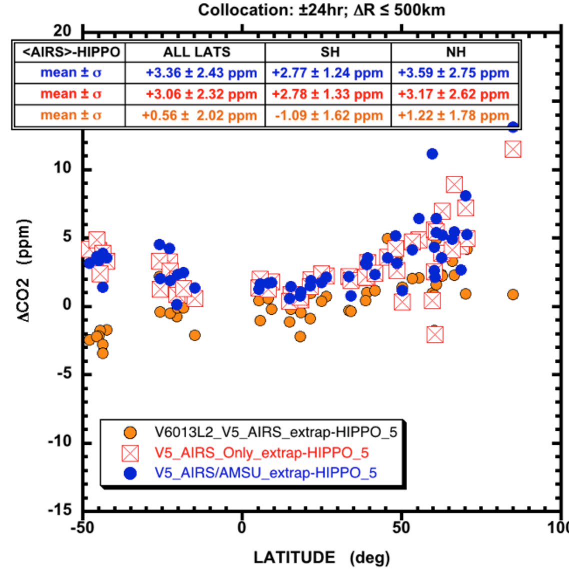
V5 AIRS/AMSU - HIPPO-4
V5 AIRS-Only - HIPPO-4
V6013L2_V5_AIRS/AMSU - HIPPO-4
13 Jun - 30 Jun, 2011
Collocation: ±24hr; ΔR ≤ 500km

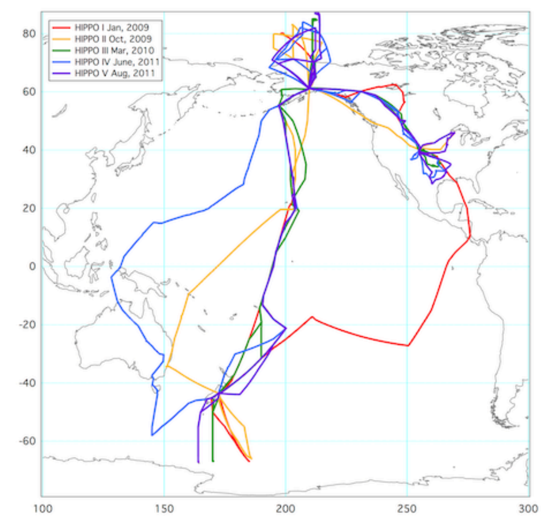
<AIRS>-HIPPO	ALL LATS	SH	NH
mean ± σ	+0.46 ± 2.59 ppm	+0.23 ± 0.85 ppm	+1.65 ± 2.9 ppm
mean ± σ	+0.74 ± 2.16 ppm	-0.55 ± 1.66 ppm	+1.23 ± 2.15 ppm
mean ± σ	-3.15 ± 2.08 ppm	-2.17 ± 1.84 ppm	-3.71 ± 2.05 ppm



V5 AIRS/AMSU - HIPPO-5
V5 AIRS-Only - HIPPO-5
V6013L2_V5_AIRS/AMSU - HIPPO-5
8 Aug - 10 Sept, 2011
Collocation: ±24hr; ΔR ≤ 500km

<AIRS>-HIPPO	ALL LATS	SH	NH
mean ± σ	+3.36 ± 2.43 ppm	+2.77 ± 1.24 ppm	+3.59 ± 2.75 ppm
mean ± σ	+3.06 ± 2.32 ppm	+2.78 ± 1.33 ppm	+3.17 ± 2.62 ppm
mean ± σ	+0.56 ± 2.02 ppm	-1.09 ± 1.62 ppm	+1.22 ± 1.78 ppm





Summary

- AIRS Mid-Tropospheric CO2
  - 11 year record provides global distribution
    - Day/Night over Ocean/Land
  - Exhibits features due to major atmospheric processes
    - Window on transport of trace gases
  - Provides some sensitivity to surface flux
    - High Correlation of CO2 and GPP for July in NH Boreal Forests
    - Sensitive to surface flux over tropical region complements GOSAT (Junji Liu presentation on Monday)
- V5 AIRS-Only retrievals consistent with V5 AIRS/AMSU retrievals
  - Assures continuity of V5 record during V6 development
- V6 prototype testing under way
  - Optimizing QA
  - Investigating high-latitude difference between V5 and V6
    - Validation with properly extended HIPPO profiles