S5P Mission Performance Centre CLOUD [L2__CLOUD_] Readme

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[1] The S5PVT AO project summaries can be found at https://earth.esa.int/web/guest/pi-community/search-results-and-projects/mission

1 Summary

This is the Product Readme File (PRF) of the Copernicus Sentinel 5 Precursor Tropospheric Monitoring Instrument (S5P/TROPOMI) Cloud Level 2 data product and is applicable for both the Near Real Time (NRTI) and Offline (OFFL) timeliness data products.

Product Identifier: **L2__CLOUD_**

Example filename:

S5P_NRTI_L2__CLOUD__20180704T085914_20180704T090414_03746_01_010000_20180704T094813.nc

S5P_OFFL_L2__CLOUD__20180803T003911_20180803T022041_04166_01_010102_20180808T235819.nc

The OFFL product has the following DOI: **http://doi.org/10.5270/S5P-ry8kaa5**

The Readme file describes the current processing baseline, product and quality limitations, and product availability status. More information on this data product is available from the Sentinel product webpage:

https://sentinels.copernicus.eu/web/sentinel/technical-guides/sentinel-5p/products-algorithms,

and from the TROPOMI product webpage http://www.tropomi.eu/data-products.

Note that the cloud parameters are given for two different cloud models:

(a) CAL (Clouds-As-Layers) [`cloud_fraction`, `cloud_top_height`, `cloud_optical_thickness`]

(b) CRB Clouds-as-Reflecting-Boundaries) [`cloud_fraction_crb`, `cloud_height_crb`, `cloud_albedo_crb`]

Note that the cloud fraction in the CLOUD Level 2 product is the Radiometric Cloud Fraction (RCF).

As a user guideline for the data quality a `qa_value` is given with the data. In order to avoid misinterpretation of the data quality, it is recommended at the current stage to only use those pixels with a `qa_value` above 0.5.

Validation by MPC Cal/Val experts concludes that version 1.0.0 of the Cloud data is in good overall agreement with (i) reference measurements collected from global ground-based networks, and (ii) the corresponding satellite data products from VIIRS & MODIS, and (iii) is compliant with the requirements as defined in Table 1.

The data product requirements are listed in the S5P Calibration and Validation Plan [RD01]

Parameter	Data product	Bias	Random
Radiometric Cloud Fraction	NRTI and OFFL	20%	0.05
Optical Thickness (Albedo)	NRTI and OFFL	20%	10 (0.05)
Cloud Height (Pressure)	NRTI and OFFL	20%	0.5 km (30 hPa)

Table 1: Cloud product requirements

2 Processing baseline description

Table 2 contains the history of the CLOUD processor versions.

Please note that the processor version annotation in the filenames of **OFFL** orbits **4147** to **4158** are not correct. Those products are actually processed with the new UPAS version 01.01.02, but in the filename it is written 01.01.01.

For **NRTI** orbits **4243** to **4244** the processor version annotations are not correct. From orbit 4245 onwards all products will have the correct (01.01.02) annotation in the filenames.

Processor Version	In operation from	In operation until
01.00.00	NRTI: orbit 3745, 2018-07-04	Initial version
01.00.00	OFFL: orbit 3661, 2018-06-28	Initial version
01.01.01	NRTI: orbit 3947, 2018-07-18	Orbit 4242, 2018-08-08
01.01.01	OFFL: orbit 3848, 2018-07-11	Orbit 4146, 2018-08-01
01.01.02	NRTI: orbit 4243, 2018-08-08	Orbit 5929, 2018-12-05
01.01.02	OFFL: orbit 4147, 2018-08-01	Orbit 5832, 2018-11-28
01.01.05	NRTI: orbit 5932, 2018-12-05	Current version
01.01.05	OFFL: orbit 5833, 2018-11-28	Current version

Table 2: History of CLOUD processor versions

3 Product Quality

3.1 Recommendations for data usage

In order to avoid misinterpretation of the data quality, it is recommended at the current stage to only use those TROPOMI pixels associated with a qa_value above 0.5. The qa_value summarizes the quality of the product by taking into consideration several aspects like the spectral channel quality flags from L1B data, geometry limitations (e.g. not reliable retrievals for SZA>75°), inhomogeneous scene warnings, high residual of the fitting process etc.

For further details, data users are encouraged to read the Product User Manual (PUM) and Algorithm Theoretical Basis Document (ATBD) associated with this data product, available on https://sentinels.copernicus.eu/web/sentinel/technical-guides/sentinel-5p/products-algorithms.

3.2 Validation results

3.2.1 Status of product validation

This section presents a summary of the key validation results obtained by the Validation data Analysis Facility (VDAF) of the S5P Mission Performance Centre (MPC). It contains preliminary results reported at the S5P First Public Release Validation Workshop (ESA/ESRIN, June 25-26, 2018). Individual contributions to the workshop are available in https://nikal.eventsair.com/QuickEventWebsitePortal/sentinel-5p-first-product-release-workshop/sentinel-5p.

Only few comparisons have been done at the time of this first validation exercise, but more recent validation results and consolidated validation reports are available through the MPC VDAF website at http://mpc-vdaf.tropomi.eu.

3.2.2 Validation approach

In order to evaluate the quality of the cloud product, the user can refer to the `qa_value` (for the CAL parameters) and the `qa_value_crb` (for the CRB parameters). The main diagnostics of the retrieval are given in the `shannon_information_content`, the `degree_of_freedom` and the `fitted_root_mean_square`. Several error- and warning flags are collected in the `processing_quality_flags` for the CAL parameters and in the `processing_quality_flags_crb` for the CRB parameters. Details on the various errors and warnings contained in the processing quality flags can be found in section 5.7 of the Cloud ATBD [RD02]. Details on the product format can be found in the Cloud PUM [RD03]. It is suggested to use only those pixels with `qa_value` above 0.5.

The spatial mis-registration between TROPOMI Bands 3-4 and Band 6 can decrease the quality of the retrieved cloud parameters especially over heterogeneous scenes (e.g., at the cloud edges). The geolocation coordinates (latitude, longitude) at the L2_CLOUD product correspond to the ones from L1B Band 3. The `cloud_coregistration_inhomogeneity_parameter` is raised to higher values when the scene is heterogeneous and the spatial mis-registration between Bands 3-4 and 6 might have a large impact on the data quality. The range for the `cloud_coregistration_inhomogeneity_parameter` is defined between 0.0 and 1.0, where 0.0 implies a totally homogeneous scene and 1.0 a totally heterogeneous scene. For further details, please refer to the CLOUD ATBD [RD02].

The errors related to the product retrieved parameters are also included in the L2_CLOUD product:

(a) CAL (Clouds-As-Layers) [`cloud_fraction_precision`, `cloud_top_height_precision`, `cloud_optical_thickness_precision`] and

(b) CRB (Clouds-as-Reflecting-Boundaries) [`cloud_fraction_crb_precision`, `cloud_height_crb_precision`, `cloud_albedo_crb_precision`].

At the current version, the uncertainty contains mainly the random error of the fitting algorithm. The errors for rows 81 and 333 should be neglected because the L1 irradiance error is anomalous high.

3.2.2.1 Ground-based lidar/radar

From the Sentinel-5P TROPOMI L2_CLOUD validation data set, the `cloud_top_height` and `cloud_height_crb` were compared with the ground-based cloud target classification data sets from CLOUDNET (http://www.cloud-net.org/), based on lidar/radar measurements. Initial results have been obtained at four CLOUDNET sites. For more details, the user might refer to the S5P MPC VDAF website at http://mpc-vdaf.tropomi.eu. Full agreement is not expected, as the S5P CLOUD cloud height depends on optical thickness while CLOUDNET does not differentiate between optically thin or thick clouds. This initial comparison was restricted to high CF (>0.5) cases containing single-cloud layer since it is more straightforward to compare. The `cloud_top_height` is on average below the CLOUDNET cloud top height, but mostly within the 20% bias requirement. The `cloud_height_crb` is on average below the CLOUDNET mid-height, but within the 20% bias requirement. Intercomparison spread is above the precision requirement, but impact of comparison error is still to be investigated.

3.2.2.2 Satellites

The initial comparison with MODIS at the latitude ranges [+60º, -60 º] shows a good agreement between the two instruments. The mean difference between the geometric and radiometric cloud fraction was 0.34 with a standard deviation of 0.04, which is consistent with the results in Loyola et al. (2018) [RD04]. The mean cloud top height difference was found 1.0 km with a standard deviation of 0.4 km. The mean cloud optical thickness difference was 3.9 and the respective standard deviation 2.4.

The pixel-by-pixel comparison using VIIRS NASA non-operational data[2] showed a negative bias in the CTH (mean bias of 850 m). A positive bias of 13 was found in the COT. However, VIIRS is especially sensitive to cirrus clouds (due to the 1.3 µm channel) leading to re-gridded COT measurements lower than 20. If optically thick clouds are excluded, the COT mean bias is ~5.

OCRA cloud fraction is more accurate for optically thick clouds. It is underestimated for scenes over optically thin clouds and over heterogeneous scenes (e.g. over small scattered clouds). The mean difference between VIIRS geometric cloud fraction and OCRA radiometric cloud fraction is about 0.2.

The `cloud_height_crb` and the `cloud_fraction_crb x cloud_albedo_crb` from the L2_CLOUD have been compared to the FRESCO auxiliary cloud product.

A sanity check has been performed by intercomparison to unvalidated FRESCO auxiliary cloud information. A histogram of the differences on 2018-05-12 (about 11 million observations, excluding snow or ice at the surface and excluding the sunglint geometries, using a `qa_value_crb` >= 0.5) shows the correlation between both products is 77%, with a mean difference of 0.09 and a standard deviation of 0.2.

The `cloud_height_crb` was compared directly for the same day, for cloud fractions > 0.2 (both products filtered separately, and otherwise the same selection criteria as for the cloud fraction `x` cloud albedo comparison). The correlation between both cloud heights is 89%, with a mean difference of 50 m and a standard deviation of 1.2 km.

[2] The VIIRS cloud datasets were obtained from a pre-production code run specifically for limited S5P team analysis. The VIIRS cloud algorithm is based on the MODIS Collection 6 algorithms [https://modis-atmosphere.gsfc.nasa.gov/documentation/collection-6; Platnick et al. (2017) [RD06]. Note that important changes to some algorithms have been required to account for missing MODIS spectral channels, including the use of the NOAA Algorithm Working Group (AWG) Cloud Height Algorithm developed by A. Heidinger et al. (2009) [RD05] as a replacement for the MODIS CO2 slicing algorithm.

3.2.3 Validation results

Overall, the quality of the initial CLOUD data product appears to comply with the mission requirements. The cloud top height for scenes with cloud fraction above 0.5 has been found within the 20% bias requirement (as outlined above). For the other two cloud parameters (cloud optical thickness and cloud fraction) the currently available data are not appropriate for the validation exercise. Only few comparisons have been done at the time of the first validation exercise, but more recent validation results and consolidated validation reports are available through the MPC VDAF website at http://mpc-vdaf.tropomi.eu.

4 Known Data Quality Issues

Currently, the following data quality issues are known, not covered by the quality flags, and should be kept in mind when looking at the Cloud product itself and also at preliminary validation results.

An instrument feature: spatial mis-registration between TROPOMI bands 3-4 (OCRA, UV trace gas fitting window) and band 6 (ROCINN fitting window)

The band 3-4 (450 pixels per scanline) footprints are not fully aligned with the band 6 (448 pixels per scanline) ones. In the worst case, the miss-alignment can be in the order of half a ground pixel. The OCRA algorithm retrieves the CF at Bands 3 and 4. This is an *a priori* to ROCINN algorithm, which works in band 6. Over heterogeneous scenes the miss-registration might have a large impact on the data quality. In the current products, a shift of two detector pixels between band 3-4 and band 6 is applied based on initial assessment.

Insensitivity to very thin clouds

The retrieval takes place in the UV-VIS-NIR bands only up to 770 nm. In this part of the spectrum, the optically thin clouds (i.e., COT < 5) are retrieved less accurately compared to, for example, MODIS that uses also channels in μm range.

Treatment of multi-layer clouds

The cloud retrieval algorithm assumes that there is a single-cloud layer in the atmosphere. For cases with more than one cloud present, the retrieved parameters might be under- or over-estimated. For more details about the quantification of multi-layer clouds, refer to Loyola et al. (2018) [RD04].

Treatment of ice clouds

Regarding the CAL model, the current parameterization of clouds is based on liquid water clouds. Therefore, ice or mixed-phase clouds might not be accurately retrieved. From the initial preliminary validation, it seems that the ice clouds are retrieved with an overestimated optical thickness.

Snow/Ice conditions

Over bright surfaces (especially when there is no permanent snow/ice coverage), the performance of the algorithm is decreased. This might result in overestimation of the cloud fraction; cloud top height is very close to the surface height and the cloud optical thickness overestimated.

Unknown straylight impact in the NIR

The TROPOMI out-off-band straylight effect is not yet well assessed. The L1B radiance data in bands 5 and 6 (near infrared wavelength range) are corrected for the out of band straylight, but the correction scheme has not been fully validated. The pixels at the poles seem to be more sensitive to non-optimal straylight correction.

Saturation

Some TROPOMI pixels might be affected by saturation. Those pixels should be flagged and their quality is reflected in the `qa_value`. Nevertheless, in the vicinity of saturated pixels there might be pixels also affected by saturation due to the so-called blooming effect. The blooming effect will be addressed in a future L1B release. For those pixels, the ROCINN cloud parameters tend to be overestimated. In general, saturation is present over bright scenes (e.g. fully cloudy scenes with large optical depths).

Metadata values exchanged

The global attributes `geospatial_lon_min` and `geospatial_lon_max` values are exchanged; therefore, the user is advised to switch the values for these fields, making note that the `geospatial_lat_min` and `geospatial_lat_max` values are correct. This is an issue traceable to L1b data (version 01.00.00) and is corrected in the following versions of the Level 1B processor.

Wrong Sensing dates in metadata (solved)

Note that there is a non-systematic problem in the sensing dates around mid-night: the reported dates in the global attributes can be wrong by one day ahead. This issue is solved with the activation of version **01.01.01** mid-July 2018.

NRTI data gaps northern hemisphere (solved)

The NRTI data stream shows data gaps over Kazakhstan, southern part of Russia and Canada due to a miss-configuration of the processing facility This issue is solved with the activation of processor version **01.01.01** mid-July 2018.

Orbit numbering in NRTI and OFFL (solved)

Note that NRTI orbit numbers are set with respect to the downlink orbit while OFFL orbit numbers are set with respect to the equator crossing time. This creates an inconsistency between the NRTI and OFFL orbit numbers, which is removed with the activation of processor version **01.01.05** beginning December 2018.

Bug in `delta_time` variable (solved)

In version **01.01.01 (2018-07-18** until **2018-08-08**) the `delta_time` variable might be wrong. The error is usually in the range of less than a minute but in the worst case it might be up to 45 min. It is therefore recommended not to use the time variable.

5 Algorithm Change Record

For a detailed description of the L2__CLOUD_ algorithms, please refer to the ATBD [RD02] or to Loyola et al. (2018) [RD04].

6 Data Format

The product is stored as NetCDF4 file. The NetCDF4 file contains both the data and the metadata for the product.

For OFFL data the product is stored as a single file per satellite orbit, for NRTI data the product is stored as multiple files per orbit.

Please note that consecutive data granules of the NRTI product show an overlap of about 12 scan lines.

Details of the data format are provided in the Product User Manual (PUM) [RD03].

6.1 Data format changes

There are no changes to report.

7 Product Availability

All S5P/TROPOMI data are available on the Copernicus Open Data Hub https://scihub.copernicus.eu.

More information on this data product and data handling tools are available from the product web page under heading 'Tools': http://www.tropomi.eu/data-products.

For further questions regarding S5P/TROPOMI data products please contact EOSupport@Copernicus.esa.int.

The access and use of any Copernicus Sentinel data available through the Copernicus Sentinel Data Hub is governed by the Legal Notice on the use of Copernicus Sentinel Data and Service Information and is given here:

https://sentinels.copernicus.eu/documents/247904/690755/Sentinel_Data_Legal_Notice.

8 References

[RD01] Sentinel-5 Precursor Calibration and Validation Plan for the Operational Phase
source: ESA; **ref**: ESA-EOPG-CSCOP-PL-0073;
url: https://sentinel.esa.int/documents/247904/2474724/Sentinel-5P-Calibration-and-Validation-Plan.pdf

[RD02] Sentinel-5 precursor/TROPOMI Level 2 Algorithm Theoretical Basis Document Cloud
source: DLR; **ref**: S5P-L2-DLR-ATBD-400I;
url: https://sentinel.esa.int/documents/247904/2476257/Sentinel-5P-TROPOMI-ATBD-Clouds

[RD03] Sentinel-5 precursor/TROPOMI Level 2 Product User Manual Cloud
source: DLR; **ref**: S5P-L2-DLR-PUM-400I;
url: https://sentinel.esa.int/documents/247904/2474726/Sentinel-5P-Level-2-Product-User-Manual-Cloud

[RD04] Loyola, D. G., Gimeno García, S., Lutz, R., Argyrouli, A., Romahn, F., Spurr, R. J. D., Pedergnana, M., Doicu, A., Molina García, V., and Schüssler, O.: The operational cloud retrieval algorithms from TROPOMI on board Sentinel-5 Precursor, Atmos. Meas. Tech., 11, 409-427, https://doi.org/10.5194/amt-11-409-2018, 2018.

[RD05] Heidinger, Andrew K. and Pavolonis, Michael J.: Gazing at cirrus clouds for 25 years through a split window, part1: Methodology. Journal of Applied Meteorology and Climatology, Volume 48, Issue 6, pp.1100-1116, 2009.

[RD06] Platnick, S. et al.: The MODIS Cloud Optical and Microphysical Products: Collection 6 Updates and Examples From Terra and Aqua, Geoscience and Remote Sensing, IEEE Transactions on, 55(1), 502-525, doi:10.1109/TGRS.2016.2610522, 2016.

More information on this data product is available from the Sentinel product webpage:

https://sentinels.copernicus.eu/web/sentinel/technical-guides/sentinel-5p/products-algorithms,

and from the corresponding TROPOMI product webpage http://www.tropomi.eu/data-products.

Abbreviations and acronyms

ATBD	Algorithm Theoretical Basis Document
BIRA-IASB	Royal Belgian Institute for Space Aeronomy
CAL	Clouds As Layers
CF	Cloud Fraction (fractional cloud cover)
CLOUDNET	Cloud properties monitoring Network
COT	Cloud Optical thickness
CRB	Clouds as Reflecting Boundaries
CTH	Cloud Top Height
DLR	German Aerospace Center / Deutsches Zentrum für Luft- und Raumfahrt
DOI	Digital Object Identifier
EARLINET	European Aerosol Research Lidar Network
ESA	European Space Agency
ESL	Expert Support Laboratory
GOME(-2)	Global Ozone Monitoring Experiment(-2)
KNMI	Royal Netherlands Meteorological Institute
lidar	LIght Detection And Ranging
MPC	Mission Performance Centre
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NRTI	Near Real Time (timeliness of products)
OFFL	Offline (timeliness of products)
OMI	Ozone Monitoring Instrument
PRF	Product Readme File
PUM	Product User Manual
QWG	Quality Working Group
RCF	Radiometric Cloud Fraction
S5P	Sentinel-5 Precursor
S5PVT	Sentinel-5 Precursor Validation Team
Suomi NPP	Suomi National Polar-orbiting Partnership
TROPOMI	Tropospheric Monitoring Instrument
VDAF	Validation Data Analysis Facility
VIIRS	Visible Infrared Imaging Radiometer Suite