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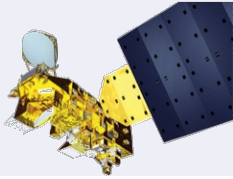

# AIRS V6 Tropospheric CO2 Retrieval QC Analysis

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California Institute of Technology, Jet Propulsion Laboratory

**AIRS Project Science Team Meeting**
**Caltech, Pasadena, CA**
**22-24 March 2016**

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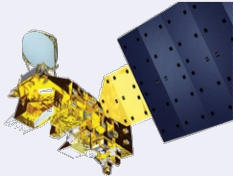
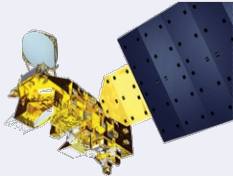
# Outline



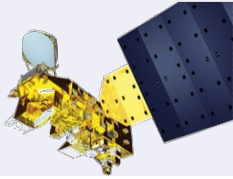
- What has changed in the AIRS $CO_2$ retrieval algorithm from V5 to V6
  - Algorithm Change V5→V6
  - Enhanced QC to filter retrievals
- Deliveries
  - Updates to V6 $CO_2$ PGE
    - Implement support for QC thresholds
    - Minor code fixes
- Refinement of QC and Validation against HIPPO Campaign in situ measurements
  - CO2 profile extended above maximum altitude of measurements with CarbonTracker model
  - Validation against HIPPO campaigns (2009-2011)
    - V6 - Original $CO_2$ post processing PGE ingesting operational V6 Level 2
    - V6d – Impact of updated QC in original $CO_2$ post processing PGE ingesting operational V6 Level 2
    - V6.28 – Original $CO_2$ post processing PGE ingesting proposed Level 2 product
- Near Future
  - Complete tests for finalized QC
  - V6 $CO_2$ retrieval operational in early April
  - Complete Documentation
- AIRS V5 $CO_2$ publications
- Comparative mission publication statistics for trace gases

# Algorithm Changes - V5 to V6



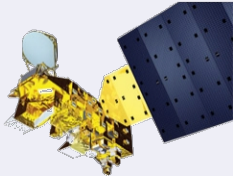
- V6 algorithm enhancements
  - Implements V6 RTA, recalculating the channel coefficients for each field of regard
    - Accounts for AIRS channel shifts due to line-of-sight motion of the scene
    - Analysis indicates impact on retrieved $CO_2$ can amount to as much as 2 ppm
  - Tightens initial L2 QC filtering of AIRS L2 data ingested by $CO_2$ post processing PGE
    - PGood ≥ 700 hPa
    - PTropopause_QC < 2
  - Three stage application of VPD Algorithm
    - First stage perturbs $CO_2$ first guess by +5ppm, identifying converged clusters for continued processing
    - Second stage perturbs $CO_2$ first guess by -5ppm, identifying converged clusters for continued processing
    - Final stage processes clusters surviving previous two stages
      - Ingests original AIRS V6 L2 T,q,$O_3$ and assumes unperturbed $CO_2$ first guess to retrieve product
      - Executes on clusters in which retrieved $CO_2$ in the first two stages agree 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
        - » Thus, sacrifices yield for stability of retrieval over a 10 ppm range of first guess

# Enhanced QC



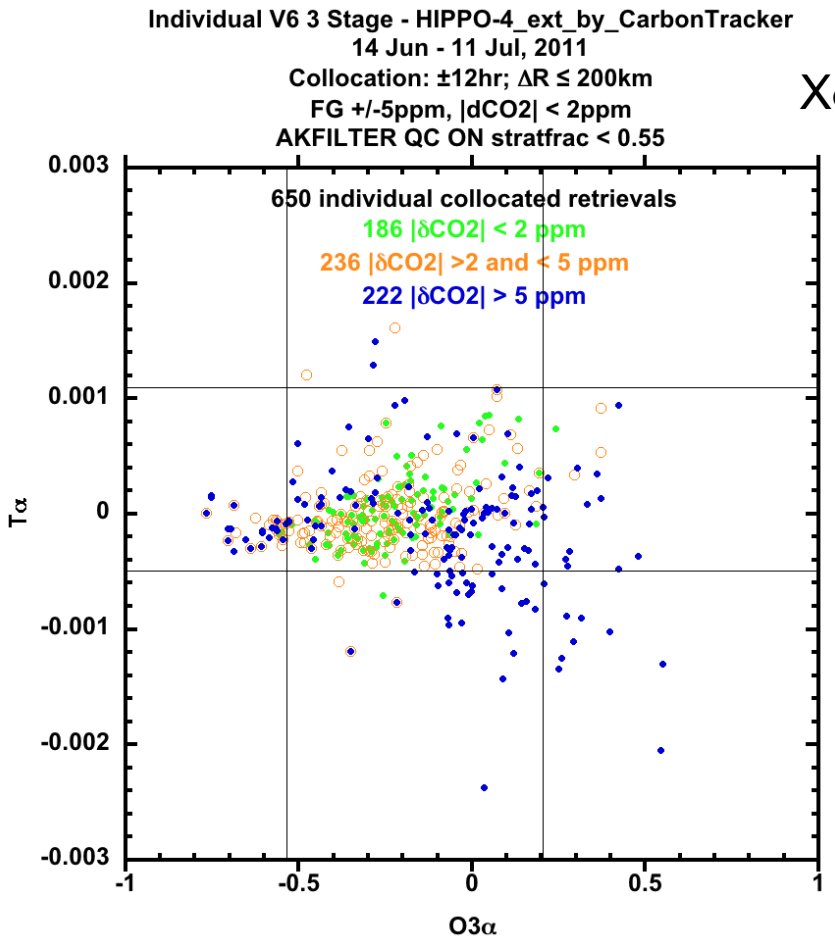
- V6 algorithm QC filtering applied to 3rd stage retrievals
  - QC filtering via calculated $CO_2$ product averaging kernel (AK)
    - Eliminate retrieval whose AK exhibits significant negative tail in stratosphere
      - Ideal is near zero AK throughout stratosphere
    - Eliminate retrieval whose AK exhibits significant secondary peak or fine structure
      - Ideal is a smooth sensitivity function peaking at ~400 hPa sampling about 200 hPa of column
    - Eliminate retrieval for which the integral of $CO_2$ AK above PTropopause exceeds 55% of total integral
      - Important for polar regions, where tropopause altitude is depressed
  - QC filtering via limits on perturbations of Temperature and Ozone profiles
    - Eliminate retrieval for which T profile shift exceeds 0.2 K
    - Eliminate retrieval for which $O_3$ profile shift exceeds 50%
    - These are constraints on the allowed AIRS L2 bias over the partial columns sampled by the ancillary channel sets
  - Research mode implementation
    - Provides expanded output for QC analysis
    - Collocations with HIPPO analyzed to determine T, $O_3$ profile shift thresholds
    - Currently executing on full months of Jan/Apr/Jul/Oct 2015 for final seasonal analysis of product before release of operational V6 product

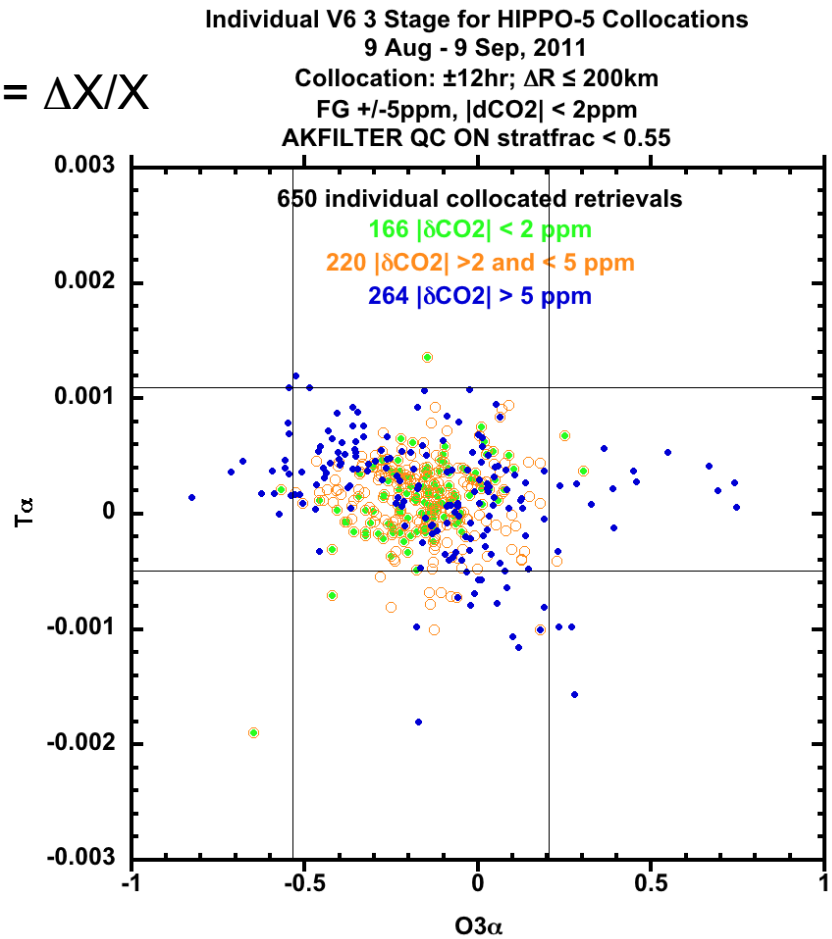
# Setting Limits on Tα, O3α
# (outliers likely unrealistic solutions or L2 out of bounds)



**Thresholds set to maximize excision of outliers in collocation statistics**

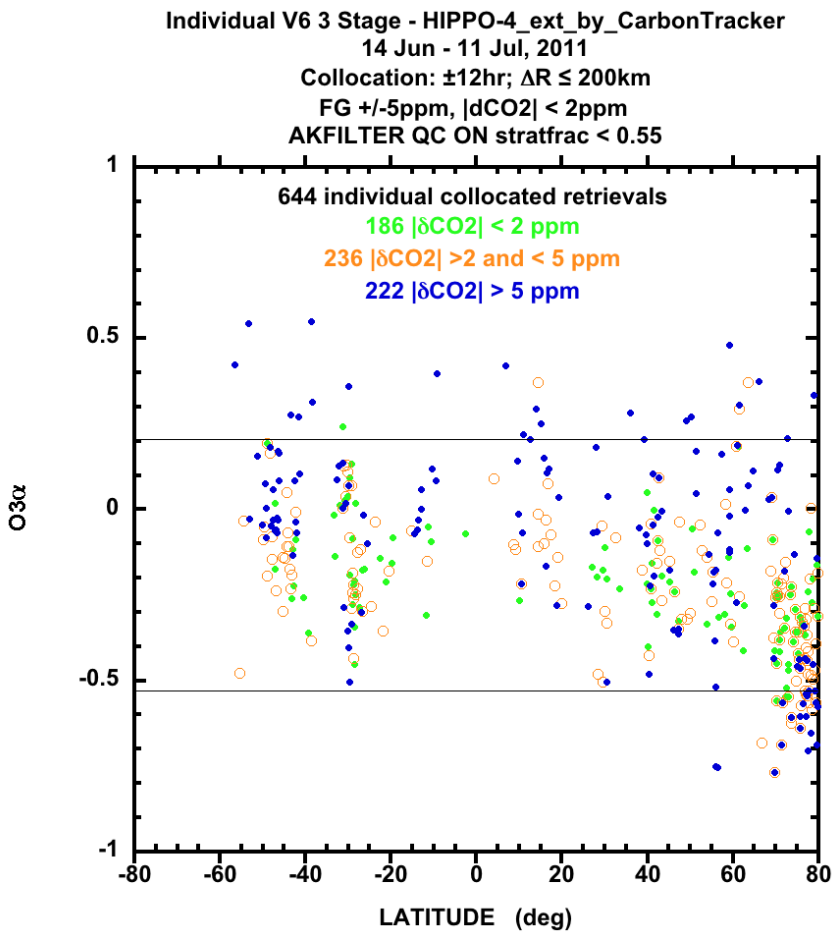
$X\alpha = \Delta X/X$

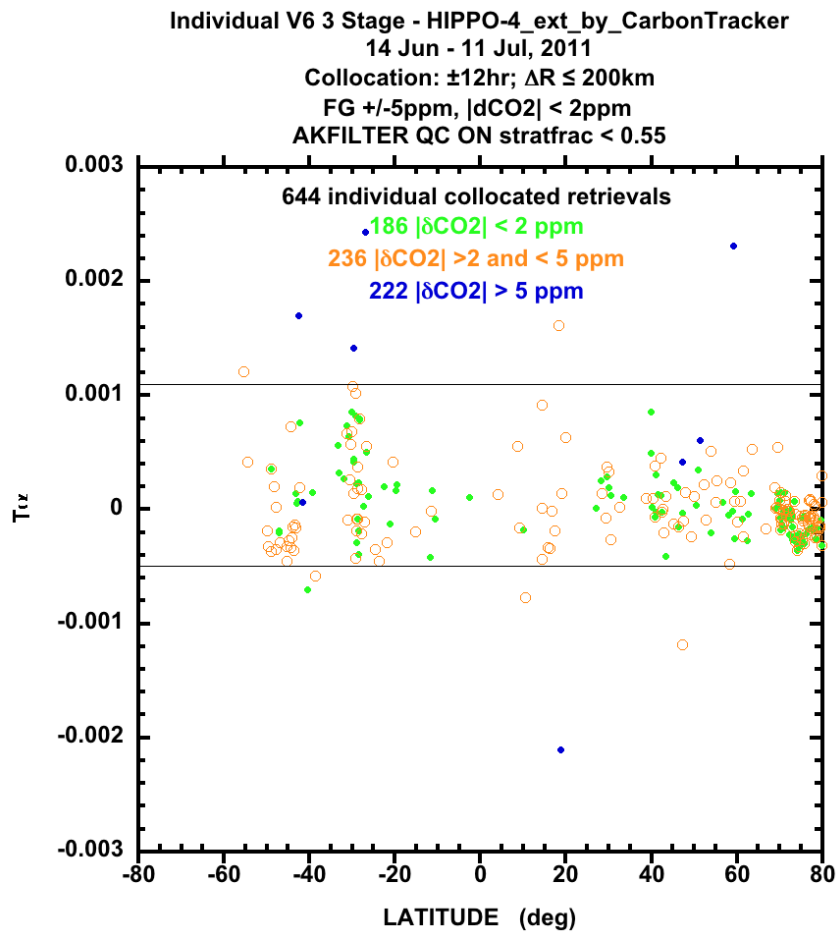



**These are global thresholds**
**There may be variation with latitude and season**

# Impact of $O_3\alpha$ and $T\alpha$ Thresholds on V6 HIPPO-4 Collocations as a Function of Latitude

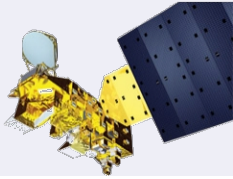


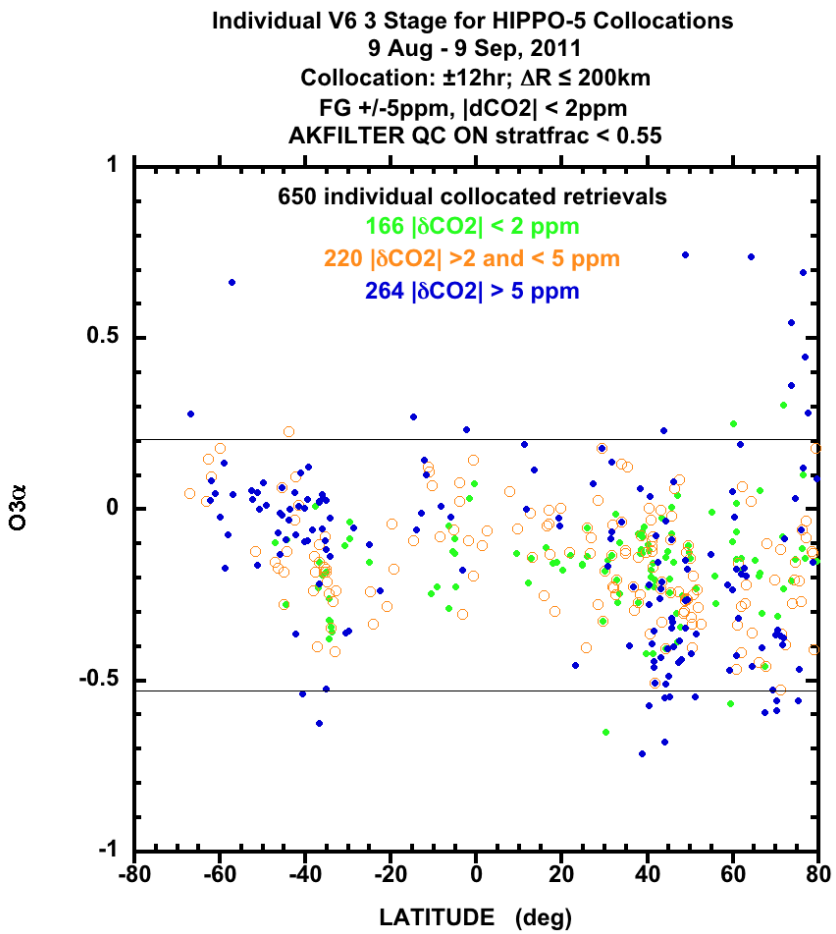




**$O_3\alpha$ threshold results in minor loss at very high northern latitudes**

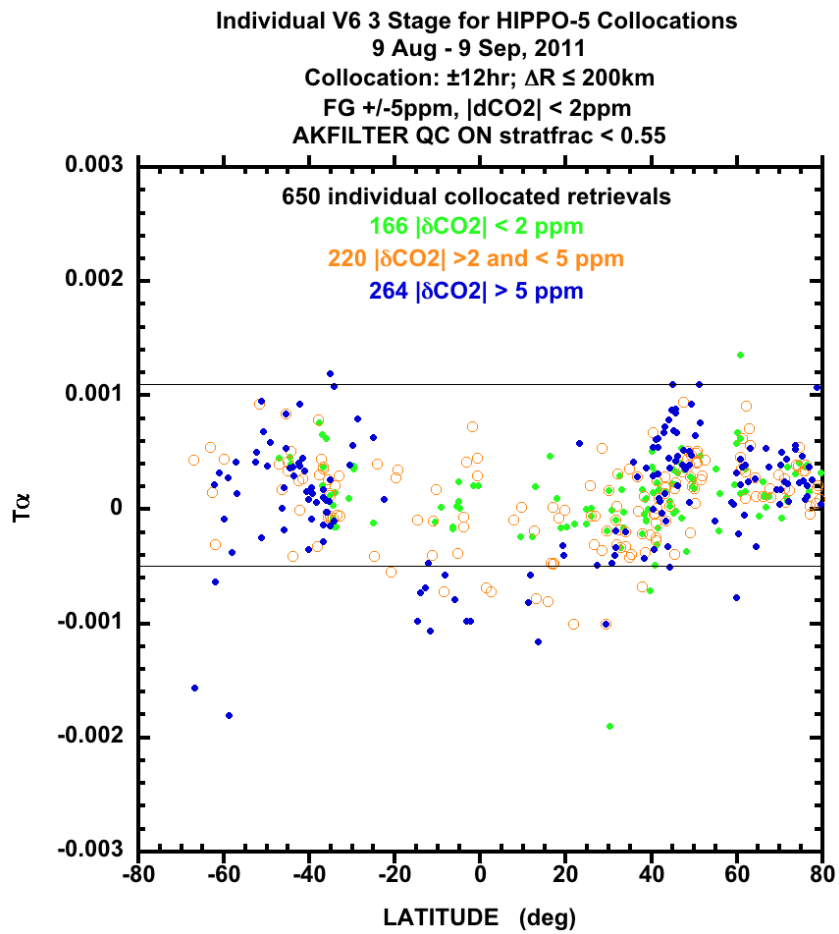
**$T\alpha$ threshold results in no loss**

# Impact of $O_3\alpha$ and $T\alpha$ Thresholds on V6 HIPPO-5 Collocations as a Function of Latitude






$O_3\alpha$ threshold results in no loss




$T\alpha$ threshold results in minor loss

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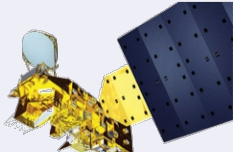
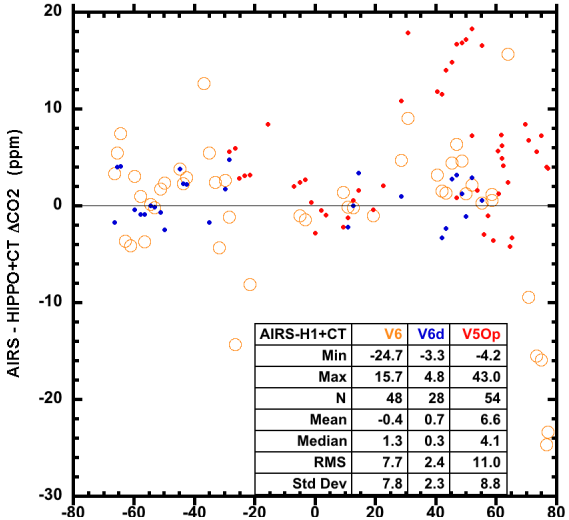
# V6, V6d and V5 Op vs HIPPO+CarbonTracker

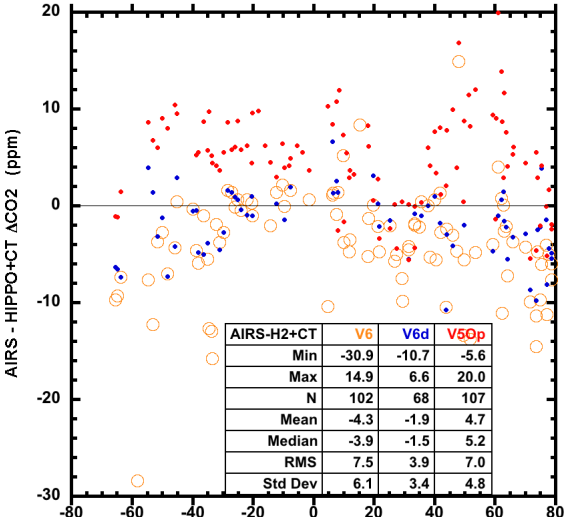


V6, V6d and V5Op 3 Stage - HIPPO-1_ext_by_CarbonTracker
9 Jan - 22 Jan, 2009
Collocation: ±12hr; ΔR ≤ 200km
(V5Op ±24hr; ΔR <= 500km)



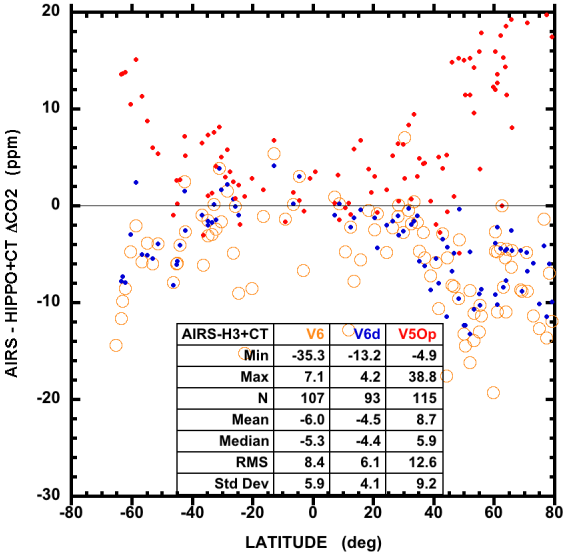

| AIRS-H1+CT | V6 | V6d | V5Op |
|---|---|---|---|
| Min | -24.7 | -3.3 | -4.2 |
| Max | 15.7 | 4.8 | 43.0 |
| N | 48 | 28 | 54 |
| Mean | -0.4 | 0.7 | 6.6 |
| Median | 1.3 | 0.3 | 4.1 |
| RMS | 7.7 | 2.4 | 11.0 |
| Std Dev | 7.8 | 2.3 | 8.8 |

V6, V6d and V5Op 3 Stage - HIPPO-2_ext_by_CarbonTracker
31 Oct - 22 Nov, 2009
Collocation: ±12hr; ΔR ≤ 200km
(V5Op ±24hr; ΔR <= 500km)



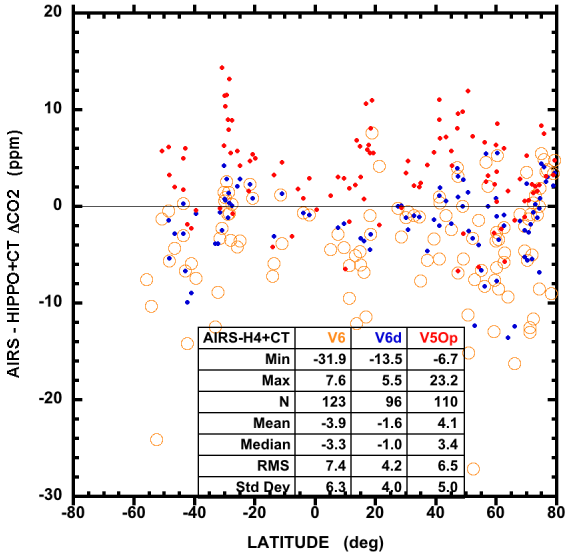

| AIRS-H2+CT | V6 | V6d | V5Op |
|---|---|---|---|
| Min | -30.9 | -10.7 | -5.6 |
| Max | 14.9 | 6.6 | 20.0 |
| N | 102 | 68 | 107 |
| Mean | -4.3 | -1.9 | 4.7 |
| Median | -3.9 | -1.5 | 5.2 |
| RMS | 7.5 | 3.9 | 7.0 |
| Std Dev | 6.1 | 3.4 | 4.8 |

V6, V6d and V5Op 3 Stage - HIPPO-3_ext_by_CarbonTracker
24 Mar - 16 Apr, 2010
Collocation: ±12hr; ΔR ≤ 200km
(V5Op ±24hr; ΔR <= 500km)



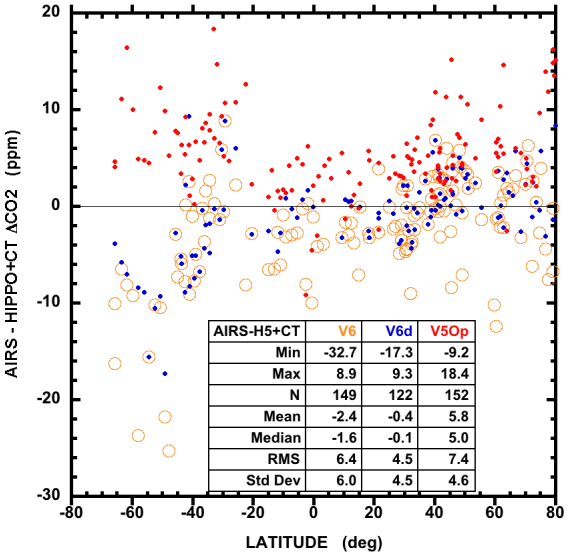

| AIRS-H3+CT | V6 | V6d | V5Op |
|---|---|---|---|
| Min | -35.3 | -13.2 | -4.9 |
| Max | 7.1 | 4.2 | 38.8 |
| N | 107 | 93 | 115 |
| Mean | -6.0 | -4.5 | 8.7 |
| Median | -5.3 | -4.4 | 5.9 |
| RMS | 8.4 | 6.1 | 12.6 |
| Std Dev | 5.9 | 4.1 | 9.2 |

V6, V6d and V5Op 3 Stage - HIPPO-4_ext_by_CarbonTracker
14 Jun - 11 Jul, 2011
Collocation: ±12hr; ΔR ≤ 200km
(V5Op ±24hr; ΔR <= 500km)

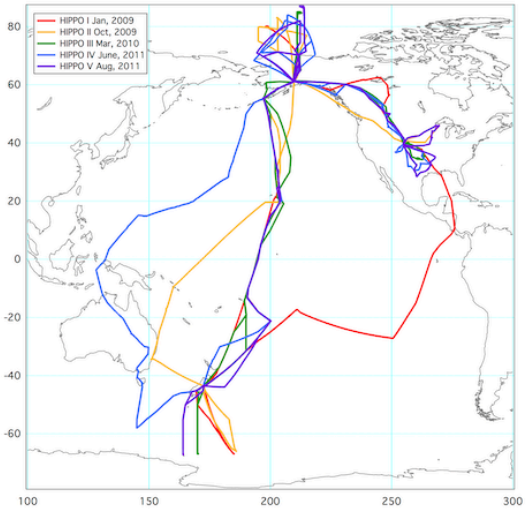



| AIRS-H4+CT | V6 | V6d | V5Op |
|---|---|---|---|
| Min | -31.9 | -13.5 | -6.7 |
| Max | 7.6 | 5.5 | 23.2 |
| N | 123 | 96 | 110 |
| Mean | -3.9 | -1.6 | 4.1 |
| Median | -3.3 | -1.0 | 3.4 |
| RMS | 7.4 | 4.2 | 6.5 |
| Std Dev | 6.3 | 4.0 | 5.0 |

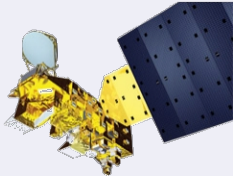
V6, V6d and V5Op 3 Stage - HIPPO-5_ext_by_CarbonTracker
9 Aug - 9 Sep, 2011
Collocation: ±12hr; ΔR ≤ 200km
(V5Op ±24hr; ΔR <= 500km)




| AIRS-H5+CT | V6 | V6d | V5Op |
|---|---|---|---|
| Min | -32.7 | -17.3 | -9.2 |
| Max | 8.9 | 9.3 | 18.4 |
| N | 149 | 122 | 152 |
| Mean | -2.4 | -0.4 | 5.8 |
| Median | -1.6 | -0.1 | 5.0 |
| RMS | 6.4 | 4.5 | 7.4 |
| Std Dev | 6.0 | 4.5 | 4.6 |



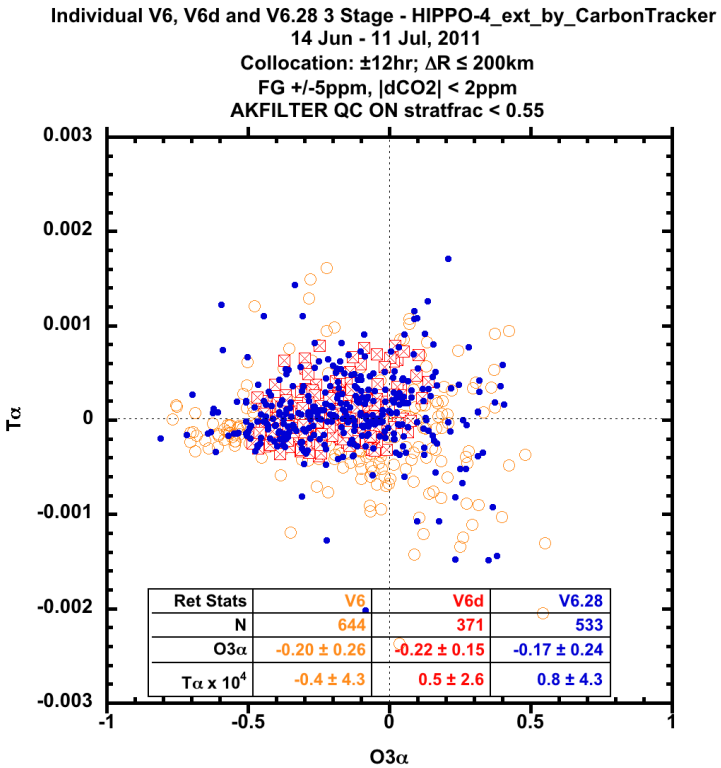
# V6, V6d and V5 Op Validation Results

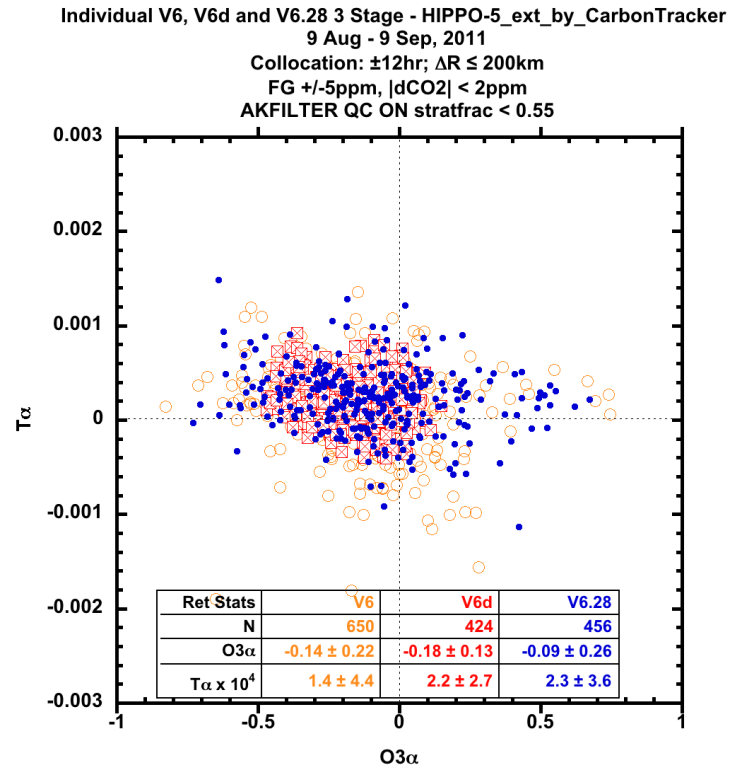


- V5 Operational Product ($\delta t \leq \pm 24$ hr; $\delta R \leq 500$ km)
  - Current product distributed by the GES DISC
  - Bias relative to All 5 HIPPO+CT Campaigns
    - Lat < -40° 55 collocations $\delta CO2 = 6.3 \pm 4.4$
    - |Lat| < 40° 259 collocations $\delta CO2 = 4.0 \pm 4.4$
    - Lat > +40° 224 collocations $\delta CO2 = 8.0 \pm 8.4$
- V6 Product ($\delta t \leq \pm 12$ hr; $\delta R \leq 200$ km)
  - Implementation incorporating 3-stage retrieval and AK QC
  - Bias relative to All 5 HIPPO+CT Campaigns
    - Lat < -40° 76 collocations $\delta CO2 = -6.7 \pm 8.2$
    - |Lat| < 40° 231 collocations $\delta CO2 = -2.2 \pm 4.3$
    - Lat > +40° 222 collocations $\delta CO2 = -4.2 \pm 7.1$
- V6d Product ($\delta t \leq \pm 12$ hr; $\delta R \leq 200$ km)
  - Adds $T\alpha$, $O_3\alpha$ thresholding to V6 implementation
  - Bias relative to All 5 HIPPO+CT Campaigns
    - Lat < -40° 63 collocations $\delta CO2 = -3.7 \pm 4.9$
    - |Lat| < 40° 160 collocations $\delta CO2 = -0.7 \pm 2.7$
    - Lat > +40° 184 collocations $\delta CO2 = -2.0 \pm 5.0$
- Common features
  - Excursions at high latitudes that are seasonally dependent
- Conclusion
  - V6d will be the V6 $CO_2$ delivery to GES DISC

# Comparison of Tα, O3α for V6, V6d and V6.28

**V6.28 outlier range similar to V6 but reduced in number**

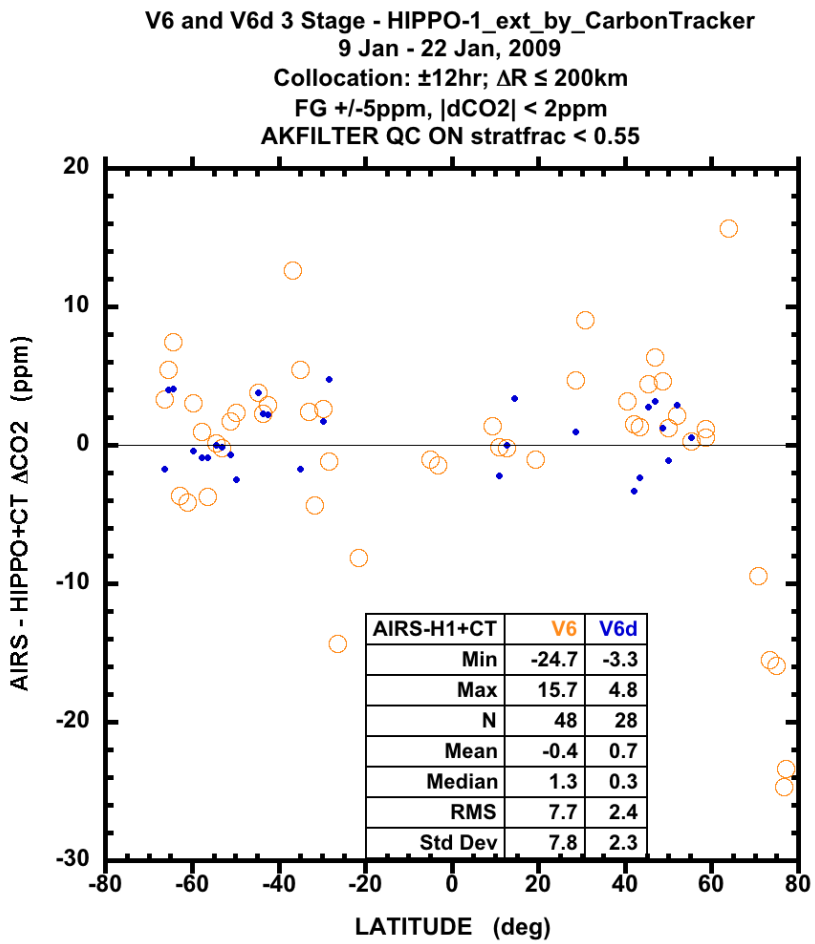



**Suggests test of V6.28 adding α thresholds**

# HIPPO-1 V6, V6d, V6.28d δCO2 vs Latitude

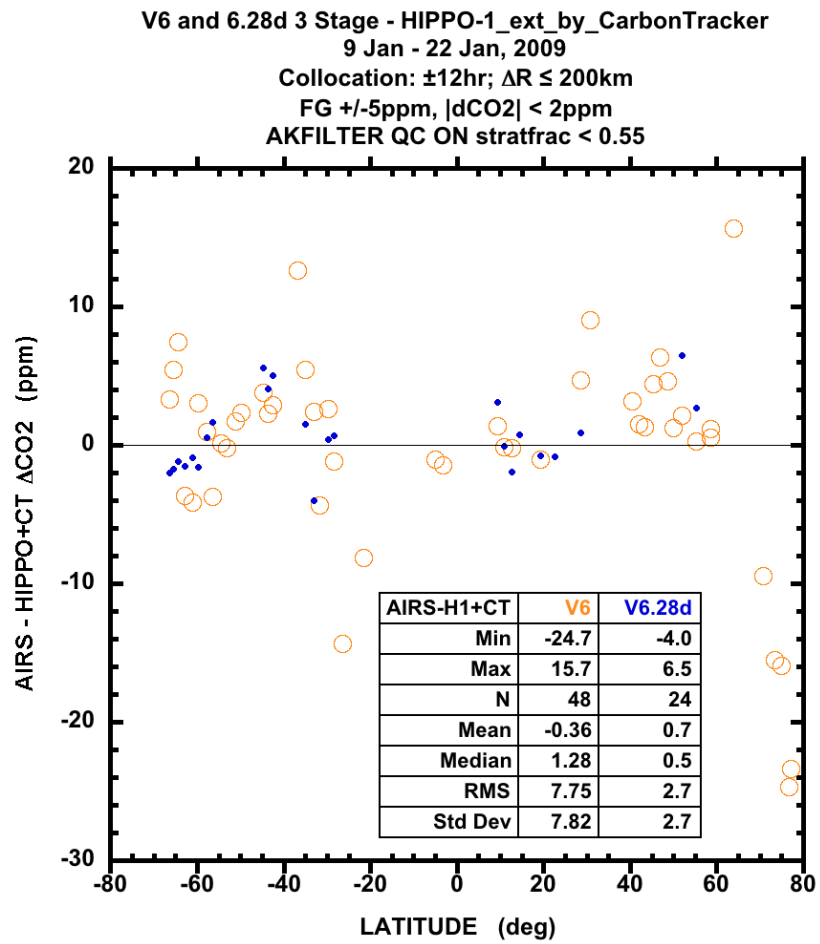
**V6 – no Tα, O3α QC filter**
**V6d – Tα, O3α filtered**




| AIRS-H1+CT | V6 | V6d |
|---|---|---|
| Min | -24.7 | -3.3 |
| Max | 15.7 | 4.8 |
| N | 48 | 28 |
| Mean | -0.4 | 0.7 |
| Median | 1.3 | 0.3 |
| RMS | 7.7 | 2.4 |
| Std Dev | 7.8 | 2.3 |

**V6d 42% fewer collocations and excises outliers**

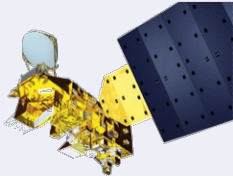
**V6 – no Tα, O3α QC filter**
**V628d – Tα, O3α filter**



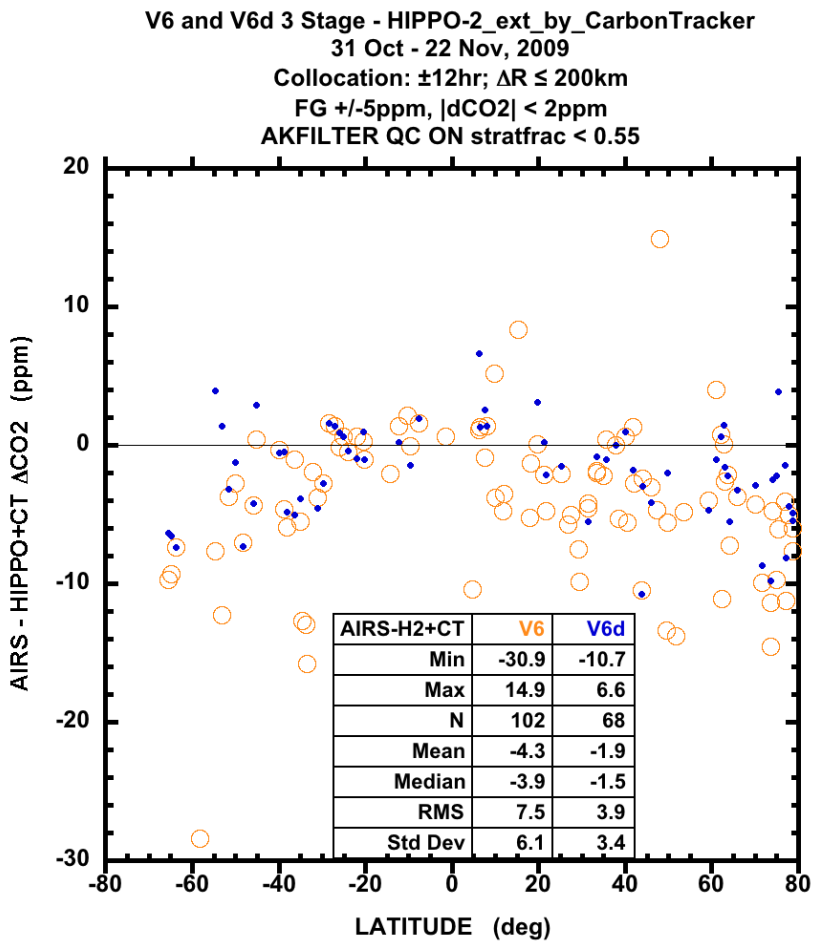

| AIRS-H1+CT | V6 | V6.28d |
|---|---|---|
| Min | -24.7 | -4.0 |
| Max | 15.7 | 6.5 |
| N | 48 | 24 |
| Mean | -0.36 | 0.7 |
| Median | 1.28 | 0.5 |
| RMS | 7.75 | 2.7 |
| Std Dev | 7.82 | 2.7 |

**V6.28d 50% fewer collocations decreases NH yield**

# HIPPO-2 V6, V6d, V6.28 δCO2 vs Latitude



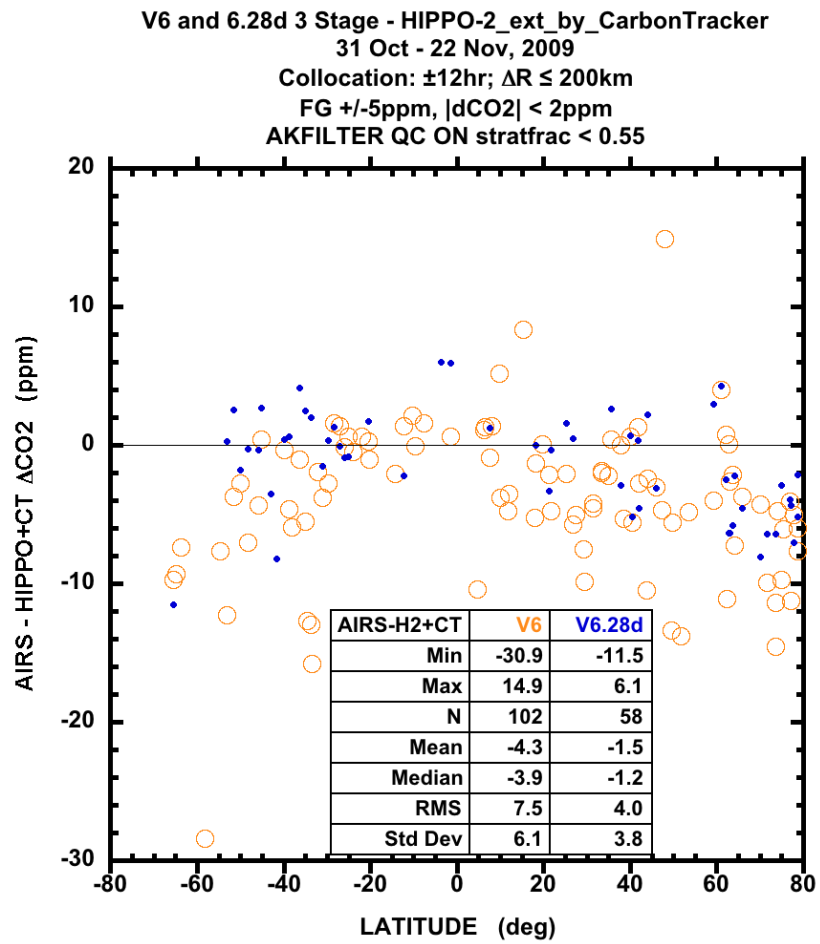
**V6 – no Tα, O3α QC filter**
**V6d – Tα, O3α filtered**




| AIRS-H2+CT | V6 | V6d |
|---|---|---|
| Min | -30.9 | -10.7 |
| Max | 14.9 | 6.6 |
| N | 102 | 68 |
| Mean | -4.3 | -1.9 |
| Median | -3.9 | -1.5 |
| RMS | 7.5 | 3.9 |
| Std Dev | 6.1 | 3.4 |

**V6d 33% fewer collocations and excises many negative outliers**

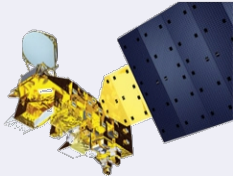
**V6 – no Tα, O3α QC filter**
**V628d – Tα, O3α filter**



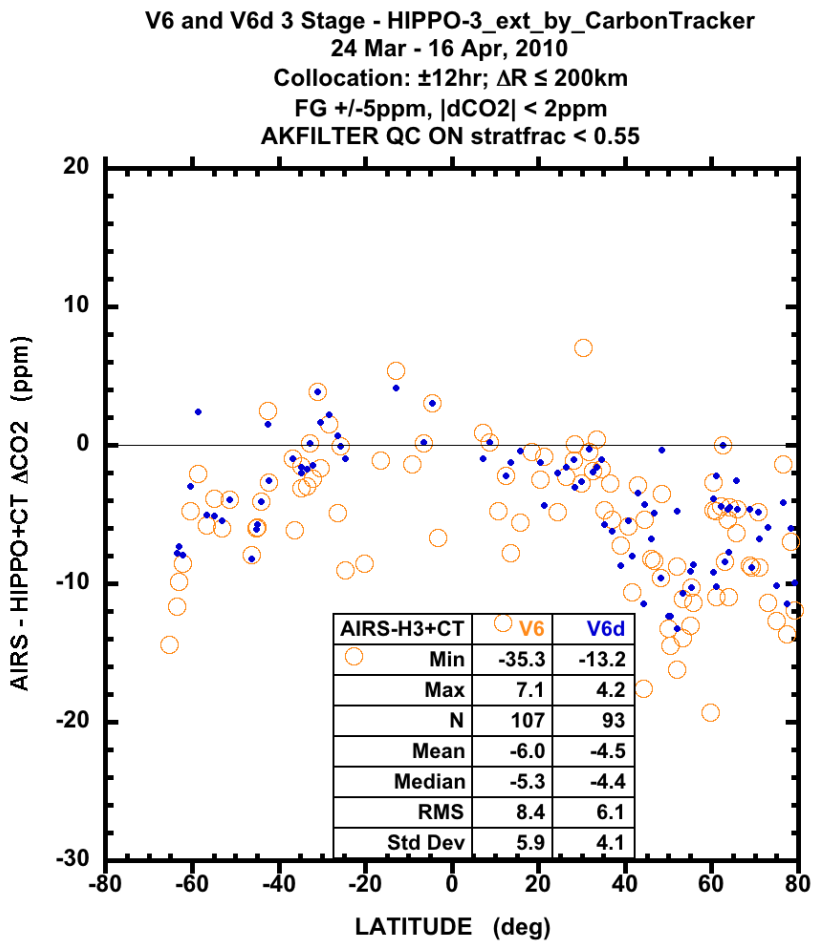

| AIRS-H2+CT | V6 | V6.28d |
|---|---|---|
| Min | -30.9 | -11.5 |
| Max | 14.9 | 6.1 |
| N | 102 | 58 |
| Mean | -4.3 | -1.5 |
| Median | -3.9 | -1.2 |
| RMS | 7.5 | 4.0 |
| Std Dev | 6.1 | 3.8 |

**V6.28d 43% fewer collocations and excises many negative outliers**

# HIPPO-3 V6, V6d, V6.28 δCO2 vs Latitude

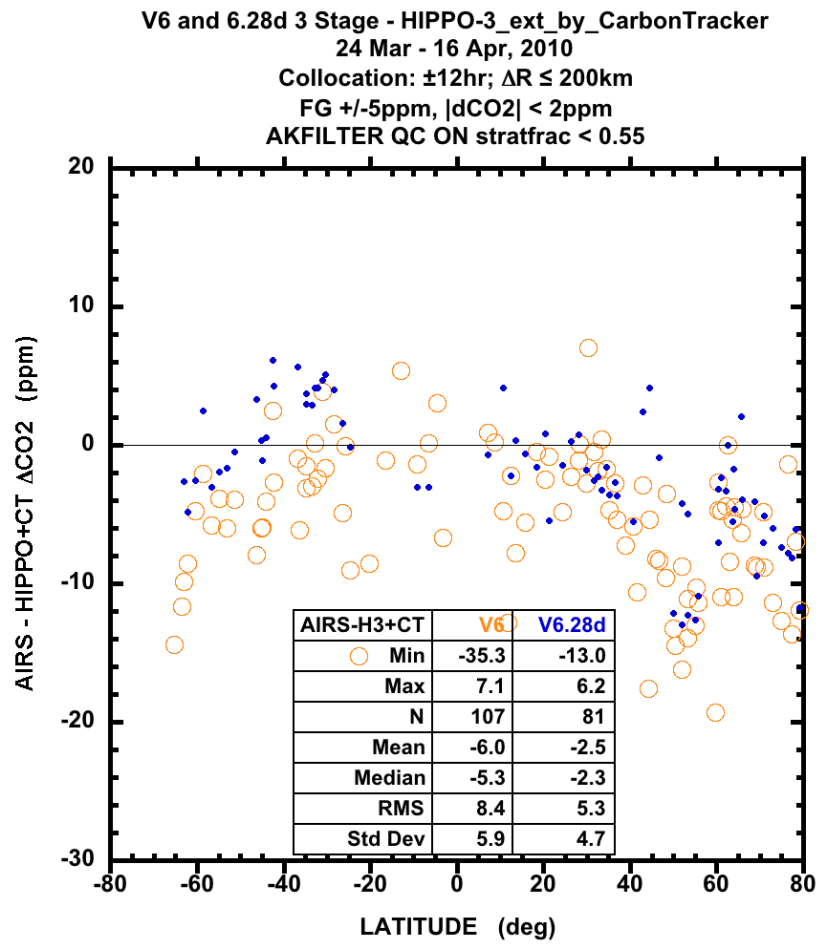


**V6 – no Tα, O3α QC filter**
**V6d – Tα, O3α filtered**




| AIRS-H3+CT | V6 | V6d |
|---|---|---|
| Min | -35.3 | -13.2 |
| Max | 7.1 | 4.2 |
| N | 107 | 93 |
| Mean | -6.0 | -4.5 |
| Median | -5.3 | -4.4 |
| RMS | 8.4 | 6.1 |
| Std Dev | 5.9 | 4.1 |

**V6 – no Tα, O3α QC filter**
**V628d – Tα, O3α filter**




| AIRS-H3+CT | V6 | V6.28d |
|---|---|---|
| Min | -35.3 | -13.0 |
| Max | 7.1 | 6.2 |
| N | 107 | 81 |
| Mean | -6.0 | -2.5 |
| Median | -5.3 | -2.3 |
| RMS | 8.4 | 5.3 |
| Std Dev | 5.9 | 4.7 |

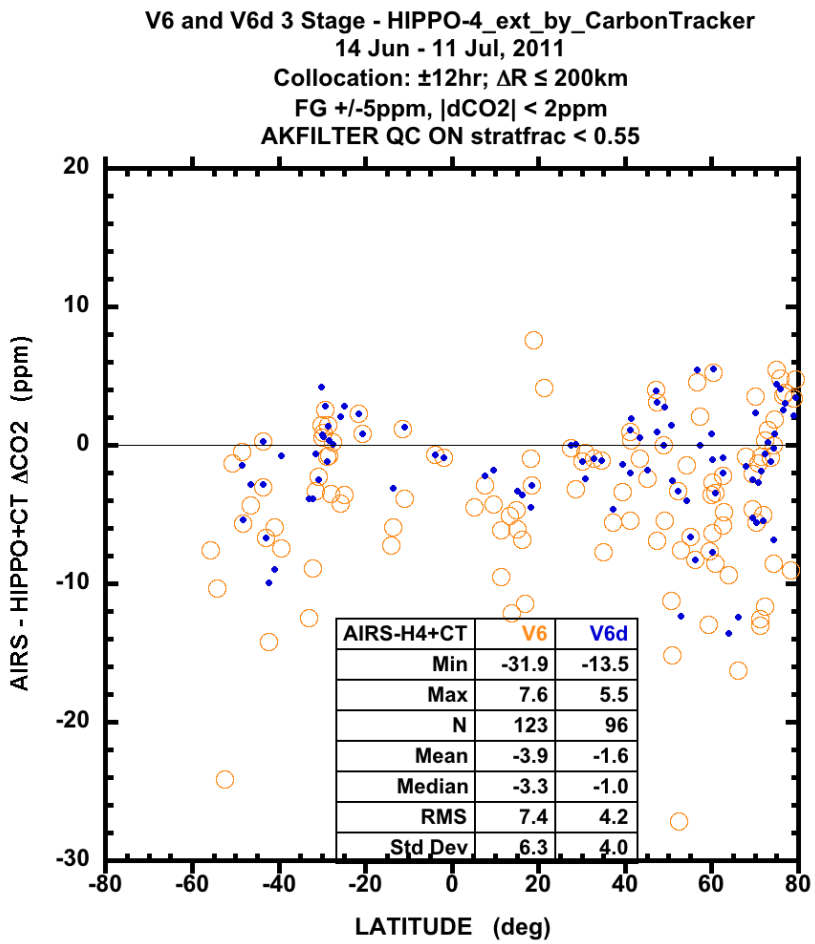
**V6d 13% fewer collocations and excises negative outliers**

**BOTH EXHIBIT NEGATIVE BIAS ABOVE 40° N**

**V6.28d 24% fewer collocations and Increases AIRS CO2 in SH**

# HIPPO-4 V6, V6d, V6.28 δCO2 vs Latitude

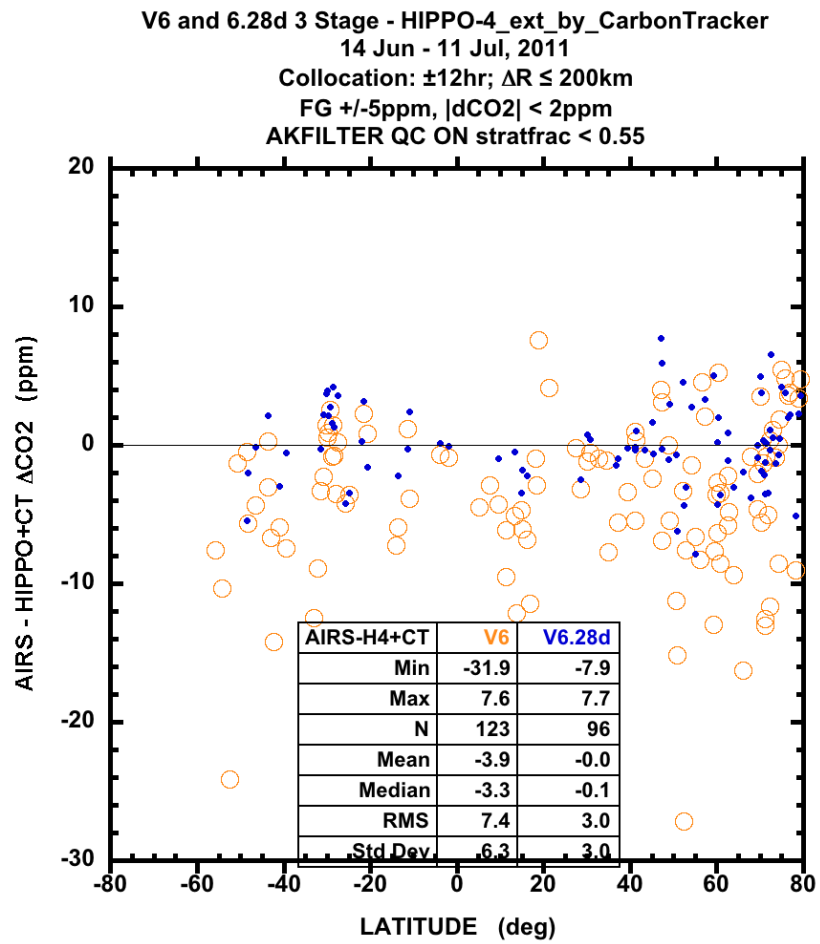
**V6 – no Tα, O3α QC filter**
**V6d – Tα, O3α filtered**




| AIRS-H4+CT | V6 | V6d |
|---|---|---|
| Min | -31.9 | -13.5 |
| Max | 7.6 | 5.5 |
| N | 123 | 96 |
| Mean | -3.9 | -1.6 |
| Median | -3.3 | -1.0 |
| RMS | 7.4 | 4.2 |
| Std Dev | 6.3 | 4.0 |

**V6d 22% fewer collocations and excises many negative outliers**

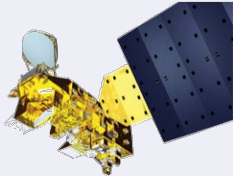
**V6 – no Tα, O3α QC filter**
**V628d – Tα, O3α filter**



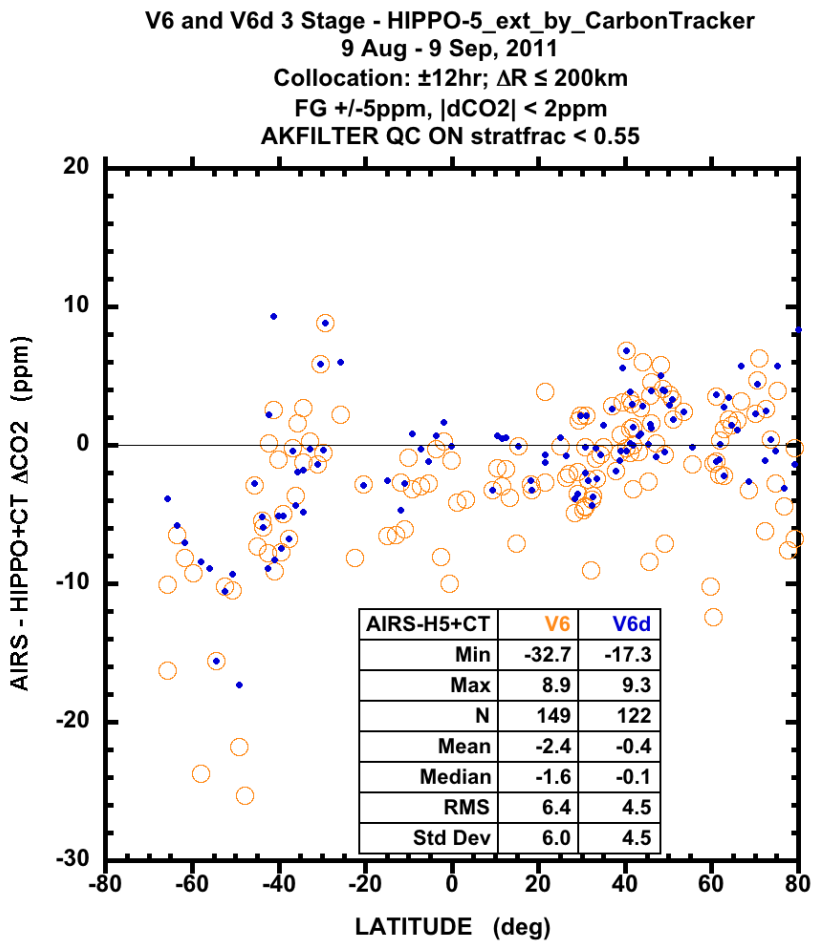

| AIRS-H4+CT | V6 | V6.28d |
|---|---|---|
| Min | -31.9 | -7.9 |
| Max | 7.6 | 7.7 |
| N | 123 | 96 |
| Mean | -3.9 | -0.0 |
| Median | -3.3 | -0.1 |
| RMS | 7.4 | 3.0 |
| Std Dev | 6.3 | 3.0 |

**V6.28d same yield as V6d and reduces scatter**

# HIPPO-5 V6, V6d, V6.28 δCO2 vs Latitude



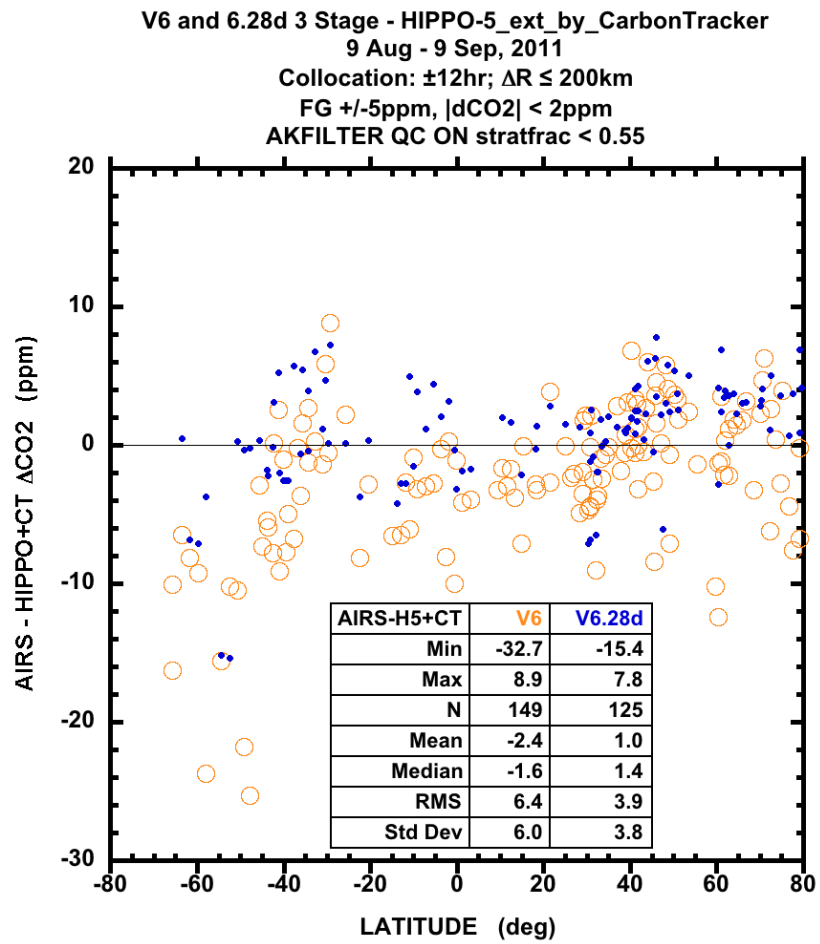
**V6 – no Tα, O3α QC filter**
**V6d – Tα, O3α filtered**




| AIRS-H5+CT | V6 | V6d |
|---|---|---|
| Min | -32.7 | -17.3 |
| Max | 8.9 | 9.3 |
| N | 149 | 122 |
| Mean | -2.4 | -0.4 |
| Median | -1.6 | -0.1 |
| RMS | 6.4 | 4.5 |
| Std Dev | 6.0 | 4.5 |

**V6d 18% fewer collocations and excises many negative outliers**

**V6 – no Tα, O3α QC filter**
**V628d – Tα, O3α filter**

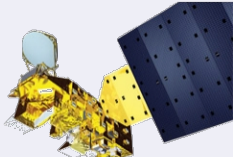



| AIRS-H5+CT | V6 | V6.28d |
|---|---|---|
| Min | -32.7 | -15.4 |
| Max | 8.9 | 7.8 |
| N | 149 | 125 |
| Mean | -2.4 | 1.0 |
| Median | -1.6 | 1.4 |
| RMS | 6.4 | 3.9 |
| Std Dev | 6.0 | 3.8 |

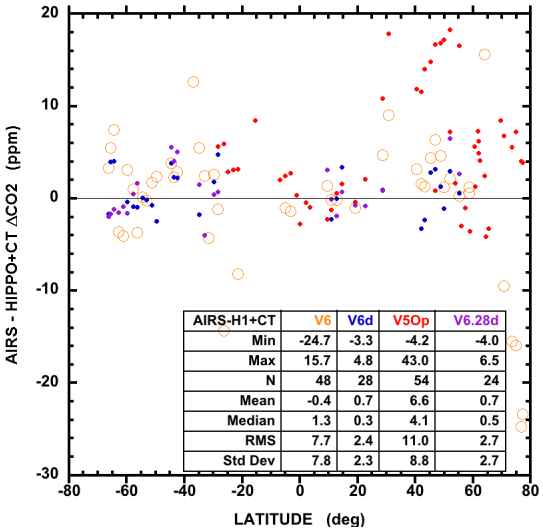
**V6.28d same yield as V6d**
**Reduced yield in SH**

Jet Propulsion Laboratory
California Institute of Technology

# V6, V6d , V6.28d and V5 Op vs HIPPO+CarbonTracker

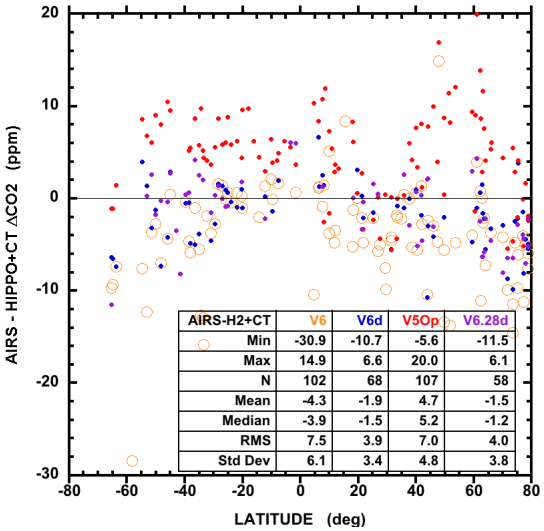


V6, V6d, V6.28d and V5Op 3 Stage - HIPPO-1_ext_by_CarbonTracker
9 Jan - 22 Jan, 2009
Collocation: ±12hr; ΔR ≤ 200km
(V5Op ±24hr; ΔR <= 500km)



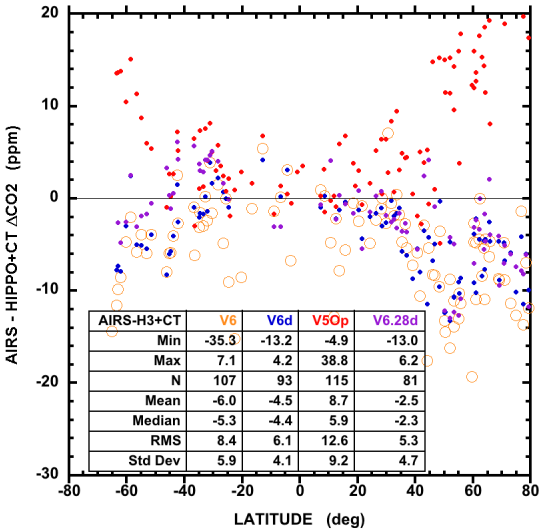

| AIRS-H1+CT | V6 | V6d | V5Op | V6.28d |
|---|---|---|---|---|
| Min | -24.7 | -3.3 | -4.2 | -4.0 |
| Max | 15.7 | 4.8 | 43.0 | 6.5 |
| N | 48 | 28 | 54 | 24 |
| Mean | -0.4 | 0.7 | 6.6 | 0.7 |
| Median | 1.3 | 0.3 | 4.1 | 0.5 |
| RMS | 7.7 | 2.4 | 11.0 | 2.7 |
| Std Dev | 7.8 | 2.3 | 8.8 | 2.7 |

V6, V6d, V6.28d and V5Op 3 Stage - HIPPO-2_ext_by_CarbonTracker
31 Oct - 22 Nov, 2009
Collocation: ±12hr; ΔR ≤ 200km
(V5Op ±24hr; ΔR <= 500km)



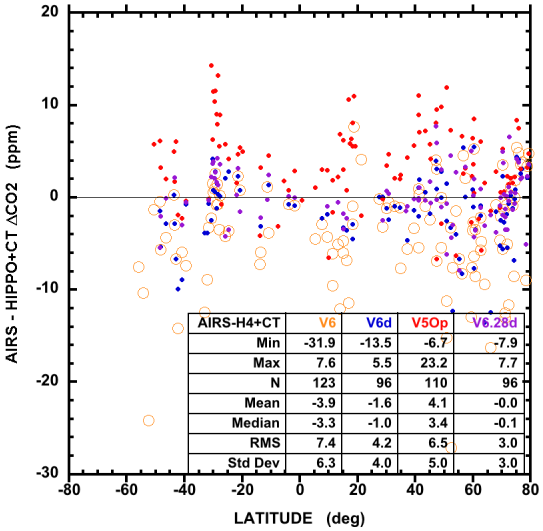

| AIRS-H2+CT | V6 | V6d | V5Op | V6.28d |
|---|---|---|---|---|
| Min | -30.9 | -10.7 | -5.6 | -11.5 |
| Max | 14.9 | 6.6 | 20.0 | 6.1 |
| N | 102 | 68 | 107 | 58 |
| Mean | -4.3 | -1.9 | 4.7 | -1.5 |
| Median | -3.9 | -1.5 | 5.2 | -1.2 |
| RMS | 7.5 | 3.9 | 7.0 | 4.0 |
| Std Dev | 6.1 | 3.4 | 4.8 | 3.8 |

V6, V6d, V6.28d and V5Op 3 Stage - HIPPO-3_ext_by_CarbonTracker
24 Mar - 16 Apr, 2010
Collocation: ±12hr; ΔR ≤ 200km
(V5Op ±24hr; ΔR <= 500km)



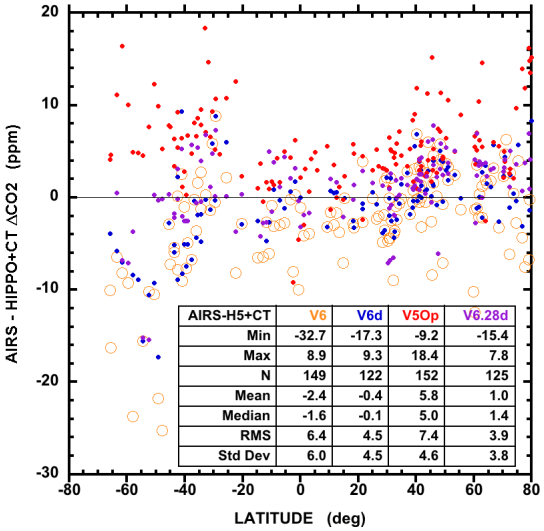

| AIRS-H3+CT | V6 | V6d | V5Op | V6.28d |
|---|---|---|---|---|
| Min | -35.3 | -13.2 | -4.9 | -13.0 |
| Max | 7.1 | 4.2 | 38.8 | 6.2 |
| N | 107 | 93 | 115 | 81 |
| Mean | -6.0 | -4.5 | 8.7 | -2.5 |
| Median | -5.3 | -4.4 | 5.9 | -2.3 |
| RMS | 8.4 | 6.1 | 12.6 | 5.3 |
| Std Dev | 5.9 | 4.1 | 9.2 | 4.7 |

V6, V6d, V6.28d and V5Op 3 Stage - HIPPO-4_ext_by_CarbonTracker
14 Jun - 11 Jul, 2011
Collocation: ±12hr; ΔR ≤ 200km
(V5Op ±24hr; ΔR <= 500km)

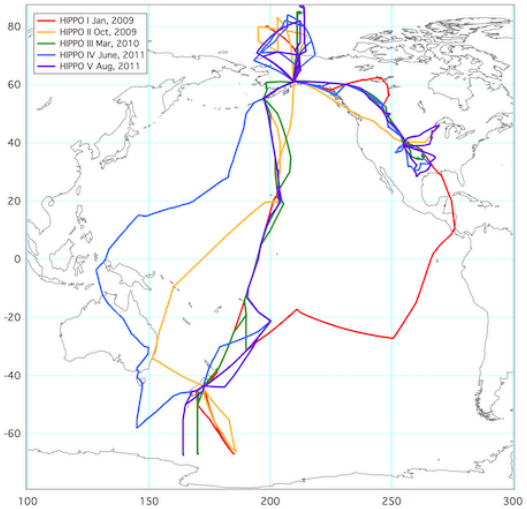



| AIRS-H4+CT | V6 | V6d | V5Op | V6.28d |
|---|---|---|---|---|
| Min | -31.9 | -13.5 | -6.7 | -7.9 |
| Max | 7.6 | 5.5 | 23.2 | 7.7 |
| N | 123 | 96 | 110 | 96 |
| Mean | -3.9 | -1.6 | 4.1 | -0.0 |
| Median | -3.3 | -1.0 | 3.4 | -0.1 |
| RMS | 7.4 | 4.2 | 6.5 | 3.0 |
| Std Dev | 6.3 | 4.0 | 5.0 | 3.0 |

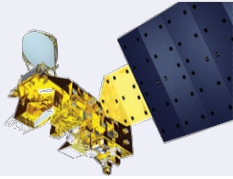
V6, V6d, V6.28d and V5Op 3 Stage - HIPPO-5_ext_by_CarbonTracker
9 Aug - 9 Sep, 2011
Collocation: ±12hr; ΔR ≤ 200km
(V5Op ±24hr; ΔR <= 500km)




| AIRS-H5+CT | V6 | V6d | V5Op | V6.28d |
|---|---|---|---|---|
| Min | -32.7 | -17.3 | -9.2 | -15.4 |
| Max | 8.9 | 9.3 | 18.4 | 7.8 |
| N | 149 | 122 | 152 | 125 |
| Mean | -2.4 | -0.4 | 5.8 | 1.0 |
| Median | -1.6 | -0.1 | 5.0 | 1.4 |
| RMS | 6.4 | 4.5 | 7.4 | 3.9 |
| Std Dev | 6.0 | 4.5 | 4.6 | 3.8 |



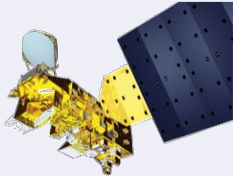
# Validation Results Relative to HIPPO+CT to those of V5 Op, V6, V6d, V6.28 and V6.28d



- V5 Op Product – Implementatation single stage with no AK QC
  - Bias relative to All 5 HIPPO+CT Campaigns
    - **Lat < -40° 55 collocations δCO2 = +6.3 ± 4.4**
    - **|Lat| < 40° 259 collocations δCO2 = +4.0 ± 4.4**
    - **Lat > +40° 224 collocations δCO2 = +8.0 ± 8.4**
- V6 Product - Implementation incorporating 3-stage retrieval and AK QC
  - Bias relative to All 5 HIPPO+CT Campaigns
    - **Lat < -40° 76 collocations δCO2 = -6.7 ± 8.2**
    - **|Lat| < 40° 231 collocations δCO2 = -2.2 ± 4.3**
    - **Lat > +40° 222 collocations δCO2 = -4.2 ± 7.1**
- V6d Product - Adds $T\alpha$, $O_3\alpha$ thresholding to V6 implementation
  - Bias relative to All 5 HIPPO+CT Campaigns
    - **Lat < -40° 63 collocations δCO2 = -3.7 ± 4.9**
    - **|Lat| < 40° 160 collocations δCO2 = -0.7 ± 2.7**
    - **Lat > +40° 184 collocations δCO2 = -2.0 ± 5.0**
- V6.28 Product (L2 essentially same as V6.22)
  - Implementation incorporating 3-stage retrieval and AK QC, ingests new L2
  - Bias relative to All 5 HIPPO+CT Campaigns
    - **Lat < -40° 74 collocations δCO2 = -4.0 ± 5.7**
    - **|Lat| < 40° 213 collocations δCO2 = -0.8 ± 5.2**
    - **Lat > +40° 211 collocations δCO2 = -2.6 ± 6.0**
- V6.28d Product
  - Adds $T\alpha$, $O_3\alpha$ to V6.28 run
  - Bias relative to All 5 HIPPO+CT Campaigns
    - **Lat < -40° 56 collocations δCO2 = -1.2 ± 4.4**
    - **|Lat| < 40° 153 collocations δCO2 = +0.4 ± 2.8**
    - **Lat > +40° 175 collocations δCO2 = -0.8 ± 4.7**

**RANK**
**according to bias**
**BEST**
**2nd**
**3rd**
**4th**
**WORST**

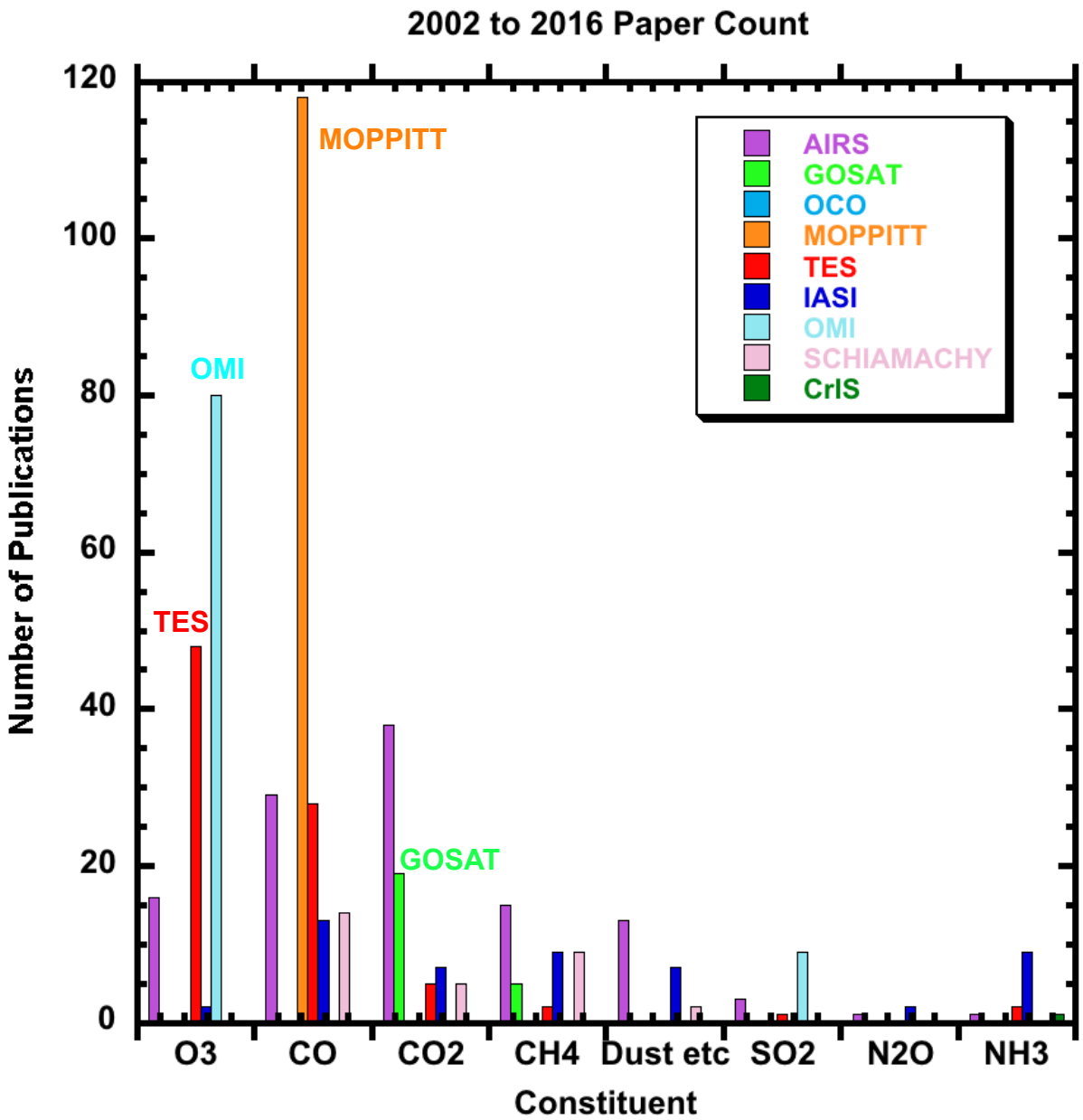
# Published Studies Bearing on $CO_2$ Transport Around the Globe



- 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.
  - 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." *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.
  - Kang, J-S et al. (2012), Estimation of surface carbon fluxes with an advanced data assimilation methodology, *JGR*, 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." *JAS,* 70, no. 1.
  - Jiang, X et al. (2013) "Influence of Stratospheric Sudden Warming on AIRS Mid-tropospheric CO2." *JAS,* 70, no. 8.
  - Pagano, T, et al. (2014) "Global variability of mid-tropospheric CO2 as measured by the Atmospheric Infrared Sounder", *JARS*, doi: 10.1117/1.JRS.8.084984.
  - Kumar, K et al. (2014) "On understanding the land–ocean CO2 contrast over the Bay of Bengal: A case study during 2009 summer monsoon." *Environmental Science and Pollution Research* 21, no. 7: 5066-5075.
  - Tiwari, Y et al. (2014), "Anomalous features of mid-tropospheric CO2 during Indian summer monsoon drought years." Atmospheric Environment 99 (2014): 94-103.
  - Xun Jiang, et al., (2015) "Modulation of Midtropospheric CO2 by the South Atlantic Walker Circulation." J. Atmos. Sci., 72, 2241–2247. doi: http://dx.doi.org/10.1175/JAS-D-14-0340.1 .
  - 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
  - Jiang, X., Crisp, D., **Olsen, E. T.,** Kulawik, S. S., Miller, C. E., Pagano, T. S., Liang, M., and Yung, Y. L. *(*2016*),* CO2 Annual and Semiannual Cycles From Multiple Satellite Retrievals and Models*.* Earth and Space Science*,* 2*, doi:* 10.1002/2014EA000045
  - 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. (2016) "An Intraseasonal Variability of mid-tropospheric CO2 over Winter Arctic.", *JGR* (submitted)

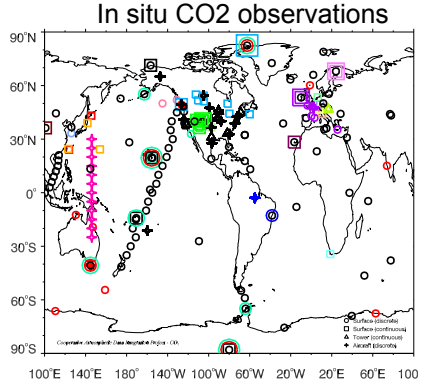
# Comparative Mission Publication Statistics for Trace Gases

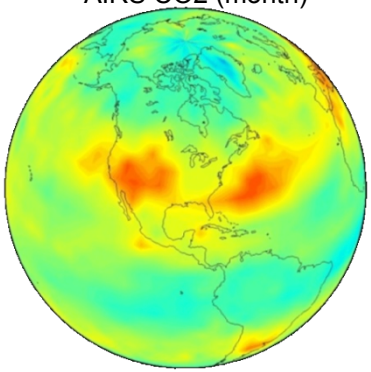


# Rationale for Retrieving Free Tropospheric $CO_2$

- 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, IASI, SCIAMACHY, TES, and now OCO-2)

In situ CO2 observations




AIRS CO2 (month)