

# AIRS Version 5 Release Tropospheric CO<sub>2</sub> Products

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## AIRS Version 5 Release Tropospheric CO<sub>2</sub> Products

### ***Introduction***

The AIRS Version 5 (V5) tropospheric CO<sub>2</sub> product is a retrieval of the weighted partial-column dry volume mixing ratio characterizing the mid- to upper-tropospheric CO<sub>2</sub> concentration. The product is derived by the technique of Vanishing Partial Derivatives (VPD) described in *Chahine et al.* [2005] and is reported at a nominal nadir resolution of 90 km x 90 km.

Beginning with an assumed CO<sub>2</sub> profile that is a linearly time-dependent global average constant volume mixing ratio throughout the atmosphere and the AIRS Level 2 products retrieved assuming that profile, the VPD derives the CO<sub>2</sub> by shifting the CO<sub>2</sub>, T, q and O<sub>3</sub> profiles and minimizing the residuals between the cloud-cleared radiances and those resulting from the forward calculation for selected sets of channels. The channel sets are selected to avoid contamination by surface emission (except in regions of high topography) and to localize the sensitivity to the profile perturbations to the pressure regime spanning 300 hPa to 700 hPa.

In normal practice, the AIRS Level 2 products ingested by the CO<sub>2</sub> post-processing retrieval stage are retrieved using the combination of the infrared instrument and a companion Advanced Microwave Sounding Unit (AMSU). The 5-7 year expected lifetime of AMSU based on NOAA experience is much shorter than that of the AIRS instrument, so an alternate Level 2 retrieval using only the infrared radiances (AIRS\_Only) was developed. The VPD retrieval ingests the combined IR/MW retrieval system products as standard practice.

AMSU Channel 5 (53.595 ± 0.115 GHz) noise equivalent differential temperature (NEdT) began to slowly increase in 2004, rising to 0.3 K in January 2008 and 0.4 K in March 2009. Subsequently, the degradation accelerated so that NEdT increased to 0.5 K in January 2010 and 0.8 K in December 2010. The acceleration continued, so that NEdT exceeded 1 K by February 2011. The V5 Level 2 combined IR/MW retrieval tests AMSU Channel 5 noise as part of its quality assurance algorithm; hence the L2 retrieval yield began to drop in late 2010. By January 2011 the loss in L2 yield was large enough to seriously degrade the CO<sub>2</sub> yield, and that processing was temporarily halted.

The V5 CO<sub>2</sub> post processing retrieval stage now ingests the AIRS Level 2 products that result from the AIRS\_Only retrieval. Testing of the CO<sub>2</sub> product retrieved ingesting the AIRS\_Only retrieved product and that retrieved ingesting the combined IR/MW retrieved product shows that the two are nearly equivalent. The CO<sub>2</sub> product has been reprocessed starting in January 2011 and released to the community. The test results are included in this documentation.



## AIRS Version 5 Release Tropospheric CO<sub>2</sub> Products

### The CO<sub>2</sub> Prior

The AIRS Level 2 products include cloud-cleared infrared radiances and retrieved profiles of atmospheric temperature  $T(p)$ , water vapor  $H_2O(p)$ , and ozone  $O_3(p)$  at a nominal nadir spatial resolution of 45 km. The V5 Level 2 retrieval algorithm used to retrieve these products assumes a global average linear time-variable CO<sub>2</sub> climatology throughout the atmosphere. This time-variable climatology is necessary to assure that the rapid transmittance algorithm employed to forward calculate radiances from the atmospheric physical state during the retrieval process remains in the linear regime for the lifetime of the mission [Maddy et al., 2008]. It is worth noting that this is the simplest possible climatology that achieves this desired result and it does not impose a seasonal or geospatial signal upon the measurements or retrievals. The linear relation is:

$$CO_{2\_clim}(t) = A + B \times (t - t_0) \quad (1)$$

Where  $CO_{2\_clim}(t)$  is the concentration of CO<sub>2</sub> everywhere in the atmosphere at date/time,  $t$ , in ppm, and

$$A = 371.92429$$

The date/time is expressed in year and fraction of year, i.e.,

$$t_0 = 2002.0$$

$$t = 2009.5 \text{ for the date and time of 1 July 2009 @ } 12^{hr} \text{ UT}$$

Although a CO<sub>2</sub> profile is part of V5, all elements are set to this climatology CO<sub>2</sub> value for the date and time of the AIRS Level 1B radiance measurements used for the Level 2 retrieval. The V5 algorithm does not retrieve CO<sub>2</sub>. That is left to a post-processing stage employing the VPD algorithm described later in this document and that post-processing stage uses the identical climatology as its prior.

## AIRS Version 5 Release Tropospheric CO<sub>2</sub> Products

### Access to AIRS Tropospheric CO<sub>2</sub> Product Files

The AIRS CO<sub>2</sub> product files may be freely downloaded from the Goddard Earth Sciences (GES) Data and Information Services Center (DISC). Although the Version 6 (V6) AIRS Level 2 data products are now released, the CO<sub>2</sub> product is still derived from the V5 AIRS Level 2 data products. The URL providing links to all methods of access to the V5 AIRS CO<sub>2</sub> data products is

<http://disc.sci.gsfc.nasa.gov/AIRS/data-holdings/by-data-product-v5>

The second table at the URL above provides links accessing the following AIRS V5 Level 2 (swath) CO<sub>2</sub> data products (select last column labeled **DataAccess**):

- AIRS\_AMSU (IR/MW) standard data product (AIRX2STC)
- AIRS\_Only (IR-Only) standard data product (AIRS2STC)
- AIRS\_AMSU (IR/MW) support data product (AIRX2SPC)
- AIRS\_Only (IR-Only) support data product (AIRS2SPC)

The third table at the URL above provides links accessing the following AIRS V5 Level 3 (gridded) CO<sub>2</sub> data products (select last column labeled **DataAccess**):

- AIRS\_AMSU (IR/MW) daily data product (AIRX3C2D)
- AIRS\_Only (IR-Only) daily data product (AIRS3C2D)
- AIRS\_AMSU (IR/MW) 8-day data product (AIRX3C28)
- AIRS\_Only (IR-Only) 8-day data product (AIRS3C28)
- AIRS\_AMSU (IR/MW) calendar monthly data product (AIRX3C2M)
- AIRS\_Only (IR-Only) calendar monthly data product (AIRS3C2M)

The **DataAccess** columns are URLs to pages for access via FTP, MIRADOR, OPENDAP, SSW and ECHO

The sample L2 swath and L3 grid data readers for all AIRS data products are provided with the AIRS V5 documentation package are available at the URL:

[http://disc.sci.gsfc.nasa.gov/AIRS/documentation/v5\\_docs](http://disc.sci.gsfc.nasa.gov/AIRS/documentation/v5_docs)

They are located in the 6<sup>th</sup> table at the URL above, titled, “**Data Product Readers**”.

## **AIRS Version 5 Release Tropospheric CO<sub>2</sub> Products**

### ***AIRS Mid-Tropospheric CO<sub>2</sub> Products***

The V5 Level 2 products and climatology CO<sub>2</sub> are assumed as the initial state for the VPD retrieval algorithm that separately determines the tropospheric CO<sub>2</sub> mixing ratio. A 2x2 array of adjacent AIRS Level 2 retrievals (2 adjacent FOVs in each of 2 adjacent scan lines) is processed together to retrieve an average value of CO<sub>2</sub> over their spatial extent. Thus the nominal spatial resolution of the VPD Level 2 CO<sub>2</sub> product at nadir is 90 km x 90 km, or approximately 1° x 1° on the Earth's surface. CO<sub>2</sub> retrievals must succeed for at least 3 of the 4 FOVs, and a spatial coherence quality assurance (QA) test requiring that the standard deviation for the (3 or 4) CO<sub>2</sub> retrievals be less than 2 ppm is applied. The retrievals that satisfy spatial coherence threshold are included in the Level 2 CO<sub>2</sub> standard product and those that do not do so are included in the Level 2 CO<sub>2</sub> support product.

There are three VPD Level 3 CO<sub>2</sub> products derived from the VPD Level 2 CO<sub>2</sub> standard product: daily, 8-day (one-half of the Aqua orbit repeat cycle), and calendar monthly (i.e., Jan, Feb, ..., Dec). The multi-day products are simply the arithmetic mean weighted by the counts of the daily data combined in each grid box, whose resolution is 2.5° in longitude and 2° in latitude.

The Level 3 CO<sub>2</sub> daily product contains information for a temporal period of 24 hours rather than midnight-to-midnight. The data included in the gridding on a particular day start at the international dateline and progress westward (as do the subsequent orbits of the Aqua satellite) so that neighboring gridded cells of data are no more than a swath of time apart (about 90 minutes). In the event that a scan line crosses the dateline, the data on either side are included in separate data sets, according to the appropriate date and UT. This ensures that data points in a grid box are always coincident in time. If the data were gridded using the midnight-to-midnight time-span, the start of the day and the end of the day could be in the same grid cell, producing an artificial time discontinuity. The earliest (initial column) Level 3 gridded cells are centered on the date line (the 180° E/W longitude boundary). When plotted, this produces a map with 0° longitude in the center of the image unless the bins are reordered. This method is preferred because the left (West) side of the image and the right (East) side of the image contain data farthest apart in time. The gridding scheme used to produce the Level 3 CO<sub>2</sub> products as well as all other AIRS Level 3 products is the same as used by the TOVS Pathfinder.

The retrievals based on AIRS\_AMSU (combined IR/MW) Level 2 data products and AIRS\_Only (IR-Only) Level 2 data products are written to separate data products. They are not combined into a single data product.

## AIRS Version 5 Release Tropospheric CO<sub>2</sub> Products

### CO<sub>2</sub> Product File Names, Shortnames and Sizes

The Level 2 and Level 3 CO<sub>2</sub> product files share the naming convention of all other AIRS data product files. The templates for file names are:

#### AIRS\_AMSU Level 2:

AIRS.YYYY.MM.DD.GGG.L2.CO2\_ppp.VER.CO2.PROCTAG.hdf

#### AIRS\_Only Level 2:

AIRS.YYYY.MM.DD.GGG.L2.CO2\_ppp\_IR.VER.CO2.PROCTAG.hdf

#### AIRS\_AMSU Level 3:

AIRS.YYYY.MM.DD.CO2pppNNN.VER.PROCTAG.hdf

#### AIRS\_Only Level 3:

AIRS.YYYY.MM.DD.CO2ppp\_IRNNN.VER.PROCTAG.hdf

IDEN	Level 2 Product	Level 3 Product
YYYY	Date year (i.e. 2009) of the measurement	Initial date year of time period
MM	Date month (i.e. 01->12) of the measurement	Initial date month of time period
DD	Date day of month (i.e. 01->31) of measurement	Initial date day of month of time period
GGG	Granule (001->240)	N/A
ppp	Standard or Support Product (Std or Sup)	Product (only Std) 001 for daily 008 for 8-day 028→031 for calendar month
NNN	N/A	
VER	Version of software used to create product (i.e., v5.4.11.0)	Version of S/W used to create product
PROCTAG	Processing tag	Processing tag

The following are examples of the product file names, shortnames and file sizes. The “X” in the shortnames indicates that the V5 Level 2 retrieval products ingested by the VPD algorithm were derived using the combined AIRS\_AMSU radiances. The “S” in the shortnames indicates that the V5 Level 2 retrieval products ingested by the VPD algorithm were derived using the AIRS\_Only radiances.

## **AIRS Version 5 Release Tropospheric CO<sub>2</sub> Products**

### **Example 1: Level 2 CO<sub>2</sub> Standard and Support Derived from AIRS\_AMSU**

#### ***L2 Standard Product file naming for granule 229 of September 6, 2002:***

**Name:** AIRS.2002.09.06.229.L2.CO2\_Std.v5.4.11.0.CO2.T09210175254.hdf

**Shortname:** AIRX2STC

**Size:** 312 KB

**Data Span:** Granule 229 of September 6, 2002

#### ***L2 Support Product file naming for granule 229 of September 6, 2002:***

**Name:** AIRS.2002.09.06.229.L2.CO2\_Sup.v5.4.11.0.CO2.T09210175254.hdf

**Shortname:** AIRX2STP

**Size:** 312 KB

**Data Span:** Granule 229 of September 6, 2002

### **Example 2: Level 2 CO<sub>2</sub> Standard and Support Derived from AIRS\_Only**

#### ***L2 Standard Product file naming for granule 229 of September 6, 2011:***

**Name:** AIRS.2011.09.06.229.L2.CO2\_Std\_IR.v5.4.11.0.CO2.T09210175254.hdf

**Shortname:** AIRS2STC

**Size:** 312 KB

**Data Span:** Granule 229 of September 6, 2011

#### ***L2 Support Product file naming for granule 229 of September 6, 2011:***

**Name:** AIRS.2011.09.06.229.L2.CO2\_Sup\_IR.v5.4.11.0.CO2.T09210175254.hdf

**Shortname:** AIRS2STP

**Size:** 312 KB

**Data Span:** Granule 229 of September 6, 2011

### **Example 3: Level 3 CO<sub>2</sub> Standard Daily, 8-Day, Calendar Monthly Derived from AIRS\_AMSU**

#### ***L3 Daily Product file for September 5, 2002:***

**Name:** AIRS.2002.09.05.L3.CO2Std001.v5.4.12.67.X09261111805.hdf

**Shortname:** AIRX3C2D

**Size:** 412 KB

**Data Span:** September 5, 2002

## **AIRS Version 5 Release Tropospheric CO<sub>2</sub> Products**

### ***L3 8-Day Product file for 1→8 September, 2002:***

**Name:** AIRS.2002.09.01.L3.CO2Std008.v5.4.12.65.X09260131026.hdf

**Shortname:** AIRX3C28

**Size:** 616 KB

**Data Span:** September 1, 2002 through September 8, 2002

### ***L3 Calendar Monthly Product file for September, 2002:***

**Name:** AIRS.2002.09.01.L3.CO2Std030.v5.4.12.65.X09260130847.hdf

**Shortname:** AIRX3C2M

**Size:** 596 KB

**Data Span:** Calendar month September 2002

### **Example 4: Level 3 CO<sub>2</sub> Standard Daily, 8-Day, Calendar Monthly Derived from AIRS\_Only**

### ***L3 Daily Product file for September 5, 2011:***

**Name:** AIRS.2011.09.05.L3.CO2Std\_IR001.v5.4.12.67.X09261111805.hdf

**Shortname:** AIRS3C2D

**Size:** 412 KB

**Data Span:** September 5, 2011

### ***L3 8-Day Product file for 1→8 September, 2011:***

**Name:** AIRS.2011.09.01.L3.CO2Std\_IR008.v5.4.12.65.X09260131026.hdf

**Shortname:** AIRS3C28

**Size:** 616 KB

**Data Span:** September 1, 2011 through September 8, 2011

### ***L3 Calendar Monthly Product file for September, 2011:***

**Name:** AIRS.2011.09.01.L3.CO2Std\_IR030.v5.4.12.65.X09260130847.hdf

**Shortname:** AIRS3C2M

**Size:** 596 KB

**Data Span:** Calendar month September 2011

## AIRS Version 5 Release Tropospheric CO<sub>2</sub> Products

### Content of L2 CO<sub>2</sub> Standard Product Files and Support Product Files

A total of 240 Level 2 CO<sub>2</sub> Standard Product Files and Level 2 CO<sub>2</sub> Support Product Files are produced each day, just as for the AIRS Level 2 physical retrieval products. They contain dimension fields, attribute fields and data fields. The data field is comprised of a single swath named **CO2**.

#### Level 2 Dimension Fields

Name	Type	Value	Description
Track	32-bit INT	22	Dimension along track for retrieval positions
XTrack	32-bit INT	15	Dimension across track for retrieval positions
AvgKernDim	32-bit INT	100	Dimension of averaging kernel array for each retrieval

#### Level 2 Attribute Fields

Name	Type	Dimensions	Description
PresLvls	32-bit FLT	[101]	Pressure levels, ordered from TOA to surface (hPa)
PresLyrs	32-bit FLT	[100]	Pressure layers, equal to geometrical mean of the pressure levels bounding the layer (hPa)
CO2retType	STRING	[15,22]	Final QA applied to separate standard from support product <b>Standard:</b> "CO2 stddev >= 0 and <= 2" <b>Support:</b> "CO2 stddev > 2"
CO2retNum	32-bit INT	[1]	# of CO2 retrievals in granule (maximum possible = 330)

## AIRS Version 5 Release Tropospheric CO<sub>2</sub> Products

### Level 2 Data Fields

Name	Type	Dimensions	Description
Latitude	32-bit FLT	[15,22]	Latitude (deg)
Longitude	32-bit FLT	[15,22]	Longitude (deg, +E/-W)
Time	32-bit FLT	[15,22]	UT (hr, 0.0 -> 23.99)
Year	32-bit INT	[15,22]	Year (i.e., 2009)
Month	32-bit INT	[15,22]	Month (1 -> 12)
Day	32-bit INT	[15,22]	Day of month (1 -> 31)
Hour	32-bit INT	[15,22]	UT HR (0 -> 23)
Minute	32-bit INT	[15,22]	UT MIN (0 -> 59)
Seconds	32-bit FLT	[15,22]	UT SEC (0.0 -> 59.9999)
LandFrac	32-bit FLT	[15,22]	Fraction FOV not water (unitless, 0.0 -> 1.0)
CO2ret	32-bit FLT	[15,22]	Retrieved CO2 (mole fraction)
CO2std	32-bit FLT	[15,22]	CO2 error measure by spatial coherence QA (mole fraction)
Solzen	32-bit FLT	[15,22]	Solar zenith angle (deg, 0.0 -> 180.0)
AvgKern	32-bit FLT	[100,15,22]	Averaging kernel, ordered from TOA to surface at preslyrs (unitless)



## AIRS Version 5 Release Tropospheric CO<sub>2</sub> Products

### Contents of Level 3 CO<sub>2</sub> Product Files

The L2 CO<sub>2</sub> Standard Product Files are binned on 2° latitude x 2.5° longitude grids to create daily, 8-day and calendar monthly L3 products. Users can combine the contents of multiple daily files to create multi-day averages over any desired period. The data field is comprised of a single grid named **CO2**.

#### Level 3 Dimension Fields

Name	Type	Value	Description
LatDim	32-bit INT	91	Number of latitude intervals (width of bins is 2 deg in latitude, save for one bin nearest to each pole, where they are 1°)
LonDim	32-bit INT	144	Number of longitude intervals (width of bins is 2.5 deg in longitude)

## AIRS Version 5 Release Tropospheric CO<sub>2</sub> Products

### Level 3 Attribute Fields

Name	Type	Dimensions	Description
Year	32-bit INT	[4]	First element is integer year of initial day for data included in the product file(i.e., 2009)
Month	32-bit INT	[4]	First element is integer month of initial day for data included in the product file (1 -> 12)
Day	32-bit INT	[1]	The day of month of the initial day for data included in the product file (1 -> 31)
NumDays	32-bit INT	[1]	The number of consecutive days over which data are averaged in the product
PresLvls	32-bit FLT	[101]	Pressure levels, ordered from TOA to surface (hPa)
PresLyrs	32-bit FLT	[100]	Pressure layers, equal to geometrical mean of the pressure levels bounding the layer (hPa)
CO2retType	STRING	[15,22]	Final QA applied to separate standard from support product <b>Standard:</b> "CO2 stddev >= 0 and <= 2" <b>Support:</b> "CO2 stddev > 2"
CO2retNum	32-bit INT	[1]	# of CO2 retrievals in granule (maximum possible = 330)

## AIRS Version 5 Release Tropospheric CO<sub>2</sub> Products

### Level 3 Data Fields

Name	Type	Dimensions	Description
Latitude	32-bit FLT	[144,91]	Latitude of center of bin (deg)
Longitude	32-bit FLT	[144,91]	Longitude of center of bin (deg, +E/-W)
mole_fraction_of_carbon_dioxide_in_free_troposphere	32-bit FLT	[144,91]	VMR (unitless)
mole_fraction_of_carbon_dioxide_in_free_troposphere_sdev	32-bit FLT	[144,91]	VMR (unitless)
mole_fraction_of_carbon_dioxide_in_free_troposphere_count	32-bit INT	[144,91]	(unitless)

### Quality Indicators

There are no specific quality indicators for the Level 2 CO<sub>2</sub> products other than **CO2std**, the QA error measure for spatial coherence over the 2x2 array of AMSU FOVs over which individual retrievals were combined to arrive at the final product. The Level 2 CO<sub>2</sub> Standard Product contains the retrievals meeting the criterion that  $CO2std \leq 2$  ppm, and retrievals not satisfying that threshold are placed in the Level 2 CO<sub>2</sub> Support Product. The Level 3 CO<sub>2</sub> Product is derived from the Level 2 Standard Product.

As described in the following section on data processing, the AIRS V5 Level 2 retrievals are filtered according to one of their internal quality factors, **PGood**, as well as the retrieved tropopause pressure, **PTrop**. Only AMSU FOVs satisfying the condition

$$(P_{Good} - P_{Trop}) > 200 \text{ hPa} \quad (2)$$

are passed to the CO<sub>2</sub> retrieval post-processing algorithm. This test ensures that the temperature profile is of sufficient quality from TOA to a level in the atmospheric column at least 200 hPa below the tropopause. Tests are also applied to excise data that may be contaminated by surface emission.

## **AIRS Version 5 Release Tropospheric CO<sub>2</sub> Products**

### **Caveats**

Guards against effects of surface emission have been built into the CO<sub>2</sub> retrieval post-processing algorithm, but it is possible that some adverse impact may remain for extreme topographies, e.g. the Andes mountain range, the Himalayan mountain range and highlands, and the Greenland ice sheet. Caution should be exercised when using retrievals over those areas.

The algorithm depends upon the AIRS Level 2 temperature profile being sufficiently accurate, as it does not allow large perturbations. It will report erroneous results if the Level 2 temperature profile is substantially biased in the lower troposphere, as may occur over very cold snow/ice fields, or if the cloud-clearing is incorrect (as may happen when continuous low stratus is present).

### **Recommended Supplemental User Documentation**

V5\_Data\_Release\_UG.pdf  
V5\_L2\_Standard\_Product\_QuickStart.pdf  
V5\_Level2\_Cloud-Cleared\_Radiances.pdf  
V5\_L2\_Standard\_Pressure\_Levels.pdf  
V5\_L2\_Support\_Pressure\_Levels.pdf  
V5\_L2\_Quality\_Control\_and\_Error\_Estimation.pdf  
V5\_CalVal\_Status\_Summary.pdf  
V5\_Retrieval\_Channel\_Sets.pdf

### ***Data Processing***

The VPD retrieval is a post-processing algorithm that ingests the AIRS Level 2 products. In brief, the VPD CO<sub>2</sub> solution for an AIRS Level 2 retrieval spot is obtained by an iterative process that minimizes the RMS difference between the Level 2 cloud-cleared radiances and radiances computed from the retrieved Level 2 atmospheric state for selected CO<sub>2</sub> channels in the 15  $\mu$ m band. The process begins with the AIRS derived Level 2 atmospheric state and then proceeds to separately perturb the T(p), H<sub>2</sub>O(p), O<sub>3</sub>(p), and CO<sub>2</sub> by shifting the profiles. The solution is obtained when the RMS of the radiance residuals for each channel set are minimized. The iterative process requires that the CO<sub>2</sub> radiance residual RMS decreases monotonically with iteration step. If this requirement is not satisfied, the retrieval is marked failed and filled with -9999.

## AIRS Version 5 Release Tropospheric CO<sub>2</sub> Products

The AIRS Level 2 tropospheric CO<sub>2</sub> product is the average of the solutions for a 2 x 2 array of adjacent AIRS Level 2 retrieval spots, covering a 90 km x 90 km area at nadir. Retrievals for which the solutions for the 2 x 2 arrays satisfy a spatial coherence QA that requires agreement of the separate retrievals to be within 2 ppm in an RMS sense are included in the standard product (AIRX2STC; AIRS2STC). Retrievals that fail this QA test are included in the support product (AIRX2STP; AIRS2STP).

The AIRS Level 3 tropospheric CO<sub>2</sub> products are derived by binning the Level 2 standard product retrievals in a grid of spatial resolution 2° in latitude by 2.5° in longitude over daily, 8-day and calendar monthly time spans. The user may easily generate custom time spans by combining one or more of these products.

## VPD Retrieval of Tropospheric CO<sub>2</sub>

Researchers have applied various methods to retrieve CO<sub>2</sub> using AIRS data [Chahine *et al.*, 2005 and 2008; Engelen *et al.*, 2005 and 2009; Maddy *et al.*, 2008; Strow *et al.*, 2008]. The tropospheric CO<sub>2</sub> products released by the AIRS Project through the GES DISC are derived by means of the VPD method of Chahine *et al.* [2005]. The VPD retrieval is a post-processing algorithm applied to an AIRS Level 2 retrieval satisfying the criterion, (PGood-PTrop) > 200 hPa.

We have constrained the V5 VPD solution by minimizing the variance, reducing the amplitude of oscillations vs. latitude, of the annual rates of growth between ± 60° latitudes, for the period from 1/2003-12/2008. This is achieved by adjusting the Level 2 cloud-cleared radiances by  $-15.24 \times (t - t_0)$  mK where  $t_0$  is January 1, 2003 (i.e. 2003.0) and  $t$  is the date of measurement expressed as a fractional year.

The VPD method is based on a general property of the total differential of multi-variable functions: at the point of local minimum (or maximum) the first partial derivatives of the function with respect to each unknown must individually vanish. The VPD CO<sub>2</sub> solution is obtained by an iterative process that minimizes the RMS residuals between the Level 2 cloud-cleared radiances and forward-computed radiances from the retrieved Level 2 atmospheric state for selected channels. The process begins with the AIRS V5 retrieved Level 2 atmospheric state and CO<sub>2</sub> climatology and then separately perturbs the T(p), H<sub>2</sub>O(p), O<sub>3</sub>(p), and CO<sub>2</sub>. The solution is obtained at the point where the partial derivatives of the channels with respect to T(p), H<sub>2</sub>O(p), O<sub>3</sub>(p), and CO<sub>2</sub> are individually equal to zero (minimized). The auxiliary T(p), H<sub>2</sub>O(p), O<sub>3</sub>(p) channels are used to accelerate the iteration process, i.e., reducing the number of iterations required. The solution is obtained when the residuals are individually minimized. Table I summarizes the IR channels whose cloud-cleared radiances are employed in the VPD retrieval.

## AIRS Version 5 Release Tropospheric CO<sub>2</sub> Products

T(p)		H <sub>2</sub> O(p)		O <sub>3</sub> (p)		CO <sub>2</sub>	
Chan	$\nu$ (cm <sup>-1</sup> )	Chan	$\nu$ (cm <sup>-1</sup> )	Chan	$\nu$ (cm <sup>-1</sup> )	Chan	$\nu$ (cm <sup>-1</sup> )
145	691.391	1616	1420.874	203	707.562	192	704.436
151	693.029	1621	1423.756	208	708.992	198	706.137
155	694.125	1646	1438.342	219	712.160	209	709.279
157	694.674	1673	1471.292	222	713.029	210	709.566
172	698.823	1711	1495.124	225	713.900	212	710.141
183	701.899	1744	1516.448	240	718.288	214	710.716
188	703.306	1745	1517.104	319	741.599	215	711.005
244	719.467	1797	1565.797	321	742.227	216	711.293
		1802	1569.288			217	711.582
		1808	1573.498			218	711.871
		1813	1577.022			228	714.773
		1825	1585.544			239	717.994
		1842	1597.769			250	721.244
		1854	1606.509				

Table I - List of channels used by the VPD iterative algorithm for the CO<sub>2</sub> retrieval.

Evaluation of the relative sensitivity of TOA radiances to the perturbation of T(p), H<sub>2</sub>O(p), O<sub>3</sub>(p), and CO<sub>2</sub> lead to the choice of two spectral ranges for use in the VPD retrieval that minimize errors due to aerosols, non-LTE effects and possible systematic differences over a broad spectral range. The range 690-742 cm<sup>-1</sup> is well-suited for selecting the channel set to retrieve the CO<sub>2</sub> mixing ratio and the two auxiliary channel sets for temperature and ozone. The range 1420-1607 cm<sup>-1</sup> is best suited for selecting the auxiliary channel set for water vapor. The three auxiliary sets are required to separate the interdependence of temperature, water vapor and ozone on each other and on CO<sub>2</sub>. Specifically, since all IR channels depend upon temperature, we select the CO<sub>2</sub> channels to have a strong dependence on CO<sub>2</sub> and a weak dependence upon O<sub>3</sub> and H<sub>2</sub>O. Similarly, we choose the H<sub>2</sub>O and O<sub>3</sub> channels to have a weak dependence on CO<sub>2</sub> and upon each other. For instance, a change of 10% in either the water vapor or ozone profiles results in a radiance change that is less than that due to a change of 1 ppm in CO<sub>2</sub> volume mixing ratio. The auxiliary set for temperature is selected to have a weak dependence upon CO<sub>2</sub>.

## AIRS Version 5 Release Tropospheric CO<sub>2</sub> Products

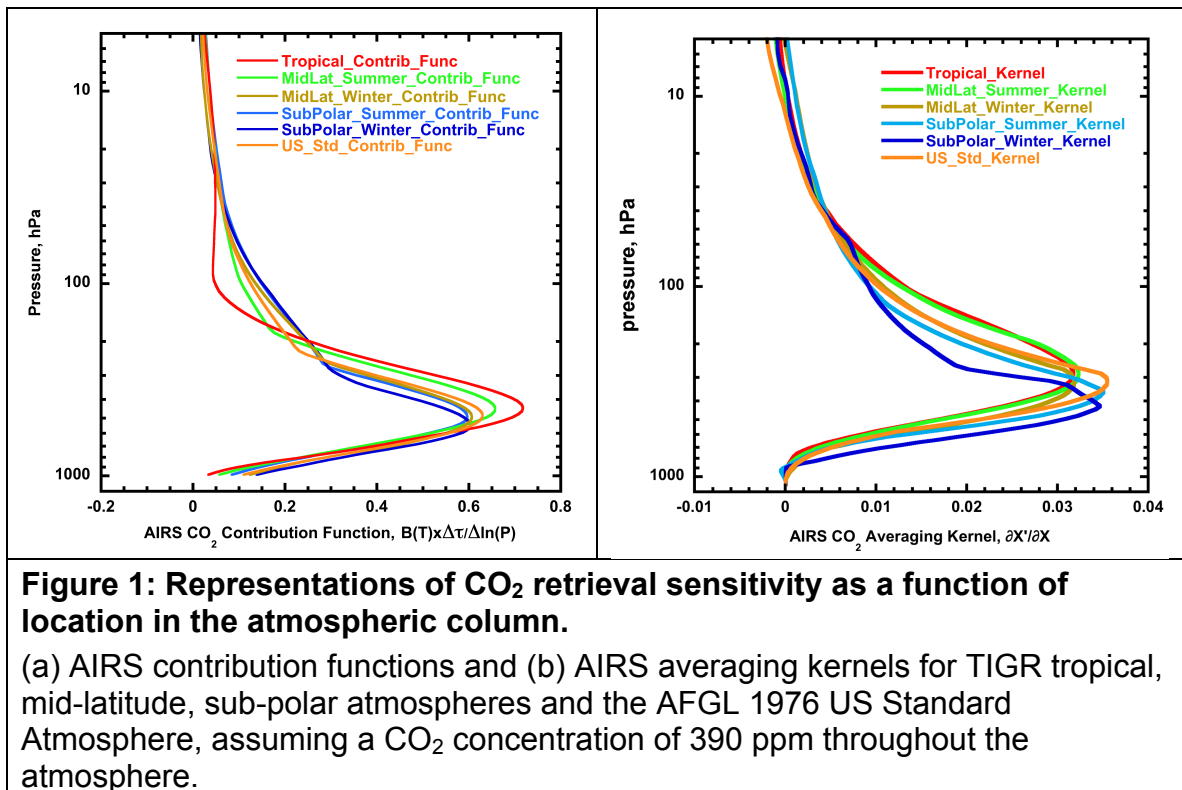
Figure 1 depicts representative AIRS vertical contribution functions and averaging kernels for the Thermodynamic Initial Guess Retrieval (TIGR) database [Chedin *et al.*, 1985] tropical, mid-latitude summer, sub-polar winter, and Air Force Geophysical Laboratory (AFGL) 1976 US standard atmospheres [Anderson *et al.*, 1986]. The contribution function is the derivative of the atmospheric transmission function with respect the natural logarithm of the pressure

$$C(v, T, p) = B(v, T, p) \times \frac{\partial \tau(v, p)}{\partial \ln(p)} \quad (3)$$

and quantifies the emitted radiation arising from the various layers in the atmosphere. It is an essential parameter in the physical inverse solution of the radiative transfer equation, used in the AIRS Level 2 retrievals. On the other hand, the averaging kernel

$$AK = \frac{\partial X'(p)}{\partial X(p)} \quad (4)$$

defines the layers in the atmosphere over which a perturbation of CO<sub>2</sub> at a given level is propagated in retrieval by estimation techniques and in data assimilation (Rodgers, 2000).



The VPD algorithm necessarily computes the contribution function at each iteration step during the retrieval as part of the forward calculation of radiances for the atmospheric state. The final step in the CO<sub>2</sub> retrieval is to derive the averaging kernel by sequentially perturbing each of the 100 layers of the atmospheric profile. The result is the theoretical change of the apparent mixing ratio of the total column that results from a perturbation at each atmospheric level, which indicates the part of the atmosphere to which our retrieved CO<sub>2</sub> applies. Depending upon the atmosphere, AIRS peak sensitivity to changes in CO<sub>2</sub> as a function of pressure, shown by the averaging kernels, occurs at 285 hPa (tropical) and 425 hPa (polar), and the kernel width at half-maximum varies from spanning 120 hPa to 515 hPa (tropical) to spanning 235 hPa to 640 hPa (polar).

The V5 implementation of the VPD algorithm does not solve for contribution to the radiances from surface emissions and steps have been taken to avoid complications due to variable surface emissivity and surface temperature. As can be seen in Figure 1, the infrared channels used in the retrieval have been chosen to minimize sensitivity to the surface temperature and surface emissivity. The implementation of the VPD algorithm avoids contamination by surface emissions by calculating the radiance contribution from the surface to each channel at each iteration step and rejecting channels in which the surface contribution to the outgoing radiance is larger than 50 mK. The net error in the

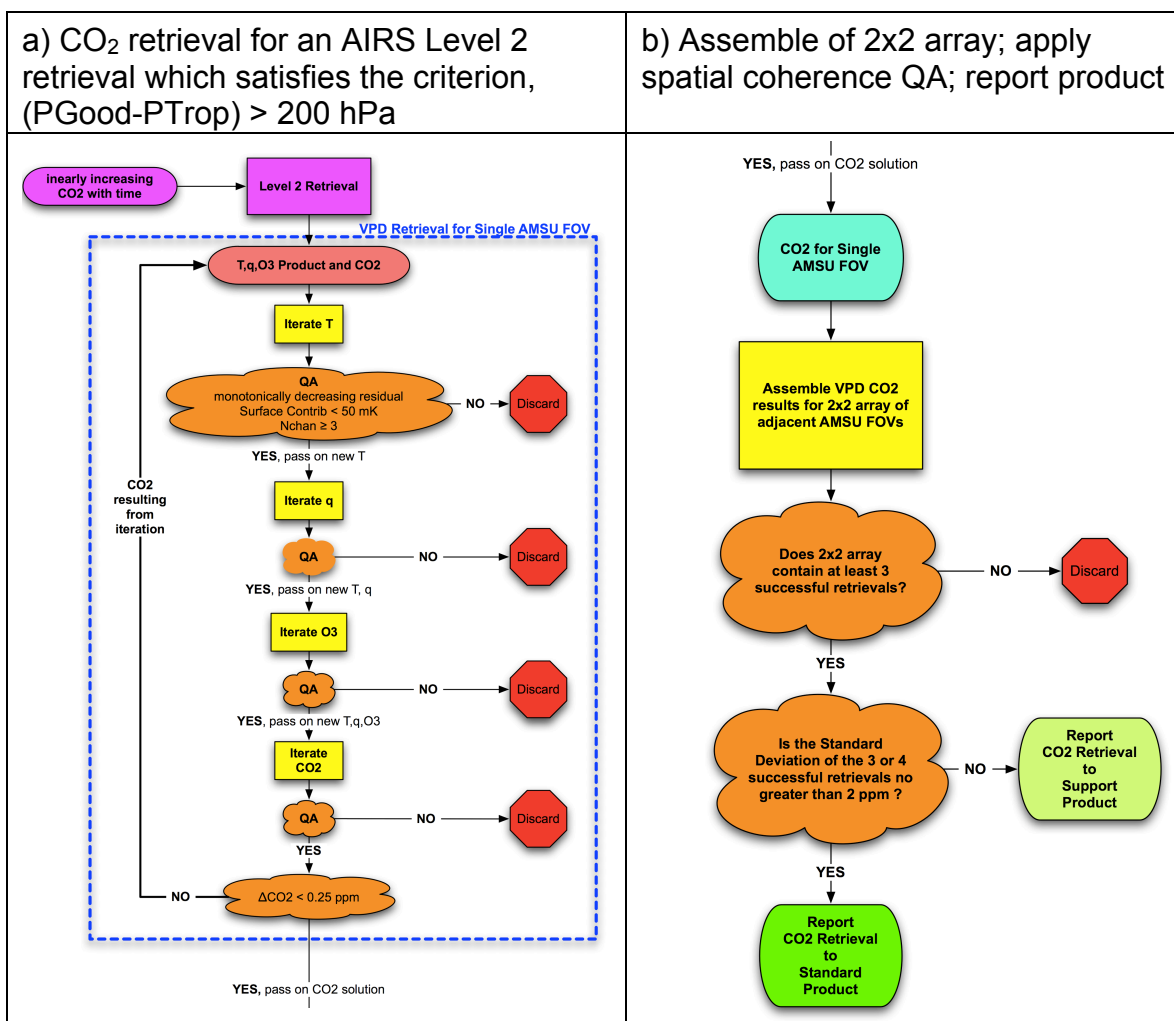


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surface emission as determined from AIRS Level 2 products is less than 2%, which is equivalent to 1 mK. Channels for which the surface contribution is found to exceed 50 mK are discarded. If fewer than three of the thirteen CO<sub>2</sub> channels used by the VPD algorithm survive, the retrieval is terminated and results discarded.

The AIRS contribution functions have tails that intrude into the stratosphere, more so in the polar regions where the tropopause height is lower. The stratospheric air is older than that of the troposphere by an amount that varies with latitude [Boering *et al.*, 1996; Waugh and Hall, 2002; Morgan *et al.*, 2004; Shia *et al.*, 2006; Stiller *et al.*, 2012]. We have investigated the impact on the AIRS CO<sub>2</sub> tropospheric product and found that incorporation of a correction would result in a latitudinally dependent increase, varying from zero at the equator and approaching 3 ppm polarward of ~ 80°. This effect is seasonally dependent and we have elected not to include a correction in the V5 released CO<sub>2</sub> products. Our current estimate of the correction is based on the fraction of the radiance originating above the tropopause with respect to the total radiance.

Figure 2 is a block diagram of the processing flow for the VPD algorithm. Figure 2a depicts the steps in the retrieval of CO<sub>2</sub> within a single AMSU FOV, whereas Figure 2b depicts the averaging of retrievals in the 2x2 array of AMSU FOVs to arrive at a reported product and the final QA step to place the report in the Level 2 CO<sub>2</sub> Standard Product or the Level 2 CO<sub>2</sub> Support Product.



**Figure 2: Block diagram of VPD post-processing retrieval of tropospheric CO<sub>2</sub>.**

Iterative solution is calculated for each AIRS Level 2 retrieval at a spatial resolution of an AMSU FOV; the reported retrieval is over a field comprised of a 2x2 array of AMSU FOVs. Radiance residuals must monotonically decrease at each iteration step or the solution is discarded.

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The VPD method is based on Gauss' method for finding the local minimum on an n-dimensional surface. It is based on a general property of the total differential of multi-variable functions: at the point of local minimum (or maximum) the first partial derivatives of the function with respect to each unknown must individually vanish. Since the goal of all retrieval methods is to minimize the residual difference in a least squares sense between measured and computed spectra, we write

$$G^{(n)} = \sum_v [\theta_M(v) - \theta_c^{(n)}(v)]^2 \quad (5)$$

where  $G^{(n)}$  is a multi-variable function of temperature, ozone, water vapor, carbon dioxide, and surface emission,  $\theta_M(v)$  is the measured brightness temperature at frequency  $v$  (after eliminating the effects of clouds),  $\theta_c^{(n)}(v)$  is the computed brightness temperature and  $n$  is the order of iteration.

To minimize the residual function  $G$  we express its total differential as

$$dG = \frac{\partial G}{\partial X_1} dX_1 + \frac{\partial G}{\partial X_2} dX_2 + \frac{\partial G}{\partial X_3} dX_3 + \frac{\partial G}{\partial X_4} dX_4 \quad (6)$$

Where  $X = [X_1, X_2, X_3, X_4]$  is the solution vector and require  $dG$  to be minimized.

Equation (6) is necessary for a minimum to exist but not sufficient for retrieving a unique solution.

To achieve uniqueness we determine the local minimum point where each of the first partial derivatives vanishes individually. Note that variables  $[X_1, X_2, X_3, X_4]$  are linearly independent in the AIRS Radiative Transfer Algorithm used to compute  $\theta_c^{(n)}(v)$ .

$$\frac{\partial G}{\partial X_1} = 0, \frac{\partial G}{\partial X_2} = 0, \frac{\partial G}{\partial X_3} = 0, \frac{\partial G}{\partial X_4} = 0 \quad (7)$$

where  $X_1$  may represent CO<sub>2</sub>(p),  $X_2$  represents T(p),  $X_3$  represents O<sub>3</sub>(p) and  $X_4$  represents H<sub>2</sub>O(p).

Condition (7) is both necessary and (ideally) sufficient to retrieve a local minimum (or maximum) for the solution of CO<sub>2</sub>.

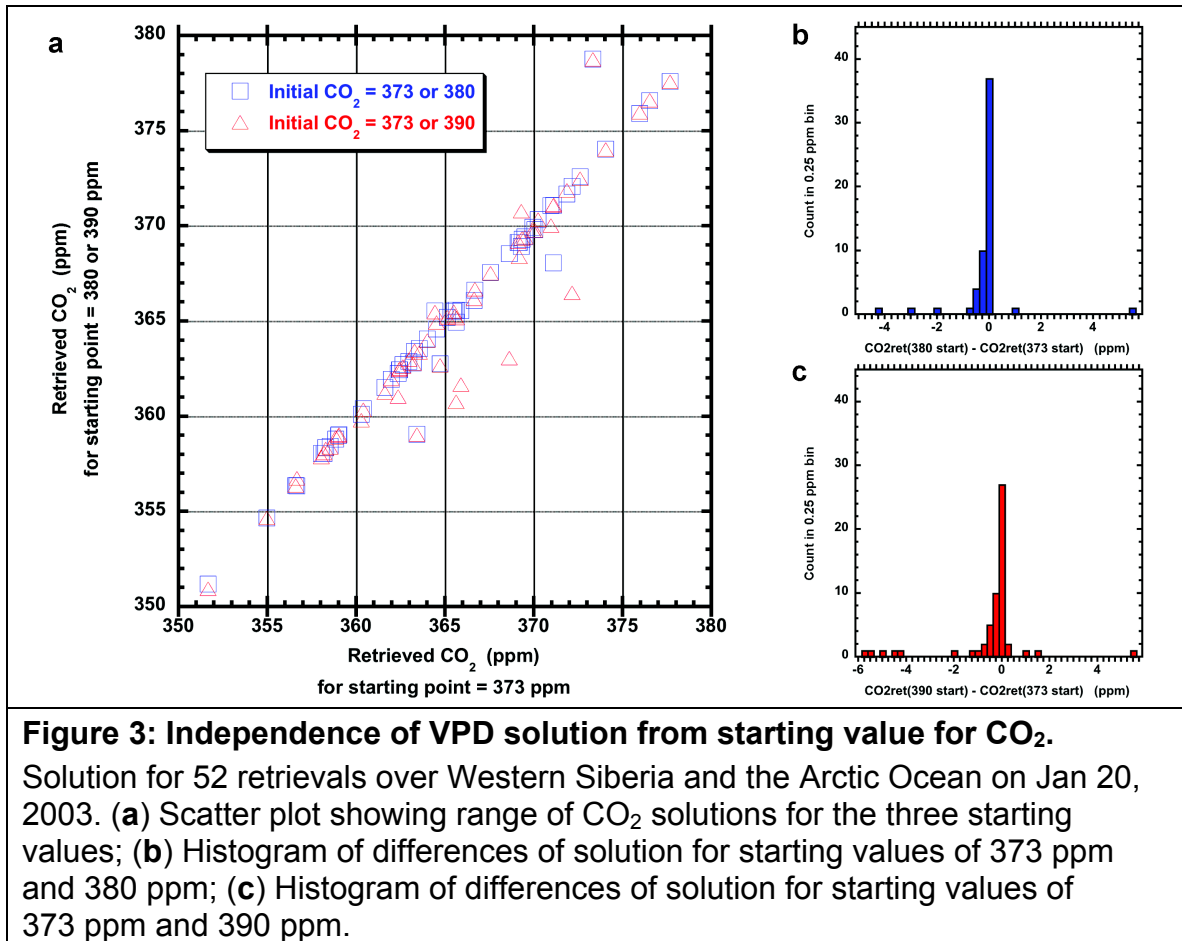
The current VPD algorithm is described in *Chahine et al.* [2005]. Because of noise and other uncertainties in the various component of the  $G$  function, the necessary condition, (7), may not be sufficient. Consequently, in order to seek

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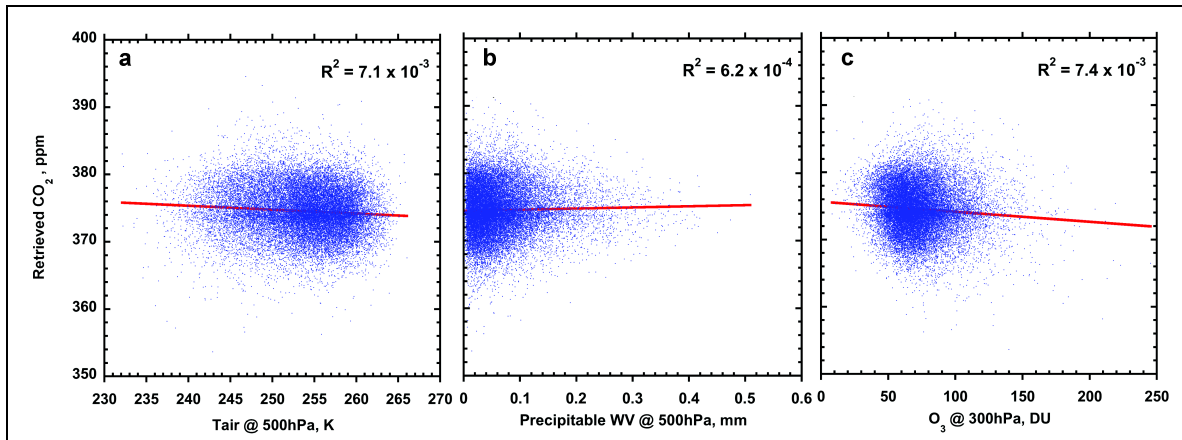
uniqueness the VPD algorithm tracks the variations of residuals with iterations and discards solutions whose residuals do not decrease monotonically with successive iterations down to the termination threshold of  $\Delta\text{CO}_2 = 0.25$  ppm. The result is that accepted solutions have a single minimum. Furthermore, the algorithm requires that at least three out of four adjacent CO<sub>2</sub> retrievals (making a cluster, or 2 x 2 array covering a 90 km x 90 km area at nadir) have solutions. Finally, a spatial coherence QA test is applied. If the surviving three or four solutions in the cluster agree to within 2 ppm in an RMS sense, a threshold chosen consistent with our goal of retrieving CO<sub>2</sub> within a data variability of 2 ppm, the retrieval is placed in the Level 2 CO<sub>2</sub> Standard Product. Retrievals failing this QA test are placed in the Level 2 CO<sub>2</sub> Support Product.

After retrieving the CO<sub>2</sub>, we compute the averaging kernel by sequentially perturbing each of the 100 layers of the atmospheric profile. The averaging kernels are not used in the VPD retrieval, but are provided in the product to aid in the assimilation of AIRS CO<sub>2</sub> data and for comparison with TCCON observations. The averaging kernels represent the change of the apparent mixing ratio that results from a perturbation at each atmospheric level and is used in assimilation studies.

The VPD algorithm has been tested using different initial CO<sub>2</sub> mixing ratios from that used for the Level 2 retrievals, ranging between 330 ppm and 390 ppm in the polar regions and between 365 ppm and 405 ppm in the tropics, to determine whether the solution depends upon the initial value for CO<sub>2</sub> used in the iterative process as illustrated in Figure 3. The granule used in Figure 3 covers far Eastern Siberia, from the shoreline of the Sea of Okhotsk to deep into the East Siberian Sea and just North of the Arctic Circle. This is a challenging area for AIRS Level 2 retrievals and a good area to stress test the stability of the VPD CO<sub>2</sub> retrieval. The results show that the CO<sub>2</sub> solution arrived at is stable with respect to the starting values of CO<sub>2</sub>. Despite a 25 ppm range of solutions, in almost all cases the same solution (within 1 ppm) is arrived regardless of whether the starting value used for CO<sub>2</sub> in the VPD algorithm is 373, 380 or 390 ppm.



We have also observed that negligible correlations among T(p), H<sub>2</sub>O(p), O<sub>3</sub>(p), and CO<sub>2</sub> are introduced by the VPD algorithm, as in the case illustrated in Figure 4. Here, R is Pearson's correlation coefficient assuming CO<sub>2</sub> is one variable and either T(p), H<sub>2</sub>O(p) or O<sub>3</sub>(p) is the other variable. However in some other cases, we do observe correlations, as would be expected when physical mechanisms such as stratospheric intrusions and stratospheric-tropospheric exchanges are present, as in the case of the sudden stratospheric warming noted in Figure 4 of *Chahine et al.* [2008]. *Li et al.* [2010] also found in their analysis of the MJO signal in AIRS CO<sub>2</sub> that the AIRS CO<sub>2</sub> variations were not correlated with those of H<sub>2</sub>O.



**Figure 4: Lack of correlation of CO<sub>2</sub> solution with temperature, water vapor and ozone.**

Demonstration of lack of correlation among the VPD solutions for 24,635 retrievals of CO<sub>2</sub> and (a) T(500 hPa); (b) H<sub>2</sub>O(500 hPa); (c) O<sub>3</sub>(300 hPa) during January 2003 in the latitude band 30N to 40N.  $R^2$  represents the portion of the variance in CO<sub>2</sub> that could be explained by the variance in the other parameter and is less than 0.8% in all cases. No more than 0.8% of the variance in CO<sub>2</sub> can be attributed to the variance of one of the other parameters.

Chahine et al. [2005] determined that the errors in the retrieved CO<sub>2</sub> are uncorrelated so that a reduction in the CO<sub>2</sub> error by averaging is possible. Averaging allowed tracking of the monthly seasonal variations of CO<sub>2</sub> between September 2002 and March 2004 with an agreement of  $0.43 \pm 1.20$  ppm with respect to collocated aircraft measurements made by Matsueda [Matsueda et al., 2002], now incorporated into the Comprehensive Observation Network for Trace gases by AirLiner (CONTRAIL).

## Auxiliary AIRS CO<sub>2</sub> Weighting Function Data File

The Level 2 CO<sub>2</sub> product files contain averaging kernels on the 100 support layer pressures. The averaging kernel defines the layers in the atmosphere over which a perturbation of CO<sub>2</sub> at a given level is propagated in retrieval by estimation techniques and in data assimilation and is a measure of the sensitivity of the AIRS retrieval to a change in the CO<sub>2</sub> concentration in an atmospheric layer. On the other hand, the AIRS weighting function profile for CO<sub>2</sub>,  $W$ , is the derivative of the atmospheric transmission function with respect the natural logarithm of the pressure,

$$W(v, p) = \frac{\partial \tau(v, p)}{\partial \ln(p)} \quad (8)$$

and the AIRS contribution function profile for CO<sub>2</sub> given in equation (3) quantifies the amount of emitted radiation arising from the various layers in the atmosphere. These are essential parameters in the physical inverse solution of the radiative

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transfer equation, used in the AIRS Level 2 retrievals. The VPD algorithm necessarily computes the weighting and contribution functions for each infrared channel at each iteration step during the retrieval as part of the forward calculation of radiances for the atmospheric state.

As an aid to researchers, an ancillary tab-delimited file provides the AIRS CO<sub>2</sub> weighting functions for the Thermodynamic Initial Guess Retrieval (TIGR) database [Chedin *et al.*, 1985] tropical, mid-latitude summer, sub-polar winter atmospheres and Air Force Geophysical Laboratory (AFGL) 1976 US standard atmospheres [Anderson *et al.*, 1986]. The unnormalized weighting functions are for constant CO<sub>2</sub> volume mixing ratio profiles of 330, 370 and 390 ppm and are given for each of the 101 levels of the supplementary pressure array. The file may be downloaded at this URL:

[http://disc.sci.gsfc.nasa.gov/AIRS/documentation/v5\\_docs/AIRS-mid-trop-CO2-330-370-390-wgt-func.txt](http://disc.sci.gsfc.nasa.gov/AIRS/documentation/v5_docs/AIRS-mid-trop-CO2-330-370-390-wgt-func.txt)

### **Comparing AIRS CO<sub>2</sub> to In Situ Measured Profiles**

Direct validation the AIRS retrieved CO<sub>2</sub> is accomplished by convolving *in situ* CO<sub>2</sub> profiles with the AIRS averaging kernel to derive a simulated AIRS observation that is directly comparable to the AIRS retrievals, i.e.:

$$\hat{x} = x_{pri} + AK(x_{ac\_obs} - x_{pri}) \quad (9)$$

where  $\hat{x}$  is the simulated observation,  $x_{pri}$  is the prior CO<sub>2</sub> assumed in the AIRS retrieval,  $x_{ac\_obs}$  is the *in situ* airborne measured profile and  $AK$  is the AIRS CO<sub>2</sub> averaging kernel. Since AIRS does not retrieve a profile,  $AK$  is a vector and  $\hat{x}$  reduces to a scalar providing a weighted partial column result to compare to the AIRS retrieval.

We advise interested researchers to use the averaging kernels accompanying the AIRS retrieved CO<sub>2</sub> to derive a value from their measured profiles that may be directly compared to the AIRS retrieved CO<sub>2</sub>. Care must be taken to interpolate each of the 101 levels taking into account the time growth of CO<sub>2</sub> over time and the latitude of their *in situ* measurement. A summary of the preferred algorithm is:

1. Interpolate the *in situ* measurement onto the 101 pressure levels. The measured profile does not extend throughout the full atmospheric column. There are several options for filling the pressure levels above and below the measured profile, the simplest being to replicate the top and bottom measured values into the unsampled regimes. Another

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option is to fill the missing partial columns at the top and bottom of the atmosphere with model values. In any event there will likely be a bias issue. The low altitude portion of the AIRS sensitivity profile is well-observed in aircraft profile measurements, but the high altitude portion is usually not observed. Compare the pressure extent to that of the *in situ* measurements to ensure that the interpolated profile encompasses a good fraction of the AIRS retrieval sensitivity. We suggest the measurements should extend upward to the 190 hPa pressure level or beyond.

2. Identify AIRS retrievals that are collocated within the desired spatial and temporal window. We suggest windows that provide a minimum of 9 collocated AIRS retrievals.
3. Average the averaging kernels of the collocated AIRS retrievals.
4. Level-by-level, multiply the *in situ* profile by the corresponding averaged averaging kernel function that results from step #3 and calculate the weighted average of the measured profile to arrive at a value that can be directly compared to the average of the collocated AIRS CO<sub>2</sub> retrievals. Thus if  $i$  is the index of the pressure layers,  $\overline{AK}_i$  is the averaged averaging kernel profile and  $CO2_i$  the *in situ* profile, then the calculated weighted partial column value is:

$$\hat{x} = \frac{\sum_{i=1}^{100} \overline{AK}_i \times CO2_i}{\sum_{i=1}^{100} \overline{AK}_i} \quad (10)$$

### ***AIRS\_Only Based Retrievals vs AIRS\_AMSU Based Retrievals***

Due to the failure of AMSU Channel 5, AIRS CO<sub>2</sub> retrievals were paused until test and evaluation of the retrievals resulting from ingesting the AIRS\_Only Level 2 products could be completed. The CO<sub>2</sub> retrieval algorithm was not modified.

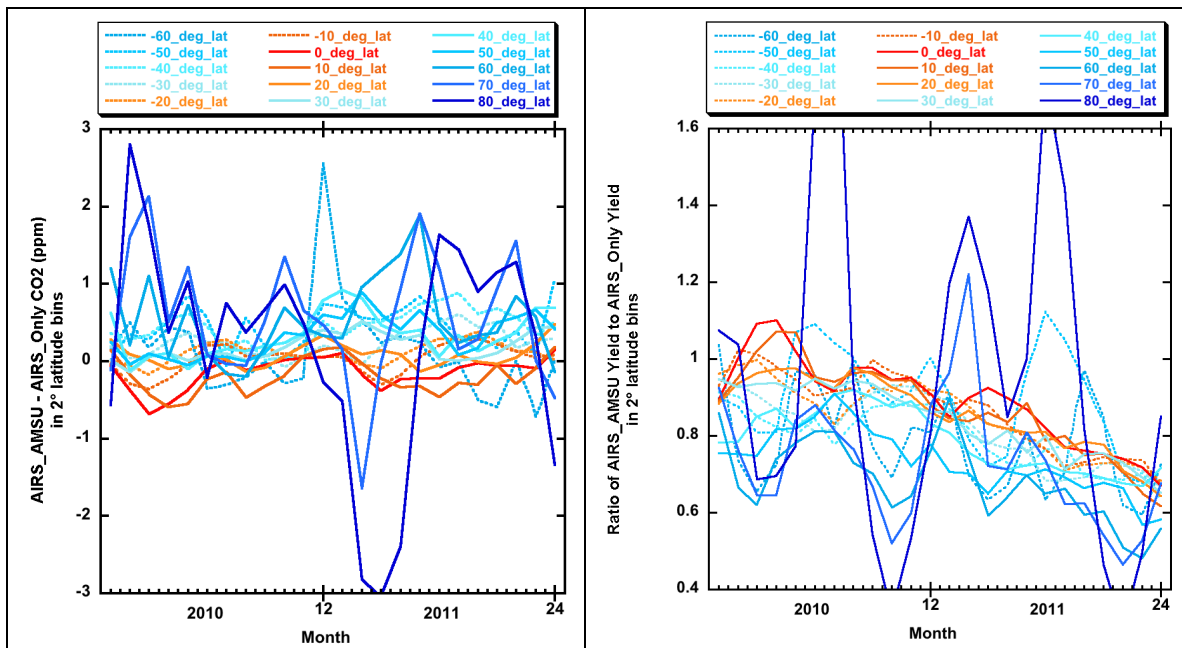
### **2010-2011 Zonal Average Comparison Retrieved CO<sub>2</sub> and Yield**

Alternative AIRS Level 2 processing was performed for 2010 and 2011 to allow V5 CO<sub>2</sub> retrievals ingesting AIRS\_Only Level 2 products to be compared to the products resulting from ingesting AIRS\_AMSU Level 2 products. During the first six months of 2010, AMSU Channel 5 NEdT was only slightly elevated and the AIRS\_AMSU Level 2 retrieval yield was not impacted. During the last half of 2010 yield began to slowly decrease. Beginning January 2011 the degradation of AMSU Channel 5 NEdT accelerated, so that by the end of 2011 its impact on yield was severe. Figure 5 compares the zonal average difference in retrieved CO<sub>2</sub> (AIRS\_AMSU – AIRS\_Only) and yield ratio (AIRS\_AMSU based relative to



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AIRS\_Only based) as a function of time in 2° latitude bands between 60°S and 80°N at 10° degree intervals.



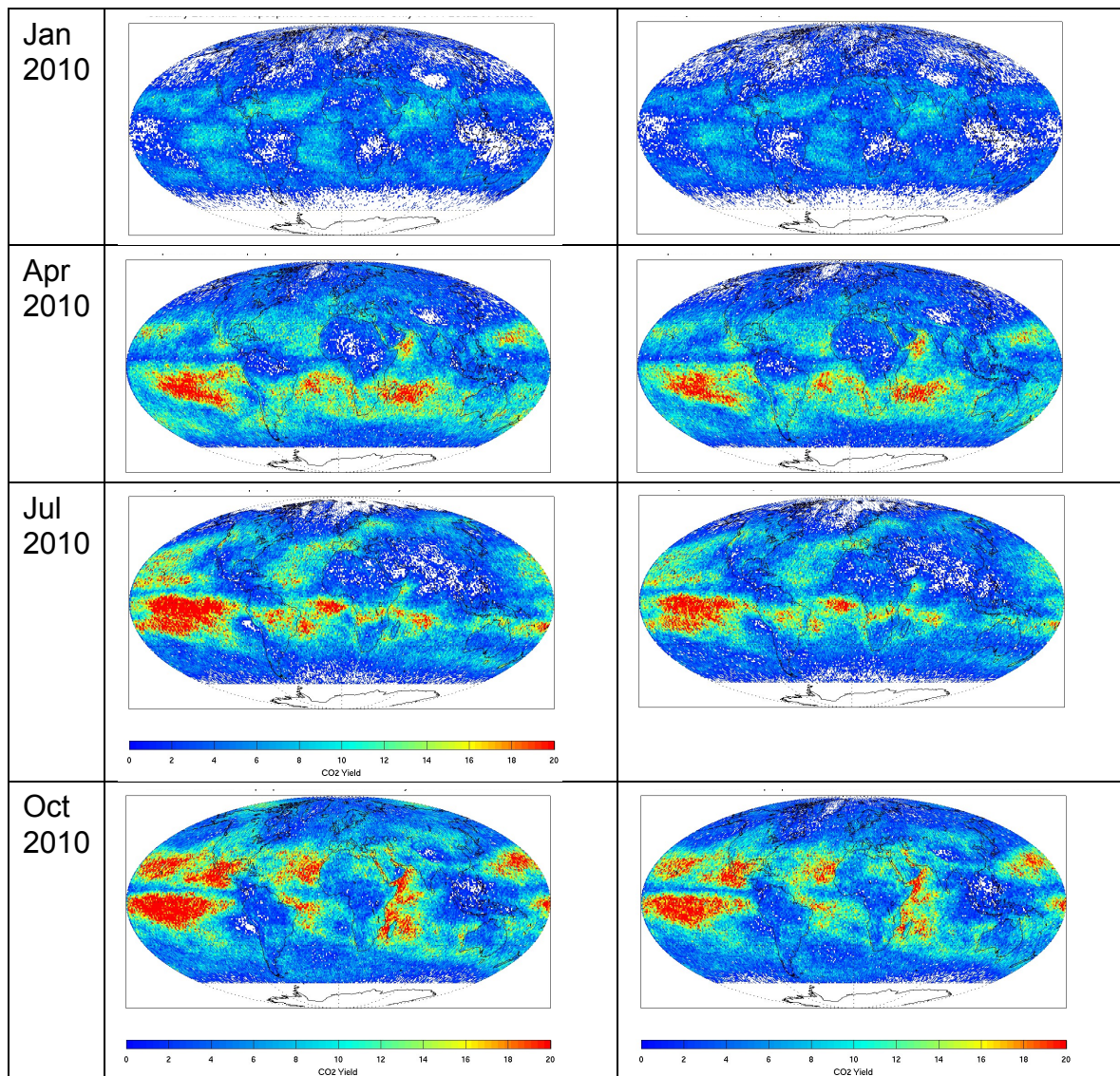
**Figure 5: Comparison of zonal averages of yield and retrieved CO<sub>2</sub> as a function of time and latitude for 2010 and 2011.**

Left panel: difference in retrieved CO<sub>2</sub> in 2° bands as a function of latitude, shown as difference (AIRS\_AMSU based – AIRS\_Only based). Fluctuations at highest northern latitudes are result of small number statistics.

Right panel: Reduction of CO<sub>2</sub> retrieval yield in 2° bands as a function of latitude, shown as ratio of number of retrievals ingesting AIRS\_AMSU L2 product to the number of retrievals ingesting AIRS\_Only L2.

By the end of 2011 the decline in AIRS\_AMSU yield relative to AIRS\_Only was more than 30%. The trend rapidly accelerated in early 2012, prompting a pause in the release of the CO<sub>2</sub> product until now. There is no apparent trend in the difference in retrieved CO<sub>2</sub> between that based on AIRS\_AMSU and that based on AIRS\_Only L2 retrieved atmospheric state. The fluctuations at the highest northern latitudes (70°N and 80°N) are due to small number statistics. The zonal average bias of the AIRS\_Only based retrievals relative to the AIRS\_AMSU based retrievals is within  $\pm 0.5$  ppm throughout the two-year period except at the highest northern latitudes.

## Global Comparison of Yield and Retrieved CO<sub>2</sub>



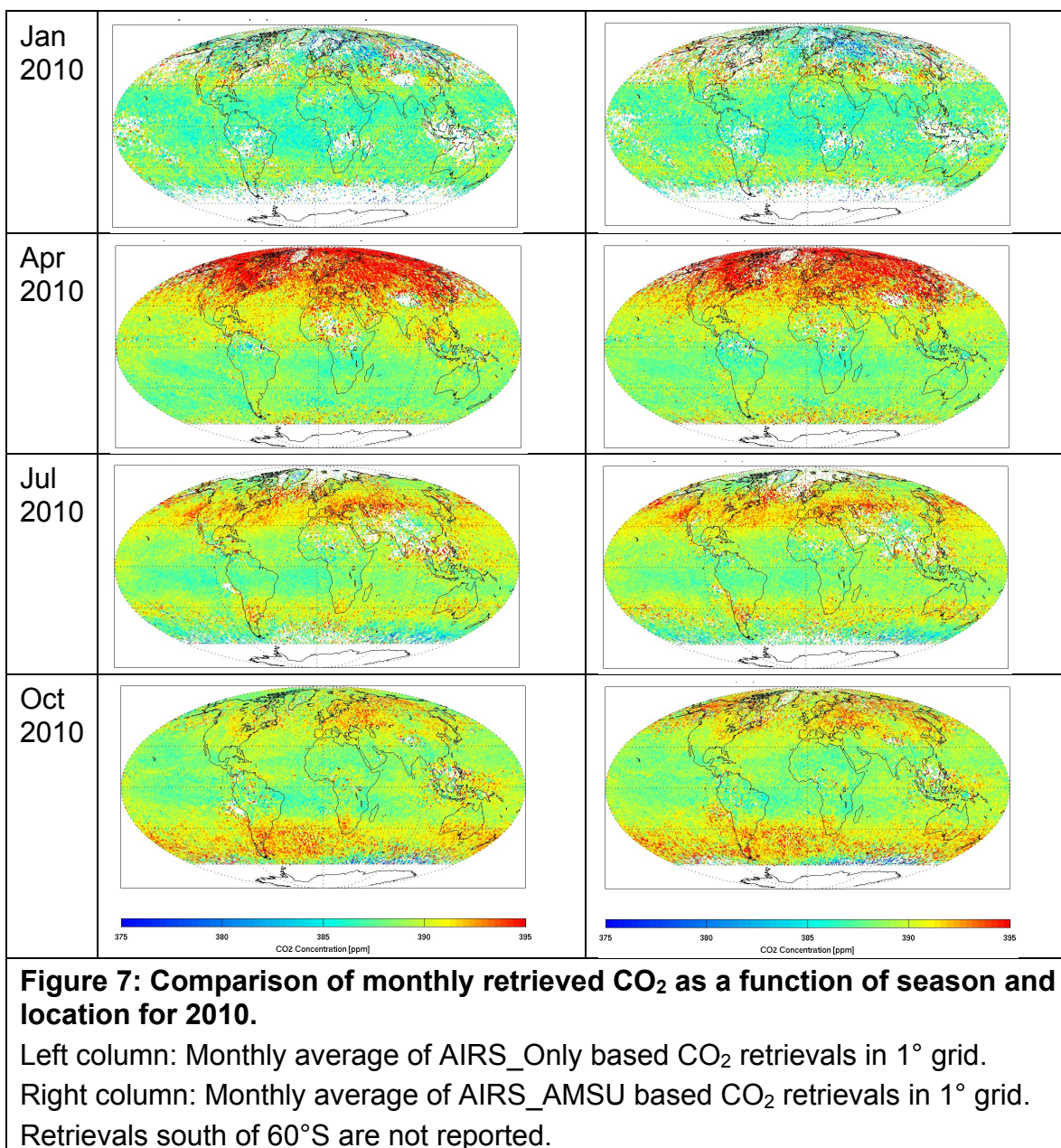
**Figure 6: Comparison of monthly retrieved CO<sub>2</sub> yield as a function of season and location for 2010.**

Left column: Accumulated yield of AIRS\_Only based CO<sub>2</sub> retrievals in 1° grid.  
 Right column: Accumulated yield of AIRS\_AMSU based CO<sub>2</sub> retrievals in 1° grid.  
 Retrievals south of 60°S are not reported.

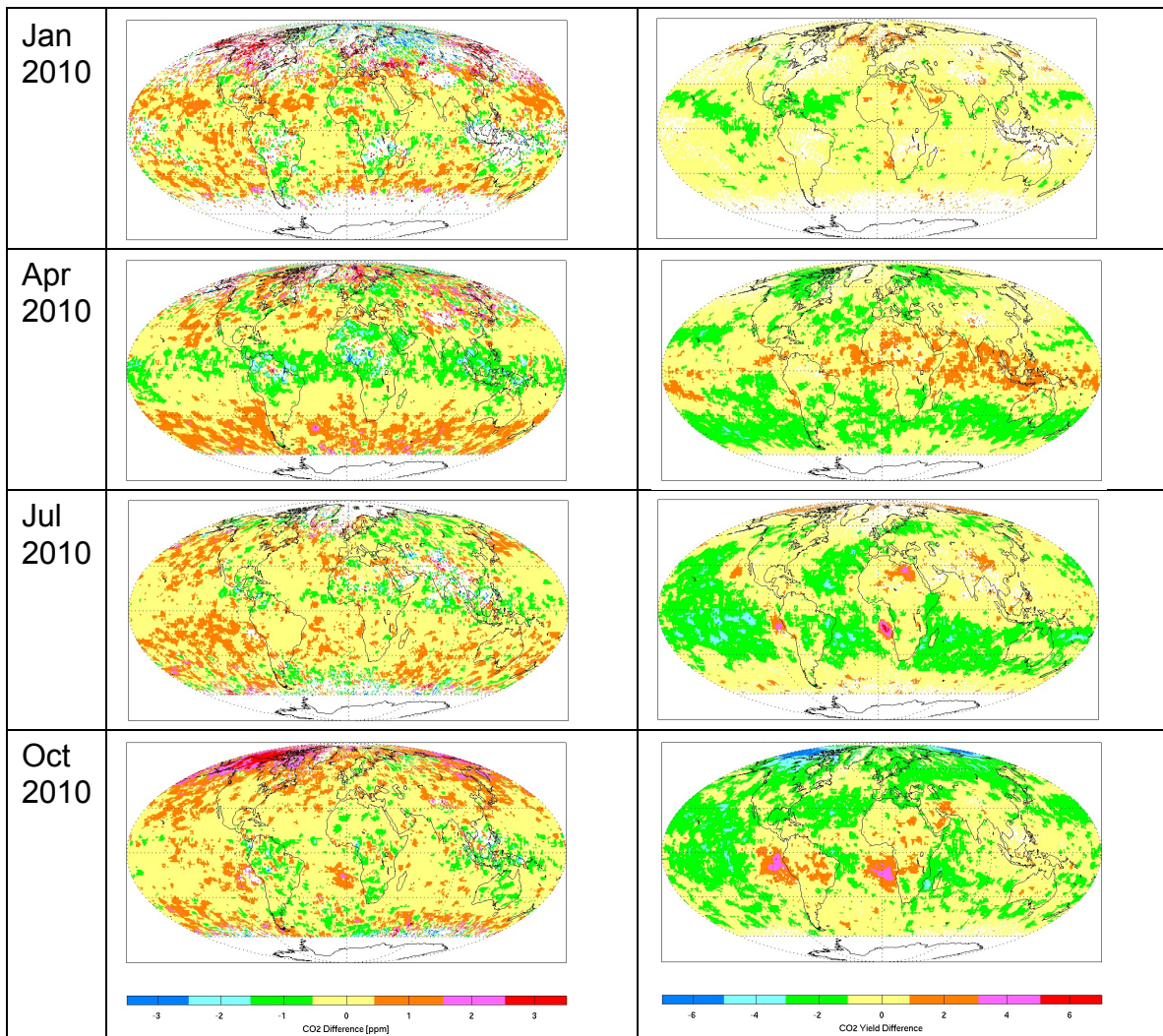
January yield reduced relative to other months due to single event upset that resulted in loss of AIRS data for 15 days of that month.



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**Figure 8: Smoothed comparison of monthly average difference of retrieved CO<sub>2</sub> and yield as a function of season and location of 2010.**

Left column: Retrieved CO<sub>2</sub> difference (AIRS\_Only based – AIRS\_AMSU based) in 1° grid smoothed to 5°, shown as difference. Differences are small except at the highest northern latitudes.

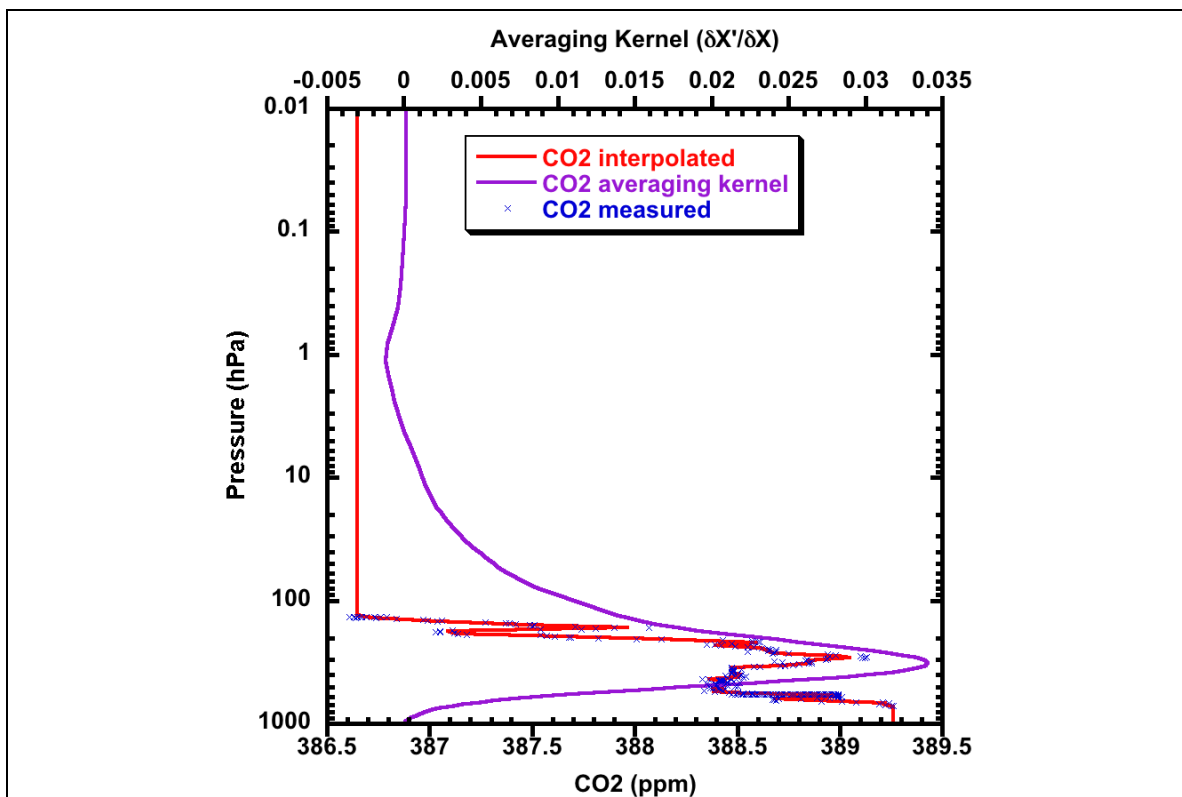
Right column: CO<sub>2</sub> retrieval yield difference (AIRS\_Only based – AIRS\_AMSU based) in 1° grid smoothed to 5°. Differences are largest in areas where extensive low stratus cloud cover occurs.

Retrievals south of 60°S are not reported.

Increased yield for AIRS\_Only in areas of low stratus (off West Coasts of South America and Africa) argues for addition of cloud filtering in CO<sub>2</sub> retrieval algorithm.

## Comparison of Retrieved CO<sub>2</sub> with In Situ Measurements

Airborne in situ measurements of the CO<sub>2</sub> profile are the best data sets for validating satellite retrievals. The HAIPER Pole-to-Pole transects of the mid-Pacific (Wofsy *et al.*, 2012) provide the opportunity to do so for an extended latitude range over the open ocean. We chose a subset of measured profiles from HIPPO-2, HIPPO-3, HIPPO-4 and HIPPO-5, the selection criteria being that the measured profiles extended beyond the 190 hPa pressure level to ensure good coverage of the AIRS sensitivity profile. We interpolated the aircraft measurements to the AIRS 100 pressure levels, extending the measured profile above its highest altitude by duplicating the highest altitude measurement. An example is shown in Figure 9.



**Figure 9: Comparison of interpolated/extended deep-dip HIPPO-5 measured CO<sub>2</sub> profile to AIRS CO<sub>2</sub> averaging kernel.**

Blue X's: Measured HIPPO-5 CO<sub>2</sub> profile (10 sec data set) (Wofsy *et al.*, 2012)  
 Purple Curve: AIRS averaging kernel (average of AKs of collocated retrievals)  
 Red Curve: Interpolated/extended CO<sub>2</sub> profile to be convolved with the AIRS averaging kernel to arrive at a value to be compared to average of collocated AIRS CO<sub>2</sub> retrievals. The extension to altitudes above the 190 hPa level is the simplest possible – replication of the highest altitude *in situ* measurement.

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The replication of the highest altitude in situ measurement is not sufficiently accurate for a true validation. It is known that the CO<sub>2</sub> abundance decreases with altitude in the stratosphere (e.g. Stiller et al., 2012). A shift of that extension by 1 ppm results in a change in bias of 0.3 ppm in the comparisons against AIRS retrievals.

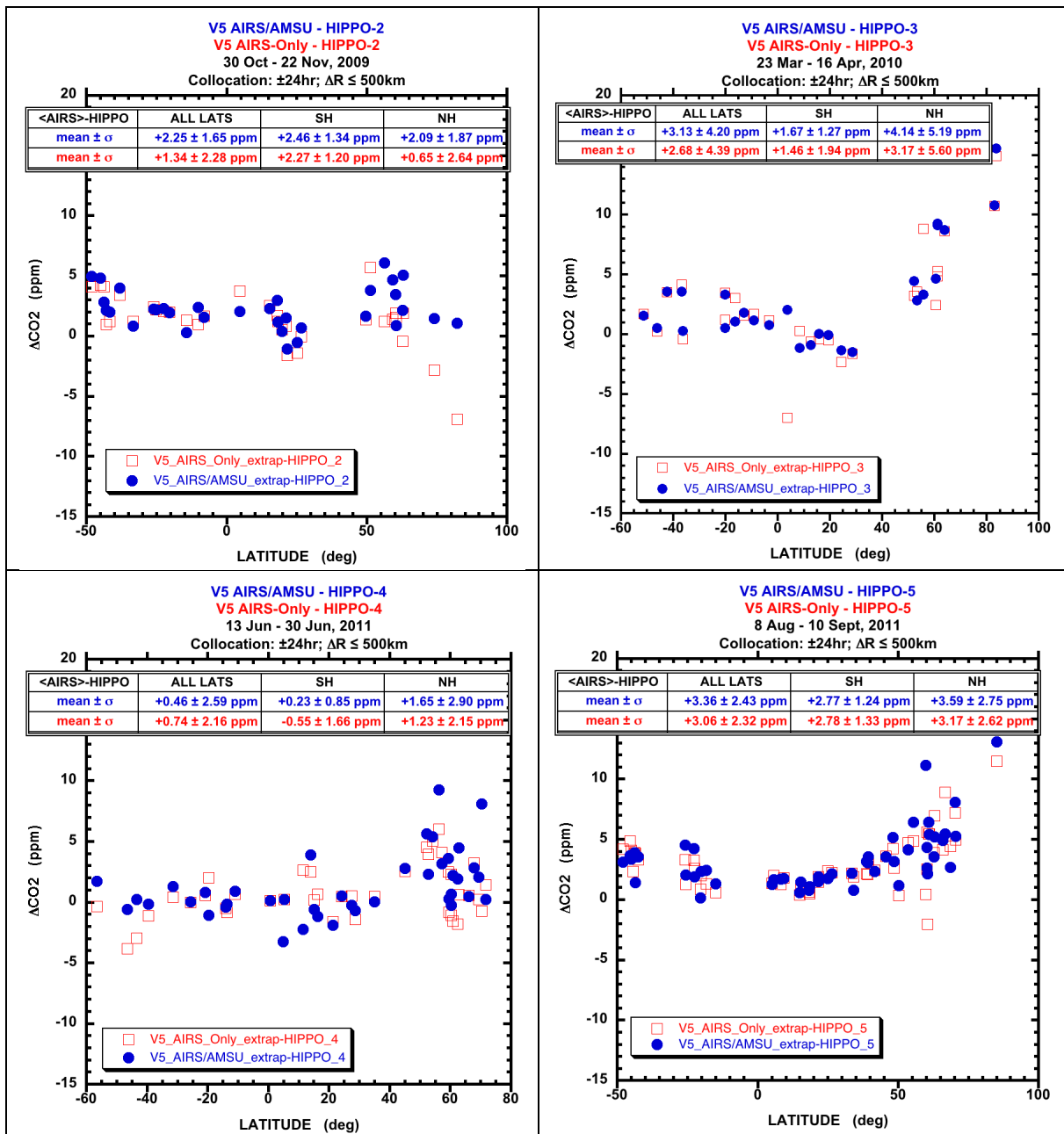
For this document, AIRS retrievals collocated with the aircraft profile within  $\pm 24$  hours and 500 km were averaged, and the extended *in situ* profile was convolved with the average of their averaging kernels. Figure 10 compares the results for CO<sub>2</sub> retrieved ingesting the V5 AIRS\_AMSU data products (blue filled circles) and CO<sub>2</sub> retrieved ingesting the AIRS\_Only data products (red open squares).

At the time of the HIPPO-2 measurements (30 October through 22 November, 2009) AMSU channel 5 NEdT was near nominal. At the time of the HIPPO-3 measurements (24 March through 16 April, 2010), AMSU channel 5 NEdT was increasing but had not reached the point where AIRS retrieval yield was impacted. During the HIPPO-4 measurements (14-20 June, 2011) the degradation had begun to noticeably reduce yield, and during the HIPPO-5 measurements (8 August through 10 September 2011) the impact of the increase NEdT on yield was severe. Despite the deterioration of AMSU channel 5, the AIRS\_AMSU and AIRS\_Only CO<sub>2</sub> products exhibit nearly identical validation statistics and variation with latitude relative to collocated HIPPO profiles for all four periods.

We conclude that CO<sub>2</sub> products derived ingesting the AIRS\_Only Level 2 products are statistically identical to those derived ingesting the AIRS\_AMSU Level 2 products. Both products exhibit an increased bias against HIPPO-3 and HIPPO-5 at the high northern latitudes (north of 50°N).



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**Figure 10: Comparison of collocated AIRS\_AMSU CO<sub>2</sub> and AIRS\_Only CO<sub>2</sub> to deep-dip HIPPO profiles convolved with their averaging kernels.**

Filled blue dots: <Collocated AIRS\_AMSU CO<sub>2</sub>> - Convolved HIPPO Profiles

Open red squares: <Collocated AIRS\_Only CO<sub>2</sub>> - Convolved HIPPO Profiles

Top Left panel: Comparison against HIPPO-2 profiles

Top Right panel: Comparison against HIPPO-3 profiles

Bottom Left panel: Comparison against HIPPO-4 profiles

Bottom Right panel: Comparison against HIPPO-5 profiles

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## ***ACRONYMS***

**AFGRL** Air Force Geophysical Laboratory  
**AIRS** Atmospheric InfraRed Sounder  
**AMSU** Advanced Microwave Sounding Unit  
**CONTRAIL** Comprehensive Observation Network for Trace gases by AirLiner  
**FOV** Field of View  
**GES DISC** Goddard Earth Sciences Data and Information Services Center  
**MJO** Madden-Julian Oscillation  
**RMS** Root Mean Square  
**TCCON** Total Carbon Column Observing Network  
**TOA** Top of Atmosphere  
**TOVS** TIROS Operational Vertical Sounder  
**TIGR** Thermodynamic Initial Guess Retrieval  
**VPD** Vanishing Partial Derivative



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