

12.07.2021

Product User Guide (PUG)

TROPOMI WFM-DOAS (TROPOMI/WFMD) XCH₄

Prepared by:

Oliver Schneising

Valid for:

TROPOMI/WFMD

Product

Methane column-averaged dry air mole fraction (XCH₄)

Version

v1.5

PRODUCT USER GUIDE TROPOMI WFM-DOAS XCH ₄ ESA CLIMATE CHANGE INITIATIVE “PLUS” (CCI+)	INSTITUTE OF ENVIRONMENTAL PHYSICS, UNIVERSITY OF BREMEN	2
---	--	----------

Contents

1	Purpose of document	3
2	Introduction	3
2.1	The TROPOMI instrument on Sentinel-5 Precursor	3
2.2	The WFM-DOAS retrieval algorithm	4
3	Product description	4
3.1	Product content and format	4
3.2	Data usage	6
3.3	Tools for reading the data	7
3.4	Known limitations and issues	7
3.5	Data file content	8
	References	12

Spectrometer Band ID	SWIR	
	7	8
Spectral Range [nm]	2300 – 2343	2343 – 2389
Spectral Resolution FWHM [nm]	0.227	0.225
Spectral Sampling [nm]	0.094	
Spatial Sampling [km ²]	7.1 × 7.5	
Detector Binning Factor	1	

Table 1: Summary of the TROPOMI SWIR spectral bands and their key features (Rozemeijer and Kleipool, 2018).

1 Purpose of document

This document describes the TROPOMI WFM-DOAS (TROPOMI/WFMD) XCH₄ data product and illustrates how to use it.

2 Introduction

2.1 The TROPOMI instrument on Sentinel-5 Precursor

The TROPOspheric Monitoring Instrument (TROPOMI) is a spaceborne nadir viewing spectrometer with bands in the ultraviolet and visible (270-495 nm), the near infrared (675-775 nm) and the shortwave infrared (2305-2385 nm) (Veefkind et al., 2012). TROPOMI combines daily global coverage with a high spatial resolution in order to focus on the troposphere where concentrations of trace gas and aerosol species rapidly change. Light from different wavelength bands is measured by TROPOMI to generate various data products. Some of the species measured by TROPOMI include ozone, nitrogen dioxide, methane, and carbon monoxide.

Sentinel-5P was launched in October 2017 into a sun-synchronous orbit with an equator crossing time of 13:30. TROPOMI’s observations of overtone absorptions in the shortwave infrared (SWIR) solar backscattered spectrum yield the vertical columns of CH₄ with high sensitivity down to the Earth’s surface (Schneising et al., 2019). The instrument has a wide swath of 2600 km consisting of single measurements with a horizontal resolution of typically 7 × 7 km² in the SWIR bands. The characteristics of the TROPOMI SWIR bands are summarised in Table 1.

PRODUCT USER GUIDE TROPOMI WFM-DOAS XCH ₄ ESA CLIMATE CHANGE INITIATIVE “PLUS” (CCI+)	INSTITUTE OF ENVIRONMENTAL PHYSICS, UNIVERSITY OF BREMEN	4
---	--	----------

2.2 The WFM-DOAS retrieval algorithm

The Weighting Function Modified Differential Optical Absorption Spectroscopy (WFM-DOAS) algorithm (Buchwitz et al., 2005a,b; Schneising et al., 2008, 2009, 2011, 2012; Heymann et al., 2012a,b; Schneising et al., 2013, 2014a,b, 2019, 2020a,b) is a least-squares method based on scaling (or shifting) pre-selected atmospheric vertical profiles. The column-averaged dry air mole fractions of methane (denoted XCH₄) are derived from the vertical column amounts of CH₄ by normalising with the dry air column, which is obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 reanalysis. The corresponding vertical columns of CH₄ are retrieved from the measured sun-normalised radiance using spectral fitting windows in the SWIR spectral region (2311-2315.5 nm and 2320-2338 nm).

The global distribution of the retrieved mole fractions XCH₄ for the years 2019 and 2020 is shown in Figure 1. Clearly visible is the interhemispheric gradient with larger methane concentrations on the northern hemisphere, where the majority of sources is located, superimposed by enhancements over prominent source regions like anthropogenic emissions from fossil fuels and rice cultivation in China, India, and Southeast Asia. Other visible source regions include tropical wetlands as well as anthropogenic emissions in California or the Padan Plain in Italy.

From the validation with ground-based Fourier Transform Spectroscopy (FTS) measurements of the Total Carbon Column Observing Network (TCCON) (Wunch et al., 2011) at the 26 TCCON sites listed in Table 2, realistic error estimates of the satellite data are provided and summarised in Table 3. For the sake of completeness, the error characteristics of XCO, which is simultaneously retrieved with XCH₄ and also included in the product, are also quoted.

3 Product description

The data product is based on TROPOMI Level 1b V01.00.00 files comprising spectra from the nominal operational mode, which started end of April 2018, and reprocessed spectra from the previous six-month commissioning phase.

3.1 Product content and format

The CH₄-TROPOMI-WFMD data products are stored per day in separate NetCDF-files (NetCDF-4 classic model). The product files contain the key product, i.e. the

Station	Latitude [°]	Longitude [°]	Altitude [km]	Reference
Eureka	80.05	−86.42	0.61	Strong et al. (2019)
Ny-Ålesund	78.92	11.92	0.02	Notholt et al. (2017)
Sodankylä	67.37	26.63	0.19	Kivi et al. (2014)
East Trout Lake	54.35	−104.99	0.50	Wunch et al. (2018)
Białystok	53.23	23.03	0.19	Deutscher et al. (2015)
Bremen	53.10	8.85	0.03	Notholt et al. (2014)
Karlsruhe	49.10	8.44	0.11	Hase et al. (2015)
Paris	48.85	2.36	0.06	Te et al. (2014)
Orléans	47.97	2.11	0.13	Warneke et al. (2014)
Garmisch	47.48	11.06	0.75	Sussmann and Rettinger (2018)
Park Falls	45.94	−90.27	0.44	Wennberg et al. (2017)
Rikubetsu	43.46	143.77	0.38	Morino et al. (2018c)
Lamont	36.60	−97.49	0.32	Wennberg et al. (2016b)
Anmeyondo	36.54	126.33	0.03	Goo et al. (2014)
Tsukuba	36.05	140.12	0.03	Morino et al. (2018a)
Nicosia	35.14	33.38	0.19	Petri et al. (2020)
Edwards	34.96	−117.88	0.70	Iraci et al. (2016)
JPL	34.20	−118.18	0.39	Wennberg et al. (2016a)
Caltech	34.14	−118.13	0.24	Wennberg et al. (2015)
Saga	33.24	130.29	0.01	Shiomi et al. (2014)
Burgos	18.53	120.65	0.04	Morino et al. (2018b)
Ascension Island	−7.92	−14.33	0.03	Feist et al. (2014)
Darwin	−12.46	130.93	0.04	Griffith et al. (2014a)
Réunion	−20.90	55.49	0.09	De Mazière et al. (2017)
Wollongong	−34.41	150.88	0.03	Griffith et al. (2014b)
Lauder	−45.04	169.68	0.37	Sherlock et al. (2014)

Table 2: TCCON sites used in the validation ordered according to latitude from north to south.

	XCH ₄ [ppb]	XCO [ppb]
Global Offset	−0.37	6.27
Random Error	12.85	5.36
Systematic Error (spatio-temporal)	5.20	2.46

Table 3: Error characterisation of the WFM-DOAS data products (valid for TROPOMI/WFMD v1.5 XCH₄ and XCO).

TROPOMI/WFMD XCH₄ 2019-2020

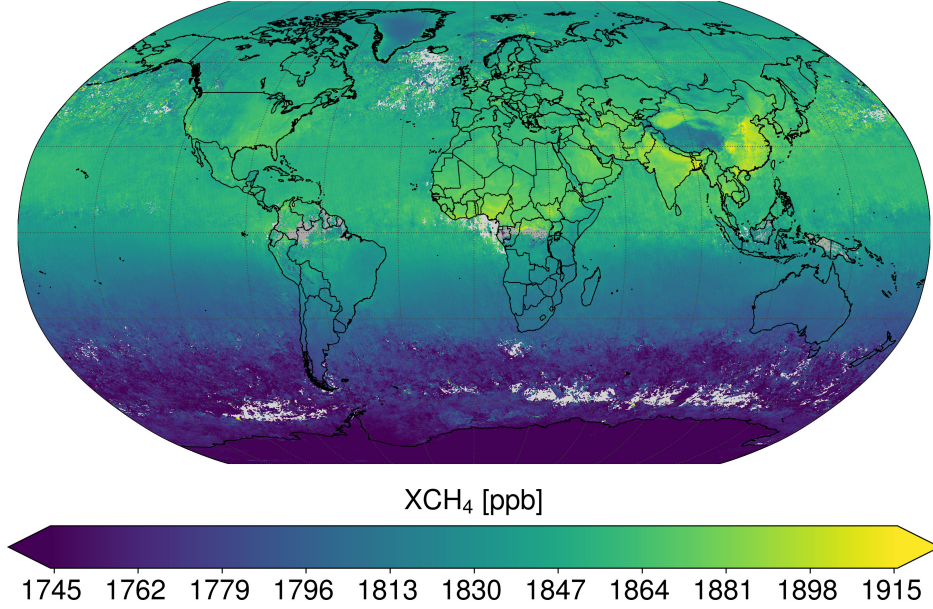


Figure 1: Biennial mean (2019-2020) of retrieved TROPOMI/WFMD v1.5 methane.

retrieved column-averaged dry air mole fractions XCH₄, as well as the column-averaged dry air mole fractions XCO and several other useful parameters (see Section 3.5 for details). Information relevant for the use of the data is also included in the data file, e.g. the averaging kernels.

3.2 Data usage

The column-averaged dry air mole fractions of methane are stored in the variable xch4 in the NetCDF product files ESACCI-GHG-L2-CH4-CO-TROPOMI-WFMD-YYYYMMDD-fv2.nc (see Section 3.5).

If the data are to be compared with other data for which vertical profile information is available (e.g. comparison to models), the column averaging kernels should be applied to the model profiles using the formula

$$X_{\text{mod}} = \sum_l \left(X_{\text{apr}}^l + A_l (X_{\text{mod}}^l - X_{\text{apr}}^l) \right) w_l \quad (1)$$

where l is the index of the vertical layer, A_l the averaging kernel (variables xch4_averaging_kernel and xco_averaging_kernel in NetCDF product files), X_{apr}^l the a-priori mole fraction (variables ch4_profile_apriori and

PRODUCT USER GUIDE TROPOMI WFM-DOAS XCH ₄ ESA CLIMATE CHANGE INITIATIVE “PLUS” (CCI+)	INSTITUTE OF ENVIRONMENTAL PHYSICS, UNIVERSITY OF BREMEN	7
---	--	----------

co_profile_apriori in product files) and X_{mod}^l the simulated mole fraction of layer l . w_l is the layer dependent pressure weight (variable pressure_weight in product files).

3.3 Tools for reading the data

The data are stored in NetCDF format (NetCDF-4 classic model) which can be read with standard tools in the common programming languages (Python, IDL, Matlab, Fortran90, C++, etc).

3.4 Known limitations and issues

The file names ESACCI-GHG-L2-CH4-CO-TROPOMI-WFMD-YYYYMMDD-fv2.nc deviate slightly from the GHG-CCI file naming convention to take into account that a comprehensive carbon monoxide mole fraction data set is also included in the product.

PRODUCT USER GUIDE TROPOMI WFM-DOAS XCH ₄ ESA CLIMATE CHANGE INITIATIVE "PLUS" (CCI+)	INSTITUTE OF ENVIRONMENTAL PHYSICS, UNIVERSITY OF BREMEN	8
---	--	----------

3.5 Data file content

The structure of the Level2 product files ESACCI-GHG-L2-CH4-CO-TROPOMI-WFMD-YYYYMMDD-fv2.nc is summarised in the following:

```
netcdf ESACCI-GHG-L2-CH4-CO-TROPOMI-WFMD-20200701-fv2 {
dimensions:
    sounding_dim = 504279 ;
    level_dim = 21 ;
    layer_dim = 20 ;
    corners_dim = 4 ;
variables:
    double time(sounding_dim) ;
        time:standard_name = "time" ;
        time:long_name = "time" ;
        time:units = "seconds since 1970-01-01 00:00:00" ;
        time:calendar = "standard" ;
    float latitude(sounding_dim) ;
        latitude:standard_name = "latitude" ;
        latitude:long_name = "latitude" ;
        latitude:units = "degree_north" ;
        latitude:valid_range = -90.f, 90.f ;
        latitude:comment = "Center latitude of the measurement" ;
    float longitude(sounding_dim) ;
        longitude:standard_name = "longitude" ;
        longitude:long_name = "longitude" ;
        longitude:units = "degree_east" ;
        longitude:valid_range = -180.f, 180.f ;
        longitude:comment = "Center longitude of the measurement" ;
    float solar_zenith_angle(sounding_dim) ;
        solar_zenith_angle:standard_name = "solar_zenith_angle" ;
        solar_zenith_angle:long_name = "solar_zenith_angle" ;
        solar_zenith_angle:units = "degree" ;
        solar_zenith_angle:comment = "Solar zenith angle is the the angle between the
            line of sight to the sun and the local vertical." ;
    float sensor_zenith_angle(sounding_dim) ;
        sensor_zenith_angle:standard_name = "sensor_zenith_angle" ;
        sensor_zenith_angle:long_name = "sensor_zenith_angle" ;
        sensor_zenith_angle:units = "degree" ;
        sensor_zenith_angle:comment = "Sensor zenith angle is the the angle between the line
            of sight to the sensor and the local vertical." ;
    float azimuth_difference(sounding_dim) ;
        azimuth_difference:long_name = "azimuth difference" ;
        azimuth_difference:units = "degree" ;
        azimuth_difference:comment = "Relative azimuth angle between sun and sensor direction." ;
    float xch4(sounding_dim) ;
        xch4:standard_name = "dry_atmosphere_mole_fraction_of_methane" ;
        xch4:long_name = "column-averaged dry air mole fraction of atmospheric methane" ;
        xch4:units = "1e-9" ;
        xch4:comment = "Retrieved column-averaged dry air mole fraction of atmospheric
            methane (XCH4) in ppb" ;
    float xch4_uncertainty(sounding_dim) ;
        xch4_uncertainty:long_name = "1-sigma uncertainty of the retrieved column-averaged
            dry air mole fraction of atmospheric methane" ;
        xch4_uncertainty:units = "1e-9" ;
        xch4_uncertainty:comment = "1-sigma uncertainty of the retrieved column-averaged
            dry air mole fraction of atmospheric methane (XCH4) in ppb" ;
    int xch4_quality_flag(sounding_dim) ;
        xch4_quality_flag:long_name = "quality flag for the retrieved column-averaged
```

PRODUCT USER GUIDE TROPOMI WFM-DOAS XCH ₄ ESA CLIMATE CHANGE INITIATIVE "PLUS" (CCI+)	INSTITUTE OF ENVIRONMENTAL PHYSICS, UNIVERSITY OF BREMEN	9
---	--	----------

```

        dry air mole fraction of atmospheric methane" ;
xch4_quality_flag:flag_values = 0, 1 ;
xch4_quality_flag:flag_meanings = "good_quality potentially_bad_quality" ;
xch4_quality_flag:comment = "0=good, 1=bad" ;
float xco(sounding_dim) ;
xco:long_name = "column-averaged dry air mole fraction of atmospheric carbon monoxide" ;
xco:units = "1e-9" ;
xco:comment = "Retrieved column-averaged dry air mole fraction of atmospheric
        carbon monoxide (XCO) in ppb" ;
float xco_uncertainty(sounding_dim) ;
xco_uncertainty:long_name = "1-sigma uncertainty of the retrieved column-averaged
        dry air mole fraction of atmospheric carbon monoxide" ;
xco_uncertainty:units = "1e-9" ;
xco_uncertainty:comment = "1-sigma uncertainty of the retrieved column-averaged
        dry air mole fraction of atmospheric carbon monoxide (XCO) in ppb" ;
int xco_quality_flag(sounding_dim) ;
xco_quality_flag:long_name = "quality flag for the retrieved column-averaged
        dry air mole fraction of atmospheric carbon monoxide" ;
xco_quality_flag:flag_values = 0, 1 ;
xco_quality_flag:flag_meanings = "good_quality potentially_bad_quality" ;
xco_quality_flag:comment = "0=good, 1=bad" ;
float pressure_levels(sounding_dim, level_dim) ;
pressure_levels:long_name = "pressure levels" ;
pressure_levels:units = "hPa" ;
pressure_levels:comment = "Pressure levels define the boundaries of the
        averaging kernel and a priori profile layers.\n",
        "Levels are ordered from surface to top of atmosphere." ;
float pressure_weight(sounding_dim, layer_dim) ;
pressure_weight:long_name = "pressure weight" ;
pressure_weight:units = "1" ;
pressure_weight:comment = "Layer dependent weights needed to apply the
        averaging kernels." ;
float ch4_profile_apriori(sounding_dim, layer_dim) ;
ch4_profile_apriori:long_name = "a priori dry air mole fraction profile of
        atmospheric methane" ;
ch4_profile_apriori:units = "1e-9" ;
ch4_profile_apriori:comment = "A priori dry-air mole fraction profile of
        atmospheric methane in ppb.\n",
        "All values represent layer averages within the corresponding pressure levels.\n",
        "Profiles are ordered from surface to top of atmosphere." ;
float xch4_averaging_kernel(sounding_dim, layer_dim) ;
xch4_averaging_kernel:long_name = "xch4 averaging kernel" ;
xch4_averaging_kernel:units = "1" ;
xch4_averaging_kernel:comment = "Represents the altitude sensitivity of the
        retrieval as a function of pressure.\n",
        "All values represent layer averages within the corresponding pressure levels.\n",
        "Profiles are ordered from surface to top of atmosphere." ;
float co_profile_apriori(sounding_dim, layer_dim) ;
co_profile_apriori:long_name = "a priori dry air mole fraction profile of
        atmospheric carbon monoxide" ;
co_profile_apriori:units = "1e-9" ;
co_profile_apriori:comment = "A priori dry-air mole fraction profile of
        atmospheric carbon monoxide in ppb.\n",
        "All values represent layer averages within the corresponding pressure levels.\n",
        "Profiles are ordered from surface to top of atmosphere." ;
float xco_averaging_kernel(sounding_dim, layer_dim) ;
xco_averaging_kernel:long_name = "xco averaging kernel" ;
xco_averaging_kernel:units = "1" ;
xco_averaging_kernel:comment = "Represents the altitude sensitivity of the
        retrieval as a function of pressure.\n",

```

PRODUCT USER GUIDE TROPOMI WFM-DOAS XCH₄ ESA CLIMATE CHANGE INITIATIVE "PLUS" (CCI+)	INSTITUTE OF ENVIRONMENTAL PHYSICS, UNIVERSITY OF BREMEN 10
---	--

```

        "All values represent layer averages within the corresponding pressure levels.\n",
        "Profiles are ordered from surface to top of atmosphere." ;

int orbit_number(sounding_dim) ;
    orbit_number:long_name = "orbit number" ;
    orbit_number:units = "1" ;
    orbit_number:comment = "Orbit number" ;

int scanline(sounding_dim) ;
    scanline:long_name = "along track dimension index" ;
    scanline:units = "1" ;
    scanline:comment = "This dimension variable defines the indices along track" ;

int ground_pixel(sounding_dim) ;
    ground_pixel:long_name = "across track dimension index" ;
    ground_pixel:units = "1" ;
    ground_pixel:comment = "This dimension variable defines the indices across track" ;

float latitude_corners(sounding_dim, corners_dim) ;
    latitude_corners:long_name = "latitude_corners" ;
    latitude_corners:units = "degree_north" ;
    latitude_corners:valid_range = -90.f, 90.f ;
    latitude_corners:comment = "Corner latitudes of the measurement" ;

float longitude_corners(sounding_dim, corners_dim) ;
    longitude_corners:long_name = "longitude_corners" ;
    longitude_corners:units = "degree_east" ;
    longitude_corners:valid_range = -180.f, 180.f ;
    longitude_corners:comment = "Corner longitudes of the measurement" ;

float altitude(sounding_dim) ;
    altitude:standard_name = "altitude" ;
    altitude:long_name = "altitude" ;
    altitude:units = "m" ;
    altitude:comment = "Average surface altitude" ;

float surface_roughness(sounding_dim) ;
    surface_roughness:long_name = "surface roughness" ;
    surface_roughness:units = "m" ;
    surface_roughness:comment = "Surface roughness" ;

float apparent_albedo(sounding_dim) ;
    apparent_albedo:long_name = "apparent surface albedo" ;
    apparent_albedo:units = "1" ;
    apparent_albedo:comment = "Retrieved surface albedo at 2313nm" ;

int land_fraction(sounding_dim) ;
    land_fraction:long_name = "land fraction" ;
    land_fraction:units = "1e-2" ;
    land_fraction:valid_range = 0, 100 ;
    land_fraction:comment = "Land fraction of the observed scene in percent" ;

float cloud_parameter(sounding_dim) ;
    cloud_parameter:long_name = "cloud parameter from strong water vapour absorption" ;
    cloud_parameter:units = "1" ;
    cloud_parameter:comment = "Ratio of measured to cloud-free reference radiance
        for selected strong water vapour lines" ;

float co_column(sounding_dim) ;
    co_column:long_name = "vertical column of carbon monoxide" ;
    co_column:units = "mol m-2" ;
    co_column:multiplication_factor_to_convert_to_molecules_per_cm2 = 6.022141e+19 ;
    co_column:comment = "Retrieved vertical column amount of carbon monoxide" ;

float h2o_column(sounding_dim) ;
    h2o_column:long_name = "vertical column of water vapour" ;
    h2o_column:units = "g cm-2" ;
    h2o_column:comment = "Retrieved vertical column amount of water vapour" ;

float h2o_column_uncertainty(sounding_dim) ;
    h2o_column_uncertainty:long_name = "1-sigma uncertainty of the retrieved vertical
        column of atmospheric water vapour" ;
    h2o_column_uncertainty:units = "g cm-2" ;

```

PRODUCT USER GUIDE TROPOMI WFM-DOAS XCH ₄ ESA CLIMATE CHANGE INITIATIVE “PLUS” (CCI+)	INSTITUTE OF ENVIRONMENTAL PHYSICS, UNIVERSITY OF BREMEN	11
---	--	-----------

```

        h2o_column_uncertainty:comment = "1-sigma uncertainty of the retrieved vertical
            column of atmospheric water vapour" ;

// global attributes:
:title = "TROPOMI/WFMD XCH4 and XCO" ;
:institution = "University of Bremen" ;
:source = "TROPOMI L1B version 01.00.00" ;
:history = "2021 - product generated with WFMD" ;
:tracking_id = "599b5b3b-ecfd-4a40-ac3b-4073d8be28ea" ;
:Conventions = "CF-1.6" ;
:product_version = "v1.5" ;
:summary = "Weighting Function Modified DOAS (WFMD) was adjusted to simultaneously
    retrieve column-averaged dry air mole fractions of atmospheric methane and
    carbon monoxide from the shortwave-infrared (SWIR) nadir spectra of the
    TROPOMI instrument onboard Sentinel-5 Precursor." ;
:keywords = "satellite, Sentinel-5 Precursor, TROPOMI, atmosphere, methane, carbon monoxide" ;
:id = "ESACCI-GHG-L2-CH4-CO-TROPOMI-WFMD-20200701-fv2.nc" ;
:naming_authority = "iup.uni-bremen.de" ;
:keywords_vocabulary = "NASA Global Change Master Directory (GCMD)" ;
:cdm_data_type = "point" ;
:comment = "These data were produced at the University of Bremen in the framework
    of the ESA GHG-CCI project" ;
:date_created = "20210713T095649Z" ;
:creator_name = "University of Bremen, IUP, Oliver Schneising" ;
:creator_email = "schneising@iup.physik.uni-bremen.de" ;
:project = "Climate Change Initiative - European Space Agency" ;
:geospatial_lat_min = -90 ;
:geospatial_lat_max = 90 ;
:geospatial_lat_units = "degree_north" ;
:geospatial_lon_min = -180 ;
:geospatial_lon_max = 180 ;
:geospatial_lon_units = "degree_east" ;
:geospatial_vertical_min = 0 ;
:geospatial_vertical_max = 100000 ;
:time_coverage_start = "20200701T000000Z" ;
:time_coverage_end = "20200701T235959Z" ;
:time_coverage_duration = "P1D" ;
:time_coverage_resolution = "P1D" ;
:standard_name_vocabulary = "NetCDF Climate and Forecast (CF) Metadata Conventions
    Version 1.6" ;
:license = "ESA CCI Data Policy: free and open access" ;
:platform = "Sentinel-5 Precursor" ;
:sensor = "TROPOMI" ;
:spatial_resolution = "7km x 7km at nadir (typically)" ;
}

```

References

- Buchwitz, M., de Beek, R., Burrows, J. P., Bovensmann, H., Warneke, T., Notholt, J., Meirink, J. F., Goede, A. P. H., Bergamaschi, P., Körner, S., Heimann, M., and Schulz, A.: Atmospheric methane and carbon dioxide from SCIAMACHY satellite data: initial comparison with chemistry and transport models, *Atmos. Chem. Phys.*, 5, 941–962, <https://doi.org/10.5194/acp-5-941-2005>, 2005a.
- Buchwitz, M., de Beek, R., Noël, S., Burrows, J. P., Bovensmann, H., Bremer, H., Bergamaschi, P., Körner, S., and Heimann, M.: Carbon monoxide, methane and carbon dioxide columns retrieved from SCIAMACHY by WFM-DOAS: year 2003 initial data set, *Atmos. Chem. Phys.*, 5, 3313–3329, <https://doi.org/10.5194/acp-5-3313-2005>, 2005b.
- De Mazière, M., Sha, M. K., Desmet, F., Hermans, C., Scolas, F., Kumps, N., Metzger, J.-M., Duflot, V., and Cammas, J.-P.: TCCON data from Réunion Island (La Réunion), France, Release GGG2014.R1. TCCON data archive, hosted by CaltechDATA, California Institute of Technology, <https://doi.org/10.14291/tccon.ggg2014.reunion01.r1>, 2017.
- Deutscher, N. M., Notholt, J., Messerschmidt, J., Weinzierl, C., Warneke, T., Petri, C., and Grupe, P.: TCCON data from Białystok, Poland, Release GGG2014.R1. TCCON data archive, hosted by CaltechDATA, California Institute of Technology, <https://doi.org/10.14291/tccon.ggg2014.bialystok01.r1/1183984>, 2015.
- Feist, D. G., Arnold, S. G., John, N., and Geibel, M. C.: TCCON data from Ascension Island, Saint Helena, Ascension and Tristan da Cunha, Release GGG2014.R0. TCCON data archive, hosted by CaltechDATA, California Institute of Technology, <https://doi.org/10.14291/tccon.ggg2014.ascension01.r0/1149285>, 2014.
- Goo, T.-Y., Oh, Y.-S., and Velazco, V. A.: TCCON data from Anmyeondo, South Korea, Release GGG2014.R0. TCCON data archive, hosted by CaltechDATA, California Institute of Technology, <https://doi.org/10.14291/tccon.ggg2014.anmeyondo01.r0/1149284>, 2014.
- Griffith, D. W., Deutscher, N. M., Velazco, V. A., Wennberg, P. O., Yavin, Y., Keppel-Aleks, G., Washenfelder, R. A., Toon, G. C., Blavier, J.-F., Paton-Walsh, C., Jones, N. B., Kettlewell, G. C., Connor, B. J., Macatangay, R. C., Roehl, C., Ryzek, M., Glowacki, J., Culgan, T., and Bryant, G. W.: TCCON data from Darwin, Australia, Release GGG2014.R0. TCCON data archive, hosted by CaltechDATA,

PRODUCT USER GUIDE TROPOMI WFM-DOAS XCH₄ ESA CLIMATE CHANGE INITIATIVE “PLUS” (CCI+)	INSTITUTE OF ENVIRONMENTAL PHYSICS, UNIVERSITY OF BREMEN 13
---	--

California Institute of Technology, <https://doi.org/10.14291/tccon.ggg2014.darwin01.r0/1149290>, 2014a.

Griffith, D. W., Velazco, V. A., Deutscher, N. M., Paton-Walsh, C., Jones, N. B., Wilson, S. R., Macatangay, R. C., Kettlewell, G. C., Buchholz, R. R., and Riggensbach, M. O.: TCCON data from Wollongong, Australia, Release GGG2014.R0. TCCON data archive, hosted by CaltechDATA, California Institute of Technology, <https://doi.org/10.14291/tccon.ggg2014.wollongong01.r0/1149291>, 2014b.

Hase, F., Blumenstock, T., Dohe, S., Groß, J., and Kiel, M.: TCCON data from Karlsruhe, Germany, Release GGG2014.R1. TCCON data archive, hosted by CaltechDATA, California Institute of Technology, <https://doi.org/10.14291/tccon.ggg2014.karlsruhe01.r1/1182416>, 2015.

Heymann, J., Schneising, O., Reuter, M., Buchwitz, M., Rozanov, V. V., Velazco, V. A., Bovensmann, H., and Burrows, J. P.: SCIAMACHY WFM-DOAS XCO₂: comparison with CarbonTracker XCO₂ focusing on aerosols and thin clouds, Atmos. Meas. Tech., 5, 1935–1952, <https://doi.org/10.5194/amt-5-1935-2012>, 2012a.

Heymann, J., Bovensmann, H., Buchwitz, M., Burrows, J. P., Deutscher, N. M., Notholt, J., Rettinger, M., Reuter, M., Schneising, O., Sussmann, R., and Warneke, T.: SCIAMACHY WFM-DOAS XCO₂: reduction of scattering related errors, Atmos. Meas. Tech., 5, 2375–2390, <https://doi.org/10.5194/amt-5-2375-2012>, 2012b.

Iraci, L. T., Podolske, J. R., Hillyard, P. W., Roehl, C., Wennberg, P. O., Blavier, J.-F., Landeros, J., Allen, N., Wunch, D., Zavaleta, J., Quigley, E., Osterman, G. B., Albertson, R., Dunwoody, K., and Boyden, H.: TCCON data from Edwards, California, USA, Release GGG2014.R1. TCCON data archive, hosted by CaltechDATA, California Institute of Technology, <https://doi.org/10.14291/tccon.ggg2014.edwards01.r1/1255068>, 2016.

Kivi, R., Heikkinen, P., and Kyrö, E.: TCCON data from Sodankylä, Finland, Release GGG2014.R0. TCCON data archive, hosted by CaltechDATA, California Institute of Technology, <https://doi.org/10.14291/tccon.ggg2014.sodankyla01.r0/1149280>, 2014.

Morino, I., Matsuzaki, T., and Horikawa, M.: TCCON data from Tsukuba, Ibaraki, Japan, 125HR, Release GGG2014.R2. TCCON data archive, hosted by CaltechDATA, California Institute of Technology, <https://doi.org/10.14291/tccon.ggg2014.tsukuba02.r2>, 2018a.

- Morino, I., Velazco, V. A., Hori, A., Uchino, O., and Griffith, D. W. T.: TCCON data from Burgos, Philippines, Release GGG2014.R0. TCCON data archive, hosted by CaltechDATA, California Institute of Technology, <https://doi.org/10.14291/tcon.ggg2014.burgos01.r0>, 2018b.
- Morino, I., Yokozeki, N., Matsuzaki, T., and Horikawa, M.: TCCON data from Rikubetsu, Hokkaido, Japan, Release GGG2014.R2. TCCON data archive, hosted by CaltechDATA, California Institute of Technology, <https://doi.org/10.14291/tcon.ggg2014.rikubetsu01.r2>, URL <https://data.caltech.edu/records/957>, 2018c.
- Notholt, J., Petri, C., Warneke, T., Deutscher, N. M., Palm, M., Buschmann, M., Weinzierl, C., Macatangay, R. C., and Grupe, P.: TCCON data from Bremen, Germany, Release GGG2014.R0. TCCON data archive, hosted by CaltechDATA, California Institute of Technology, <https://doi.org/10.14291/tcon.ggg2014.bremen01.r0/1149275>, 2014.
- Notholt, J., Warneke, T., Petri, C., Deutscher, N. M., Weinzierl, C., Palm, M., and Buschmann, M.: TCCON data from Ny-Ålesund, Spitzbergen, Norway, Release GGG2014.R0. TCCON data archive, hosted by CaltechDATA, California Institute of Technology, <https://doi.org/10.14291/tcon.ggg2014.nyalesund01.r0/1149278>, 2017.
- Petri, C., Rousogonous, C., Warneke, T., Vrekoussis, M., Sciare, S., and Notholt, J.: TCCON data from Nicosia, Cyprus, Release GGG2014.R0. TCCON data archive, hosted by CaltechDATA, California Institute of Technology, <https://doi.org/10.14291/tcon.ggg2014.nicosia01.R0>, 2020.
- Rozemeijer, N. C. and Kleipool, Q.: S5P Mission Performance Centre Level 1b Readme, Reference: S5P-MPC-KNMI-PRF-L1B, Issue: 1.0.0, Product Version: V01.00.00, <https://sentinel.esa.int/documents/247904/3541451/Sentinel-5P-Level-1b-Product-Readme-File>, 2018.
- Schneising, O., Buchwitz, M., Burrows, J. P., Bovensmann, H., Reuter, M., Notholt, J., Macatangay, R., and Warneke, T.: Three years of greenhouse gas column-averaged dry air mole fractions retrieved from satellite - Part 1: Carbon dioxide, Atmos. Chem. Phys., 8, 3827–3853, <https://doi.org/10.5194/acp-8-3827-2008>, 2008.
- Schneising, O., Buchwitz, M., Burrows, J. P., Bovensmann, H., Bergamaschi, P., and Peters, W.: Three years of greenhouse gas column-averaged dry air mole fractions retrieved from satellite - Part 2: Methane, Atmos. Chem. Phys., 9, 443–465, <https://doi.org/10.5194/acp-9-443-2009>, 2009.

- Schneising, O., Buchwitz, M., Reuter, M., Heymann, J., Bovensmann, H., and Burrows, J. P.: Long-term analysis of carbon dioxide and methane column-averaged mole fractions retrieved from SCIAMACHY, *Atmos. Chem. Phys.*, 11, 2863–2880, <https://doi.org/10.5194/acp-11-2863-2011>, 2011.
- Schneising, O., Bergamaschi, P., Bovensmann, H., Buchwitz, M., Burrows, J. P., Deutscher, N. M., Griffith, D. W. T., Heymann, J., Macatangay, R., Messerschmidt, J., Notholt, J., Rettinger, M., Reuter, M., Sussmann, R., Toon, G. C., Velazco, V. A., Warneke, T., Wennberg, P. O., and Wunch, D.: Atmospheric greenhouse gases retrieved from SCIAMACHY: Comparison to ground-based FTS measurements and model results, *Atmos. Chem. Phys.*, 12, 1527–1540, <https://doi.org/10.5194/acp-12-1527-2012>, 2012.
- Schneising, O., Heymann, J., Buchwitz, M., Reuter, M., Bovensmann, H., and Burrows, J. P.: Anthropogenic carbon dioxide source areas observed from space: assessment of regional enhancements and trends, *Atmos. Chem. Phys.*, 13, 2445–2454, <https://doi.org/10.5194/acp-13-2445-2013>, 2013.
- Schneising, O., Reuter, M., Buchwitz, M., Heymann, J., Bovensmann, H., and Burrows, J. P.: Terrestrial carbon sink observed from space: variation of growth rates and seasonal cycle amplitudes in response to interannual surface temperature variability, *Atmos. Chem. Phys.*, 14, 133–141, <https://doi.org/10.5194/acp-14-133-2014>, 2014a.
- Schneising, O., Burrows, J. P., Dickerson, R. R., Buchwitz, M., Reuter, M., and Bovensmann, H.: Remote sensing of fugitive methane emissions from oil and gas production in North American tight geologic formations, *Earth’s Future*, 2, 548–558, <https://doi.org/10.1002/2014EF000265>, 2014b.
- Schneising, O., Buchwitz, M., Reuter, M., Bovensmann, H., Burrows, J. P., Borsdorff, T., Deutscher, N. M., Feist, D. G., Griffith, D. W. T., Hase, F., Hermans, C., Iraci, L. T., Kivi, R., Landgraf, J., Morino, I., Notholt, J., Petri, C., Pollard, D. F., Roche, S., Shiomi, K., Strong, K., Sussmann, R., Velazco, V. A., Warneke, T., and Wunch, D.: A scientific algorithm to simultaneously retrieve carbon monoxide and methane from TROPOMI onboard Sentinel-5 Precursor, *Atmos. Meas. Tech.*, 12, 6771–6802, <https://doi.org/10.5194/amt-12-6771-2019>, 2019.
- Schneising, O., Buchwitz, M., Reuter, M., Bovensmann, H., and Burrows, J. P.: Severe Californian wildfires in November 2018 observed from space: the carbon monoxide perspective, *Atmos. Chem. Phys.*, 20, 3317–3332, <https://doi.org/10.5194/acp-20-3317-2020>, 2020a.

- Schneising, O., Buchwitz, M., Reuter, M., Vanselow, S., Bovensmann, H., and Burrows, J. P.: Remote sensing of methane leakage from natural gas and petroleum systems revisited, *Atmos. Chem. Phys.*, 20, 9169–9182, <https://doi.org/10.5194/acp-20-9169-2020>, 2020b.
- Sherlock, V., Connor, B., Robinson, J., Shiona, H., Smale, D., and Pollard, D. F.: TCCON data from Lauder, New Zealand, 125HR, Release GGG2014.R0. TCCON data archive, hosted by CaltechDATA, California Institute of Technology, <https://doi.org/10.14291/tccon.ggg2014.lauder02.r0/1149298>, 2014.
- Shiomi, K., Kawakami, S., Ohyama, H., Arai, K., Okumura, H., Taura, C., Fukamachi, T., and Sakashita, M.: TCCON data from Saga, Japan, Release GGG2014.R0. TCCON data archive, hosted by CaltechDATA, California Institute of Technology, <https://doi.org/10.14291/tccon.ggg2014.saga01.r0/1149283>, 2014.
- Strong, K., Roche, S., Franklin, J. E., Mendonca, J., Lutsch, E., Weaver, D., Fogal, P. F., Drummond, J. R., Batchelor, R., and Lindenmaier, R.: TCCON data from Eureka, Canada, Release GGG2014.R3. TCCON data archive, hosted by CaltechDATA, California Institute of Technology, <https://doi.org/10.14291/tccon.ggg2014.eureka01.r3>, 2019.
- Sussmann, R. and Rettinger, M.: TCCON data from Garmisch, Germany, Release GGG2014.R2. TCCON data archive, hosted by CaltechDATA, California Institute of Technology, <https://doi.org/10.14291/tccon.ggg2014.garmisch01.r2>, 2018.
- Te, Y., Jeseck, P., and Janssen, C.: TCCON data from Paris, France, Release GGG2014.R0. TCCON data archive, hosted by CaltechDATA, California Institute of Technology, <https://doi.org/10.14291/tccon.ggg2014.paris01.R0/1149279>, 2014.
- Veefkind, J. P., Aben, I., McMullan, K., Förster, H., de Vries, J., Otter, G., Claas, J., Eskes, H. J., de Haan, J. F., Kleipool, Q., van Weele, M., Hasekamp, O., Hoogeveen, R., Landgraf, J., Snel, R., Tol, P., Ingmann, P., Voors, R., Kruizinga, B., Vink, R., Visser, H., and Levelt, P. F.: TROPOMI on the ESA Sentinel-5 Precursor: A GMES mission for global observations of the atmospheric composition for climate, air quality and ozone layer applications, *Remote Sensing of Environment*, 120, 70–83, <https://doi.org/10.1016/j.rse.2011.09.027>, 2012.
- Warneke, T., Messerschmidt, J., Notholt, J., Weinzierl, C., Deutscher, N. M., Petri, C., and Grupe, P.: TCCON data from Orléans, France, Release GGG2014.R0. TCCON data archive, hosted by CaltechDATA, California Institute of Technology, <https://doi.org/10.14291/tccon.ggg2014.orleans01.r0/1149276>, 2014.

Wennberg, P. O., Wunch, D., Roehl, C. M., Blavier, J.-F., Toon, G. C., and Allen, N. T.: TCCON data from California Institute of Technology, Pasadena, California, USA, Release GGG2014.R1. TCCON data archive, hosted by CaltechDATA, California Institute of Technology, <https://doi.org/10.14291/tccon.ggg2014.pasadena01.r1/1182415>, 2015.

Wennberg, P. O., Roehl, C. M., Blavier, J.-F., Wunch, D., Landeros, J., and Allen, N. T.: TCCON data from Jet Propulsion Laboratory, Pasadena, California, USA, Release GGG2014.R1. TCCON data archive, hosted by CaltechDATA, California Institute of Technology, <https://doi.org/10.14291/tccon.ggg2014.jpl02.r1/1330096>, 2016a.

Wennberg, P. O., Wunch, D., Roehl, C. M., Blavier, J.-F., Toon, G. C., and Allen, N. T.: TCCON data from Lamont, Oklahoma, USA, Release GGG2014.R1. TCCON data archive, hosted by CaltechDATA, California Institute of Technology, <https://doi.org/10.14291/tccon.ggg2014.lamont01.r1/1255070>, 2016b.

Wennberg, P. O., Roehl, C. M., Wunch, D., Toon, G. C., Blavier, J.-F., Washenfelder, R., Keppel-Aleks, G., Allen, N. T., and Ayers, J.: TCCON data from Park Falls, Wisconsin, USA, Release GGG2014.R1. TCCON data archive, hosted by CaltechDATA, California Institute of Technology, <https://doi.org/10.14291/tccon.ggg2014.parkfalls01.r1>, 2017.

Wunch, D., Toon, G. C., Blavier, J.-F. L., Washenfelder, R. A., Notholt, J., Connor, B. J., Griffith, D. W. T., Sherlock, V., and Wennberg, P. O.: The Total Carbon Column Observing Network, *Phil. Trans. R. Soc. A*, 369, 2087–2112, <https://doi.org/10.1098/rsta.2010.0240>, 2011.

Wunch, D., Mendonca, J., Colebatch, O., Allen, N. T., Blavier, J.-F., Roche, S., Hedelius, J., Neufeld, G., Springett, S., Worthy, D., Kessler, R., and Strong, K.: TCCON data from East Trout Lake, Canada, Release GGG2014.R1. TCCON data archive, hosted by CaltechDATA, California Institute of Technology, <https://doi.org/10.14291/tccon.ggg2014.easttroutlake01.r1>, 2018.