**MOPITT V9 Level 2 Data Quality Summary**

The following information applies to MOPITT Level 2 (L2) data, Version 9 (V9; L2V19.9.x), first released June, 2021.

Further details on MOPITT data quality and recommended analysis methods may be found in the updated V9 User's Guide, which is available on the MOPITT Publications page (https://www2.acom.ucar.edu/mopitt/publications). Featured improvements in the V9 retrieval product involve revisions to (1) the forward radiative transfer model, (2) the cloud detection algorithm, and (3) the strategy used for NIR calibration.

**CO Retrieval Products**

Similar to the V5 to V8 products, three different types of V9 Level 2 products are available based on different subsets of the MOPITT calibrated thermal- and near-infrared (TIR and NIR) radiances. TIR-only, NIR-only and 'multispectral' TIR-NIR retrieval products are available. The format and data fields of these three types of files are identical. The choice of which type of product to use for a particular application depends on the relative importance of sensitivity to CO in the boundary layer, long-term stability, sensitivity to random retrieval errors, required geographical coverage, and other factors. Users of MOPITT products are encouraged to contact members of the MOPITT Science Team for advice on the appropriate product for particular applications.

The V9 Level 2 retrieval products include:

- A TIR-only product. *Example filename:* MOP02T-20010101-L2V19.9.1.he5.

- A NIR-only product, which is produced only for daytime observations over land. This product exhibits relatively large random errors and may require significant spatial and/or temporal averaging. *Example filename:* MOP02N-20010101-L2V19.9.2.he5.

- A TIR/NIR product, which features the maximum sensitivity to near-surface CO. In this product, information from the NIR channels is exploited only in daytime observations over land. This product exhibits relatively large random errors and may require significant spatial and/or temporal averaging. *Example filename:* MOP02J-20010101-L2V19.9.3.he5.

CO layer average mixing ratio profiles are retrieved for clear-sky scenes on the 9 standard MOPITT pressure layers with level values: surface, 900, 800, 700, 600, 500, 400, 300, 200, and 100 hPa. Layer values are reported corresponding to the higher pressure level in each layer, e.g., the value reported for 900 hPa represents the uniformly weighted layer average CO mixing ratio for 900 to 800 hPa. This is the same CO profile representation as used for V5-V8. Retrieved CO total columns are calculated by integrating the retrieved mixing ratio profile and are not retrieved independently. The horizontal footprint of each MOPITT retrieval is 22 km by 22 km at nadir. The contents of the Level 2 (MOP02) files are listed in the V9 User's Guide.

**Estimated errors**

For CO vertical profiles, estimated errors (i.e., uncertainties) are available in the error field (second element) of the 'Retrieved CO Mixing Ratio Profile' and 'Retrieved CO Surface Mixing Ratio' variables of the MOP02 files. These values represent the cumulative error from smoothing error, model parameter error, forward model error, geophysical noise, and instrumental noise.

**Missing data when surface pressure < 900 mb**

For the standard case when surface pressure p_sfc exceeds 900 mb, there are 10 valid levels in the retrieved profile (including the surface-level retrieval), and the Retrieval Averaging Kernel Matrix *A* (provided in the Level 2 product) is a 10 by 10 matrix. For the case where 800 mb < p_sfc < 900 mb, the surface level moves to the second row and column of *A*. In this case, the first row and column of *A* is populated by the value 0. For cases where there are even more missing levels (e.g., p_sfc < 800 mb), the surface level always skips down to replace the missing level closest to p_sfc. For the vertical profile mixing ratios, the values at the standard retrieval levels that are greater than the surface pressure will be reported as 'no data' (-9999).

**Cloud detection**

MOPITT retrievals are performed only on scenes that are determined to be sufficiently cloud-free. The clear/cloudy determination is based both on MOPITT's thermal-channel radiances and on the MODIS cloud mask. For the cloud detection algorithm used for MOPITT V9 products, two significant changes have been made, resulting in substantially increased retrieval coverage over land. See the V9 User's Guide for more information. The diagnostic 'Cloud Description' contained in the L2 product files identifies the outcome of the MOPITT cloud detection algorithm for each retrieval as follows:

Cloud Description Value -> Basis of Clear-sky Determination
1 -> MOPITT clear / MODIS unused
2 -> MOPITT clear / MODIS clear
3 -> MOPITT cloudy / MODIS clear
4 -> MOPITT clear / MODIS 'low clouds'
5 -> MOPITT unused / MODIS clear in high-latitude scenes
6 -> MOPITT clear / MODIS cloudy

Additional information regarding the MODIS cloud mask values corresponding to each MOPITT pixel are contained in the 'MODIS Cloud Diagnostics' vector in the L2 product files.

**Data Interpretation**

Averaging Kernels: Averaging kernels indicate the sensitivity of the retrievals to different levels of the atmosphere, and must be analyzed in order to properly interpret the retrieved data, due to significant spatial variations in sensitivity, both vertical and horizontal. For V9 (and earlier products), the 'Retrieval Averaging Kernel Matrix' is provided for each retrieval. Details on properly applying the retrieval averaging kernels are included in the V9 User's Guide and MOPITT validation papers.

High latitude data: Retrievals south of 65S and north of 65N should be used with caution, because of potential problems with cloud detection and due to difficulties in performing retrievals over very cold surfaces. Moreover, TIR-only and TIR/NIR retrievals in these regions tend to have low information

content as quantified by the 'Degrees of Freedom for Signal' diagnostic because of poor thermal contrast conditions.

Day-Night and Land-Ocean differences: Due to the sensitivity of the MOPITT radiances to surface temperature, differences between day and night may appear in retrievals over land. This effect can be identified through analysis of the retrieval averaging kernels. At land-ocean boundaries, similar differences may be seen. These differences are the result of radiative transfer effects (e.g., thermal contrast variability) and should not be mistaken by users as actual changes in the atmospheric concentration of CO.

**Validation**

Currently, the V9 product is considered unvalidated, since validation results have not yet been published. Validation studies are underway in which MOPITT CO mixing ratios will be validated with numerous aircraft profiles measured by NOAA/ESRL, as well as with datasets from field campaigns including HIPPO (https://www.eol.ucar.edu/field_projects/hippo-outreach) and ATom (https://espo.nasa.gov/atom). A manuscript documenting the validation results for the V9 product is in preparation.

**CO Retrieval Diagnostics**

Level 2 diagnostics include

'TotalColumnAveragingKernel': 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 of the V9 User's Guide.

'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. The row-sum value is a measure of the retrieval's sensitivity to the a priori. Small row-sum values indicate retrieval levels heavily weighted by the a priori while values approaching unity indicate levels weakly weighted by the a priori.

'DryAirColumn' and 'WaterVaporColumn': 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.

'SmoothingErrorCovarianceMatrix' and 'MeasurementErrorCovarianceMatrix': 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).

'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. 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.

'RetrievalErrorCovarianceMatrix': For each retrieval, a floating point array (10 x 10) containing the a posteriori covariance matrix in base-10 log(VMR).

'SurfaceIndex': For each retrieval, an integer equal to 0 for open water (oceans, seas and large lakes), 1 for land, and 2 for mixed (e.g., coastline).

'CloudDescription': For each retrieval, an integer describing the results of the MOPITT cloud detection algorithm, as described above.

'RetrievalAveragingKernelMatrix': For each retrieval, a floating point array (10 x 10) containing the matrix describing the sensitivity of the retrieved CO profile to the true CO profile.

'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.

'Level1RadiancesandErrors': For each retrieval, a floating point array (2 x 12) containing the L1 radiances and corresponding radiance uncertainties. Radiance sequence is 7A, 3A, 1A, 5A, 7D, 3D, 1D, 5D, 2A, 6A, 2D, 6D. Radiances and uncertainties are in units of W/(m2Sr).

'DEMAltitude': Altitude of retrieval in m.

'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.

'MODISCloudDiagnostics': This diagnostic has been revised for V9, and includes added information. For each retrieval, a twelve-element floating point vector containing a variety of MODIS cloud mask statistics, as follows.

> (1) Number of 'determined' MODIS pixels
> (2) Percentage of cloudy MODIS pixels
> (3) Percentage of clear MODIS pixels, test 1
> (4) Percentage of clear MODIS pixels, test 2
> (5) Percentage of clear MODIS pixels, test 3
> (6) Average value of 'sun glint' MODIS flag
> (7) Average value of 'snow/ice background' MODIS flag
> (8) Average value of 'non-cloud obstruction' MODIS flag
> (9) Average value of 'IR threshold test' MODIS flag
> (10) Average value of 'IR temperature difference tests' MODIS flag
> (11) Average value of 'visible reflectance test' MODIS flag
> (12) Fraction of 'determined' MODIS pixels

See the V9 User's Guide for more information.

**Methane Retrieval Products**

Methane (CH4) retrievals are not available in this data version, or any previous version.