Algorithm Theoretical Basis Document (*ATBD*) for the ReOBS processing

ReOBS data sources, description, treatments,

quality check, merging, averaging, formating

ACTRIS-CCRES version

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Table of content

1 ACTRIS-CCRES context

The purpose of this document is to present the Algorithm Theoretical Basis Document (ATBD) for ReOBS processing, tailored to the ACTRIS-CCRES cloud expertise center. It starts with an overview of the ReOBS tool (https://ReOBS.aeris-data.fr/en/welcome/; Chiriaco et al., 2018) and its features for processing both 1D and 2D variables. Furthermore, the document details the processing workflows (data stream hereafter) for each ACTRIS-CCRES instrument or product, outlining the data considered, the quality control (QC) processes applied, and the nomenclature used. The Palaiseau station at the SIRTA Observatory (France) is used as an example throughout. If QC thresholds vary by site, these values are provided in an additional table for each data stream and site by site.

ACTRIS-CCRES Context with the Labeling Phase Step 1B for each National Facility (NF) validating the CCRES requirements: The tool enables monitoring of this labeling step, provides feedback to stations, and links the NFs to the CLU Data Center. With countries committing to ACTRIS-ERIC for at least 20 years, the benefit of having a multi-variable, high-quality dataset that is spatially and temporally homogeneous is a significant asset. This will enhance the use of ACTRIS data and the associated scientific studies.

2 ReOBS tool, methodology and algorithm

2.1 Introduction of ReOBS

To study and better understand regional climate variability, multi-decadal and multi-variable time series of measurements are now available from ground-based and satellite monitoring infrastructures. However, these long-term datasets remain difficult to use because they have not been harmonized, qualified, and formatted, consistently over time and space (https://doi.org/10.5281/zenodo.10925332).
Regional climate is influenced by large-scale atmospheric circulation and local processes, involving many variables, complex feedback, and a large range of spatial and temporal scales. The small magnitude of the signals that we are looking for, and connections between processes at local scales and anomalies at climate scale, add to this complexity. Datasets dedicated to study these regional climate issues must contain a large range of variables, observed over multiple years (or decades), yet including high temporal resolution (e.g. hourly), that have been reprocessed to remove trends and inaccurate measurements due to instrument failures, calibration problems, evolution of sensors or measurement methods.

To produce datasets suited for regional climate studies, a scientific and technical framework specifically dedicated for the reprocessing of long time series must be

developed. This framework can be applied to measurements collected at climate observatories (e.g. those facilities involved in ACTRIS). We call this framework ReOBS. It is designed to handle data from a large variety of sources, to provide a processing expertise that harmonizes the data over the whole time series, to include a high-level of quality control, to collect and provide all metadata necessary for the end users.

This approach is consistent with different international initiatives such as the COPERNICUS Climate Change Service (C3S) European project. It is also discussed in the framework of ACTRIS European project, and it has been identified as recommendation #12 by the WCRP climate symposium 2014.

This ATBD document presents the ReOBS processing applied to the data collected at the SIRTA atmospheric observatory. Here we focus only on the instruments used through the ACTRIS CCRES European cloud expertise center. Note that the treatments applied to the various data streams are valid from the year 2023, the year in which CCRES labelling step 1b started to be implemented. The ReOBS final dataset is proposed as a single NetCDF file in which all variables are provided with an hourly temporal resolution and quality control indices.

In this document, we present the analysis done for Cloudnet SIRTA observatory measurements. In figure 1, we can see most of the CCRES instruments included in the ReOBS processing.

Figure 1. Most of the CCRES instruments on the SIRTA site will be included in ReOBS processing. From left to right: IPSL CHM 15k lidar ceilometer, IPSL HATPRO-G5 scanning

microwave radiometer, and IPSL BASTA Doppler non-scanning cloud radar.

The technical specifications of the instruments are given in the table below:

Instrument	PID	Model
Doppler Cloud Radar	https://hdl.handle.net/21.12132/3.643b7b5b43814e6f	Meteomodem BASTA 95 GHz
Lidar Ceilometer	https://hdl.handle.net/21.12132/3.b14e15ec9c9b43fb	Lufft CHM15K
Microwave radiometer	https://hdl.handle.net/21.12132/3.770aaf228a974dd6	RPG HATPRO G5
Doppler Lidar	https://hdl.handle.net/21.12132/3.455010e11c0545ae	Vaisala WindCube WLS400S
Disdrometer	https://hdl.handle.net/21.12132/3.7e13f3f243854ae8	OTT Hydromet GmbH Parsivel2
Weather station	https://hdl.handle.net/21.12132/3.739041931dac4de5 https://hdl.handle.net/21.12132/3.bed07e5e8e1c44e1 https://hdl.handle.net/21.12132/3.32440f7a40784873 https://hdl.handle.net/21.12132/3.d2ded6bad88e47a4 https://hdl.handle.net/21.12132/3.f7c9957b2a154054 https://hdl.handle.net/21.12132/3.5a665b04e96547f6	Tipping bucket rain gauge (3070A), cup anometer (A100R), windvane (W200P), temperature sensor (PT100), relative humidity sensor (HMP110), barometer (PTB330)

	https://hdl.handle.net/21.12132/3.3a1bc8952cf04a72	

Table 1. List of instruments, Persistent Identifiers (PIDs), and models used by the Palaiseau instrumented site and the SIRTA observatory through ACTRIS-CCRES.

2.2 ReOBS quality check: methodology and thresholds

The SIRTA ACTRIS-CCRES ReOBS dataset, which spans several years, is contained in a single netCDF file containing the mean values of several dozen variables listed in this document. The short and standard names used for each variable in the ReOBS dataset and the units try to follow as much as possible the Climate Forecast (CF) conventions, when available.

For each 1D-variable, the mean values (over a time range t) are calculated from the native resolution data (ranging from 5 seconds to 1 minute or other irregular temporal resolutions) by averaging all available data within a left-aligned window (e.g., for an hourly mean at 14:00, all data between 14:00 and 14:59 are included). Note the code allows flexibility in choosing the alignment of the averaging window: left, right, or centered. Each mean variable can be completed by its intra-time range standard deviation, median, inter-quartiles, maximum or even minimum value. The time-range standard deviation (SD) of each variable helps in detecting non-physical spikes (i.e., successive increase and decrease) and dips (i.e., successive decrease and increase in the signal). This temporal variability information is also useful to document large changes in the atmospheric conditions such as a cold front for air temperature.

Variables entering the ReOBS dataset are quality controlled at their native time resolution. We define two levels of quality check:
1. **Simple informative quality flags that consist in adding a comment for each type of data** ;
   a. *Data Quality Flag (DQF)*
      i. **DQF**=0 : automatic check done & manual check done
      ii. **DQF**=1 : automatic check done
   b. *Instrument Quality Flag (IQF)*
      i. **IQF** = 0 means that the instrument complies with the international standard (sensor and set-up) ;
      ii. **IQF**= 1 means that the instrument does not complies with the international standard (sensor or/and set-up) ;

iii. **IQF= 2** means that the instrument cannot be used (sensor or/and set-up problem) and we fix value to NaN ;

This comment will have a special structure to be able to automatically analyze these flags (DQF and IQF): *start date, end start, DQF; start date, end date, IQF*

1. **Quality control tests to remove the inaccurate/non-physical data** :
    i. A first quality control test, **QC1**, consists in verifying that the variable lies within physical bounds (min and max acceptable values). This quality check is applied to all variables.
    ii. A second quality control test, **QC2**, consists in verifying that the variables have a minimum of variability during a specific time extent (15, 30 or 60min for example) which makes sense for each variable being checked. This quality check is not applied to high variability variables such as rain rate or liquid water path.
    iii. A third quality control test, **QC3**, consists in verifying that the variability of each variable is not too large (spikes) compared to a **climatological** hourly standard-deviation. And QC3 is defined by $\alpha + \beta * \gamma$ with :
        a) α the median value of the hourly standard deviation of each variable ;
        b) γ the standard deviation of the standard deviation of each variable ;
        c) For this processing we can modify the number of standard deviations, named here β, and the temporal window (named here Δ) used as reference to compare this instantaneous value at t+1 with the previous moving median between t-Δmin and t.
    iv. A fourth quality control test, QC4, consists in verifying that the variability of each variable is not too large (local spikes) compared to a dynamical hourly standard-deviation (rolling std).
    v. A fifth quality control test, QC5, consists in verifying that the average value is based on a minimum valid amount of points, after all the previous quality checks have been applied, compared to the total number of points within the time range considered. This percentage of valid points needed to accept the final computed value depends on each variable but is set to 50% by default.
    vi. A sixth quality control test, QC6, consists in directly using flags available in level 1 or 2 output products.

If any of the first four **QC**s and **QC6** are not successful, the checked value at its native time resolution is set to NaN. If the number of such quality-checked valid points within the averaging time extent is less than the minimum number of points required by **QC5** (50% of points by default), then the final mean value is set to NaN.

2.3 ReOBS processing for 2D variables

2.3.1 Vertical grid

The processing of the 2D variables requires a vertical grid that will be the same for all the profilers installed on the different sites.

For ReOBS processing we consider the following resolution and range until 20km agl :

- Between surface and 100m agl : resolution of **20m** ;
- Between 100 and 1000m agl : resolution of **50m** ;
- Between 1000 and 3000m agl : resolution of **100m** ;
- Between 3000 and 20000m agl : resolution of **250m** ;

The total number of points is 111 between surface and 20km agl. The following figure shows the ReOBS vertical grid compared to the French operational numerical weather prediction AROME and ARPEGE models.
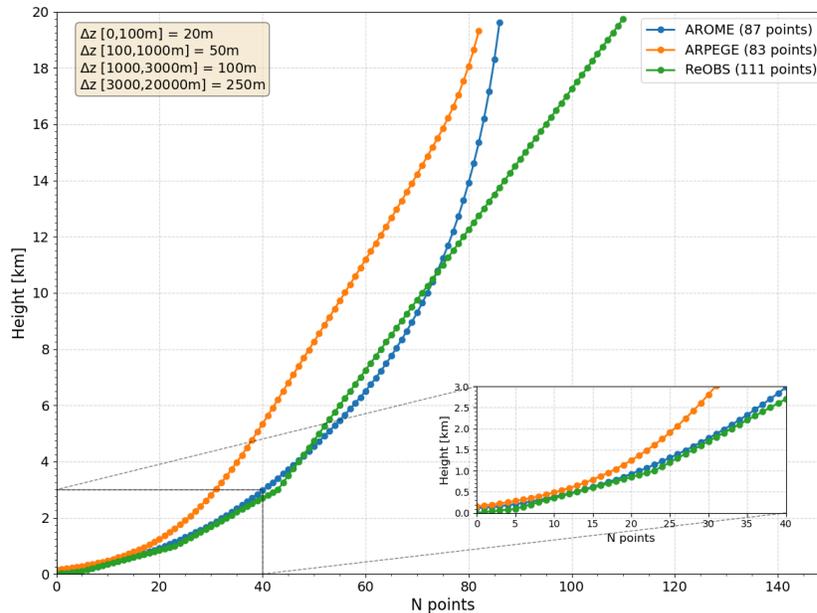

Figure 2. ReOBS vertical grid compared to AROME and ARPEGE models

2.3.2 Profiling method

For ReOBS processing of the 2D variables, three methods of profiling can be used :

1. Method 1 : Sampling.
2. Method 2 : Averaging
3. Method 3 : Interpolating

The three methods account for the measurements inside a temporal and vertical box. When it is possible, we prefer having the best temporal resolution when the quality check is done.

For method 1 (i.e sampling method), we consider only the measurement closest to the middle of the box.

For the method 2 (i.e averaging method), we consider all the measurements inside the box where (1) the center corresponds to the vertical grid point, (2) the bottom corresponds to the vertical grid point, and (3) the top corresponds to the vertical grid point.

The method 3 (i.e interpolating method), is not available (date 01/02/2022) for ReOBS processing. It consists to interpolate data to each vertical grid point, for example when the native measurement has a coarse vertical resolution compared to the ReOBS vertical grid.
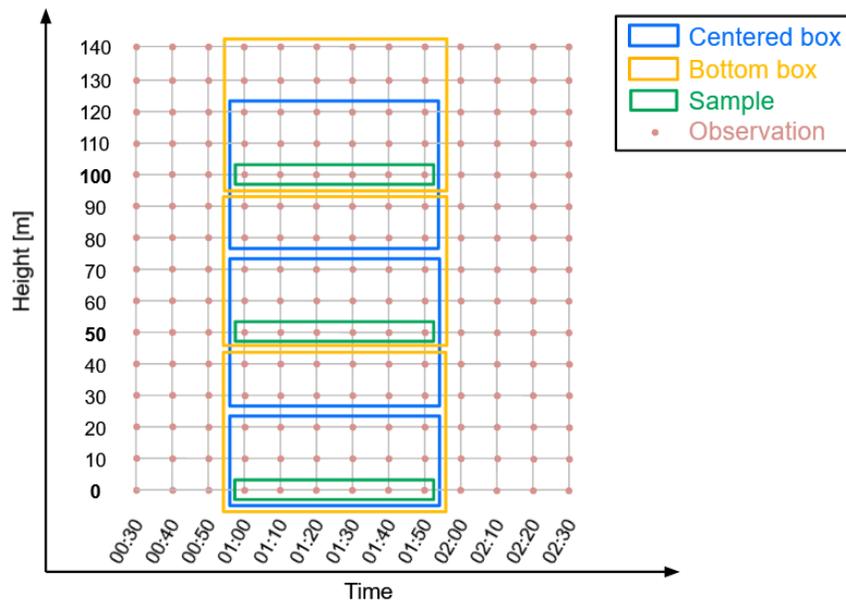
Figure 3. Profiling method used for ReOBS processing

2.3.3 Comparison of profiling method for CHM15K

We have compared the different methods that can be used for ReOBS processing using (1) sampling and (2) centered box (used by default in the rest of the document). The figure 4 shows the monthly mean value of the ReOBS output file processing for CHM15K ceilometer: each line corresponds to the backscatter signal value (average, median, standard deviation, maximum and minimum), the two first columns correspond to each method (sample and centered box) and the third column is the relative difference between the two methods.

10
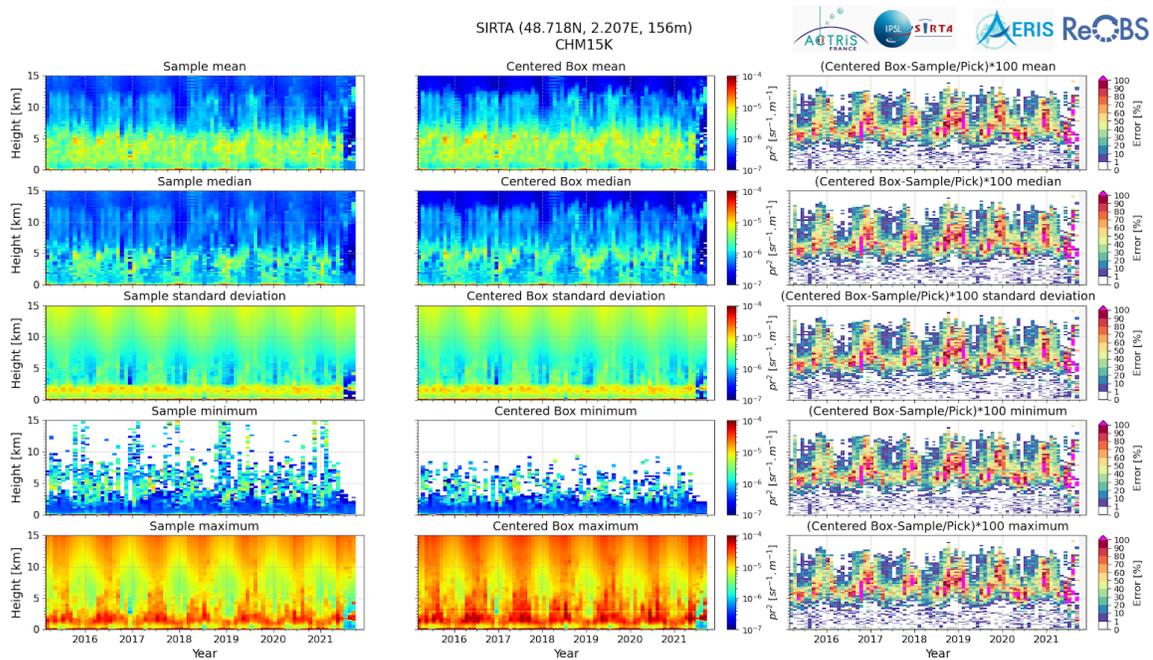
Figure 4. Time series of CHM15K ReOBS processing between 2015 and 2021 for two methods (sample and centered box) and for five values of backscatter signal provided by ReOBS processing (average, median, standard deviation, minimum, and maximum).

2.4 ReOBS general processing chain

The new architecture of the production chain of the ReOBS project was defined on the basis of a few principles which aim to facilitate the readability, maintenance and evolution of the codes, but also to be a scalable tool that is flexible to easily integrate new functionalities and thus adapt to new situations.

These principles are implemented by modular developments dedicated to a well-defined task of limited scope.

This resulted in:

- Separate management of information related to the working environment (location of databases, name of files, etc.) and information related to processing provided by the data streams. The former are used by a supervisory code whose role is to control all aspects of production. The second are used for the parameterization of the data streams;
- Limitation to two languages, **bash** for aspects related to the environment, ie to the operating system (cluster), to local or remote databases, etc., and **python** for the codes of the data streams;

11

- Systematic use of **configuration files** to configure the most generic possible codes and allow the behavior of a code to be quickly adapted without rewriting it.
- A design pattern based on **4 modules** to facilitate understanding, maintenance and establishment of new data streams.

The result is a ReOBS production chain whose construction is based on a supervision script and 4 simple and configurable modules which together make it possible to build the data streams. These data streams can themselves be combined to develop more complex ones while keeping the reliability of the main modules.
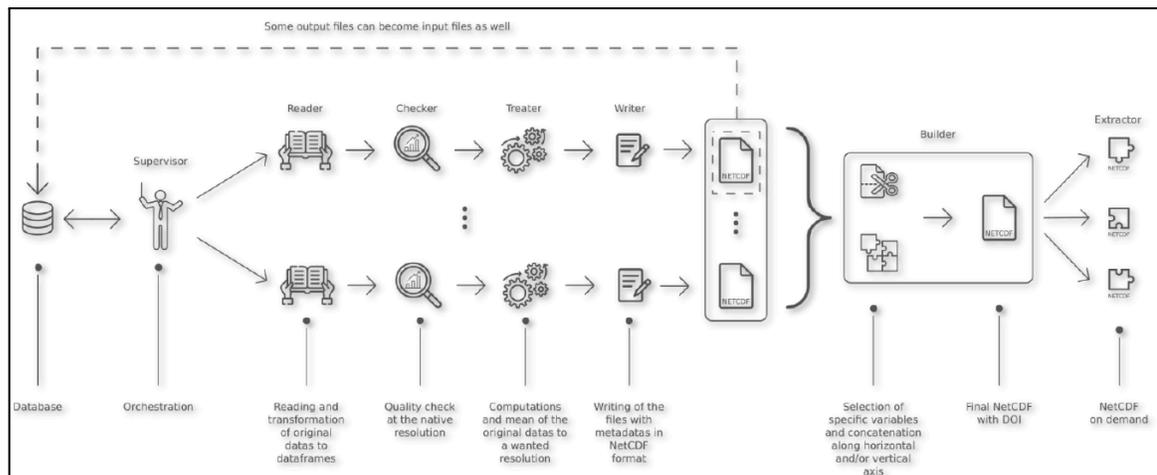
Figure 5. ReOBS processing chain

2.4.1 Specifications of the database

Any well-structured text file (csv-like) or NetCDF file is readable as a database source file for the ReOBS processing chain. Ideally, all the files for a given ReOBS data stream should have the same structure and format throughout the whole time series. Metadatas within the source files are recommended in order to be able to correctly read and interpret the information provided by the database. If such metadatas are not provided, a document explaining the content of the dataset is required. Extra documents providing further details on the construction of the database (concerning the sensor itself or the way the measurements were performed) to be used for a data stream are welcomed/required in order to take full advantage of all the available information.

In fact, the ReOBS production system is not intended to solve the problems that may be encountered in native databases. They must follow some conditions to be able to be used by ReOBS, such as :
- Timestamp in Universal Time for each measurement and uniformly increasing (not redundant)

- Documentation of the various measurements present in the files (header, metadata)
- Instrument set-up modifications (place, obstacle, configuration)
- Instrument change (rotation, calibration)
- etc.

The objective of ReOBS is also to respect the FAIR principles (Findable, Accessible, Interoperable, Reusable) in particular the Reusable aspect which is more obvious for a production chain. The respect of these principles impose rules of good management of the databases which will be used to inside the ReOBS system. The datasets will be permanent, identified by digital signature or versioning, accessible. It is the responsibility of the data providers, data center or measurement site, to put ensure the tools that will guarantee the quality of the databases to ensure the reliability of ReOBS reference (DOI).

2.4.2 Supervisor

The whole processing chain to create or update a ReOBS file from a set of source files corresponding to a site database is managed by what we call the supervisor. The supervisor is the master bash script of the whole architecture which will launch all the calculations needed to build the desired output ReOBS file. The way it works is rather complex but its main task is to retrieve all the paths for a given period of time and call all the data streams to be executed in order to produce the ReOBS output file with all the needed information. This master script relies on the well-structured data streams which are all built the same way in order to standardize the data processing and make it simple when a new data stream has to be created or updated.

2.4.3 Data stream processing

All data streams consist of the same four Python scripts and a configuration file (.cfg). These four scripts always have the same names for all data streams, and they are executed one after the other having each of them a specific task to accomplish in the data processing. The first script reads the source file data (read.py), the second script check the quality of the data at its native resolution (check.py), the third script performs all the calculations needed to compute the output data (treat.py), and the fourth and last script writes the data and the associated metadata in the data stream output NetCDF file (write.py). These four scripts get all the information they need in order to perform their task from the configuration file called "datastream.cfg". Hereafter we briefly describe what is performed by each of the four Python scripts.

- **Reading script: read.py**

The role of this script is only to read the data from the source files, and possibly to modify the names of these read variables. This script must be adapted to the source

files when creating a new data stream, but this adaptation is quick for any NetCDF or well-structured text (csv-like) source file.

- **Quality check script: check.py**

In this script are defined all the quality control algorithms that will be applied to the source data at their original temporal resolution. This is done in order to get rid of all the time series values that do not meet the quality criteria in terms of possible physical values and/or lack of realistic variability and/or noisy or non-physical variability. Values that are considered as not valid by these quality checks are set to NaN.

- **Treatment/calculation script: treat.py**

This script contains all the algorithms in order to perform the calculations to be carried out on the source data having passed the quality checks. By default, the computation which is always done, and which also represents the last quality control check, is the calculation of the average / median / cumulative value over a defined period of time (one hour by default). This final value is considered valid if at least a user-defined percentage (50% by default) of the values measured in the hour extent considered have passed all previous quality checks.

- **Output data writing script: write.py**

This last script writes in NetCDF format, adding all the associated metadata, the calculated data having passed all the quality checks, including that of a minimum required number of valid measurements in the hour (50% by default) applied in the previous treatment script.

- **Configuration file: datastream.cfg**

All data streams have a configuration file. The configuration file is structured into sections, in which each script of the data stream will read the information it needs to perform its task. Most of the changes to bring to the code when creating a new data stream occur in this file. For example, in the "[read]" section, you will find the variable/entry "selected_var_name", which contains the names of all the variables that have to be read from the source files. You can also find in that section, depending on the source files, the number of the columns to be read in a csv-like file, if the source file does not contain the appropriate names over the data columns to be read for example. The structure of this file is today sufficiently robust to meet the standard needs of ReOBS, but improvements are possible provided they keep the spirit of simplicity, readability and genericity specific to the structure that was built around the four scripts that make up all the data streams.

▪ **Builder**

In order to provide a single final NetCDF from the multiple data streams' outputs, an additional operation is required. In this step, multiple concatenations and selections are executed. Some of the data streams' output can have more variables than the final wanted file, so they have to be picked up. Also, concatenation can be performed along two axis. The first one is a horizontal one in which we add up the variables alongside the others in the dataset. The other one is a vertical one in which some variables with the same name but from different locations are added one below the other over the time axis.

▪ **Extractor**

After the creation of the final NetCDF, part of it can be extracted in order to be shared and distributed easily. Such extractions have the benefit to preserve the Digital Object Identifier (DOI).

2.5 ReOBS groups, output-files and variables

ReOBS processing is organized into different dataframes or datasets, and groups of variables are proposed to merge some types of variables / instruments. The Cloudnet products used in ACTRIS CCRES are presented in section 2.

For each 1D-data, ReOBS processing can produce by default:

- The **average value** of each native variable during the 1-hour temporal step;
- The **median value** of each native variable during the 1-hour temporal step;
- The **maximum value** of each native variable during the 1-hour temporal step;
- The **minimum value** of each native variable during the 1-hour temporal step;
- The **standard deviation** of each native variable during the 1-hour temporal step;
- The **number of correct data** (QC_{1-4} OK) used to process each value (average, min and max) ;

For each 2D-data, ReOBS processing can produce by default:

- The **average value** of each native variable during the 1-hour temporal step for a vertical grid defined in 1.3.1 ;
- The **median value** of each native variable during the 1-hour temporal step for a vertical grid defined in 1.3.1;
- The **maximum value** of each native variable during the 1-hour temporal step for a vertical grid defined in 1.3.1;

- The **minimum value** of each native variable during the 1-hour temporal step for a vertical grid defined in 1.3.1;
- The **standard deviation** of each native variable during the 1-hour temporal step for a vertical grid defined in 1.3.1;
- The **number of correct data** used to process each value (average, min and max) ;

Two ReOBS output-files are proposed:

- **ReOBS intermediate file**: this ReOBS file is processed for each dataframe/dataset and contains, by default, the mean value and standard deviation of each variable, the maximum, minimum, median, quartiles and the number of data used for this processing. By default, we apply QC1 to QC6 as shown in the following tables and the temporal time stamp is one hour.
- **ReOBS standard file**: this ReOBS file is processed starting from the ReOBS full output-file to produce a final file with by default the average value at 1 hour temporal resolution and the use of QC1 to QC6. This ReOBS standard file will be identified with a Digital Object Identifier.
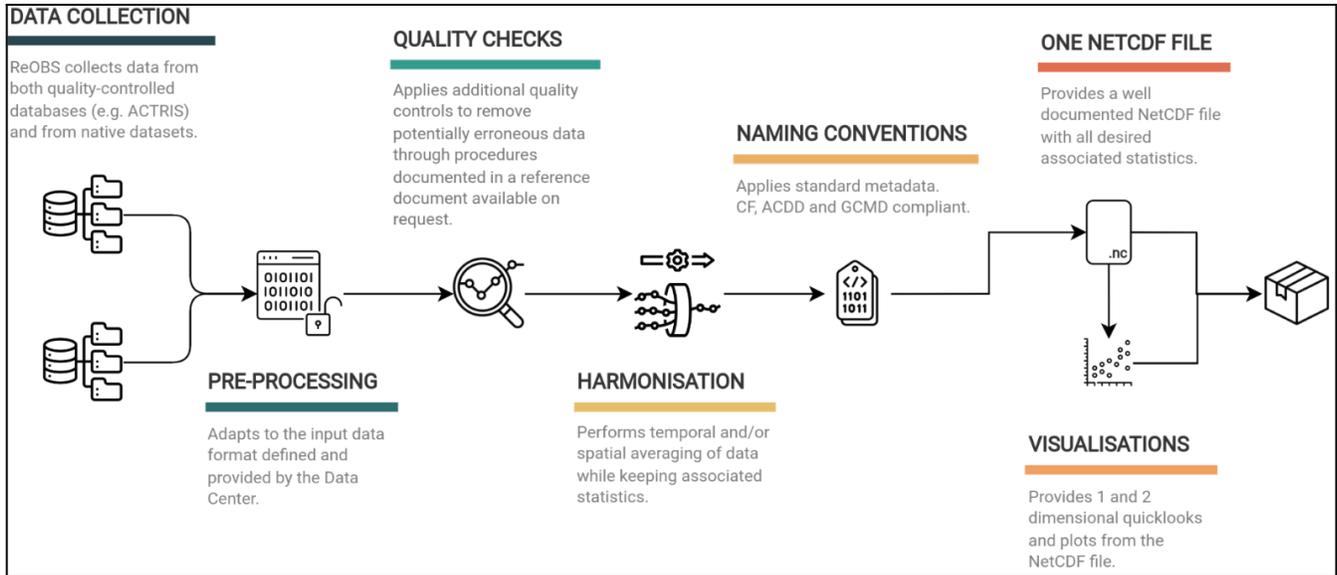
Figure 6. ReOBS : a new approach to synthetize long term multi-variable dataset

3 CLOUDNET products used by ACTRIS-CCRES

Cloudnet-Py algorithm (Tukiainen et al., 2020) products are available on the Cloudnet Data Portal : https://docs.cloudnet.fmi.fi/api/data-portal.html.

Cloudnet Data Portal provides data processing and curation service of ground-based cloud remote sensing measurements. This includes centralized processing, quality control, provenance, data harmonization and archiving. Level 1b, level 1c, and level 2 data are available.

- Level 1b data corresponds to direct measurement of the automatic lidar, cloud radar and microwave-radiometer.
- Level 1c data corresponds to more advanced products such as target categorization.
- Level 2 data corresponds to the most advanced products such as Liquid Water Content (LWC), Ice Water Content (IWC), Drizzle properties, and cloud classification.

It should be noted that Cloudnet internally uses quality controls (particularly min/max limits) for most of the processed variables (https://github.com/actris-cloudnet/cloudnetpy-qc/). These quality controls are applied and are the subject of a quality report associated with each file, which is available on their website (example for Doppler Cloud Radar BASTA at SIRTA Observatory https://cloudnet.fmi.fi/file/df7bc199-c98b-4cd3-8a05-40a23f0fb37d/quality). However, these quality controls neither delete any data in the output files/products nor produce

quality flags. In contrast, the quality controls used in ReOBS remove data (i.e., replace values with NaN) if the conditions are not met (based on QCs).

Please note that the following QCs and flags are given as a guide for the Palaiseau site at the SIRTA observatory (48.718N, 2.207E, 156m) and the related instruments presented in Table 1. It can be adapted according to location (site), instruments, wavelengths, or even the scanning mode used, respectively.

3.1 Categorize

This variable contains information on the nature of the targets at each pixel, thereby facilitating the application of algorithms that work with only one type of target. The information is in the form of an array of bits, each of which states either whether a certain type of particle is present (e.g. aerosols), or the whether some of the target particles have a particular property. The definitions of each bit are given in the definition attribute corresponding to the variable named *target_cat*. Bit 0 is the least significant.

- Bit 0: Small liquid droplets are present.
- Bit 1: Falling hydrometeors are present; if Bit 2 is set then these are most likely ice particles, otherwise they are drizzle or rain drops.
- Bit 2: Wet-bulb temperature is less than 0 degrees C, implying the phase of Bit-1 particles.
- Bit 3: Melting ice particles are present.
- Bit 4: Aerosol particles are present and visible to the lidar.
- Bit 5: Insects are present and visible to the radar.

And the *target quality* variable contains information on the quality of the data at each pixel. The information is in the form of an array of bits, and the definitions of each bit are given in the definition attribute. Bit 0 is the least significant.

- Bit 0: An echo is detected by the radar.
- Bit 1: An echo is detected by the lidar.
- Bit 2: The apparent echo detected by the radar is ground clutter or some other non-atmospheric artifact.
- Bit 3: The lidar echo is due to clear-air molecular scattering.
- Bit 4: Liquid water cloud, rainfall or melting ice below this pixel will have caused radar and lidar attenuation; if bit 5 is set then a correction for the radar attenuation has been performed; otherwise do not trust the absolute values of reflectivity factor. No correction is performed for lidar attenuation.

- Bit 5: Radar reflectivity has been corrected for liquid-water attenuation using the microwave radiometer measurements of liquid water path and the lidar estimation of the location of liquid water cloud; be aware that errors in reflectivity may result.

In the final ReOBS file, we have the following categorization products:

Short_name	Long_name	Unit	Comment / Variables
target_cat_most_frequent_cl	The most frequent target category	/	Keep: the most frequent target category. Occurrence of *target_cat1* Quality control : only for target_quality bit 0 & 1
target_cat_second_most_frequent_cl	The 2nd most frequent target category	/	Keep: the 2nd most frequent target category. Occurrence of *target_cat2* Quality control : only for target_quality bit 0 & 1

Table 2. ReOBS product for cloudnet categorization level 1c cloudnet file

3.2 Classification

The Cloudnet classification scheme is based on methodology proposed by Hogan R. and O'Connor E. (2004), and its proprietary Matlab implementation. Some individual classification methods are changed in this Python implementation compared to the original Cloudnet methodology. Especially methods classifying insects, melting layer and liquid droplets.

The following variables provide the main atmospheric target classifications that can be distinguished by radar and lidar.

- Value 0: Clear sky.
- Value 1: Cloud liquid droplets only.
- Value 2: Drizzle or rain.
- Value 3: Drizzle or rain coexisting with cloud liquid droplets.
- Value 4: Ice particles.
- Value 5: Ice coexisting with supercooled liquid droplets.
- Value 6: Melting ice particles.

- Value 7: Melting ice particles coexisting with cloud liquid droplets.
- Value 8: Aerosol particles, no cloud or precipitation.
- Value 9: Insects, no cloud or precipitation.
- Value 10: Aerosol coexisting with insects, no cloud or precipitation

Moreover, cloud base height and cloud top height are derived with cloudnet-py algorithm.

And a *target status* is defined to report on the reliability of the radar and lidar data used to perform the classification.

- Value 0: Clear sky.
- Value 1: Lidar echo only.
- Value 2: Radar echo but reflectivity may be unreliable as attenuation by rain, melting ice or liquid cloud has not been corrected.
- Value 3: Good radar and lidar echos.
- Value 4: No radar echo but rain or liquid cloud beneath mean that attenuation that would be experienced is unknown.
- Value 5: Good radar echo only.
- Value 6: No radar echo but known attenuation.
- Value 7: Radar echo corrected for liquid attenuation using microwave radiometer data.
- Value 8: Radar ground clutter.
- Value 9: Lidar clear-air molecular scattering.

In the final ReOBS file, we have the following classification products:

Short_name	Long_name	Unit	Comment / Variables
cbh_cl	Height of cloud base above ground level	m	Keep: min, max, mean, median, q25, q75, % occ.
cth_cl	Height of cloud top above ground level	m	Keep: min, max, mean, median, q25, q75, % occ.
target_class_most_frequent_cl	The most frequent target classification	/	Keep: the most frequent target classification.

			Occurrence of *target_class1*
target_class_second_most_frequent_cl	The 2nd most frequent target classification	/	The 2nd most frequent target classification. Occurrence of *target_class2*

Table 3. ReOBS product for cloudnet classification level 2 cloudnet file

3.3 Disdrometer

Quality flag considered for all disdrometer variables:

- State sensor = 0 (0 = OK, 1 = Dirty, 2 = No measurement possible)
- V_power_supply = [10, 28]
- Sig_laser = [1e4, 1e6]

For ReOBS file, we consider the following variables:

Short_name	Long_name	Unit	Comment / Variables
pr_dd	Rainfall rate	m.s^{-1}	Keep: sum + min + max
sr_dd (if recorded)	Snowfall rate	m.s^{-1}	Keep: sum + min + max
n_dd	Number of particles in time interval	1	Keep: sum + min + max
zh_dd	Equivalent radar reflectivity factor	dBZ	Keep: mean + std + number of used data
raw_dd	Raw data as a function of particle diameter and velocity	1	Keep: mean + std + number of used data

Table 4. ReOBS product for disdrometer level 1b cloudnet file

3.4 Doppler Wind Lidar

3.4.1 Doppler Lidar Wind

The Doppler lidar wind product provides wind profiles derived from Doppler wind lidar (DWL) scans.

For ReOBS file, we consider the following variables:

Short_name	Long_name	Unit	Comment / Variables
uwind_dwl	Zonal wind	$m.s^{-1}$	Keep: mean + std + number of used data
vwind_dwl	Meridional wind	$m.s^{-1}$	Keep: mean + std + number of used data

Table 5: ReOBS product for Doppler lidar Wind cloudnet file

3.4.2 Doppler Lidar

The Doppler lidar product provides attenuated backscatter coefficient and Doppler velocity profiles measured by a vertical-pointing Doppler wind lidar (DWL).

For ReOBS file, we consider the following variables:

Short_name	Long_name	Unit	Comment / Variables
bck_dwl	Attenuated backscatter coefficient	$sr^{-1}.m^{-1}$	Keep: Median + 25% + 75% + number of used data Beta_min threshold = 10^{-8} $sr^{-1}.m^{-1}$, Beta_max threshold = 10^{-2} $sr^{-1}.m^{-1}$,
v_dwl	Doppler velocity	$m.s^{-1}$	Keep: mean + std + number of used data

Table 6: ReOBS product for Doppler lidar cloudnet file

3.4.3 Dissipation rate of TKE

Turbulent kinetic energy (TKE) dissipation rate is estimated using the variance of vertical Doppler velocity and horizontal wind speed measured by a Doppler wind lidar (DWL).

For ReOBS file, we consider the following variables:

Short_name	Long_name	Unit	Comment / Variables
epislon_dwl	Dissipation rate of turbulent kinetic energy	$m^2.s^{-3}$	Keep: mean + std + number of used data

Table 7: ReOBS product for dissipation rate of TKE (lidar) cloudnet file

3.5 Droplet Effective Radius (Der)

Liquid droplet effective radius is derived using the method of Frisch et al. (2002), based on the attenuation-corrected radar reflectivity and liquid water path.

The droplet effective radius product is based on these products: categorize.

The droplet effective radius retrieval status is also included in the file and is defined as follows:

- Value 0: No data: No cloud observed.
- Value 1: Reliable retrieval.
- Value 2: Mix of drops and ice: Droplets and ice crystals coexist within pixel. Z may be biased by large crystals.
- Value 3: Precipitation in profile: Drizzle and rain affects LWP retrieval of MWR but also the target reflectivity.
- Value 4: Surrounding ice: Less crucial! Ice crystals in the vicinity of a droplet pixel may also bias its reflectivity.

For ReOBS file, we consider:

Short_name	Long_name	Unit	Comment / Variables

n_scaled	Cloud droplet number concentration	1	Keep: mean + std + number of used data Quality control : der_retrieval_status values (0, 1, 2)
der	Droplet effective radius	m	Keep: mean + std + number of used data Quality control : der_retrieval_status values (0, 1, 2)
der_error	Absolute error in droplet effective radius	m	Keep: mean + std + number of used data Quality control : der_retrieval_status values (0, 1, 2)
der_retrieval _status_mos t_frequent	Most frequent droplet effective radius retrieval status	1	Keep: the most frequent der retrieval status Quality control : der_retrieval_status values (0, 1, 2)
der_retrieval _status_seco nd_most_fre quent	Second most frequent droplet effective radius retrieval status	1	Keep: the second most frequent der retrieval status Quality control : der_retrieval_status values (0, 1, 2)

Table 8. ReOBS product for Der properties level 2 cloudnet file

3.6 Drizzle properties

Drizzle properties are derived from cloud radar and lidar measurement (O'Connor et al., 2005).

The function that calculates liquid droplet effective radius (def) uses the Frisch method. In this method, *def* is calculated from radar reflectivity factor and microwave radiometer liquid water path.

The function that calculates ice particle effective radius uses the Grieche et al. 2020 method which uses Hogan et al. 2006 to estimate ice water content and alpha from Delanoë et al. 2007. In this method, effective radius of ice particles is calculated from attenuated-corrected radar reflectivity and model temperature.

For ReOBS file, we consider:

Short_name	Long_name	Unit	Comment / Variables
Do_cl	Drizzle median diameter	m	Keep: mean + std + number of used data Do_min threshold = 0m Do_max threshold =0.01 m
mu_cl	Drizzle droplet size distribution shape parameter	/	/
drizzle_N_c	Drizzle number concentration	m^{-3}	Keep: mean + std + number of used data drizzle_N_min threshold = 0 # m^{-3} drizzle_N_max threshold = 10^9 # m^{-3}
drizzle_lwc_cl	Drizzle liquid water content	$kg.m^{-3}$	Keep: mean + std + number of used data drizzle_lwc_min threshold = 0 $kg.m^{-3}$ drizzle_lwc_max threshold = 0.006 $kg.m^{-3}$
v_drizzle_cl	Drizzle droplet fall velocity	$m.s^{-1}$	Positive values are towards the ground Keep: mean + std + number of used data v_drizzle_min threshold = -5 $m.s^{-1}$ v_drizzle_max threshold = 0 $m.s^{-1}$
v_air_cl	Vertical air velocity	$m.s^{-1}$	Positive values are towards the sky Keep: mean + std + number of used data v_air_min threshold = -5 $m.s^{-1}$ v_air_max threshold = +10 $m.s^{-1}$

Table 9. ReOBS product for Drizzle properties level 2 cloudnet file

3.7 Ice effective radius (Ier)

The ice particle effective radius is derived from attenuation-corrected radar reflectivity and model temperature using the method of Grieche et al. (2020), which incorporates the approach of Hogan et al. (2006) to estimate ice water content and uses the parameterization of alpha from Delanoë et al. (2007).

The ice effective radius product is based on these products: categorize.

The ice effective radius retrieval status is also included in the file and is defined as follows:

- Value 0: No ice present.
- Value 1: Reliebale retrieval.
- Value 2: Unreliable retrieval due to uncorrected liquid, rain or melting attenuation.
- Value 3: Retrieval performed with radar corrected for liquid, rain, and melting attenuation.
- Value 4: Ice detected only by the lidar.
- Value 5: Uncorrected rain attenuation (deprecated).
- Value 6: Clear sky above rain and wet-bulb temperature less than 0 deg C: if rain attenuation is strong, ice could be present but undetected.
- Value 7: Drizzle or rain that would have been classified as ice if the wet-bulb temperature were less than 0degC: may be ice if temperature is in error.

For ReOBS file, we consider:

Short_name	Long_name	Unit	Comment / Variables
ier	Ice Effective Radius	m	Keep: mean value + std + number of used data lwc_min threshold = 0 kg m-3 lwc_max threshold = 0.002 kg m-3 Quality control : only for iwc_status (0, 1, 3, 4)
ier_error	Random error in ice effective radius	m	Keep: mean value + std + number of used data

ier_retrieval _status_mos t_frequent	Most frequent ice effective radius retrieval status	1	Keep: the most frequent der retrieval status
ier_retrieval _status_seco nd_most_fre quent	Second most frequent ice effective radius retrieval status	1	Keep: the second most frequent der retrieval status

Table 10. ReOBS product for Ice Effective radius level 2 cloudnet file

3.8 Ice Water Content (IWC)

This variable was calculated for the profiles where the categorization data has diagnosed that liquid water is present and liquid water path is available from a coincident microwave radiometer. The model temperature and pressure were used to estimate the theoretical adiabatic liquid water content gradient for each cloud base and the adiabatic liquid water content is then scaled that its integral matches the radiometer measurement so that the liquid water content now follows a quasi-adiabatic profile.

The function that calculates ice water content uses the so-called Z-T method. In this method, ice water content is calculated from attenuated-corrected radar reflectivity and model temperature (Hogan et al., 2006).

And one *IWC retrieval status* describes the quality of the *IWC* product in the form of 8 different classes.

- Value 0: No ice present.
- Value 1: Reliable retrieval.
- Value 2: Unreliable retrieval due to uncorrected attenuation from liquid water below the ice (no liquid water path measurement available).
- Value 3: Retrieval performed but radar corrected for liquid attenuation using radiometer liquid water path which is not always accurate.
- Value 4: Ice detected only by the lidar.

- Value 5: Ice detected by radar but rain below so no retrieval performed due to very uncertain attenuation.
- Value 6: Clear sky above rain and wet-bulb temperature less than 0degC: if rain attenuation is strong, ice could be present but undetected.
- Value 7: Drizzle or rain that would have been classified as ice if the wet-bulb temperature were less than 0 deg C: may be ice if temperature is in error

For ReOBS file, we consider:

Short_name	Long_name	Unit	Comment / Variables
iwc_cl	Ice Water Content	kg.m^{-3}	Keep: mean value + std + number of used data lwc_min threshold = 0 kg m-3 lwc_max threshold = 0.002 kg m-3 Quality control : only for iwc_status (0, 1, 3, 4)

Table 11. ReOBS product for Ice Water Content level 2 cloudnet file

3.9 Automatic lidar and Ceilometer data

The lidar product provides attenuated backscatter coefficient profiles from automatic low-power lidars and ceilometers (ALC). The data are corrected for tilt angle and screened for background noise and saturation caused by conditions like fog. However, absolute calibration of the instruments is not performed, so the data should not be used to derive quantitative aerosol properties.

For ReOBS file, we consider the following variables:

Short_name	Long_name	Unit	Comment / Variables
bck_smooth_alc	Attenuated backscatter coefficient	sr^{-1}.m^{-1}	Keep: Median + 25% + 75% + number of used data SNR-screened attenuated backscatter coefficient. Weak background smoothed using Gaussian 2D-kernel. SNR threshold applied: 5.

| | | | Beta_smooth_min threshold = 10^{-8} $sr^{-1}.m^{-1}$, |
| | | | Beta_smooth_max threshold = 10^{-2} $sr^{-1}.m^{-1}$, |

Table 12. ReOBS product for automatic lidar ceilometer level 1b cloudnet file

3.10 Liquid Water Content (LWC)

This variable was calculated from the 94-GHz radar reflectivity factor after correction for gaseous attenuation, and temperature taken from a forecast model. LWC is processed when "categorization" data has diagnosed that the radar echo is due to ice, but note that in some cases supercooled drizzle will erroneously be identified as ice. Missing data indicates either that ice cloud was present but it was only detected by the lidar so its ice water content could not be estimated, or that there was rain below the ice associated with uncertain attenuation of the reflectivities in the ice.

The function that calculates cloud liquid water content uses the so-called adiabatic-scaled method. In this method, liquid water content measured by microwave radiometer is used to constrain the theoretical liquid water content of observed liquid clouds (Illingworth et al., 2007).

And one *LWC retrieval status* describes the quality of the *LWC* product in the form of 6 different classes. The classes are defined in the definition attribute.

- Value = 1: both radar and lidar detect the liquid layer, and
- microwave radiometer data is present;
- Value = 2: microwave radiometer data is used to adjust the cloud depth when the radar does not detect the liquid layer
- Value = 3: cloud pixels that have been added at cloud top to avoid the profile becoming super-adiabatic
- Value = 4: microwave radiometer data were not available or not reliable (melting level present or unphysical values) but the liquid layers were well defined
- Value = 5: cloud top was not well defined
- Value = 6: no lwc if rain is present

For ReOBS file, we consider:

Short_name	Long_name	Unit	Comment / Variables

lwc_cl	Liquid Water Content	kg.m^{-3}	Keep: mean value + std + number of used data
			lwc_min threshold = 0 kg.m^{-3}
			lwc_max threshold = 0.015 kg.m^{-3}
			Quality control : only for lwc_status (0, 1, 2)

Table 13. ReOBS product for Liquid Water Content level 2 cloudnet file

3.11 Weather

The weather station product provides meteorological data collected by an automatic weather station (AWS).

For ReOBS file, we consider the following variables:

Short_name	Long_name	Unit	Comment / Variables
ta_ws	Air temperature	K	Keep: Mean + std + number of used data
			ta_min threshold = -30 °C
			ta_max threshold = 50 °C
			min_std_window = 60 minutes
			min_std = 0
			min_std_nb_sigma = 1
			QC3_window = 15
			QC3_alpha = 0.25
			QC3_gamma = 0.2
			QC3_beta = 10
rh_ws	Relative humidity	1	Keep: Mean + std + number of used data
			rh_min_threshold = 3 %
			rh_min_threshold = 103 %

			min_std_window = 60 minutes
			min_std = 0
			min_std_nb_sigma = 1
			QC3_window = 15
			QC3_alpha = 1.2
			QC3_gamma = 1.1
			QC3_beta = 10
press_ws	Air pressure	Pa	Keep: Mean + std + number of used data
			ps_min_threshold = 960 hPa
			ps_max_threshold = 1030 hPa
			min_std_window = 60 minutes
			min_std = 0
			min_std_nb_sigma = 1
			QC3_window = 15
			QC3_alpha = 0.15
			QC3_gamma = 0.12
			QC3_beta = 10
pr_ws	Precipitation rate	$m.s^{-1}$	Keep: mean + std + min + max
			rr_min_threshold = 0 mm min-1
			rr_min_threshold = 5 mm min-1
ra_ws	Rainfall amount	m	Keep: sum + min + max
			ra_min_threshold = 0 mm min-1
			ra_min_threshold = 5 mm min-1

ws_ws	Wind speed	m.s^{-1}	Keep: Mean + std + number of used data
			ws_min_threshold = 0 m s-1
			ws_max_threshold = 40 m s-1
			QC3_window = 15
			QC3_alpha = 0.3
			QC3_gamma = 1.8
			QC3_beta = 10
wd_ws	Wind direction	degree	Keep: mean + std + number of used data
			wd_min_threshold = 0°
			wd_max_threshold = 360°

Table 14. ReOBS product for weather station level 1b cloudnet file

3.12 Microwave radiometer data

3.12.1   Single product

The MWR single pointing product provides microwave radiometer data processed with MWRpy (Marke et al., 2024), providing temperature/humidity profiles and integrated quantities with high temporal resolution. This product is available for HATPRO, LHATPRO and LHUMPRO instruments.

The MWR single pointing product is based on these products:MWR brightness temperature.

For ReOBS file, we consider the following variables:

Short_name	Long_name	Unit	Comment / Variables
lwp_mwr	Liquid Water Path	g.m^{-2}	Keep: mean value + std + number of used data
			Quality control : keep only lwp_quality_flag equals to 0 (0 indicates

			data with good quality according to applied tests) lwp_min threshold = -20 g.m^{-2}, lwp_max threshold = 2000 g.m^{-2}
iwv_mwr	Integrated Water Vapour	kg.m^{-2}	Keep: mean value + std + number of used data Quality control : keep only iwv_quality_flag equals to 0 (0 indicates data with good quality according to applied tests) + iwp_min threshold = 0 kg.m^{-2} iwp_max threshold = 70 kg.m^{-2}
ah_mwr	Absolute Humidity	kg.m^{-3}	Keep: mean value + std + number of used data Quality control: keep only absolute_humidity_quality_flag equals to 0 (0 indicates data with good quality according to applied tests) + Absolute_humidity_min threshold = 0 kg.m^{-3} Absolute_humidity_max threshold = 0.05 kg.m^{-3}

Table 15. ReOBS product for microwave radiometer single pointing level 2 cloudnet file

3.12.2   L1C product

The MWR brightness temperature product includes microwave radiometer data processed using MWRpy (Marke et al., 2024), providing brightness temperature measurements and optionally measurements from an infrared sensor and an integrated weather station. The product can also use lidar data to detect liquid clouds.

For ReOBS file, we consider the following variables:

Short_name	Long_name	Unit	Comment / Variables
tb_mwr	Microwave brightness temperature	K	Keep: mean value + std + number of used data Quality control: keep only tb_quality_flag equals to 0 (0 indicates data with good quality according to applied tests) + tb_min threshold = 2.7K, tb_max threshold = 330K
t_amb_mwr	MWR ambient target temperature	K	Keep: mean value + std + number of used data
t_rec_mwr	MWR receiver physical temperature	K	Keep: mean value + std + number of used data
t_sta_mwr	MWR receiver temperature stability	K	Keep: mean value + std + number of used data

Table 16. ReOBS product for microwave radiometer level 1c cloudnet file

3.12.3 Multi product

The MWR multiple pointing product provides microwave radiometer data processed with MWRpy (Marke et al., 2024), providing temperature and humidity profiles with high-quality profile information. This product is only available for HATPRO and LHATPRO instruments.

The MWR multiple pointing product is based on these products: MWR brightness temperature.

For ReOBS file, we consider the following variables:

Short_name	Long_name	Unit	Comment / Variables
ta_mwr	Temperature	K	Keep: mean value + std + number of used data Quality control: keep only temperature_quality_flag equals to 0 (0 indicates quality check has been applied) + temperature_min threshold = 210K, temperature_max threshold = 330K
theta_mwr	Potential temperature	K	Keep: mean value + std + number of used data Quality control: keep only temperature_quality_flag equals to 0 (0 indicates quality check has been applied) + potential_temperature_min threshold = 210K, potential_temperature_max threshold = 400K
theta_e_mwr	Equivalent potential temperature	K	Keep: mean value + std + number of used data Quality control: keep only temperature_quality_flag equals to 0 (0 indicates quality check has been applied)

			+ potential_temperature_min threshold = 210K, potential_temperature_max threshold = 400K
rh_mwr	Relative humidity	1	Keep: mean value + std + number of used data
			Quality control: keep only temperature_quality_flag equals to 0 (0 indicates quality check has been applied)
			+ relative_humidity_min threshold = 0, relative_humidity_max threshold = 1.05

Table 17. ReOBS product for microwave radiometer multi pointing level 2 cloudnet file

3.13 Cloud radar data

The radar product provides Doppler spectral moments (reflectivity, mean velocity, etc.) calculated from the measurements by a vertical-pointing Doppler cloud radar (DCR). The data are not corrected for atmospheric attenuation, velocity aliasing/folding, or instrument mispointing.

For the radar reflectivity, the calibration convention is: in the absence of attenuation, a cloud at 273 K containing one million 100-micron droplets per cubic meter will have a reflectivity of 0 dBZ at all frequencies.

For ReOBS file, we consider the following variables:

Short_name	Long_name	Unit	Comment / Variables

| zh_dcr | Radar reflectivity factor | dBZ | Keep : mean value + std + number of used data

Zh_min threshold = - 50 dBZ

Zh_max threshold = + 30 dBz |
| v_dcr | Doppler velocity | m.s^{-1} | This parameter is the radial component of the velocity, with positive velocities are away from the radar.

Keep : mean value + std + number of used data

v_min threshold = - 10 m.s^{-1}

v_max threshold = + 10 m.s^{-1} |

Table 18. ReOBS product for cloud radar level 1b cloudnet file

4 List of variables in the final standard ReOBS files concerning the 1D-variables

Variables	Short_name	Unit
Radar reflectivity factor	zh_dcr	dBZ
Doppler Velocity	v_dcr	m.s^{-1}
Liquid Water Path	lwp_mwr	g.m^{-2}
Integrated Water Vapour	iwp_mwr	kg.m^{-2}
Absolute Humidity	ah_mwr	kg.m^{-3}

Microwave brightness temperature	tb_mwr	K
Microwave ambient target temperature	t_amb_mwr	K
Microwave receiver physical temperature	t_rec_mwr	K
Microwave receiver temperature stability	t_sta_mwr	K
Microwave temperature	ta_mwr	K
Microwave potential temperature	theta_mwr	k
Microwave Equivalent potential temperature	theta_e_mwr	K
Microwave Relative humidity	rh_mwr	1
ALC Attenuated backscatter coefficient	bck_smooth_alc	$sr^{-1}.m^{-1}$
DWL zonal wind	u_dwl	$m.s^{-1}$
DWL meridional wind	v_dwl	$m.s^{-1}$
Rainfall rate	pr_dd	$m.s^{-1}$

Snowfall rate	sr_dd	$m.s^{-1}$
Number of particles in time interval	n_dd	1
Raw data as a function of particle diameter and velocity	raw_dd	1
Air temperature	ta_ws	K
Relative humidity	rh_ws	1
Air pressure	press_ws	Pa
Rainfall rate	pr_ws	$m.s^{-1}$
Wind speed	ws_ws	$m.s^{-1}$
Wind direction	wd_ws	degree
Ice Water Content	iwc_cl	$kg.m^{-3}$
Liquid Water Content	lwc_cl	$kg.m^{-3}$
Drizzle median diameter	Do_cl	m
Drizzle droplet size distribution shape parameter	mu_cl	/
Drizzle number concentration	drizzle_N_cl	m^{-3}

Drizzle liquid water content	drizzle_lwc_cl	kg.m^{-3}
Drizzle droplet fall velocity	v_drizzle_cl	m.s^{-1}
Vertical air velocity	v_air_cl	m.s^{-1}
The most frequent target category	target_cat_most_frequent_cl	/
The 2nd most frequent target category	target_cat_second_most_frequent_cl	/
Height of cloud base above ground level	cbh_cl	m
Height of cloud top above ground level	cth_cl	m
The most frequent target classification	target_class_most_frequent_cl	/
The 2nd most frequent target classification	target_class_second_most_frequent_cl	/

Table 19. List of variables inside the final ReOBS file

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