EUMETSAT Satellite Application Facility on Climate Monitoring

Requirements Review

TCDR ERA_WV_T ed. 2 CM-14712

(Upper Tropospheric Humidity)

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1.2	17/03/2020	SAF/CM/UKMO/RR/3.6	Added FY-3A to Table 31-2, corrected a couple of typos.

Applicable Documents

Reference	Title	Code
AD 1	CM SAF Product Requirements Document	SAF/CM/DWD/PRD/2.10

Reference Documents

Reference	Title	Code
RD 1	ERACLIM2-D3.11 - Microwave Humidity Sounder Radiance Data Record, v1B Draft, 10 August 2017 (available from www.era-clim2.eu/products under D3.11	EUM/OPS/TEM/17/926984
RD 2	Algorithm Theoretical Basis Document CM SAF Upper Tropospheric Humidity TCDR Edition 1.0	SAF/CM/UKMO/ATBD/UTH/1.2
RD 3	EUMETSAT/C3S Fundamental Climate Data Record of 183 GHz Microwave Brightness Temperatures, Validation Report	SAF/CM/UKMO/VAL/FCDR_MWAVE/1.1
RD 4	CM SAF Upper Tropospheric Humidity (UTH) Edition 1.0 Validation Report	SAF/CM/UKMO/VAL/UTH/1.2

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1 Executive Summary

This report provides the requirements for version 2 (v2) of the CM SAF MicroWave (MW) Upper Troposphere Humidity (UTH) product. Requirements are defined based on:

1. A review of existing requirements for MW UTH, e.g. from GCOS
2. Open actions resulting from the review process for the CM SAF UTH v1 (CM-14711) product
3. Advances in satellite remote sensing at 183 GHz and UTH since the CDOP-2 Requirements Review (RR)
4. Results from an online survey with global reach
5. Insights gained from discussions with users, including the CM SAF User Workshop in 2019
6. A validation strategy based on expert knowledge

Throughout this document "%" refers to the fraction of saturation, not the fractional accuracy of a measurement.

Three types of requirement are utilised in this RR:

- “REQ”: A requirement that must be addressed. When questions are asked in terms of a threshold, breakthrough or objective requirement, the threshold requirement is used here.
- “OPT”: An optional requirement that should be met where possible. This aligns with the breakthrough requirement definition.
- “ADV”: An advisory requirement that should be considered where feasible. These are used where requirements cannot be defined quantitatively, for example from discussions with users, or free text questions provided in online questionnaire.

Where the:

- Threshold level is defined here to be “the limit beyond which the data is of no use for the given application”,
- Breakthrough is “the level at which significant improvement in the given application would be achieved”, and
- Objective is “the level beyond which no further improvement would be of value for the given application

A key objective for this RR is to provide requirements with clear traceability. To assist with this, requirements are defined in this document with an identification number. This number includes traceability to this requirement review (CM SAF RR3.6), the type of requirement (“REQ”, “OPT” or “ADV”), and the source, which may be one or more of:

- ‘E’: Existing requirements, e.g. from GCOS
- ‘A’: Open actions from previous CM SAF UTH review meetings, or from the CM SAF Steering Group
- ‘Q’: Online questionnaire
- ‘U’: User insights

- 'O': Other, e.g. project team expertise, state of the art.

A summary of the complete set of requirements for the CM SAF UTH v2 (CM-14712) product is provided in the table below. Mandatory requirements are highlighted in blue, optional requirements are highlighted in green and advice notes are highlighted in grey.

ID	Requirement	Source
Spatial Domain and Resolution		
CMSAF-RR3.6-03-ADV-E	Provide a UTH product with spatial resolution of ≤25 km	GCOS
CMSAF-RR3.6-13-ADV-Q	Provide global UTH data	Questionnaire Q12
CMSAF-RR3.6-17-REQ-Q	Provide UTH data at a spatial resolution of 1° latitude/longitude	Questionnaire question 15
CMSAF-RR3.6-18-OPT-Q	Provide UTH data at a spatial resolution of 0.5° latitude/longitude	Questionnaire question 15
Data set length and temporal resolution		
CMSAF-RR3.6-04-ADV-E	Provide a UTH product with temporal resolution of ≤hourly	GCOS
CMSAF-RR3.6-15-REQ-Q	Provide at UTH record of 20 years	Questionnaire question 14
CMSAF-RR3.6-16-OPT-Q	Provide a UTH record of at least 30 years	Questionnaire question 14
CMSAF-RR3.6-19-REQ-QU	Provide UTH data at 12-hourly temporal resolution	Questionnaire question 16, user insights
CMSAF-RR3.6-20-OPT-Q	Provide UTH data at 3-hourly temporal resolution	Questionnaire question 16
CMSAF-RR3.6-21-REQ-Q	Provide UTH data arranged by Universal Time (e.g. global time slices at 0 UT)	Follow-up to questionnaire question 16.
Data set accuracy, precision and stability		
CMSAF-RR3.6-02-ADV-E	Provide a UTH product with accuracy of ≤5%	GCOS

ID	Requirement	Source
CMSAF-RR3.6-22-REQ-QU	Provide UTH data with accuracy of 5%	Questionnaire question 17, user insights
CMSAF-RR3.6-23-OPT-Q	Provide UTH data with accuracy of 1%	Questionnaire question 17
CMSAF-RR3.6-24-REQ-Q	Provide UTH data with precision of 2%	Questionnaire question 18
CMSAF-RR3.6-25-OPT-Q	Provide UTH data with precision of 1%	Questionnaire question 18
CMSAF-RR3.6-01-ADV-E	Provide a UTH product with stability of 0.4 %/decade	Theoretically defined based on the literature
CMSAF-RR3.6-26-REQ-Q	Provide UTH data with stability of 1%/decade	Questionnaire question 19
CMSAF-RR3.6-27-OPT-Q	Provide UTH data with stability of 0.1%/decade	Questionnaire question 19
Quality flags and uncertainty information		
CMSAF-RR3.6-07-ADV-AOU	Provide uncertainties for each pixel/grid cell	Review board suggestion, project team expertise/state of the art, user insights
CMSAF-RR3.6-08-REQ-AOQU	Provide a set of detailed quality flags per pixel/grid cell indicating any specific problems with the data, e.g. suspected surface contamination, suspected thick cloud contamination, calibration concerns, etc	Review board suggestion, questionnaire question 20, project team expertise/state of the art, user insights
CMSAF-RR3.6-28-REQ-Q	Provide simple statements on the general accuracy, precision and stability of the data set e.g. from validation studies	Questionnaire question 20
Validation		
CMSAF-RR3.6-12-ADV-QU	Validate pixel/grid-cell uncertainties provided with the UTH data	Questionnaire question 11, user insights

ID	Requirement	Source
CMSAF-RR3.6-33-ADV-O	Validate UTH using ERA-5, assessing mean differences, standard deviations, percentiles and anomalies.	Project team expertise, literature
	Data set construction	
CMSAF-RR3.6-05-ADV-A	Investigate the use of a surface temperature and/or cloud climatology to distinguish between pixels contaminated with cloud or surface.	Review board suggestion
CMSAF-RR3.6-06-ADV-A	Investigate the use of a simple mean to calculate daily averages, rather than weighting overpasses	Review board suggestion
CMSAF-RR3.6-10-ADV-O	Derive the CM SAF UTH v2 product from the consistent FIDUCEO and EUMETSAT FCDRs for SSM/T-2, AMSU-B, MHS, ATMS, and MWHS-1 & -2.	State of the art, project team expertise
CMSAF-RR3.6-11-ADV-O	Investigate the retrieval approach used in FIDUCEO for producing the CM SAF UTH v2 product	State of the art, project team expertise
CMSAF-RR3.6-14-REQ-Q	Provide both time-averaged and single-overpass time data on a uniform grid	Questionnaire Q13
	Data set documentation, user feedback and other data	
CMSAF-RR3.6-09-ADV-OQU	Provide users with a clear explanation of what the CM SAF UTH v2 product represent, full details of how the data were derived and how they can be used (ideally as published papers). This should also include a short 'quick start guide' that communicates the most important points.	Project team expertise, questionnaire Q10 & Q23, user insights
CMSAF-RR3.6-	Include elements from the examples of existing good data sets in UTH	Questionnaire question 21.

ID	Requirement	Source
29-ADV-Q	products	
CMSAF-RR3.6-30-ADV-QU	Include additional variables in UTH products	Questionnaire question 23, user insights
CMSAF-RR3.6-31-ADV-QUA	Provide height or pressure information with the UTH data	
CMSAF-RR3.6-32-ADV-Q	Provide examples of good data portals and feedback mechanisms to the CM SAF team.	Questionnaire question 23

2 The EUMETSAT SAF on Climate Monitoring

The importance of climate monitoring with satellites was recognized in 2000 by EUMETSAT Member States when they amended the EUMETSAT Convention to affirm that the EUMETSAT mandate is also to “contribute to the operational monitoring of the climate and the detection of global climatic changes". Following this, EUMETSAT established within its Satellite Application Facility (SAF) network a dedicated centre, the SAF on Climate Monitoring (CM SAF, http://www.cmsaf.eu).

The consortium of the CM SAF currently comprises the Deutscher Wetterdienst (DWD) as host institute, and the partners from the Royal Meteorological Institute of Belgium (RMIB), the Finnish Meteorological Institute (FMI), the Royal Meteorological Institute of the Netherlands (KNMI), the Swedish Meteorological and Hydrological Institute (SMHI), the Meteorological Service of Switzerland (MeteoSwiss), and the Meteorological Office of the United Kingdom (UK Met Office). Since the beginning in 1999, the EUMETSAT Satellite Application Facility on Climate Monitoring (CM SAF) has developed and will continue to develop capabilities for a sustained generation and provision of Climate Data Records (CDRs) derived from operational meteorological satellites.

In particular the generation of long-term data records is pursued. The ultimate aim is to make the resulting data records suitable for the analysis of climate variability and potentially the detection of climate trends. The CM SAF works in close collaboration with the EUMETSAT Central Facility and liaises with other satellite operators to advance the availability, quality and usability of Fundamental Climate Data Records (FCDRs) as defined by the Global Climate Observing System (GCOS). As a major task the CM SAF utilizes FCDRs to produce records of Essential Climate Variables (ECVs) as defined by GCOS. Thematically, the focus of the CM SAF is on ECVs associated with the global energy and water cycle.

Another essential task of the CM SAF is to produce data records that can serve applications related to the new Global Framework of Climate Services initiated by the World Meteorological Organisation (WMO) World Climate Conference-3 in 2009. The CM SAF supports climate services at national meteorological and hydrological services (NMHSs) with long-term data records but also with data records produced close to real time that can be used to prepare monthly/annual updates of the state of the climate. Both types of products together allow for a consistent description of mean values, anomalies, variabilities and potential trends for the chosen ECVs. The CM SAF ECV data records also serve the improvement of climate models both at global and regional scales.

As an essential partner in the related international frameworks, in particular WMO SCOPE-CM (Sustained Coordinated Processing of Environmental satellite data for Climate Monitoring), the CM SAF, together with the EUMETSAT Central Facility, assumes the role as main implementer of EUMETSAT’s commitments in support to global climate monitoring. This is achieved through:

- Application of the highest standards and guidelines as outlined by GCOS for satellite data processing,

- Processing of satellite data within a true international collaboration benefiting from developments at international level and pollinating the partnership with its own ideas and standards,
- Intensive validation and improvement of the CM SAF climate data records,
- Taking a major role in data record assessments performed by research organisations such as World Climate Research Program (WCRP). This role provides the CM SAF with strong contacts to research organizations that form a substantial user group for the CM SAF CDRs,
- Maintaining and providing an operational and sustained infrastructure that can serve the community within the transition of mature CDR products from the research community into operational environments.

A catalogue of all available CM-SAF products is accessible via the CM-SAF webpage, www.cmsaf.eu/. There, detailed information about product ordering, add-on tools, sample programs and documentation is provided.

3 Background of the CM SAF UTH product under review

Table 3-1 provides details of the product under review for this RR 3.6. This product constitutes version 2 (v2) of the CM SAF Upper Tropospheric Humidity (UTH) product. The product will be based on version 1 (v1) of the CM SAF UTH product, but with modifications reflecting recommendations and experience acquired in CDOP-2 (Section 6), advances in technology, available data and knowledge (Section 7), and user requirements (Sections 8 and 9).

Table 3-1: CM SAF products under review

Product Family	New CM SAF Product Identifier	Product Name	Previous CM SAF Product Identifier
Water Vapour	CM-14712	TCDR ERA_WV_T ed. 2	CM-14711

3.1 Heritage of product

Möller (1961) explained how emission to space in the 6-7 µm region around the v2 line of water vapour at 6.3 µm "can be used as a hygrometer rather than as a thermometer." Emission there is dominated by tropospheric water vapour, whose concentration is given by RH and by temperature. This temperature dependence and that of the Planck function effectively cancel to leave the emission depending on the RH. This does not depend on any physics specific to this spectral region, although of course it would be exactly true only under idealised approximations. (RH and lapse rate are assumed constant with height and the pressure broadening of spectral lines is ignored.)

The term UTH seems to have been introduced by Schmetz and Turpeinen (1988), in their analysis of the early Meteosat's 6.3 µm radiometer. The physics applies equally well to water-vapour dominated regions at microwave frequencies. However, where total column water vapour (TCWV) is very low, for example at high latitudes or high altitudes, UTH cannot be estimated because the signal is dominated by emission from the surface.

In the infrared (IR), UTH has been derived using clear-sky profiles from Channel 12 of HIRS (High-resolution Infrared Radiation Sounder) in the 6.3 µm band. This flew from 1978 and is planned to continue until at least 2022, although the wavelength significantly in the transition from HIRS/2 to HIRS/3 in 1999. In the microwave (MW), UTH has been derived from Channel 3 (183.31±1.00 GHz) of the AMSU-B (Advanced Microwave Sounding Unit-B), which evolved into the MHS (Microwave Humidity Sounder), flown from 1998. Very recently, data going back to 1994 from the SSM/T-2 (Special Sensor Humidity Sounder) onboard the DMSP satellites have also been used to derive UTH within the FIDUECO project (see Section 7.2), so that a time series of almost 25 years of UTH data is available to the community for climate monitoring and other applications. UTH can also be derived from the ATMS (Advanced Technology Microwave Sounder) on S-NPP and MWHS (MicroWave Humidity Sounder) instruments on the Chinese FY satellites, which carry similar channels to those on AMSU-B, MHS and SSM/T-2. Together with the MWS (MicroWave Sounder) on

EPS-SG, which is planned for the 2022-2043 timeframe, these instruments ensure continuity of measurements that will span several decades.

The main advantage of MW based UTH is the availability of all-sky data, whereas IR data sample only clear-sky areas (John et al., 2011). MW based UTH was first introduced by Spencer and Braswell (1997). They used two months (January and July of 1994) of SSM/T-2 data to study the dryness of the tropical free troposphere. Buehler and John (2005) adapted the method for AMSU-B radiances and later a UTH dataset was derived from the AMSU-B and MHS measurements, which is described in Buehler et al. (2008). V1 of the CM SAF UTH product was essentially an update to the Buehler et al. (2008) dataset, as it used the same fundamental approach. The data set typically represents the mean relative humidity over a range from about 500 hPa to 200 hPa but can be considerably higher or lower depending on the atmospheric water loading. In particular, at high latitudes or over high ground, the total column water is often so small that the surface emission affects, or even dominates, the signal. Further details of the CM SAF UTH product are outlined in the following section.

3.1.1 The CM SAF UTH product v1

The CM SAF UTH v1 product offers several advancements compared with the Buehler and John (2005). Firstly, it adopted an improved retrieval scheme by using local Jacobian in RH (Brogniez et al, 2004), which gives smaller retrieval error for a mean RH (like UTH) compared with the Jacobian in volume mixing ratio (VMR) used by Buehler and John (2005). Secondly, CM SAF UTH v1 product was based on the ERA-Clim fundamental climate data records (FCDR) [RD 1]. For the purposes of this report, an FCDR is defined here to be a well-characterised, long-term data record where the intercalibration between overlapping sensors is sufficient to enable the generation of products that are accurate and stable, in both space and time, to support climate applications. FCDRs are typically calibrated radiances, backscatter of active instruments, or radio occultation bending angles. FCDRs also include the ancillary data used to perform the calibration. The brightness temperatures (BT) of the different MW humidity sounders that comprise the ERA-Clim FCDRs have been intercalibrated with reference to MHS on NOAA-18, which should ensure that the different sensor records are harmonised.

The CM SAF UTH v1 has been calculated from MW observations using the following equation:

Equation 3-1

$$\boldsymbol{UTH} = \mathbf{100} * \boldsymbol{e}^{(\boldsymbol{a}+\boldsymbol{b}*BT)}$$

where a and b are constants with values 23.467520 and -0.099240916 K^(-1) respectively, and BT is the brightness temperature measured from the channel 183.31±1 GHz close to nadir. For observation angles further away from nadir the limb darkening effect is taken into account. This is performed by subtracting a view-angle dependent value (up to 6 K) from the observed brightness temperature. Measurements contaminated by the surface or clouds (convective or precipitating) have also been removed. In the case of clouds, the observed brightness temperatures have been discarded if these are greater than the respective values of the channel 183.31±7 GHz (or 190.31 GHz for MHS) or lower than a minimum view-angle dependent value. Regarding the surface contamination, a similar test is used and brightness temperature observations at 183.31±1 GHz greater than the respective values at 183.31±3 GHz are discarded. More details are provided in the CM SAF UTH v1 Algorithm Theoretical Basis Document (ATBD) [RD 2].

The final product is a global data set with a spatial resolution of 1.0°x1.0°. The CM SAF UTH v1 product covers the period from 1 January 1999 to 31 December 2015, using observations from the AMSU-B on board NOAA-15, NOAA-16 and NOAA-17, and the MHS on board NOAA-18, MetOp-A and MetOp-B. However, it should be noted that the first nine months of the data set are of lower quality because of radio-frequency interference (RFI). The data are provided as daily means, and daily means over ascending and descending passes separately are also provided. The mean, median and standard deviation of the UTH retrievals in each grid cell are provided, together with the number of measurements used and the number discarded because of surface or cloud contamination. The mean and standard deviation of the brightness temperatures used are also included for ascending and descending passes. The UTH retrieval is generally not valid outside ±60° latitude because of the very low water vapour loading at these high latitudes in the upper troposphere. The CM SAF UTH v1 product has been evaluated against UTH calculated from the ERA-Interim reanalysis, derived using 183.31±1.00 GHz channel BTs that have been simulated using the NWP SAF radiative transfer model RTTOV. Considering the global UTH differences between the two data sets, this analysis suggests that the data record fulfils the requirements specified by the Global Climate Observing System (GCOS) Implementation Plan of 5% measurement accuracy and 0.3% decadal stability, within ±60° latitude.

3.2 Application areas

As explained above, the emission to space in a spectral region dominated by tropospheric water vapour is primarily a function of RH. It follows that the water vapour greenhouse effect is primarily controlled by RH - specifically UTH - since the lower troposphere emits at temperatures closer to the those of the surface. Thus, UTH data are relevant to anyone interested in the radiative heat balance of the clear troposphere, but in particular to studies of the water vapour feedback on climate change. (Since the concentration of water vapour is determined by saturation, a warmer atmosphere holds more water vapour, adding to the water vapour greenhouse effect – a positive feedback on climate change.) With the greatest physical uncertainty and interest being at the dry end of the RH distribution, the limited cloud contamination may not be a significant concern for users, as these observations occur at the wet end of the RH distribution.

With around 25 years of UTH data from MW observations, and 40 years of data from the IR, satellite UTH data are becoming valuable for climate monitoring, provided the required homogeneity can be assured. Satellite UTH data from both MW and IR observations are already reported by the State of the Climate Report issued by BAMS each year (e.g. John et al., 2019). With global warming accelerating again in recent years after the end of the “hiatus”, it will now show a stronger climate change signal, and the MW and IR UTH records are long enough to look at effects associated with El Niño Southern Oscillation (ENSO), and shorter-period variations such as the Madden-Julian Oscillation (MJO), and the seasonal and diurnal cycles. The application of UTH data could extend to detection and attribution of climate change, through detailed studies of physical processes, and to validation of a wide range of models, but particularly general circulation models (GCMs, the most detailed and physically-based models of climate), NWP (Numerical Weather Prediction) models, and testbeds for parametrisations to be used in these models.

An unusual point is that the expected climate change signal is zero to leading order. The response of humidity to climate change that is expected from the basic physics, and confirmed by GCMs, is that to leading order the distribution of RH does not change, so that SH (specific humidity) increases following the Clausius-Clapeyron relationship.

As well as climate research, a long-term UTH dataset could also be used in a wide range of process studies. Upper-tropospheric moisture is central to tracking, understanding, modelling and predicting convection and advection at low latitudes. UTH data can be combined synergistically with a wide range of other datasets such as cloud, precipitation and flow, whether derived from satellites, reanalyses or other sources, for model evaluation, variability analysis, predictability research, and perhaps most of all, physical process studies. For example, Tian et al. (2004) have used satellite UTH in process studies of the diurnal cycle.

It is possible to compare satellite-derived UTH with simple measures of UTH from GCMs or forecast models. For example, Bennhold and Sherwood (2008) reported that, at least in the three GCMs they analysed, UTH was well approximated by the mean of the RH at the 300 and 500 hPa levels. However, comparisons of satellite-based data with detailed atmospheric models increasingly use the “gold standard” method of adding a satellite simulator to the model and running with suitable options to obtain compatible radiances. This was done for IR UTH by Bodas-Salcedo et al. (2011) in the “industry standard” integrated satellite simulator, COSP (the CFMIP Observation Simulator Package).

It is expected that a wide range of researchers will be interested in UTH Thematic Climate Data Records (TCDR), from all parts of the world. Current and potential applications areas for UTH are establish through an online survey issued to users as part of this CM SAF requirements review (Section 8). Making MW UTH available as part of the Obs4MIP initiative (https://esgf-node.llnl.gov/projects/obs4mips) should encourage its use both by broadening awareness of its existence and making it more accessible to climate and NWP modellers.

3.3 Uniqueness of product

Although there are now many water vapour products available to users, the CM SAF UTH v2 product is expected to offer the best, state-of-the-art, long term satellite UTH dataset with near-global spatial sampling (given the limitation of IR-based UTH datasets to clear skies). This product will make use of state-of-the-art FCDRs from passive MW sounders, including those that have never been used for a public UTH data set before (e.g. MWHS), and its design will be strongly user-driven. The CM SAF UTH v2 product will be the first UTH product that is based on requirements defined by users through a comprehensive survey that has global reach.

Many other water vapour datasets exist, and many have advantages that complement observed UTH. While the rapid temperature-driven decrease of SH with height means it can be profiled by nadir sounders with more detail than other quantities, there are still only a few degrees of freedom available. This encourages the use of integrated quantities such as total column water vapour, which gives the total mass and latent heat of water vapour, and UTH, which gives its radiative effect at top of atmosphere to a good approximation. Limb sounders can give more vertical resolution, but with far reduced sampling, and far more cloud interference in even the upper troposphere. Reanalyses provide a complete and consistent sampling, but of a model informed by observations rather than of the real world, and although artefacts due to changes in the observing system are fewer in more recent reanalyses, they are still present. The water vapour project in European Space Agency's (ESA) Climate Change Initiative is producing total column water vapour and vertical profiles (http://cci.esa.int/watervapour).

4 Approach for requirements gathering

The approach adopted for gathering requirements for the CM SAF UTH v2 product is based on previous experience surveying climate scientists' requirements for Land Surface Temperature (LST) for the ESA's LST Climate Change Initiative (http://cci.esa.int/lst). In this exercise, the requirements were based on the results from a ten-question paper survey distributed at a conveniently-timed specialist conference, followed by a much longer online user survey that had global distribution. Structured interviews with LST users were also conducted to gather requirements not captured by the surveys and to gain a deeper insight into how the data were/would be used. An important aspect of this process was to provide requirements with clear traceability.

For the CM SAF UTH v2, requirements are formulated based upon:

1. A review of existing requirements for MW UTH, e.g. GCOS (Section 11)
2. Open actions resulting from the review process for the CM SAF UTH v1 product (Section 6)
3. Advances in satellite remote sensing at 183 GHz and UTH since the CDOP-2 RR (Section 7)
4. Results from an online survey with global reach (Section 8)
5. Insights gained from discussions with users, including the CM SAF User Workshop in 2019 (Section 9)

In addition, a validation strategy for the CM SAF UTH v2 based on current knowledge is proposed in Section 10.

The objective of the online survey was to gather requirements from as many users as possible, working across a range of applications. The quantitative method for defining requirements from the survey results follows the approach of Bulgin & Merchant (2016) used for the SST_cci (http://www.esa-sst-cci.org/) and GlobTemperature (http://www.globtemperature.info/) projects, also used later by the LST_cci project (Aldred et al., 2019). This is summarised in

Table 4-1. For questions where respondents were asked to select a single option from a range of options, the corresponding requirement was set where at least 50% of the respondents would be satisfied; this is termed a ‘majority requirement’. Where multiple options for a question could be selected, requirements were defined where at least 45% of the respondents had selected that option; this is termed a ‘soft requirement’. For UTH data resolution, accuracy, precision, stability and data set length, respondents were asked to select their requirements at the threshold, breakthrough and objective levels (Table 4-2; these are defined similarly by WMO/GCOS). For these cases, the UTH data set requirements were defined at each level where at least 75% of respondents would be satisfied, termed here a ‘hard requirement’. Objective requirements are not included in the formal list of requirements defined in this document because the threshold and breakthrough requirements are already quite ambitious for MW UTH products.

Table 4-1: Definition of the quantitative requirements defined for the CM SAF UTH product. Source: LST_cci User Requirements Document Table 10 (Aldred et al., 2019)

Requirement type	Application	Definition
Hard requirement	Questions where the specification is selected from a scale	Requirement must satisfy at least 75% of respondents
Majority requirement	Questions where one option must be selected from a range of options	Requirement must satisfy at least 50% of respondents
Soft requirement	Question where multiple options can be selected from a range of options	Any requirement chosen by at least 45% of respondents

Table 4-2: Definition of the requirement levels of 'threshold', 'breakthrough' and 'objective'. Source: LST_cci User Requirements Document Table 11 (Aldred et al., 2019)

Requirement Level	Definition
Threshold	The limit beyond which the data is of no use for the given application
Breakthrough	The level at which significant improvement in the given application would be achieved
Objective	The level beyond which no further improvement would be of value for the given application

Requirements that cannot be defined quantitatively, for example from free text boxes in the online survey, discussions with users, or from the literature are defined differently and are termed here as 'advice notes'. All the requirements for the CM SAF UTH product v2 resulting from this collective process are summarised in Section 11. A requirement identification string is attached to each requirement to provide clear traceability. This identification string (ID) has the following format:

CMSAF-RR3.6-<number>-<type>-<source>

Where:

- CMSAF-RR3.6 indicates that the requirement or advice note has originated from this requirement review (RR3.6)
- <number> is a two-digit counter that increments from 1, across all requirement <type> (e.g. the digit 01 is used only once and CMSAF-RR3.6-01-REQ-<source> and CMASAF-RR3.6-01-ADV-<source> cannot both exist)
- <type> decan be one of three options:

  - “REQ”: A requirement that must be addressed. When questions are asked in terms of a threshold, breakthrough or objective requirement, the threshold requirement is used here.
  - “OPT”: An optional requirement that should be met where possible. This aligns with the breakthrough requirement definition.
  - “ADV”: An advisory requirement that should be considered where feasible. These are used where requirements cannot be defined quantitatively, for example from discussions with users, or free text questions provided in online questionnaire.
- <source> identifies where the requirement originated from, in this case it can be one or more of five options:
  - ‘E’: Existing requirements, e.g. from GCOS
  - ‘A’: Open actions from previous CM SAF UTH review meetings, or from the CM SAF Steering Group
  - ‘Q’: Online questionnaire
  - ‘U’: User insights
  - ‘O’: Other, e.g. project team expertise, state of the art.

Where similar requirements originate from multiple sources, a single requirement is defined to satisfy all sources as closely as possible and the appendage to the requirement identification string indicates these sources. The exception to this rule in this report is for existing requirements, for example from GCOS, which are defined in Section 5. These requirements have the appendage ‘-E’ and are not combined with similar requirements defined elsewhere in the document. The requirement ID is cited in the report text, e.g. [CMSAF-RR3.6-01-REQ-A], where it is associated with the definition of a requirement in Section 11 to provide traceability.

5 Requirements for the detection of climate change

Absolute accuracy, although crucial for the understanding of the underlying processes, is less important for climate trend detection than stability. Theoretical requirements for decadal stability in this context are usually derived from assumptions about the minimum anticipated signal to detect climate trends. For example, Ohring et al. (2004, 2005) assume the required stability to be the "somewhat arbitrary" 1/5 of the expected climate signal, which they add "should be periodically re-evaluated". However, for UTH the expected signal is zero to leading order (e.g. Boucher et al, 2013), although at higher order local signals of both signs are expected (Sherwood et al, 2010).

In this RR, the theoretical threshold stability is assumed to be that which would distinguish between the expected climate signal and the conventional reference case. The expected climate signal is that RH in general, and so UTH, will not change to leading order. The conventional reference case is that water vapour concentrations will not change to leading order, giving a strong nearly-exponential decrease in RH with global warming. (Also, climate change denialists argue for the realism of the latter.) As in Ohring et al. (2004, 2005), stability is required to be 1/5 the size of the latter change. A warming rate of 0.25 K/decade is also assumed, roughly what has been seen in recent decades and typical of what is projected for the next couple of decades, even assuming the Paris Agreement target of 1.5 K mean near-surface warming is met. The Clausius-Clapeyron rate is about 10 %/K for saturation with respect to liquid water and 12 %/K for saturation with respect to ice at the temperatures relevant to UTH, with the first perhaps more appropriate. Warming at those levels is typically around 1.3-1.5 times the surface warming, giving a threshold stability of 0.8% (fraction of humidity present) per decade. With UTH typically around 50%, this corresponds to a threshold stability of 0.4% (fraction of saturation, as used throughout this RR) per decade [CMSAF-RR3.6-01-ADV-E].

(The use of percentages to mean both fraction of the total quantity and fraction of saturation is a fertile source of confusion when discussing UTH and RH generally. This document is consistent throughout, and the user survey stated that '"%" [in the survey] refers to the fraction of saturation, not the fractional accuracy of the measurement'. Still, respondents may not all have read and understood this, as will be considered when the responses are discussed below.)

GCOS-154 (GCOS, 2011) gives a stability requirement of "0.3 %" for total column water vapour (TCWV), water vapour (WV) profiles and "upper tropospheric humidity". The context makes it clear that here the "%" means fraction of humidity present, so the GCOS requirement is significantly more demanding than the one derived above. GCOS-154 gives no explanation of how this UTH requirement was derived but says that TCWV and WV "are based on constant RH and 0.2 K/decade temperature trend." They are close to the 0.26 %/decade obtained by Ohring et al. (2004) for "water vapour" in general, presumably taking the near-surface warming and the conventional representative Clausius-Clapeyron rate of 6-7 %/K. Since the actual Clausius-Clapeyron rate, and the actual warming, are greater at the heights relevant to UTH, both these impose a more stringent requirement on UTH than seems justified in isolation. GCOS may have felt it inappropriate to give a conspicuously lower requirement for UTH even though its expected signal is larger. (Another issue is that the requirements of Ohring et al. (2004, 2005) and GCOS (2011) are all given as “%”, not “%/decade”. However, it seems plain from the text that “%/decade” is meant.)

For UTH, GCOS also gives an accuracy requirement of 5% (presumably fraction of humidity present) [CMSAF-RR3.6-02-ADV-E] and spatial resolution requirements of 25 km [CMSAF-RR3.6-03-ADV-E] and 1 hour [CMSAF-RR3.6-04-ADV-E], "set by the need to fully describe water-vapour (specific humidity) profiles and general atmospheric climatology (monitoring) and for use of data in reanalysis."

The theoretical objective stability adopted here is the quantity that can confirm and quantify the small changes that are expected in UTH. Sherwood et al. (2010) quantified RH changes under global warming simulated by GCMs in four latitude-height boxes. The boxes relevant to UTH are TU (roughly tropical-mean UTH, but with a vertical range not extending as far down) and XL (a mid-latitude mean RH overlapping the lower part of the vertical UTH range). Their results point to TU changing by about -0.3% to -2.5% per 1 K global-mean surface warming, and XL by about -0.3% to -1% (where “%” means fraction of saturation). Mid-latitude UTH will be an average, about equally weighted, of the XL range (the ranges being chosen for comparatively homogenous changes) and a range with about zero net change, implying a target of half this quantity. This points to an objective stability almost two orders of magnitude more stringent, of 0.008 % per decade, which does not seem achievable in the foreseeable future.

6 Related open actions from previous meetings and Steering Groups

As part of the development of the CM SAF UTH v1 product, a number of actions were assigned to the project team to consider for the development of the CM SAF UTH v2 product (Table 6-1, Table 3-1). These are described in more detail below.

Table 6-1: Open actions from the reviews conducted during the development of the CM SAF UTH product in CDOP-2. PCR refers to the Product Consolidation Review.

Action	Actionnee	Description	Due Date	Related RID
001	Project Team (PT)	PT to consider applying cloud climatology and surface temperature climatology in order to differentiate between cloud and surface contamination.	Next Version of UTH (PCR)	[011]
003	Project Team (PT)	PT to revisit the daily mean computation in order to avoid any diurnal cycles.	UTH v2 PCR (CM-14712).	-
005	Project Team (PT)	PT to consider providing individual uncertainties for each grid point in the next version of the data record	RR (CM-14712) UTH v2	-
007	Project Team (PT)	PT to consider including a quality flag in order to handle problems such as the jumps due to NOAA-15 (1999) data	Next RR of the UTH v2	-

Action 001

In the CM SAF UTH v1 product the number of pixels excluded from the grid-cell statistics due to cloud and/or surface contamination is provided in addition to the total number of pixels in the cell. As it difficult to differentiate between the two types of contamination, no distinction is made between affected pixels in the product. The Review Board suggested that a surface temperature and/or cloud climatology could be used to make this distinction, and this could be investigated for v2 of the product [CMSAF-RR3.6-05-ADV-A].

Action 003

In the CM SAF UTH v1 product, daily means are calculated according to the following equation:

Equation 6-1

$$UTH_{daily} = \frac{N_{asc} * UTH_{asc} + N_{desc} * UTH_{desc}}{N_{asc} + N_{desc}}$$

where N is the number of UTH retrievals for ascending (asc) or descending (desc) observations. The Review Board suggested that a simple mean with no weighting may be better at removing any diurnal cycle effects, and this could be considered for v2 of the product [CMSAF-RR3.6-06-ADV-A].

Action 005

Only general statements regarding the global accuracy and precision of the CM SAF UTH v1 product are provided to users, which are estimated based on the results of the product evaluation. The Review Board suggested that users may find grid-cell uncertainties useful, and that the provision of these uncertainties could be considered for v2 of the product [CMSAF-RR3.6-07-ADV-AOU].

Action 007

Evaluation of the CM SAF UTH v1 product highlighted some quality issues in the data set, for example during the early part of the NOAA-15 record. The Review Board suggested that the provision of quality flags could be considered for v2 of the product that would indicate the parts of the record that should be treated with caution or used with confidence [CMSAF-RR3.6-08-REQ-AOQU].

7 Advances in satellite remote sensing at 183 GHz and derived UTH

The objective of this section is to provide a summary of the major advances in remote sensing at 183 GHz, and the associated derivation of satellite UTH since the previous CM SAF UTH RR (January 2015).

Brogniez et al. (2016a) highlighted and reviewed the evidence from a range of sources that satellite observations around the 183 GHz line are consistently cold compared to radiative transfer calculations by up to 3 K. The higher spectral resolution of more recent instruments (ATMS and SAPHIR) have demonstrated that this difference increases away from line centre (lower in the troposphere). Errors in in-situ water vapour observations (radiosondes in particular) would be expected to produce the opposite spectral dependence. Brogniez et al. (2016a) concluded that traces of cloud surviving cloud clearing could account for some, but not most, of the difference. They also considered 3 possible sources of error in the radiative transfer calculations. The uncertainties in spectral parameters agreed by laboratory and modelling spectroscopists were found to be too small to contribute significantly. The uncertainties from the actual modelling calculations were still less important. However, missing spectroscopic physics were judged possibly important, including possible error in the line shape, and absorption by the water vapour dimers recently reported by Russian workers. Both the antenna pattern correction and the pass bands of the instruments are typically not known from pre-flight calibration. Brogniez et al. (2016a) concluded the antenna pattern correction was unlikely to contribute significantly to the observed difference with radiative transfer calculations, but the error arising from the conventional assumption that the pass bands are rectangular might be significant.

However, Bobryshev et al. (2018) concluded that the apparent bias ceased to be significant when the standards for comparison were made more rigorous. They used only radiosondes from the reference-quality GRUAN (GCOS Reference Upper-Air Network) network and they applied the GRUAN adjustments (for different characteristics of different models of sonde) throughout. For the satellite BT they took the average over a 50-km radius. They required that the radiosonde ascent did not move more than 15 km in the horizontal, that there was no sign of cloud in the radiosonde ascent or in satellite data in the IR (more sensitive than the MW), and that the satellite overpass and radiosonde launch were within 3 hours. Also, they then calculated their mean difference with inverse weighting by the standard deviation of BT in that 50-km radius. Their final result was still that the satellites see the world as colder, but only by 0.4 K, within the main uncertainties (radiosonde error, radiometric uncertainty of the satellite instruments, and radiative transfer uncertainty). They were also able to conclude that any non-rectangularity of the passbands is very small. This result emphasises the need for well-characterised uncertainties with the BT data and derived UTH [CMSAF-RR3.6-07-ADV-AOU].

Other papers considered the point and nature of UTH. Gierens and Eleftheratos (2016) pointed out that the usual assumption in climate change science that the large-scale distribution of RH will remain much the same as climate warms is ambiguous in principle. This is because at temperatures colder than melting-point, RH can meaningfully be defined with respect to liquid water or to ice, which cannot both remain the same under warming.

They also showed that UTH, if defined as a mean RH over a fixed range of altitudes, would not remain constant under that assumption, although the change would be small. More recently Gierens and Eleftheratos (2019) have explained the discrepancies when the high-UTH end of the distributions from HIRS/2 and from HIRS/3 are compared. These are large using all previous methods of "correcting" the two instruments to force them to match. Gierens and Eleftheratos (2019) showed they can be attributed to the linearization of the Clausius-Clapeyron and Planck functions introduced by Soden and Bretherton (1993), and are not present when second-order expansions were used. They also pointed out that although UTH is usually thought of as an average RH, in the formulation of Soden and Bretherton (1993) it lacks the basic property of an average that if the quantity concerned is constant, the average equals that constant. These studies highlight the need for a clear definition of what the CM SAF UTH v2 product represents [CMSAF-RR3.6-09-ADV-OQU].

One paper looking more specifically at calibration issues is Moradi et al. (2018). They used "natural targets" with little mean diurnal cycle, tropical oceans and polar night, to derive radiometric calibrations linear in scene temperature. Moradi et al. (2018) treated AMSU-B and MHS separately because differences in polarization for channels 3 (the 183.31±1 GHz UTH channel) and 4, and in pass-band for channel 5, mean that the measurements should not match in principle. Indeed, they showed scan-dependent differences between their reference instruments that they attributed to the differences in polarization. For AMSU-B they took NOAA-17 as the reference and found large drifts in channels 1, 3, 4, and 5 of NOAA-16 and channels 1 and 4 of NOAA-15. For MHS they took NOAA-18 as the reference but found NOAA-19 and MetOp-A generally consistent. This highlights the importance of deriving UTH from high-quality, state-of-the-art FCDRs where calibration issues have been considered carefully [CMSAF-RR3.6-10-ADV-O].

Brogniez et al. (2016b) applied a new approach to retrieval, aiming not at a best guess but an uncertainty range. Their case was RH averaged over six layers defined in terms of pressure and covering almost all the tropical troposphere, from the six channels of SAPHIR. Duruisseau et al. (2019) applied this to NWP, where state-of-the-art data assimilation requires uncertainties to be specified for all observations, but these had never previously been directly based on each individual retrieval. Such an approach could, however, also be applied to providing uncertainty information for climate datasets, although it was not available to the FIDUCEO project (Section 7.2), which has performed a far more thorough analysis of uncertainties in UTH than ever before.

Berg et al. (2016) reported the GPM (Global Precipitation Measurement) mission's comparison of a large number of microwave sensors using a variety of methods. Their calibration standard was GMI (Global Microwave Instrument), launched on the GPM satellite in February 2014. They reported that "[T]he calibration of SAPHIR and the MHS instruments on board MetOp-A, MetOp-B, NOAA-18, and NOAA-19 are remarkably consistent with GMI, with differences consistently below 0.5 K". They did proceed to say that for the UTH channel "There are slightly larger differences … although still within 1 K", but this was "not unexpected" given GMI's lack of a channel sounding similarly high.

The general approach of Berg et al. (2016) was to have several teams addressing each calibration issue separately, providing a natural indication of the spread due to different plausible choices of algorithm ("structural uncertainty"). This has never been done in calibration and bias correction of the cross-track scanning instruments - when different techniques have been applied it has been in unrelated studies, so the limited comparisons have been both post-hoc and ad-hoc.

Other major advances since the CDOP-2 CM SAF UTH RR include new instruments that have been launched and the FIDUCEO (FIDelity and Uncertainty in Climate data records from Earth Observations) project, which has developed state-of-the-art methods for producing satellite FCDRs with well-characterised uncertainties. These are described in the following sections of this report.

7.1 New Instruments

Since the previous CM SAF UTH RR there has been a major extension of the data under consideration, adding two ATMS and four MWHS to the existing suite of three SSM/T-2, four AMSU-B and three MHS. These instruments have similar bands and similar orbits to AMSU-B and MHS. See Table 7-1 for and information regarding dates and orbits for these instruments.

ATMS flies on two American satellites, Suomi-NPP (National Polar-orbiting Partnership) and NOAA-20. It has 22 bands, five of which are around the 183 GHz water vapour line, with the notional passbands of three exactly matching AMSU-B's. Weng et al. (2013) reported that the nonlinearity of the first ATMS, determined from pre-launch tests, is below 0.5 K. As its integration time is almost an order of magnitude less than AMSU-A's, its Noise-Equivalent Differential temperature (NEDT) is higher; it is also very variable across bands but stable in time. After corrections they concluded that the absolute accuracy for all channels is “generally about 0.2 to 0.5 K”. They did not consider the cross-track striping, about 1 K in the water vapour channels, but Qin et al. (2013) did, finding it consistent in shape, so that it can be removed as a PC (Principal Component). However, Weng and Yang (2016), taking advantages of manoeuvres where the “Earth scans” actually pointed to cold space, found a new bias attributable to the previously neglected emissivity of the plane reflector that was not in the existing calibration error budget. Data from the ATMS on NOAA-20 has not yet been the subject of publications in the climate and atmospheric science literature, but initial publications from the engineering community show that the performance is similar to ATMS/S-NPP.

An MWHS has been flown on each of the four satellites to date in the FY-3 series, China's second series of sun-synchronous polar-orbiting meteorological satellites. FY-3A and FY-3B, considered experimental, carried MWHS-1. MWHS-1 has five bands that include two novel ones on the wings of the 118 GHz oxygen line mainly aimed at clouds, and three on the wings of the 183 GHz water vapour line. These 183 GHz channels have exactly the same notional passbands as AMSU-B. FY-3C and FY-3D, considered operational, carried MWHS-2. MWHS-2 has eight bands around 118 GHz, one at 89 GHz one at 150 GHz aimed at detecting contamination by scattering, and five around 183 GHz, with exactly the same notional passbands as ATMS, but different polarization.

Wang et al. (2011) reported pre-launch calibration of the first MWHS-1, applying a substantial nonlinearity correction with a noticeable dependence on instrument temperature.

They noted that the bias in channels 4 and 5, the worst affected by shielding deficiencies, is dependent on the scan angle and shows zigzags around nadir, although they note their reviewer judged these to be an artefact of the test chamber. Chen et al. (2015) report on both MWHS-1 in the ECMWF forecast system. After bias correction they find mean biases similar to MHS's, but the random noise is about 1 K higher. This seems to be largely due to the ECMWF bias correction being cubic in scan angle and so by construction unable to correct the zigzags.

Lu et al. (2015) perform a similar analysis for the first MWHS-2. The mean biases are large and vary across bands unlike any previous instrument, possibly due to interference from the 150 GHz channel. After bias correction they reduce to less than 0.1 K across the humidity-sounding channels, with standard deviations a little larger than for ATMS's. The bias again shows small-scale variation as a function of scan angle, but smaller and less structured than for MWHS-1. However, a serious problem for operational use was the frequent jumps due to unannounced changes in ground processing and to changes in instrument temperature, for example, due to changes in operating mode of other instruments.

The CM SAF UTH product v2 will be based on data from SSM/T-2, AMSU-B, MHS, ATMS, and MWHS-1 & -2. Two primary reasons support this choice. Firstly, all these sensors carry the same channel that is required for UTH retrieval (183.31±1 GHz) and the channels used to screen for surface and cloud contamination at this frequency (183.31±3 and 183.31±7 GHz). Secondly, consistent, state of the art FCDRs are now available for these instruments that also include uncertainties derived from the fundamental principles of metrology and detailed quality flags. Use of these FCDRs therefore permits consistent UTH records to be derived with uncertainties and quality flags [CMSAF-RR3.6-07-ADV-AOU, CMSAF-RR3.6-08-REQ-AOQU, CMSAF-RR3.6-10-ADV-O]. These FCDRs are described in Sections 7.2 and 7.3.

A further instrument, the Sounder for Atmospheric Profiling of Humidity in the Intertropics by Radiometry (SAPHIR) onboard Megha-Tropiques, has also been launched since the last CM SAF UTH RR, on 12 October 2011. However, this instrument is not considered for the CM SAF UTH product v2 firstly because the channels on SAPHIR are slightly different to those on MHS, ATMS, etc, and secondly because the suite of FCDRs that are proposed for the product do not include data from this instrument (Sections 7.2.2 and 7.3). SAPHIR also has a different orbit from the other 183 GHz instruments, and covers the tropics only, normally seeing points at least twice a day but not regularly. Thus, SAPHIR has potential for cross-calibration between the instruments used for the CM SAF UTH product v2. Moradi et al. (2015) did compare ATMS with SAPHIR, finding “good consistency”. An analysis of simultaneous nadir overpasses (SNO) between SAPHIR and MWHS-1/2 onboard FY-3A/B/C, MHS onboard MetOp-A/B , and ATMS onboard S-NPP for the three channels close to 183.31±1, ±3 and ±7 GHz also shows that the agreement is typically within 1-2 K, and is often much lower than this, particularly for MHS [RD 2].

7.2 FIDUCEO

7.2.1 Overview of FIDUCEO project

FIDUCEO aims to “bring insights from metrology (measurement science) to the observation of Earth’s climate from space”. Its vision is to introduce rigorous metrological analysis to satellite retrieval, creating a suitable framework for general use, as well as datasets that exemplify it with complete and traceable estimates of stability and uncertainty. Specifically, FIDUCEO set out to create new versions of four Fundamental Climate Data Records (FCDRs) and five CDRs, for the first time with detailed and traceable estimates of the uncertainty and stability of the data. Previously no such information was available apart from the NEDT (http://www.fiduceo.eu/).

This report is concerned with the 183 GHz brightness temperature FCDRs and the UTH CDR. Two features of FIDUCEO’s work that were not familiar in study of this part of the spectrum were 1) the use of the Allan deviation, a standard deviation calculated over only a short sequence of numbers, which they found gave a much better representation of the real instrument noise than the traditional whole-sample standard deviation, and 2) consideration of intrusions of the Moon into the space view. They found considerable potential for future use of Moon views deliberately created by satellite manoeuvres to check long-term stability of MW sounders (Burgdorf et al. 2016).

7.2.2 The FIDUCEO 183 GHz FCDRs

As part of the FIDUCEO project, FCDRs were created for the SSM/T-2, AMSU-B and MHS (on both the MetOp and NOAA platforms). The aim of this section is to summarise these FCDRs, which were subsequently used to derive the FIDUCEO UTH CDR, which is described in Section 7.2.3.

Soon after the launch of the first AMSU-B, on NOAA-15 in 1998, it was realized that it had biases up to 40 K. This was confirmed as radio-frequency interference (RFI) from the transmitters communicating with Earth, by switching them on and off. Corrections were calculated and applied but updated only until 2001. Extra shielding was added to subsequent instruments, and tests were made during in-orbit verification. The AMSU-B on NOAA-16 was found to have no detectable contamination from RFI, but the AMSU-B on NOAA-17 had a little in two channels, including the UTH channel, and a small correction was derived for this sensor. However, these and subsequent instruments were seen to develop substantial biases varying slowly with time, and John et al. (2013) pointed out that the RFI could be expected to become more important, perhaps dominating the bias, as the gains of the instruments decreased with age. FIDUCEO reported “compelling evidence” that RFI was indeed responsible for the biases of the AMSU-B on NOAA-16 and the MHS on NOAA-19, relative to the MHS on NOAA-18 (Hans et al 2019a). They showed that the dependence on scan angle is qualitatively like that known for the RFI on NOAA-15: a very short zigzag (two-scan-position-wave) superimposed on a smoother variation, the combined pattern different for each channel but remaining the same in time, or evolving only slowly, as its magnitude increases. Also, the magnitude increases inversely to the gain, as expected for RFI leaking into the back of the instrument, bypassing the amplifiers. For NOAA-16, Burgdorf et al. (2018) had already ruled out all competing explanations as inconsistent with the observed constancy across the sounding channels of the effect of intrusions of the Moon into the space view.

Hans et al. (2019a) derived corrections for NOAA-16 and NOAA-19 depending on month and scan angle, but not on BT. These were the double differences of the monthly global mean BT for that scan angle between the satellite in question and NOAA-18, and between the month in question and a reference month approximated as having no error in either satellite. For NOAA-16, where they could compare to those derived by John et al. (2013) by a completely different method (simultaneous all-angle collocations), the results were encouragingly close. They did note that:

- Their preferred scheme could not be applied to NOAA-15 or NOAA-17 for lack of suitable low-error reference months: a preliminary version of their scheme was used. (They did not apply it to the MHS on MetOp-A or MetOp-B, where they noted only “weak but stable” zigzag patterns.)
- The SSM/T-2 instruments, the earliest, lowest-resolution, least-documented and least-used, do not overlap with NOAA-18 and so no corrections at all were estimated.
- Given the orbital drift of all these satellites, as well as removing the instrumental differences it is aimed at, this will remove some of the diurnal and seasonal cycles. They minimized this effect by calculating the correction from months when the satellite orbits were close.
- It ignores the effect of RFI on the calibration views (more precisely, the difference of its effects on the space view and the warm target view – any identical effects of RFI on these would be accounted for).

The impact on BT of this correction is often over 1K, and sometimes a few K. The FCDR contains several other, more technical, corrections and improvements compared to previous data processing by the AAPP package (Hans et al 2019b), none of whose impacts ever exceed a fraction of a K. The greatest innovation is of course the provision of detailed uncertainty information, but FIDUCEO also took care to create files that run precisely from one equator crossing to the next in the same direction, removing all duplication of data between files. Each FCDR file contains the calibrated brightness temperature for each channel, the uncertainties in it assigned to independent, structured and common effects, quality flags and auxiliary variables that maintain traceability to the level 1b files.

An important point is that this is not a “homogenised” data record as FIDUCEO provides only harmonised data. Harmonised data are described by FIDUCEO to be: “…characterised by the fact that each sensor is calibrated to the reference in a way that maintains the characteristics of that individual sensor such that the calibration radiances represent the unique nature of each sensor…”. Strictly speaking, the 183 GHz FCDRs are not fully harmonised, but as they are considered to be the current best-available data set and state of the art, they are the best choice for deriving the CM SAF UTH v2 product [CMSAF-RR3.6-10-ADV-O].

7.2.3 The FIDUCEO MW UTH Product

In principle the FIDUCEO MW UTH CDR has a major departure in that it uses a novel definition of UTH (Lang et al, 2019). The established definition is that the MW UTH is an upper-tropospheric mean RH, weighted with the humidity Jacobian of the satellite instrument channel concerned. Such weighting roughly corresponds to a mean over a broad layer between 200 and 500 hPa, but depends on water vapour concentrations as well as channel pass band and viewing angle. This means that MW and IR measurements of the same profile, or ones in the same region of the spectrum but with different passbands, should not match exactly except by chance, and that for precise comparison with climate models a detailed radiative transfer simulation is needed to get a Jacobian or a BT.

FIDUCEO adopted a new definition, independent of instrument and requiring no radiative calculation at all, so allowing in principle the combination of MW and IR data into a consistent data set covering over 40 years. It is the average RH between two "characteristic water vapour overburdens", the two levels at which the total column water integrated down from the top of the atmosphere reaches two thresholds. This formulation removes some of the problems with the definition of UTH pointed out by Gierens and Eleftheratos (2019). These thresholds were derived from regression for every viewing angle to minimize the root-mean-square difference of the resulting UTHs from those given by the Jacobians of the longstanding 183.31±1.0 GHz and 6.72 µm channels when a radiative transfer code is run on a large set of profiles. They do not vary much within 14° of nadir, and only those viewing angles were used in the CDR. The conversion is designed for the tropics only, and Lang et al. (2019) acknowledge that it does not work as well for the very few profiles with UTH > 80%. This approach to retrieving UTH from MW observations differs somewhat from that used to create the CM SAF UTH v1 product, which is global. However, the approach used by FIDUCEO should be considered for the CM SAF UTH v2 product [CMSAF-RR3.6-11-ADV-O].

There are further differences in coverage of FIDUCEO's MW UTH CDR from their MW FCDR. First, it covers only the "tropics", 30°N to 30° S, on a 1°x1° grid. Brightness temperatures that fail the cloud contamination test of Buehler et al. (2007) are excluded from the calculation of UTH. The time coverage also differs as the CDR uses the 183.31±1 GHz channel, and so cannot be created when only other channels are available in the FCDR. The instruments, satellites and time periods included are given in Table 7-1.

Table 7-1: Instruments, satellites and time periods of the FCDRs provided by FIDUCEO and EUMETSAT. The local equator crossing time (LECT) corresponds to the descending node of the orbit. The LECT is indicative at the launch time of each satellite. LECT source: https://www.wmo-sat.info/oscar/

Sensor	Platform	Start	End	LECT (Desc)	Source
SSM/T-2	DMSP F11	07/1994	04/1995	05:00	FIDUCEO

SSM/T-2	DMSP F12	10/1994	01/2001	03:35	FIDUCEO
SSM/T-2	DMSP F14	04/1997	01/2005	05:00	FIDUCEO
SSM/T-2	DMSP F15	01/2000	01/2005	02:50	FIDUCEO
AMSU-B	NOAA-15/K	01/1999	09/2010	06:54	FIDUCEO
AMSU-B	NOAA-16/L	01/2001	05/2011	09:01	FIDUCEO
AMSU-B	NOAA-17/M	10/2002	12/2009	07:03	FIDUCEO
MHS	NOAA-18/N	08/2005	12/2017	08:32	FIDUCEO
MHS	NOAA-19/N	11/2009	12/2017	04:46	FIDUCEO
MHS	MetOp-A	10/2006	12/2018	09:30	FIDUCEO/EUMETSAT
MHS	MetOp-B	04/2013	12/2018	09:30	FIDUCEO/EUMETSAT
MWHS-1	FY-3A	07/2008	05/2014	09:05	EUMETSAT
MWHS-1	FY-3B	12/2010	12/2018	01:38	EUMETSAT
MWHS-2	FY-3C	09/2013	12/2018	10:15	EUMETSAT
ATMS	SUOMI NPP	11/2017	12/2018	02:00	EUMETSAT
ATMS	NOAA-20	11/2017	12/2018	01:25	EUMETSAT

The actual data include monthly mean UTH and brightness temperature (meaned over pixels that pass the cloud contamination test, and also over all pixels in the cell), each separately from ascending and descending overpasses, and uncertainties for each, split into independent, structured and common components. However, these uncertainties are only those propagated from the MW FCDR, i.e. those associated with the measurement process, and the additional sources of uncertainty due to the conversion to UTH are not quantified.

Thus, FIDUCEO has demonstrated the practicability of applying a rigorous traditional metrological approach to satellite measurements. A very different way of considering uncertainties has, however, become usual in climate science, which is the use of ensembles. The use of ensembles has some benefits over the presentation of uncertainty ranges and whether users would like ensembles for MW UTH products is assessed in the online survey that is presented in Section 8. It should be noted that the FIDUCEO MW UTH product does not include ATMS and MWHS-1/2, which is addressed from a CM SAF perspective in the following section.

7.3 C3S FCDR product by EUMETSAT

As part of their commitment to the Copernicus Programme, EUMETSAT has produced 183 GHz FCDRs for the MHS onboard MetOp-A and -B, ATMS onboard S-NPP, and MWHS-1 and -2 (Work Package 250C3S; see also the EUMETSAT Climate Service Development Plan). These FCDRs have been produced using a modified version of the software developed within the FIDUCEO project that was used to generate the FCDRs for SSM/T-2, AMSU-B and MHS described in Section 7.2.2. The EUMETSAT data sets are complementary to the FIDUCEO FCDRs and include the same per-pixel uncertainty components and detailed quality flags. Thus, the two suites of FCDRs can be used together to produce consistent TCDRs. The EUMETSAT FCDRs have been rigorously evaluated by the CM SAF through comparisons with operational BT data sets (e.g. from NOAA-CLASS) and BTs simulated using a radiative transfer model, and the analysis of simultaneous nadir overpasses (SNOs) [RD 3]. The uncertainties and quality flags were also analysed through data exploration and inter-comparison between the FCDRs. The collective results of this study concluded that:

1) The FCDRs for MHS/MetOp-A, MHS-MetOp-B and ATMS/S-NPP were consistent and stable. In particular, MHS/MetOp-A and MHS/MetOp-B are found to agree almost exactly with each other, and with the operational data sets (typically ≤0.1 K differences).

2) FCDRs for MWHS-1/FY-3A, MWHS-1/FY-3B and MWHS-2/FY-3C are found to be rather unstable with several significant discontinuities and differences of up to several K with respect to the reference data sets used in the study. These issues were attributed to the raw data, rather than the FCDR production method.

3) The quality flags appear to be effective at identifying poor-quality data.

4) The uncertainties appear to be underestimated for all sensors, but particularly for the FY-3 instruments. The total uncertainties for all the FCDRs are typically <1 K but it is likely that the true errors frequently exceed this limit.

8 Online survey

8.1 Aims of the survey

The objective of the survey was to establish the use and general requirements for satellite UTH data from both IR and MW. It was aimed at all users or potential users of any source of UTH data. This includes users who have only ever used reanalyses, for example, or users who have not yet used observation-based datasets at all. Thus, the survey was carefully worded to gather genuine user requirements without constraining responses to the known technical limitations of satellite data. The intention was to find out how existing users use the data, and what changes or additions would make it easier for them to do so, as well as finding out the barriers and concerns of those who do not yet use these data.

The survey design was balanced between asking enough questions to get a useful level of insight into a range of issues and keeping it short enough that potential respondents would be encouraged to complete the survey. To encourage the latter, all questions were voluntary, and the survey could be submitted without completing every question. Therefore, the results presented in the following sections include a varying number of responses. Following some background text on the CM SAF and UTH, there were 16 multiple-choice questions and 7 free-text questions. The survey started with free-text questions asking the respondent for their name, email address and place of work. All the multiple-choice questions had an “Other” option, but many were complex, with several options with detailed wording and the request to choose several ranked answers.

For questions 14-19, respondents were asked to define their requirements at the *threshold*, *breakthrough* If they had one) and *objective* levels (as defined in Table 4-2, Section 4). This introduced some complication when analysing the results for these questions as it was not possible to set more than one level to the same option, and some responses had levels in the wrong order. In the analysis of these questions in Sections 8.2.5.3 to 8.2.5.8 the following conditions and adjustments were therefore imposed:

1. In each single response (one person responding to one question), the conditions that
    - threshold ≤ objective
    - breakthrough < objective
    - threshold < breakthrough

   were checked, where < and ≤ denote ‘more stringent than’ and ‘at least as stringent as’, respectively. Where this condition was not met, the answers were swapped. For example, if a respondent specified their objective data set length to be 5 years, their breakthrough to be 10 years and their threshold to be 30 years, this order was effectively reversed.

2. In each single response, if the threshold level or objective level was not specified, but another level was specified as an extreme value (i.e. one end of the scale of options offered), the ‘missing’ levels were assumed and counted. For example, three respondents chose “> 30 years” (the longest data set length option) as their threshold level for dataset length, and five chose it as their breakthrough. This implies that their objective level must also be more than 30 years, but they had not been able to

specify this. All eight were therefore counted as having an objective level of "> 30 years". Similarly, one respondent chose the coarsest spatial resolution (> 1° lat/long) as their objective level had it counted as their threshold level too.

For the questions asking for threshold, breakthrough, and objective levels, a line for each of these levels is plotted that shows the cumulative percentage of respondents satisfied. Although the three conditions specified in point (1) above must be true for a single response, this need not be true for the cumulative percentage. This would apply even if all respondents selected options for all levels that applied to them, as some would not have a breakthrough. Therefore, in some cases, these three cumulative lines cross unintuitively. None of the hard requirements are affected (i.e. where at least 75% of the respondents are satisfied – see Section 4).

The survey went live at the end of June 2019 and was publicised at the start of July by the CM SAF newsletter and the CM SAF twitter account, which was re-tweeted by various other accounts. An initial closing date of 26 July was circulated, but this was extended towards the end of the period to allow for additional responses after reminder emails were issued. The link to the survey was also circulated at the Met Office, via Climlist (http://climlist.wku.edu/), and to the personal contacts of the project team. All emails encouraged recipients to forward the survey link to colleagues to ensure the survey was circulated as widely as possible. In total, 47 responses were received, although most respondents did not complete every question. The more detailed questions received at least partial responses from between half and two-thirds of the respondents. All partial responses have been included because the information in them is considered valid and useful. Results are presented for all questions. These include the questions targetted at IR UTH requirements, although the discussion in each results section focuses on the results for MW UTH requirements, which is the subject of this requirements review. It should be noted that the results of this survey are taken on 'face value' and it is recognised that respondents may be overly aspirational regarding their intended use of the data.

Appendix B contains the full text of the survey. The results are presented in the next section of this report on a per-question basis. However, it should be noted that the text for some of the multiple-choice options is too long to be used to label plots and has therefore been shortened. The shortened text is intuitive, but the reader is referred to Appendix B for the full text version.

8.2 Results of the survey

8.2.1 General information

Table 8-1 shows the general information provided by 35 respondents who indicated at least their country. Of these, 31 respondents also gave their institution. A good number of responses are from Europe and Africa, from several different countries, but there are only a few responses from North America. No respondents reported themselves in mainland Asia or S. America. However, with 12 respondents providing no personal information, respondents from these areas could be included.

Table 8-1: List of countries (first column) and institutions (second column) from where responses were received. The number of respondents from each institution is provided in parentheses.

Country	***Institution (if provided)***
Angola	*(1)*
Australia	*UNSW Sydney (1)*
Benin	*(1)*
Botswana	*SADC CSC (Southern African Development Community Climate Services Centre) (1)*
Bulgaria	*National Institute of Meteorology and Hydrology (1)*
Czech Republic	*Czech University of Life Sciences (1)*
France	*LATMOS / University of Paris-Saclay (1), Sorbonne University (1)*
Germany	*DLR (German Aerospace Center) (1), University of Hamburg (3)*
Ghana	*Kwame Nkrumah University of Science and Technology (1)*
Greece	*National and Kapodistrian University of Athens (2)*
Guinea	*(1)*
India	*Indian Institute of Tropical Meteorology (1)*
Italy	*(1)*
Mexico	*CIMMYT (International Maize and Wheat Improvement Center) (1)*
Nigeria	*Federal University Lafia (1), Nigerian Meteorological Agency (2)*
North Macedonia	*UHMR (the North Macedonian NMHS) (1)*
Poland	*IMGW-PIB (the Polish NMHS) (1)*
South Africa	*South African Weather Service (1)*
Taiwan	*Academia Sinica (1)*
UK	*ECMWF (1), Met Office (3), University of Reading (1), University of Leicester (1)*
USA	*NOAA (1), University of Maryland College Park (1), Texas A&M University (1)*

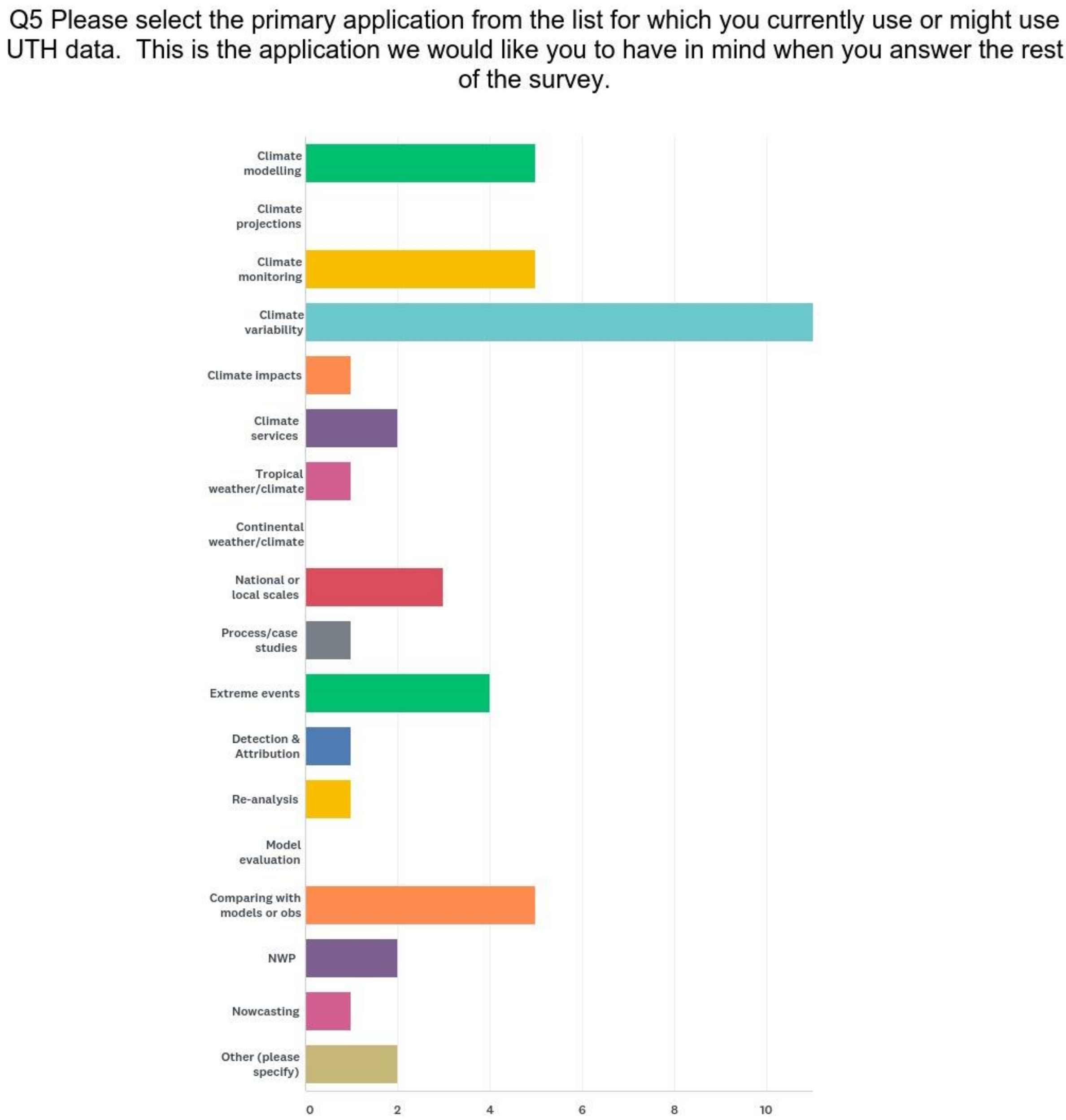


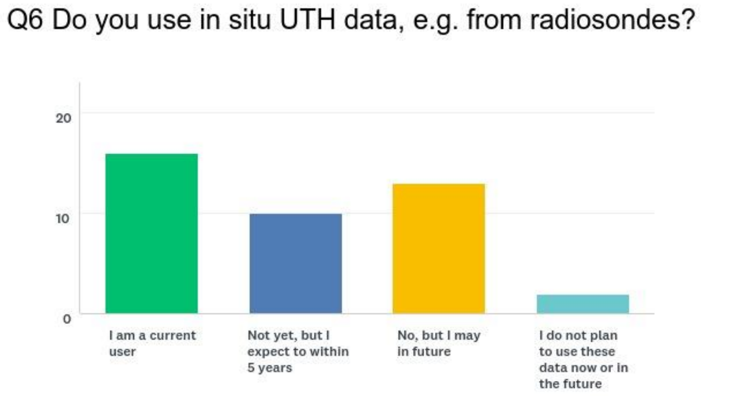
Figure 8-1: Primary application of the online survey respondents. (Single option response required) There were 45 responses to this question.

8.2.2 Primary application

Figure 8-1 shows primary application areas of the respondents. This is useful to know the breadth of applications where UTH data are being used and so that data providers can engage with these communities in the future. No application area is strongly favoured by the respondents and the results suggest UTH data are used in a wide range of applications. The four most popular application areas are climate variability, climate modelling, climate monitoring, and comparing with models or observations. However, the popularity of options early in the list may indicate respondents whose application areas could be classified under more than one of the options provided. The respondents who selected “Other” gave “Satellite” and “ice-supersaturation”.

8.2.3 Current data use

Figure 8-2 shows the current data use of the survey respondents. Respondents had the same four use categories to choose from for all four data sources considered (in situ, satellite MW, satellite IR and reanalysis). All respondents saw themselves as at least potential users of both MW and IR UTH. However, for each of the in-situ UTH and reanalysis UTH questions, two respondents did not see themselves even as potential users. For MW UTH, current users (19) are outnumbered by potential users (22), but the reverse is true for the IR UTH (23 current users vs. 18 potential users). There are more current users of IR UTH data (23) compared with MW UTH data (19), which is unsurprising given that the CM SAF IR UTH product (more accurately the CM SAF Free Tropospheric Humidity product) was released long before the CM SAF MW UTH product. However, the number of current MW UTH users is higher than the number of current users of in situ data (16) and reanalyses (18). Additionally, almost half the number of potential MW UTH users expected to use such data in the next 5 years. This suggests a significant increase in the number of CM SAF UTH product users could occur if it is provided in a way that works well for these users.



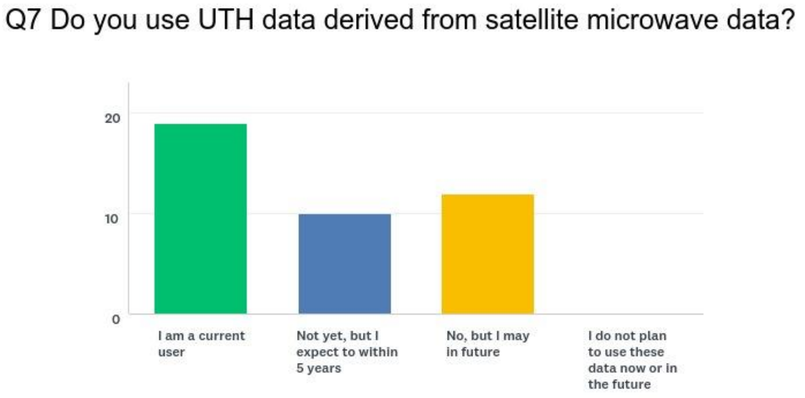
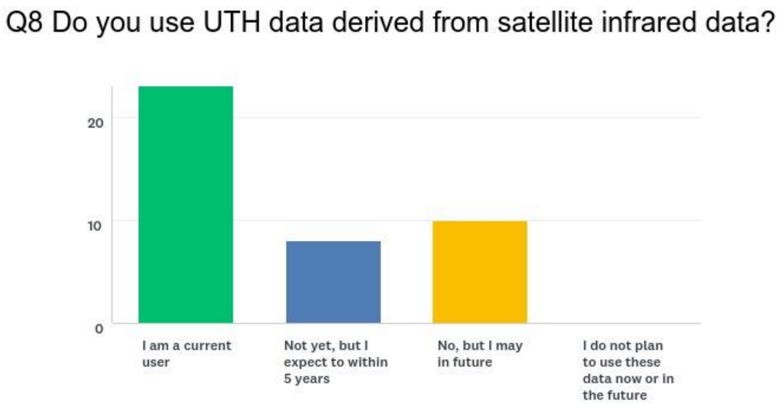


Figure 8-2: (continued on the next page) Survey respondents’ current UTH data source (single option response required). There were 41 responses for each of these questions. Note that the y-axis range is the same in each plot and that the options (x-axis categories) are also the same for each question.



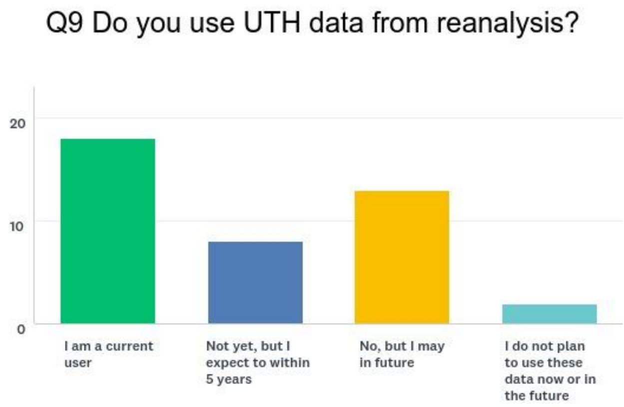


Figure 8-3: continued… Survey respondents' current UTH data source (single option response required). There were 41 responses for each of these questions. Note that the y-axis range is the same in each plot and that the options (x-axis categories) are also the same for each question.

Q10 Please rank the top three concerns or barriers (if any) that you consider to be an issue for using UTH data from satellite microwave data (with 1 being the most important, and 3 the least):

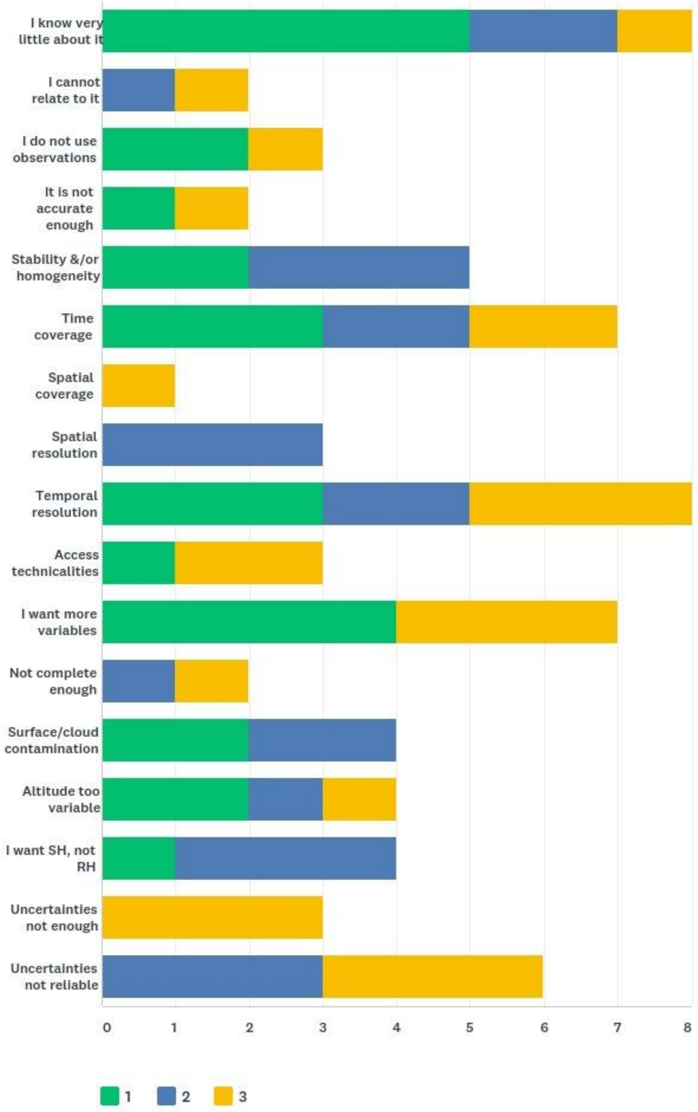


Figure 8-4: Concerns and barriers for using MW UTH data. The colours indicate the number of respondents that rank the issue as the most important (green), second most important (blue) and third most important (yellow). There were 31 responses including partial responses.

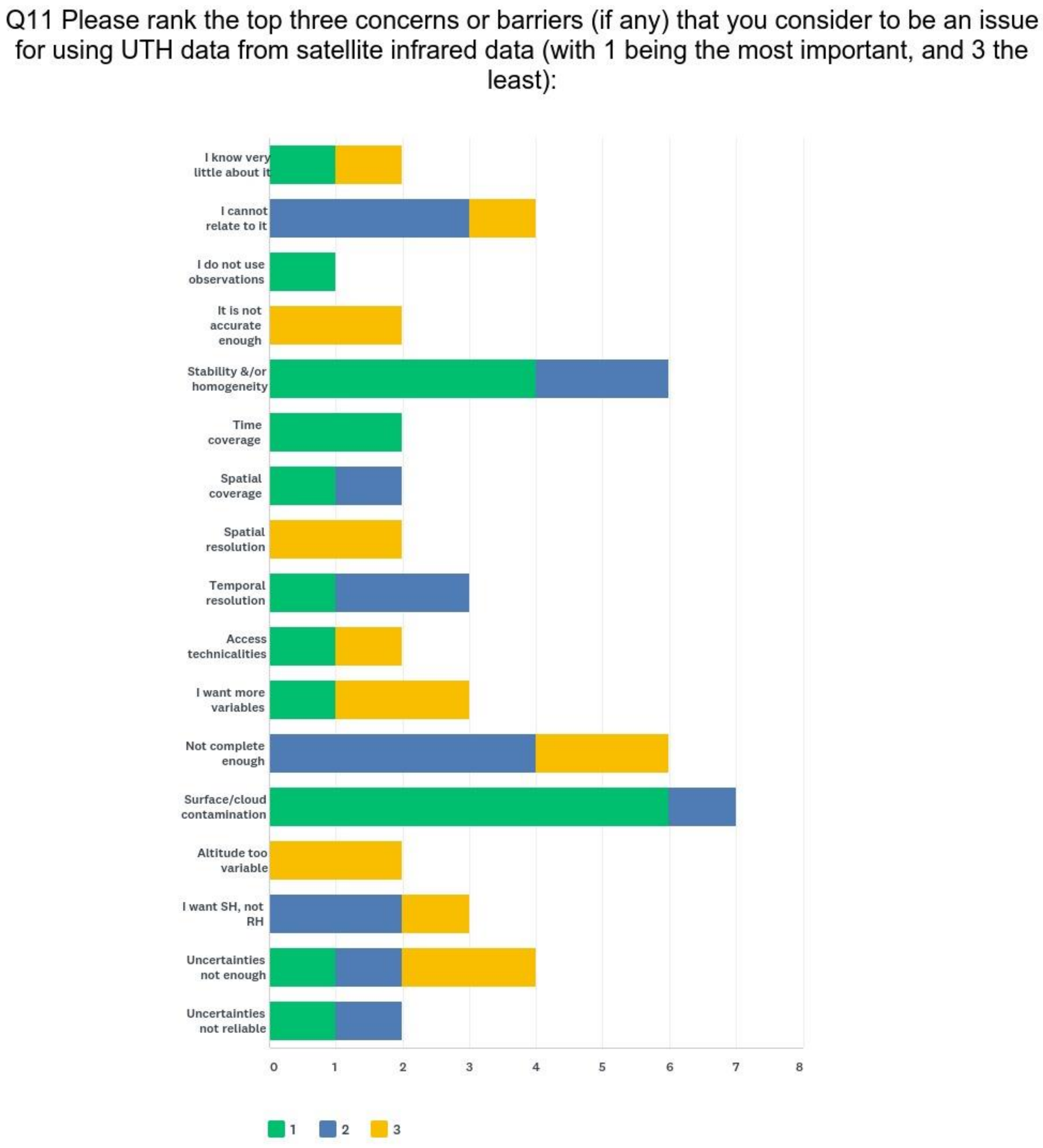


Figure 8-5: Concerns and barriers for using IR UTH data. The colours indicate the number of respondents that rank the issue as the most important (green), second most important (blue) and third most important (yellow). There were 26 responses for the IR, including partial responses.

8.2.4 Concerns and barriers

Figure 8-4 and Figure 8-5 show the rankings for the concerns and barriers that the respondents consider to be an issue in using satellite MW and IR UTH data, respectively. The results show that all the issues listed in the questionnaire are of concern to at least one respondent for both spectral regions, and that no single problem dominates.

Typical concerns did differ between the two spectral regions. The five concerns most cited (any prioritisation) for MW UTH were “I don’t know enough to assess whether it would be useful/I have never investigated the possibilities” [CMSAF-RR3.6-09-ADV-OQU], “Temporal resolution is too low”, “I am only interested in data sets with multiple variables sampled together / I prefer data sets with maximal information (e.g. merged MW & IR, LEO & GEO observations, or reanalyses)” [CMSAF-RR3.6-30-ADV-QU], “Data set time series are not long enough”, and “I distrust/am not certain I should trust the uncertainty Information” [CMSAF-RR3.6-09-ADV-OQU, CMSAF-RR3.6-12-ADV-QU]. Not knowing enough about the data was the issue with the most ‘priority 1’ rankings.

For IR UTH, the five most popular concerns were “I am concerned about the contamination by the surface and/or very thick cloud”, “Stability/homogeneity is unknown / too poor”, “The data are not complete enough for me / I am concerned about the lack of all-sky sampling.”, “The uncertainty information is not good enough/specific enough (e.g. lack of per-grid cell uncertainties)” and “It is not clear to me exactly what it represents / I cannot relate it to other data that I am using”. The first and third of these are presumably related.

Notably, no single option appears in both the top five most popular options for each type of UTH product.

Compared with the IR UTH, many more respondents felt they currently know too little about MW UTH to use the data. This indicates a requirement for more information and publicity regarding MW UTH data [CMSAF-RR3.6-09-ADV-OQU]. However, this may be related to the earlier release of the CM SAF IR UTH product compared with the CM SAF MW UTH product, which were only released in January 2019. Stability and/or homogeneity was a concern for both spectral regions, but slightly more for the IR UTH, with the length of record seen to be more of a problem for the MW UTH. Temporal resolution was also more of a concern for the MW with eight respondents selecting this issue compared with three for the IR. Completeness, and contamination by surface and cloud, were less important concerns for the MW compared with the IR, as might be expected. Concern about data set uncertainties is quite similar for both the MW (eight) and the IR (six).

Several respondents used the “Other” free-text option for one or both questions:

- From a single respondent:
    - MW - “my number one issue is vertical resolution. UT science would be greatly aided by high vertical resolution (1 km or less)”
    - IR - “also, contamination by aerosol, especially near the tropopause”
- From a single respondent: “require uncertainties” was entered for both the MW and the IR after not choosing either of the “uncertainties” options, or giving the top two priorities.
- From a single respondent: “I was [too] busy during the recent years to get high UTH in HIRS right. There was simply no time to look at MW UTH”.
- From a single respondent:
    - MW - “One potentially valuable use for our group would be to use the data for independent validation of global reanalyses (ERA5 ...). Although not fully

independent (as we assimilate geostationary satellite radiances and MW radiances) - the comparison could shed light on biases in the reanalyses. Hence the (inexact) prioritisation provided above."

- IR - "N/A ? - we use (Level 1) IR data for our global reanalysis. We do not (yet) use UTH products to validate the reanalysis, but could do this in future. See comments on previous question."

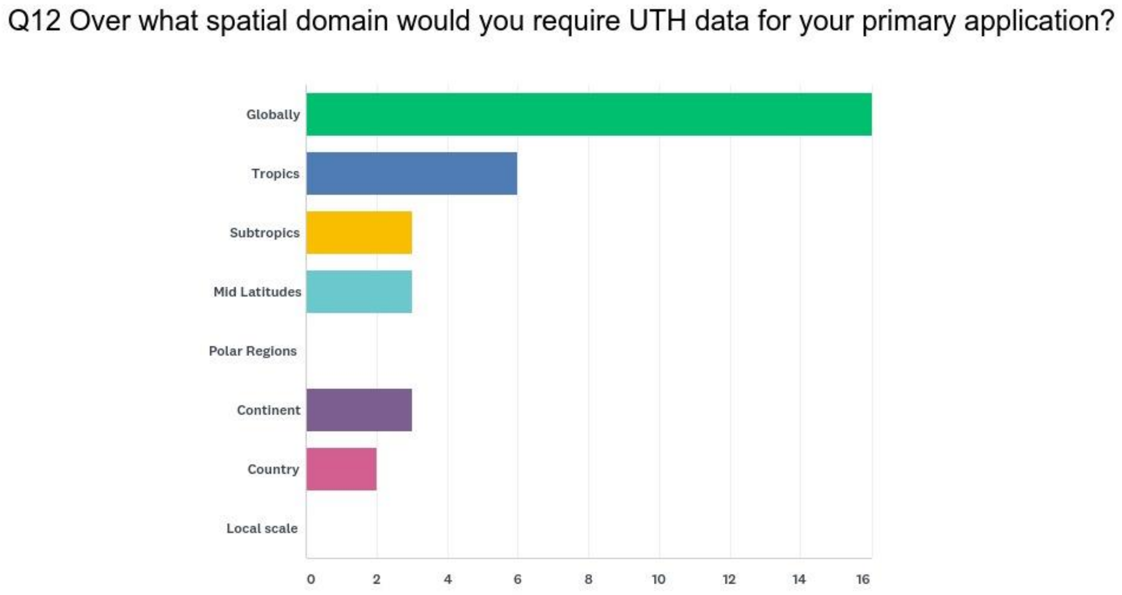


Figure 8-6: Spatial domain for UTH data use (single option response required). There were 33 responses.

8.2.5 Data specification

8.2.5.1 Spatial domain

Figure 8-6 shows the requirements for spatial domain for the online survey respondents. Just under half (16 from 33) of the respondents specified that they required the data on global scales [CMSAF-RR3.6-13-ADV-Q]. There are requirements for data over all spatial domains except polar regions and at local scales. Respondents who specified a continent or country said "Africa", "West Africa", "Benin" and "Poland".

8.2.5.2 Satellite data level use

Figure 8-7 shows the use or potential use of satellite data at different levels. Data mapped on uniform space-time grid scales and collated over multiple observations ('uniform grid, time-mean') was the most popular choice in the survey. The second most popular option was satellite UTH at native satellite resolution and projection (Level 2 orbit data; 'native resolution'). Satellite UTH mapped on uniform space grid scales from a single orbit (Level 3U; 'uniform grid, single orbit') was the third most popular option. Together, the two uniform-grid options account for 58% of the responses, thus leading a majority requirement to provide users with both time-averaged and single-overpass time data on a uniform grid [CMSAF-RR3.6-14-REQ-Q].

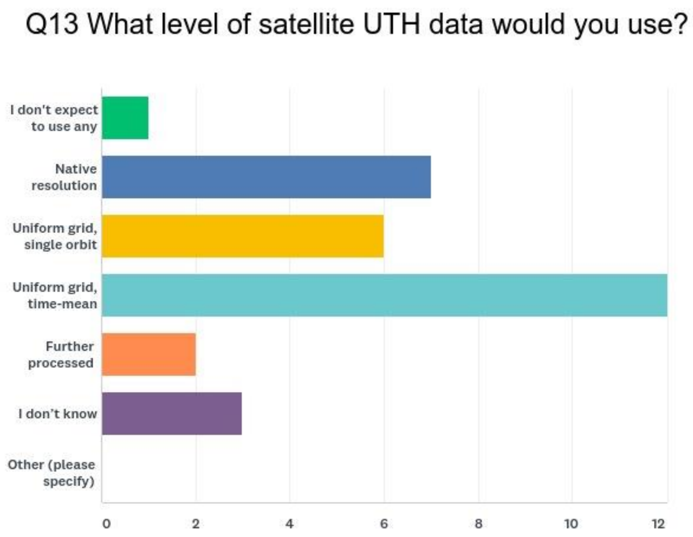


Figure 8-7: Satellite data level use. (Single option response required). There were 31 responses.

8.2.5.3 Data set length

There were a very wide range of threshold responses for the minimum length of record, consistent with the wide range of applications reported (Figure 8-8). Less than a year could be useful to some respondents, while others need over 30 years. No respondent's threshold length was 30 years, the traditional WMO standard minimum length of a climatological dataset (WMO, 2017). This was, however, the most popular choice for the breakthrough length. Unsurprisingly most objectives stated or implied were the longest option – for most respondents a longer series is always better. The threshold, breakthrough and objective requirements are respectively 20 years, 30 years, and >30 years [CMSAF-RR3.6-15-REQ-Q, CMSAF-RR3.6-16-OPT-Q].

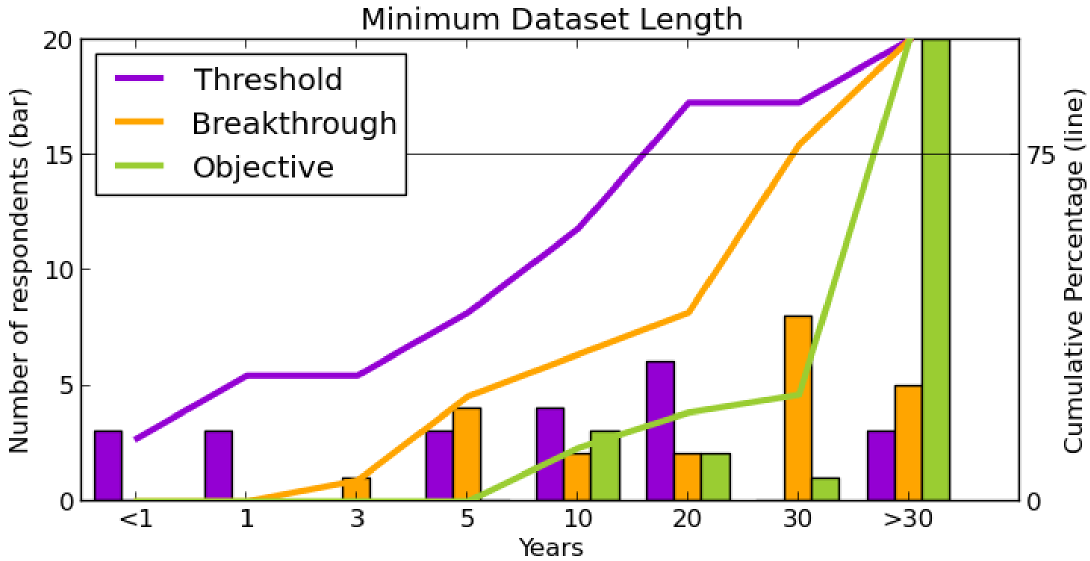


Figure 8-8: Minimum data set length. (Single option response for each of threshold, breakthrough and objective requirements.) There were 29 responses (including, as always, partial responses).

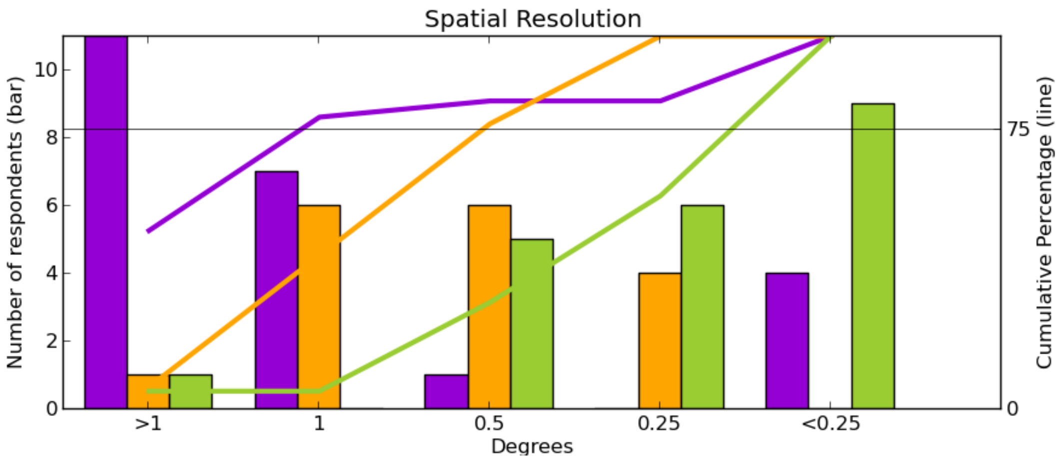


Figure 8-9: Spatial resolution. Again threshold is shown in purple, breakthrough in orange, and objective in green. (Single option response for each of threshold, breakthrough and objective requirements.) There were 28 responses.

8.2.5.4 Spatial resolution

Figure 8-9 shows the spatial resolution required by the survey respondents. The *threshold* requirement is 1° latitude/longitude, the *breakthrough* requirement is 0.5°, and the *objective* requirement is better than 0.25° latitude/longitude [CMSAF-RR3.6-17-REQ-Q, CMSAF-RR3.6-18-OPT-Q]. A spatial resolution of 0.25° is also the most frequent *objective* option. One respondent selected >1° latitude/longitude as their *objective* spatial resolution. One other respondent selected >1° latitude/longitude as their *breakthrough* requirement.

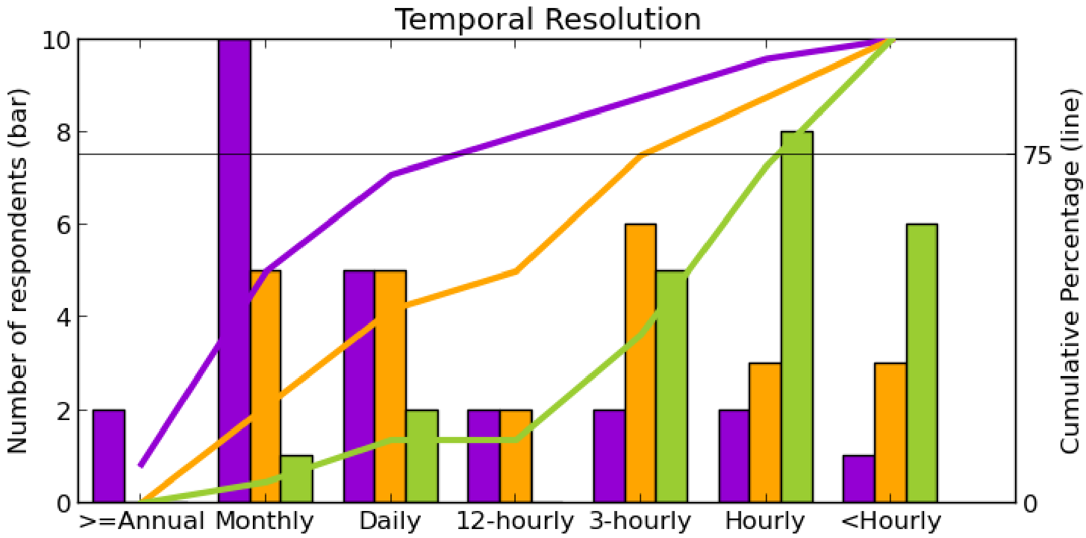


Figure 8-10: Temporal resolution. Again threshold is shown in purple, breakthrough in orange, and objective in green. (Single option response for each of threshold, breakthrough and objective requirements.) There were 30 responses.

8.2.5.5 Temporal resolution

Figure 8-10 shows the temporal resolution required by the survey respondents. The threshold requirement is 12-hourly [CMSAF-RR3.6-19-REQ-QU], the breakthrough requirement is 3-hourly resolution [CMSAF-RR3.6-20-OPT-Q], and the objective requirement is more frequent than hourly. The demand for sub-daily data raises the question whether this is better arranged by Universal Time or by local time / satellite orbit. Of the 28 respondents who chose a sub-daily option, 20 had given email addresses and so were emailed to ask their preferences. Of the answers received in time for this report, three preferred local time and eleven preferred Universal Time, although two of the latter suggested both be provided if possible. Thus, there is a majority requirement (79%) for data arranged by Universal Time, but local time would also be used by some users if this was available. [CMSAF-RR3.6-21-REQ-Q].

8.2.5.6 Accuracy

Figure 8-11 shows the accuracy, which was defined in the survey to be the “theoretical degree of conformity of the measurement to the unknown ‘true’ value”, required by the survey respondents. The requirements for accuracy were less spread than for any of the previous questions, but still wide, with five respondents having no use for accuracy better than 5% while four could make no use at all of data unless it was more accurate. The threshold, breakthrough and objective requirements are respectively 5 %, 1 % and 1 % [CMSAF-RR3.6-22-REQ-QU, CMSAF-RR3.6-23-OPT-Q].

One caveat is the ambiguity in the meaning of % - fraction of the humidity present or of saturation – already mentioned in Section 5. A sentence above this question and the next two very clearly said fraction of saturation was meant, but this does not mean that all respondents necessarily read it and acted accordingly. Any who did not would tend to enter larger values (less stringent requirements) than they meant for these three questions. Hopefully any such effect is small.

8.2.5.7 Precision

Figure 8-12 shows the precision, defined in the survey to be the "closeness of agreement between independent measurements of a quantity under the same conditions", required by the survey respondents. The threshold values for precision were more clearly separated overall, but one respondent still had no use for data unless it was in the highest-quality option, < 1%. Respondents were in closer agreement for breakthrough and for objective. The threshold, breakthrough and objective requirements are respectively 2 %, <1 % and <1 % [CMSAF-RR3.6-24-REQ-Q, CMSAF-RR3.6-25-OPT-Q].

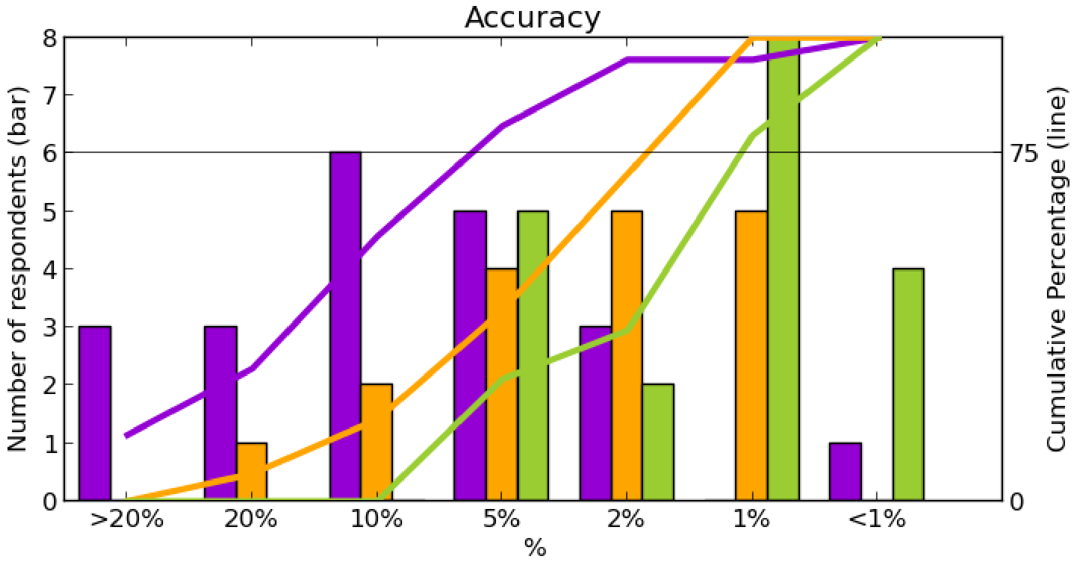


Figure 8-11: Accuracy. Again threshold is shown in purple, breakthrough in orange, and objective in green. (Single option response for each of threshold, breakthrough and objective requirements.) There were 24 responses.

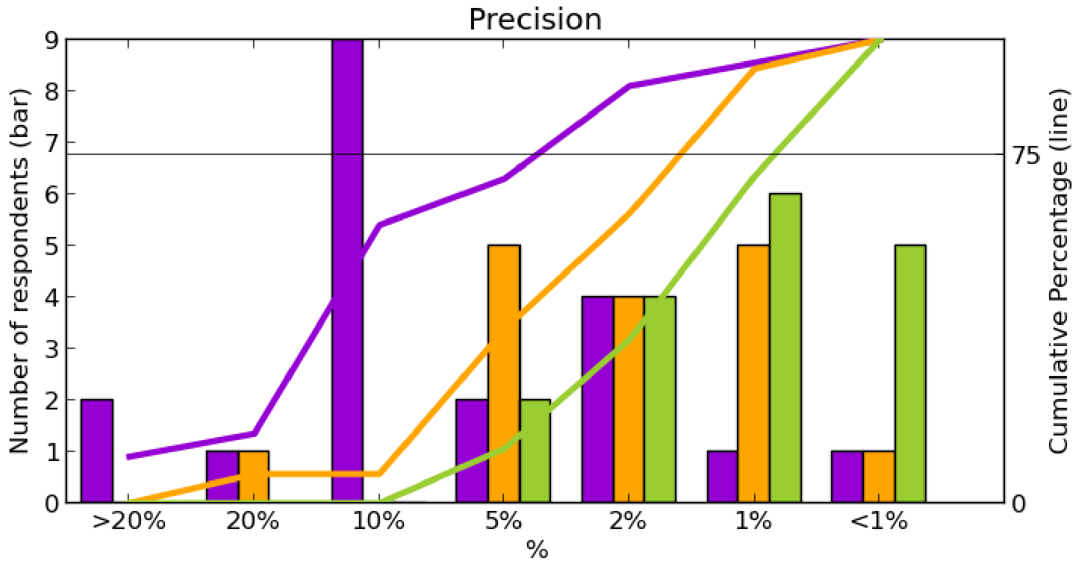


Figure 8-12: Precision. Again threshold is shown in purple, breakthrough in orange, and objective in green. (Single option response for each of threshold, breakthrough and objective requirements.) There were 24 responses.

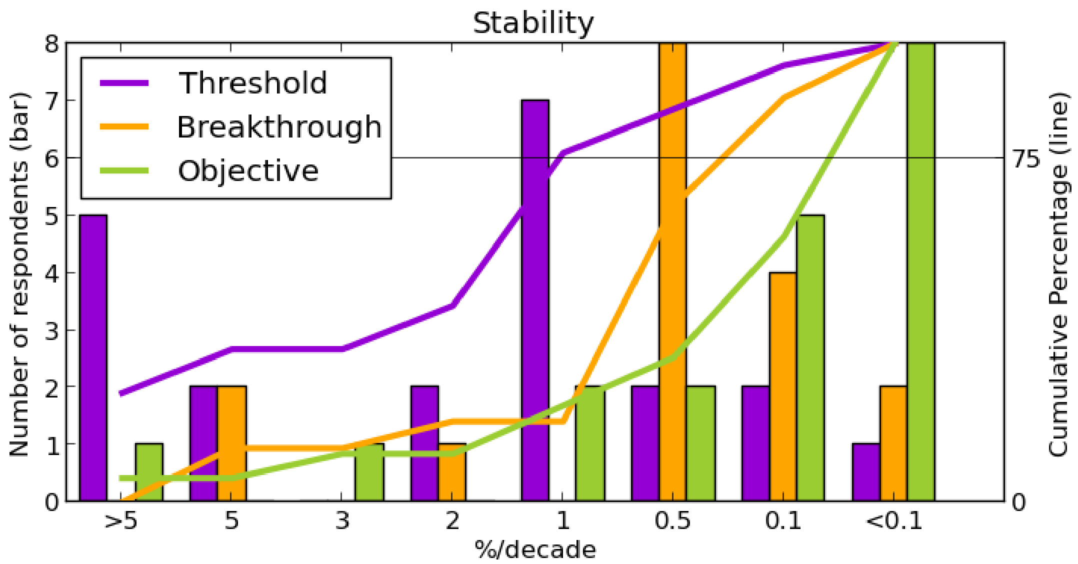


Figure 8-13: Stability. Again threshold is shown in purple, breakthrough in orange, and objective in green. (Single option response for each of threshold, breakthrough and objective requirements.) There were 25 responses.

8.2.5.8 Stability

Figure 8-13 shows the stability (consistency of the dataset over time) requirements derived from the online survey required by the survey respondents. Most choices are for at least 1 %/decade. The *threshold*, *breakthrough* and *objective* requirements are respectively 1 %/decade, 0.1 %/decade and <0.1 %/decade [CMSAF-RR3.6-26-REQ-Q, CMSAF-RR3.6-27-OPT-Q]

The range of stability options offered in the survey did not approach the *objective* derived in Section 5, as this does not seem within reach in the foreseeable future.

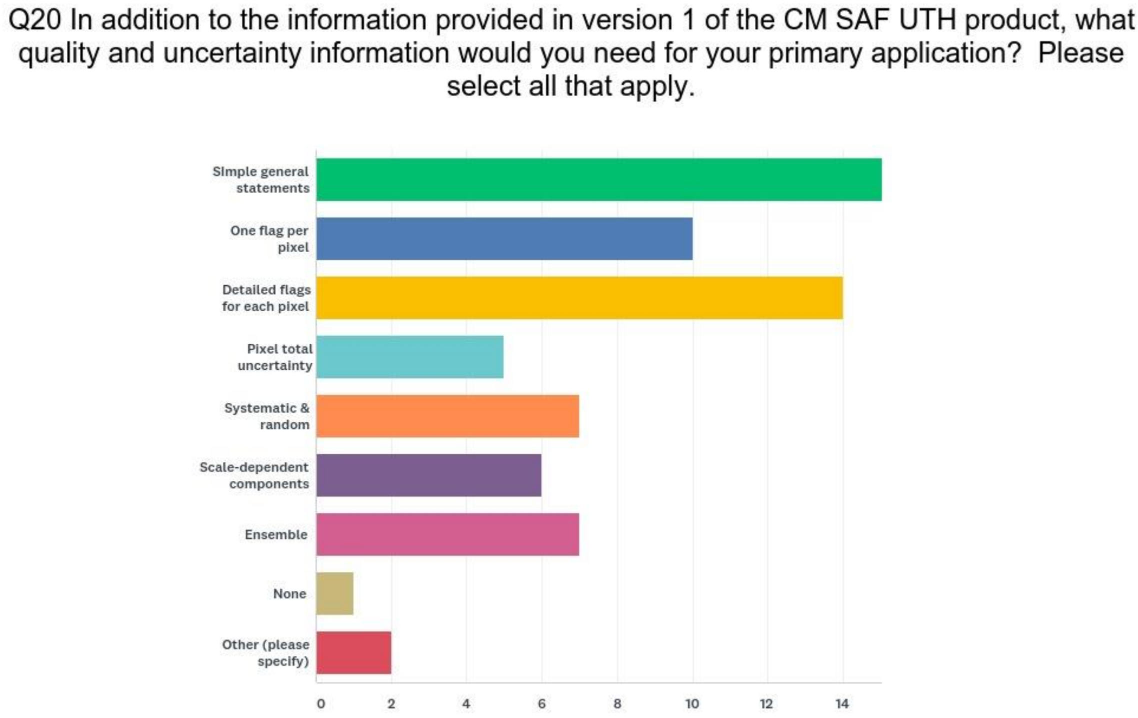


Figure 8-14: Quality and uncertainty information. (Multiple option response possible.) There were 26 responses.

8.3 Quality and uncertainty information

Figure 8-14 shows the respondents requirements for quality and uncertainty information. Soft requirements (options that satisfy >45% of the respondents) can be defined for the two most popular options selected:

- “Simple statements on the general accuracy, precision and stability of the data set e.g. from validation studies” [CMSAF-RR3.6-28-REQ-Q]
- “A set of detailed quality flags per pixel/grid cell indicating any specific problems with the data, e.g. suspected surface contamination, suspected thick cloud contamination, calibration concerns, etc. [CMSAF-RR3.6-08-REQ-AOQU]

Quality flags were considerably more popular than quantified uncertainties. Seven respondents asked for “An ensemble of data sets covering the range of uncertainty”. One of the two respondents who chose “Other” wanted information on the weight of the prior vs. evidence in the retrievals. The other respondent wanted information on the high (moist) tail of the distribution.

8.4 Examples of good practice and final comments

Questions 21 and 22 asked respondents to name any “observational data set that you have used that you consider to be a particularly good example of presenting observational data”, and “what is it about this data set that you particularly like”. Respondents were asked to provide any further comments in the free text box for question 23. The results from this question are presented in Appendix C, where all comments from a single respondent can be seen across one row of the table.

Several examples of good data sets were provided by the respondents (questions 21 & 22):

- MLS on Aura has a good document on data quality
- CM SAF SARAH2 has good data accessibility, file format, file contents, meta data, presentation and documentation
- Sea surface temperature data from the IRI website, where the data are tabulated well, with graphical illustration of the ensembles.
- CERES SSF CloudSat level 2 and CERES-EBAF, where lots of ancillary data are provided, with variables from other sensors, quality statements, and substantive publications. The CERES data were provided by two respondents as examples of good data sets.
- FIDUCEO MW UTH, where the user documentation is good.

These data sets can be investigated by the project team to identify the good aspects of these data, and assess whether they can be incorporated into the CM SAF UTH v2 product [CMSAF-RR3.6-29-ADV-Q].

General comments from the survey included the following points (question 23):

- Several respondents mention NetCDF as a good file format, which is already used by the CM SAF for all data products.
- Several respondents commented on the need for good documentation and metadata, including guidance on using the data, details of the intercalibration of the underlying FCDR, the spectral response functions used for coefficient generation and information on training data [CMSAF-RR3.6-09-ADV-OQU]
- There is a need to improve vertical resolution of UTH data. Although this is not appropriate for MW UTH data alone, this could be achieved with other data sets.
- Some respondents felt it would be useful to include additional variables/information in the UTH data files, specifically, the BTs used to retrieve the UTH, co-located information about cloud variables and temperature, and approximate pressure-level range of each pixel [CMSAF-RR3.6-30-ADV-QU, CMSAF-RR3.6-31-ADV-Q]
- One respondent commented that the long-term stability, homogeneity, characterisation of changepoints etc. is more important than the exact uncertainty quantification of single measurements [CMSAF-RR3.6-26-REQ-Q, CMSAF-RR3.6-27-OPT-Q].
- One respondent found that the NASA JPL feedback mechanism for AIRS L2 to improve the documentation is good [CMSAF-RR3.6-32-ADV-Q].

- One respondent commented that the NASA Giovanni system is good, with easy access to data [CMSAF-RR3.6-32-ADV-Q].

9 User Insights

Discussions were held with some potential users. These aimed to complement the survey by allowing more detailed and to an extent subjective investigation of the sort of issue for which the survey provided a wider and more apparently objective sampling. A list of issues to raise and prompts were prepared in advance, but the aim was that the interviewees' interests should lead the directions as much as possible.

9.1 Met Office Hadley Centre

UTH plays little role in MOHC's standard model validation, which looks more at the zonal-mean vertical distribution of humidity. It also often uses reanalyses, given their convenience and the fact that they should benefit from all the observations. There is no motivation to use an observational dataset unless it seems clearly superior or offers clear advantages over other data sets. This is not true for the climatology of UTH, but could well be for the diurnal cycle, and for process-oriented correlations, e.g. between UTH and cirrus cover. However, this would need a dataset holding multiple variables collocated [CMSAF-RR3.6-30-ADV-Q], or at least a set of datasets in consistent format so collocated data could easily be extracted. Orbital drift and calibration drift would not matter much for such uses.

Modellers would need positive motivation - peer-reviewed papers using GCMs from the CFMIP database, particularly ones showing beneficial impacts on model development from having a new perspective on systematic error [CMSAF-RR3.6-09-ADV-OQU]. A slightly better dataset does not motivate the effort to change existing practise. Something genuinely new would encourage change, ideally something modelling centres would like to evaluate, or evaluate better than they are currently able. Relationships between multiple variables seemed a candidate, and UTLS (Upper Troposphere and Lower Stratosphere), or more specifically the TTL (Tropical Tropopause Layer) was mentioned as an area of particular research interest. UTH is important for upper-tropospheric chemistry and differences within the uncertainties can have major impacts on composition.

A simple and familiar-style interface would be essential to get wide take-up. General circulation modellers are asked to include many diagnostics than they have the resources to analyse. Talking of a "Jacobian" will baffle most of them, and although they would understand "a weighting function for a vertical average", coding this into a GCM would require real motivation. If a COSP module were available it could easily be switched on in any GCM already using COSP, as almost every state-of-the-art GCM does now.

The extra uncertainty information planned for the next release was cautiously welcomed, with emphasis on the need for all sources of uncertainty to be covered and for uncertainty data to be accurate [CMSAF-RR3.6-12-ADV-QU]. Using ensembles for insight into uncertainties was suggested, although it was acknowledged that most users would want only e.g. mean and 5-95% range, or total spread.

Another Met Office colleague asked about the dependence on the prior. This is in fact low, probably much lower than for multi-level humidity retrievals - a benefit of the UTH dataset that most potential users probably do not realise and which is not mentioned in any documentation. This again reinforces the need for clear and accessible documentation that provides users with full information about the product [CMSAF-RR3.6-09-ADV-OQU].

9.2 University of Reading

Reanalyses, despite their convenience, are not reality, and are not to be trusted for long-term trends in particular.

Initially, interest would be in simple transformations such as zonal means, differences, trends, variability including ENSO, metrics of water vapour feedback, with more complex analysis following where initial results showed something interesting. Combining with other channels or non-satellite data always adds value, and ideally they would be supplied collocated (e.g. different sensors on the same satellite) [CMSAF-RR3.6-30-ADV-QU]. Vertical variation is always of interest, and with a quantity like UTH the level needs to be clear [CMSAF-RR3.6-09-ADV-OQU, CMSAF-RR3.6-31-ADV-QU].

What is needed is daily (sub-daily for some purposes) gridded NetCDF with clear simple indications of missing data [CMSAF-RR3.6-08-REQ-AOQU] and clear, short documentation of the issues related to missing data [CMSAF-RR3.6-09-ADV-OQU], of the uncertainties [CMSAF-RR3.6-07-ADV-AOU] and the vertical level the data represent [CMSAF-RR3.6-31-ADV-QUA]. Ideally the documentation should include a very short summary of the data, the main issues from a user perspective, and where to find more detailed information should this be required [CMSAF-RR3.6-09-ADV-OQU]. For example, if an early instrument is less reliable, it should be very clear that, for example, the absolute values are not comparable with later data in the record. The fewer data are missing the less it matters that some data are missing and how missing data are dealt with, and the fact that missing data is not random (concentrated at the wettest points) is not a real problem. Uncertainties are required not at the grid point but at whatever scales are being analysed, from decadal seasonal zonal-mean trends, to convective space and time scales. However, the uncertainties do not need to be precise, but their reliability is a concern [CMSAF-RR3.6-12-ADV-QU].

Requirements for e.g. accuracy, stability and resolution depend on the application. Resolution is more important for case studies of the physics, where 5% accuracy would be acceptable [CMSAF-RR3.6-22-REQ-QU]. Good stability is more important for climate trends. Sub-daily sampling would be useful for case studies, whatever times were available, and there are no issues in the observation times changing over time, e.g. due to orbital drift. In fact, this may even be useful in some cases. Ambiguity about the vertical level the data represent [CMSAF-RR3.6-31-ADV-QUA], and the possibility of surface contamination in colder profiles are concerns [CMSAF-RR3.6-08-REQ-AOQU].

Pre-existing studies, while potentially interesting, were not seen as very important.

9.3 Insights related to UTH from the CM SAF 5th User Workshop

The CMSAF's 5th User Workshop was held 3 – 5 June 2019 in Mainz. The need for explicit uncertainties was mentioned many times and there was general support for plans to introduce and/or improve them across the board in CDOP-4 along the lines of what FIDUCEO has already done for UTH [CMSAF-RR3.6-07-ADV-AOU]

One user showed the value of MW UTH and IR FTH data for process studies, provided its resolution is daily or better [CMSAF-RR3.6-19-REQ-QU]. Another user spoke about the barriers preventing his colleagues from using satellite data. They are not familiar with satellite datasets, customers do not specifically ask for satellite data, and many customer requests can be satisfied using surface observations. However, by asking not "Which parameter do you need?" but "What are you doing?" he found many uses for its spatial completeness, particularly over complex terrain. Therefore, there is great value in demonstrating how data sets can be used – ideally these examples should be available in the published literature [CMSAF-RR3.6-09-ADV-OQU].

10 Validation strategy

The conventional method to validate remotely-sensed observations is through comparison with equivalent in situ measurements. To have good coverage for an upper-tropospheric quantity this would mean validation against radiosondes. Radiosonde humidity measurements do have the apparent advantage for validating UTH that the sensors generally respond directly to RH, but they have many problems at the low temperatures found in the upper troposphere (e.g. Seidel et al, 2009). Sensors may also be unreliable at low RH. Sensor response may be badly lagged - in particular, passing through a cloud may leave the sensor damp for some time as it rises through cold air where evaporation is slow, reporting saturation regardless of the actual humidity. In daytime, solar heating of the sonde can corrupt measurements of humidity as well as temperature. Even though the modern operational radiosonde network uses better instruments overall than in the past, the main signal from comparing UTH sensed from space and the operational radiosonde network is conspicuous nationally, where differences vary due to different errors in different sensors (Moradi et al, 2013). As reported in Section 7, Bobryshev et al. (2018) found the GRUAN network good enough for validation with stringent additional conditions, but GRUAN covers less than half the period of the CMSAF UTH dataset, and validation of the full period is essential, given the importance of homogeneity for many users.

Comparison with other satellite-based estimates of UTH is valuable, but more as consistency checking rather than validation. First, as each instrument has different weighting functions, their measurements should not match. FIDUCEO's definition of UTH as the mean RH between two water vapour overburdens aims to remove this problem, and Lang et al. (2019) show that the optimal overburdens for MHS and AMSU-B were close to those for HIRS/2. (They did not consider HIRS/3, which has been providing data since 1999, but as it is significantly further from the line centre it presumably will not fit as well.) This approach is thus promising, but so far, no other UTH datasets that follow this definition exist, nor are there any plans to create any. Secondly, even if this approach had widely been applied with success, differences in horizontal and temporal sampling would continue to introduce inconsistencies. Thirdly, most measurements suitable for comparison are made in the IR (HIRS, MVIRI and SEVIRI), and this approach could do nothing about the difference between the MW and the IR in the amount of data that must be rejected because of cloud contamination. Fourthly, the value of satellite inter-comparisons is limited by the fact that any discrepancies seen could be from either dataset - or partly from both. This would be particularly true for one of the most important open questions: Long-term homogeneity. Lastly, even agreement could be partly spurious due to common assumptions and similarities in algorithms. However, a EUMETSAT visiting scientist, for example, might do valuable work comparing MW and IR observations and such a study looking at the CM SAF MW and IR observations of UTH and FTH is currently being considered (Section 12). Systematic differences between different datasets generally matter less for studies of climate variation, and such studies may offer valuable insights into data set quality. This has been performed successfully for UTH by Garot et al. (2017) for the MJO (Madden-Julian Oscillation), and Shi et al. (2018) for ENSO (El Niño/Southern Oscillation). Variability studies are unfortunately beyond the current scope of the CDOP-3 UTH work, but will be considered for CDOP-4, or for other opportunities should they arise earlier than this (e.g. PhD or Master’s project).

Consistency checking will also be done against the previous version of the dataset – the differences should be consistent with expectations from the changes made to the processing.

This leaves reanalyses. Chung et al. (2016) found ERA-Interim trends to be comparatively close to the MW and IR satellite data for UTH. Other reanalyses were not close to the MW and IR UTH data, although their spatial and temporal patterns of interannual variability were consistent with the satellite data. The ECMWF operational system also shows good agreement of relative humidity in the upper troposphere with in situ observations made from the CARIBIC aircrafts (Dyroff et al, 2015). ERA-Interim is now being superseded by ERA-5 (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5), which is broadly similar but provides output with higher temporal and spatial resolution. So, although it is not a true observational data set, and it did assimilate a version of the data to be compared, ERA-5 is closer to being a reliable, spatially and temporally complete (over the period covered by the CM-SAF UTH), observationally-based dataset than anything else that is currently available. It will therefore be used as the available best option for the primary validation, although not treated as absolute truth, given its uncertainties.

After consistency checking against the CM SAF UTH v1 product and validation against reanalyses, in-situ data may be used for further validation of parts of the dataset. GRUAN (https://www.gruan.org) has high-quality radiosonde data from a small number of stations for the more recent years of the CMSAF dataset. However, it is spatially sparse, with only 12 certified stations, all in the developed world. Another possibility is the GCOS Upper Air Network (GUAN), with over 150 stations, well distributed across the world and with quality standards imposed. However, the quality is not as high as GRUAN's. IAGOS (In-Service Aircraft for a Global Observing System; https://www.iagos.org/) has a much larger amount of data from humidity sensors carried routinely on commercial aircraft. Although the data are not of the quality of GRUAN, the sensors are consistent across the fleet and one of the more reliable types (Vaisala Humicap-H). However, their typical cruising altitude of 12-13 km gives profiles that do not sample the full range of heights that contribute to UTH, at least at low latitudes. The UK research aircraft FAAM has several humidity instruments, including a frost-point hygrometer, traditionally considered the "gold standard". However, its ceiling is 11 km and many flights never reach heights relevant to UTH, and it flies on average only one hour a day.

Any of these would need thorough and careful checking for full representativity, as well as vertical integration (ideally, radiative transfer modelling) of the in-situ data to give UTH. Apart from FAAM, all are assimilated in ERA-5.

The primary validation of the CM SAF UTH v2 with ERA-5 will be very similar to that carried out for CM SAF UTH v1 product using ERA-Interim [RD 2]. The validation is expected to include analysis of [CMSAF-RR3.6-33-ADV-O]:

- mean difference (this is often referred to as the "bias", but this suggests one of the datasets is known to be free from errors, which is impossible)
- standard deviation, which quantifies the overall variation
- quartiles and extreme percentiles (probably 1%, 5%, 95% and 99%), which together provide excellent comparison of the distributions as a whole, including skewness and of course extrema

- anomaly correlations, which show how similar the variation is in pattern

In addition to examining the overall distributions of the data, the metrics above will be analysed through time series, maps and Hovmöller diagrams to assess any variation in agreement between the CM SAF UTH v2 product and ERA-5 in time and space. This will provide information on accuracy, precision and stability of the data. The data set uncertainties will also be explored, potentially through the analysis of simultaneous nadir overpasses (SNO), where the agreement within uncertainty ranges between UTH derived from different sensors can be assessed [CMSAF-RR3.6-12-ADV-QU]. This type of analysis has already been performed successfully during the evaluation of the EUMETSAT FCDRs, which suggested these uncertainties were underestimated [RD 3].

The higher time resolution of ERA-5 will allow the validation of fields with different observation times, and provide more rigorous (like-for-like) validation than was possible with the 6-hour resolution of ERA-Interim. Direct analysis of ERA-5 may also be used to inform the method used for generating the daily means in the CM SAF UTH v2 product. This analysis will be documented for users in the ATBD.

11 Requirements for the MW UTH products

The purpose of this section is to define and justify each requirement as many are based multiple sources of information. Requirements are cited throughout this document with an identification string based on the following formulation:

CMSAF-RR3.6-<number>-<type>-<source>

Where:

- CMSAF-RR3.6 indicates that the requirement or advice note has originated from this requirement review (RR3.6)
- <number> is a two-digit counter that increments from 1, across all requirement <type> (e.g. the digit 01 is used only once and CMSAF-RR3.6-01-REQ-<source> and CMASAF-RR3.6-01-ADV-<source> cannot both exist)
- <type> decan be one of three options:
  - "REQ": A requirement that must be addressed. When questions are asked in terms of a threshold, breakthrough or objective requirement, the threshold requirement is used here.
  - "OPT": An optional requirement that should be met where possible. This aligns with the breakthrough requirement definition.
  - "ADV": An advisory requirement that should be considered where feasible. These are used where requirements cannot be defined quantitatively, for example from discussions with users, or free text questions provided in online questionnaire.
- <source> identifies where the requirement originated from, in this case it can be one or more of five options:
  - 'E': Existing requirements, e.g. from GCOS
  - 'A': Open actions from previous CM SAF UTH review meetings, or from the CM SAF Steering Group
  - 'Q': Online questionnaire
  - 'U': User insights
  - 'O': Other, e.g. project team expertise, state of the art.

Although the requirement <number> is incremented as the requirements are cited through Sections 5 to 10, they are discussed below by category.

11.1 Spatial domain and resolution

The CM SAF UTH v2 product should be produced at a spatial resolution of 1° latitude/longitude with global coverage. Data with a spatial resolution of 25 km and/or 0.5° latitude/longitude should be produced if feasible.

The requirement for global UTH data is defined from the results of the online questionnaire. The requirement is an advisory note because only 48% of respondents required global data, which falls short of the 50% required to define a hard requirement. However, in practise, this requirement will of course satisfy 100% of users, although some users may prefer smaller regions to reduce data volume. The requirements for the lower spatial resolutions also originate from the online questionnaire, where 1° latitude/longitude is the threshold level and 0.5° is the breakthrough level. Both these requirements satisfy at least 75% of the survey respondents. The requirement for UTH data at ≤25 km originates from GCOS, but as noted earlier, this requirement has no traceability so is not prioritised (Table 11-1)

Table 11-1: Requirements for spatial domain and resolution

ID	Requirement	Type	Source	Notes
CMSAF-RR3.6-03-ADV-E	Provide a UTH product with spatial resolution of ≤25 km	Advisory	GCOS	No traceability for requirement
CMSAF-RR3.6-13-ADV-Q	Provide global UTH data	Advisory	Questionnaire Q12	48% of respondents require global data
CMSAF-RR3.6-17-REQ-Q	Provide UTH data at a spatial resolution of 1° latitude/longitude	Threshold	Questionnaire question 15	75% of respondents satisfied by this requirement
CMSAF-RR3.6-18-OPT-Q	Provide UTH data at a spatial resolution of 0.5° latitude/longitude	Breakthrough	Questionnaire question 15	75% of respondents satisfied by this requirement

11.2 Data set length and temporal resolution

The CM SAF UTH v2 product should be 20 years long with 12-hourly temporal resolution. At least 30 years of data with 3-hourly temporal resolution should be provided if possible. Data should be arranged by Universal Time (UT).

The requirement for 20 years of UTH data with 12-hourly temporal is based on the results from the online questionnaire and corresponds to the threshold requirements for these specifications. Breakthrough requirements are at least 30 years and 3-hourly temporal resolution. After following up with those respondents who requested sub-daily temporal resolution, a majority requirement for the data to be arranged (e.g. for global time slices) by UT was also defined. The GCOS requirement for temporal resolution is ≤hourly but as noted earlier, this requirement has no traceability so is not prioritised (Table 11-1)

Table 11-2: Requirements for data set length and temporal resolution

ID	Requirement	Type	Source	Notes
CMSAF-RR3.6-04-ADV-E	Provide a UTH product with temporal resolution of ≤hourly	Advisory	GCOS	No traceability for requirement
CMSAF-RR3.6-15-REQ-Q	Provide at UTH record of 20 years	Threshold	Questionnaire question 14	75% of respondents satisfied by this requirement
CMSAF-RR3.6-16-OPT-Q	Provide a UTH record of at least 30 years	Breakthrough	Questionnaire question 14	75% of respondents satisfied by this requirement
CMSAF-RR3.6-19-REQ-QU	Provide UTH data at 12-hourly temporal resolution	Threshold	Questionnaire question 16, user insights	75% of respondents satisfied by this requirement
CMSAF-RR3.6-20-OPT-Q	Provide UTH data at 3-hourly temporal resolution	Breakthrough	Questionnaire question 16	75% of respondents satisfied by this requirement
CMSAF-RR3.6-21-REQ-Q	Provide UTH data arranged by Universal Time (e.g. global time slices at 0 UT)	Majority	Follow-up to questionnaire question 16.	20 respondents contacted by email for preference of UT or local time

11.3 Data set accuracy, precision and stability

The CM SAF UTH v2 product should have an accuracy of 5 %, precision of 2 % and stability of 1 %/decade. Data should be provided with an accuracy of 1 %, precision of 1 % and stability of 0.1 %/decade if possible.

With the exception of the 0.4 %/decade stability, the requirements for accuracy, precision and stability stated above are based on results from the online questionnaire for both the threshold and breakthrough levels. GCOS defines the requirement for accuracy to be ≤5 %, which is very well aligned with the 5% threshold accuracy defined by the questionnaire and user insights. By contrast, the GCOS requirement for stability (0.3 %/decade) is more stringent than the questionnaire threshold stability but is similar to the theoretical threshold stability (0.4 %/decade). As the remit of this RR is to provide traceable requirements, the theoretical stability of 0.4 %/decade is adopted here (Table 11-3).

Table 11-3: Requirements for data set accuracy, precision and stability

ID	Requirement	Type	Source	Notes
CMSAF-RR3.6-02-ADV-E	Provide a UTH product with accuracy of ≤5%	Advisory	GCOS	No traceability for requirement
CMSAF-RR3.6-22-REQ-QU	Provide UTH data with accuracy of 5%	Threshold	Questionnaire question 17, user insights	75% of respondents satisfied by this requirement
CMSAF-RR3.6-23-OPT-Q	Provide UTH data with accuracy of 1%	Breakthrough	Questionnaire question 17	75% of respondents satisfied by this requirement
CMSAF-RR3.6-24-REQ-Q	Provide UTH data with precision of 2%	Threshold	Questionnaire question 18	75% of respondents satisfied by this requirement
CMSAF-RR3.6-25-OPT-Q	Provide UTH data with precision of 1%	Breakthrough	Questionnaire question 18	75% of respondents satisfied by this requirement
CMSAF-RR3.6-01-ADV-E	Provide a UTH product with stability of 0.4 %/decade	Advisory	Theoretically defined based on the literature	GCOS requirement is 0.3 %/decade, but with no traceability
CMSAF-RR3.6-26-REQ-Q	Provide UTH data with stability of 1%/decade	Threshold	Questionnaire question 19	75% of respondents satisfied by this requirement
CMSAF-RR3.6-27-OPT-Q	Provide UTH data with stability of 0.1%/decade	Breakthrough	Questionnaire question 19	75% of respondents satisfied by this requirement

11.4 Quality flags and uncertainty information

The CM SAF UTH v2 product should include per-pixel/grid cell uncertainties and detailed quality flags. Simple statements of on the general accuracy, precision and stability of the data set should also be provided.

Respondents to online questionnaire provided soft requirements (any option satisfying at least 45% of the respondents) for detailed quality information for each pixel/grid cell and simple statements on the accuracy, precision and stability of the UTH data based on e.g. validation studies. The requirement to provide quality flags was also supported by the CM SAF UTH Review Board, user insights, and by the project team and state-of-the-art technical information from the FIDUCEO project. A requirement for per-pixel/grid-cell uncertainties was not a clear outcome from the online questionnaire, but uncertainties are required by many users and this was highlighted through the discussions with users, including many who attended the 2019 CM SAF User Workshop (Table 11-4).

Table 11-4: Requirements uncertainty and quality information

ID	Requirement	Type	Source	Notes
CMSAF-RR3.6-07-ADV-AOU	Provide uncertainties for each pixel/grid cell	Advisory	Review board suggestion, project team expertise/state of the art, user insights	CM SAF User Workshop 2019 clear support for including FIDUCEO-like uncertainties with CM SAF data
CMSAF-RR3.6-08-REQ-AOQU	Provide a set of detailed quality flags per pixel/grid cell indicating any specific problems with the data, e.g. suspected surface contamination, suspected thick cloud contamination, calibration concerns, etc	Soft	Review board suggestion, questionnaire question 20, project team expertise/state of the art, user insights	Option satisfies more than 45% of survey respondents
CMSAF-RR3.6-28-REQ-Q	Provide simple statements on the general accuracy, precision and stability of the data set e.g. from validation studies	Soft	Questionnaire question 20	Option satisfies more than 45% of survey respondents

11.5 Validation

The CM SAF UTH v2 product be validated using simulated UTH data based on ERA-5. The per-pixel/grid-cell uncertainties should also be validated.

A validation strategy has been developed by the project team. Through the online survey and user insights, there is a clear requirement for reliable and accurate uncertainties so these also need to be evaluated (Table 11-5).

Table 11-5: Requirements for validation

ID	Requirement	Type	Source	Notes
CMSAF-RR3.6-12-ADV-QU	Validate pixel/grid-cell uncertainties provided with the UTH data	Advisory	Questionnaire question 11, user insights	Important to users that the uncertainties are reliable/accurate
CMSAF-RR3.6-33-ADV-O	Validate UTH using ERA-5, assessing mean differences, standard deviations, percentiles and anomalies.	Advisory	Project team expertise, literature	

11.6 Data set construction

The CM SAF UTH v2 product should be based on the EUMETSAT and FIDUCEO MW FCDRs. The data should be provided on both time-averaged and single-overpass time data on a uniform grid. The following should also be investigated and considered for the final CM SAF UTH v2 product:

- Using a surface temperature and/or cloud climatology to distinguish between cloud- and surface-contaminated pixels
- Using the FIDUCEO UTH retrieval process
- Investigate the use of a simple mean to calculate daily averages, rather than weighting overpasses

Table 11-6 provides further details on the requirements above.

Table 11-6: Requirements for data set construction

ID	Requirement	Type	Source	Notes
CMSAF-RR3.6-05-ADV-A	Investigate the use of a surface temperature and/or cloud climatology to distinguish between pixels contaminated with cloud or surface.	Advisory	Review board suggestion	
CMSAF-RR3.6-06-ADV-A	Investigate the use of a simple mean to calculate daily averages, rather than weighting overpasses	Advisory	Review board suggestion	
CMSAF-RR3.6-10-ADV-O	Derive the CM SAF UTH v2 product from the consistent FIDUCEO and EUMETSAT FCDRs for SSM/T-2, AMSU-B, MHS, ATMS, and MWHS-1 & -2.	Advisory	State of the art, project team expertise	
CMSAF-RR3.6-11-ADV-O	Investigate the retrieval approach used in FIDUCEO for producing the CM SAF UTH v2 product	Advisory	State of the art, project team expertise	
CMSAF-RR3.6-14-REQ-Q	Provide both time-averaged and single-overpass time data on a uniform grid	Majority	Questionnaire Q13	Derived from combined options for 'uniform grid' data in questionnaire

11.7 Data set documentation, user feedback and other data

Provide users with clear and unambiguous documentation, inducing a short 'quick start' or 'key information' version. This should include examples of applications and how the data might be used: User case studies should be considered. Provide additional data in the UTH data files, including the height of the UTH data sensed.

The need for clear documentation detailing all aspects of the data was highlighted by several users, through both discussions and free-text boxes in the online questionnaire. Some users emphasised requirements for publications showing how the data could be used. Several users mentioned including additional variables in the UTH data files, for example, height/pressure information relating to the UTH retrieval, atmospheric temperature data, and cloud. Users suggested the need to make the CM SAF UTH v2 product unique, with clear benefits for users over other similar data sets

Table 11-7: Summary of requirements for the CM SAF UTH v2 product

ID	Requirement	Type	Source	Notes
CMSAF-RR3.6-09-ADV-OQU	Provide users with a clear explanation of what the CM SAF UTH v2 product represent, full details of how the data were derived and how they can be used (ideally as published papers). This should also include a short 'quick start guide' that communicates the most important points.	Advisory	Project team expertise, questionnaire Q10 & Q23, user insights	Need for user case studies and publications highlighted by some users.
CMSAF-RR3.6-29-ADV-Q	Include elements from the examples of existing good data sets in UTH products	Advisory	Questionnaire question 21.	Good data sets: MLS on Aura, CM SAF SARAH2, SST from IRI, CERES, FIDUCEO MW UTH.
CMSAF-RR3.6-30-ADV-QU	Include additional variables in UTH products	Advisory	Questionnaire question 23, user insights	
CMSAF-RR3.6-31-ADV-QUA	Provide height or pressure information with the UTH data	Advisory		
CMSAF-RR3.6-32-ADV-Q	Provide examples of good data portals and feedback mechanisms to the CM SAF team.	Advisory	Questionnaire question 23	

11.8 Summary of requirements for MW UTH

Table 11-8 lists the requirements for the CM SAF UTH v2 product.

Table 11-8: Summary of all requirements for the CM SAF UTH v2 product. Mandatory requirements are highlighted in blue, optional requirements are highlighted in green and advice notes are highlighted in grey.

ID	Requirement	Source
	Spatial Domain and Resolution	
CMSAF-RR3.6-03-ADV-E	Provide a UTH product with spatial resolution of ≤25 km	GCOS
CMSAF-RR3.6-13-ADV-Q	Provide global UTH data	Questionnaire Q12
CMSAF-RR3.6-17-REQ-Q	Provide UTH data at a spatial resolution of 1° latitude/longitude	Questionnaire question 15
CMSAF-RR3.6-18-OPT-Q	Provide UTH data at a spatial resolution of 0.5° latitude/longitude	Questionnaire question 15
	Data set length and temporal resolution	
CMSAF-RR3.6-04-ADV-E	Provide a UTH product with temporal resolution of ≤hourly	GCOS
CMSAF-RR3.6-15-REQ-Q	Provide at UTH record of 20 years	Questionnaire question 14
CMSAF-RR3.6-16-OPT-Q	Provide a UTH record of at least 30 years	Questionnaire question 14
CMSAF-RR3.6-19-REQ-QU	Provide UTH data at 12-hourly temporal resolution	Questionnaire question 16, user insights
CMSAF-RR3.6-20-OPT-Q	Provide UTH data at 3-hourly temporal resolution	Questionnaire question 16
CMSAF-RR3.6-21-REQ-Q	Provide UTH data arranged by Universal Time (e.g. global time slices at 0 UT)	Follow-up to questionnaire question 16.

ID	Requirement	Source
	Data set accuracy, precision and stability	
CMSAF-RR3.6-02-ADV-E	Provide a UTH product with accuracy of ≤5%	GCOS
CMSAF-RR3.6-22-REQ-QU	Provide UTH data with accuracy of 5%	Questionnaire question 17, user insights
CMSAF-RR3.6-23-OPT-Q	Provide UTH data with accuracy of 1%	Questionnaire question 17
CMSAF-RR3.6-24-REQ-Q	Provide UTH data with precision of 2%	Questionnaire question 18
CMSAF-RR3.6-25-OPT-Q	Provide UTH data with precision of 1%	Questionnaire question 18
CMSAF-RR3.6-01-ADV-E	Provide a UTH product with stability of 0.4 %/decade	Theoretically defined based on the literature
CMSAF-RR3.6-26-REQ-Q	Provide UTH data with stability of 1%/decade	Questionnaire question 19
CMSAF-RR3.6-27-OPT-Q	Provide UTH data with stability of 0.1%/decade	Questionnaire question 19
	Quality flags and uncertainty information	
CMSAF-RR3.6-07-ADV-AOU	Provide uncertainties for each pixel/grid cell	Review board suggestion, project team expertise/state of the art, user insights
CMSAF-RR3.6-08-REQ-AOQU	Provide a set of detailed quality flags per pixel/grid cell indicating any specific problems with the data, e.g. suspected surface contamination, suspected thick cloud contamination, calibration concerns, etc	Review board suggestion, questionnaire question 20, project team expertise/state of the art, user insights
CMSAF-RR3.6-28-REQ-Q	Provide simple statements on the general accuracy, precision and stability of the data set e.g. from validation studies	Questionnaire question 20

ID	Requirement	Source
Validation		
CMSAF-RR3.6-12-ADV-QU	Validate pixel/grid-cell uncertainties provided with the UTH data	Questionnaire question 11, user insights
CMSAF-RR3.6-33-ADV-O	Validate UTH using ERA-5, assessing mean differences, standard deviations, percentiles and anomalies.	Project team expertise, literature
Data set construction		
CMSAF-RR3.6-05-ADV-A	Investigate the use of a surface temperature and/or cloud climatology to distinguish between pixels contaminated with cloud or surface.	Review board suggestion
CMSAF-RR3.6-06-ADV-A	Investigate the use of a simple mean to calculate daily averages, rather than weighting overpasses	Review board suggestion
CMSAF-RR3.6-10-ADV-O	Derive the CM SAF UTH v2 product from the consistent FIDUCEO and EUMETSAT FCDRs for SSM/T-2, AMSU-B, MHS, ATMS, and MWHS-1 & -2.	State of the art, project team expertise
CMSAF-RR3.6-11-ADV-O	Investigate the retrieval approach used in FIDUCEO for producing the CM SAF UTH v2 product	State of the art, project team expertise
CMSAF-RR3.6-14-REQ-Q	Provide both time-averaged and single-overpass time data on a uniform grid	Questionnaire Q13
Data set documentation, user feedback and other data		
CMSAF-RR3.6-09-ADV-OQU	Provide users with a clear explanation of what the CM SAF UTH v2 product represent, full details of how the data were derived and how they can be used (ideally as published papers). This should also include a short 'quick start	Project team expertise, questionnaire Q10 & Q23, user insights

ID	Requirement	Source
	guide' that communicates the most important points.	
CMSAF-RR3.6-29-ADV-Q	Include elements from the examples of existing good data sets in UTH products	Questionnaire question 21.
CMSAF-RR3.6-30-ADV-QU	Include additional variables in UTH products	Questionnaire question 23, user insights
CMSAF-RR3.6-31-ADV-QUA	Provide height or pressure information with the UTH data	
CMSAF-RR3.6-32-ADV-Q	Provide examples of good data portals and feedback mechanisms to the CM SAF team.	Questionnaire question 23

12 Outlook and next steps

Requirements for v2 of the CM SAF UTH product have been defined in the previous section. The CM SAF UTH v2 product will include all mandatory requirements, i.e. those defined with an 'REQ' identifier. Where possible, the optional ('OPT') and advisory ('ADV') requirements will also be met. Based on these requirements, a new product requirement table is proposed, which is provided in Appendix A, together with the current version that is included in the CM SAF Product Requirements Document (PRD) version 3.4.

The CM SAF UTH v2 product will be developed over the coming months, with the Produce Consolidation Review (PCR) planned for June 2020, and the Delivery Readiness Review (DRR) for December 2020. Those requirements that may not be addressed in v2 of the CM SAF UTH product developed in CDOP-3 provide useful information for a possible further version of the UTH product that could be produced in CDOP-4. For example, providing a UTH product with accuracy, precision and stability that meet the breakthrough or objective levels [CMSAF-RR3.6-23-OPT-Q, CMSAF-RR3.6-25-OPT-Q, CMSAF-RR3.6-27-OPT-Q], with height or pressure information [CMSAF-RR3.6-31-ADV-QUA], or with additional variables in the data files [CMSAF-RR3.6-30-ADV-QU]. Plans for CDOP-4 activities are currently being formulated and this requirements review has been informative in developing these plans.

The online questionnaire conducted as part of this RR included surveying user requirements for the CM SAF IR UTH product (also referred to as 'Free Tropospheric Humidity' or 'FTH'). This product is based on observations at 6.3 µm from METEOSAT 2-5 and METEOSAT 7-9 and provides the mean relative humidity over a deep layer of the troposphere within ±45° longitude and ±45° latitude. Requirements specific to this IR UTH product have not been analysed in detail here as this is covered separately by the IR UTH RR. However, most of the questions asked in the online survey are relevant to both the CM SAF MW and IR UTH products and it is expected that there will be some overlap and similarities between the two products. Of course, there will also be many differences. In particular, the MW UTH product is nearly all-sky and global, whereas the IR UTH product is produced only under clear sky and low-level cloud conditions. The IR UTH product can be produced with higher temporal and spatial resolution as it is derived from observations every 15-30 minutes that are available at a few km spatial resolution, compared with the twice-daily MW sensor overpasses at >25 km spatial resolution. There will also be differences in the theoretically-possible accuracy, precision and stability because of the differing wavelengths used to derive these data sets.

Given both the MW and IR datasets are providing information about UTH, a key question concerns the consistency of these CM SAF products. To address this, the CM SAF plans to propose that a visiting scientist, funded by the CM SAF, perform and inter-comparison between the two products. This could, in theory, lead the possibility of a combined CM SAF UTH product, or a more synergistic provision of the products through the CM SAF data portal.

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14 Appendix A: Product requirements for the data set under review

Table 14-1: Requirements as stated in the CM SAF Product Requirements Document (PRD), version 3.4. These are the existing requirements for the CM SAF UTH product prior to this requirements review

CM-14712	Global Upper Tropospheric Humidity R233	UTH_R2_WVGLOB_TCDR

Type:
Dataset

Input Satellite Data:
Operational Satellite: AMSU-B
Operational Satellite: ATMS
Operational Satellite: MHS
Operational Satellite: MWHS FCDR
Operational Satellite: SSM/T2

Application Areas

Dissemination Information

Distribution format
L3:NetCDF4

Generation frequency:

Generation timeliness

Spatio-temporal Information

Spatial Coverage
L3:Global

Spatial Resolution
L3:HORIZONTAL:1x1°

Temporal Resolution:
L3: Daily Mean

Temporal Coverage
01/01/1992 – 12/31/2020

Uncertainty Characteristics			Optimum	Target	Threshold
UTH-Daily Mean	ACCURACY	bias	5 %	10 %	15 %

Verification: Compare with reference in-situ data, e.g. GRUAN.

Comment:

Table 14-2: Proposed updated requirements review based on this RR3.6.

CM-14712	Global Upper Tropospheric Humidity R233	UTH_R2_WVGLOB_TCDR

Type:
Dataset

Input Satellite Data:
Operational: MHS (MetOp-A, MetOp-B, NOAA-18, NOAA-19)
Operational: ATMS (S-NPP, NOAA-20)
Operational: MWHS-1 (FY-3B)
Operational: MWHS-2 (FY-3C)
Other: SSM/T2 (DMSP F11/F12/F14/F15)
Other: AMSU-B (NOAA-15/16/17)
Other: MWHS-1 (FY-3A)

Application Areas:
Climate modelling, climate monitoring, climate variability, climate impacts, climate services, process studies, extreme events, detection and attribution, reanalysis, model evaluation/comparison, NWP, nowcasting.

Dissemination Information

Distribution format
L3:NetCDF4

Generation frequency:
N/A

Generation timeliness:
N/A

Spatio-temporal Information

Spatial Coverage
L3:Global

Spatial Resolution
L3: HORIZONTAL:1x1°

Temporal Resolution:
L3: Daily Mean, 12-hourly

Temporal Coverage
07/1994 – 12/31/2018

Uncertainty Characteristics			Optimum	Target	Threshold
UTH-Daily Mean	ACCURACY	bias	<1 %	1 %	5 %
UTH-Daily Mean	PRECISION		<1 %	1 %	2 %
UTH-Daily Mean	STABILITY		<0.1 %/dec	0.1 %/dec	1 %/dec

Verification: Comparison with ERA-5 or equivalent reanalysis.

Comment: Further verification using high-quality in situ data, e.g. GRUAN radiosonde network, may be used. However, these data are spatially sparse and cannot provide true global validation.

15 Appendix B: Online Questionnaire

This Appendix contains a copy of the online survey released as part of the user requirements gathering process. Question response options denoted by '○' indicate where only one option can be selected, while '□' are where multiple response options can be selected.

Introduction

The Satellite Application Facility on Climate Monitoring (CM SAF; https://www.cmsaf.eu) develops, produces, archives and disseminates satellite-data-based products to support climate monitoring. The product suite mainly covers parameters related to the energy and water cycle and addresses many of the Essential Climate Variables (ECVs) as defined by the Global Climate Observing System (GCOS; https://gcos.wmo.int/en/home). The CM SAF produces several types of Climate Data Records (CDR), which are time series of measurements of sufficient length, consistency, and continuity to determine climate variability and change.

Global microwave-based UTH product

The CM SAF Upper Tropospheric Humidity (UTH) data record is based on passive microwave (MW) observations. It is an exponential transform, following Soden and Bretherton (1993), of nadir-adjusted brightness temperatures of the 183.31±1.00 GHz channel, which is on the flanks of a strong microwave line of water vapour. UTH typically represents the mean relative humidity over a range from about 500 hPa to 200 hPa but can be considerably higher or lower depending on the atmospheric water loading. In particular, at high latitudes or over high ground, the total column water is often so small that the surface emission affects, or even dominates, the signal. UTH data are near-all-sky observations because cloud contaminates the MW data only if it contains many large ice particles or it is precipitating (these data are excluded from the CM SAF UTH data record).

The CM SAF UTH product is based on MW observations from sun-synchronous polar-orbiting satellites from circa 1994 to the present day and will continue for decades into the future. The low-earth orbits of these satellites mean that each one passes over most points twice a day, about 12 hours apart, e.g. 9 am and 9 pm local time. Some observational periods have data from more than one MW sensor, thus more than two observations per day are sometimes available. Overpasses become more frequent approaching the poles. However, the CM SAF UTH data should be treated with caution outside of ±60° latitude because of surface contamination and sampling at lower levels in the troposphere.

Version 1 of the CM SAF UTH is available from the CM SAF webpages (https://doi.org/10.5676/EUM_SAF_CM/UTH/V001). It is a global gridded data record at 1° x 1° latitude-longitude. Data are provided separately for the ascending (South to North) and descending overpasses, and also as daily means for six platforms: the Advanced Microwave Sounding Unit B (AMSU-B) on board NOAA-15, NOAA-16 and NOAA-17, and the Microwave Humidity Sounder (MHS) on board NOAA-18, MetOp-A and MetOp-B. The data record covers the period from 1999 to 2015.

References:

Soden, B. J. and F. P. Bretherton (1993), Upper Tropospheric Relative Humidity From the GOES 6.7 µm Channel: Method and Climatology for July 1987, J. Geophys. Res., 98, 16,669-16,688, doi:10.1029/93JD01283

Regional infrared-based UTH product

The CM SAF Free Tropospheric Humidity (FTH, also referred to in this survey as UTH) data set utilises observations at 6.3 µm from METEOSAT2-5 and METEOSAT7-9 and provides the mean relative humidity over a deep layer of the troposphere within ±45° longitude and ±45° latitude. The retrieval was developed at Centre National de la Recherche Scientifique (CNRS) and - after transfer to CM SAF - CM SAF and CNRS jointly extended the time series into the SEVIRI era. The product is defined under clear sky and low level cloud conditions and is available at 3-hourly temporal resolution and as monthly averages (straightforward averages over all valid observations) on a regular latitude/longitude grid with a spatial resolution of 0.625° × 0.625°. The temporal coverage of the data sets ranges from July 1983 to December 2009. The METEOSAT-6 period, March 1997-May 1998, is not covered. The FTH layer position and thickness depends on atmospheric condition, and in particular water vapour content in the free troposphere. The clear sky radiance is provided as auxiliary information. More details on the retrieval, the data records and validation results can be found in Schröder et al. (2014). Version 1 of the CM SAF FTH product is available from the CM SAF webpages (https://www.cmsaf.eu; https://doi.org/10.5676/EUM_SAF_CM/FTH_METEOSAT/V001).

References:

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Survey objectives

The objective of this questionnaire is to gather user requirements for new versions of the CM SAF UTH products. It aims to understand the requirements of your application, or potential application for UTH data, with a particular focus on what is required for developments in the next 5-10 years.

General Information

This survey can be completed in full or in part; it is not necessary to answer all questions to submit your responses. You can move back at any time if you wish to, but nothing will be submitted until you click the "Done" button on the last page.

The personal information entered in questions 1-4 of this survey will be stored until 31 December 2019 by the CM SAF project teams at the UK Met Office and DWD. It will only be used where clarification of your answers is required (e.g. if we do not understand a comment entered in a free text box). We will not share your personal information with any third party or use the information you provide for any other purpose. You may request that your personal details are removed from the CM SAF UTH questionnaire database before 31 December 2019 by emailing contact.cmsaf@dwd.de.

If you are not yet a CM SAF user and would like to receive the CM SAF Newsletter in the future, please register via https://wui.cmsaf.eu. You can subscribe and un-subscribe to the newsletter via your personal settings in your user profile.

1. If you are happy for us to make contact with you about your questionnaire responses by email, please provide your email address:

2. If you are happy for your responses to be attributed to you, please provide your full name (optional)

3. At which institution do you currently work (optional)?

4. In which country do you currently work (optional)?

UTH Applications

Please tell us about how you currently use or might use UTH data (from any source, e.g. satellite, in situ, reanalysis) in the next 5 years. This will help us to understand how UTH data is being used in the scientific community and provide context for the rest of the survey.

5. Please select the primary application from the list for which you currently use or might use UTH data. This is the application we would like you to have in mind when you answer the rest of the survey.

- Climate modelling
- Climate projections
- Climate monitoring
- Climate variability and analysis
- Climate impacts
- Climate services
- Tropical weather/climate
- Continental weather/climate
- Climate/weather in a particular country or at local scales
- Process/case studies
- Extreme events
- Detection/attribution of climate change
- Re-analysis
- Model evaluation
- Validation / inter-comparison with other observational data
- Numerical weather prediction
- Nowcasting
- Other (please specify):

Current Data Use

These questions are to understand the types of data you currently use for your primary application.

6. Do you use in situ UTH data, e.g. from radiosondes?

- ○ I am a current user
- ○ I am not a current user, but I expect to use these data in the next 5 years
- ○ I have no definite plans to use these data at present, but may use them in the future
- ○ I do not plan to use these data now or in the future

7. Do you use UTH data derived from satellite microwave data?

- ○ I am a current user
- ○ I am not a current user, but I expect to use these data in the next 5 years
- ○ I have no definite plans to use these data at present, but may use them in the future
- ○ I do not plan to use these data now or in the future

8. Do you use UTH data derived from satellite infrared data?

- ○ I am a current user
- ○ I am not a current user, but I expect to use these data in the next 5 years
- ○ I have no definite plans to use these data at present, but may use them in the future
- ○ I do not plan to use these data now or in the future

9. Do you use UTH data from reanalysis?

- ○ I am a current user
- ○ I am not a current user, but I expect to use these data in the next 5 years
- ○ I have no definite plans to use these data at present, but may use them in the future
- ○ I do not plan to use these data now or in the future

10. Please rank the top three main concerns or barriers (if any) that you consider to be an issue for using UTH data from satellite microwave data (with 1 being the most important, and 3 the least):

	1	2	3
I don't know enough to assess whether it would be useful/I have never investigated the possibilities	○	○	○
It is not clear to me exactly what it represents / I cannot relate it to other data that I am using	○	○	○

I am not currently using/I have never used any observational data *(do not include reanalysis data here)*	○	○	○
It is not accurate enough	○	○	○
Stability/homogeneity is unknown / too poor	○	○	○
Data set time series are not long enough	○	○	○
Spatial coverage is not sufficient	○	○	○
Spatial resolution is too low	○	○	○
Temporal resolution is too low	○	○	○
Technical issues accessing the data (e.g. dataset size, format, data portal)	○	○	○
I am only interested in data sets with multiple variables sampled together / **I prefer data sets with maximal information (e.g. merged MW & IR, LEO & GEO observations, or reanalyses)**	○	○	○
The data are not complete enough for me / I am concerned about the lack of all-sky sampling.	○	○	○
I am concerned about the contamination by the surface and/or very thick cloud			
The data vary too much in altitude for me/I want only data guaranteed to be genuinely upper-tropospheric	○	○	○
I am interested in specific humidity and conversion of UTH to this is too difficult/too unreliable/not something I understand	○	○	○
The uncertainty information is not good enough/specific enough (e.g. lack of per-grid cell uncertainties)	○	○	○
I distrust/am not certain I should trust the uncertainty information	○	○	○

11. Please rank the top three main concerns or barriers (if any) that you consider to be an issue for using UTH data from satellite infrared data (with 1 being the most important, and 3 the least):

	1	**2**	**3**
I don't know enough to assess whether it would be useful/I have never investigated the possibilities	○	○	○

It is not clear to me exactly what it represents / I cannot relate it to other data that I am using	○	○	○
I am not currently using/I have never used any observational data *(do not include reanalysis data here)*	○	○	○
It is not accurate enough	○	○	○
Stability/homogeneity is unknown / too poor	○	○	○
Data set time series are not long enough	○	○	○
Spatial coverage is not sufficient	○	○	○
Spatial resolution is too low	○	○	○
Temporal resolution is too low	○	○	○
Technical issues accessing the data (e.g. dataset size, format, data portal)	○	○	○
I am only interested in data sets with multiple variables sampled together / I prefer data sets with maximal information (e.g. merged MW & IR, LEO & GEO observations, or reanalyses)	○	○	○
The data are not complete enough for me / I am concerned about the lack of all-sky sampling.	○	○	○
I am concerned about the contamination by the surface and/or cloud			
The data vary too much in altitude for me/I want only data guaranteed to be genuinely upper-tropospheric	○	○	○
I am interested in specific humidity and conversion of UTH to this is too difficult/too unreliable/not something I understand	○	○	○
The uncertainty information is not good enough/specific enough (e.g. lack of per-grid cell uncertainties)	○	○	○
I distrust/am not certain I should trust the uncertainty information	○	○	○

Data Specification

These questions ask about your requirements of UTH data in terms of product level, coverage, resolution and quality. Please consider the fundamental requirements of your primary application rather than specific instruments or data sets, or what you think is technically achievable.

Please also think about what is required to enable developments in your work in the next 5 - 10 years.

12. Over what spatial domain would you require UTH data for your primary application?

- Globally
- Tropics
- Subtropics
- Mid Latitudes
- Polar Regions
- Continent (please specify)
- Country (please specify)
- Local scale (such as a city or a field experiment) (please specify)
- Other (please specify):

13. What level of satellite UTH data would you use?

- I don't plan to use satellite UTH data / I haven't considered using satellite UTH data
- Satellite UTH at native satellite resolution and projection (Level 2 orbit data)
- Satellite UTH mapped on uniform space grid scales from a single orbit (Level 3U)
- Satellite UTH mapped on uniform space-time grid scales, collated over multiple observations (Level 3C)
- Further processed satellite UTH data such as model output or data derived from multiple data sets (Level 4)
- I don't know
- Other (please specify):

For the following requirements, please indicate the "threshold", "breakthrough" and "objective" levels specific to your primary application (or potential application) using the definitions below.

Threshold: Data below this level would be useless.

Breakthrough: A level (if there is one) which would significantly improve the value.

Objective: Improvement beyond this level would bring no benefit.

Please consider the fundamental requirements of your primary application rather than specific instruments or data sets, or what you think is technically achievable. Please also think about what is required to enable developments in your work in the next 5 - 10 years.

14. What is the length of UTH data that you require for your primary application?

	< 1 year	1 year	3 years	5 years	10 years	20 years	30 years	> 30 years
Threshold	○	○	○	○	○	○	○	○
Breakthrough	○	○	○	○	○	○	○	○
Objective	○	○	○	○	○	○	○	○

15. At what spatial resolution do you require UTH data for your primary application?

	<0.25 °	0.25 °	0.5 °	1 °	> 1°
Threshold	○	○	○	○	○
Breakthrough	○	○	○	○	○
Objective	○	○	○	○	○

16. At what temporal resolution do you require UTH data for your primary application?

	<Hourly	Hourly	3-hourly	Every 12 hours	Daily	Monthly	Annual or longer
Threshold	○	○	○	○	○	○	○
Breakthrough	○	○	○	○	○	○	○
Objective	○	○	○	○	○	○	○

In questions 17-19, "%" refers to the fraction of saturation, not the fractional accuracy of the measurement.

17. What accuracy do you require for UTH in your primary application? Accuracy is the degree of conformity of the measurement to the 'true' value? (Note this is theoretical, as the true value cannot be known due to measurement error.)

	<1 %	1 %	2 %	5 %	10 %	20%	>20%
Threshold	○	○	○	○	○	○	○
Breakthrough	○	○	○	○	○	○	○

Objective	○	○	○	○	○	○	○

18. What precision do you require for UTH in your primary application? Precision is the closeness of agreement between independent measurements of a quantity under the same conditions.

	<1 %	1 %	2 %	5 %	10 %	20 %	>20%
Threshold	○	○	○	○	○	○	○
Breakthrough	○	○	○	○	○	○	○
Objective	○	○	○	○	○	○	○

19. What stability do you require for UTH in your primary application? Stability (or "homogeneity") is the consistency of the data set over time.

	<0.1 %/decade	0.1 %/decade	0.5 %/decade	1 %/decade	2 %/decade	3 %/decade	5 %/decade	>5 %/decade
Threshold	○	○	○	○	○	○	○	○
Breakthrough	○	○	○	○	○	○	○	○
Objective	○	○	○	○	○	○	○	○

Quality and uncertainty information

Both CM SAF UTH products contain the grid-cell median/mean, standard deviation and number of observations. The grid-cell mean and standard deviation of the brightness temperatures for the channel used for the UTH retrieval is also provided.

20. In addition to the information provided in version 1 of the CM SAF UTH product, what quality and uncertainty information would you need for your primary application? Please select all that apply.

- □ Simple statements on the general accuracy, precision and stability of the data set e.g. from validation studies
- □ A simple quality flag per pixel/grid cell indicating a possible problem with the data e.g. good data / suspect data / bad data
- □ A set of detailed quality flags per pixel/grid cell indicating any specific problems with the data, e.g. suspected surface contamination, suspected thick cloud contamination, calibration concerns, etc.
- □ Per pixel/grid cell total uncertainty

- □ Per pixel/grid cell total uncertainty, separately for uncertainty arising from systematic or random effects, applying assumptions on error correlations.
- □ Per pixel/grid cell uncertainty which has been separated into components that describe errors correlated on different spatial and/or temporal scales
- □ An ensemble of data sets covering the range of uncertainty
- □ No additional information about quality and uncertainty is required
- □ Other (please specify):

21. Thinking about aspects such as accessibility, file format, file contents, meta data, data presentation, user documentation, etc, rather than accuracy or data quality, is there an observational data set that you have used that you consider to be a particularly good example of presenting observational data?

22. If you have provided an example of a good observational data set in question 21, what is it about this data set that you particularly like?

Comments

23. Do you have any further comments on your current or potential requirements for UTH data before exiting and submitting your responses to the survey?

Thank you for your time!

Your responses will help us to understand the scientific requirements for UTH data sets. These responses will feed directly into the CM SAF UTH projects to define the user requirements that feed into the specification of data products and formats.

16 Appendix C: Free-text responses to questions 21, 22 and 23

Question 21: Data set name	Question 22: Data set advantages	Question 23: Further comments
		For climate analyses, it is very important to have the longest possible time series. All efforts to increase the period of archives (IR and MW) are fundamental
netcdf		
For gridded data (Ive worked with model fields) I find NetCDF easy to work with, and the metadata easy to access. I expect a level 3C product on UTH would look like a complete field and hence this solution would work ? For irregularly sampled (e.g . Level 1) observational data I work with (ECMWF) ODB format, or plain ASCII. All of the observations assimilated in ERA5 are available in this format. Therefore for me - that is a good example. However for a gridded (level 3/4) observational dataset, such as could be provided by CMSAF, the ERA5 model fields in NetCDF format files available from the ECMWF MARS archive are a good example. I expect this is a fairly straightforward example of NetCDF fields data though.	I can access the NetCDF (model fields) data in MATLAB using a single line of code: data=ncread(filename,variable) - then I can inspect, visualise, analyse very quickly. I expect similar interfaces are availble in Python, IDL, ...	In order to use for the validation of ERA5 (6,7 ....) I would need good documentation on the transformations required to generate the equivalent estimates from reanalysis fields.
the L2 support product from the AIRS team at JPL	A lot of detail for each retrieval with clear	I think meta data is really important for these

	documentation/examples for using some of the more complicated components. They also have a simple feedback mechanism so that if you find aspects are not so clear they will help clarify and then implement those changes into documentation.	products and should include information on the SRFs used in the generation of coefficients, and maybe some information on the training dataset(?).
MLS on Aura has a particularly good data quality document (https://mls.jpl.nasa.gov/data/v4-2_data_quality_document.pdf)	they have good guidance for how to use the data: where it is good, weighting functions, accuracy, precision, etc. just about everything you might want to know is in there.	"spatial resolution" is a bit ambiguous in this survey. I presume the emphasis is on horizontal resolution, but vertical resolution is extremely important. I think real breakthroughs will come from improvements in vertical resolution, much more so than horizontal.
		Information on whether and how sensors have been inter-calibrated (in the underlying FCDR) would be useful in the documentation.
not really. All datasets that I have used have pros and cons.		
		Only that my responses relate to the primary purpose at the moment of using the data for case studies. Another great use is long-term climate trends but I hope others will respond along that line (I have no plans to look at it)
Yes i think its a good way to present a	Me with a MATLAB code i can easily use this	I would like to thank you for the work you do. I hope that you will continue to exist as long as

meteorological data.	data.	possible
the NASA Giovanni system is good	ease of access to data	
Yes, CM SAF SARAH2	All listed in question 21: accessibility, file format, file contents, meta data, data presentation, user documentation	
SST(Sea surface temperature) data set from IRI website.	It is tabulated in a manner easily understood and there are graphical illustration of its ensembles analysis., UTH data set are very vital for monsoonal activities in July and August over the tropics. Daily UTH analysis and reanalysis data are key during these periods.	
CERES SSF CloudSat level 2 CERES-EBAF	CERES SSF or CloudSat are good examples because of the large amount of additional information they contain (ancillary data and variables from other sensors). They would be even better if the format were CF-compliant NetCDF. For spatially- and time-averaged data, CERES-EBAF is a good example.	My main interest is in cloud studies. Within this context, I think it is important to have access to co-located information about cloud variables (e.g.cirrus cloud microphysical properties, ice water content) at high spatiotemporal resolution.
netCDF files, conforming to the requirements of the CEDA archive, please.		
CERES	NetCDF cf-complient, range of products to suite needs, quality statements, substantive	Some way of combining with reanalysis temperature to provide estimates of specific humidity anomaly would be interesting but I guess

	publications	something the user can do. The approximate pressure-level range of each pixel would be useful.
NOAA/NCEI-UMD OLR CDR, only in some aspects	length, continuity, coverage	
		I think that long-term stability, homogeneity, characterisation of changepoints etc. is more important than the exact uncertainty quantification of single measurements.
FIDUCEO MW UTH	user documentation	The file with UTH data should also contain the brightness temperatures, from which they were derived.

17 Glossary

AAPP	ATOVS (Advanced TIROS (Television Infra-Red Observation Satellite) Operational Vertical Sounder) and AVHRR (Advanced High Resolution Radiometer) Processing Package
AMSU-B	Advanced Microwave Sounding Unit - B
ATBD	Algorithm Theoretical Basis Document
ATMS	Advanced Technology Microwave Sounder (name of a US instrument)
BT	Brightness temperature
CAF	Central Application Facility
CCI	Climate Change Initiative
CDOP	Continuous Development and OPerations
CDR	Climate Data Record
CFMIP	Cloud Feedback Model Intercomparison Project
CM SAF	EUMETSAT's Satellite Application Facility on Climate Monitoring
COSP	CFMIP Observation Simulator Package
DMSP	Defense Meteorological Satellite Program (USA)
DWD	Deutscher Wetterdienst (the German National Meteorological Service)
DRR	Delivery Readiness Review
ECV	Essential Climate Variable (as defined by GCOS).
ENSO	El Niño/Southern Oscillation
EPS-SG	EUMETSAT Polar System-Second Generation
ESA	European Space Agency
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FCDR	Fundamental Climate Data Record
GCOS	WMO's Global Climate Observing System project
GCM	Global Circulation Model
GMI	Global Microwave Instrument
GPM	Global Precipitation Measurement
GRUAN	GCOS Reference Upper-Air Network
GUAN	GCOS Upper Air Network
HIRS	High-resolution Infrared Radiation Sounder (name of a particular instrument)
IPWG	International Precipitation Working Group
IR	Infra-Red

MHS	Microwave Humidity Sounder (name of a particular instrument)
MJO	Madden-Julian Oscillation
MW	MicroWave
MWS	MicroWave Sounder (name of a particular instrument)
MWHS	MicroWave Humidity Sounder (name of a Chinese instrument)
NEDT	Noise-Equivalent Differential Temperature
NMHS	National Meteorological and Hydrological Service
NOAA	National Oceanic and Atmospheric Administration (USA)
NPP	National Polar-orbiting Partnership
NWP	Numerical Weather Prediction
Obs4MIP	Observation for Model Intercomparison Project
OSCAR	Observing Systems Capability Analysis and Review tool Review (WMO website for Earth Observation from space)
PCR	Product Consolidation Review
PRD	Product Requirement Document
RFI	Radio Frequency Interference
RH	Relative Humidity
RR	Requirements Review
SAF	Satellite Application Facility
SAPHIR	Sondeur Atmosphérique du Profil d'Humidité Intertropical par Radiométrie
SSM/T-2	Special Sensor Microwave - Humidity
TCWV	Total Column Water vapour
TCDR	Thematic Climate Data Record
TTL	Tropical Tropopause Layer
UTH	Upper Tropospheric Humidity
UTLS	Upper Troposphere and Lower Stratosphere
WMO	World Meteorological Organization
VMR	Volume Mixing Ratio