Dataset description

MAIR: MethaneAir Flight Demonstration Project –
NSF_1856426_EAGER
July – August 2021
Five flights designated RF04 – RF09

MAIR-E: Methane Source Quantification/MethaneAIR Extended Mission –
NSF_AGS_220211
October – November 2022
Four flights designated RF01E – RF04E

Background: Project Description

MethaneAIR ("MAIR") is an imaging spectrometer observing reflected sunlight at 1.65 µm (CH_4 and CO_2). A second similar spectrometer centered at 1.27 µm ($O_2(^1\Delta_g)$ band) helps with cloud screening and determining the optical path. The following table provides a summary of the spectrometer specifications.

MethaneAIR and MethaneSAT
Dual spectrometers: 1.65 mm (CO_2 and CH_4) and 1.27 mm ($O_2(^1\Delta)$)

Specification	MethaneAIR	MethaneSAT
O_2 passband (nm)	1237–1319	1249–1305
O_2 dispersion (nm/pixel)	0.08	0.06
O_2 spectral FWHM (nm)	0.23	0.18
CH_4 passband (nm)	1592–1678*	1598–1683
CH_4 dispersion (nm/pixel)	0.10	0.08
CH_4 spectral FWHM (nm)	0.28	0.24
Field of view (swath, km)	4.7	200
Cross-track pixel† (m)	~ 5 at 12 km	~ 108
Along-track pixel† (m)	~ 25	~ 400
Point spread function (pixels)	2.5	1.8
Single pixel SNR‡	~ 110	~ 190
Flat images σ gridded (oversampled)	(ppb) 26 (10m x 10m) (5 px x 1 px)	19 (45m) (1 x 1 px)

*MethaneAIR uses an InGaAs detector with reduced QE beyond ~ 1660 nm
†Distance between pixel centers at nadir
‡CH_4 band with nominal radiance of 1.4×10^{13} photons cm^{-2} nm^{-1} sec^{-1} sr^{-1}

Downlink capacity limits MethaneSAT to 30 200x200 kmxkm scenes per day

MethaneAIR measures absorption spectra with high spectral resolution, fine spatial resolution, wide swath, and high signal-to-noise ratio, enabling dramatically enhanced images of CH_4 column mean dry mole fraction compared to other airborne or spaceborne imagers. MAIR duplicates the spectroscopy of the MethaneSAT satellite ("MSAT", launched March 2024). Development of the MAIR sensor and associated retrieval algorithms was supported by MethaneSAT LLC (a subsidiary of the Environmental Defense Fund). The modest cost compared to comparable sensors (800k for both spectrometers), plus the availability of MAIR's extensive data processing and algorithm software, brings this technology within reach of a broad scientific community.

In 2019, NSF supported science demonstration flights of MAIR with an EAGER grant, carried out in August 2021. Two engineering flights in Nov. 2019 were successful, but the flight series was terminated due to avionics failures on the GV. The series was rescheduled for March 2020, but the US shut down that month due to COVID-19. We rescheduled for June 2021, and then pushed to August to accommodate a mission displaced by unavailability of the C-130.

The results from these science demonstration flights showed MAIR to be capable of observing enhancements of CH_4 due to both point sources and area sources over wide areas (results presented below). The delay from Nov. 2019 enabled the team to fully develop and test out the data algorithms using data from the engineering flights, enabling first-tier processing of high-value data within a week of acquisition in Aug. 2021. Images of oil and gas (O&G) provinces and of Salt Lake City were created from a composite of tracks 4.7 km wide, with pixels 5 x 25m (across track x along track), sampled from 13.1 km (43 kft) with ground speed around 250 m/s. They show a full range of emission sources, from huge to relatively modest, as well as extensive areas with excess CH_4 due to diffuse emission sources. A 120 km x 80 km image of the Delaware Basin was obtained in 2.2 hours. Salt Lake City was imaged in 90 minutes.

During the 2021 flight program, MAIR emissions estimates were tested on two flights focusing on controlled releases of methane conducted near Midland, TX, by Adam Brandt's group at Stanford. Emissions estimates for these flights were submitted in a single-blind protocol to the Stanford team. The results showed excellent accuracy for determination of the metered emissions (Chulakadabba et al., 2024).

MAIR-E

MAIR-E was proposed to NSF to apply the MethaneAIR sensor to address scientific questions that are central to understanding the processes driving increases in atmospheric methane.

Scientific goals and focus of the project:

1. *Full analysis and publication of the data from the EAGER project.* EAGER covered the GV mission costs, and initial processing, and the MSAT project (methanesat.org) covered algorithm development. Synthesis of science results and publication of papers were supported by the MAIR-E project:
   (a) determine the emission rates from O&G facilities, and
   (b) obtain emission rates from whole regions, including diffuse emissions that have never been directly observed hitherto; and
   (c) publishing the analysis of controlled releases and area sources. The controlled releases provide the strictest form of validation for the sensor and our objective to be able to measure emissions.

2. *Quantify and understand the process that drive human-caused methane emissions to the atmosphere*:

   a. To measure the emission rates of methane from production regions accounting for 80% of oil and gas production in the CONUS.
   b. Partition emissions into dispersed or diffuse ("area") emission and distinct or point source emissions.
   c. Assess the fraction of gas production lost to the atmosphere in the observed upstream operations.
   d. Assess methane emission rates from landfills across the US.
   e. Measure emissions from several urban regions: New York City, Phoenix, and Salt Lake City.

Flight plans originally called for conducting about 90 hours of flights during fall, 2022, to fulfill this goal. Due to operational issues at RAF only 3 full flights and a partial flight were carried out in fall of 2022. The full flight series was conducted in 2023 using the IO-Sys Lear 35a, supported by the Environmental Defense Fund.

In 2024 we returned to the GV to conduct intensive benchmark flights for three large areas, leveraging the availability of imagery from MethaneSAT. Once again this flight series was terminated by NSF, after 3 flights, apparently due to issues of documentation of flight worthiness dating back to the first flights of the GV in 2007.

References for these data sets

Instrumentation and algorithms

Chan Miller, Chrisotpher, Sebastien Roche, Jonas S. Wilzewski, Xiong Liu, Kelly Chance, Amir H. Souri, Eamon Conway, Bingkun Luo, Jenna Samra, Jacob Hawthorne, Kang Sun, Carly Staebell, Apisada Chulakadabba, Maryann Sargent, Joshua S. Benmergui, Jonathan E. Franklin, Bruce C. Daube, Yang Li, Joshua L. Laughner, Bianca C. Baier, Ritesh Gautam, Mark Omara, and Steven C. Wofsy, Methane retrieval from MethaneAIR using the CO2 Proxy Approach: A demonstration for the upcoming MethaneSAT mission, Atmos. Meas. Tech., 17, 5429–5454, 2024 https://doi.org/10.5194/amt-17-5429-2024.

Conway, EK, Souri, AH, Benmergui, J, Sun, K, Liu, X, Staebell, C, Chan Miller, C, Franklin, J, Samra, J, Wilzewski, J , Roche, S,Luo, BK, Chulakadabba, A , Sargent, M, Hohl, J , Daube, B, Gordon, I, Chance, K, Wofsy, S, Level0 to Level1B processor for MethaneAIR, ATMOSPHERIC MEASUREMENT TECHNIQUES 17, 1347-1362, DOI: 10.5194/amt-17-1347-2024, 2024.

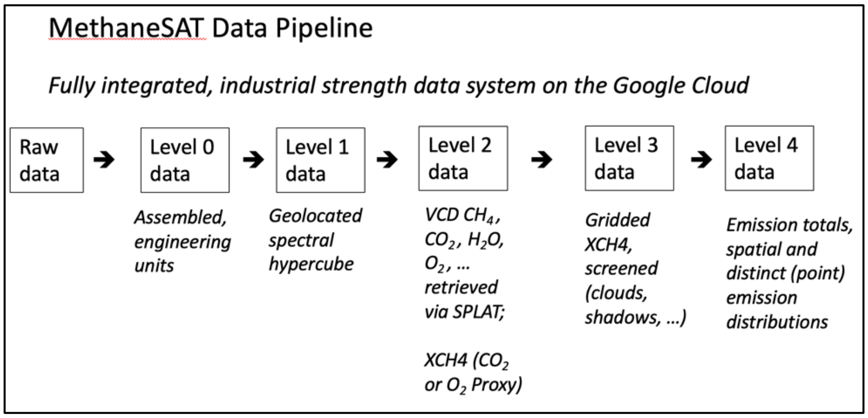
Staebell, C, Sun, K, Samra, J, Franklin, J, Miller, CC, Liu, X, Conway, E, Chance, K, Milligan, S, Wofsy, S., Spectral calibration of the MethaneAIR instrument, Atmospheric Measurement Techniques 14, 3737-3753, do: 10.5194/amt-14-3737-2021, 2021.

Controlled releases

Chulakadabba, A, Sargent, M, Lauvaux, T, Benmergui, JS, Franklin, JE, Chan Miller, C, Wilzewski, JS, Roche, S, Conway, E, Souri, AH, Sun, K, Luo, BK, Hawthrone, J, Samra, J,Daube, BC, Liu, X , Chance, K, Li, Y, Gautam, R, Omara, M, Rutherford, JS, Sherwin, ED, Brandt, A, Wofsy, SC, Methane point source quantification using MethaneAIR: a new airborne imaging spectrometer, ATMOSPHERIC MEASUREMENT TECHNIQUES 16, 5771-5785, DOI: 10.5194/amt-16-5771-2023, 2023.

Data reported in this data release

MethaneAIR data are processed in a data pipeline structured according to commonly used data “levels” for remote sensing by imaging spectrometers:



This data archive reports Level 3 (gridded) data, in two configurations.

1. Non-overlapping segments, representing ~4.7 km wide swaths, arranged sequentially in time and grouped by target (e.g. "CR" = controlled release, "priority target" = oil/gas production target area, or city target).
2. Mosaics of the non-overlapping segments covering the whole target. The mosaics proving the user with map-like images of methane concentrations (column mean dry mole fraction, XCH4) and other quantities. They are created from the segments accounting for spatial oversampling by the sensors, using information about pixel corners as described in Chan Miller et al. (2024). *The mosaics need to be interpreted with care because they present averages of concentrations observed at different times.* This feature may be inconsequential for some applications, but confusing or invalidating for other uses. For example, resampling a point source may give rise to images of two methane plumes propagating from the source in divergent directions.

Level 0, Level 1b (gridded spectral hypercubes) and Level 2 (3-d concentration fields, averaging kernels, retrieval diagnostics) are too large to archive here. Each flight consists of ~ 1TB of data, at each level. These data products are freely available from the Google Cloud upon application to the PI (wofsy@g.harvard.edu) or to MethaneSAT.org. Requestors will need to register for a Google Cloud account, where they will be granted access to the requested buckets. Users are responsible for the cost of downloading as charged by Google. Raw data are export controlled and cannot be made available.

Data file tree structure

The data file format is netCDF. The files are arranged in a tree structure like this example:

./MAIR/2021/08/11/RF08/po-1503a/level3/5x1/mosaic/20240614T140454_po-1503a/03_inbound-map-SLC/30m/MethaneAIR_L3_mosaic_20210811T154505_20210811T155343_dpp.nc

MAIR = flight series
2021/08/11 = YYYY/MM/DD
RF08 = flight moniker
po-1503a = MSAT pipeline unique processing identification
mosaic = data type (possible values, mosaic or segment)
20240614T140454_po-1503a = processing date on time (POSIX format, UTC) and proc ID

03_inbound-map-SLC = target area moniker
30m = approximate grid spacing (possible values, **10m** or **30m**, corresponding 0.33 or 1 arc second; at 42N the pixels are 10.3 or 30.9m N-S by 7.6 or 22.9 m E-W).

MethaneAIR_L3_mosaic_20210811T154505_20210811T155343_dpp.nc = file name
Sensor level mosaic start time end time (POSIX, UTC)
or segment

For the segment files, the start and end times represent the time for the first and last observation. The times are also given for each observation in the grid, within the file, representing the average time of the closely spaced level 2 data points going into the gridded data point.

For the mosaic files, the times cover the whole of the target survey time (up to several hours duration). It is not meaningful to give an observation time for an individual grid point.

The netCDF files are self-documenting, as provided in the examples below. The headers provide all the information needed to read the files and to determine definitions, units etc.

Important notes:
All XCH4 retrievals reported here use the CO_2 *proxy algorithm (Chan Miller et al., 2024).*

The num_samples variable in these tables represents the number of pixel values from Level 2 that went into the weighted mean for a Level 3 gridded pixel. Any pixels with num_samples < 0.5 should be set to NA. Users may need to check this feature. If any pixel with num_samples < 0.5 is set to a finite value in the data file, it should be set to NA or NaN by the user.

```
netcdf MethaneAIR_L3_segment_20221025T164019_20221025T164513_dpp {
dimensions:
	lat = UNLIMITED ; // (5724 currently)
	lon = UNLIMITED ; // (4536 currently)
variables:
	int64 crs ;
		crs:grid_mapping_name = "latitude_longitude" ;
		crs:longitude_of_prime_meridian = 0. ;
		crs:semi_major_axis = 6378137. ;
		crs:inverse_flattening = 298.257223563 ;
		crs:crs_wkt = "GEOGCRS[\"WGS 84\", ENSEMBLE[\"World Geodetic System 1984 ensemble\", MEMBER[\"World Geodetic System 1984 (Transit)\"], MEMBER[\"World Geodetic System 1984 (G730)\"], MEMBER[\"World Geodetic System 1984 (G873)\"], MEMBER[\"World Geodetic System 1984 (G1150)\"], MEMBER[\"World Geodetic System 1984 (G1674)\"], MEMBER[\"World Geodetic System 1984 (G1762)\"], MEMBER[\"World Geodetic System 1984 (G2139)\"], ELLIPSOID[\"WGS 84\",6378137,298.257223563, LENGTHUNIT[\"metre\",1]], ENSEMBLEACCURACY[2.0]], PRIMEM[\"Greenwich\",0, ANGLEUNIT[\"degree\",0.0174532925199433]], CS[ellipsoidal,2], AXIS[\"geodetic latitude (Lat)\",north, ORDER[1], ANGLEUNIT[\"degree\",0.0174532925199433]], AXIS[\"geodetic longitude (Lon)\",east, ORDER[2], ANGLEUNIT[\"degree\",0.0174532925199433]], USAGE[ SCOPE[\"Horizontal component of 3D system.\"], AREA[\"World.\"], BBOX[-90,-180,90,180]], ID[\"EPSG\",4326]]" ;
	double lat(lat) ;
		lat:long_name = "latitude" ;
		lat:units = "degrees_north" ;
		lat:standard_name = "latitude" ;
		lat:actual_range = 33.8100462962963, 34.3399537037037 ;
	double lon(lon) ;
		lon:long_name = "longitude" ;
		lon:units = "degrees_east" ;
		lon:standard_name = "longitude" ;
		lon:actual_range = -111.319953703704, -110.900046296296 ;
	float num_samples(lat, lon) ;
		num_samples:_FillValue = 0.f ;
		num_samples:grid_mapping = "crs" ;
	float total_sample_weight(lat, lon) ;
		total_sample_weight:_FillValue = 0.f ;
		total_sample_weight:grid_mapping = "crs" ;
	double time(lat, lon) ;
		time:_FillValue = 0. ;
		time:grid_mapping = "crs" ;
		time:units = "seconds since 1970-1-1 0:0:0, in UTC" ;
	float xch4(lat, lon) ;
		xch4:_FillValue = 1.e+36f ;
		xch4:grid_mapping = "crs" ;
		xch4:long_name = "retrieved column-averaged dry-air CH4 mole fraction" ;
		xch4:standard_name = "dry_atmosphere_mole_fraction_of_methane" ;
		xch4:units = "1e-9" ;

// global attributes:
		string :product_type = "segment" ;
		string :geospatial_lat_min = "33.81" ;
		string :geospatial_lat_max = "34.34" ;
		string :geospatial_lon_min = "-111.32" ;
		string :geospatial_lon_max = "-110.90" ;
		string :geospatial_lat_resolution = "1/3 arcseconds" ;
		string :geospatial_lon_resolution = "1/3 arcseconds" ;
		string :time_coverage_start = "2022-10-25T16:40:19Z" ;
		string :time_coverage_end = "2022-10-25T16:45:14Z" ;
		:date_created = "2024-06-14T14:04:45Z" ;
		:id = "[prod]/MAIR-E/2022/10/25/RF01E/po-1495a/level3/5x1/segment/20240614T135952_po-1495a/03_inbound-map/10m/MethaneAIR_L3_segment_20221025T164019_20221025T164513_dpp.nc" ;
		:metadata_link = "[prod]/MAIR-E/2022/10/25/RF01E/po-1495a/level3/5x1/segment/20240614T135952_po-1495a/03_inbound-map/10m/MethaneAIR_L3_segment_20221025T164019_20221025T164513_dpp.xml" ;
		:metadata_id = "682d7b5a-1176-451c-bef2-05705289acc0" ;
```

```
group: Provenance {

  // group attributes:
                :__auto__ = "Version not found" ;
                :Python = "3.9.5" ;
                :msat-netcdf = "0.4.3" ;
                :__schema__ = "1.2.4.dev1+g3a9b7e1" ;
                :msat_level3 = "1.2.4.dev1+g3a9b7e1" ;
                :pytest = "8.2.2" ;
                :strenum = "0.4.15" ;
                :pytest-mock = "3.10.0" ;
                :black = "24.4.2" ;
                :mypy = "1.10.1" ;
                :msat-common = "0.12.1" ;
                :types-PyYAML = "6.0.12.20240311" ;
                :flake8 = "7.1.0" ;
                :mashumaro = "3.13.1" ;
                :shapely = "2.0.5" ;
                :coverage = "7.0.5" ;
                :numpy = "1.26.4" ;
                :click = "8.1.7" ;
                :netCDF4 = "1.7.1.post1" ;
                :popy = "0.2.2" ;
                :time-machine = "2.14.2" ;
                :google-cloud-storage = "2.17.0" ;
                :opencv-python = "4.5.5.64" ;
                :GitPython = "3.1.43" ;
                :scipy = "1.13.1" ;
                :flytekit = "1.13.0" ;
  } // group Provenance

group: apriori_data {
  variables:
        float xco2(lat, lon) ;
                xco2:_FillValue = 1.e+36f ;
                xco2:long_name = "a priori column-averaged dry-air CO2 mole fraction" ;
                xco2:standard_name = "dry_atmosphere_mole_fraction_of_carbon_dioxide" ;
                xco2:units = "1e-6" ;
        float xch4(lat, lon) ;
                xch4:_FillValue = 1.e+36f ;
                xch4:long_name = "a priori column-averaged dry-air CH4 mole fraction" ;
                xch4:standard_name = "dry_atmosphere_mole_fraction_of_methane" ;
                xch4:units = "1e-9" ;
        float co2_vcd(lat, lon) ;
                co2_vcd:_FillValue = 1.e+36f ;
                co2_vcd:grid_mapping = "crs" ;
                co2_vcd:long_name = "a priori CO2 vertical column density (TCCON GGG2020)" ;
                co2_vcd:proposed_standard_name = "atmosphere_mole_content_of_carbon_dioxide" ;
                co2_vcd:units = "molecules/cm2" ;
        float ch4_vcd(lat, lon) ;
                ch4_vcd:_FillValue = 1.e+36f ;
                ch4_vcd:grid_mapping = "crs" ;
                ch4_vcd:long_name = "a priori CH4 vertical column density (TCCON GGG2020)" ;
                ch4_vcd:standard_name = "atmosphere_mole_content_of_methane" ;
                ch4_vcd:units = "molecules/cm2" ;
        float h2o_vcd(lat, lon) ;
                h2o_vcd:_FillValue = 1.e+36f ;
                h2o_vcd:grid_mapping = "crs" ;
                h2o_vcd:long_name = "a priori H2O vertical column density (GEOS-FP)" ;
                h2o_vcd:standard_name = "atmosphere_mole_content_of_water_vapor" ;
                h2o_vcd:units = "molecules/cm2" ;
        float air_vcd(lat, lon) ;
```

```
			air_vcd:_FillValue = 1.e+36f ;
			air_vcd:grid_mapping = "crs" ;
			air_vcd:long_name = "sum of a priori N2, O2, Ar, CO2, CH4, and H2O vertical column densities" ;
			air_vcd:units = "molecules/cm2" ;
		float albedo_ch4band(lat, lon) ;
			albedo_ch4band:_FillValue = 1.e+36f ;
			albedo_ch4band:grid_mapping = "crs" ;
			albedo_ch4band:long_name = "clear-sky surface albedo derived from 1622nm radiance" ;
			albedo_ch4band:standard_name = "surface_albedo" ;
			albedo_ch4band:units = "1" ;
			albedo_ch4band:valid_range = 0.f, 1.f ;
		float surface_pressure(lat, lon) ;
			surface_pressure:_FillValue = 1.e+36f ;
			surface_pressure:grid_mapping = "crs" ;
			surface_pressure:long_name = "a priori surface pressure" ;
			surface_pressure:standard_name = "surface_air_pressure" ;
			surface_pressure:units = "hPa" ;
		float zonal_wind(lat, lon) ;
			zonal_wind:_FillValue = 1.e+36f ;
			zonal_wind:grid_mapping = "crs" ;
			zonal_wind:standard_name = "eastward_wind" ;
			zonal_wind:long_name = "eastward wind component at 10 m, from GEOS-5" ;
			zonal_wind:units = "m/s" ;
		float meridional_wind(lat, lon) ;
			meridional_wind:_FillValue = 1.e+36f ;
			meridional_wind:grid_mapping = "crs" ;
			meridional_wind:standard_name = "northward_wind" ;
			meridional_wind:long_name = "northward wind component at 10 m, from GEOS-5" ;
			meridional_wind:units = "m/s" ;
  } // group apriori_data

group: geolocation {
  variables:
		float terrain_height(lat, lon) ;
			terrain_height:_FillValue = 1.e+36f ;
			terrain_height:standard_name = "surface_height_above_geopotential_datum" ;
			terrain_height:comment = "the vertical distance above either the EGM96 (MethaneAIR) or EGM2008 (MethaneSAT)
geoid, though having been interpolated by L1b and regridded by L3; this exists for diagnostic purposes only" ;
			terrain_height:units = "km" ;
		float sza(lat, lon) ;
			sza:_FillValue = 1.e+36f ;
			sza:grid_mapping = "crs" ;
			sza:standard_name = "solar_zenith_angle" ;
			sza:units = "degrees" ;
			sza:valid_range = 0.f, 90.f ;
		float vza(lat, lon) ;
			vza:_FillValue = 1.e+36f ;
			vza:grid_mapping = "crs" ;
			vza:standard_name = "sensor_zenith_angle" ;
			vza:units = "degrees" ;
			vza:valid_range = 0.f, 90.f ;
		float saa(lat, lon) ;
			saa:_FillValue = 1.e+36f ;
			saa:grid_mapping = "crs" ;
			saa:standard_name = "solar_azimuth_angle" ;
			saa:units = "degrees" ;
			saa:valid_range = 0.f, 360.f ;
		float vaa(lat, lon) ;
			vaa:_FillValue = 1.e+36f ;
			vaa:grid_mapping = "crs" ;
			vaa:standard_name = "sensor_azimuth_angle" ;
			vaa:units = "degrees" ;
```

```
                vaa:valid_range = 0.f, 360.f ;
  } // group geolocation

group: co2proxy_fit_diagnostics {
  variables:
        float bias_corrected_co2_vcd(lat, lon) ;
                bias_corrected_co2_vcd:_FillValue = 1.e+36f ;
                bias_corrected_co2_vcd:grid_mapping = "crs" ;
                bias_corrected_co2_vcd:long_name = "retrieved CO2 vertical column density with across-track bias correction" ;
                bias_corrected_co2_vcd:proposed_standard_name = "atmosphere_mole_content_of_carbon_dioxide" ;
                bias_corrected_co2_vcd:units = "molecules/cm2" ;
        float bias_corrected_ch4_vcd(lat, lon) ;
                bias_corrected_ch4_vcd:_FillValue = 1.e+36f ;
                bias_corrected_ch4_vcd:grid_mapping = "crs" ;
                bias_corrected_ch4_vcd:long_name = "retrieved CH4 vertical column density with across-track bias correction" ;
                bias_corrected_ch4_vcd:standard_name = "atmosphere_mole_content_of_methane" ;
                bias_corrected_ch4_vcd:units = "molecules/cm2" ;
  } // group co2proxy_fit_diagnostics

group: o2dp_fit_diagnostics {
  variables:
        float bias_corrected_o2_vcd(lat, lon) ;
                bias_corrected_o2_vcd:_FillValue = 1.e+36f ;
                bias_corrected_o2_vcd:grid_mapping = "crs" ;
                bias_corrected_o2_vcd:long_name = "retrieved O2 vertical column density with across-track bias correction" ;
                bias_corrected_o2_vcd:proposed_standard_name = "atmosphere_mole_content_of_oxygen" ;
                bias_corrected_o2_vcd:units = "molecules/cm2" ;
        float bias_corrected_delta_pressure(lat, lon) ;
                bias_corrected_delta_pressure:_FillValue = 1.e+36f ;
                bias_corrected_delta_pressure:grid_mapping = "crs" ;
                bias_corrected_delta_pressure:long_name = "retrieved minus a priori surface pressure with across-track bias correction"
;
                bias_corrected_delta_pressure:units = "hPa" ;
  } // group o2dp_fit_diagnostics

group: h2o_w1_fit_diagnostics {
  variables:
        float bias_corrected_h2o_vcd(lat, lon) ;
                bias_corrected_h2o_vcd:_FillValue = 1.e+36f ;
                bias_corrected_h2o_vcd:grid_mapping = "crs" ;
                bias_corrected_h2o_vcd:long_name = "retrieved H2O vertical column density with across-track bias correction" ;
                bias_corrected_h2o_vcd:standard_name = "atmosphere_mole_content_of_water_vapor" ;
                bias_corrected_h2o_vcd:units = "molecules/cm2" ;
  } // group h2o_w1_fit_diagnostics

group: h2o_w2_fit_diagnostics {
  variables:
        float bias_corrected_h2o_vcd(lat, lon) ;
                bias_corrected_h2o_vcd:_FillValue = 1.e+36f ;
                bias_corrected_h2o_vcd:grid_mapping = "crs" ;
                bias_corrected_h2o_vcd:long_name = "retrieved H2O vertical column density with across-track bias correction" ;
                bias_corrected_h2o_vcd:standard_name = "atmosphere_mole_content_of_water_vapor" ;
                bias_corrected_h2o_vcd:units = "molecules/cm2" ;
  } // group h2o_w2_fit_diagnostics
}
```

```
netcdf MethaneAIR_L3_mosaic_20221025T160940_20221025T161511_dpp {
dimensions:
	lat = UNLIMITED ; // (6480 currently)
	lon = UNLIMITED ; // (4428 currently)
variables:
	int64 crs ;
		crs:grid_mapping_name = "latitude_longitude" ;
		crs:longitude_of_prime_meridian = 0. ;
		crs:semi_major_axis = 6378137. ;
		crs:inverse_flattening = 298.257223563 ;
		crs:crs_wkt = "GEOGCRS[\"WGS 84\", ENSEMBLE[\"World Geodetic System 1984 ensemble\", MEMBER[\"World Geodetic System 1984 (Transit)\"], MEMBER[\"World Geodetic System 1984 (G730)\"], MEMBER[\"World Geodetic System 1984 (G873)\"], MEMBER[\"World Geodetic System 1984 (G1150)\"], MEMBER[\"World Geodetic System 1984 (G1674)\"], MEMBER[\"World Geodetic System 1984 (G1762)\"], MEMBER[\"World Geodetic System 1984 (G2139)\"], ELLIPSOID[\"WGS 84\",6378137,298.257223563, LENGTHUNIT[\"metre\",1]], ENSEMBLEACCURACY[2.0]], PRIMEM[\"Greenwich\",0, ANGLEUNIT[\"degree\",0.0174532925199433]], CS[ellipsoidal,2], AXIS[\"geodetic latitude (Lat)\",north, ORDER[1], ANGLEUNIT[\"degree\",0.0174532925199433]], AXIS[\"geodetic longitude (Lon)\",east, ORDER[2], ANGLEUNIT[\"degree\",0.0174532925199433]], USAGE[ SCOPE[\"Horizontal component of 3D system.\"], AREA[\"World.\"], BBOX[-90,-180,90,180]], ID[\"EPSG\",4326]]" ;
	double lat(lat) ;
		lat:long_name = "latitude" ;
		lat:units = "degrees_north" ;
		lat:standard_name = "latitude" ;
		lat:actual_range = 36.3900462962963, 36.9899537037037 ;
	double lon(lon) ;
		lon:long_name = "longitude" ;
		lon:units = "degrees_east" ;
		lon:standard_name = "longitude" ;
		lon:actual_range = -108.609953703704, -108.200046296296 ;
	float num_samples(lat, lon) ;
		num_samples:_FillValue = 0.f ;
		num_samples:grid_mapping = "crs" ;
	float total_sample_weight(lat, lon) ;
		total_sample_weight:_FillValue = 0.f ;
		total_sample_weight:grid_mapping = "crs" ;
	float xch4(lat, lon) ;
		xch4:_FillValue = 1.e+36f ;
		xch4:grid_mapping = "crs" ;
		xch4:long_name = "retrieved column-averaged dry-air CH4 mole fraction" ;
		xch4:standard_name = "dry_atmosphere_mole_fraction_of_methane" ;
		xch4:units = "1e-9" ;

// global attributes:
		string :product_type = "mosaic" ;
		string :geospatial_lat_min = "36.39" ;
		string :geospatial_lat_max = "36.99" ;
		string :geospatial_lon_min = "-108.61" ;
		string :geospatial_lon_max = "-108.20" ;
		string :geospatial_lat_resolution = "1/3 arcseconds" ;
		string :geospatial_lon_resolution = "1/3 arcseconds" ;
		string :time_coverage_start = "2022-10-25T16:09:40Z" ;
		string :time_coverage_end = "2022-10-25T16:15:12Z" ;

group: Provenance {

  // group attributes:
		:__auto__ = "Version not found" ;
		:Python = "3.9.5" ;
		:msat-netcdf = "0.4.3" ;
		:__schema__ = "1.2.2" ;
		:msat_level3 = "1.2.2" ;
		:time-machine = "Version not found" ;
		:GitPython = "3.1.43" ;
```

```
		:mashumaro = "3.13" ;
		:flytekit = "1.12.0" ;
		:strenum = "0.4.15" ;
		:numpy = "1.26.4" ;
		:black = "Version not found" ;
		:click = "8.1.7" ;
		:pytest-mock = "3.14.0" ;
		:pytest = "8.2.0" ;
		:opencv-python = "4.5.5.64" ;
		:msat-common = "0.10.2" ;
		:netCDF4 = "1.6.5" ;
		:popy = "0.2.2" ;
		:coverage = "Version not found" ;
		:shapely = "2.0.4" ;
		:flake8 = "Version not found" ;
		:types-PyYAML = "Version not found" ;
		:scipy = "1.13.0" ;
		:google-cloud-storage = "2.16.0" ;
		:mypy = "Version not found" ;
  } // group Provenance

group: apriori_data {
  variables:
	float xco2(lat, lon) ;
		xco2:_FillValue = 1.e+36f ;
		xco2:long_name = "a priori column-averaged dry-air CO2 mole fraction" ;
		xco2:standard_name = "dry_atmosphere_mole_fraction_of_carbon_dioxide" ;
		xco2:units = "1e-6" ;
	float xch4(lat, lon) ;
		xch4:_FillValue = 1.e+36f ;
		xch4:long_name = "a priori column-averaged dry-air CH4 mole fraction" ;
		xch4:standard_name = "dry_atmosphere_mole_fraction_of_methane" ;
		xch4:units = "1e-9" ;
	float co2_vcd(lat, lon) ;
		co2_vcd:_FillValue = 1.e+36f ;
		co2_vcd:grid_mapping = "crs" ;
		co2_vcd:long_name = "a priori CO2 vertical column density (TCCON GGG2020)" ;
		co2_vcd:proposed_standard_name = "atmosphere_mole_content_of_carbon_dioxide" ;
		co2_vcd:units = "molecules/cm2" ;
	float ch4_vcd(lat, lon) ;
		ch4_vcd:_FillValue = 1.e+36f ;
		ch4_vcd:grid_mapping = "crs" ;
		ch4_vcd:long_name = "a priori CH4 vertical column density (TCCON GGG2020)" ;
		ch4_vcd:standard_name = "atmosphere_mole_content_of_methane" ;
		ch4_vcd:units = "molecules/cm2" ;
	float h2o_vcd(lat, lon) ;
		h2o_vcd:_FillValue = 1.e+36f ;
		h2o_vcd:grid_mapping = "crs" ;
		h2o_vcd:long_name = "a priori H2O vertical column density (GEOS-FP)" ;
		h2o_vcd:standard_name = "atmosphere_mole_content_of_water_vapor" ;
		h2o_vcd:units = "molecules/cm2" ;
	float air_vcd(lat, lon) ;
		air_vcd:_FillValue = 1.e+36f ;
		air_vcd:grid_mapping = "crs" ;
		air_vcd:long_name = "sum of a priori N2, O2, Ar, CO2, CH4, and H2O vertical column densities" ;
		air_vcd:units = "molecules/cm2" ;
	float albedo_ch4band(lat, lon) ;
		albedo_ch4band:_FillValue = 1.e+36f ;
		albedo_ch4band:grid_mapping = "crs" ;
		albedo_ch4band:long_name = "clear-sky surface albedo derived from 1622nm radiance" ;
		albedo_ch4band:standard_name = "surface_albedo" ;
		albedo_ch4band:units = "1" ;
```

```
			albedo_ch4band:valid_range = 0.f, 1.f ;
		float surface_pressure(lat, lon) ;
			surface_pressure:_FillValue = 1.e+36f ;
			surface_pressure:grid_mapping = "crs" ;
			surface_pressure:long_name = "a priori surface pressure" ;
			surface_pressure:standard_name = "surface_air_pressure" ;
			surface_pressure:units = "hPa" ;
		float zonal_wind(lat, lon) ;
			zonal_wind:_FillValue = 1.e+36f ;
			zonal_wind:grid_mapping = "crs" ;
			zonal_wind:standard_name = "eastward_wind" ;
			zonal_wind:long_name = "eastward wind component at 10 m, from GEOS-5" ;
			zonal_wind:units = "m/s" ;
		float meridional_wind(lat, lon) ;
			meridional_wind:_FillValue = 1.e+36f ;
			meridional_wind:grid_mapping = "crs" ;
			meridional_wind:standard_name = "northward_wind" ;
			meridional_wind:long_name = "northward wind component at 10 m, from GEOS-5" ;
			meridional_wind:units = "m/s" ;
  } // group apriori_data

group: geolocation {
  variables:
		float terrain_height(lat, lon) ;
			terrain_height:_FillValue = 1.e+36f ;
			terrain_height:standard_name = "surface_height_above_geopotential_datum" ;
			terrain_height:comment = "the vertical distance above either the EGM96 (MethaneAIR) or EGM2008 (MethaneSAT)
geoid, though having been interpolated by L1b and regridded by L3; this exists for diagnostic purposes only" ;
			terrain_height:units = "km" ;
  } // group geolocation

group: co2proxy_fit_diagnostics {
  variables:
		float bias_corrected_co2_vcd(lat, lon) ;
			bias_corrected_co2_vcd:_FillValue = 1.e+36f ;
			bias_corrected_co2_vcd:grid_mapping = "crs" ;
			bias_corrected_co2_vcd:long_name = "retrieved CO2 vertical column density with across-track bias correction" ;
			bias_corrected_co2_vcd:proposed_standard_name = "atmosphere_mole_content_of_carbon_dioxide" ;
			bias_corrected_co2_vcd:units = "molecules/cm2" ;
		float bias_corrected_ch4_vcd(lat, lon) ;
			bias_corrected_ch4_vcd:_FillValue = 1.e+36f ;
			bias_corrected_ch4_vcd:grid_mapping = "crs" ;
			bias_corrected_ch4_vcd:long_name = "retrieved CH4 vertical column density with across-track bias correction" ;
			bias_corrected_ch4_vcd:standard_name = "atmosphere_mole_content_of_methane" ;
			bias_corrected_ch4_vcd:units = "molecules/cm2" ;
  } // group co2proxy_fit_diagnostics

group: o2dp_fit_diagnostics {
  variables:
		float bias_corrected_o2_vcd(lat, lon) ;
			bias_corrected_o2_vcd:_FillValue = 1.e+36f ;
			bias_corrected_o2_vcd:grid_mapping = "crs" ;
			bias_corrected_o2_vcd:long_name = "retrieved O2 vertical column density with across-track bias correction" ;
			bias_corrected_o2_vcd:proposed_standard_name = "atmosphere_mole_content_of_oxygen" ;
			bias_corrected_o2_vcd:units = "molecules/cm2" ;
		float bias_corrected_delta_pressure(lat, lon) ;
			bias_corrected_delta_pressure:_FillValue = 1.e+36f ;
			bias_corrected_delta_pressure:grid_mapping = "crs" ;
			bias_corrected_delta_pressure:long_name = "retrieved minus a priori surface pressure with across-track bias correction"
;
			bias_corrected_delta_pressure:units = "hPa" ;
  } // group o2dp_fit_diagnostics
```

```
group: h2o_w1_fit_diagnostics {
  variables:
        float bias_corrected_h2o_vcd(lat, lon) ;
                bias_corrected_h2o_vcd:_FillValue = 1.e+36f ;
                bias_corrected_h2o_vcd:grid_mapping = "crs" ;
                bias_corrected_h2o_vcd:long_name = "retrieved H2O vertical column density with across-track bias correction" ;
                bias_corrected_h2o_vcd:standard_name = "atmosphere_mole_content_of_water_vapor" ;
                bias_corrected_h2o_vcd:units = "molecules/cm2" ;
  } // group h2o_w1_fit_diagnostics

group: h2o_w2_fit_diagnostics {
  variables:
        float bias_corrected_h2o_vcd(lat, lon) ;
                bias_corrected_h2o_vcd:_FillValue = 1.e+36f ;
                bias_corrected_h2o_vcd:grid_mapping = "crs" ;
                bias_corrected_h2o_vcd:long_name = "retrieved H2O vertical column density with across-track bias correction" ;
                bias_corrected_h2o_vcd:standard_name = "atmosphere_mole_content_of_water_vapor" ;
                bias_corrected_h2o_vcd:units = "molecules/cm2" ;
  } // group h2o_w2_fit_diagnostics
}
```