AIRS Version 5 Release Tropospheric CO_2 Products

by:

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Introduction

The AIRS Version 5 (V5) tropospheric CO_2 product is a retrieval of the weighted partial-column dry volume mixing ratio characterizing the mid- to upper-tropospheric CO_2 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_2 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_2 by shifting the CO_2, T, q and O_3 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_2 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_2 yield, and that processing was temporarily halted.

The V5 CO_2 post processing retrieval stage now ingests the AIRS Level 2 products that result from the AIRS_Only retrieval. Testing of the CO_2 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_2 product has been reprocessed starting in January 2011 and released to the community. The test results are included in this documentation.

The CO_2 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_2 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:

$$CO_2\_clim(t) = A + B \times (t - t_0) \tag{1}$$

Where $CO_2\_clim(t)$ is the concentration of CO_2 everywhere in the atmosphere at date/time, t, in ppm, and

$A = 371.92429$
$B = 1.840618$
$t_0 = 1\,Jan\,2002\ @\ 0^{hr}\ UT$

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

$t_0 = 2002.0$
$t = 2009.5$ for the date and time of $1\,July\,2009\ @\ 12^{hr}\ UT$

Although a CO_2 profile is part of V5, all elements are set to this climatology CO_2 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_2. 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.

Access to AIRS Tropospheric CO_2 Product Files

The AIRS CO_2 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_2 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_2 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_2 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_2 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

They are located in the 6th table at the URL above, titled, "**Data Product Readers**".

AIRS Mid-Tropospheric CO_2 Products

The V5 Level 2 products and climatology CO_2 are assumed as the initial state for the VPD retrieval algorithm that separately determines the tropospheric CO_2 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_2 over their spatial extent. Thus the nominal spatial resolution of the VPD Level 2 CO_2 product at nadir is 90 km x 90 km, or approximately 1° x 1° on the Earth's surface. CO_2 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_2 retrievals be less than 2 ppm is applied. The retrievals that satisfy spatial coherence threshold are included in the Level 2 CO_2 standard product and those that do not do so are included in the Level 2 CO_2 support product.

There are three VPD Level 3 CO_2 products derived from the VPD Level 2 CO_2 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_2 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 edge of the Level 3 gridded cells is at 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_2 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.

CO_2 Product File Names, Shortnames and Sizes

The Level 2 and Level 3 CO_2 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)
NNN	N/A	001 for daily 008 for 8-day 028→031 for calendar month
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.

Example 1: Level 2 CO_2 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_2 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_2 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

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_2 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

Content of L2 CO_2 Standard Product Files and Support Product Files

A total of 240 Level 2 CO_2 Standard Product Files and Level 2 CO_2 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 **Standard**: "CO2 stddev >= 0 and <= 2" **Support**: "CO2 stddev > 2"
CO2retNum	32-bit INT	[1]	# of CO2 retrievals in granule (maximum possible = 330)

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)

Contents of Level 3 CO_2 Product Files

The L2 CO_2 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)

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 **Standard**: "CO2 stddev >= 0 and <= 2" **Support**: "CO2 stddev > 2"
CO2retNum	32-bit INT	[1]	# of CO2 retrievals in granule (maximum possible = 330)

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_2 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_2 Standard Product contains the retrievals meeting the criterion that CO2std ≤ 2 ppm, and retrievals not satisfying that threshold are placed in the Level 2 CO_2 Support Product. The Level 3 CO_2 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

$$(PGood - PTrop) > 200\ hPa \tag{2}$$

are passed to the CO_2 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.

Caveats

Guards against effects of surface emission have been built into the CO_2 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_I2_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_2 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_2 channels in the 15 μm band. The process begins with the AIRS derived Level 2 atmospheric state and then proceeds to separately perturb the T(p), H_2O(p), O_3(p), and CO_2 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_2 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_2 Products

The AIRS Level 2 tropospheric CO_2 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_2 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_2

Researchers have applied various methods to retrieve CO_2 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_2 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 x $(t-t_0)$ mK where $\mathbf{t_0}$ 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_2 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_2 climatology and then separately perturbs the T(p), H_2O(p), O_3(p), and CO_2. The solution is obtained at the point where the partial derivatives of the channels with respect to T(p), H_2O(p), O_3(p), and CO_2 are individually equal to zero (minimized). The auxiliary T(p), H_2O(p), O_3(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.

T(p)		H_2O(p)		O_3(p)		CO_2	
Chan	ν (cm^{-1})	Chan	ν (cm^{-1})	Chan	ν (cm^{-1})	Chan	ν (cm^{-1})
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_2 retrieval.

Evaluation of the relative sensitivity of TOA radiances to the perturbation of T(p), H_2O(p), O_3(p), and CO_2 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^{-1} is well-suited for selecting the channel set to retrieve the CO_2 mixing ratio and the two auxiliary channel sets for temperature and ozone. The range 1420-1607 cm^{-1} 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_2. Specifically, since all IR channels depend upon temperature, we select the CO_2 channels to have a strong dependence on CO_2 and a weak dependence upon O_3 and H_2O. Similarly, we choose the H_2O and O_3 channels to have a weak dependence on CO_2 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_2 volume mixing ratio. The auxiliary set for temperature is selected to have a weak dependence upon CO_2.

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

$$B(\upsilon, T, p) \times \frac{\partial \tau(\upsilon, p)}{\partial ln(p)}$$

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

$$\partial X'(p) / \partial X(\mathrm{p})$$

defines the layers in the atmosphere over which a perturbation of CO_2 at a given level is propagated in retrieval by estimation techniques and in data assimilation.

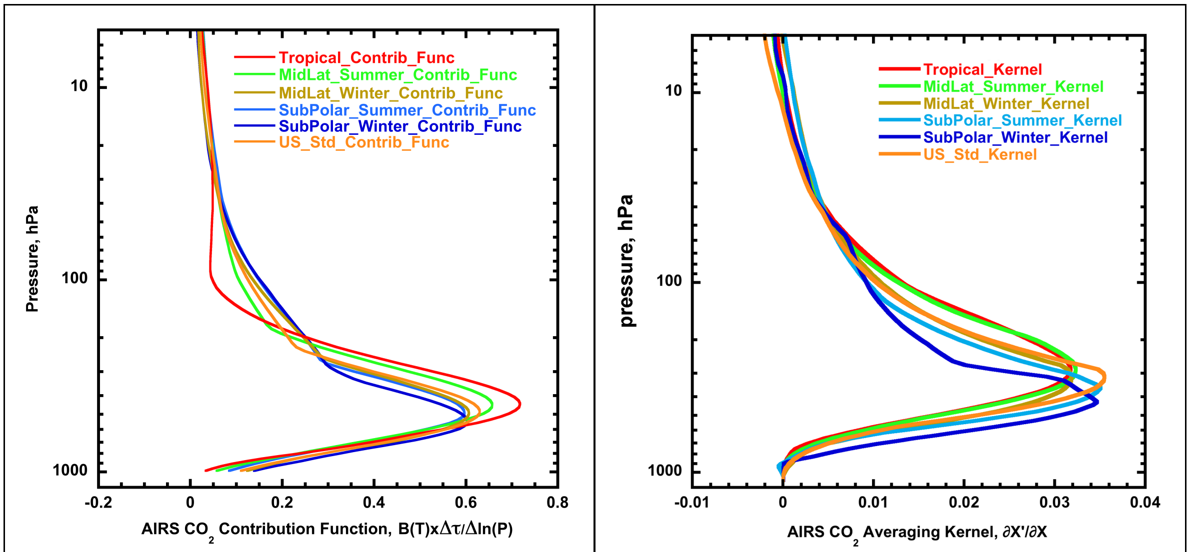


Figure 1: Representations of CO_2 retrieval sensitivity as a function of location in the atmospheric column.
(a) AIRS contribution functions and (b) AIRS averaging kernels for TIGR tropical, mid-latitude, sub-polar atmospheres and the AFGL 1976 US Standard Atmosphere, assuming a CO_2 concentration of 390 ppm throughout the atmosphere.

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_2 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_2 applies. Depending upon the atmosphere, AIRS peak sensitivity to changes in CO_2 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 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_2 channels used by the VPD algorithm survive, the retrieval is terminated and results discarded.

The AIRS contribution functions have tails that intrudes 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_2 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_2 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_2 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_2 Standard Product or the Level 2 CO_2 Support Product.

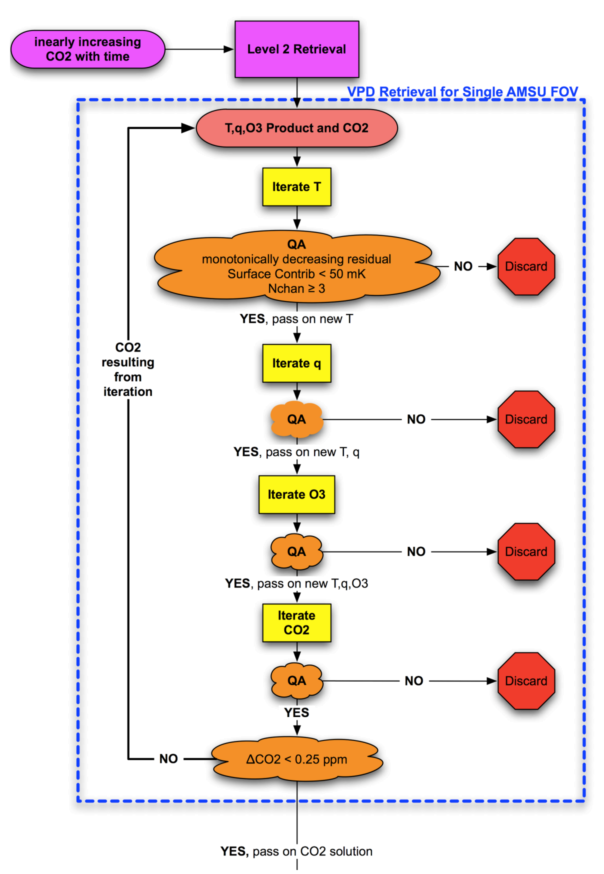
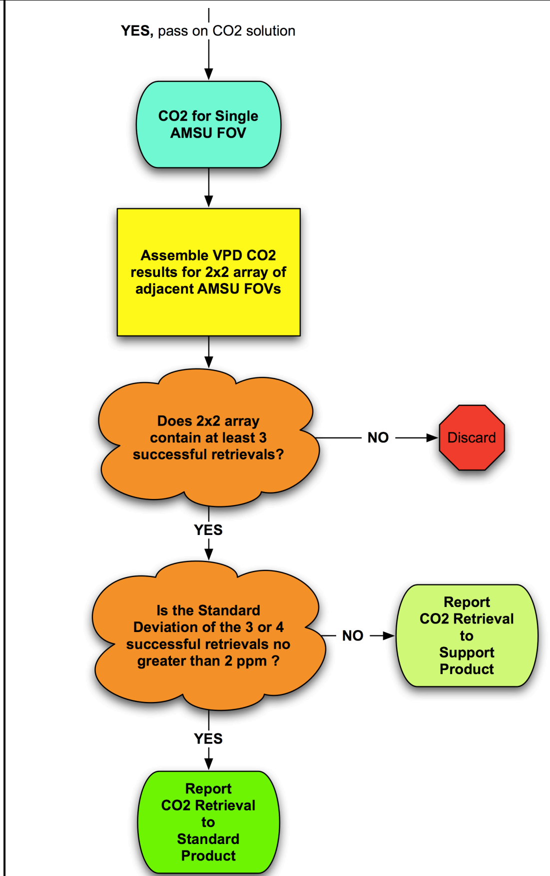
a) CO_2 retrieval for an AIRS Level 2 retrieval which satisfies the criterion, (PGood-PTrop) > 200 hPa	b) Assemble of 2x2 array; apply spatial coherence QA; report product
	

Figure 2: Block diagram of VPD post-processing retrieval of tropospheric CO_2.

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.

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

$$G^{(n)} = \sum_{v} \left[\theta_M(v) - \theta_C^{(n)}(v) \right]^2 \quad (4)$$

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

$$dG = \frac{\partial G}{\partial X_1} dX_1 + \frac{\partial G}{\partial X_2} dX_2 + \frac{\partial G}{\partial X_3} dX_3 + \frac{\partial G}{\partial X_4} dX_4 \quad (5)$$

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

Equation (5) 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 $\theta_C^{(n)}(v)$.

$$\frac{\partial G}{\partial X_1} = 0,\ \frac{\partial G}{\partial X_1} = 0,\ \frac{\partial G}{\partial X_1} = 0,\ \frac{\partial G}{\partial X_1} = 0 \quad (6)$$

where X_1 may represent CO_2(p), X_2 represents T(p), X_3 represents O_3(p) and X_4 represents H_2O(p).
Condition (6) is both necessary and (ideally) sufficient to retrieve a local minimum (or maximum) for the solution of CO_2.

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, (6), may not be sufficient. Consequently, in order to seek 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 ΔCO_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_2 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_2 within a data variability of 2 ppm, the retrieval is placed in the Level 2 CO_2 Standard Product. Retrievals failing this QA test are placed in the Level 2 CO_2 Support Product.

After retrieving the CO_2, 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_2 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_2 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_2 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_2 retrieval. The results show that the CO_2 solution arrived at is stable with respect to the starting values of CO_2. 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_2 in the VPD algorithm is 373, 380 or 390 ppm.

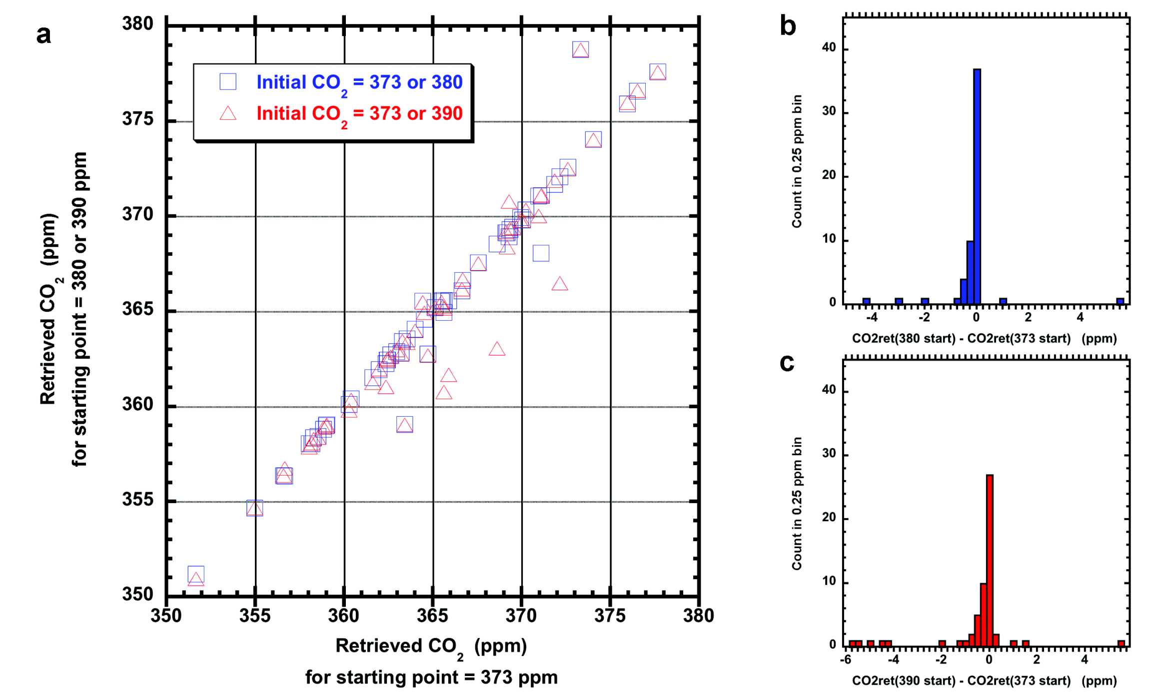


Figure 3: Independence of VPD solution from starting value for CO_2. Solution for 52 retrievals over Western Siberia and the Arctic Ocean on Jan 20, 2003. (**a**) Scatter plot showing range of CO_2 solutions for the three starting values; (**b**) Histogram of differences of solution for starting values of 373 ppm and 380 ppm; (**c**) Histogram of differences of solution for starting values of 373 ppm and 390 ppm.

We have also observed that negligible correlations among T(p), H_2O(p), O_3(p), and CO_2 are introduced by the VPD algorithm, as in the case illustrated in Figure 4. Here, R is Pearson's correlation coefficient assuming CO_2 is one variable and either T(p), H_2O(p) or O_3(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_2 that the AIRS CO_2 variations were not correlated with those of H_2O.

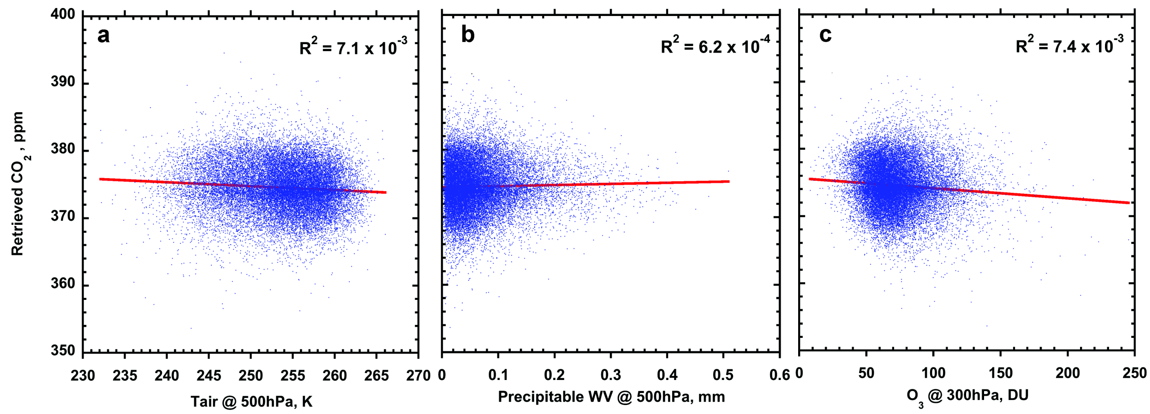


Figure 4: Lack of correlation of CO2 solution with temperature, water vapor and ozone.

Demonstration of lack of correlation among the VPD solutions for 24,635 retrievals of CO_2 and (**a**) T(500 hPa); (**b**) H_2O(500 hPa); (**c**) O_3(300 hPa) during January 2003 in the latitude band 30N to 40N. R^2 represents the portion of the variance in CO_2 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_2 can be attributed to the variance of one of the other parameters.

Chahine et al. [2005] determined that the errors in the retrieved CO_2 are uncorrelated so that a reduction in the CO_2 error by averaging is possible. Averaging allowed tracking of the monthly seasonal variations of CO_2 between September 2002 and March 2004 with an agreement of 0.43 ± 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_2 Weighting Function Data File

The Level 2 CO_2 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_2 at a given level is propagated in retrieval by estimation techniques and in data assimilation. On the other hand, the AIRS weighting function for CO_2 is the derivative of the atmospheric transmission function with respect the natural logarithm of the pressure,

$$\frac{\partial\tau(v,p)}{\partial ln(p)}$$

and quantifies the fraction of 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. The VPD algorithm necessarily computes the weighting function 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_2 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_2 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

Comparing AIRS CO_2 to In Situ Measured Profiles

Direct validation the AIRS retrieved CO_2 is accomplished by convolving *in situ* CO_2 profiles with the AIRS averaging kernel to derive a value that is directly comparable to the AIRS result.

We advise interested researchers to use the averaging kernels accompanying the AIRS retrieved CO_2 to derive a value from their measured profiles that may be directly compared to the AIRS retrieved CO_2. Care must be taken to interpolate each of the 101 levels taking into account the time growth of CO_2 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 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_2 retrievals. Thus if i is the index of the pressure layers, $\overline{\mathrm{AK}}_i$ is the averaged averaging kernel profile and $\mathrm{CO2}_i$ the *in situ* profile, then the calculated weighted partial column value is:

$$\overline{CO2} = \frac{\sum_{i=1}^{100} \overline{AK}_i \times CO2_i}{\sum_{i=1}^{100} \overline{AK}_i} \qquad (7)$$

AIRS_Only Based Retrievals vs AIRS_AMSU Based Retrievals

Due to the failure of AMSU Channel 5, AIRS CO_2 retrievals were paused until test and evaluation of the retrievals resulting from ingesting the AIRS_Only Level 2 products could be completed. The CO_2 retrieval algorithm was not modified.

2010-2011 Zonal Average Comparison Retrieved CO_2 and Yield

Alternative AIRS Level 2 processing was performed for 2010 and 2011 to allow V5 CO_2 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_2 (AIRS_AMSU – AIRS_Only) and yield ratio (AIRS_AMSU based relative to AIRS_Only based) as a function of time in 2° latitude bands between 60°S and 80°N at 10° degree intervals.

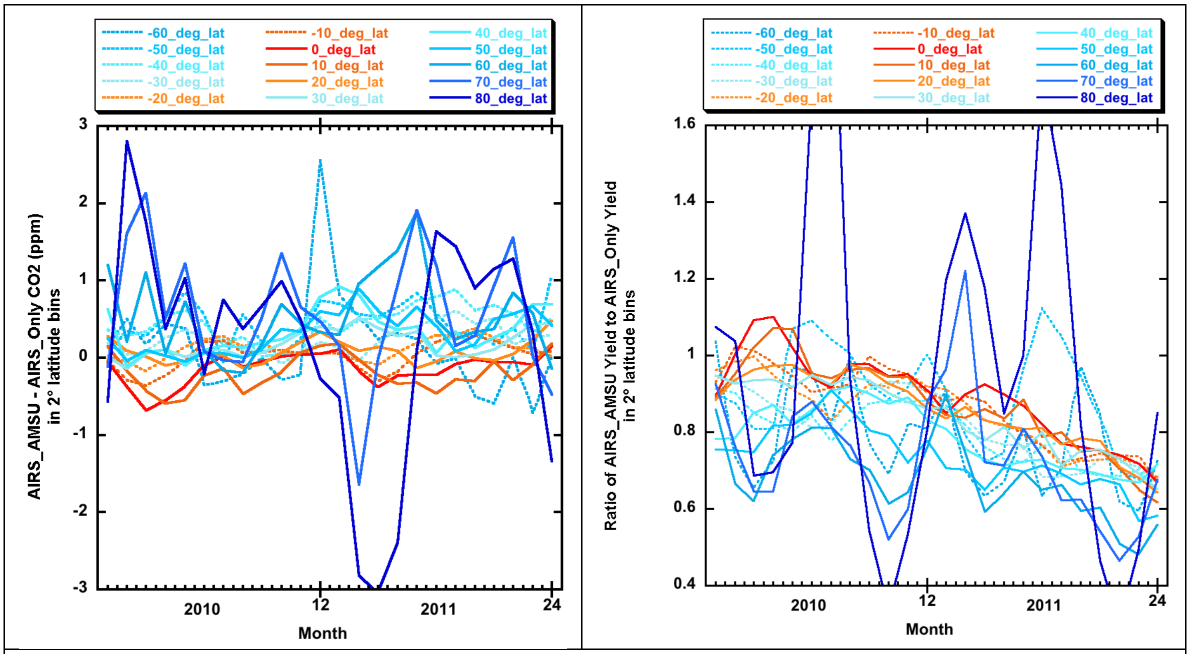


Figure 5: Comparison of zonal averages of yield and retrieved CO_2 as a function of time and latitude for 2010 and 2011.

Left panel: difference in retrieved CO_2 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_2 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_2 product until now. There is no apparent trend in the difference in retrieved CO_2 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 ±0.5 ppm throughout the two-year period except at the highest northern latitudes.

Global Comparison of Yield and Retrieved CO_2

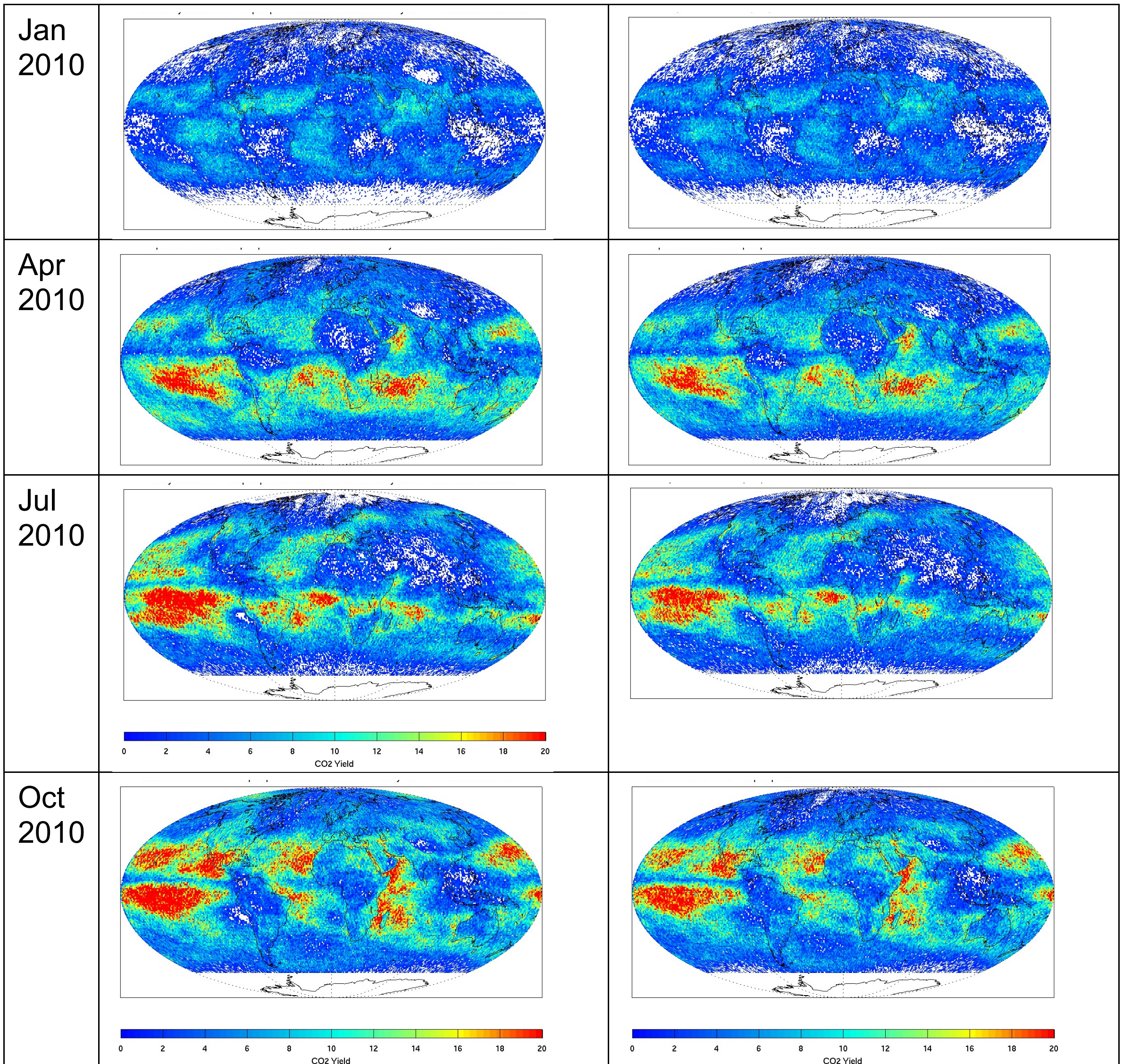


Figure 6: Comparison of monthly retrieved CO_2 yield as a function of season and location for 2010.

Left column: Accumulated yield of AIRS_Only based CO_2 retrievals in 1° grid.

Right column: Accumulated yield of AIRS_AMSU based CO_2 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.

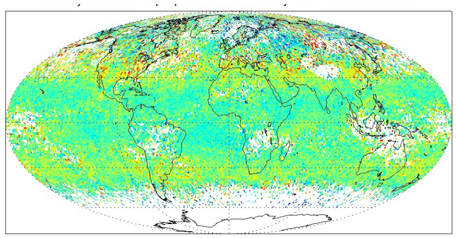
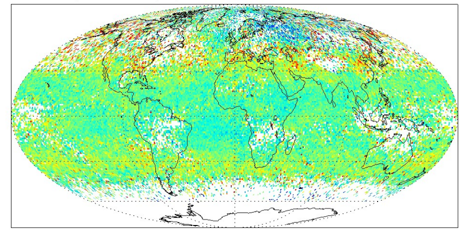
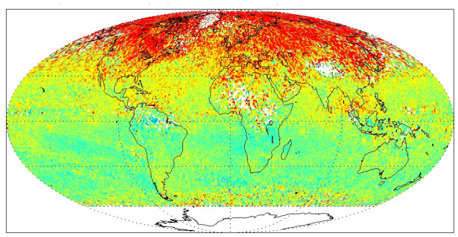
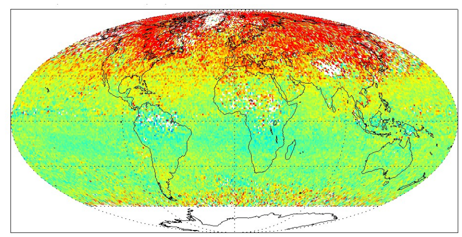
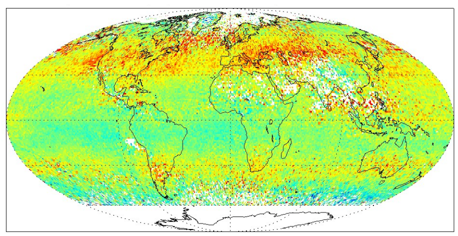
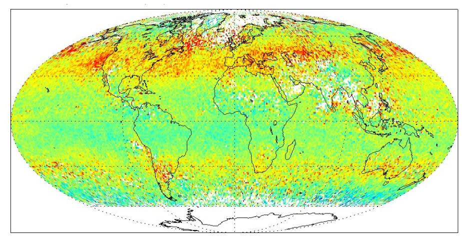
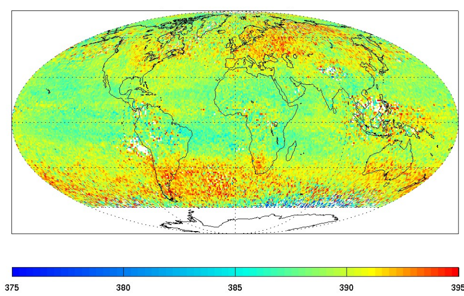
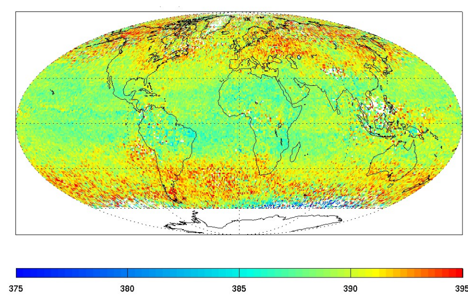
Jan 2010		
Apr 2010		
Jul 2010		
Oct 2010		

Figure 7: Comparison of monthly retrieved CO_2 as a function of season and location for 2010.

Left column: Monthly average of AIRS_Only based CO_2 retrievals in 1° grid.

Right column: Monthly average of AIRS_AMSU based CO_2 retrievals in 1° grid.

Retrievals south of 60°S are not reported.

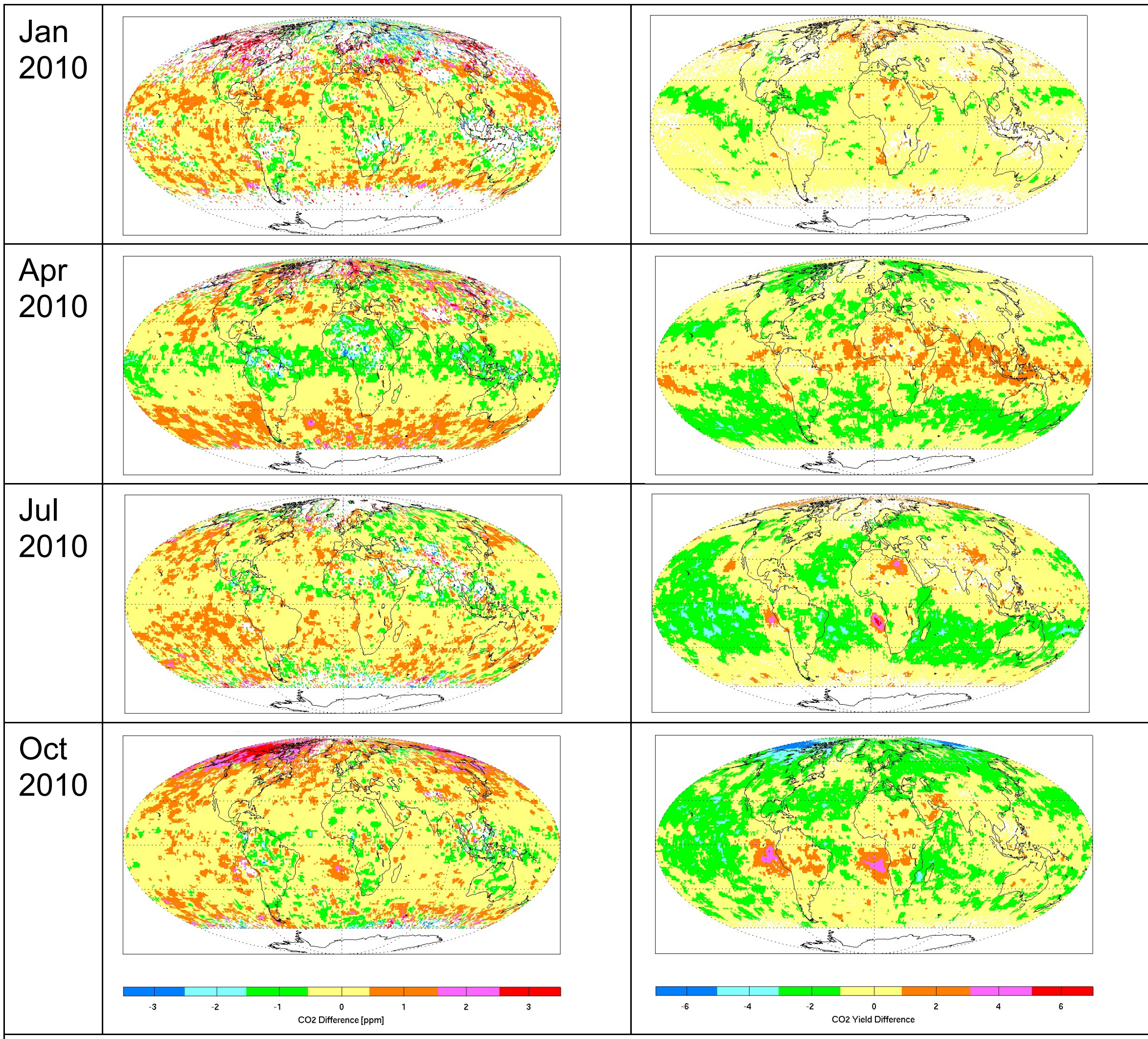


Figure 8: Smoothed comparison of monthly average difference of retrieved CO_2 and yield as a function of season and location of 2010.

Left column: Retrieved CO_2 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_2 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_2 retrieval algorithm.

Comparison of Retrieved CO_2 with In Situ Measurements

Airborne in situ measurements of the CO_2 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.

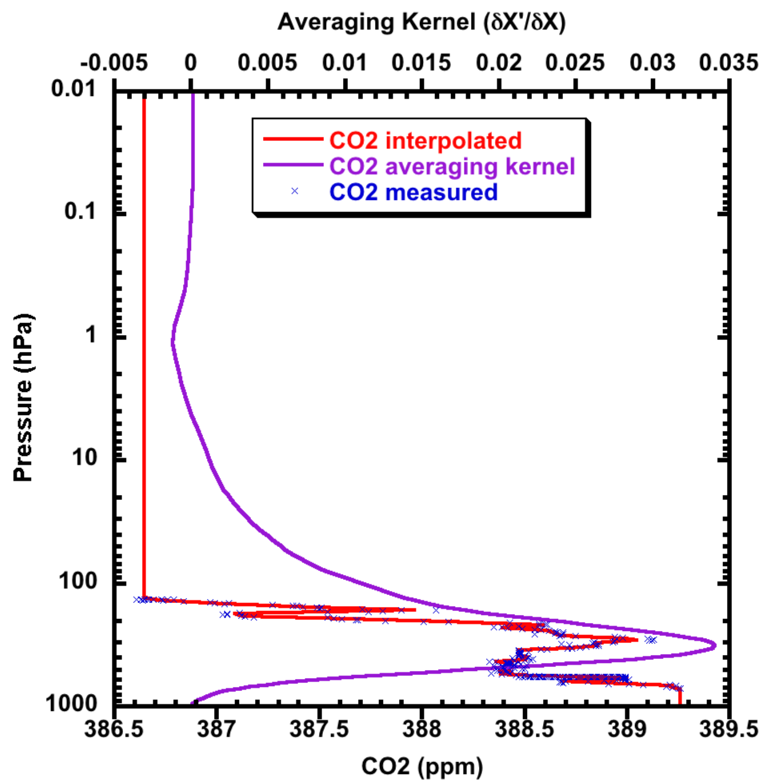


Figure 9: Comparison of interpolated/extended deep-dip HIPPO-5 measured CO_2 profile to AIRS CO_2 averaging kernel.

Blue X's: Measured HIPPO-5 CO_2 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_2 profile to be convolved with the AIRS averaging kernel to arrive at a value to be compared to average of collocated AIRS CO_2 retrievals. The extension to altitudes above the 190 hPa level is the simplest possible – replication of the highest altitude *in situ* measurement.

The replication of the highest altitude in situ measurement is not sufficiently accurate for a true validation. It is known that the CO_2 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 ±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_2 retrieved ingesting the V5 AIRS_AMSU data products (blue filled circles) and CO_2 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_2 products exhibit nearly identical validation statistics and variation with latitude relative to collocated HIPPO profiles for all four periods.

We conclude that CO_2 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).

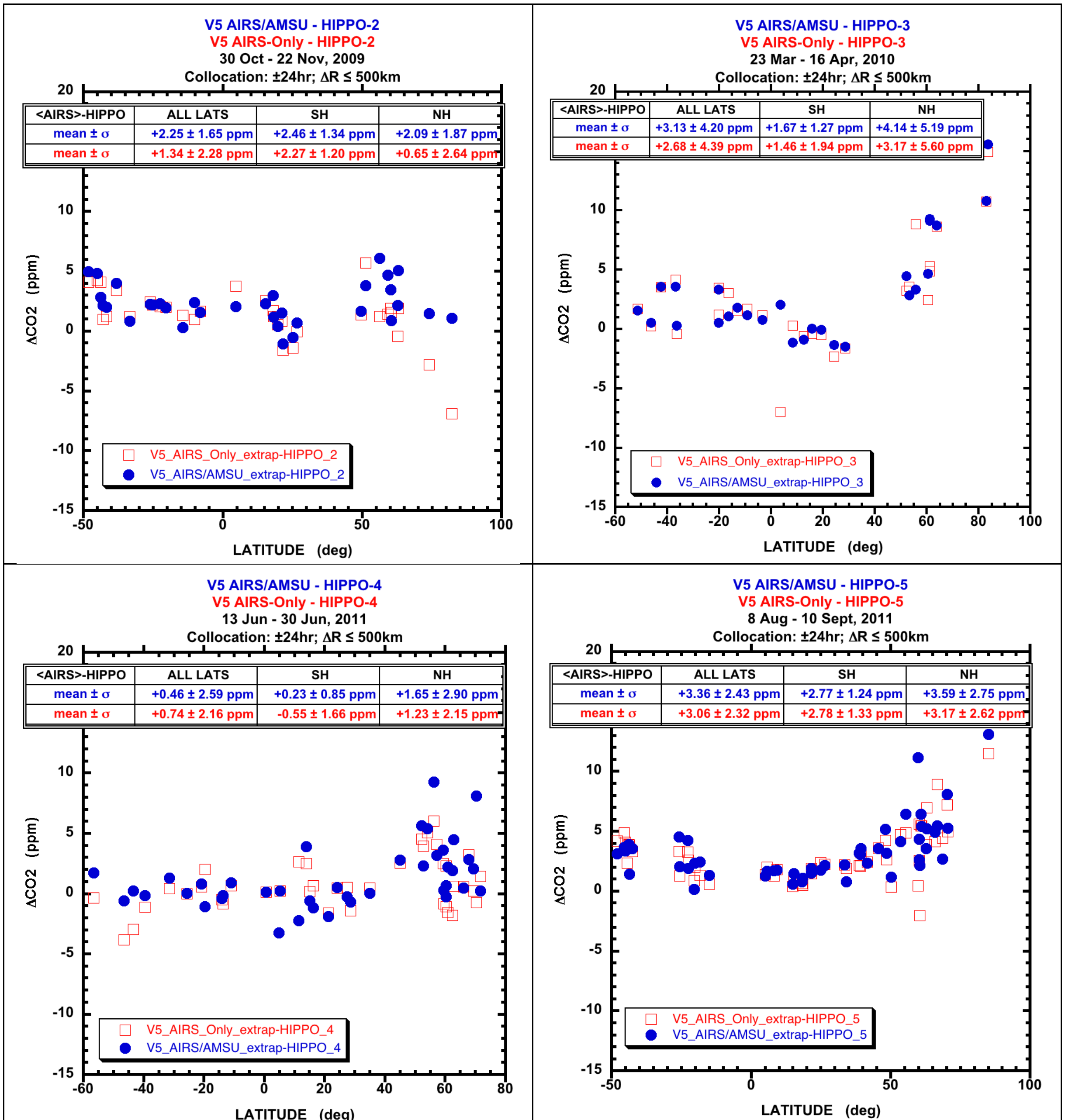


Figure 10: Comparison of collocated AIRS_AMSU CO_2 and AIRS_Only CO_2 to deep-dip HIPPO profiles convolved with their averaging kernels.

Filled blue dots: <Collocated AIRS_AMSU CO_2> - Convolved HIPPO Profiles

Open red squares: <Collocated AIRS_Only CO_2> - 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

ACKNOWLEDGMENT

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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

REFERENCES

Anderson, G. P., S. A. Clough, F. X. Kneizys, J. W. Chetwynd, and E. P. Shettle (1986), AFGL atmospheric constituent profiles (0 – 120 km), *Tech. Rep. AFGL-TR-86-0110*, Phillips Lab., Hanscom Air Force Base, Mass.

Boering, K. A. (1996), Stratospheric Mean Ages and Transport Rates from Observations of Carbon Dioxide and Nitrous Oxide, *Science, 274*, 1340-1343, doi: 10.1126/science.274.5291.1340.

Chahine, M.T., C. Barnet, E. T. Olsen, L. Chen, and E. Maddy (2005), On the determination of atmospheric minor gases by the method of vanishing partial derivatives with application to CO2, *Geophys. Res. Lett., 32*, L22803, doi:10.1029/2005GL024165.

Chahine, M.T. *et al.,* (2006), AIRS: Improving Weather Forecasting and Providing New Data on Greenhouse Gases, *Bull. Am. Meteor. Soc., 87*, 911-926, doi:10.1175/BAMS-87-7-911

Chahine, M.T. et al., (2008), Satellite Remote Sounding of Mid-Tropospheric CO2, *Geophys. Res. Lett., 35*, L17807, doi:10.1029/2008GL035022.

Chedin, A., N. A. Scott, C. Wahiche and P. Moulinier, (1985), The improved initialization inversion method: a high resolution physical method for temperature retrievals from satellites of the TIROS-N series, *J. Appl. Meteorol., 24*, 128-143, doi: 10.1175/1520-0450(1985)024<0128:TIIIMA>2.0.CO;2

Engelen, R. J., and A. P. McNally (2005), Estimating atmospheric CO2 from advanced infrared satellite radiances within an operational four-dimensional variational (4D-Var) data assimilation system: Results and validation, *J. Geophys. Res., 110*, D18305, doi:10.1029/2005JD005982.

Engelen, R. J., S. Serrar, and F. Chevallier (2009), Four-dimensional data assimilation of atmospheric CO2 using AIRS observations, *J. Geophys. Res., 114*, D03303, doi:10.1029/2008JD010739.

Jiang, X. et al. (2008), Simulation of upper troposphere CO2 from chemistry and transport models, *Global Biogeochemical Cycles*, 22, doi:10.1029/2007GB003049.

Li, King-Fai, et al. (2010) Tropical mid-tropospheric CO2 variability driven by the Madden–Julian oscillation, *Proceedings of the National Academy of Sciences 107*,45: 19171-19175.

Matsueda, H., H. Y. Inoue, and M. Ishii (2002), Aircraft observation of carbon dioxide at 8-13 km altitude over the western Pacific from 1993 to 1999. *Tellus*, *54B*(1), 1- 21,
doi: 10.1034/j.1600-0889.2002.00304.x; (Data are available at ftp://gaw.kishou.go.jp/pub/data/current/co2/event/eom999900.mri.am.fl.co2.nl.ev.dat).

Maddy E. S., C. D. Barnet, M. Goldberg, C. Sweeney, X. Liu (2008), CO2 retrievals from the Atmospheric Infrared Sounder: Methodology and validation, *J. Geophys. Res., 113*, D11301, doi:10.1029/2007JD009402.

Morgan, C. G., M. Allen, M. C. Liang, R. L. Shia, G. A. Blake, and Y. L. Yung (2004), Isotopic fractionation of nitrous oxide in the stratosphere: Comparison between model and observations, *J. Geophys. Res., 109*, D04305, doi:10.1029/2003JD003402.

Shia, R. L., M. C. Liang, C. E. Miller and Y. L. Yung (2006), CO2 in the Upper Troposphere: Influence of Stratophere-Troposphere Exchange, *Geophys. Res. Lett. 33*, doi:10, 1029/2006/GRL026141.

Stiller, G. P., T. von Clarmann, F. Haenel, B. Funke, N. Glatthor, U. Grabowski, S. Kellmann, et al. (2012), Observed Temporal Evolution of Global Mean Age of Stratospheric Air for the 2002 to 2010 Period, Atmospheric Chemistry and Physics 12, no. 7: 3311-31.

Strow, L. L., S. E. Hannon, (2008), A 4-year zonal climatology of lower tropospheric CO2 derived from ocean-only Atmospheric Infrared Sounder observations, *J. Geophys. Res., 113*, D18302, doi:10.1029/2007JD009713.

Waugh, D., and T. Hall (2002), Age of stratospheric air: Theory, observations, and models, *Rev. Geophys., 40*(4), 1010, doi:10.1029/2000RG000101.

Wofsy et al, (2012), HIPPO Merged 10-second Meteorology, Atmospheric Chemistry, Aerosol Data (R_20121129), used data file "HIPPO_all_missions_merge_10s_20121129.tbl",Carbon Dioxide Information Analysis Center, OakRidge National Laboratory, Oak Ridge, Tennessee, USA, doi:10.3334/CDIAC/hippo_010