MOPITT

(Measurements of Pollution in the Troposphere)

Version 7 Product User's Guide

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1 MOPITT Version 7 Product Highlights

This guide describes new product features in the MOPITT Version 7 (V7) Level 2 products for tropospheric carbon monoxide (CO). This comprehensive version of the User's Guide has been revised to serve as a "standalone" document, and includes relevant material from earlier User's Guides. Any updates to this document will be announced on the MOPITT News webpage at https://www2.acom.ucar.edu/mopitt/news .

Featured improvements in the V7 retrieval product include:

- **Improved radiative transfer modeling. Details in Sec. 3.1**

- **Improved meteorological fields used in Level 2 processing. Details in Sec. 3.3**

- **Improved cloud detection. Details in Sec. 3.4**

- **Improved radiance bias correction. Details in Sec 3.5**

- **Improved NIR calibration method for archival products. Details in Sec. 3.6**

2 Review of Earlier MOPITT Products

Following the launch of Terra near the end of 1999, the MOPITT Version 3 (V3) product became available in 2000 [1]. This was the first satellite dataset for tropospheric CO featuring global coverage. This product was followed in 2009 by the Version 4 (V4) product [2]. Significant improvements first introduced in the V4 product included (1) temporally and geographically variable a priori for CO based on the chemical transport model MOZART, (2) representation of CO variability by log-normal statistics, (3) extension of the forward radiative transfer model MOPFAS to simulate much higher CO concentrations, and (4) improved observation-based a priori values for surface emissivity. Processing of the V4 product ended at the end of 2012. The V5 product became available in 2011 in three retrieval configurations: thermal infrared-only ("TIR-only"), near infrared-only ("NIR-only") and multispectral ("TIR/NIR"). (The previous V3 and V4 products were TIR-only products.) V5 retrieval products also benefited from a new time-dependent radiative transfer model to reduce the influence of long-term instrumental changes on retrieval biases (i.e., "bias drift"). The V5 product was validated using a variety of in-situ and satellite datasets [3,4]. The V6 product was released in 2013 and featured (1) correction of a systematic geolocation error, (2) use of the MERRA (Modern-Era Retrospective Analysis For Research And Applications) reanalysis for needed meteorological fields and (3) an updated model-based a priori for CO [5].

3 Features of the MOPITT Version 7 Retrieval Algorithm

Improvements to the content of the V7 retrieval products are described in the following section.

Significant changes in the V7 product (with respect to both scientific content and format) are emphasized in **bold** text.

3.1 Radiative Transfer Modeling

The radiative transfer model on which the MOPITT retrieval algorithm is based has been updated for V7. The model now accounts for the steady growth of atmospheric N_2O concentrations over the MOPITT mission. Global-mean N_2O concentrations increased between 2000 and 2015 at a rate of ~ 0.28%/yr (see http://www.esrl.noaa.gov/gmd/hats/combined/N2O.html). Because of the proximity of CO and N_2O spectral absorption lines in the TIR region, increasing N_2O concentrations are believed to have contributed to long-term bias drift in previous MOPITT products. The operational radiative transfer model for V7 has also been updated with the HITRAN 2012 spectral database [6].

3.2 Retrieval Grid

V7 retrieved profiles are expressed on the same ten-level grid (surface, 900 hPa, 800 hPa, ..., 100 hPa) used for V4, V5 and V6 products. For V4 products, each retrieval level was assigned to a layer centered on that level, with a weighting that tapered to zero at the adjacent retrieval levels. For V5, V6 and V7 products, in contrast, each retrieval level simply corresponds to a uniformly-weighted layer immediately above that level. For example, for retrievals where the surface pressure exceeds 900 hPa, the V7 surface-level retrieval product corresponds to the mean volume mixing ratio over the layer between the surface and 900 hPa. Thus, when comparing MOPITT profiles with model results, we suggest first applying simple (unweighted) averaging to the model results in the layers above each retrieval level. (For the topmost MOPITT retrieval level at 100 hPa, the uniform-VMR layer extends from 100 hPa to 50 hPa. Assumed VMR values in the layer from 50 hPa to TOA are based on the CAM-chem model climatology and are fixed.)

3.3 Meteorological Fields

For each observation at a particular time and geographic location, the MOPITT retrieval algorithm requires temperature and water vapor profiles as well as a priori surface temperature values.   For V6 processing, meteorological profiles were derived from the NASA MERRA reanalysis product (http://gmao.gsfc.nasa.gov/reanalysis/MERRA/). **For all V7 products, meteorological profiles are extracted from the more recently released MERRA-2 product.** As described here (http://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/), MERRA-2 " ... was introduced to replace the original MERRA dataset because of the advances made in the assimilation system that enable assimilation of modern hyperspectral radiance and microwave observations, along with GPS-Radio Occultation datasets. It also uses NASA ozone observations after 2005. Additional advances in both the GEOS-5 model and the GSI assimilation system are included in MERRA-2. Spatial resolution remains

about the same (about 50 km in the latitudinal direction) as in MERRA." **Generally higher quality retrieval results for V7 are expected using MERRA-2 due to the assimilation of more satellite datasets (e.g., IASI) and other improvements.**

3.4 Cloud Detection

Only MOPITT observations made in clear sky conditions are used in Level 2 retrieval processing. The clear/cloudy determination is based both on MOPITT's thermal-channel radiances and the MODIS cloud mask. Since about 2010, electronic crosstalk affecting MODIS thermal-channel Bands 29 to 31 ([documented here](#)) has resulted in a false trend towards increasing cloudiness, particularly for tropical nighttime scenes over the ocean. This issue affects MODIS products from both Collections 5 (used until February 2016 in MOPITT V5 and V6) and 6 (used since March 2016 in MOPITT V5 and V6). **For the cloud detection algorithm used for MOPITT V7 products, two changes have been made. First, MODIS Collection 6 cloud mask files are used consistently for processing the entire MOPITT mission. (Characteristics of the Collection 6 cloud mask files are described in https://modis-atmos.gsfc.nasa.gov/Webinar2014/MODIS_C6_MOD35_Ackerman.pdf.) Second, a new Level 2 Cloud Description diagnostic index value ("6") is assigned to night and day ocean scenes where the MODIS cloud mask-based tests indicate that the area was cloudy (with the exception of scenes with low clouds) but the test based on MOPITT's thermal-channel radiances finds that the area was clear; such MOPITT scenes were previously discarded but are now retained. Compared to earlier MOPITT products, the addition of this new "clear" class may significantly increase the number of MOPITT retrievals in a given scene.** The other possible Cloud Description diagnostic values (1-5) retain their original meanings, as follows. A value of 1 means "MOPCLD only clear, thermal channels only," a value of 2 means "MOPCLD and MODIS cloud mask agree on clear," a value of 3 means "MODIS cloud mask only clear," a value of 4 means "MOPCLD overriding MODIS cloud mask over low clouds" and a value of 5 means "MODIS cloud mask only, clear over polar regions." Like previous versions, the V7 cloud detection algorithm accepts MOPITT pixels with up to 5% cloudiness as effectively clear and passes those observations on to the retrieval algorithm.

A diagnostic is also provided for each retrieval (in the Level 2 product file) to statistically describe the cloud test results for the set of MODIS Cloud Mask pixels matched to each MOPITT pixel. These diagnostics may be of use for analyzing potential retrieval biases associated with particular types of clouds. Elements of the 10-element "MODIS Cloud Diagnostics" floating point vector indicate:

> (1) Number of "determined" MODIS pixels
> (2) Percentage of cloudy MODIS pixels
> (3) Percentage of clear MODIS pixels
> (4) Average value of "sun glint" MODIS flag

(5) Average value of "snow/ice background" MODIS flag

(6) Average value of "non-cloud obstruction" MODIS flag

(7) Average value of "IR threshold test" MODIS flag

(8) Average value of "IR temperature difference tests" MODIS flag

(9) Average value of "visible reflectance test" MODIS flag

(10) Fraction of "determined" MODIS pixels

Users are referred to [7] for more information regarding details of the MODIS cloud mask tests.

3.5 *Radiance Bias Correction*

The MOPITT Level 2 processor exploits a set of radiance-bias correction factors to compensate for relative biases between (1) simulated radiances calculated by the operational radiative transfer model and (2) actual calibrated Level 1 radiances. Without some form of compensation, radiance biases produce biases in the retrieved CO profiles. Radiance bias correction factors compensate for a variety of potential bias sources including errors in instrumental specifications, forward model errors, spectroscopy errors, and geophysical errors. **New strategies were developed for deriving radiance-bias correction factors for V7 products. For the TIR radiances (Channels 5 and 7), radiance-bias scaling factors were determined by minimizing observed retrieval biases at 400 and 800 hPa as determined using in-situ CO profiles from the HIPPO (HIAPER Pole to Pole Observations) field campaign [3,4,5].** To the extent that the HIPPO campaign produced a near-global set of in-situ CO profiles (i.e., over a wide latitudinal range spanning both the Northern and Southern Hemispheres), this strategy effectively yields globally-minimized retrieval biases. **For the NIR radiances (Channel 6), radiance bias scaling factors were determined by minimizing NIR-only retrieval biases as determined using the NOAA aircraft profile set.** (The HIPPO dataset primarily represents oceanic scenes and was therefore not useful for optimizing the NIR radiance-bias scaling factors.) Validation results confirming the success of the radiance bias correction methods have been published [8].

3.6 *NIR Calibration*

Calibration of MOPITT's NIR channels (e.g., Channel 6) relies on a two-point calibration scheme involving both cold-calibration ("cold-cal") events and hot-calibration ("hot-cal") events. Cold-cals occur many times per day, while hot-cals are performed only about once per year. Ideally, NIR channels are calibrated with gain and offset values determined by interpolating the information from hot-cals occurring both before and after the time of observation. While this method is feasible in retrospective processing mode (i.e., processing previous years of data), it is not possible in forward processing mode (i.e., when processing recently acquired observations). Thus, in forward processing mode, only information from the most recent hot-cal is used to calibrate MOPITT's NIR radiances. Comparisons of NIR-only retrieval products generated in retrospective and forward processing modes have revealed significant differences (10% to 20%) in total column results, with the retrospectively

processed data in better agreement with daytime/land TIR-only total column values and time dependence. **Therefore, because of the degraded quality of MOPITT products processed in forward processing mode, V7 products generated in this manner will be labeled as "beta" products. These products will be reprocessed and replaced by standard archival files following the next hot-cal. Typically, this will occur no more than a year from the time of a particular observation (depending on the date of the most recent hot-cal). The beta products should not be considered for examining long-term records of CO although these products should still be useful for some applications. See Sec. 5.**

4 Product Format and Content

The contents of the V7 Level 2 and Level 3 product files are described and tabulated in Appendices A and B. Beginning with the MOPITT V6 products, the format of the archival Level 1, Level 2 and Level 3 data files switched from HDF-EOS2, based on HDF4 libraries, to HDF-EOS5, based on HDF5 libraries. **V7 products are in the same HDF5 format as V6 products and should be readable with analysis tools developed for V6 products.** HDF is a standard format for large datasets (https://www.hdfgroup.org/). The HDF-EOS format is an extension of HDF developed by the HDF-EOS group (http://hdfeos.org/index.php). Files distributed in the HDF-EOS5 format can be accessed with a wide range of software tools including IDL, NCL and MATLAB (https://support.hdfgroup.org/products/).

4.1 Level 1 Data

The content of the Level 1 product files containing the MOPITT calibrated radiances is unchanged for V7, with the exception of a new diagnostic, "Daily Gain Dev." This diagnostic provides the standard deviation of the gain values used to calibrate the radiances for a particular channel and pixel on one day. This diagnostic may be useful as a metric for the Channel 5 calibration issue described in Sec. 5. The Daily Gain Dev diagnostic is also included in V7 Level 2 data files.

4.2 Level 2 Data

The contents of the V7 Level 2 product files are described in table form in Appendix A. The file content is nearly identical to that of the V6 Level 2 files, with the exception of several new diagnostics. New diagnostics include

- **Total Column Averaging Kernel.** This diagnostic allows users to properly compare MOPITT total column retrievals with total columns derived from in-situ profiles or model simulations. Use of the total column averaging kernel is discussed in Sec. 5.5.

- **Averaging Kernel Row Sums.** This diagnostic provides a single scalar value for each row of the averaging kernel matrix (representing a particular retrieval level) equal to the sum of the

elements in that row. Small row-sum values indicate retrieval levels heavily weighted by the a priori while row sum values approaching unity indicate levels with relatively weak sensitivity to the a priori.

- **Dry Air Column and Water Vapor Column.** Along with the retrieved CO total column, these diagnostics facilitate the computation of the equivalent dry-air or moist-air mixing ratio averaged over the atmospheric column.

- **Smoothing Error and Measurement Error Covariance Matrices.** These diagnostics represent the two components of the Retrieval Error Covariance Matrix. Smoothing error represents the retrieval uncertainty due to the influence of a priori and the features of the weighting functions. Measurement error represents the retrieval uncertainty due to uncertainties in the measured radiances (including instrument noise). These diagnostics are described further in Sec. 3.2 of Rodgers' book [9].

- **Retrieval Anomaly Flags.** These flags are set to true when particular anomalous conditions are observed, suggesting that the retrievals should either be ignored or used cautiously. The first four flags (i.e., elements 1-4 of the Retrieval Anomaly Diagnostic array) are set to true (i.e., a value of 1) when one of the thermal channel weighting functions exhibits a sign change vertically. This can occur, for example, in some nighttime/land scenes when the surface skin temperature is less than the temperature of the air immediately above the surface. Elements 1-4 correspond respectively to the 5A, 5D, 7A, and 7D weighing functions. The fifth flag of the Retrieval Anomaly Diagnostic array is set to true when the retrieval averaging kernel matrix includes at least one negative element on the matrix diagonal.

Appendices C and D provide examples of IDL and NCL code used to open and read the contents of V7 Level 2 data files.

4.3 Level 3 Data

MOPITT Level 3 products are available as gridded daily-mean and monthly-mean files. Data averaging is performed on a one-degree latitude/longitude grid. Compared to Level 2 products, these gridded products typically are less affected by random retrieval errors (e.g., due to instrument noise or geophysical noise) and are packaged into much smaller HDF5 data files. Within each type of Level 3 file, data-averaged products are separately available for daytime and nighttime MOPITT observations. The contents of the V7 L3 files are described in Appendix B; for brevity, only daytime-overpass L3 fields are listed. New Level 3 diagnostics include the total column averaging kernel, dry air column, water vapor column, smoothing error covariance matrix and measurement error covariance matrix.

Previously, for V6 TIR-only and TIR/NIR Level 3 products, "pixel filtering" was employed to exclude observations from two specific detector elements in MOPITT's linear detector array; these two detector

elements generally exhibited greater noise than the other two elements. **V7 Level 3 processing employs a new strategy (in addition to pixel filtering) for improving information content. The new method involves signal-to-noise ratio (SNR) thresholds for Channel 5 and 6 Average radiances (i.e., 5A and 6A).** SNR values for each observation are obtained using radiance and radiance uncertainty values contained in the diagnostic "Level1RadiancesandErrors" in the Level 2 data files. Observations with relatively low SNR tend to yield retrievals weighted heavily by the a priori and generally result in low DFS. Excluding these observations from the Level 3 cell-averaged values raises overall mean DFS values. Specific filtering rules used for both the daily-mean and monthly-mean V7 Level 3 products are:

- V7 Level 3 TIR-only products exclude all observations from Pixel 3 in addition to observations where the 5A SNR < 1000

- V7 Level 3 NIR-only products exclude all observations where the 6A SNR < 400

- V7 Level 3 *daytime* TIR/NIR products exclude all observations from Pixel 3 in addition to observations where both (1) the 5A SNR < 1000 *and* (2) the 6A SNR < 400

- V7 Level 3 *nighttime* TIR/NIR products exclude all observations from Pixel 3 in addition to observations where the 5A SNR < 1000

5 Data Analysis Considerations

5.1 Data Quality

Compared to V6, validation results for V7 CO products indicate (1) generally smaller retrieval biases and (2) reduced bias variability [8].

As described in Sec. 3.6, the MOPITT algorithm development team discovered a new source of retrieval bias affecting the V5 and V6 NIR-only and TIR/NIR retrieval products. Retrieval biases found in V5 and V6 products resulted from the fact that hot calibration events used to calibrate the MOPITT NIR radiances only occur approximately once per year. **Users of affected V5 and V6 MOPITT products are cautioned that the newly discovered source of bias might significantly affect multi-year analyses of CO.** For V7, the MOPITT team will release products generated in forward-processing mode as "beta" products, and will later reprocess these data following the next hot calibration. Beta products are considered unvalidated and should generally be used with caution.

V7 beta products are easily identifiable as the filenames of such files include the word "beta" (e.g., "MOP02T-20160501-L2V17.8.1.beta.he5"). At the ASDC ftp and OPeNDAP sites (accessible at https://eosweb.larc.nasa.gov/datapool), beta files will also be stored in separate directories from archival products. For example, the archival V7 Level 2 TIR-only products will be found in subdirectories under the main directory "MOP02T.007"; this convention is

consistent with previous MOPITT releases. Corresponding V7 beta TIR-only products are found in subdirectories under "MOP02T.107".

Another type of retrieval anomaly has been noticed in a small number of nighttime/land scenes. This anomaly is typically manifested as a striping pattern in retrieved surface-level CO concentrations and surface temperature for one or two pixels in the four-element detector array over a series of tracks. This type of anomaly primarily affects Pixels 1 and 4 and appears to be partly the result of a calibration issue affecting Channel 5 radiances in which gain and offset values exhibit frequent sudden jumps throughout the day. These gain and offset discontinuities have been traced back to cold calibration (space-view) events. The new Daily Gain Dev diagnostic (included in both Level 1 and Level 2 files) may be useful for identifying days where this type of anomaly is most likely to occur. However, analyses of "outlier" retrievals suggest that retrieval anomalies due to this effect are typically small (e.g., less than 10 ppbv).

5.2 Data Averaging

Because of both geophysical and instrumental noise, individual MOPITT retrieved profiles do not provide a strong basis for scientific analysis. This is especially true for the NIR-only and TIR/NIR products. Instead, users should employ statistical methods applied to ensembles of retrievals. Simple data averaging is the most common statistical method for reducing the effects of random instrument noise. The tradeoff to this benefit is reduced spatial and/or temporal resolution. When averaging over an ensemble, retrieval uncertainties associated with random radiance errors (such as geophysical noise and instrumental noise) decrease as the square root of the number of retrievals in the ensemble.

The retrieval state vector represents CO volume mixing ratio (VMR) variability as a log-normal quantity. This has important implications for data averaging. For MOPITT data subsets where the main source of retrieval variability is random retrieval noise (rather than CO variability), retrieved VMR values will follow a log-normal distribution. In such cases, the appropriate method for reducing the effects of instrument noise is to (1) convert individual VMR profiles into log(VMR) profiles, (2) compute the mean, and (3) convert the mean log(VMR) profile back to a VMR profile. Because of the asymmetry of the log-normal distribution, directly computing the mean VMR profile from a set of VMR profiles in such cases will produce a positive bias relative to "truth." In contrast, when CO variability is the dominant source of retrieval variability (such as when averaging over large regions and temporal intervals), directly calculated mean VMR values are most meaningful.

5.3 Inclusion of A Priori

Besides retrieval noise, a variety of effects influence MOPITT data quality. For example, the relative weight of the a priori profile x_a in the retrieval x_{rtv}, which ideally should be as small as possible, is quantified by the retrieval averaging kernel matrix according to

$$x_{rtv} \approx x_a + A\,(x_{true} - x_a) = A\,x_{true} + (I - A)\,x_a \qquad (1)$$

where x_{true} is the true profile, A is the averaging kernel matrix, and I is the identity matrix. Inclusion of a priori information is associated with all remote sensing methods based on optimal estimation. The optimal estimation method exploits a priori information to complement the information contained in the observations; the a priori profile plays a strong role for retrieval levels where the measurements are are insensitive. This effect is well understood. An important consequence of this effect is that, when comparing MOPITT retrieved profiles against in-situ data or model results, users must transform these comparison datasets using Eq. 1, so that the comparison data exhibit the same degree of smoothing and a priori dependence as the MOPITT product [1,2]. For the V5, V6 and V7 products, users must make this transformation in terms of $\log_{10}$(VMR) rather than VMR. Users should also observe the level-layer associations described in Sec. 3.2.

Other effects have less quantifiable influence on retrieval data quality. Examples of such effects include forward model error, errors in assumed meteorological profiles, and instrumental degradation. For these effects, robust estimates of the associated retrieval errors are not feasible. Quantifying such errors is also complicated because they may be highly variable in space and time.

5.4 Data Filtering

Because of the potential variability of MOPITT data quality, as discussed above, users may decide to exclude particular subsets of the Level 2 data in their analyses. This is a reasonable strategy, *unless such methods could impose retrieval bias*. For example, filtering based on the "Degrees of Freedom for Signal" (DFS) parameter tends to retain high-CO profiles and discard low-CO profiles, thereby imposing a positive retrieval bias on the filtered subset. Filtering on DFS, or other characteristics of the retrieval averaging kernels, is therefore not recommended.

Alternatively, filters based on geophysical criteria which are known to provide better conditions for remote sensing retrievals may be appropriate. For example, over land, daytime conditions typically provide better thermal contrast conditions for TIR- and TIR/NIR-based retrievals than nighttime conditions.

5.5 Analysis of Retrieved CO Total Column Values

For users interested in quantitatively comparing MOPITT retrieved CO total column values with other datasets (or model output), the V7 Level 2 and Level 3 product files include the total column averaging kernel a; this vector quantifies the sensitivity of the retrieved total column to perturbations at each level of the CO profile. Thus, if C_{rtv} is the retrieved CO total column, and x is the CO state vector comprised of CO $\log_{10}$(VMR) values, the total column averaging kernel element for level j in the CO profile is defined by

$$a_j = \partial \, C_{rtv} \, / \, \partial \, x_j \tag{2}$$

Given a comparison CO profile x_{cmp} (e.g., either from in-situ measurements or model output), the total column averaging kernel vector is used to simulate MOPITT total column retrievals using the equation

$$C_{sim} = C_a + a(x_{cmp} - x_a) \tag{3}$$

where C_a is the a priori total column value corresponding to the a priori profile x_a. Both C_a and x_a are also provided in the V7 Level 2 product files for each retrieval.

6 References

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Appendices

A. Tabulated Contents of V7 Level 2 Product Files

DIMENSIONS

Dimension Name	Definition	Size
nTime	Number of retrievals	Varies with each granule
nChan	Number of channels of the instrument	8
nTwo	For data fields which include associated variability (or uncertainty), first element is the parameter and second element is variability/uncertainty, unless otherwise specified.	2
nPrs	Number of fixed pressure levels	9
nPrs2	Number of pressure levels, including the surface	10
nPix	The number of pixels (i.e., number of detector elements)	4

GEOLOCATION FIELDS ('HDFEOS/SWATHS/MOP02/Geolocation Fields/…')

Field Name	Definition	Dimension	Units	Data Type
SecondsinDay	Time of the measurement in seconds from the beginning of the day.	nTime	s	F
Latitude	Geolocation of the pixel	nTime	deg	F
Longitude	Geolocation of the pixel	nTime	deg	F
Pressure	Pressure Levels	nPrs	hPa	F
Pressure2	Pressure Levels including the surface	nPrs2	hPa	F
Time	TAI Time of the observation	nTime	s	F
F = Floating Point **I** = Integer				

RETRIEVED CO FIELDS ('HDFEOS/SWATHS/MOP02/Data Fields/…')

Field Name	Definition	Dimension	Units	Data Type
RetrievedCOTotalColumn	CO Total Column	nTwo, nTime	mol/cm^2	F
RetrievedCOMixingRatioProfile	CO Mixing Ratio for the layer above each pressure level	nTwo, nPrs, nTime	ppbv	F
RetrievedCOSurfaceMixingRatio	CO Mixing Ratio at the surface	nTwo, nTime	ppbv	F

A PRIORI FIELDS ('HDFEOS/SWATHS/MOP02/Data Fields/…')

Field Name	Definition	Dimension	Units	Data Type
APrioriCOMixingRatioProfile	Temporally and geographically variable a priori CO profile based on a climatology for 2000-2009 simulated with the CAM-Chem model	nTwo, nPrs, nTime	ppbv	F
APrioriCOSurfaceMixingRatio	Temporally and geographically variable a priori surface CO based on a climatology for 2000-2009 simulated with the CAM-Chem model	nTwo, nTime	ppbv	F
APrioriCOTotalColumn	Temporally and geographically variable a priori total column CO based on a climatology for 2000-2009 simulated with the CAM-Chem model	nTwo, nTime	mol/cm^2	F

AVERAGING KERNEL FIELDS ('HDFEOS/SWATHS/MOP02/Data Fields/…')

Field Name	Definition	Dimension	Data Type
RetrievalAveragingKernelMatrix	For each retrieval, a floating point array (10 x 10) containing the matrix describing the sensitivity of the retrieved CO log(VMR) profile to the true CO log(VMR) profile. Dimensions of Retrieval Averaging Kernel Matrix are ordered (nrow, ncolumn, ntime)	nPrs2, nPrs2, nTime	F
AveragingKernelRowSums	This diagnostic provides a single scalar value for each row of the averaging kernel matrix equal to the sum of the elements in that row. Small row-sum values indicate retrieval levels heavily weighted by the a priori while values approaching unity indicate levels with relatively weak sensitivity to the a priori.	nPrs2, nTime	F
TotalColumnAveragingKernel	This diagnostic allows users to properly compare MOPITT total column retrievals with total columns derived from in-situ profiles or model simulations.	nPrs2, nTime	F
TotalColumnAveragingKernelDimless	This diagnostic allows users to properly compare MOPITT total	nPrs2, nTime	F

	column retrievals with total columns derived from in-situ profiles or model simulations based on partial columns instead of log(VMR).		

CLOUD FIELDS ('HDFEOS/SWATHS/MOP02/Data Fields/…')

These quantities are unitless

Field Name	Definition	Dimension	Data Type
CloudDescription	0 = clear, only MOPITT thermal and cloudtop used 1 = clear, only MOPITT thermal used 2 = MOPITT and MODIS cloud mask agree on clear 3 = MODIS cloud mask only clear (when MOPITT determines cloudy) 4 = MOPITT overriding MODIS cloud mask over low clouds (MODIS test flags used) 5 = MODIS cloud mask only, clear over polar regions and daytime 6 = Nighttime ocean scenes where the MODIS cloud mask-based test finds that the area was cloudy but MOPITT's thermal-channel radiances finds that the area was clear (new for V7)	nTime	I
MODISCloudDiagnostics	(1) Number of "determined" MODIS pixels (2) Percentage of cloudy MODIS pixels (3) Percentage of clear MODIS pixels (4) Average value of "sun glint" MODIS flag (5) Average value of "snow/ice background" MODIS flag (6) Average value of "non-cloud obstruction" MODIS flag (7) Average value of "IR threshold test" MODIS flag (8) Average value of "IR temperature difference tests" MODIS flag (9) Average value of "visible reflectance test" MODIS flag (10) Fraction of "determined" MODIS pixels	10, nTime	F

SURFACE PROPERTY FIELDS ('HDFEOS/SWATHS/MOP02/Data Fields/…')

Field Name	Definition	Dimension	Units	Data Type
APrioriSurfaceEmissivity	A priori surface emissivity from static map	nTwo, nTime		F
APrioriSurfaceTemperature	A priori surface temperature from MERRA2 analysis	nTwo, nTime	K	F
DEMAltitude	Digital Elevation Model surface height	nTime	m	F
SurfaceIndex	0 = water 1 = land 2 = mixed (coastline)	nTime		I
SurfacePressure	Surface pressure from MERRA2 analysis	nTime	hPa	F
RetrievedSurfaceEmissivity	Surface emissivity from the retrieval	nTwo, nTime		F
RetrievedSurfaceTemperature	Surface temperature from the retrieval	nTwo, nTime	K	F

RADIANCE FIELDS ('HDFEOS/SWATHS/MOP02/Data Fields/…')

Field Name	Definition	Dimension	Units	Data Type
DailyGainDev	This diagnostic provides the standard deviation of the gain values used to calibrate the radiances for a particular channel and pixel on one day. In this case, nTwo is the Average and Difference signal gains.	nTwo, nChan, nPix		F
Level1RadiancesandErrors	First dimension corresponds to radiances/uncertainties; second dimension corresponds to channel (in sequence 7A, 3A, 1A, 5A, 7D, 3D, 1D, 5D, 2A, 6A, 2D, 6D).	nTwo, 12, nTime	W/m^2Sr	F

RETRIEVAL DIAGNOSTICS ('HDFEOS/SWATHS/MOP02/Data Fields/...')

These quantities are unitless

Field Name	Definition	Dimension	Data Type
DegreesofFreedomforSignal	For each retrieval, a floating point value describing the number of pieces of independent information in the retrieval, equal to the trace of the averaging kernel matrix.	nTime	F
MeasurementErrorCovarianceMatrix	Measurement error represents the retrieval log(VMR) uncertainty due to uncertainties in the measured radiances (including instrumental and geophysical 'noise').	nPrs2, nPrs2, nTime	F
RetrievalAnomalyDiagnostic	These flags are set to true when particular anomalous conditions are observed, suggesting that the retrievals should either be ignored or used cautiously. The first four flags (i.e., elements 1-4 of the Retrieval Anomaly Diagnostic array) are set to true (i.e., a value of 1) when one of the thermal channel weighting functions exhibits a sign change vertically. Elements 1-4 correspond respectively to the 5A, 5D, 7A, and 7D weighing functions. The fifth flag of the Retrieval Anomaly Diagnostic array is set to true when the retrieval averaging kernel matrix includes at least one negative element on the matrix diagonal.	5,nTime	I
RetrievalErrorCovarianceMatrix	For each retrieval, a floating point array (10 x 10) containing the a posteriori covariance matrix in base-10 log(VMR).	nPrs2, nPrs2, nTime	F
RetrievalIterations	The number of retrieval algorithm iterations needed for convergence	nTime	I
SignalChi2	A measure of the retrieval's goodness of fit.	nTime	F
SmoothingErrorCovarianceMatrix	Smoothing error represents the retrieval log(VMR) uncertainty due to the influence of the a priori and weighting functions.	nPrs2, nPrs2, nTime	F

RetrievedCOTotalColumnDiagnostics	This two-element vector contains both the estimated smoothing error and measurement error contributions (in that order) to the total retrieval error for CO total column. Smoothing error represents the uncertainty in the retrieved total column due to to the influence of the a priori and weighting functions. Measurement error describes the uncertainty due to random errors in the measured radiances.	nTwo, nTime	F

ATMOSPHERIC AND OBSERVATIONAL FIELDS ('HDFEOS/SWATHS/MOP02/Data Fields/ …')

Field Name	Definition	Dimension	Units	Data Type
PressureGrid	Fixed pressure levels (i.e., 900, 800, 700, 600, 500, 400, 300, 200 and 100 hPa)	nPrs	hPa	F
SolarZenithAngle	Solar zenith angle	nTime	deg	F
SatelliteZenithAngle	Viewing angle of the satellite	nTime	deg	F
SwathIndex	For each retrieval, a three-element integer vector containing the unique 'pixel' (varies from 1 to 4), 'stare' (varies from 1 to 29), and 'track' indices. 29 stares (equivalent to the mirror pivoting out and back) define one track.	3, nTime		I
DryAirColumn	Dry-air atmospheric column to facilitate the computation of the equivalent mixing ratio of CO averaged over the atmospheric column	nTime	mol/cm^2	F
WaterVaporColumn	Moist-air atmospheric column to facilitate the computation of the equivalent mixing ratio of CO averaged over the atmospheric column	nTime	mol/cm^2	F

NOTES: Fill Values are -9999

B. Tabulated Contents of V7 Level 3 Product Files

All fields listed below reside in HDF5 directory 'HDFEOS/GRIDS/MOP03/Data Fields/…'. Find data field descriptions in Appendix A. Field names of nighttime-overpass L3 products, e.g., RetrievedCOMixingRatioProfileNight, are also included in L3 files but are not shown in tables below. All L3 fields are floating point, except for integer-valued fields SurfaceIndexDay and SurfaceIndexNight. L3 files also contain mean uncertainty and variability (i.e., standard deviation) statistics for fields in table marked with dagger symbol (†). For example, mean uncertainty and variability statistics for RetrievedCOMixingRatioProfileDay are included in L3 files as RetrievedCOMixingRatioProfileMeanUncertaintyDay and RetrievedCOMixingRatioProfileVariabilityDay .

GEOLOCATION FIELDS

Field Name	Definition	Dimension	Units
Latitude	Latitudes of grid cell centers	180	deg
Longitude	Longitudes of grid cell centers	360	deg
Pressure	Fixed pressure grid	9	hPa

RETRIEVED CO FIELDS

Field Name	Dimension	Units
RetrievedCOMixingRatioProfileDay†	9, 180, 360	ppbv
RetrievedCOSurfaceMixingRatioDay†	180, 360	ppbv
RetrievedCOTotalColumnDay†	180, 360	mol/cm^2

A PRIORI FIELDS

Field Name	Dimension	Units
APrioriCOMixingRatioProfileDay	9, 180, 360	ppbv
APrioriCOSurfaceMixingRatioDay	180, 360	ppbv
APrioriCOTotalColumnDay	180, 360	mol/cm^2

AVERAGING KERNEL FIELDS

Field Name	Dimension
RetrievalAveragingKernelMatrixDay	10, 10, 180, 360
TotalColumnAveragingKernelDay	10, 180, 360

SURFACE PROPERTY FIELDS

Field Name	Dimension	Units
RetrievedSurfaceTemperatureDay[†]	180, 360	K
RetrievedSurfaceEmissivityDay[†]	180, 360	
APrioriSurfaceTemperatureDay	180, 360	K
APrioriSurfaceEmissivityDay	180, 360	
DEMAltitudeDay	180, 360	m
SurfaceIndexDay (integer-valued)	180, 360	
SurfacePressureDay	180, 360	hPa

RETRIEVAL DIAGNOSTICS

Field Name	Dimension
DegreesofFreedomforSignalDay	180, 360
RetrievalErrorCovarianceMatrixDay	10, 10, 180, 360
MeasurementErrorCovarianceMatrixDay	10, 10, 180, 360
SmoothingErrorCovarianceMatrixDay	10, 10, 180, 360
RetrievedCOTotalColumnDiagnosticsDay	180, 360
SignalChi2Day	180, 360

ATMOSPHERIC AND OBSERVATIONAL FIELDS

Field Name	Dimension	Units
SolarZenithAngleDay	180, 360	deg
SatelliteZenithAngleDay	180, 360	deg
DryAirColumnDay	180, 360	mol/cm^2
WaterVaporColumnDay	180, 360	mol/cm^2

NOTES: Fill Values are -9999.

C. Sample IDL Code for Opening and Reading V7 Level 2 files

```
pro example_v7_lev2

; sample IDL code for opening and reading MOPITT Version 7 Level 2 files

; note different paths for 'Geolocation Fields' and 'Data Fields'

infile = 'MOP02T-20030101-L2V17.8.1.he5'

print, infile

print, 'open hdf5 file'
file_id = H5F_OPEN(infile)

; read latitudes into variable 'moplat'
print, 'read latitudes'
dataset_id = H5D_OPEN(file_id, '/HDFEOS/SWATHS/MOP02/Geolocation Fields/Latitude')
moplat = H5D_Read(dataset_id)
H5D_CLOSE, dataset_id

; read longitudes into variable 'moplon'
print, 'read longitudes'
dataset_id = H5D_OPEN(file_id, '/HDFEOS/SWATHS/MOP02/Geolocation Fields/Longitude')
moplon = H5D_Read(dataset_id)
H5D_CLOSE, dataset_id

; read retrieved profiles into variable 'rtvprofl'
print, 'read retrieved CO profiles'
dataset_id = H5D_OPEN(file_id, '/HDFEOS/SWATHS/MOP02/Data Fields/RetrievedCOMixingRatioProfile')
rtvprofl = H5D_Read(dataset_id)
H5D_CLOSE, dataset_id

; read averaging kernel matrices into variable 'avkrn'
print, 'read AK matrix'
dataset_id = H5D_OPEN(file_id, '/HDFEOS/SWATHS/MOP02/Data Fields/RetrievalAveragingKernelMatrix')
avkrn = H5D_Read(dataset_id)
H5D_CLOSE, dataset_id

H5F_CLOSE, file_id

; print lat and lon of first retrieval
print, moplat(0), moplon(0)
; print retrieved profile of first retrieval (fixed-levels only, surface retrieval missing)
print, rtvprofl(0,0:8,0)
; print AK matrix for first retrieval
print, avkrn(0:9,0:9,0)

return
end
```

D. Sample NCL Code for Opening and Reading V7 Level 2 files

```
;=======================================================;
;  example-mopitt-v7-lev2.ncl
;=======================================================;
;
;
; Concepts illustrated:
;   - For use with MOPITT CO version 7, level 2 product
;   - Loading CO data, AK, latitude and longitude from
;     MOPITT level 2 hdf5 file
;
; To run type:
;     ncl example-mopitt-v7-lev2.ncl
;
;=======================================================;

begin

; -----------------------------
; MOPITT file location
; -----------------------------
  indir = "/MOPITT/V7T/Archive/L2/200301/0101/"
  fname = "MOP02T-20030101-L2V17.8.1.he5"
  infile = indir+fname
  print(infile)

;-------------------------------------------
; load file and extract data structures
;-------------------------------------------
  ; -----------------------------
  ; names of data structures
  ; determined from an ncl_filedump
  print("load hdf5 file")
  fin = addfile(infile, "r")
    ; extract longitude
    moplon      = fin->$"Longitude_MOP02"$
    ; extract latitude
    moplat      = fin->$"Latitude_MOP02"$
    ; extract profile
    ret_profile  = fin->$"RetrievedCOMixingRatioProfile_MOP02"$
    ; extract averaging kernel
    avkrn       = fin->$"RetrievalAveragingKernelMatrix_MOP02"$


;-------------------------------------------
; print data structure information
;-------------------------------------------
  ; Determine dimensions of data structures
  printVarSummary(moplon)
  printVarSummary(moplat)
  printVarSummary(ret_profile)
  printVarSummary(avkrn)

  ; print lat, lon of first retrieval
  print("Latitude: "+ moplat(0)+", Longitude: "+moplon(0))
  ; print first retrieved profile on fixed levels - surface retrieval is in a separate data structure
  print(ret_profile(0,:,0))
```

```
; print AK matrix for first retrieval
print(avkrn(0,:,:))

end
```