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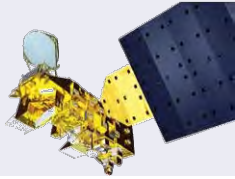

AIRS V6 CO2 Tropospheric Retrieval and Product Validation

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Jet Propulsion Laboratory, California Institute of Technology

NASA Sounder Science Team Meeting
13-16 October 2015

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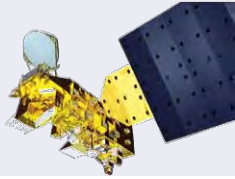
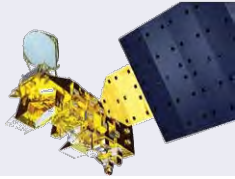
Outline



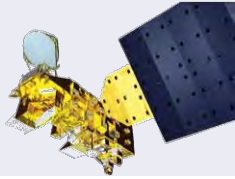
- What has changed in the AIRS CO2 retrieval algorithm from V5 to V6
  - Algorithm Change V5→V6
  - Enhanced QC in V6
- Deliveries
  - V6 CO2 PGE Delivery
  - AIRS CO2 provided to JPL Virtual Data Environment Server
- Validation against airborne in situ measurements
  - Extending CO2 profile above maximum altitude of measurement with CarbonTracker model
  - Comparison of V5 and V6 validation against multiple campaigns (2004-2011) as function of season and latitude
    - One or more AIRS retrievals collocated within ±12 hr and 200 km
    - Two or more AIRS retrievals collocated within ±12 hr and 200 km
  - Does fine vertical structure in L2 Tair impact V6 CO2 retrievals?
  - V6.19 and V6 based CO2 retrievals
    - Comparison of validation against HIPPO campaigns (2009-2011) as a function of season and latitude
- Summary
  - Completed Tasks
  - Near-term future tasks
- Publications using AIRS V5 CO2

Algorithm Changes - V5 to V6



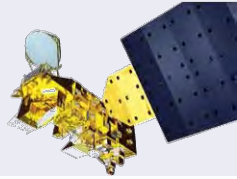
- V5 algorithm
  - Single stage application of the Vanishing Partial Derivative (VPD) Algorithm
    - Ingests V5 AIRS L2 retrieved atmospheric state: T,q,O3 profiles
    - Assumes a first guess CO2 profile that is constant throughout the atmosphere and increasing linearly year-to-year by 1.8 ppm/yr
    - implements original “at launch” rapid transmittance algorithm (RTA)
    - Retrieves CO2 for “good” AIRS L2 retrievals in a 2x2 array of fields of regard and reports their average and standard deviation in the product
- V6 algorithm enhancements
  - Implements V6 RTA, recalculating the channel coefficients for each field of regard
    - Accounts for AIRS channel shifts due to line-of-sight motion of the scene
    - Analysis indicates impact on retrieved CO2 can amount to as much as 2 ppm
  - Tightens L2 QC requirements for AIRS L2 retrievals to qualify for CO2 retrieval attempt
  - Three stage application of VPD Algorithm
    - First stage perturbs CO2 first guess by +5ppm, identifying converged clusters for continued processing
    - Second stage perturbs CO2 first guess by -5ppm, identifying converged clusters for continued processing
    - Final stage processes clusters surviving previous two stages
      - Requires that retrieved CO2 for cluster in the first two stages agrees to within 2 ppm to eliminate insufficiently robust solutions from further consideration, i.e. those:
        - » Not strongly constrained by radiance residuals
        - » Liable to run away to another radiance residuals local minimum
        - » Eliminates 16% to 27% of potential yield, depending upon season and latitude
      - Ingests original AIRS V6 L2 T,q,O3 and assumes unperturbed CO2 first guess to retrieve product
      - Applies additional QC filtering of the resulting CO2 product averaging kernel (AK)
    - Research mode implementation provides expanded output allowing analysis for additional QC augmentation in PGE implementation

Enhanced QC in V6



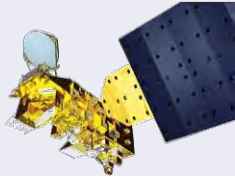
- Additional AIRS L2 QC currently operational in V6 CO2 PGE implementation that must be satisfied for inclusion in a 2x2 field of regard cluster:
  - PGood ≥ 700 hPa
  - PTropopause_QC < 2
- V6 CO2 PGE implementation currently excises cluster from consideration in stage3 if:
  - ABS(CO2_stage1 - CO2_stage2) ≤ 2 ppm
- V6 CO2 PGE implementation being modified to excise retrieval from product if:
  - Calculated CO2 AK exhibits significant negative tail in stratosphere
  - Calculated CO2 AK exhibits significant secondary peak (>10% of main peak)
  - Integral of calculated CO2 AK above PTropopause exceeds 50% of AK total integral (important for polar regions, where tropopause altitude is depressed)
- Additional L2 QC under consideration and awaiting analysis using research implementation expanded output:
  - Spatial inhomogeneity of atmospheric states of cluster members (in 2x2 array)
    - T, q, O3 profiles and their QCs
    - Cloud fraction
  - Surface retrieval problems that impact T,q,O3 profiles at altitude of CO2 sensitivity
    - Surface class
    - Surface skin temperature

V6 CO2 PGE Delivery



- Current status
  - V6 L2 CO2 three stage code delivered and validated to operate in PGE Environment
    - Product file content identical to that for V5
  - Expanded L2 output file providing auxiliary data
    - Implemented in research code and content validated
      - Will be produced by research mode implementation
    - Allows finalization of product QC tests to be added to PGE implementation at end of CY
      - Implementation of expanded output in PGE output requires additional work by PGE engineer
      - Workaround is to use research mode implementation to test additional QC and then install identified valuable QC filtering in PGE code
  - V6 L3 CO2 PGE has been modified to create 1°x1° degree gridded product
    - Replaces V5 2°x2.5° degree gridded product
    - Gridding is consistent with other AIRS L3 products
- Tasks for November/December
  - Finalize V6 L2 CO2 product generation QC filtering
    - Assess impact of bias in Tair at high altitude
    - Analyze expanded L2 file created by research mode implementation
      - Example: impact upon CO2 retrieval of spatial inhomogeneity of original atmospheric states in cluster members
    - Add finalized QC filters to V6 L2 PGE implementation code
  - Create User Document
- V6 CO2 product release
  - January, 2016
    - Reprocessing will be ordered from most recent to earliest to facilitate OCO-2 synergy
  - Create ATBD

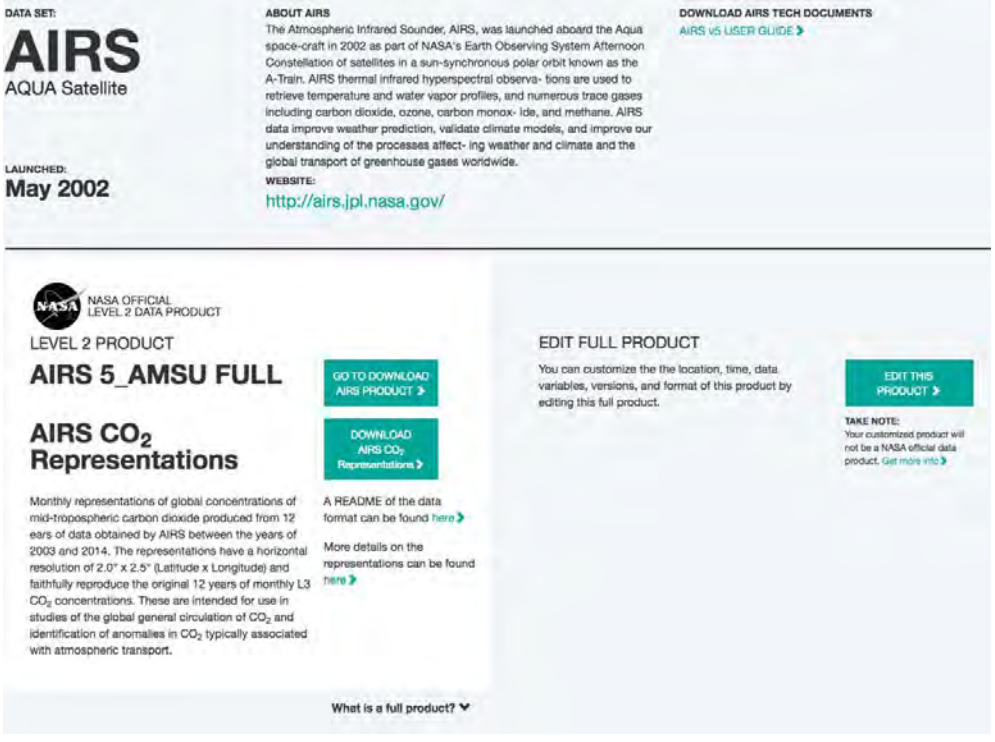
AIRS CO2 Provided to JPL CO2 Virtual Data Environment Server



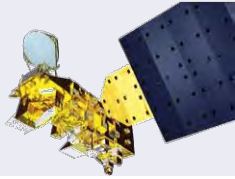
- JPL CO2 Virtual Data Environment Server
  - URL: co2.jpl.nasa.gov
  - Provides CO2 data from GOSAT, AIRS, OCO-2, TES and TCCON
    - Users can subset the data by time, location and data variables
- AIRS Data
  - AIRS/AMSU based V5 Level 2 from beginning of mission through 2011
    - Includes User Guide:

      AIRS V5 Release Tropospheric CO2 Products
  - Monthly representations based on the L2 data from 2003 through 2010
    - Includes documentation:

      Pagano, T.S. 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.



Validation



Airborne Validation Data Sets	Latitude Range
INTEX-NA	
• 20040701 through 20040814	28N to 50N
INTEX-B	
• 20060224 through 20060515	20N to 60N
ARCTAS	
• 20080320 through 20080419	35N to 89N
• 20080622 through 20080713	33N to 79N
START-08	
• 20080418 through 20080627	27N to 62N
ICEBRIDGE-1	
• 20091012 through 20091124	70S to 34N
OIB	
• 20091028 through 20091124	55S to 34N
RR Valley	
• 20110623 through 20110626	38N
HIPPO	
• HIPPO-1 – 20090109 through 20090121	66S to 77N
• HIPPO-2 – 20091031 through 20091122	65S to 82N
• HIPPO-3 – 20100324 through 20100416	65S to 84N
• HIPPO-4 – 20110614 through 20110711	57S to 83N
• HIPPO-5 – 20110809 through 20110909	66S to 87N

- CarbonTracker 2013B Model Output
  - Employed to extend aircraft CO2 profiles above highest altitude of measurements
  - Data available at ftp://aftp.cmdl.noaa.gov/products/carbontracker/co2/CT2013B

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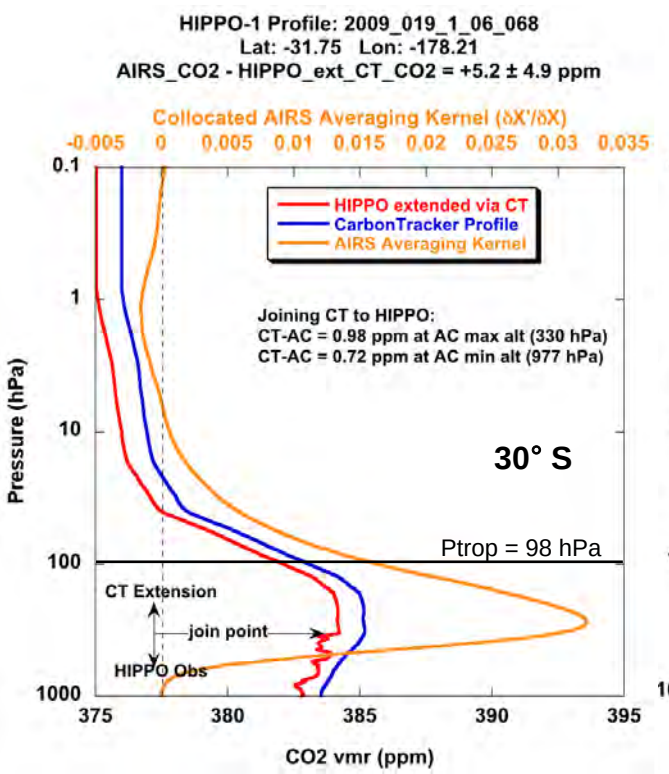
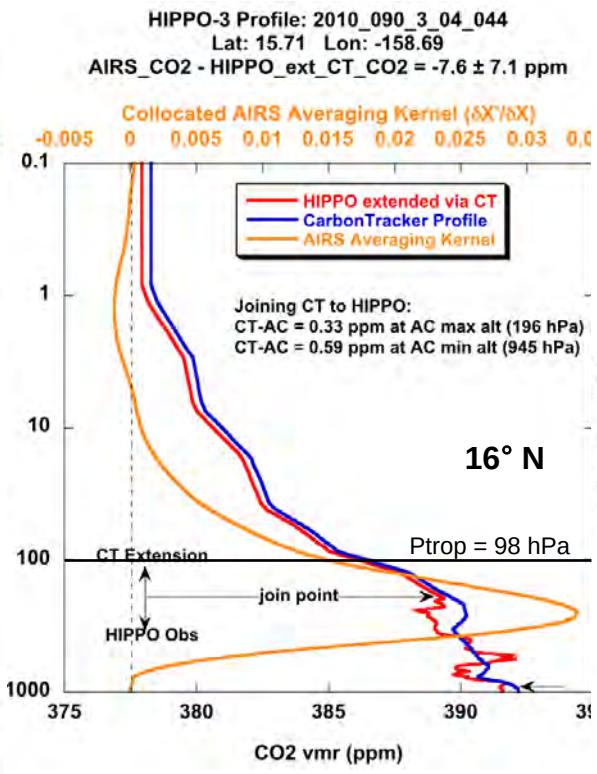
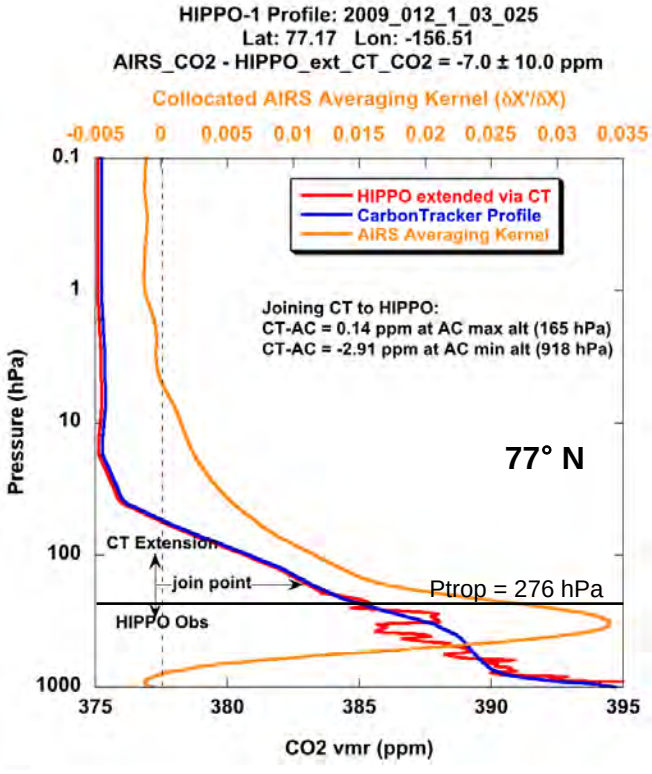
Example Aircraft Profile Extension via CarbonTracker for Validation of Collocated AIRS CO_2 Retrievals

Extending the *in situ* measurements to higher altitude via the CarbonTracker vertical transport model that assimilates low altitude and surface measurements allows the validation task to use aircraft measurements that do not span extent of column where AIRS is most sensitive to CO2







AIRS sensitivity to CO2 is shown by the Averaging Kernel profile (gold)
It peaks at ~ 400 hPa and AIRS retrievals represent the average CO2 in an atmospheric layer that is approximately 200 hPa thick. Thus it is a partial column sample of the CO2 concentration.

CT2013B data sets are available at
ftp://aftp.cmdl.noaa.gov/products/carbontracker/co2/CT2013B

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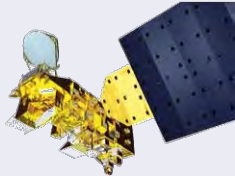
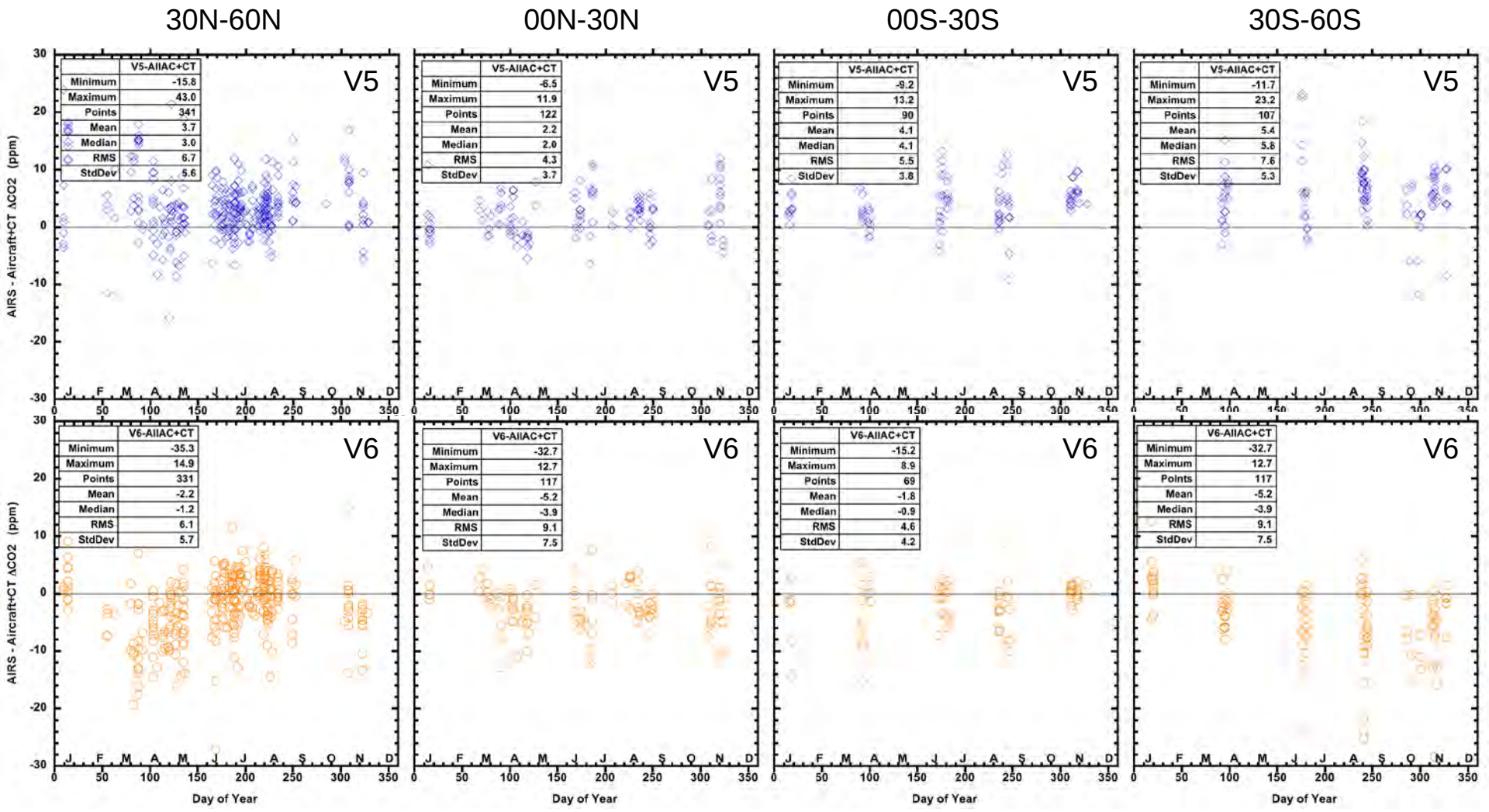
V5 vs V6 – Seasonal (ncoll≥1)
Validation against Multiple Aircraft Campaigns





V5 Biased high, all latitudes, all seasons by 2-4 ppm in tropics and 4-6 ppm in mid-latitudes
V6 Biased low ~5 ppm Mar-May in NH mid-latitudes and Jul-Oct in SH and low by 2-3 ppm in tropics

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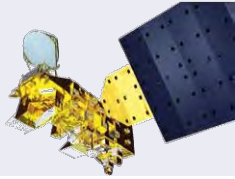
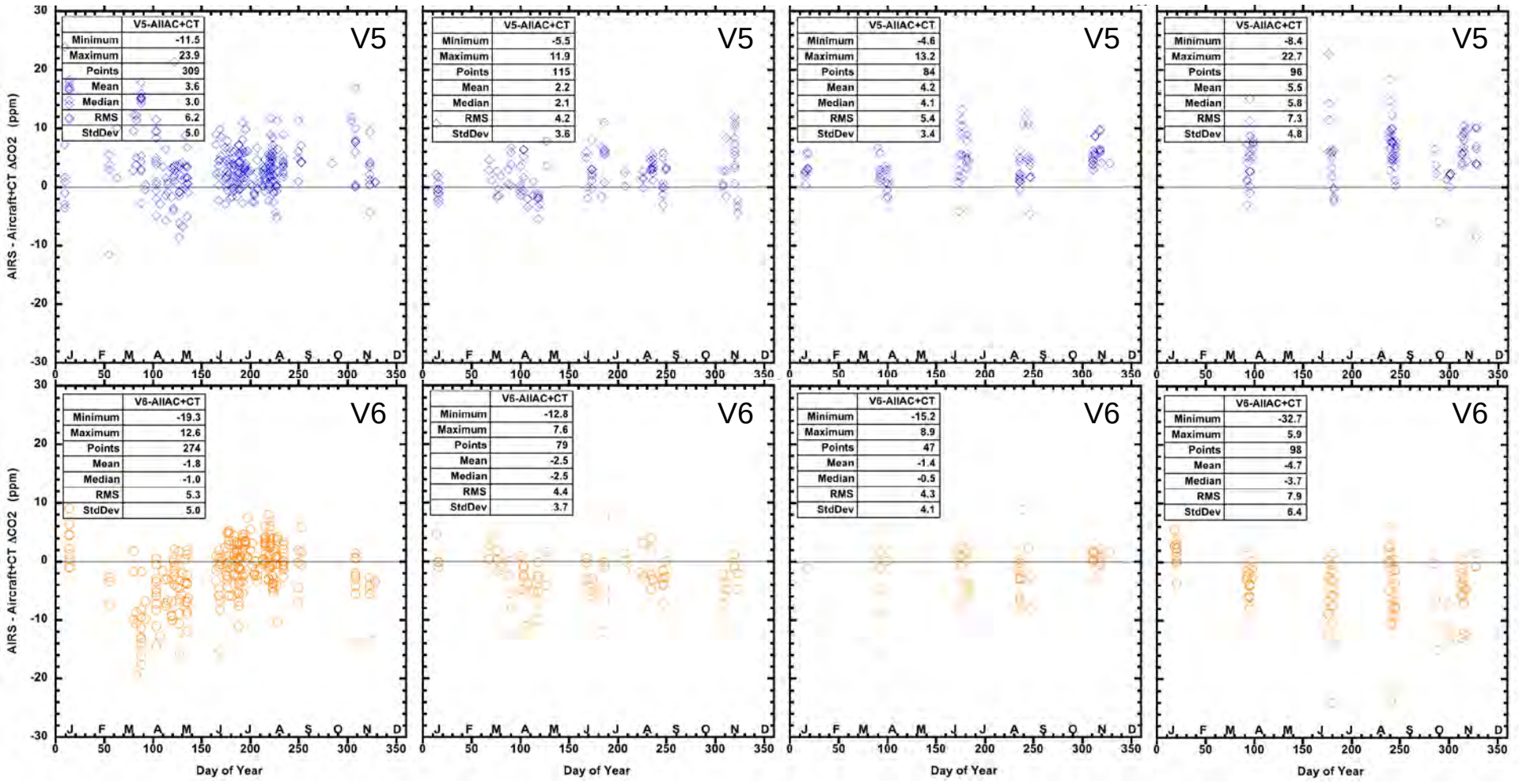
V5 vs V6 – Seasonal (ncoll≥2)
Validation against Multiple Aircraft Campaigns



30N-60N | 00N-30N | 00S-30S | 30S-60S



V5 – Outlier scatter reduced by eliminating single retrieval collocations but positive bias unaffected
V6 – Outlier scatter reduced and negative bias slightly reduced in all latitudes and seasons

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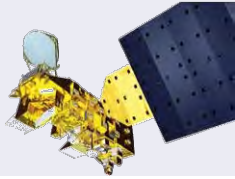
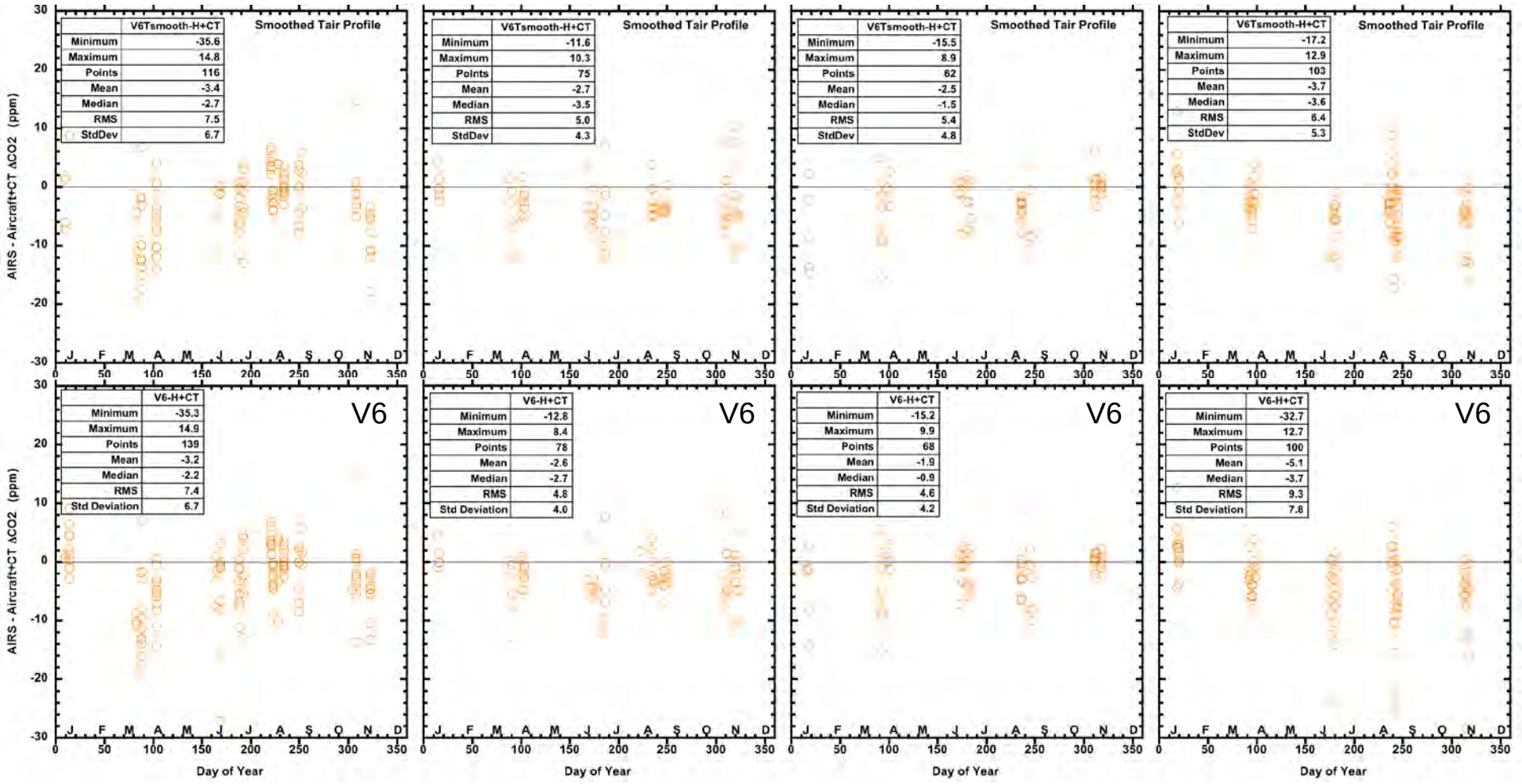
V6 Tair Smoothed vs V6 - Seasonal Validation against HIPPO-1 through HIPPO-5



	30N-60N	00N-30N	00S-30S	30S-60S
Smoothed Tair Profile	V6Tsmooth-H+CT	V6Tsmooth-H+CT	V6Tsmooth-H+CT	V6Tsmooth-H+CT
Minimum	-35.6	-11.6	-15.5	-17.2
Maximum	14.8	10.3	8.9	12.9
Points	116	75	62	103
Mean	-3.4	-2.7	-2.5	-3.7
Median	-2.7	-3.5	-1.5	-3.6
RMS	7.5	5.0	5.4	6.4
StdDev	6.7	4.3	4.8	5.3
V6	V6-H+CT	V6-H+CT	V6-H+CT	V6-H+CT
Minimum	-35.3	-12.8	-15.2	-32.7
Maximum	14.9	8.4	9.9	12.7
Points	139	78	68	100
Mean	-3.2	-2.6	-1.9	-5.1
Median	-2.2	-2.7	-0.9	-3.7
RMS	7.4	4.8	4.6	9.3
Std Deviation	6.7	4.0	4.2	7.8



Smoothing the V6 Tair profiles to remove vertical fine structure has no impact on retrieved CO2

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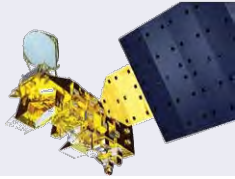
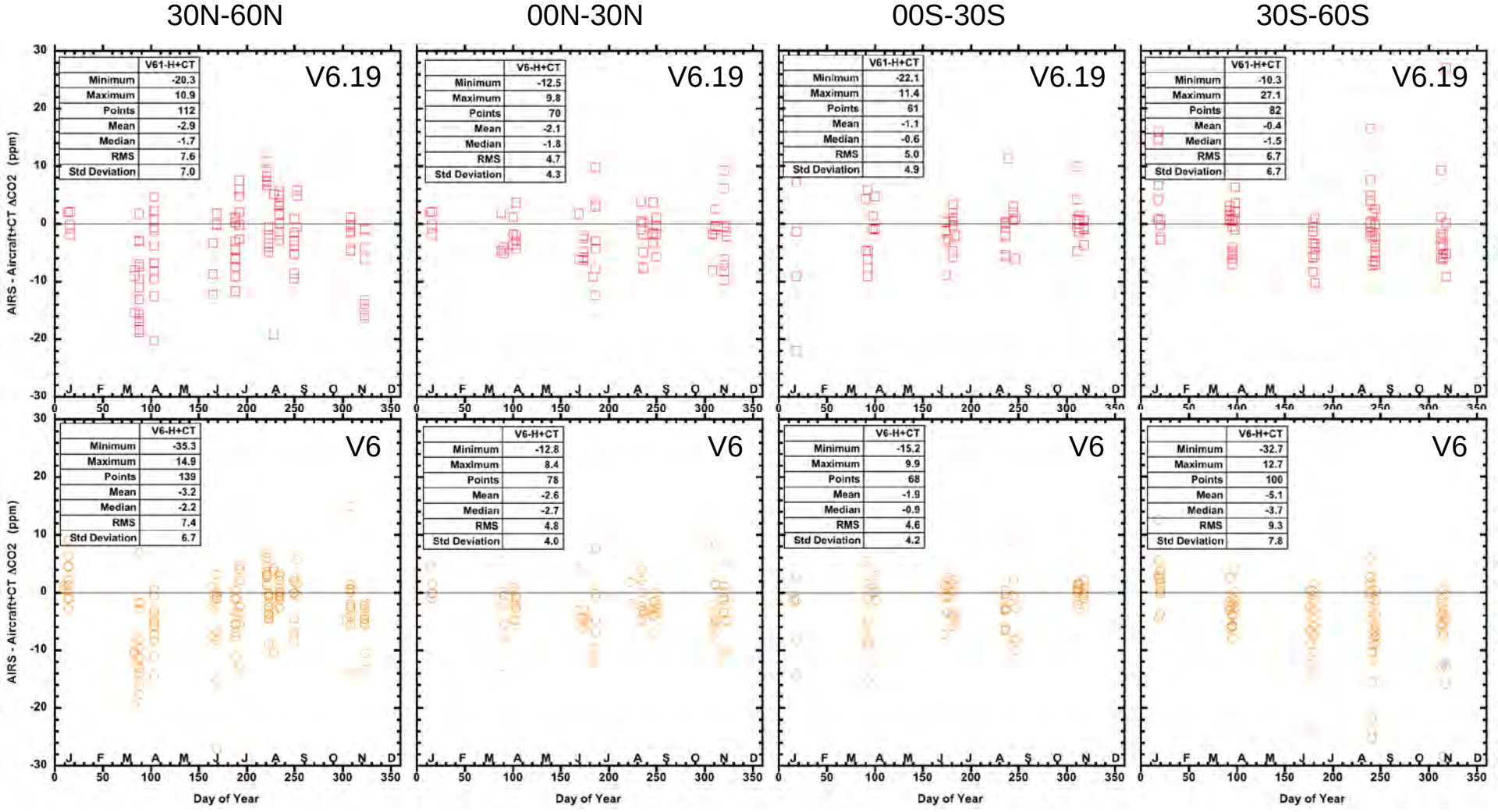
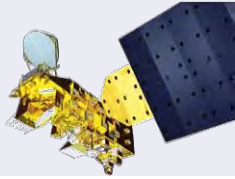
V6.19 vs V6 - Seasonal
Validation against HIPPO-1 through HIPPO-5





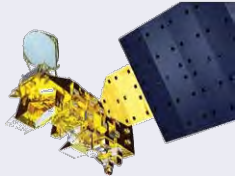
V6.19 exhibits smaller negative mean bias than V6, most noticeably Jul-Nov in SH mid-latitudes
Mean bias reduced by ~4.5 in SH mid-latitudes and by ~0.5 ppm everywhere else
V6 yield is ~20% higher in the mid-latitudes and ~10% higher in the tropics

Summary – Completed Tasks



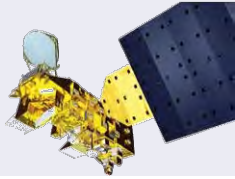
- V6 L2 CO2 code now under configuration management and successfully executed as PGE
  - Algorithm employs full functionality of V6 RTA
  - Algorithm requires stability of retrieval product against perturbation of first guess
  - Algorithm tests calculated CO2 averaging kernel to determine acceptability of product
- Stand-alone research version of code with expanded output for QC analysis completed
  - Will be used for final refinement of QC tests to be installed in PGE version
- AIRS V5 CO2 data and climatologies provided to JPL Virtual Data Environment Server
- 13 airborne CO2 validation data sets spanning 2004 through 2011 prepared
- Validation tools extend airborne profiles to higher altitude via CarbonTracker 2013B model
- Validation Results
  - V6 removes global bias present in V5, but exhibits negative bias in mid-latitudes during some seasons
  - V6.19 mitigates the negative bias in mid-latitudes present in V6
  - Fine structure in AIRS L2 temperature profile has no noticable impact on CO2 retrieval

Summary – Near Term Future Tasks



- Next Steps
  - Validation
    - Add COBRA 2003 and COBRA 2004 airborne measurements
  - Assess stability of CO2 retrieval with respect to bias in atmospheric temperature at high altitude
    - Quantify impact of bias by perturbing the temperature profile
  - Finalize QC optimization
  - Document (ATBD and User Doc)
    - Create ATBD and User Documentation

Published Studies Bearing on CO_2 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." *PNAS*, 107, no. 45, 19171-19175.
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  - Feng, et al. (2011) "Evaluating a 3-D transport model of atmospheric CO2 using ground-based, aircraft, and space-borne data." *ACP*, 11, no. 6, 2789-2803.
  - Liu, J et al. (2011), "CO2 transport uncertainties from the uncertainties in meteorological fields." *GLR,* 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.
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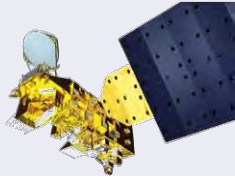
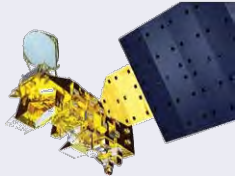
  - Zhang, L et al. (2015) Comparison analysis of the global carbon dioxide concentration column derived from SCIAMACHY, AIRS, and GOSAT with surface station measurements, International Journal of Remote Sensing, 36:5, 1406-1423, DOI: 10.1080/01431161.2015.1009656
  - Zhou, C et al. (2015) "Data fusion of CO2 retrieved from GOSAT and AIRS using regression analysis and fixed rank kriging." In *SPIE Optical Engineering+ Applications*, pp. 96101A-96101A. International Society for Optics and Photonics.
  - Li, K-F et al. (2015) “An Intraseasonal Variability of mid-tropospheric CO2 over Winter Arctic.”, *JGR* (submitted)
  - Jiang, X et al. (2015) “CO2 Annual and Semiannual Cycles From Multiple Satellite Retrievals and Models”, Earth and Space Science (submitted)

Thank You



- Acknowledgement
  - This task is funded by the AIRS project and a ROSES grant for algorithm maintenance
    - Special thanks to Tom Pagano and Ramesh Kakar for their encouragement and support

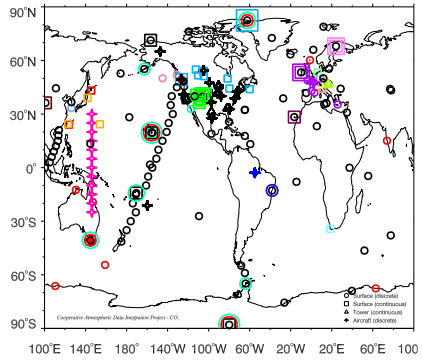


BACKUP

Rationale for Retrieving Free Tropospheric CO_2

- Why is the retrieval of free tropospheric CO_2 important?
  - Atmospheric CO_2 is a major agent for radiative forcing
    - Interannual increase due to human activity, and ~50% of anthropogenic CO_2 remains in the atmosphere
    - Increased CO_2 concentration warms the troposphere and cools the stratosphere
  - 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 and transported to the stratosphere
    - SH, “the garbage dump for the NH CO_2 emissions”, very sparsely observed from surface/airborne
  - The free tropospheric (and stratospheric) CO_2 are the background which must be accounted for in the process of determining the near-surface concentration most closely coupled to the local carbon flux by remote sensing of total column
  - Modeling of atmospheric transport processes are continuing to be refined and can benefit from the study of the distribution and transport of the long-lived trace gas
    - Vertical lofting
    - Inter-hemispherical transport
- Combined satellite retrievals provide the vertical, 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 OCO-2)

In situ CO2 observations



AIRS CO2 (month)