Water Vapour Climate Change Initiative (WV_cci) - CCI+ Phase 1

User Requirements Document (URD)

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1.0	10 Dec 2018	Formal issue to ESA
1.1	25 Jan 2019	RIDs from ESA implemented
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3.0	11 Feb 2021	Updates according to feedback from CMUG (D2.3 v1.3 Dec 2020) and water vapour user group. Formal issue of v3.0 to ESA (as update to v2.0)

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1. INTRODUCTION

1.1 Purpose

This User Requirements Document (**URD**) identifies and consolidates the performance requirements for the data products of the Essential Climate Variable (**ECV**) water vapour that will be generated within the Water_Vapour_cci (WV_cci). These data products feature climate data records (**CDR**) of total column water vapour (**TCWV**), and nadir- and limb-based vertical profiles of water vapour in the troposphere and stratosphere, respectively.

Considered requirement sources include international bodies such as Global Climate Observing System (**GCOS**) and the World Meteorological Organization (**WMO**), CCI-internal feedback from the Climate Modelling User Group (**CMUG**), Climate Research Group (**CRG**) and other Climate Change Initiative (**CCI**) projects, and feedback from the WV_cci user community. These requirements are analysed and condensed into requirements for WV_cci data products. When available we also provide the applicable terminology and discuss our interpretation when analysing the requirements.

1.2 Scope

The general scope of this document is to inform the WV_cci project of the quality and performance standards that the climate data records it envisages to generate need to achieve in order to be useful for the end user and for a range of climate research applications. The URD is also intended to inform data users of the guiding requirements WV_cci adopted to develop and produce its CDRs. The URD's findings will thereby form the basis of the Product Specification Document (**PSD**), in which the CDRs are being characterised.

The CDR user requirements and characteristics that are being defined in this document include

- Accuracy
- Precision
- Spatial Resolution (horizontal and vertical)
- Temporal Resolution (frequency)
- Stability
- Record length

Note, specific data product requirements that deal with the data formatting will be provided in the PSD.

2. RELEVANCE OF WATER VAPOUR IN THE CLIMATE SYSTEM

Water vapour is the single most important natural greenhouse gas in the atmosphere, thereby constraining the Earth's energy balance, and is also a key element of the water cycle. Water vapour is also essential to atmospheric chemistry, because it is the source of the hydroxyl radical, which is the most important oxidant (cleansing detergent) in the atmosphere. The following sections explain the relevance of tropospheric and stratospheric water vapour in the climate system, respectively.

2.1 Relevance of water vapour in the troposphere

Most of the atmosphere's water vapour is found in the troposphere, with 95% residing between the surface and 5 km altitude. Water vapour concentrations vary by as much as four orders of magnitude between Earth's surface and the tropopause, with the hygropause defining the lowest water vapour concentrations in the vertical.

Tropospheric water vapour results from evaporation from ocean and land surfaces that is driven by solar heating, with its abundance determining the development of clouds, precipitation, and extreme events (see Figure 2-1). Redistribution of water through these atmospheric processes is a key part of the hydrological cycle, which determines soil moisture and surface fluxes and ultimately, where life on Earth can be sustained. The latent heat of water vapour is thereby responsible for half of the heat transport from the tropics to the extra-tropics that maintains the climate in the extratropics (Sherwood et al., 2010).

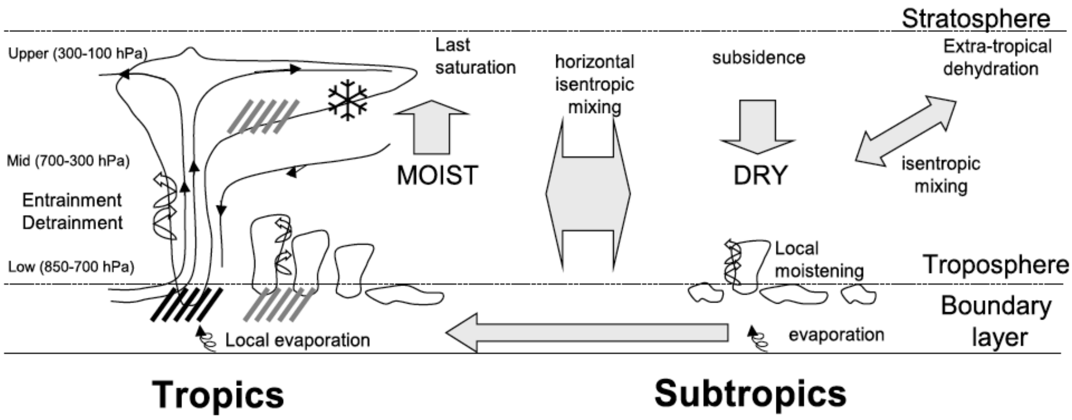

Figure 2-1: Processes affecting the transport and distribution of tropospheric water vapour (from Sherwood et al., 2010).

Water vapour is an essential natural greenhouse gas that influences the Earth's radiation budget both directly and indirectly via clouds. The Clausius–Clapeyron relationship predicts that per degree Kelvin increase in temperature, the atmosphere can contain around 7% more water vapour. Climate models indicate that this important positive feedback may increase the sensitivity of surface temperatures to carbon dioxide by a factor of two to three, depending on whether other Earth system feedbacks (including clouds) are considered (Held and Soden, 2000). Fully understanding the water vapour feedbacks and better estimating its magnitude rely on observed variability, from seasonal to the decadal scales (Del Genio, 2002).

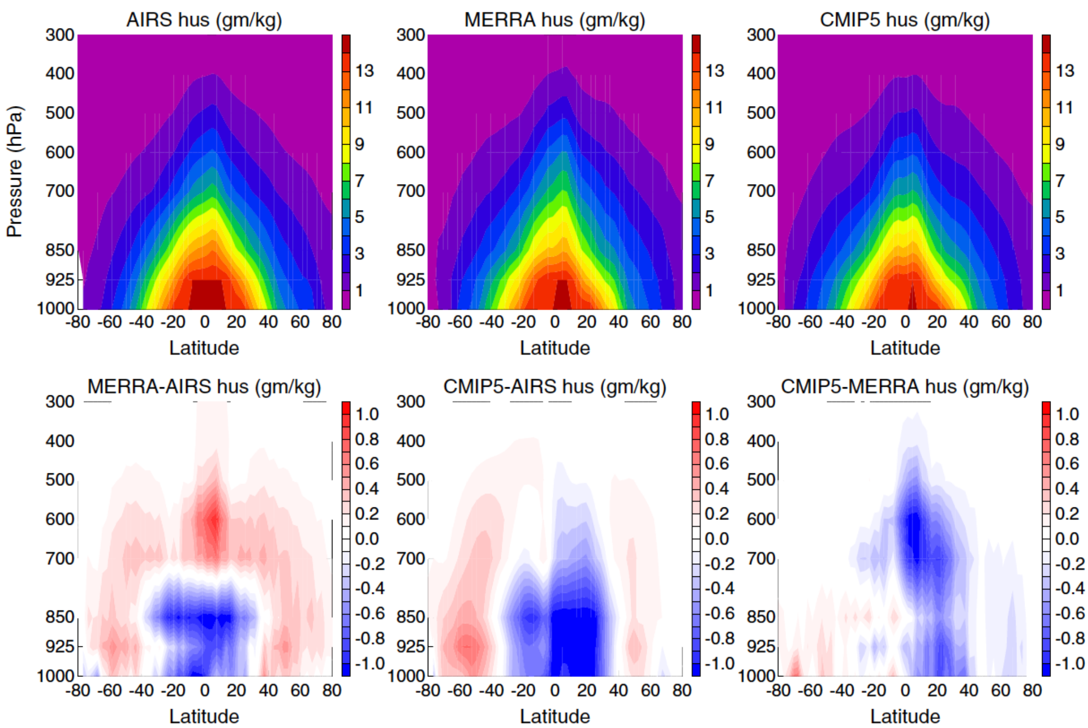

Figure 2-2: Global zonal mean of climatological mean (January 1986–December 2005) tropospheric specific humidity (g/kg) for AIRS, MERRA and CMIP5 and their differences (from Tian et al., 2013).

Total column water vapour (TCWV) measurements are commonly used to represent the water vapour content of the troposphere. It is important to note that TCWV mainly represents water vapour of the lowest 2 km. CDRs of TCWV are essential to validate the above processes in global climate models and reanalyses, and also to provide a reference for the climatological distribution and natural variability of tropospheric water vapour, including (particularly regional) trends in these variables. Reanalyses, which are often taken as observational reference, have been shown to have substantial shortcomings in representing the residence time of water in the atmosphere, do not conserve water within the hydrological cycle mainly due to analysis increments (Trenberth et al., 2011), and are affected by stability issues (e.g., Schröder et al., 2016; Davis et al., 2017; Schröder et al., 2019). These limitations need to be taken into account when using them for the evaluation of global climate models. On the other hand, while global climate models have been successfully used to reproduce observed TCWV increases derived from satellite measurements over the oceans (with these increases being consistent with the Clausius–Clapeyron relationship of approximately 7% per degree Celsius of warming), the mechanisms behind a recent decrease in the trend in specific humidity over land are still to be investigated (IPCC, 2014).

Despite an overall consistency on the global scale for TCWV, global climate models fail at simulating correctly the observed vertical and latitudinal distribution of moisture (Figure 2-2), on average with a too dry tropical lower troposphere and too moist mid-latitudes (Tian et al., 2013). Also, low-resolution models are generally not capable of providing useful information on atmospheric water vapour for downscaling of extreme events (WMO, 2016).

2.2 Relevance of water vapour in the stratosphere

In the stratosphere, knowledge of the vertical distribution, its variability and trends, is of particular importance since the radiative forcing resulting from changes in water vapour exhibits a strong sensitivity to the altitude at which the changes occur, with the largest changes found around the tropopause where temperatures are coldest (Forster and Shine, 1999). An increase in stratospheric water vapour thereby results in a cooling (warming) of the stratosphere (troposphere). In contrast, an increase of humidity in the upper troposphere would lead to a warming due to increased absorption of outgoing longwave radiation. This effect is strongest at the dry end of the humidity PDF.

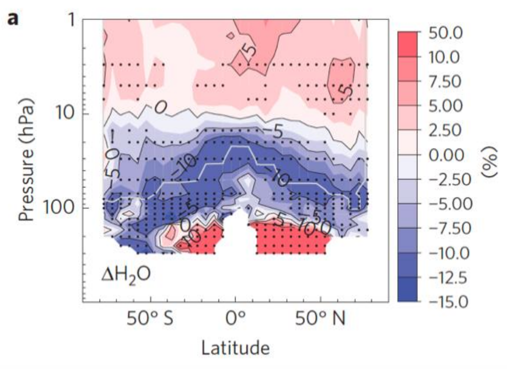

Figure 2-3: Zonal mean water vapour changes as derived from merged satellite limb sounders between the late 1980s and 2010 (from Hegglin et al., 2014). Note, lower stratospheric water vapour changes are negative.

Stratospheric water vapour changes are not well understood due to a lack of accurate long-term measurements (both *in situ* and remote) that would be able to capture very small changes against small background values. Not surprisingly, there exist conflicting results between trends in stratospheric water vapour derived from *in situ* balloon (Hurst et al., 2011) and space-based remote sensing instruments (Hegglin et al., 2014) (see Figure 2-3 and Figure 2-4).

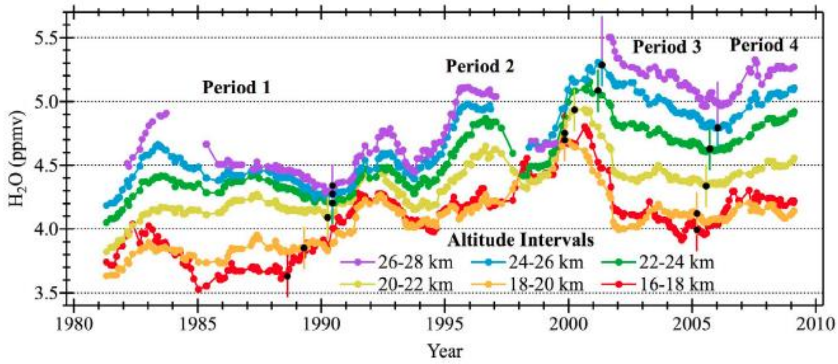

Figure 2-4: Water vapour changes between 1980s and 2010 from balloon frost point hygrometer measurements (from Hurst et al., 2011). Note, lower stratospheric water vapour changes are positive.

A knowledge gap in particular exists even for climatological water vapour distributions in the upper troposphere and lower stratosphere (**UTLS**) due to the lack of an observing system that can handle the difficulties of measuring in this region. Increasing opacity of the atmosphere challenges remote sensors, while low ambient pressures and temperatures challenge *in situ* observations.

Finally, the importance of accurately representing water vapour in global models and reanalyses can be understood from the impact that has been shown from water vapour changes around the tropopause on climate sensitivity (Nowack et al., 2015) and also (as recently pointed out in a technical report by ECMWF) in determining weather forecast skills (Shepherd et al., 2018). The fact that accurate representation of water vapour in reanalyses and global climate models is a general problem for modelling tools has been shown recently by Davis et al. (2017) and Hegglin et al. (2010) (see Figure 2-5), respectively, with models consistently showing too large water vapour values in the UTLS.

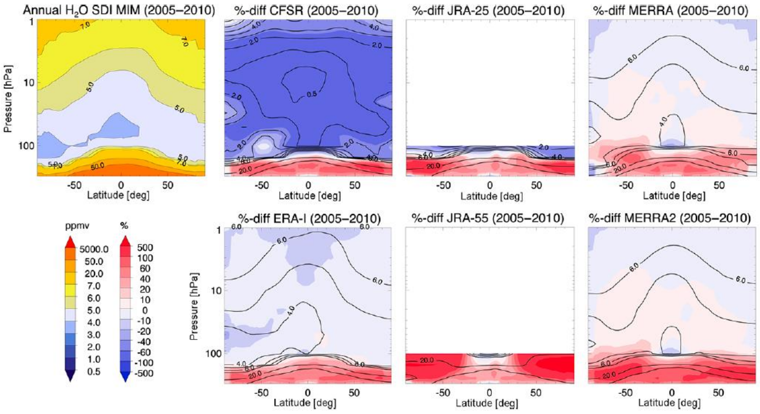

Figure 2-5: Comparison of zonal mean water vapour climatologies from reanalyses and the SPARC Data Initiative multi-instrument mean (from Davis et al., 2017). Note the large positive biases in water vapour in the UTLS.

3. REQUIREMENTS FOR ECV WATER VAPOUR

This section summarises publicly available user requirements for climate data records from different sources, organised according to the different ECVs of water vapour, i.e. TCWV, tropospheric, UTLS, and stratospheric profiles of water vapour. If not stated otherwise global coverage is required. Note that explicit user requirements on temporal coverage are typically not available. However, the climate user group was asked to provide feedback on this variable (see consolidated results in Section 6).

Some sources provide different categories of requirement standards (e.g. threshold, target, objective) in order to accommodate different levels of stringency of climate user needs. The following definitions are adopted to define threshold, breakthrough (also referred to as target), and goal (also referred to as objective) for observation requirements.

- **Threshold:** The limit beyond which the data is of no use to a given application.
- **Breakthrough / Target:** The level at which significant improvement in the given application would be achieved.
- **Goal / Objective:** The level beyond which further improvement would be of no value for the given application.

The following definitions are adopted for the different requirements, closely following the VIM uncertainty definition guidelines (JGCM, 2012), where not otherwise stated:

- **Accuracy:** Here refers to the closeness between a measured value and the true value of the measurand, including the effects of systematic errors. JGCM (2012) also states that "the concept 'measurement accuracy' is not a quantity and is not given a numerical quantity value. A measurement is said to be more accurate when it offers a smaller measurement error."
- **Bias**: An estimate of the systematic measurement error.
- **Precision:** Here describes the random (unpredictable) variability of repeated measurements of the measurand.
- **Uncertainty:** Non-negative parameter, associated with the result of a measurement that characterises the dispersion of the values that could reasonably be attributed to the measurand.
- **Temporal resolution:** Frequency the observations are provided in.
- **Spatial resolution (horizontal and vertical):** Nominal resolution of an observation (taking into account the influence of the satellite's viewing geometry).
- **Stability:** Refers to the property of a measuring instrument, whereby its metrological properties remain constant in time. Alternatively, the maximum acceptable long-term change in the systematic error, usually per decade.
- **Length of data record:** Time period a data record covers.

3.1 Total Column Water Vapour (TCWV)

Table 3-1 provides requirements for TCWV as defined by different organisations (or user groups).

Table 3-1: Requirements for TCWV by application and user group. Threshold, breakthrough, and goal requirements are given where available

Source	Frequency	Resolution (spatial)	Measurement Uncertainty	Stability	Reference
Global NWP					
WMO	12 h 6 h 1 h	250 km 50 km 25 km	5 kg/m^2 2 kg/m^2 2 kg/m^2	Not available	WMO OSCAR
Climate Monitoring & Applications					
WMO (AOPC)	6 h 4 h 3 h	200 km 100 km 50 km	3 kg/m^2 1.4 kg/m^2 1 kg/m^2	Not available	WMO OSCAR*
GCOS	4 h	25 km	2%	0.3% dec^{-1}	GCOS (2016)
GEWEX	3 h	10 km	2%	0.3% dec^{-1}	G-VAP assessment plan (2013)
ESA DUE GlobVapour	daily and monthly	≤ 0.5°, 55 km	5 kg/m^2 2 kg/m^2 1 kg/m^2	Not available	Saunders et al. (2010)
Climate Science & Modelling					
CMUG	daily and monthly	100 km	5%	0.08 kg m^{-2} dec^{-1}	CMUG (2020)

***** Values are provided despite deemed deprecated by WMO.

Some notes to the different sources of requirements. *WMO OSCAR* defines the following application areas with direct links to climate: climate monitoring (GCOS), climate application (WMO, Commission for Climatology, climate services) and climate science (WCRP, international research). While WMO is still updating the requirements that are compiled and accessible via https://www.wmo-sat.info/oscar/requirements, we provide the requirements for the application areas Global NWP, Climate Monitoring and Applications, and Climate Science and Modelling, separately.

The *GCOS* requirements should be considered target requirements, here defined as the requirements that data providers should aim to achieve over the next 10 years. As this would be applicable in 2026 we consider the GCOS requirements to be the goal requirements when applied to the WV_cci CDR products. Note, the GCOS requirements are currently being updated with a new version due in 2022. It is further noted in GCOS-200 that "t*he required measurement uncertainties are presented as 95% confidence intervals (approximately two standard deviations)*", following WMO (2012). WMO (2012) further outlines that the uncertainty should include contributions "*from random effects and from imperfect correction of the results of systematic effects*". However, WMO (2012) also states that "*a compensation factor can be applied to compensate for the systematic effect. Typically, appropriate calibrations and/or adjustments should be performed to eliminate systematic errors of sensors*". Such approaches would introduce uncertainties by themselves which subsequently would need to be quantified.

GEWEX requirements are taken from the G-VAP assessment plan (available at http://gewex-vap.org/?page_id=19). GEWEX requires global products covering the period 1979 to present and verified quality.

The ESA DUE GlobVapour project information was obtained from a survey of user requirements which was summarised in the requirements baseline document (Saunders et al., 2010, not available online anymore).

The CMUG requirements were obtained from the CMUG Baseline Requirements Document (D1.1 v2.2, 2020) and reflect requirements specifically defined by the climate modellers.

3.2 Tropospheric vertically resolved water vapour (VRes WV)

Table 3-2 provides requirements for tropospheric VRes WV as defined by different organisations (or user groups). See Section 3.1 for additional details of the different sources.

Table 3-2: Requirements for tropospheric VRes WV by application and user group. Threshold, breakthrough, and goal requirements are given where available

Source	Frequency	Resolution (spatial/vertical)	Measurement Uncertainty	Stability	Reference
Global NWP					
WMO (AOPC)	12 h 6 h 1 h	250 km / 3 km 50 km / 1 km 15 km / 0.5 km	20% 5% 2%	Not available	WMO OSCAR*
Climate Monitoring & Applications					
GCOS	4 h	25 km / 2 km	5%	0.3% dec^{-1}	GCOS (2016)

GEWEX**	3 h	10 km	5%	0.3%	GVAP (2013)
ESA DUE GlobVapour	hourly, daily, or monthly	0.25°, 28 km / 10, 5, 2 layers	20% 8% 5%	Not available	Saunders et al. (2010)

***** Values are provided despite deemed deprecated by WMO.
** These values are specified for profiles of specific humidity.

3.3 UTLS vertically resolved water vapour (VRes WV)

Table 3-3 provides requirements for UTLS VRes WV as defined by different organisations (or user groups). See Section 3.1 for details of the different sources. An additional source for measurement requirements that can be seen to reflect community consensus is obtained from the satellite mission selection report of the Earth Explorer 7 candidate PREMIER (ESA, 2012). Note, SPARC is contributing regularly to the GCOS observation requirement updates and its requirements are obtained from the OSCAR WMO RRR website (https://www.wmo-sat.info/oscar/requirements).

Table 3-3: Requirements for UTLS vertically resolved water vapour by application and user group

Source	Frequency	Resolution (spatial/vertical)	Measurement Uncertainty	Stability	Reference
Climate Monitoring & Applications					
WMO (AOPC)	6 h 4 h 3 h	200 km / 3 km 100 km / 2.5 km 50 km / 2 km	20% 5% 2%	Not available	WMO OSCAR*
PREMIER**	daily	50 km / 0.5 km 100 km / 2 km	5% 30%	Not available	ESA (2012)
Climate Science & Modelling					
WMO (WCRP)	12 h 6 h 3 h	50 km / 2km 37 km / 1 km 25 km / 0.5 km	20% 10% 5%	Not available	WMO OSCAR*
WMO (SPARC)	3 days 12 h 6 h	500 km / 2 km 100 km / 1 km 50 km / 0.5 km	5% 3% 2%	Not available	WMO OSCAR*
CMUG***	Daily / monthly	100 km / not available	5%	0.08 kg m^{-2} dec^{-1}	CMUG (2020)

* Values are provided despite deemed deprecated by WMO.
**Values reflect target and threshold requirements.
***Values specify UTLS column water vapour, however, depth or vertical resolution are not specified.

3.4 Stratospheric vertically resolved water vapour (VRes WV)

Table 3-4 provides requirements for stratospheric VRes WV as defined by different organisations (or user groups). See Sections 3.1 and 3.3 for details of the different sources.

Table 3-4: Requirements for stratospheric vertically resolved water vapour by application and user group

Source	Frequency	Resolution (spatial/vertical)	Measurement Uncertainty	Stability	Reference
Climate Monitoring & Applications					
WMO (AOPC)	6 h 4 h 3 h	200 km / 5 km 100 km / 3 km 50 km / 2 km	20% 5% 2%	Not available	WMO OSCAR*
GCOS	daily	100–200 km / 2 km	5%	0.3% dec^{-1}	GCOS (2016)
PREMIER**	daily	50 km / 0.5 km 100 km / 2 km	5% 30%	Not available	ESA (2012)
Climate Science & Modelling					
WMO	12 h 6 h 3 h	250 km / 3 km 100 km / 2.5 km 50 km / 2 km	20% 10% 5%	Not available	WMO OSCAR*

* Values are provided despite deemed deprecated by WMO.
**Values reflect target and threshold requirements.

4. ANALYSIS OF USER FEEDBACK ON ECV WATER VAPOUR REQUIREMENTS

The aim of the user requirements survey was to help identify user needs and data requirements for water vapour CDRs in climate applications, which complement and potentially update GCOS requirements and which then will guide the project in the CDRs' design and evaluation.

The survey was carried out between September and November 2018 (with answers being sent in before the end of February 2019) and included 18 questions on the primary and secondary CDRs that people are interested in (**Q1, Q2, Q5**), the kind of applications these CDRs are being used for (**Q3, Q5**), other ESA CCI CDRs that the people use (**Q4**), spatial domain (**Q6**), preferred data level (L2, L3, L4) (**Q7**), spatial resolution (vertical **Q8**; horizontal **Q9**), CDR length (**Q10**), temporal resolution (**Q11**), accuracy requirements (**Q12**), precision requirements (**Q13**), stability requirements (**Q14**), other uncertainty information (**Q15**), clarifications and further comments (**Q16**), other aspects of CDR development (**Q17**), and interest in contributing to WV_cci (**Q18**). The questionnaire has been kept short (about 12 minutes on average to provide answers to all questions) in order to enhance the likelihood of obtaining answers to all of the questions.

Results from the survey are interpreted as follows: *Threshold* – weakest requirement with more than one response; *target* – peak in response; and *objective* – most demanding requirement with more than one response.

This survey was sent out to members of the WV_cci Climate Research Group (CRG), the WV_cci extended user group, CMUG, participants of the SPARC OCTAV-UTLS activity, and the wider research community identified to have a potential interest in atmospheric water vapour (including IGAC/SPARC CCMI and GEWEX G-VAP mailing lists). The survey received **38 responses** in total by the end of February 2019. Note, not all questions have been answered comprehensively.

4.1 Primary and secondary uses of water vapour CDRs (Q1/Q2)

Here we will look at the first two questions

Q1 – Please indicate the WV climate data record(s) you are most interested in

Q2 – Please indicate other WV climate data record(s) you may be interested in

The answers to Q1 and Q2 are compiled in Figure 4-1 and Figure 4-2, respectively. The analysis indicates that there is about equal interest in stratospheric (VRes WV) and tropospheric (TCWV) water vapour CDRs among the respondents. Notably, the most chosen answer was the CDR in the UTLS (VRes WV), potentially due to no such consolidated dataset being available as of yet. While the water vapour isotopologues have only obtained two votes in Q1, Q2 indicates that there is substantial interest in such a CDR as well (see Figure 4-2) as a secondary source of information. Scientifically, these results make sense since water vapour isotopologues on their own are not enough to infer process-knowledge, but their usage is most often combined with vertical profiles of water vapour. For Q2, additional answers included total atmospheric water vapour, planetary boundary layer (PBL) water vapour, free lower tropospheric water vapour (950–700 hPa), and highly resolved tropopause temperature.

It seems important to note, as pointed out by one of the respondents, that the results of the survey do not necessarily reflect the relative importance of the different CDRs in fundamentally advancing the field in one or the other respect, because the different user communities may not have been sampled in a statistically representative way.

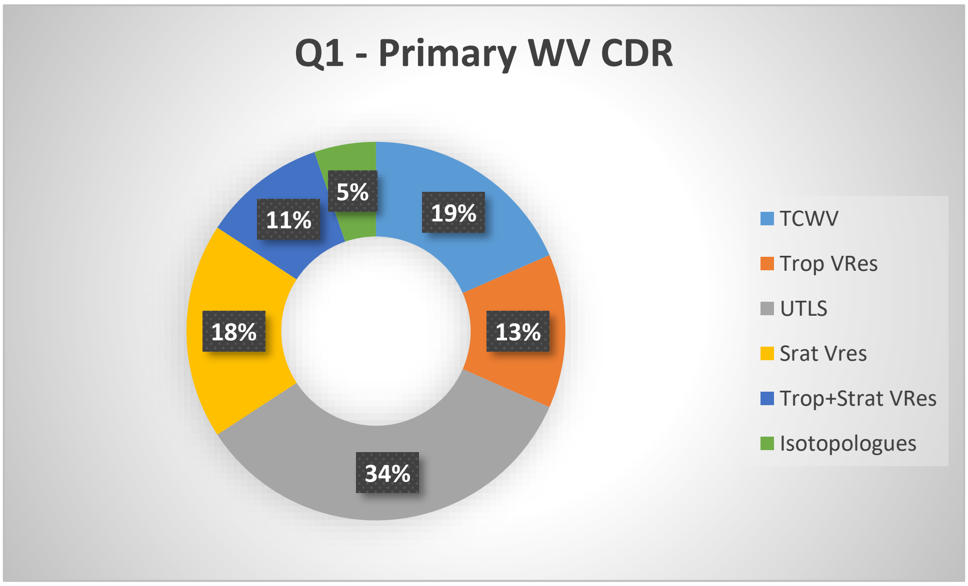

Figure 4-1: Analysis of Q1. The primary water vapour CDR of interest to our users as expressed in percentage numbers.

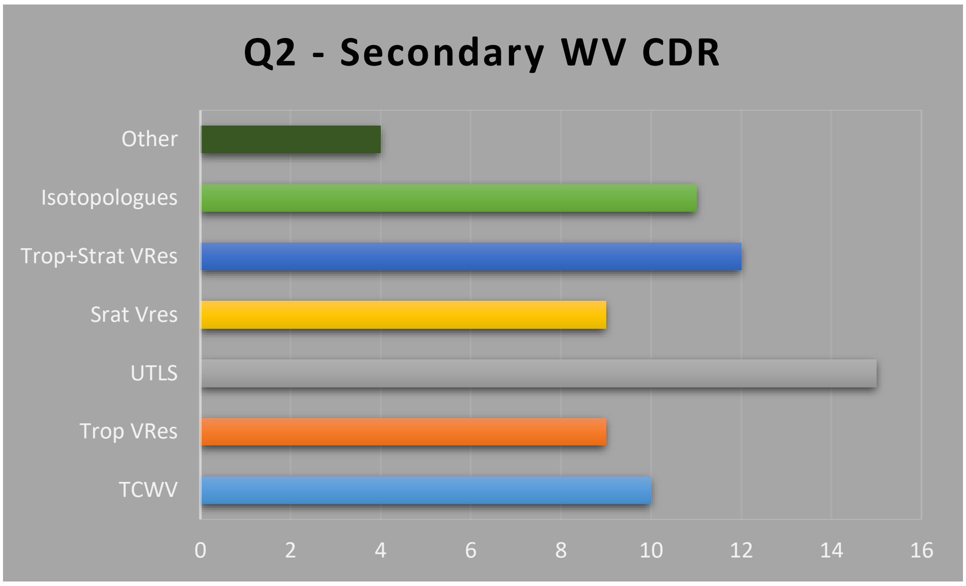

Figure 4-2: Analysis of Q2. The secondary water vapour CDR of interest to our users as expressed in absolute numbers.

4.2 What are the main applications of WV CDRs? (Q3)

Q3 – Please choose up to five activities you are using WV CDRs for

Q3 asked for information on the main application the users intend to use the WV CDRs for. The results can be seen in Figure 4-3. Most of the responders (55%–65%; or 21, 25, and 22, respectively) use or will use the WV CDRs for climate monitoring, the study of climate variability, or the study of climate processes. A total of 17 responders (45%) indicated to use WV CDRs for budget considerations (atmospheric radiation budget, water cycle, and energy cycle, although the latter to a lesser extent). Currently, around 18% of the users use WV CDRs for the study of climate and weather impacts (but did not specify droughts and flooding as such). More users are interested in the midlatitudes and polar regions than in the tropics. Other applications the respondents mentioned under the category 'other applications' were model evaluation, chemistry–climate interactions, study of dynamical processes in the UTLS, and cloud distribution and changes.

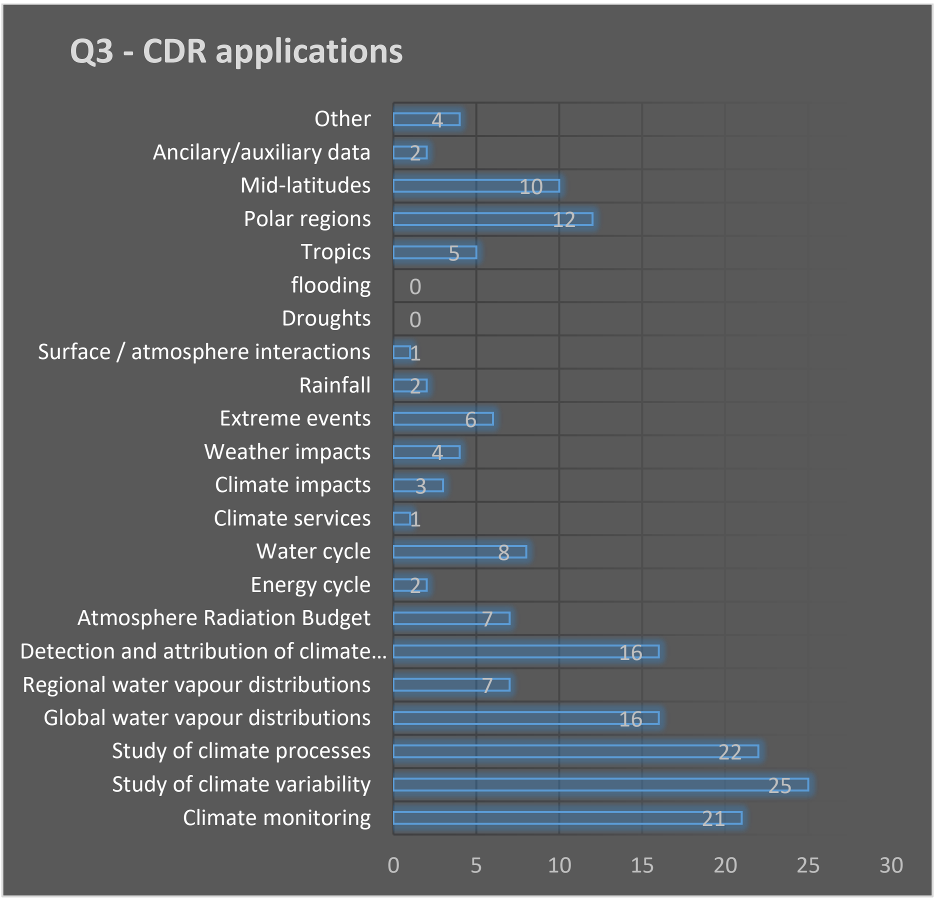

Figure 4-3: Analysis of Q3. Main applications given as number of total users.

4.3 Other ESA ECVs of interest (Q4)

Q4 – What other CDRs from ESA CCI are/will you be using along with the WV CDR?

Between 40% and 70% of the respondents to our survey expressed interest in using each of the following ESA CCI ECVs along with the WV CDR: **Ozone, aerosol, clouds, sea surface temperature, and GHGs**. The ECVs of **land surface temperature, sea-ice, snow and soil moisture** also attracted at least some interest (with around 15% of all respondents choosing at least one of them), while **fire, salinity, biomass, ocean colour, and permafrost** were chosen less frequently (by only 10% of all respondents). A CDR of interest that is currently not among the list of the ESA CCI ECVs **is vertically resolved atmospheric temperature** (indicated by almost 10% or three respondents).

4.4 Current use of WV CDRs (Q5)

Q5 – Do you currently use WV CDRs?

About half of the respondents have indicated that they already use WV CDRs, while the other half (except one respondent) are intending to use WV CDRs in the future (Q4). The list of CDRs of vertically resolved water vapour in the troposphere or UTLS as currently used by the community, include ECMWF and spatially limited passenger aircraft measurements (IAGOS and MOZAIC). These responses point towards the need for consolidated CDRs based on satellite observations for the ECVs: vertically resolved water vapour in the troposphere and UTLS.

TCWV:	HIRS, METEOSAT, ROM SAF, and the G-VAP archive
Vertically resolved tropospheric WV:	ECMWF
Vertically resolved UTLS WV:	ECMWF, MOZAIC, IAGOS
Vertically resolved stratospheric WV:	Frostpoint hygrometer, GOZCARDS, and SWOOSH
WV isotopes:	NDACC isotope observations

4.5 WV CDR spatial domain (Q6)

Q6 – Over what spatial domain do you require WV CDRs for your primary application?

The WV CDR spatial domain requested most is **global** (and three-dimensional), but there are also roughly 20% of the stratospheric VRes WV CDR users who are interested in zonal mean WV CDRs. Almost equal respondents were valuing information on the tropics (35%), the subtropics and midlatitudes (31%) or polar regions (34%). Note this is in contrast to Figure 4-3, for which we currently do not have an explanation, but which may reflect the difference between current use and future (preferred) use. Interestingly, the answers to this question were indicating interest between stratospheric and tropospheric focus to be about equal, although this may reflect only that more responses from the stratospheric user community were received.

4.6 WV CDR data level (Q7)

Q7 – What is the preferred data level for your primary application?

Data users indicate using **L2 (swath data)** and **L3 (gridded data)** about equally frequently. Only 2 out of the 38 respondents would use **L4 (gridded and model enhanced**, e.g. through data assimilation). These two respondents were users of TCWV products. This tendency is consistent with attitudes from researchers and modellers within the SPARC/IGAC Chemistry–Climate Model Initiative, who hitherto tend not to trust data assimilation products as much as original, 'clean' observations despite the benefits of being able to address sampling issues and data gaps.

4.7 WV CDR spatial resolution requirements (Q8/Q9)

Information on spatial resolution requirements were asked for both vertical and horizontal resolution. While the user survey did not ask these questions for the TCWV and VRes WV products separately, we here tried to disentangle the results based on what the respondents indicated as primary CDR for their research.

Q8 – For vertically resolved WV CDRs, what vertical resolution do you require?

Table 4-1 and Table 4-2 provide the numbers of answers for threshold, breakthrough, and objective as defined in Section 3 for the vertical resolution requirement for the troposphere/UTLS and stratosphere, respectively.

For the troposphere and UTLS, the threshold, breakthrough and goal requirements for the vertical resolution are **5 km, 100 m, and <100 m**, respectively. 5 km is really the minimum requirement, although a 1 km threshold was indicated by an equal number of respondents.

For the stratosphere, the threshold, breakthrough and goal requirements for the vertical resolution are **3 km, 1 km, and 500 m**, respectively.

Table 4-1: Analysis of Q8. Threshold, breakthrough, and goal vertical resolution requirements for vertically resolved WV CDRs in the troposphere and UTLS. The number of answers is given

	<100 m	100m	500m	1km	2km	3km	5km	8km
threshold	1	0	2	4	2	1	**4**	0
breakthrough	2	**7**	3	1	1	1	0	0
objective	**6**	4	0	1	1	0	0	0

Table 4-2: Analysis of Q8. Threshold, breakthrough, and goal vertical resolution requirements for vertically resolved WV CDRs in the stratosphere. The number of answers is given

	<100 m	100m	500m	1km	2km	3km	5km	8km
threshold	0	0	0	0	0	**4**	0	0
breakthrough	0	1	1	**1**	1	0	0	0
objective	1	0	**1**	2	0	0	0	0

Q9 – At what horizontal scale do you require WV CDRs?

Table 4-3 and Table 4-4 provide the numbers of answers for threshold, breakthrough, and objective as defined in Section 3 for the horizontal scale requirements for the troposphere/UTLS and TCWV products, respectively. The stratospheric CDR only got two answers for this question, so is not presented in a table but just summarised in words.

For the troposphere and UTLS, the threshold, breakthrough and goal requirements for the horizontal resolution are **500 km, 25 km, and <1 km**, respectively.

For the stratosphere (not shown), the threshold, breakthrough and goal requirements for the horizontal resolution are **500 km, 200 km, and 100 km**, respectively.

For TCWV, the threshold, breakthrough and goal requirements for the horizontal resolution are **100 km, 5 km, and 1 km**, respectively.

Table 4-3: Analysis of Q9. Threshold, breakthrough, and goal horizontal resolution requirements for WV CDRs in the troposphere and UTLS. The number of answers is given

	<1km	1km	5km	10km	25km	50km	100km	200km	500km
threshold	0	0	1	3	2	2	2	3	**2**
breakthrough	0	3	0	1	**5**	3	0	0	0
objective	**5**	2	1	3	1	0	0	0	0

Table 4-4: Analysis of Q9. Threshold, breakthrough, and goal horizontal resolution requirements for WV CDRs for the TCWV product. The number of answers is given

	<1km	1km	5km	10km	25km	50km	100km	200km	500km
threshold	0	0	1	1	2	0	**2**	0	0
breakthrough	0	2	**2**	0	0	1	1	0	0
objective	1	**1**	1	0	1	0	0	0	0

4.8 WV CDR temporal characteristics requirement (Q10/Q11)

This section presents the results for the temporal characteristics (CDR length and temporal resolution) that users require for their primary applications. The following two questions were asked in the survey:

Q10 – What is the length of the WV CDR that your primary application requires?

Table 4-5 shows the answers to Q10. From the answers to this survey question, the threshold for a useful CDR length is set at 10 years, while 20 years is considered breakthrough, and more than 30 years objective. Note, the length requirement for the vertically resolved troposphere and UTLS CDR is making up for most of the answers for thresholds smaller than and equal to 5 years. Answers for this CDR also lead to a bimodal distribution in the breakthrough and objective values when looked at closely. The numbers are hence given in bold and red, indicating the need for such a data record even if available for only a short time period.

Table 4-5: Analysis of Q10. Threshold, breakthrough, and goal for length requirements of WV CDRs. The number of answers is given. Black bold indicates the values for the TCWV and stratospheric vertically resolved CDRs, red bold the values for the tropospheric vertically resolved CDR

	<1 yr	1 yr	2 yrs	5 yrs	10 yrs	20 yrs	30 yrs	>30 yrs
threshold	1	**5**	2	4	**13**	1	2	2
breakthrough	0	0	1	**4**	5	**10**	7	3
objective	0	0	0	0	3	**4**	6	**12**

Q11 – What is the temporal resolution of the WV CDR that your primary application requires?

Table 4-6 shows the answers to Q11 for the VRes WV CDR in the troposphere and UTLS. From the answers to this survey question, the threshold for a useful CDR temporal resolution is set at **monthly**, while **daily** is considered breakthrough, and **<6-hourly** as objective. The one person voting for a temporal resolution threshold of one year is considered to lie in the noise level and we went for the more stringent value of monthly resolution instead.

For the stratosphere, where only three respondents gave an answer (results not shown in table format) threshold, breakthrough, and objective are **monthly, weekly, and daily**, respectively.

Table 4-6: Analysis of Q11. Threshold, breakthrough, and goal for temporal resolution requirements of CDRs for the VRes WV in the troposphere and UTLS. The number of answers is given

	<6-hrly	6-hrly	12-hrly	daily	weekly	monthly	yearly
threshold	1	1	0	4	2	**9**	1
breakthrough	3	3	0	**7**	3	0	0
objective	**8**	1	0	4	0	0	0

Table 4-7 shows the answers to Q11 for the TCWV CDR. From the answers to this survey question, the threshold requirement is **monthly,** and the objective requirement set at **<6-hourly**. For the breakthrough, daily and monthly would satisfy an equal number of respondents as <6 hourly, so the daily value is chosen as requirement. The one person voting for a temporal resolution threshold of one year is considered to lie in the noise level and we went for the more stringent value of monthly resolution instead.

Table 4-7: Analysis of Q11. Threshold, breakthrough, and goal for temporal resolution requirements of WV CDRs for the TCWV product. The number of answers is given

	<6-hrly	6-hrly	12-hrly	daily	weekly	monthly	yearly
threshold	1	2	0	0	0	**2**	1
breakthrough	3	0	0	**1**	0	2	0
objective	**3**	0	0	0	1	1	0

4.9 WV CDR quality (Q12/Q13/Q14)

Possibly the most relevant questions for the specification of the new WV CDRs are the ones around the quality requirements of the WV CDRs including accuracy, precision, and stability.

Q12 – What is the required accuracy for your primary application?

The term '*accuracy'* in this question should be understood as '*measurement uncertainty',* which determines whether a CDR is useful for a given climate application or not.

Table 4-8 shows the answers to Q12. The requirement for accuracy were generally defined by both the TCWV and VRes WV users at the same level with **25%, 5%, and <1%** for threshold, breakthrough, and objective, respectively. No significant differences were found between the different CDRs.

Table 4-8: Analysis of Q12. Threshold, breakthrough, and goal for accuracy requirements of WV CDRs. The percentage number of answers is given

	<1%	1%	5%	10%	20%	25%	>25%
threshold	6.7%	3.3%	16.7%	60%	3.3%	**10%**	0.0%
breakthrough	3.3%	26.7%	**56.7%**	13.3%	0.0%	0.0%	0.0%
objective	**20.7%**	55.2%	20.7%	3.4%	0.0%	0.0%	0.0%

Q13 - What is the required precision for your primary application?

Table 4-9 shows the answers to Q13. Maximum percentages are highlighted in bold. Requirements for the precision at threshold, breakthrough, and objective level were set at **25%, 5%, and <1%** respectively. No notable differences were found between TCWV and VRes WV CDRs. The 4% voting for a precision threshold of >25% are considered to lie in the noise level and we went for the more stringent value of 25%.

Table 4-9: Analysis of Q13. Threshold, breakthrough, and goal for precision requirements of WV CDRs. The percentage number of answers is given

	<1%	1%	5%	10%	20%	25%	>25%
threshold	8%	4%	20%	48%	8%	**8%**	4%
breakthrough	3.6%	35.7%	**57.1%**	3.6%	0.0%	0.0%	0.0%
objective	**25%**	50%	25%	0.0%	0.0%	0.0%	0.0%

Q14 - What is the required stability for your primary application?

Table 4-10 shows the answers to Q14. The answers for the stability requirements for both the TCWV and VRes WV CDRs were at **5% dec^{-1}, <1% dec^{-1}, and <0.5% dec^{-1}** for threshold, breakthrough, and objective requirements, respectively. No notable differences were found between TCWV and VRes WV CDRs.

Table 4-10: Analysis of Q14. Threshold, breakthrough, and goal for stability requirements. The percentage number of answers is given

	<0.5%/dec	<1%/dec	1%/dec	2.5%/dec	5%/dec	>5%/dec
threshold	3.7%	7.4%	40.7**%**	22.2%	**26%**	0.0%
breakthrough	11.1%	**48.2%**	29.6%	7.4%	3.7%	0.0%
objective	**54.2%**	25.0%	20.8%	0.0%	0.0%	0.0%

4.10 Other important quality indicators

Precision, accuracy, and stability as presented in Section 4.9 may not be the only quality requirements an end user may have, so the survey was also inquiring for other quality indicators of use to the user's specific application with the question:

Q15 - Please indicate what type of uncertainty you would like to obtain along with your water vapour CDR

Answers to this question are ordered here in the order of priority, with those highlighted in bold indicating those requested by more than 40% of the respondents:

- **Quality flags**
- **Full budget error analysis**
- **Systematic contribution to uncertainty (overall/mean bias)**
- Random uncertainty
- Uncertainty correlation (spatial and temporal)
- Bulk uncertainty.

4.11 Other comments (Q16/Q17/Q18)

Q16 – Please provide us here with any clarifications/comments on above questions

Only few clarifications were noted, of which the following should be taken into account:

- Precision can only be associated with L2 profiles, it is hence meaningless for L3 CDRs.
- Accuracy and stability are related terms, and accuracy is only meaningful if stability is assured.

Q17 – Please provide us here with any other comments about what you find important for the development of WV CDRs

Important points to consider when defining our WV CDRs according to the respondents are

- Stability, calibration, and anchoring of CDRs
- CDR should be generated from recognised FCDRs
- Better coverage should be achieved in the UTLS, and in particular for WV isotopes.

Q18 – Would you be interested in establishing further links to our project?

Twenty respondents are interested in establishing further links to the WV_cci, obtaining the summary of the data survey, a notification of new data releases, or getting involved in the research user group.

5. REQUIRED CLIMATE DATA RECORDS

Due to the importance of water vapour as ECV, there is a need to consolidate our knowledge of past and current changes as derived from observations and to establish climate data records for use in climate research. In accordance with the above research, the WV_cci goal was defined at delivering four climate data records, which were designed towards satisfying the key user requirements of the climate research community as identified in this URD. The CDRs include both total column water vapour (TCWV) and vertically resolved (VRes WV) data products, with the different CDRs sketched out in Figure 5-1 and explained in more detail below.

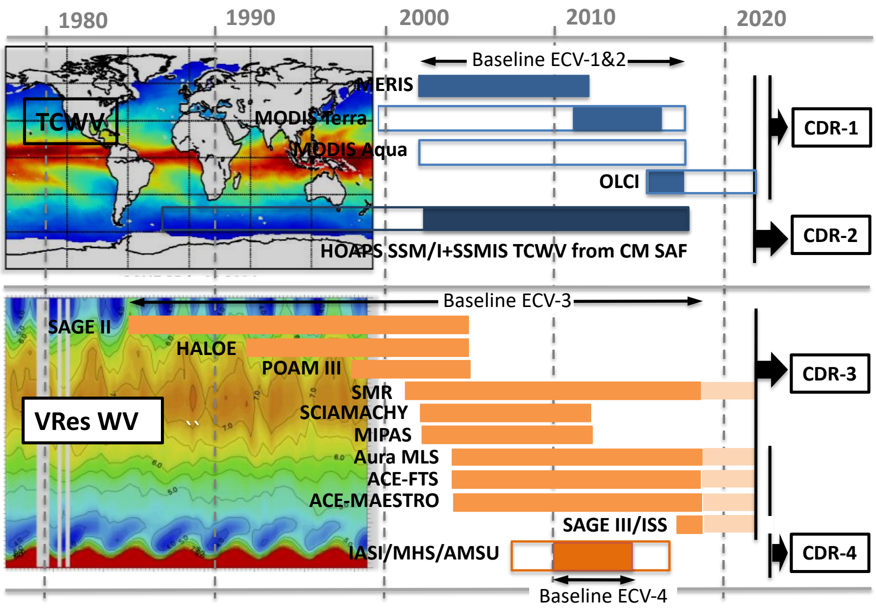

Figure 5-1: Climate data records (CDRs) prepared within the WV_cci.

In Figure 5-1, the different input observations are given in blue for the TCWV CDR outputs (CDR-1 and CDR-2) and in orange for the vertically resolved CDR outputs (CDR-3 and CDR-4). The black vertical line with the thick arrow on the right-hand side of the figure indicates which observations were merged in the different CDRs. The black double-headed horizontal and thin arrows indicate the time periods over which the merging of the data has been conducted. In the following a more detailed description of the different ECVs that were the main deliverables of the WV_cci is provided:

1) **TCWV CDR-1:** This total column water vapour CDR is based on NIR observations by MERIS, MODIS, and OLCI spanning the time period 2002 to 2017 with a spatial resolution of 0.05°/0.5° and as daily averages. Key challenges were to harmonise the time series due to issues around calibration performance, long-term stability and inconsistency between records. Consequently, sub-periods with at least one year of

temporal overlap between MERIS and MODIS as well as between MODIS and OLCI were processed and validated first to improve the stability of the product.

2) **TCWV CDR-2:** This total column water vapour CDR is based on NIR observations by MERIS, MODIS, and OLCI and complemented by microwave imager observations of HOAPS SSM/I and SSMIS spanning the time period 2002 to 2017 from EUMETSAT CM SAF with a spatial resolution of 0.05°/0.5° and as daily averages. The product takes advantage of the developments carried out within the ESA DUE GlobVapour project and makes use of the spatial complementarity of the land-based NIR and ocean-based microwave observations. Thus, the combined product has global coverage. Key challenges were to fill coastal and ice-covered areas and to achieve consistency between both products. The former aspect was addressed as in the GlobVapour project while the latter was not observed to be an issue within the precursor project.

3) **Stratospheric zonal mean water vapour CDR-3:** This vertically resolved, zonal mean (2D) water vapour CDR is based on a range of ESA, third-party and NASA instruments starting from SAGE II, HALOE, UARS-MLS, POAM III, SAGE III, SMR, SCIAMACHY, MIPAS, Aura-MLS, ACE-FTS, ACE-MAESTRO, and SAGE III/ISS, spanning the time period 1985 to the end of 2019. Before merging, the data records of the individual instruments have been validated following the approaches applied in the SPARC Data Initiative and WAVAS-II activities, in order to characterise the data records in terms of biases and stability. The merged data records will undergo another independent validation. Key challenge here is to overcome sampling issues and homogenisation of instruments that utilise rather different observation techniques, feature different vertical resolutions, precision and accuracies.

4) **Vertically resolved water vapour CDR-4:** This product delivers a prototype CDR of three-dimensional vertically resolved water vapour in the troposphere and lower stratosphere from 2010 to 2014 based on IMS, MIPAS, ACE-FTS, ACE-MAESTRO, and Aura-MLS. Key challenge is that the upper troposphere/lower stratosphere (UTLS) is the interface between the troposphere and the stratosphere with very complex dynamical, physical, and chemical properties, greatly challenging the performance of EO instruments. Production and validation of a water vapour ECV that spans this region needs to identify and take into account instrument limitations and sampling issues, which required the development of new merging and validation methodologies. The quality of the CDR thereby has been found to strongly dependent on the quality of the observations used in the merging process (which remains unsatisfactorily characterised due to a lack of independent reference data for validation).

6. USER REQUIREMENTS ON WV_cci PRODUCTS

In this section we present the consolidated information on water vapour CDR requirements as obtained from the user requirements survey conducted within WV_cci (see Section 4), but also taking into account the user requirements established from different sources (Section 3). Where conflicting requirements resulted, we justified our choice of WV_cci product requirements. We also accounted for the often very different answers for TCWV, vertically resolved WV in the UTLS, and vertically resolved WV in the stratosphere.

For the CDR length requirements threshold, target, and objective are **2, 20, and >30 years**, respectively, with the exception of vertically resolved WV in the UTLS, which indicated a lower threshold of only 5 years. This is notable since it clearly indicates the need for information (i.e. an observational reference) on UTLS water vapour distributions (presumably for model evaluation), independent of its length.

Generally, the user requirements derived from the survey provided more stringent requirements than those defined in other locations (see Section 3). An exception to this were the temporal requirements, where the survey seemed to request somewhat lower temporal resolution than those specified in these other sources. This is mostly due to the fact that our users reflect climate researchers and to a lesser extent people interested in numerical weather prediction, for which higher resolution data would be more valuable.

Finally, climate services define their products as '*climate information prepared and delivered to meet a user's needs*' (GCOS-200). The WV_cci will design its products according to this definition, with the aim to fulfil the above user requirements and support climate services. Consequently, requirements given in GCOS-200 are considered to be applicable for climate services as well. However, climate services in addition include the timely production and delivery of science-based trustworthy climate data, which is beyond what WV_cci could deliver. Other principles of climate services, such as involvement of customers and stakeholders (here users) in product development, free open access to essential data and metadata, and mechanisms to allow for user feedback will be incorporated in WV_cci.

Table 6-1: Threshold, breakthrough (target), and objective (goal) requirements obtained from the user requirements survey for L3 CDR-1 and CDR-2. Results from the survey are interpreted as follows: threshold – weakest requirement with more than one response; target – peak in response; and objective – most demanding requirement with more than one response

Product	Frequency	Resolution (spatial/vertical)	Accuracy: Systematic component	Accuracy: Random component	Stability
WV_cci CDR requirements					
CDR-1 and CDR-2 (TCWV)					
L3	monthly	100 km	25%	25%	5% dec^{-1}
	daily	5 km	5%	5%	<1% dec^{-1}
	<6-hourly	1 km	<1%	<1%	<0.5% dec^{-1}

* It is recalled that 18 (38) respondents accept a more relaxed threshold of up to 5 %/dec.

Table 6-2: Threshold, breakthrough (target), and objective (goal) requirements obtained from the user requirements survey for L2 and L3 CDR-3 and CDR-4

Product	Frequency	Resolution (spatial/vertical)	Accuracy: Systematic component	Accuracy: Random component	Stability
WV_cci CDR requirements					
CDR-3					
L2 & L3 (strat)	monthly	500 km / 3 km	25%	25%	*2.5% dec^{-1}
	weekly	200 km / 1 km	5%	5%	<1% dec^{-1}
	daily	100 km / 500 m	<1%	<1%	<0.5% dec^{-1}
CDR-4					
L2 & L3 (UTLS)	monthly	200 km / 5 km	25%	25%	1% dec^{-1}
	daily	25 km / 100 m	5%	5%	<1% dec^{-1}
	<6 hourly	<1 km / <100 m	<1%	<1%	<0.5% dec^{-1}

* It is recalled that 18 (38) respondents accept a more relaxed threshold of up to 5 %/dec.

For the following reasons it is proposed to consider separation of accuracy requirements into systematic and random components in case of global satellite remote sensing of atmospheric water vapour: (1) it is anticipated that it is hardly possible to estimate and verify a bias which is applicable on global scale and over the full period. Thus, if estimated and verified for a subsample of atmospheric conditions it may over-/under correct in other conditions and indicates superior quality what is at least not known, (2) the bias should be understood and then reduced by improved calibration or retrieval schemes. If not understood it seems fair to increase the uncertainty rather than correcting for an unknown effect. WMO (2012) states that "the observed mean value has to be corrected for the systematic error insofar it is known." (3) For applications which include adaptations of resolution or averaging it is desirable to have separate uncertainty terms for systematic and random uncertainty components.

7. SUMMARY AND CONCLUSIONS

Generally, the user requirements for the WV_cci derived from the survey answers provided more stringent requirements than those defined in other sources (see Section 3). These may reflect the achievements made in instrument development over the past decade, which led generally to better performance of remote sensors.

An exception to this were the temporal requirements, where the survey seemed to request somewhat lower temporal resolution than those specified. Likely reason for the latter is that our users represent researchers from the climate and to a lesser extent from the weather and numerical weather prediction (NWP) community. Nonetheless, the requirements pose a great challenge to WV_cci given the currently available observations. In particular, for the vertically resolved observations in the UTLS, users require a threshold for vertical resolution that is just about achievable, but with breakthrough and objective values being much higher than what any of the current instruments can offer. Also, both the thresholds for systematic and random components of the uncertainty will be very difficult to comply with for the CDR-4 product. While a 'proper' evaluation of the quality of satellite observations in the UTLS is still lacking, current estimates look at biases that are ±15% from the multi-instrument mean (or 30% maximum for inter-instrument biases; see Hegglin et al., 2013). We further note that an uncertainty requirement of 10% as threshold for TCWV can be challenging at least on regional scale because the clear-sky bias is in the order of 10%.

The PSD compares in detail how the expected data specification agrees with the user requirements.

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APPENDIX 2: GLOSSARY

Term	Definition
CCI	Climate Change Initiative
CDR	Climate Data Records
CMUG	Climate Modelling User Group
CRG	Climate Research Group
ECV	Essential Climate Variable
GAW	Global Atmosphere Watch
GCOS	Global Climate Observing System
GEWEX	Global Energy and Water Exchanges
PSD	Product Specification Document
SPARC	Stratosphere-troposphere Processes and their Role in Climate
TCWV	Total Column Water Vapour
URD	User Requirements Document
UTLS	Upper Troposphere and Lower Stratosphere
WCRP	World Climate Research Programme
WMO	World Meteorological Organization

End of Document