CDR-derived WTC

Development and release on AVISO/ODATIS of a Wet Troposphere Correction (WTC) for climate series derived from a water vapor Climate Data Record (CDR)

Product User Manual

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1. Introduction

1.1. Scope

The standard global mean sea level (GMSL) record provided by AVISO+ uses the microwave radiometer (MWR) wet troposphere correction (WTC) which has a much better accuracy than WTC provided by operational models at the local scale. However due to lack of stability over time (Legeais et al., 2014), the MWR WTC is one of the most important contributors to the uncertainty on the GMSL record (Ablain et al., 2019; Guérou et al., 2022). To overcome the lack of long term stability of the MWR WTC, an alternative WTC computed from water vapour climate data records (CDRs) can be used (Barnoud et al., 2023).

The product contains the global mean WTC (GMWTC) combining the high frequencies (below 2 months) from the MWR and the low frequencies (above 2 months) derived from the water vapour CDRs. This solution is therefore stable over long periods of time and accurate over short time scales. The product also contains a GMSL record solution using the CDR-derived WTC and the correction to apply to the standard GMSL record computed with the MWR WTC to replace the latter by the combined MWR/CDR WTC for a more stable solution.

This document is the Product User Manual (PUM) of the product of WTC derived from water vapour CDRs. This is the primary document that users should read before handling the product. It provides an overview of processing algorithms and technical content of the product.

1.2. Document structure

In addition to this introduction, the PUM is organised as follows:

- Section 2 summarises the input data and algorithms involved in the derivation of the wet troposphere correction from water vapour data,
- Section 3 describes the content of the distributed product file,
- Section 4 explains how to access and use the data.

1.3. Related documents

1.3.1. Applicable documents

Table 1 *List of applicable documents.*

Id.	Ref.	Description
AD1	GIECCO-DT-081-MAG_FinalReport_CDR_WTC_2023_V2.1	Rapport final version 2.1 de la tâche 6 de l'étude "développement, génération et valorisation d'indices climatiques pour ODATIS pour l'Earth energy imbalance"
AD2	SALP-CCTP-ODAT-EA-17555-CN	"Développement et diffusion sur AVISO/ODATIS d'une correction de troposphère humide pour les séries climatiques", cahier des clauses techniques particulières
AD3	ACCORD-CADRE N°18012/00	Accords-Cadres Algorithmie Scientifique pour l'Observation de la Terre
AD4	MAG-24-PTF-067_Proposition_WTC_CDR	Proposition administrative, technique et financière
AD5	CLS-SALP- 24-015 221079	Contrat du marché n° 221332/00
AD6	GIECCO-DT-083-MAG_WTC_from_WV_CDR_PUM_v1.1	Product user manual for the distribution of the water vapor CDR-derived WTC on the AVISO ODATIS portal.
AD7	WTC_CDR-DT-008-MAG_FinalReport_2024	Final Report of the WTC CDR study

1.3.2. References

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1.4. Acronyms

Table 2 details the acronyms that can be found in this document.

Table 2 *List of acronyms.*

Acronyms	Description
AD	Applicable document
AMSR-E	Advanced Microwave Scanning Radiometer for EOS
CDR	Climate Data Record
CLS	Collecte Localisation Satellites
CM SAF	Satellite Application Facility on Climate Monitoring
CNES	National Centre for Space Studies
DOI	Digital Object Identifier
DWD	Deutscher Wetterdienst
ECMWF	European Centre for Medium-Range Weather Forecasts
EEI	Earth Energy Imbalance
EOS	Earth Observing System missions
ERA	ECMWF re-analysis
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FCDR	Fundamental Climate Data Record
GMSL	Global Mean Sea-Level
GMWTC	Global Mean Wet Troposphere Correction
GNSS	Global Navigation Satellite Systems
GOHC	Global Ocean Heat Content
GPD+	GNSS derived Path Delay +
GPS	Global Positioning System

HOAPS	Hamburg Ocean-Atmosphere Fluxes and Parameters from Satellite
ICDR	Instantaneous Climate Data Record
JPL	Jet Propulsion Laboratory
L2P	Level-2+
L2P DT 2021	Level-2+ data product version 2021
L2P DT 2024	Level-2+ data product version 2024
MWR	Microwave Radiometer
ODATIS	Pôle de données et services pour l’océan
OHC	Ocean Heat Content
OSTST	Ocean Surface Topography Science Team
PUM	Product User Manual
RANSAC	RANdom SAmple Consensus
REMSS	Remote Sensing Systems
SSE	Sum of Squared Errors
SSM/I	Special Sensor Microwave/Imager
SSMI/S	Special Sensor Microwave Imager/Sounder
TCWV	Total Column Water Vapour
WCSS	Within-Cluster Sums of Squares
WTC	Wet Tropospheric Correction

2. Data and algorithm

2.1. Input data

2.1.1. Product V1

The CDR-derived WTC product V1 is based on the Level-2+ along-track altimetry products version 2021 (L2P 2021) distributed on the AVISO+ website (https://www.aviso.altimetry.fr).

We use water vapour CDRs from two datasets:

- REMSS V7.0 Release 1 dataset providing data until 2021 (available at http://www.remss.com/measurements/atmospheric-water-vapor/tpw-1-deg-product/),
- HOAPS CM SAF V4.0 dataset providing data until 2014 (available at https://wui.cmsaf.eu).

2.1.2. Product V1.1

The CDR-derived WTC product V1.1 is based on the Level-2+ along-track altimetry products version 2021 (L2P 2021) distributed on the AVISO+ website (https://www.aviso.altimetry.fr).

We use water vapour CDRs from two datasets:

- REMSS V7R2 dataset providing data until 2022 (available at http://www.remss.com/measurements/atmospheric-water-vapor/tpw-1-deg-product/),
- Precursor HOAPS V5 dataset from EUMETSAT CM SAF, providing data until 2020. Note that the precursor version is not an official CM SAF product, i.e. a full product validation, review and public release is pending. The precursor HOAPS V5 relies on HOAPS V4 algorithms, with the following adaptations and enhancements:
  - Data from TMI and AMSR-E were included.
  - The aggregation process was changed by first computing hourly averages and then higher level averages.
  - The estimation of uncertainties has been improved.

  HOAPS V4 and V5 data is and will be available at https://wui.cmsaf.eu.

2.1.2. Product V2

The CDR-derived WTC product V2 is based on the Level-2+ along-track altimetry products version 2024 (L2P 2024) distributed on the AVISO+ website (https://www.aviso.altimetry.fr).

We use the same two water vapour CDRs datasets as for V1.1. To compute the V2 product we use ai coefficients constant in time but varying spatially. The estimation of those coefficients is explained in [AD7] and will lead to a publication in a peer reviewed journal.

2.2. Algorithm

Wet Tropospheric Correction can be approximated as a polynomial function from TCWV as follows:

$$\mathrm{WTC} = (a_0 + a_1 \mathrm{TCWV})\mathrm{TCWV}$$

With a_0 and a_1 constant coefficients estimated regionally. Note that other studies have used higher order polynomials, with global coefficients (Barnoud et al., 2023; Keihm et al., 2000; Stum et al., 2011b).

Note: in the following paragraphs, the WTC is considered as a positive value, but as it corresponds to a path delay, this correction should be **subtracted** from the range.

a_0 and a_1 coefficients are computed with the following processing steps:

1. Each gridcell is classified in one of 7 classes based on a K-mean fitting on ERA5 geophysical parameters. The goal is to create coherent physical regions where the 2 coefficient polynomial approximation is valid.
2. A linear fit is applied between the reference WTC value and the TCWV value from ERA5 for each month, by grouping each gridcell corresponding to the same classes together over 1 month periods. This linear fit provides monthly a_0 and a_1 coefficients for each gridcell.
3. Monthly values are then averaged over the studied period in order to get constant coefficients.
4. In order to avoid sharp transitions at class boundaries, a 12° by 12° rolling mean window is applied.

The associated coefficient uncertainties are estimated at the same spatial resolution and are constant in time. They are computed using the following formula:

$$u_{a_i} = mean_{12°x12°}(std_{time}(a_i(t))) + std_{12°x12°}(mean_{time}(a_i(t))) \quad \text{[Eq. 1]}$$

With u_{a_i} the uncertainty of the coefficient a_i with $i \in \{0,1\}$, $a_i(t)$ being the monthly coefficient estimated at step 2. std_{time} is the temporal standard deviation of monthly $a_i(t)$ values, and $std_{12°x12°}$ is the function describing the spatial standard deviation over the 12° by 12° rolling window.

Equation 1 incorporates the uncertainty due to the temporal averaging of $a_i(t)$ done in step 3 with the term: $mean_{12°x12°}(std_{time}(a_i(t)))$. It also takes into account the uncertainty due to the spatial averaging of several a_i classes together in step 4 with the term $std_{12°x12°}(mean_{time}(a_i(t)))$. This expression is conservative, as the uncertainties are added and not the variances.

2.3. Computation of the combined MWR/CDR WTC

The water vapor CDRs are derived from fundamental climate data records (FCDRs) of brightness temperatures measured by SSM/I and SSMI/S meteorological satellites. As such, these measurements are not colocalized in time and space with the microwave radiometer (MWR) measurements from the altimetry missions. Besides, we use monthly gridded products of water vapor that cannot describe any high frequency content below 2 months. Therefore, a purely CDR-derived WTC cannot contain relevant high frequency signals.

To avoid any potential subsequent aliasing effect, we produce a combined MWR/CDR global mean WTC (GMWTC) using the high frequencies from the MWR GMWTC and the low frequencies from the water vapor CDR-derived GMWTC. When combining the low frequencies from CDRs and the high frequencies from MWR, a cut-off frequency needs to be chosen. The cut-off frequency employed up till now was equal to 1 year, this is a conservative choice as the study focuses on the long term uncertainties. After sensitivity tests to the choice of cut-off frequency showed a negligible impact, we opted for a cut-off period of 2 months. This allows us to take full advantage of the CDR signal and complement it with the high-frequency components it cannot capture.

In practice, the combined GMWTC (noted $GMWTC_{CDR\_LF+MWR\_HF}$ is obtained from the initial MWR-based GMWTC along-track ($GMWTC_{MWR}$, removing the MWR-based GMWTC low-frequencies ($GMWTC_{MWR\_LF}$) and adding back the CDR-derived GMWTC low-frequencies ($GMWTC_{CDR\_LF}$) following Equation 2. The low-pass filtering is performed with a Lanczos filter.

$$GMWTC_{CDR\_LF+MWR\_HF} = GMWTC_{MWR} - GMWTC_{MWR\_LF} + GMWTC_{CDR\_LF} \quad \text{[Eq. 2]}$$

The processing workflow is described in Figure 1.

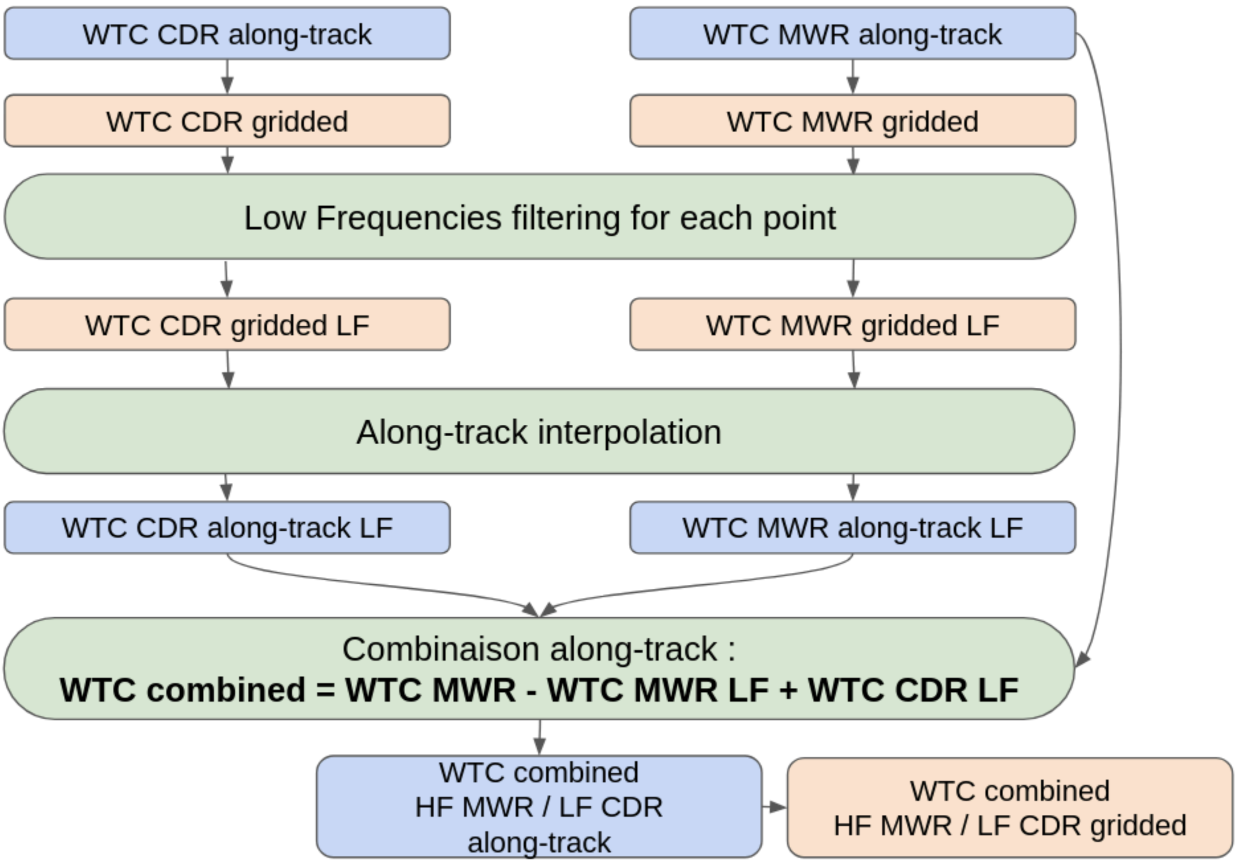

Figure 1 Processing workflow illustrating the combination of the high-frequency signals of the altimeter's MWR based WTC and the low-frequency signals of the CDR based WTC along track.

2.3. WTC CDR uncertainties propagation

Uncertainties on TCWV, a_0 and a_1 can be formally propagated to get uncertainties on WTC values. The expression linking TCWV and WTC can be written in matricial form using $V = \begin{bmatrix} tcwv_1 \\ \vdots \\ tcwv_n \end{bmatrix}$, the vector of TCWV values for each month number from ***1*** to ***n***:

$$\text{WTC} = f(a_0, a_1, V) = a_0 V + a_1 V \circ V$$

with $\circ$ the Hadamard operator ie. the term by term vector multiplication.

We now assume the following:

- There is **no modeling error**, i.e., the expression of ***f*** fully describes the path delay caused by water vapor.
- The errors on ***V***, $\boldsymbol{a_0}$ and $\boldsymbol{a_1}$ are small enough to justify the use of the **first-order approximation**.
- The errors on ***V***, $\boldsymbol{a_0}$ and $\boldsymbol{a_1}$ are **uncorrelated**.

The time covariance matrix of the errors on the WTC correction, Σ_{WTC}, can be written as:

[Eq. 3] $$\Sigma_{\mathrm{WTC}} = \Sigma_{a_0} \circ \left(\frac{\partial f}{\partial a_0}\right)\left(\frac{\partial f}{\partial a_0}\right)^T + \Sigma_{a_1} \circ \left(\frac{\partial f}{\partial a_1}\right)\left(\frac{\partial f}{\partial a_1}\right)^T + \Sigma_V \circ \left(\frac{\partial f}{\partial V}\right)\left(\frac{\partial f}{\partial V}\right)^T$$

Here, Σ_V, Σ_{a_0}, and Σ_{a_1} are the time covariance matrices for errors on ***V***, $\boldsymbol{a_0}$ and $\boldsymbol{a_1}$.

Note: the independence of $\boldsymbol{a_0}$ and $\boldsymbol{a_1}$ is a strong assumption, as the 2 coefficients are estimated jointly. This topic is discussed further in the discussion paragraph.

Since $\boldsymbol{a_0}$ and $\boldsymbol{a_1}$ are constants, we can simplify the expression and compute the derivatives explicitly:

[Eq. 4] $$\Sigma_{\mathrm{WTC}} = \sigma_{a_0}^2 \cdot VV^T + \sigma_{a_1}^2 \cdot (V \circ V)(V \circ V)^T + \Sigma_V \circ (a_0 I + 2a_1 V)(a_0 I + 2a_1 V)^T$$

where I is a vector of ones (same size as V), and $\sigma_{a_0}^2$ and $\sigma_{a_1}^2$ are the variances of a_0 and a_1, respectively.

Equation 4 can be applied globally, in this case each value tcwv_i represents the global mean over one month. It can also be used regionally, by using regionalized values of TCWV, a_0 and a_1.

3. Product description

3.1.1. Along track WTC CDR

3.1. File format and naming conventions

The product is now provided in Level-2+ (L2P) format along the satellite ground track. Each mission is distributed as a compressed directory (.tar.gz) containing one Network Common Data Form version 4 (netCDF4) file per mission cycle, with metadata attributes compliant with version 1.8 of the Climate & Forecast (CF) conventions.

Archives follow the naming convention:

<mission>_WTC_from_WV_CDR_<version>.tar.gz

where <mission> is the two-letter mission code (TP for TOPEX/Poseidon, J1 for Jason-1, J2 for Jason-2, J3 for Jason-3) and <version> is the two-digit version number, starting with V2 for the latest release of the product.

Each archive contains one NetCDF (.nc) file per mission cycle, following the naming convention:

<mission>_C<cycle>.nc

where <mission> is the two-letter mission code and <cycle> is the four-digit cycle number (e.g., C0001 for cycle 1).

Example: TP_WTC_from_WV_CDR_V2.tar.gz → tp_C0001.nc , for the first cycle of TOPEX/Poseidon mission.

3.2. Product content

3.2.1. Dimensions

One dimension is defined:

- time

3.2.2. Variables

Table 3 describes the variables included in the product file. For both the REMSS and HOAPS CDRs, the file provides the combined MWR/CDR WTC.

The combined MWR/CDR WTC are provided so that it can be used to replace the WTC in any SL L2P computed using a WTC other than the MWR one (e.g. using the ECMWF operational WTC model).

Table 4 Description of the variables of the CDR-derived WTC product (NetCDF file).

Variable(dimensions)	Description	Unit	Type
time(time)	Time since 2000-01-01 (Gregorian calendar)	Seconds since 2000-01-01	double
Latitude(time)	Latitude along track (positive north, negative south)	degrees_north	Int
Longitude(time)	Longitude along track (east of Greenwich)	degrees_east	Int

latitude(time)	GMWTC combining MWR HF values and REMSS CDR LF values	meters	double
wet_tropospheric_correction_ai_class_2months_combined_mwr_hoaps (time)	WTC combining high-frequency MWR measurements and low-frequency HOAPS CDR data, with 2-month cut-off	meters	double
wet_tropospheric_correction_ai_class_2months_combined_mwr_remss (time)	WTC combining high-frequency MWR measurements and low-frequency REMSS CDR data, with 2-month cut-off	meters	double

These two combined MWR/CDR WTC variables are provided so they can be used to replace the standard MWR WTC in any along-track analysis.

3.1.2. WTC CDR uncertainties

3.1. File format and naming conventions

The product is distributed as a single Network Common Data Form version 4 (netCDF4) file.
The file name follows the convention: wtc_trend_uncertainties.nc

This file contains gridded fields of regression coefficients and trends, derived from the statistical relationship between Total Column Water Vapour (TCWV) and Wet Tropospheric Correction (WTC).

3.1.2. Product content

This is the first version of a dedicated product providing not only WTC CDR (HOAPS) trends, but also uncertainty estimates on the trend of the WTC CDR.

- The uncertainties are propagated according to the methodology described in Section 2.3, and are expressed as one–sigma confidence intervals.
- The product provides not only the total uncertainty on the WTC CDR (HOAPS) trend, but also the individual contributions of each source of uncertainty (uncertainties associated with the regression coefficients a_0 and a_1, and uncertainties inherited from the TCWV HOAPS fields).

- In addition, the product includes the input regression variables (a_0, a_1 and their standard deviations), which allow users to recompute or further propagate uncertainties if needed.

This design makes the product suitable both for direct use in climate analyses of WTC trends and for investigations into the relative importance of different sources of uncertainty.

3.2.1. Dimensions

The dataset is defined on a regular latitude–longitude grid with temporal information:

Table 5 Description of the dimensions of the CDR-derived WTC trend uncertainties product (NetCDF file).

Dimension	Description	Unit
lat	Latitude (−90° to +90°)	degrees_north
lon	Longitude (0°–360°)	degrees_east
time	Analysis time axis	

Additionally, a `decimal_time` variable provides the same axis in decimal years.

3.2.2. Variables

The file contains:

1. Regression coefficients and their uncertainties (a_0, a_1, a_0_std, a_1_std) used to derive WTC from TCWV.
2. Trends in TCWV and WTC CDR, estimated by extended OLS regression.
3. Uncertainty estimates for each trend, both total and decomposed into contributions from TCWV, a_0, and a_1.

#table_desprod22 Description of the variables of the CDR-derived WTC trend uncertainties product (NetCDF file).

Variable(dimensions)	Description	Unit	Type
a_0(lat,lon)	Linear regression coefficient for WTC as function of TCWV (term in $a_0 \times$ tcwv)	m^3/kg	float
a_1(lat,lon)	Quadratic regression coefficient	m^5/kg^2	float

	for WTC as function of TCWV (term in $a_1 \times tcwv^2$)		
a_0_std(lat,lon)	Standard deviation of a_0	m^3/kg	float
a_1_std(lat,lon)	Standard deviation of a_1	m^5/kg^2	float
tcwv_trend(lat,lon)	Linear trend in TCWV estimated by extended OLS	$kg/m^2/year$	double
tcwv_trend_unc(lat,lon)	1-sigma uncertainty of tcwv_trend	$kg/m^2/year$	double
wtc_trend(lat,lon)	Linear trend in WTC estimated by extended OLS	mm/year	double
wtc_trend_unc(lat,lon)	Total 1-sigma uncertainty of wtc_trend (propagated from all sources)	mm/year	double
wtc_trend_tcwv_unc(lat,lon)	Contribution of TCWV uncertainty to wtc_trend	mm/year	double
wtc_trend_a0_unc(lat,lon)	Contribution of a_0 uncertainty to wtc_trend	mm/year	double
wtc_trend_a1_unc(lat,lon)	Contribution of a_1 uncertainty to wtc_trend	mm/year	double

4. How to access and use the CDR-derived WTC product?

4.1. Downloading

The data product (NetCDF file) and associated documentation can be found and downloaded on the AVISO+ webpage:

https://www.aviso.altimetry.fr/en/data/products/auxiliary-products/wet-troposphere-correction-from-water-vapour-climate-data-records.html

Once downloaded, NetCDF data can be browsed and used through a number of software, like:

- ncBrowse: https://www.pmel.noaa.gov/epic/java/ncBrowse/
- NetCDF Operator (NCO): http://nco.sourceforge.net/
- Panoply: https://www.giss.nasa.gov/tools/panoply/
- IDL, Matlab, GMT, Python...
-

Useful information on UNIDATA: http://www.unidata.ucar.edu/software/netcdf/

4.2. Dataset DOI

The product is referenced with the following digital object identifier (DOI):
10.24400/527896/a01-2022.018

4.3. Citing and referencing

When using the CDR-derived WTC product, please refer to Barnoud et al. (2023) and acknowledge "The CDR-derived WTC product was produced by Magellium, Fluctus and LEGOS and distributed on the AVISO+ ODATIS portal (https://www.aviso.altimetry.fr) with support from CNES (https://doi.org/10.24400/527896/a01-2022.018 version XX).".

4.4. Support

For any technical issues or additional information related to the CDR-derived WTC product, users are advised to contact the project team:

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- Michaël Ablain: michael.ablain@magellium.fr

END OF THE DOCUMENT