EUMETSAT Satellite Application Facility on Climate Monitoring

Requirements Review 3.9

Regional Land Fluxes

Meteosat Fractional Cloud Cover	**CM-23012**
Meteosat Surface Radiation Budget	**CM-23271**
Meteosat Free Tropospheric Humidity	**CM-23722**
Latent and Sensible Heat Flux	**CM-23811**
Meteosat Land Surface Temperature	**CM-23922**

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Applicable documents

Reference	Title	Code
AD 1	CM SAF CDOP3 Project Plan	SAF/CM/DWD/PP/1.4

Reference Documents

Reference	Title	Code
RD 1	CM SAF Product Requirements Document	SAF/CM/DWD/PRD/3.4
RD 2	Validation Report. CM SAF Cloud, Albedo, Radiation dataset, AVHRR-based, Edition 2 (CLARA-A2). Surface Radiation Products.	SAF/CM/DWD/VAL/GAC/RAD/2.1
RD 3	Validation Report. Meteosat Solar Surface Radiation and effective Cloud Albedo Climate Data Record.	SAF/CM/DWD/VAL/METEOSAT_HEL/1.1
RD 4	Requirements Review. AVHRR GAC Edition 3 data records. (CLARA Edition 3).	SAF/CM/CDOP3/SMHI/RR32/1.0
RD 5	Validation Report. Meteosat Cloud Fractional Cover (COMET) Edition 1.	SAF/CM/MeteoSwiss/VAL/MET/CFC/1.2
RD 6	Validation Report Land Surface Temperature (LST) Edition 1	SAF/CM/MeteoSwiss/VAL/MET/LST/1.1
RD 7	Visiting Scientist Report: Intercomparison of the CM SAF and GlobTemperature LST TCDR	UoL_Intercomparison_CM SAF_and_GlobTemp_LST_TCDR/1.0

Summary of highlights of the TCDR Regional Land Fluxes

Meteosat Fractional Cloud Cover (CM-23012)

- 35 years+ record length
- New requirements follow GCOS requirements

Meteosat Free Tropospheric humidity (CM-23722)

- Increased spatial and temporal resolution.
- Utilisation of CM SAF cloud mask and cloud top pressure

Meteosat Land Surface Temperature (CM-23922)

- 35 years+ record length
- Improved stability and uncertainty characterisation

Meteosat Surface Radiation Budget (CM-23271)

- Unique joint retrieval of all components of the surface radiation budget

Latent and Sensible Heat Flux (CM-23811)

- New CM SAF product based on the LSA SAF v2 algorithm with adapted input data (consistency, stability, etc).

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1 Purpose of the document

This document consolidates the position of the CM SAF project team concerning the product requirements for CM-23012, CM-23271, CM-23722, CM-23811, CM-23922 in preparation for the Requirements Review (RR) 3.9.

2 Introduction

2.1 The Climate Monitoring SAF (CM SAF)

EUMETSAT has setup and operates a Network of ***Satellite Application Facilities*** (SAF) which together with the EUMETSAT central facilities constitute the EUMETSAT Application Ground Segments for MSG and EPS. The SAFs are located in a National Meteorological Service or other approved institutes of a EUMETSAT member state. The scope of the SAF activities is to deliver products, at the level of geophysical parameters, based primarily on the satellite data. Also, in EUMETSAT's Implementation Plan (EUMETSAT IP, 2010) it is declared that the generation of FCDRs at CAF and through its SAF Network should be the main focus of EUMETSAT activities to support climate monitoring. It is further stated that CM SAF continues the generation of CDRs from SSM/I.

Each SAF is developed and operated according to a Cooperation Agreement, signed between EUMETSAT and the Host Institute, which manages the programme. Funding from the Host Institute and co-operating entities complements the EUMETSAT contribution to the project.

Overview information on the CM SAF can be found at its web page under http://www.cmsaf.eu.

3 Background of products under review

For RR 3.9 the following products from PRD 3.4 (RD-1) are under review:

Table 3-1: CM SAF products under review.

Product Family	CM SAF Product Identifier	Product Name
COMET-2	CM-23012	Meteosat Fractional Cloud Cover
	CM-23271	Meteosat Surface Radiation Budget
	CM-23722	Meteosat Free Tropospheric humidity
	CM-23811	Meteosat Latent and Sensible Heat Flux
SUMET-2	CM-23922	Meteosat Land Surface Temperature

CM-23012 and CM-23922 are follow up versions of the previously released CM SAF COMET and SUMET TCDR (CM-23011 and CM-23921).

3.1 Related open actions from previous meetings and SGs

A1 RR 2..8: CM-23722: PT to add into the PUM the discussion about the possibility of FTH>100% and how these pixels are handled (rejection, flagging, etc.).
Due: DRR 2.8.

A2 DRR 2.8/2.9: PT to consider the GCOS requirements for LST in the next release.
Due: RR 3.9

A3 DRR 2.8/2.9: PT to consider performing an investigation about the Elevation-dependency bias of LST.
Due: RR 3.9

A4 DRR 2.8/2.9: PT to include a larger-scale LST comparison using T2m air temperatures for the next release.
Due: RR 3.9

4 Current Planning

The CM SAF Project Plan [AD 1] provides the CM SAF review schedule. The part relevant for RR 3.9 is recalled in **Table 4-1**. The RR 3.9 is followed by the Product Consolidation Review (PCR) in the second quarter of 2020 and by the Data set Readiness Review (DRR) in the third quarter of 2021.

Table 4-1: Product to review mapping.

Product Family	RR 3.9	PCR 3.9	DRR 3.9
TCDR Regional Land Fluxes	Q2 2019	Q2 2020	Q3 2021

5 Definition of product requirements

This section provides information on the traceability of requirements, the validation approach, expected user and application area and the uniqueness of the product. Traceability, product specific validation and uniqueness details are discussed per product.

Details for each product are given in Appendix A.

5.1 Meteosat Fractional Cloud Cover (CM-23012)

5.1.1 Traceability of requirements

Requirements for the use of Essential Climate Variables (ECVs) Cloud Fractional Cover (CFC) have been formulated by the World Meteorological Organization (WMO) in the Global Climate Observing System (GCOS) report (GCOS-107) and its updates (GCOS-154, GCOS-200). GCOS requirements are provided in terms of resolution, accuracy and stability. The new defined CM-23012 requirements follow the GCOS requirements.

Resolution Requirement

CM-23012 serves various applications, many of which are related to regional climate studies and climate model evaluations. As regional models are now available with a very high spatial (up to 1 km) and temporal (up to hourly) resolution, high resolution cloud observations are needed to evaluate those models. MeteoSwiss for example is currently using COMET version 1.0 cloud fractions to evaluate low level cloudiness of the regional 1.1 km COSMO-1 model.

GCOS-154 therefore addresses some of the growing needs for data sets with higher spatial and temporal resolution for climate research and regional climate monitoring. High temporal and spatial resolution CFC data sets are required for evalution of high resolution models (such as the bias correction of the COSMO NWP Model ongoing at MeteoSwiss and as reference for downscaling global climate model output for regional and local applications especially in mountainous terrain). In turn the spatial resolution requirement was sharpened to 10 km and the temporal resolution is requested to be 1 hour or better (e.g. for CMIP5 studies with results discussed in the IPCC-AR5 report, IPCC 2013). Both temporal and spatial resolution requirements are fulfilled by CM-23012. The final TCDR is sampled to hourly, daily and monthly on a 0.05° longitude and latitude grid.

Accuracy Requirement

For CM-23012 we use the bias and the bias-corrected root-mean-square error (bc-RMS) to reflect systematic (accuracy) and random uncertainty (precision). The accuracies (bias) and precision measures (bc-RMS) are applied for the entire Meteosat disk with respect to SYNOP observations.

GCOS-154 specifies accuracy requirements in the form of absolute cloud fraction units (0-1) and as global (spatially averaged) values. In GCOS-154 the accuracy requirement for cloud fraction was sharpened from 0.1 (GCOS-107) to a range of 0.01 (thick clouds) to 0.05 (thin clouds). CM-23012 accuracy requirements do exactly match those GCOS definitions and requirements.

The threshold accuracy (bias) is set to the GCOS accuracy requirement for thin clouds (0.05). The CM-23012 optimal requirement reflects the GCOS requirement for thick clouds (0.01). Typically, the target accuracy is set in between the optimal and threshold accuracy. COMET version 1.0 matches those GCOS requirements for all aggregation steps (RD 5).

GCOS-200 does not provide requirements for precision. We have therefore added precision requirements (bc-RMS) to the GCOS accuracy requirements. The newly defined threshold precisions for CM-23012 corresponds to the optimal precision requirement from COMET version 1.0 (RD 5). We account here for the fact that the precision for COMET version 1.0 matched the previously defined optimal requirement (RD 5). The threshold precision is now set to 0.15 for monthly means.

Stability Requirement

The temporal stability advised by GCOS-154 is a range of 0.003 to 0.03 per decade. CM-23012 stability requirements (stability of the bias) exactly reflect this uncertainty range. The defined threshold and optimal stabilities of 0.03 and 0.003, respectively, reflect the upper and lower limits of the GCOS stability range. COMET version 1.0 has a stability smaller than 0.01 and we are hence confident that CM-23012 will match those GCOS requirements for the 1991-2020 period. Especially since we are planning to use updated Meteosat calibration for both the optical and thermal Meteosat (MVIRI) channels.

Table 5-1: Summary of requirement values for CFC.

	Threshold	*Target*	*Optimal*
Stability	0.03/dec	0.02/dec	0.003/dec
Bias	0.05	0.03	0.01
RMS	0.15	0.10	0.05

5.1.2 Validation approach

We will follow excatly the validation approach used to evaluate the COMET version 1.0 cloud fractional cover (RD 5).

The two reference data records for validation are ground-based observation sources (SYNOP) and retrievals from an active satellite instrument (CALIPSO/CALIOP). Inter-comparisons to other passive satellite imager derived CFC data records such as MODIS, PATMOS-x, CLARA-A3, CLAAS-3 and CC4CL-AVHRR are provided as well. For the CM-23012 release we will also include an intercomparision to the novel ISCCP H release.

The validation task comprises evaluation of the daily and monthly CFC to check if they comply with CM-23012 requirements. However, to evaluate Meteosat CFC against reference data records (i.e. SYNOP and CALIPSO/CALIOP), the collocations are performed for instantaneous level-2 data. The accuracy and precision are then provided on the instantaneous time scale (for which no requirement is formulated) and for the collocations aggregated to daily and monthly time scale.

To assess the accuracy of Meteosat CFC at both level-2 and level-3 we use the mean bias error, i.e. mean difference between Meteosat CFC and reference data. To express the precision of Meteosat CFC compared to a reference data record, the bias-corrected root mean squared error is used. In addition, to compare the discrete level-2-based binary cloud condition (clear or cloudy derived from CFC thresholds), we use the skill scores such as probability of detection (POD), false alarm ratio (FAR) and the Hanssen-Kuiper's discriminant (KSS). For a trend analysis we use linear trends derived using Theil-Sen estimates and their significance is estimated with the Mann-Kendall test.

Stability will be tested against SYNOP observations. SYNOP measurements over Europe and Africa are available back to the 80s and provide an excellent stability reference. For trend analysis we use linear trends derived using Theil-Sen estimates and their significance is estimated with the Mann-Kendall test.

5.1.3 Expected users and application area

COMET version 1.0 serves as a final TCDR for climate analysis and climate model evaluation. With a time of 37 years and the expected high decadal stability (<0.01 for the period 1991 to 2022) CM-23012 will be of very high interest for climate analysis and model evaluations.

A cloud mask algorithm covering climatological periods is required for the generation of climate data records such as land surface temperature and albedo, surface energy fluxes and free tropospheric humidity. This explicitly includes the TCDR's:

- CM SAF Land Surface Temperature (CM-23921, CM-23922), CM SAF Surface Radiation Budget (CM-23271) and CM SAF Latent and Sensible Fluxes (CM-23811) which require a thorough clear-sky conservative cloud screening
- CM SAF Free Tropospheric Humidity (FTH, CM-23722) where only thick and mid-to-high level clouds have to be removed.
- EUMETSAT Central Facility (CF) Geostationary Surface Albedo (GSA). The new data release planned for 2019 will use COMET version 1.0 for cloud masking.

Within the WMO SCOPE-CM project SCM-03 (Lattanzio et al. 2013) COMET version 1.0 cloud fraction is extended to the GEO sensors of the National Oceanic and Atmospheric Administration (NOAA) and the Japan Meteorological Agency (JMA) in order to retrieve GEO surface albedo fully exploiting the geostationary "ring" to increase spatial coverage.

5.1.4 Uniqueness of product

CM-23012 will be a unique high resolution cloud fraction TCDR with unprecedented record length (37 years) combined with an unprecedented decadal stability (within GCOS requirements) which resolves the full diurnal cycle.

This is achieved by an unique retrieval approach (Stöckli et al. submitted):

- It builds on inter-calibrated radiances now available for historical GEO sensors.
- It uses spatio-temporal information and a robust clear sky retrieval.
- The real strength of GEO observations – the diurnal cycle of reflectance and brightness temperature – is fully exploited instead of just accounting for single "imagery".
- The commonly used naïve Bayesian classifier is extended with covariance information of cloud state and variability.

5.2 Meteosat Surface Radiation Budget (CM-23271)

5.2.1 Traceability of requirements

CM-23271 labelled as SRB the longwave and shortwave net radiation. Single radiation components i.e. the Surface Incoming Solar radiation (SIS), the Surface Albedo (SAL), the Surface Outgoing Longwave radiation (SOL) and the Surface Downwelling Longwave radiation (SDL) will be provided as ancillary data.

The surface radiation budget (SRB) is an essential climate variable identified by GCOS (GCOS-200, 2016). The high accuracy of the SRB is of high importance to close the surface energy budget. As a consequence, the accuracy and decadal stability requirements for the SRB defined by GCOS are 1 W/m² and 0.2 W/m²/dec, respectively. The CM SAF requirements are based on the recommendations by GCOS and on user feedback.

The temporal and spatial resolution requested by GCOS are monthly (resolving diurnal cycle) and 100 km (GCOS-200, 2016). Such resolutions are enabled by MVIRI and SEVIRI instruments.

For the surface radiation, the accuracy requirement is measured with the mean absolute bias (MAB). In contrast, the accuracy requirement for surface albedo is measured with the mean bias. The temporal stability of the bias against the surface observations will be used to assess the compliance of the data records with the stability requirement.

The SRB is derived from the four individual fluxes at the surface: the Surface Incoming Solar radiation (SIS), the Surface Albedo (SAL), the Surface Outgoing Longwave radiation (SOL) and the Surface Downwelling Longwave radiation (SDL). Their accuracies are based on the accuracy of the input data. In the following we also provide accuracy and precision for the single SRB components that were used to set the SRB requirements.

SIS:

The surface incoming shortwave radiation is, as part of the surface radiation budget, an essential climate variable as identified by GCOS (GCOS-200, 2016). The CM SAF accuracy requirements are based on the recommendations by GCOS and on user feedback. The target accuracy requirement for SIS is 1 W/m² as defined by GCOS (GCOS-200, 2016). The precision of well-maintained ground measurements of shortwave radiation is 4 W/m^2 (monthly means) (Raschke et al., 2012). In addition, the point to area mean comparison adds further uncertainties to the validation process. Hence, a threshold accuracy of 9 W/m² proposed here is based on the accuracy of the SARAH data record (RD 3). The optimal accuracy considered is 4 W/m².

SAL:

The target GCOS accuracy requirement for black-sky and white-sky surface albedo is 5% (relative; 0.0025 absolute) and the stability target requirement is 1% (0.0001 absolute) (GCOS-154). However, these requirement targets currently appear to be barely possible to reach from space-borne observations as discrepancies partly come from a lack of spatial representativeness between the footprint of the ground station and the satellite measurements. CLARA-A2 and CLARA-A3 defined more reachable requirements for SAL. The optimal, target and threshold accuracy requirements are 5% / 10% / 15%, respectively, for CLARA-A2 (RD 2) and CLARA-A3 (RD 4). The values are defined for flat land targets for 90% of observed cases. Since we account for a better spatial resolution of Meteosat, we slightly adapt the accuracy for the optimal, target and threshold requirements to 3% / 8% / 13%, respectively.

SOL and SDL:

The longwave surface radiation is, as part of the surface radiation budget, an essential climate variable identified by GCOS (GCOS-200, 2016). The accuracy requirement for surface longwave radiation data defined by GCOS is 1 W/m².

The precision of well-maintained BSRN ground measurements of longwave radiation is 2 W/m² (Raschke et al., 2012). The point to area mean comparison adds further uncertainties to the validation process. The threshold accuracy for SDL and SOL is 8 W/m^2 and 14 W/m^2, respectively. These thresholds correspond to achieved accuracies for CLARA A2 longwave fluxes (RD 2). With the target of 10 W/m^2 for SOL and 6 W/m^2 for SDL, we account for a novel retrieval approach and the higher spatial resolution of Meteosat. The optimal threshold of 2 W/m^2 reflects the BSRN measurement uncertainty.

Threshold requirements:

Published diagrams of the surface energy budget show large discrepancies (Wild 2018). Differences of 10 to 20 W/m^2 for SIS and SDL for global averages are not uncommon (Wild 2018). Even the newest generation of global climate models, which were used for the Fifth

IPCC Assessment Report (IPCC 2013), shows differences of 20 W/m^2 for the solar and thermal radiation components (overall global average, Wild et al. 2013). Over land those differences can be up to 30 – 40 W/m^2 (overall global average, Wild et al. 2015). Climate users therefore request satellite SRB fluxes with an enhanced accuracy (Wild pers. comm.). The monthly mean absolute bias for single radiation components from previous CM SAF TCDRs is 8 W/m^2 for SDL (RD 2), 8 W/m^2 for SIS (RD 3), and 14 W/m^2 for SOL (RD 2). Assuming a constant surface albedo, the propagated SRB accuracy is 19 W/m^2 (square root of the sum of the squares of the individual errors). Following the user requests and the currently acchieved accuracy we have therefore set the threshold accuracy requirement for this CM SAF land-only SRB to 20 W/m^2.

Target requirements:

To account for the novel retrieval approach foreseen for this TCDR (joint retrieval of all SRB components) we have set the target accuracy to 15 W/m^2. This yields a significant improvement in accuracy compared to existing satellite-based SRB data.

Optimal requirements:

The optimal requirement of 4 W/m^2 is based upon the precision of in-situ measurements. Here we have slightly altered the GCOS requirement. The Baseline Surface Radiation Network (BSRN) performs high quality surface radiance measurements of the full SRB. Target accuracies associated with operational BSRN measurements are 5 W/m^2 for SIS, 3 W/m^2 for SDL, 3% for SAL and 3 W/m^2 for SOL (Lee et. al. 2018). The precision for monthly BSRN data is estimated to be 4 W/m^2 for SIS, and 2 W/m^2 for SOL and SDL (Raschke et al. 2012). This results in a precision of 4 W/m^2 for monthly BSRN SRB data. Since it is impossible to validate SRB beyond the in-situ measurement precision, our optimal accuracy requirements reflect the BSRN precision.

Stability requirements:

Threshold, target and optimal stability requirements for the SRB are set to 2 / 1 / 0.2 W/m^2/dec. The optimal stability requirement is in line with the GCOS stability. For the threshold we follow the observed decadal trends of the surface fluxes. Recent studies show a trend of 2.0 W/m^2/dec for SDL since the early 90s and a trend of 2-4 W/m^2/dec for SIS over Europe since the early 80s (Wild 2012, Wild 2016). The stability of the new data record must be sufficient to be used for the assessment of these temporal changes. We consider a threshold stability of 2 W/m^2/dec as an appropriate compromise between the expected changes and the stability that can be achieved from satellite-based data. It is however expected that the data record will be more stable than the threshold stability requirement for certain regions and time frames.

Overall, by considering accuracies of every single components of the SRB described above, the optimal, target and threshold accuracy requirement for SRB has been set up to 4 / 15 / 20 W/m^2, respectively.

Table 5-2: Summary of requirement values for SRB. The accuracy provided is the monthly mean absolute bias.

	Threshold	*Target*	*Optimal*
Stability	2 W/m²/dec	1 W/m²/dec	0.2 W/m²/dec
Accuracy	20 W/m²	15 W/m²	4 W/m²

5.2.2 Validation approach

The validation of the surface radiation data records will be conducted against high-quality surface reference measurements from the Baseline Surface Radiation Network (BSRN), recognized as the GCOS reference network. Note that the validation of our data cannot get over the precision of the reference measurements (here BSRN stations). Raschke et al. (2012) indicated that this precision is 4 W/m² and 2 W/m² for the solar and thermal radiation, respectively. However, these values strongly depend on the quality and the availability of the measurements within each particular month. The precision can deviate from the reported mean value for individual months and BSRN stations. The temporal stability of the measurements varies even more between the BSRN stations. Since very few BSRN stations measure all the components of the SRB (Payerne, Cabauw, Toravere and Gobabeb), we might add some non-BSRN stations (e.g., SwissMetNet) for inter-comparison, and some assimilated data (e.g., ERA5) for validation of the stability.

For albedo products, attention shall be paid in the selection of the evaluation sites to ensure the reference observations' spatial representativeness at the 0.05 degree resolution of the albedo product. Comparisons with existing satellite-based datasets (e.g., MTAL, MODIS) will complement the validation and provide a spatio-temporally complete baseline for evaluation of possible differences.

5.2.3 Expected users and application area

SRB is the key driver of all land surface processes (including the surface layer atmospheric states (Sellers et al. 1997, Bonan 2002). Apart from precipitation, SRB is the singlemost important ECV influencing the anthroposphere through many socio-economic sensitive terrestrial ecosystem processes. It is a primordial for plant net primary production and can be used as a surrogate for the state of soil moisture (Reichle et al. 2010). SRB is a main input variable for hydrological and agricultural applications. Climate Services benefit from the SRB for applications like temperature downscaling, drought stress analysis, analysis and monitoring of surface states (icing, surface fog or vegetation growth condition).

5.2.4 Uniqueness of products

SRB is a GCOS ECV with satellite capability and it is a central component for the monitoring of climate variability and change (Wild et al. 2012). It is generally under-represented with ground-based measurements. Switzerland for instance has one of the densest ground-based measurement networks, but the components of the SRB are only measured at 4 places. One of the reasons for this under-representation is that the upwelling thermal and reflected solar radiation components of the SRB are spatially very heterogeneous and cannot be spatially aggregated from single point measurements.

Satellite sensors provide the unique potential to measure SAL and SOL in a spatially aggregated way. While SAL is a fully satellite-based quantity, SOL is the integration of clear sky LST with a process-based land surface model physically representing the land energy and water balance constrained by satellite-based downward shortwave and longwave fluxes.

The expected benefits of a GEO-based SRB from CM SAF are:

• Simultaneous consistency and realism of SRB components to each other through a joint retrieval of all components highly constrained with inter-calibrated satellite radiances.

• Consistency of the SRB to the downstream TCDR's such as LE/H, FTH and SAL.

• Hourly temporal resolution and 0.05 degree spatial resolution.

5.3 Meteosat Free Tropospheric (CM-23722)

5.3.1 Traceability of requirements

Table 5-3: Overview for FTH.

Measure	***Value***	***Category***	***Remark***
Ohring			
Bias	5%	Optimal	
Stability	0.26 %/decade	Optimal	
OSCAR-RRR	Climate AOPC		
Uncertainty	2%	Optimal	Specific humidity, Climate AOPC, HT (Higher troposphere)
Uncertainty	5%	Target	
Uncertainty	20%	Threshold	
GCOS-154			
Accuracy	5%	Optimal	Upper tropospheric humidity
Stability	0.3 %/decade	Optimal	

Measure	***Value***	***Category***	***Remark***
GCOS-200			
Uncertainty	5%	Optimal	WGClimate
Stability	0.3 %/decade	Optimal	

Optimal requirements:

The optimum product requirement on stability (0.3%/decade) is taken from GCOS-200 and is similar to the value given in Ohring et al. (2005) (0.26%/decade).

The optimal bias product requirement (2%) is taken from WMO-OSCAR.

The RMS optimal product requirement (5%) is taken from GCOS-200.

Target requirements:

Considering the expected upper range of trends (5%/decade) in relative humidity given in Wang et al. (2001) and Trenberth et al. (2007) and further applying a factor of 0.2 following Ohring et al. (2005) yields a target stability requirement of 1%/decade.

The target bias product requirement (5%) is taken from WMO-OSCAR.

The RMS target requirement (10%) is determined by applying a Student`s t-test using the bias product requirements and t-values tabulated in Von Storch and Zwiers (1999). When computing the optimal RMS product requirement the same way a value of ~5% is found which is consistent with GCOS-200.

Threshold requirements:

Applying a factor of 2 to the target requirement on stability yields 2%/decade which is used as threshold product requirement on stability.

The threshold bias product requirement (20%) is taken from WMO-OSCAR.

The RMS threshold requirement (28%) is determined by applying a Student`s t-test using the bias product requirements and t-values tabulated in Von Storch and Zwiers (1999).

This way the accuracy requirements are fully traceable to WMO OSCAR or GCOS-200 requirements.

The CM SAF user community expressed its interest in increased spatial and temporal resolution of CM SAF products. CM SAF is reacting to this requirement with increased temporal and spatial resolutions: The temporal resolution of 1h (instead of 3h in the precursor version) meets the GCOS-200 requirement (1 h). The spatial resolution of 0.25°

(instead of 0.625°) is with 28 km at equator slightly larger than the GCOS-200 requirement (25 km).

5.3.2 Validation approach

As for the precursor product (CM-139) the Analysed RadioSoudings Archive (ARSA) will form the basis for validation against PRD. The validation involves radiative transfer simulations with RTTOV and proper radiosonde water vapour profile integration using relative humidity Jacobians. Validation results for CM-139 have been published in Schröder et al. (2014). Additionally, the product will be compared to other satellite based upper tropospheric humidity products, namely, UTH from HIRS and microwave-based sensors (CM-14712 or its precursor version if not available in time).

Results achieved within the GEWEX water vapor assessment (www.gewex-vap.org) may be cited to describe the quality of this product.

Other satellite products, such as from AIRS, IASI or CrIS can be considered for quality analysis at subperiods during more recent years when distinct features are observed during intercomparison.

5.3.3 Expected users and application area

Water vapour has an amplifying role in a warming environment through a strong positive climate feedback loop as evident in climate predictions, and this water vapour feedback loop is dominated by water vapour in the tropical free troposphere (Held and Soden, 2000). The importance of humidity in the free troposphere originates from the non-linear interaction between humidity and long-wave radiation. Sherwood et al. (2010) recently reviewed the processes that determine the humidity distribution in the intertropical region. They emphasize the strong connection between the large scale dynamics and water vapour and the roles of eddies (mesoscale convection, circulation transients) in establishing these links pointing out to a broad range of scale implied in the humidity distribution. They further indicate that there is a need to better constrain the available theory. Satellites that observe the humidity of the free troposphere, and particularly, geostationary platfoRMS are very well suited to contribute to this constraint by providing observations at kilometres and hours scale resolution over a 35 years long period.

Thus, the application areas of FTH are regional climate analysis (long term trend monitoring, pattern shifts, variability on diurnal to decadal scales, anomalies caused by e.g., ENSO), process studies, and comparison with output from global and regional climate models.

The temporal length (eventually more than 30 years over Africa), the consistent application of cloud screening and retrieval algorithms and the use of an FCDR as input make this product interesting for global and regional climate trends monitoring as well as global (and regional) climate modelling evaluation. This value has been demonstrated, e.g., by Brogniez et al. (2006) and Schröder et al. (2014). Also, Brogniez et al. (2005) compared the FTH product to the 14 climate models of the Atmospheric Model Intercomparison Project (AMIP2) phase 2 and conclude that the models significantly improved in simulating the seasonal cycle relative to AMIP1 but still exhibit significant moist biases.

The link between FTH and OLR as well as FTH and tropical convection are relevant (e.g., Horvath and Soden, 2008) and therefore expected to be of interest for (climate) research and modelling institutes for process studies.

The precursor version (FTH edition 1, CM 139) was released in 2013. Among the users are the Free University Berlin, the University of Washington and the University of Bologna. Further, the Rossby Centre (Norrköping, Sweden), the University of Hamburg, and the Seoul National University (SNU, Seoul, Korea) expressed their interest in utilising the updated FTH product from CM SAF.

5.3.4 Uniqueness of products

FTH can be retrieved directly from satellite observations at 6-7 microns through relatively simple and easy to handle relations (Soden and Bretherton, 1993, 1996). Buehler and John (2005) adapted the method described in Soden and Bretherton (1996) to Advanced Microwave Sounding Unit-B (AMSU-B) observations. A further enhanced data record based on AMSU-B is described in Chung et al. (2013).

The AMSU-B based FTH data record is affected by orbital drift and contains valid observations under all sky conditions except in presence of intense scattering such as during precipitation events.

Shi and Bates (2011) spent significant effort on inter-calibrating the water vapour observations at 6.7 µm of the High-resolution Infrared Radiation Sounder (HIRS). A subsequent application of the Soden and Bretherton (1996) method yields a FTH record of more than 30 years length (Shi et al., 2013). The time series is also affected by orbital drift.

Satellites that observe the humidity of the free troposphere, and particularly, geostationary platforms are very well suited to contribute to the constraint formulated by Sherwood et al. (2010) by providing observations at kilometres and hours scale resolution over a 35 years long period. The CM SAF Meteosat based FTH data record provides one of the longest time series of water vapour observations together with a unique temporal resolution and a high spatial resolution.

The planned common utilisation of the MVIRI/SEVIRI FCDR from EUMETSAT during cloud mask, CTP and FTH generation will increase the consistency and likely also the quality of the FTH product.

5.4 Meteosat Land Surface Temperature (CM-23922)

5.4.1 Traceability of requirements

Table 5-4: Overview for LST.

Measure	***Value***	***Category***	***Remark***
GlobTemperature	(Bulgin and Merchant, 2016)		
Temporal Res.	3 hourly	Optimal	Regional
Spatial Res.	0.05°	Optimal	Regional
Dataset Length	25 years	Optimal	Regional
GCOS-200			
Accuracy	1 K	Treshold	
Precision	1 K	Treshold	
Stability	0.1 K/decade	Optimal	
Stability	0.3 K/decade	Threshold	
Stability	0.3 %/decade	Optimal	

Land Surface Temperature (LST) has recently been identified as an Essential Climate Variable (ECV) with threshold and target requirements defined within the Global Climate Observing System implementation plan (GCOS-200). GCOS-200 requirements follow user requirements collected within the ESA GlobTemperature project. LST was defined as an ECV within the lifetime of the GlobTemperature project. In order to set appropriate requirements within the GCOS implementation plan, a GlobTemperature survey of user requirements from a climate perspective was undertaken (Bulgin and Merchant 2016). Those requirements were very recently confirmed by a comprehensive user survey conducted within the ESA CCI project (Aldred et al. 2019).

GCOS-200 and GlobTemperature requirements are summarized in Table 5-4. GCOS requirements are provided in terms of resolution, accuracy and stability. The newly defined CM-23922 requirements follow the GCOS and GlobTemperature requirements.

Resolution Requirement

The CM-23922 spatial resolution requirement of 0.05° is in line with the GlobTemperature optimal spatial resolution for the regional scale and hence meets the evolving needs of climate services and science in terms of spatial coverage. The spatial resolution selected for CM-23922 also meets the ESA CCI requirement REQ-17-TR to provide data at a resolution of 0.05° or less (Aldred et al. 2019).

CM-23922 LSTs are provided at hourly time steps. The optimal requirement from GlobTemperature is a 3 hour resolution. CM-23922 resolves the full LST diurnal cycle and responds to the ESA CCI requirement LST-URD-OPT-13-O (Aldred et al. 2019) to provide data with a temporal resolution of one hour.

Accuracy Requirement

For CM-23922 LST we use the bias and the bias-corrected root-mean-square error (bc-RMS) to reflect systematic (accuracy) and random uncertainty (precision) respectively.

Threshold requirements:

The CM-23922 threshold requirement of 1.5 K accuracy and precision reflects the achieved accuracy for SUMET version 1.0 (RD 6). Here, we achieved a bias (accuracy) and bc-RMS (precision) < 1.5 K for monthly data.

Target requirements:

The CM-23922 target requirement was set to 1 K for both accuracy and precision. This reflects the GCOS-200 accuracy and precision thresholds.

Optimal requirements:

GCOS-200 does not define an optimal requirement for precision and accuracy. For CM-23922 we have set the optimal precision and accuracy requirement to 0.5 K to account for user requests from the ESA CCI survey. ESA CCI data accuracy priorities are set to 0.5 K (LST-URD-OPT-14-O, Aldred et al. 2019).

Stability Requirements

We use the change of bias over time as stability measure. The CM-23922 stability threshold reflects the achieved 0.4 to 0.8 K stability from SUMET version 1.0 (RD 6). Target and optimal stabilities for CM-23922 correspond to the GCOS-200 threshold and optimal requirement respectively (0.3 K and 0.1 K).

Table 5-5: Summary of requirement values for LST.

	Threshold	***Target***	***Optimal***
Stability	1 K/dec	0.3 K/dec	0.1 K/dec
Accuracy (bias)	1.5 K	1 K	0.5 K
Precision	1.5 K	1 K	0.5 K

5.4.2 Validation approach

The reference data records for validation of CM-23922 are ground-based observation from the LSA SAF validation stations. The four LSA SAF validation sites are located in different climate zones and include a wide range of atmospheric conditions. We also plan to compare CM-23922 with FLUXNET stations particular with those located in forests areas.

The validation of satellite-based LST using ground data is challenging: There are only four stations from the LSA SAF which can be used as reference. Hence, it is difficult to prove accuracy and precision for the entire MSG disk. There are e.g. no stations located in mountain regions. Here, only comparisons with other satellite data and model-based sensitivity studies can give an idea about the uncertainty. In addition, LSTs vary strongly in space space and time. Although the LSA SAF validation stations are located in very homogeneous terrain, some LST variations due to uneven vegetation cover/terrain cannot be excluded and up-scaling leads to uncertainties of up to 1K. The temporal stability of CM-23922 will be evaluated through inter-comparison with: (1) surface skin temperature of European Centre for Medium Range Forecast (ECMWF) Re-Analysis dataset (ERA-5), (2) other satellite based LST climate data from the GlobTemperature and ESA CCI projects and (3) station-based gridded air temperature data from the EUSTACE project: https://www.eustaceproject.eu/).

Inter-comparisons to near-real-time LSTs such as the LSA SAF and MODIS LST are provided as well. For the CM-23922 release, we will also include an inter-comparision to the novel ESA CCI short-term LST TCDRs.

The evaluation scores and their compliance with the accuracy, precision and decadal stability requirements will be evaluated. We will evaluate the accuracy of CM-23922 hourly product samples in terms of bias (median difference to reference), decadal stability (change of bias over time) and bc-rms (estimate of the variance between the bias corrected data set) following exactly the validation approach used to evaluate SUMET version 1.0 (RD 6). For trend analysis (stability) we use linear trends derived using Theil-Sen estimates and their significance is estimated with the Mann-Kendall test.

5.4.3 Expected users and application area

CM-23922 provides a valuable parameter to characterize land surface states and land-atmosphere exchange. Satellite-based LSTs are increasingly recognized as an essential parameter for diagnosing Earth System behavior and evaluating Earth System Models (GCOS-200) because it provides a consistent long-term record of radiative temperatures of the Earth's surface and a crucial constraint on the surface energy balance, particularly on soil moisture. Moreover, LST is an important parameter of the surface state and when combined with vegetation parameters, it contains information on soil moisture and drought conditions. Good (2016) and Good et al. (2017) have recently outlined that LST and 2m air temperatures are well coupled and that satellite-based LSTs can be used to augment 2m air temperature fields in regions with poor station coverage (EUSTACE project: https://www.eustaceproject.eu/).

Thus, the primary application areas of SUMET version 1.0 (precursor version of CM-23922) are:

- Regional climate analysis (e.g. LST-based Climate Extreme Indices, Pörtge et al. 2018)
- Regional climate model evaluations (e.g. evaluation of the COSMO CLM land surface model, Bessenbacher 2018)
- Regional climate monitoring (e.g. LST-based drought monitoring, MeteoSwiss 2018)
- Drought assessment (e.g. assessment of the drought impact on vegetation health, Bento et al. 2018).

In addition, CM-23922 serves as input for CM SAF downstream ECV generation algorithms for the surface energy balance, which highly depend on land surface temperatures. The Meteosat Latent and Sensible Heat Flux algorithms (CM-23811, section 5.5) uses CM-23922 LSTs to constrain soil moisture, particularly in moisture-limited states. The Meteosat Surface Radiation Budget (CM-23271, section 5.2) uses CM-23922 LSTs to calculate Surface Outgoing Longwave Radiation.

5.4.4 Uniqueness of products

CM-23922 will be a unique high resolution regional Land Surface TCDR with unprecedented record length (37 years) which resolves the full LST diurnal cycle. Currently, the precursor SUMET TCDR is the only existing LST TCDR which fulfills the GCOS-200 temporal and spatial requirements concurrently (25 years data length and 3 hourly temporal resolution). LST climate data records from polar orbiting satellites provide LST only twice per day.

With CM-23922, we directly respond to the ESA CCI user request to provide TCDRs with 30 years+ (LST-URD-REQ-12-O, Aldred et al. 2019). The objective of the ESA CCI LST project is to provide global LST TCDRs spanning the last 20-25 years from a variety of satellite datasets. Hence, CM-23922 will complement short-term ESA CCI LST TCDRs and will provide users the unique opportunity to analyze climate signals back to the 80s over Africa and Europe.

In addition, the following enhancements are planned for CM-23922:

- Improved uncertainty characterization: Advanced methods to characterize uncertainties for satellite-based TCDRs are now available from the Horizon 2020 project FIDUCEO. The new methods include a state-of-the art error propagation from level 1 to level 3.

- Improved emissivity retrieval: Accurate land surface emissivity input is very important to its retrieved LST. For CM-23922 release, it is planned to use dynamic emissivity maps instead of monthly climatological averages.

- Improved stability: Ghent et al. (RD 7) have observed a 0.5 K inconsistency between SUMET MVIRI and SEVIRI during daytime LSTs. For the CM-23922 release, it is planned to remove this inconsistency by using updated calibration coefficients and a better characterization of the spectral surface emissivity.

5.5 Meteosat Latent and Sensible Heat Flux (CM-23811)

5.5.1 Traceability of requirements

5.5.1.1 GCOS / TOPC requirements

Currently, the latent and sensible heat fluxes from the land surface are not considered as an of Essential Climate Variables (ECV), although they are essential parameters in closing the energy cycle, together with similar fluxes over the oceans and the radiant heat fluxes. The GCOS Implementation Plan [GCOS-200] highlighted the need for an ECV covering terrestrial heat fluxes (analogous to the ocean heat flux ECV). The latent and sensible heat fluxes are more difficult to evaluate over land than over the oceans. This is explained by the higher inhomogeneity of the land surfaces as well as the fact that the ground heat fluxes are only poorly measured over land. This contributes to the energy imbalance that is observed in surface energy partitions. The GCOS-200 Implementation Plan mandated the Terrestrial Observation Panel for Climate (TOPC) to examine the practicality of such a land heat flux ECV and its feasibility on a global scale.

In light of recent literature, the TOPC concluded at its 19th session [TOPC-19] that evaporation from land (i.e. latent and sensible heat fluxes) can now be measured with a sufficient uncertainty to be proposed as a new ECV. The designation of a new ECV has therefore been submitted to the GCOS Steering Committee for final approval. The TOPC has undertaken a review of the measurements to date and their reliability, and made the proposal on the following requirements for the new ECV evaporation from land (see Table 5-6).

Table 5-6: GCOS / TOPC requirements.

ECV	**Products**	**Frequency**	**Resolution**	**Required measurement uncertainty**	**Stability (per decade)**
Evaporation from land	Latent heat flux Sensible heat flux	sub-daily, latency of less than 1 month	threshold 25km goal 1km	<10%	Better than 1%

5.5.1.2 WACMOS-ET requirements

To define the technical requirements of the ET product, the WACMOS-ET team made an online questionnaire that was filled out completely by 25 potential users. Results of this survey (see Table 5-6 for a summary) highlighted that for 28% of the users, real-time or near real-time availability is crucial and that most of the users are interested in daily and monthly values with a spatial resolution of 1 km (preferable range between 0 and 1 km). The majority of users require ET data for the time period from the 1970ies or 80ies to present. An acceptable accuracy between 5 and 30% (mean of 17%) is needed. Finally, all the users wish to receive the data in NetCDF.

Table 5-7: Summary of the results from the WACMOS-ET requirements questionnaire.

Products	Frequency	Resolution	Required measurement uncertainty	Time period	Format
Evapotranspiration	NRT, daily, monthly	goal ≤1km	5% - 30% (mean 17%)	1970-present	NetCDF

5.5.1.3 Parameters of interest

The proposed data record will be of interest for users from a wide variety of expertise areas. The LE and H heat fluxes will of course be very useful to scientists working on the surface energy budget. In addition, the evapotranspiration (ET) estimates will be provided to the users as ancillary field in the LE product. The ET estimates are highly requested by the community working on closing the water cycle. The agriculture and water management communities are also very interested in this product.

Given the wide range of application areas for the proposed data record, the data will come with various “flags” providing information, at pixel level, about the data quality and the processing. In particular, these “flags” should indicate to which extend the LE/H fluxes depends on ancillary reanalysis data or are extensively based on satellite observations. Information about cloudiness will also be propagated as cloud flag(s).

Another important field frequently requested by the users is information about uncertainty and errors. This information will be inferred from an extensive evaluation of the products (see details in section 5.5.2). We may consider providing this information as an error bar in order to meet the most up-to-date user requirements.

5.5.1.4 Spatial resolution

The proposed LE/H data record will be provided on a regular grid at the spatial resolution of 0.05 degrees (i.e. about 5.5 km). This agrees with the [TOPC-19] analysis which recommends a minimum horizontal resolution of 25 km for a proposed new GCOS ECV on terrestrial heat fluxes (1 km is considered as optimal for such ECVs). These proposed requirements should be approved by the GCOS Steering Committee in the near future.

A spatial resolution of 0.05° also ensures consistency with other CM SAF products, such as the TOA Radiation MVIRI/SEVIRI Data Record, the SARAH or CLAAS datasets, as well as the SUMET (Land SUrface Temperature) and COMET (Cloud Fractional Cover) data records. This helps to increase the synergy between the available CM SAF products. This synergy is seen as an important requirement from the user’s communities, such as to gain in consistency.

Such a fine spatial resolution also allows a better resampling of the data, for instance to match the grid of a climate model or the grid of any other data records used for comparison purpose. It also eases the comparison with point observations, such as the FLUXNET network of in-situ measurements.

However, at this resolution, the product may be affected by some random error coming from the MVIRI or SEVIRI image rectification, the processing of coastal pixels, the parallax effect, the effect of adjacent pixels' surface properties, the horizontal transport of photons between grid points, shadows, etc. The users will be informed via the Product User Manual (PUM).

5.5.1.5 Spatial coverage

The [GCOS-200] implementation plan emphasized, in light of recent literature, the importance of developing such terrestrial heat flux ECVs. An in-depth analysis of the expected users' requirements for the proposed LE/H data record lead to the same conclusion. Currently, the global coverage is highlighted by the user communities as being a priority in the development of such datasets. In this way, two new data records of terrestrial heat fluxes are expected to be published in the near future which will offer a (near-)global coverage. These are the High res-Olution Land Atmosphere Parameters from Space (HOLAPS) 1.0 (Loew et al., 2016) and the GEWEX LandFlux v1 (Jiménez et al., 2012; Jiménez et al., 2015) data records.

During CDOP-3, the CM SAF of EUMETSAT is committed to producing a data record of terrestrial LE/H fluxes from satellite data covering the Meteosat disk (60°N to 60°S and 60°W to 60°E). The Meteosat field of view is especially interesting for process studies as it includes various climate areas (temperate area, tropical area, semi-arid zones, etc.), various vegetation types (rainforest, grassland, crops, etc.), a monsoon regime (West Africa), etc. During CDOP-3, the CM SAF is also committed to preparing the generation of a global dataset of LE/H fluxes for implementation in CDOP-4.

5.5.1.6 Temporal resolution

For the proposed new GCOS ECV on terrestrial heat fluxes, [TOPC-19] recommends a sub-daily measurement frequency. So far most initiatives aimed at developing TCDRs of latent and/or sensible heat fluxes on a daily basis (Miralles et al., 2011; Jiménez et al., 2012). However, there is a large demand from the user communities to access sub-daily data records of both components. Such sub-daily estimates will soon become accessible with the forthcoming release of the GEWEX LandFlux v1 (Jiménez et al., 2012; Jiménez et al., 2015) and HOLAPS 1.0 (Loew et al., 2016) data records.

The CM SAF proposed dataset will provide hourly estimates of the LE/H fluxes over land, as well as daily and monthly averages. The monthly mean diurnal cycle will also be issued in hourly intervals. Currently there are no identified requirements from the user community for a diurnal cycle product with a higher temporal frequency such as 15 or 30 minutes. The daily and monthly mean products should give a better representation of the daily mean than products that are based on a single observation at fixed solar time (as obtained with polar orbiting instruments). Please note that daily and monthly data will be accumulated for ET and not averaged.

5.5.1.7 Stability

Following the [TOPC-19] proposed requirements for a new GCOS ECV on terrestrial heat fluxes, we suggest 0.1 W/m²/dec as optimal requirement for stability. Such a requirement would correspond to the maximum change in retrieved LE/H for a given scene due to changes in instrument calibration (switch from one instrument to another or instrumental drift) and/or in the Meteosat orbit characteristics (e.g. Met-8 was located at 3.5°W while Met-9 and -10 have been operated at 0°). However, it is not expected that such a challenging stability could be reached with the MVIRI and SEVIRI instruments, especially as long as the measured radiances have not been reprocessed as a Fundamental Climate Data Record (FCDR).

As for HOAPS, the target and threshold stability requirements are set at respectively 4 and 9 W/m²/dec. The stability of the product will be evaluated during the validation process from the monthly mean values. The transition between MFG and MSG in 2004 will receive a particular attention.

5.5.1.8 Retrieval accuracy

Contrary to the evapotranspiration, no recent survey is available for heat fluxes. However, given the objectives of CM SAF, evaluations of climate models and reanalysis are considered as primordial by allowing thereafter various applications (climate monitoring, climate processes, etc). A large number of studies evaluated reanalysis (e.g. ERA-Interim, ERA-Interim/Land) and models (e.g. MOD16, SEBAL, SEBS, GLEAM, etc.) with RMS between ~10 and ~140 W m^{-2} (roughly between 5% and 50% of the mean observed value) (Gillies et al., 1997; Watts et al., 2000; Jiang et al., 2001, 2003, 2004; Caparinni et al., 2004; Batra et al., 2006; Su et al., 2007; Foken et al., 2008; Kalma et al., 2008; Stisen et al., 2008; Verstraeten et al., 2008; Andersson et al., 2012; Hong et al., 2014; Balsamo et al., 2015; Yang et al., 2015; Loew et al., 2016; McCabe et al., 2016; Michel et al., 2016; Zuang et al., 2016; Zhou et al., 2016; Laounia et al., 2017; Feng et al., 2017). Zhou et al., 2016 evaluated ERA-Interim by comparing estimations with measurements from observations at AmeriFlux sites from 1998 to 2012. For hourly values, relative errors were around 50% for H and LE. From an assessment of 30 published validations, Kalma et al., (2008) observed an average RMS of about 50 W m^{-2} and relative typical error of 15 - 30%. Su et al., (2007) assessed the Surface Energy Balance System (SEBS) model and ET predictions based on MODIS Land Surface Temperature plus Coordinated Enhanced Observing Period (CEOP) meteorological observations or Global Land Data Assimilation System (GLDAS) forcing. For MODIS based ET estimation, RMSs between 61 and 141 W m-2 (up to 50% of the mean observed values) were obtained. Concerning sensible heat fluxes estimated from the SEBS model, RMS ranged from 26 to 57 W m-2 (20 to 60% of the mean observed values) were calculated. Recent study from Loew et al., (2016) evaluated HOLAPS latent heat flux estimates with 48 FLUXNET worldwide stations. Overall the RMS was 51.2 (30.7) W m−2 for hourly (daily) latent heat flux, and 84 (38) Wm−2 for sensible heat flux when compared against measurement stations.

RMSRMSRMSRMSWorth-noting that in situ measurements are subject to typical error between 10% and 30% (Chehbouni et al., 1999, Chavez et al., 2009; Watts et al., 2000; Wilson et al., 2002; Drexler et al., 2004; McJannet et al., 2011; Perez et al., 2017; Hirschi et al., 2017; Foken et al., 2008 and reference there in). For instance, recent study of Perez-Priego et al., (2017) compared LE measured from lysimiters (LELys) with eddy covariance measurements at 1.6 (LE1.6) and 15m (LE15) above ground. Results revealed underestimation of LE1.6 (up to 35%) compared to LELys. Moreover, eddy covariance measurements do not allow a closure of the energy balance in the surface layer. Indeed, the energy imbalance can be between 10 and 30% (average 20%) (e.g., Wilson et al., 2002).

Please note that typical errors referenced in models and reanalysis evaluations correspond to the WACMOS-ET requirements. Indeed, the questionnaire pointed out that the users expect an accuracy for the ET product between 5% and 30% (median ~20%). In the literature, most of the studies concluded, by comparing modelled values with ground station measurements, that uncertainty in daily ET is on the order of 10% - 30% or RMSs between 0.3 and 1.2 mm/d (8.6 - 35 W m^{-2}) (Peng et al., 2013; Colaizzi et al., 2006; Jia et al., 2012; Mu et al., 2011; Jiang et al., 2009; Gallego et al., 2013). For instance, Mu et al., (2011) observed a mean absolute bias of 24% by comparing daily ET values from ET algorithm with values from 46 eddy covariance flux tower sites. Similarly, Peng et al., (2013) calculated a relative error of 23.28% between estimated ET using MODIS top of atmosphere (TOA) radiances and MODIS products and observations at Nanchang station with a weighing lysimeter.

Concerning the optimal requirements, as suggested by the [TOPC-19], an error lower than 10% for retrieval accuracy is expected, Similar error would be optimal for ET which is directly derived from LE. Indeed, Glenn et al., (2007) and more recently Fisher et al., (2017) highlighted that relative error lower than 10% would improve differentiation of water use and water stress among different crops, species, and ecosystems, as well as to enable more efficient water management.

We notice that for all parameters lower bias were observed than RMSs (Jiang et la., 2001, 2003, 2004, 2009; Stisen et al., 2008; Peng et al., 2013; Gallego et al., 2013; Yang et al., 2015; Zuang et al., 2016; Feng et al., 2017). Therefore, lower bias will be adopted in the requirement table.

Selected values for the optimal, target and threshold accuracy are given in Table 5-8. The ET values are indicatives as the dataset will be validated on LE and H.

Table 5-8: Product requirements for evapotranspiration and surface heat fluxes.

Product	Metrics	Optimal	Target	Threshold
Evapotranspiration				
hourly-mean **(ET)** [mm/h]				
	Bias	<0.1 x ET_{Obs}	< (0.2 x ET_{Obs} + 0.02)	< (0.4 x ET_{Obs} + 0.03)
	RMS	<0.1 x ET_{Obs}	< (0.2 x ET_{Obs} + 0.06)	< (0.4 x ET_{Obs} + 0.12)
Daily-accumulated **(DET)** [mm]				
	Bias	<0.1 x ET_{Obs}	< (0.2 x ET_{Obs} + 0.35)	< (0.4 x ET_{Obs} + 0.71)
	RMS	<0.1 x ET_{Obs}	< (0.2 x ET_{Obs} + 0.53)	< (0.4 x ET_{Obs} + 1.06)
Monthly-accumulated **(MET)** [mm]	Stability [mm/dec]	<0.1	<4	<9
	Bias	<0.1 x ET_{Obs}	< (0.2 x ET_{Obs} + 10.6)	< (0.4 x ET_{Obs} + 21.2)
	RMS	<0.1 x ET_{Obs}	< (0.2 x ET_{Obs} + 10.6)	< (0.4 x ET_{Obs} + 21.2)
Latent heat flux				
hourly-mean **(LE)** [W/m²]				
	Bias	<0.1 x LE_{Obs}	< (0.2 x LE_{Obs} + 10)	< (0.4 x LE_{Obs} + 20)
	RMS	<0.1 x LE_{Obs}	< (0.2 x LE_{Obs} + 40)	< (0.4 x LE_{Obs} + 80)
Daily-mean **(DLE)** [W/m²]				
	Bias	<0.1 x LE_{Obs}	< (0.2 x LE_{Obs} + 10)	< (0.4 x LE_{Obs} + 20)
	RMS	<0.1 x LE_{Obs}	< (0.2 x LE_{Obs} + 15)	< (0.4 x LE_{Obs} + 30)
Monthly-mean **(MLE)** [W/m²]	Stability [W/m²/dec]	<0.1	<4	<9
	Bias	<0.1 x LE_{Obs}	< (0.2 x LE_{Obs} + 10)	< (0.4 x LE_{Obs} + 20)
	RMS	<0.1 x LE_{Obs}	< (0.2 x LE_{Obs} + 10)	< (0.4 x LE_{Obs} + 20)
Sensible heat flux				
hourly-mean **(H)**				
	Bias	<0.1 x H_{Obs}	< (0.3 x H_{Obs} + 10)	< (0.6 x H_{Obs}+ 20)

Product	Metrics	Optimal	Target	Threshold
[W/m²]	RMS	<0.1 x H_{Obs}	< (0.3 x H_{Obs} + 50)	< (0.6 x H_{Obs} + 100)
Daily-mean **(DH)** [W/m²]				
	Bias	<0.1 x H_{Obs}	< (0.3 x H_{Obs} + 10)	< (0.6 x H_{Obs} + 20)
	RMS	<0.1 x H_{Obs}	< (0.3 x H_{Obs} + 15)	< (0.6 x H_{Obs} + 30)
Monthly-mean **(MH)** [W/m²]	Stability	<0.1	<4	<9
	Bias	<0.1 x H_{Obs}	< (0.3 x H_{Obs} + 10)	< (0.6 x H_{Obs} + 20)
	RMS	<0.1 x H_{Obs}	< (0.3 x H_{Obs} + 10)	< (0.6 x H_{Obs} + 20)

5.5.2 Validation approach

The climate data record will be validated from 5 different approaches:

a) <u>In-situ validation</u>: ET, LE, H will be compared to ground measurements at selected locations in different climatic/vegetation conditions. While the FLUXNET network provides data from 212 stations (117 in the field of view of METEOSAT) we selected 19 of them (Figure 5-1, Table 5-9) to perform analysis. Four criteria were used to select the stations: i) well established stations and already used datasets by the LSA SAF; ii) data quality and representatively (Rebmann et al., 2005); iii) ability to sample different climates and biomes; and iv) spatial homogeneity of the station. This list may be subject to change in the future if the performance of measurements at stations is altered. Moreover, time series comparisons would allow an evaluation of the consistency over all the TCDR period. Indeed, 13 and 4 STATIONS have data covering period higher than respectively 10 and 19 years allowing multi-decadal analysis.

b) <u>Consistency check:</u> Comparison with the current (v2) LSA SAF ET operational product and with the LSA SAF land surface temperature product.

c) <u>Models inter-comparison</u>: ET, LE and H will be compared to the output of models (ingesting satellite data or not) recognized to produce valuable meteorological information in about the same conditions: near-real time and intra-day variations of evapotranspiration and fluxes, e.g. ECMWF IFS (0.1°), GLDAS Noah (0.25°), ERA5 (0.25°) and ERA5-Land (9km).

d) <u>Products inter-comparison</u>: ET, LE and H will be compared to the estimations from other satellite products, e.g. MOD16-ET (Mu et al., 2007, 2011), HOLAPS (Loew et al., 2016).

e) <u>Comparison based on water balance</u>: water budget closure studies over hydrological basins.

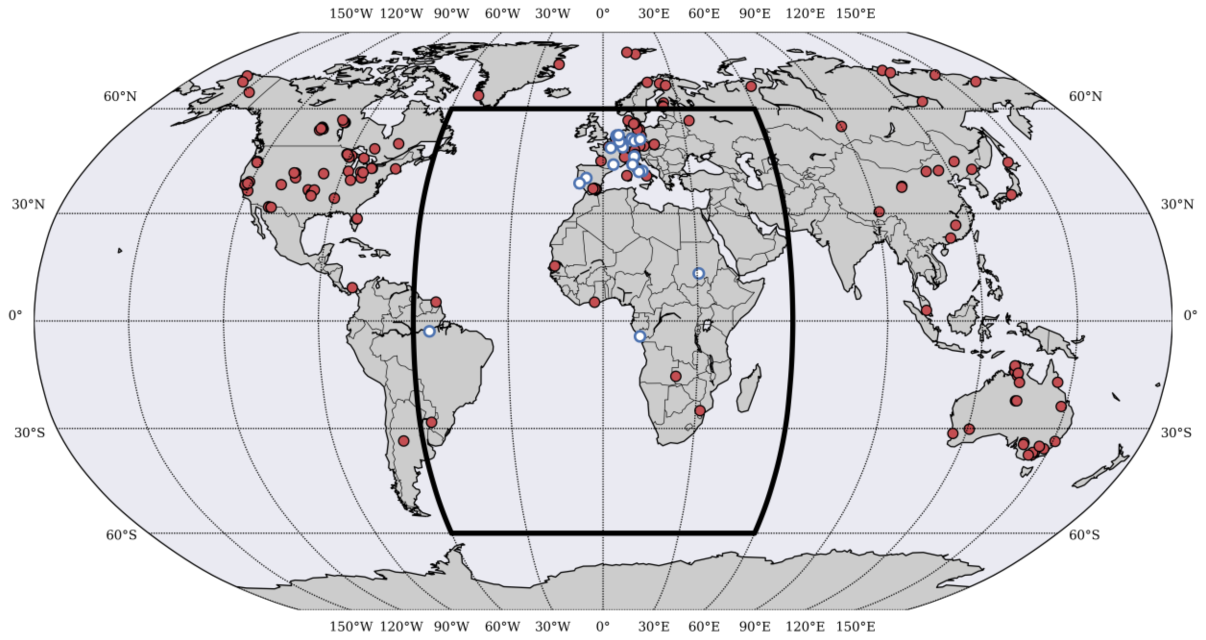

Figure 5-1: Localization of the FLUXNET stations. The white-blue dots are the positions of the validation stations that will be used for comparison. The black solid line corresponds to the limits of the TCDR.

Table 5-9: Characteristics of the selected validation stations, including geographical location.

Station (country)[1]	Latitude (°N)	Longitude (°E)	Area[2]	Climate[3]
Cabauw (NL)	51.97	4.93	Euro	Cfb
Santarem (BR)	-2.857	-54.959	SAme	Am
Hesse (FR)	48.67	7.07	Euro	Cfb
Hainich (DE)	51.066667	10.45	Euro	Cfb
Amplero (IT)	41.9	13.61	Euro	Cfa
Las MAjadas (ES)	39.94	-5.77	Euro	Csa
Monte Bondone (IT)	46.02	11.04	Euro	Dfb
Tojal (PT)	38.48	-8.02	NAfr	Csa
Wetzstein (DE)	50.45	11.45	Euro	Cfb
Vielsalm (B)	50.3051	5.9981	Euro	Cfb
Klingenberg (DE)	50.8929	13.5225	Euro	Cfb
Tharandt (DE)	50.9636	13.5669	Euro	Cfb
Fontainebleau-Barbeau (FR)	48.4764	2.7801	Euro	Cfb

Puechabon (FR)	43.7414	3.5958	Euro	Csa
Castelporziano (IT)	41.7052	12.3761	Euro	Csa
San Rossore (IT)	43.7279	10.2844	Euro	Csa
Loobos (NL)	52.1666	5.7436	Euro	Cfb
Demokeya (SD)	13.2829	30.4783	NAfr	Bwh
Tchizalamou (CG)	-4.2892	11.6564	SAfr	Aw

[1]United State (US), The Netherlands (NL), Brazil (BR), France (FR), Germany (DE), Italy (IT), Spain (ES), Finland (FI), Portugal (PT), Sudan (SD), Congo (CG), Belgium (B).

[2] Euro: Europe; NAfr: North Africa; SAfr: South Africa; SAme: South America.

[3]Climate classification following Kottek et al. (2006): equatorial (A), arid (B), warm temperate (C), Snow (D), fully humid (f), monsoonal (m), summer dry (s), winter dry (w), hot summer (a), warm summer (b), cool summer (c), hot arid (h).

5.5.3 Expected users and application area

Regional climate change analysis is identified as a major application area for a Meteosat Surface Radiation Budget (SRB) and LE/H TCDRs. Consistent SRB radiation components are required to constrain the terrestrial energy and water cycle through a land surface model based LE/H retrieval. The SRB is a major driver for hydrological and agricultural modelling. Users include agricultural planners, Re-Insurance companies and national authorities dealing with the assessment of climate vulnerability and associated risks.

All SRB and turbulent LE/H flux variables are of importance for climate analysis, reanalysis and NWP model evaluation. For instance, having spatial resolution in the same order of magnitude than our TCDR, the ERA5-Land data (9km) could be evaluated.

The TCDR could also help to understand the Earth's energy imbalance. Over recent years, the budget imbalance has amounted to 0.5-1 W m^{-2} globally (Hakuba et al., 2018 and reference there in). Improving quantification, land surface temperature, latent and sensible heat fluxes from ocean and land to the atmosphere should improve our understanding of the budget imbalance.

Scientist working on closing the water cycle would be really interested in our product. Indeed, to close the water cycle, the principal requirement is the turbulent flux of latent heat (evapotranspiration) from ocean and land to the atmosphere. Thus the evapotranspiration estimates will be provided to the users as ancillary field of the LE product. The agriculture and water management communities are also very interested in this product. The TOPC noted that accurate knowledge of evaporation is important for closing the water, energy and carbon cycles. It is used to, inter alia:

a. diagnoses the influence of the land surface on air temperature

b. constrains estimates of convection and cloud formation in the troposphere

c. understands the relevance of water vapour, lapse rate and cloud feedbacks

d. unravels the two-way interaction between vegetation and climate

e. monitor drought and heat-wave occurrence and their impacts

f. benchmark climate model representation of these processes

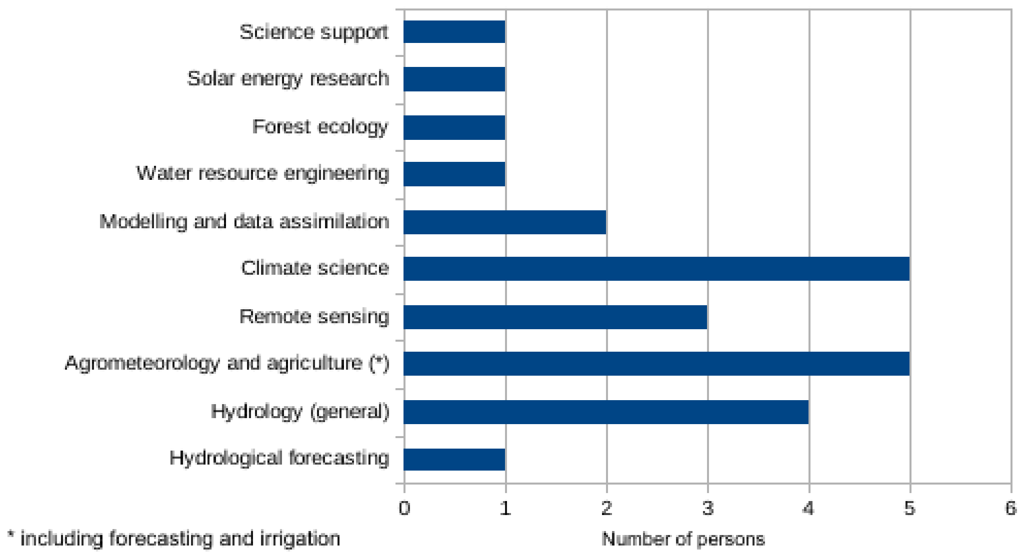

Figure 5-2: Information on user, field of work (extracted from the WACMOS-ET report WP 1100).

Fisher et al. (2017) noted that the science communities that can capitalize on improved information on ET are broad and include: (i) Agronomy; (ii) Ecology; (iii) Hydrology; (iv) Atmospheric Science; (v) Climate; (vi) Carbon Cycle; and, (vii) Policy/ Economics. We can add that the WACMOS-ET project identified similar potential users from the survey.

5.5.4 Uniqueness of products

A climate data record based on LSA SAF land surface model forced with the Meteosat satellites data provides several added values to the currently available datasets:

- Combination of high temporal (30 min) and spatial (3-5 km) resolutions.
- Land surface model mostly driven by remote sensing database.
- All weather conditions (incl. cloudy).
- Long time period covered (38 years 1983-2020).Applicability on a large domain, while empirical ET algorithm would not be applicable.

- Product extensively validated through information available in-situ, determining exact capabilities of the method.
- The algorithm has showed a very good agreement with observations in Europe and for well-watered sites and a good seasonal variation for temperate forests.
    - Better accuracy in semi-arid areas of Africa (e.g., Sahel) and temperate areas of Europe than in ERA-Interim.
- Consistency and synergy with several other climate variables (surface radiation, albedo, LST, TOA radiation, cloud product, etc) all based on Meteosat images.

6 Summary and Conclusion

The CM SAF project team recommends to take the partly updated requirements as baseline for the development of CM-23012, CM-23271, CM-23722, CM-23811, CM-23922 The new and the previous requirements are given in the Annex A.

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8 List of Abbreviations

CAF	Central Application Facility
CDOP	Continuous Development and Operations
CDR	Climate Data Record
CEOP	Coordinated Enhanced Observing Period
CGMS	Coordination Group for Meteorological Satellites
CLAAS	Cloud property DAtAset
CM SAF	Satellite Application Facility on Climate Monitoring
COMET	ClOud Fraction Cover dataset from METeosat First and Second Generation
DET	Daily-accumulated EvapoTranspiration product
DFG	Deutsche Forschungsgemeinschaft
DH	Daily mean Sensible heat flux product
DLE	Daily mean Latent heat flux product
DWD	Deutscher Wetterdienst (German MetService)
ECMWF	European Center for Medium-Range Weather Forecasts
ECV	Essential Climate Variables
EPS	European Polar System
ERA	ECMWF Re-Analysis
ET	EvapoTranspiration
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FCDR	Fundamental Climate Data Record

GCOS	Global Climate Observing System
GDAP	GEWEX Data and Analysis Panel
GEWEX	Global Energy and Water Exchanges Project
GLDAS	Global Land Data Assimilation System
GLEAM	Global Land Evaporation Amsterdam Model
GPCP	Global Precipitation Climatology Project
H	Sensible heat flux
HOAPS	Hamburg Ocean Atmosphere Fluxes and Parameters from Satellite data
HOLAPS	High res-Olution Land Atmosphere Parameters from Space
ICOADS	International Comprehensive Ocean-Atmosphere Data Set
ICWG	International Clouds Working Group
IPWG	International Precipitation Working Group
IR	Infrared
LE	Latent heat flux
LSA SAF	Land Surface Analysis Satellite Application Facility
LST	Land Surface Temperature
LWP	Liquid Water Path
MET	Monthlly-accumulated EvapoTranspiration product
METEOSAT	Meteorological Satellite(s) series operated by EUMETSAT
MFG	METEOSAT First Generation
MH	Monthly mean Sensible heat flux product
MiKlip	Mittelfristige Klimaprognosen (Decadal Predictions)

MLE	Monthly mean Latent heat flux product
MODIS	MODerate resolution Image Spectroradiometer
MSG	Meteosat Second Generation
MVIRI	METEOSAT Visible and Infrared Imager
NIR	Near IR
NOCS	The National Oceanography Centre Southampton
NWP	Numerical Weather Prediction
OSCAR	Observing Systems Capability Analysis and Review Tool
PACRAIN	Pacific Rainfall Database
PRD	Product Requirement Document
PUM	Product User Manual
RMS	Root Mean Square Deviation
RR	Requirements Review
RSS	Remote Sensing Systems
SAF	Satellite Application Facility
SARAH	Surface Solar Radiation Data Set - Heliosat
SEBAL	Surface Energy Balance Algorithm for Land
SEBS	Surface Energy Balance System
SEVIRI	Spinning Enhanced Visible and Infrared Imager
SRB	Surface Radiation Budget
SSM/I	Special Sensor Microwave Imager

SSMIS	Special Sensor Microwave Imager Sounder
SUMET	Land SUrface Temperature dataset from METeosat First and Second Generation
TAO	Tropical Atmosphere Ocean (project)
TOA	Top Of Atmosphere
TOPC	Terrestrial Observation Panel for Climate
TCWV	Total Column Water vapour
TCDR	Thematic Climate Data Record
TRMM	Tropical Rainfall Measuring Mission
UV	Ultraviolet
WACMOS-ET	WAter Cycle Multi-mission Observation Strategy-EvapoTranspiration
WGASF	Working Group on Air-Sea Fluxes
WMO	World Meteorological Organization

9 Appendix A: Updated Product requirements for the data set under review

Updated requirements for the CM SAF product CM-23722.

CM-23722	Meteosat Free Tropospheric Humidity TCDR R3	FTH_R3_METLAND_TCDR

Type
Dataset

Input Satellite Data Operational Satellite:MVIRI Operational Satellite:SEVIRI	*Application Areas* Climate Research National Meteorological and/or Hydrological Services
Dissemination Information	
Distribution format L3:NetCDF-CF	*Generation frequency* N/A *Generation timeliness*
Spatio-temporal Information	
Spatial Coverage L3:METEOSAT disk (45S-45N, 55W-55E)	*Spatial Resolution* L3:HORIZONTAL:(0.25°)²
Temporal Resolution L3:Hourly:Sample L3:Monthly:Mean	*Temporal Coverage* 1/1/1983 12/31/2020

Uncertainty Characteristics			Optimum	Target	Threshold
FTH-Hourly Sample	ACCURACY	bias	2%	5 %	20 %
FTH-Hourly Sample	PRECISION	RMS	5%	10 %	28 %
FTH-Hourly Sample	STABILITY	decadal	0.3 %	1%	2%
FTH-Monthly Mean	ACCURACY	bias	2%	5 %	20 %
FTH-Monthly Mean	PRECISION	RMS	5 %	10 %	28 %
FTH-Monthly Mean	STABILITY	decadal	0.3 %	1%	2%

Verification:
radiosondes and other satellite products
Comment:

Updated requirements for the CM SAF product CM-23012.

CM-23012	Meteosat Fractional Cloud Cover TCDR R2	SRB_R1_METLAND_TCDR

Type
Dataset

Input Satellite Data
Operational Satellite:MVIRI
Operational Satellite:SEVIRI

Application Areas
Climate Modelling and Evaluation

Dissemination Information

Distribution format
L3:NetCDF-CF

Generation frequency
N/A

Generation timeliness
N/A

Spatio-temporal Information

Spatial Coverage
L3: Meteosat full disk (includes Europe, Africa, Atlantic Ocean)

Spatial Resolution
L3:HORIZONTAL:(0.05°)²

Temporal Resolution
L3: Hourly Mean
L3: Daily Mean
L3: Monthly Mean
L3: Monthly Mean diurnal-cycle

Temporal Coverage
1/1/1983
31/12/2020

Uncertainty Characteristics			Optimum	Target	Threshold
Fractional Cloud Cover – Hourly Mean					
	ACCURACY	bias	0.01	0.03	0.05
	PRECISION	bc-RMS	0.25	0.30	0.35
	STABILITY	decadal	0.003	0.02	0.03
Fractional Cloud Cover – Daily Mean					
	ACCURACY	bias	0.01	0.03	0.05
	PRECISION	bc-RMS	0.15	0.20	0.25
	STABILITY	decadal	0.003	0.02	0.03
Fractional Cloud Cover – Monthly Mean					
	ACCURACY	bias	0.01	0.03	0.05
	PRECISION	bc-RMS	0.05	0.10	0.15
	STABILITY	decadal	0.003	0.02	0.03
Fractional Cloud Cover – Monthly Mean diurnal cycle					
	ACCURACY	bias	0.01	0.03	0.05
	PRECISION	bc-RMS	0.05	0.10	0.15
	STABILITY	decadal	0.003	0.02	0.03

Verification:
Comparison with SYNOP measurements
Comment:
The stability threshold refers to the period 1991-2020.

Updated requirements for the CM SAF product CM-23922.

CM-23922	Meteosat Land Surface Temperature TCDR R2	SRB_R1_METLAND_TCDR

Type
Dataset

Input Satellite Data
Operational Satellite:MVIRI
Operational Satellite:SEVIRI

Application Areas
Climate Model Evaluations
Climate Studies
Drought analysis

Dissemination Information

Distribution format
L3:NetCDF-CF

Generation frequency
N/A

Generation timeliness
N/A

Spatio-temporal Information

Spatial Coverage
L3: Meteosat full disk (includes Europe, Africa, Atlantic Ocean)

Spatial Resolution
L3:HORIZONTAL:(0.05°)²

Temporal Resolution
L3: Hourly Samples
L3: Monthly Mean diurnal-cycle

Temporal Coverage
1/1/1983
31/12/2020

Uncertainty Characteristics			Optimum	Target	Threshold
Land Surface Temperature– Hourly Samples					
	ACCURACY	bias	0.5 K	1 K	1.5 K
	PRECISION	bc-RMS	1 K	1.5 K	2.5 K
	STABILITY	decadal	0.1 K/dec	0.3 K/dec	1 K/dec
Land Surface Temperature – Monthly Mean diurnal cycle					
	ACCURACY	bias	0.5 K	1 K	1.5 K
	PRECISION	bc-RMS	0.5 K	1 K	1.5 K
	STABILITY	decadal	0.1 K/dec	0.3 K/dec	1 K/dec

Verification:
Comparison with LSA SAF validation stations
Comment:
The uncertainty charachteristics refer to clear sky LST.

The defined stability refers to the period 1991 to 2020.

Updated requirements for the CM SAF product CM-23271.

CM-23271	Meteosat Surface Radiation Budget TCDR R1	SRB_R1_METLAND_TCDR

Type
Dataset

Input Satellite Data Operational Satellite: MVIRI Operational Satellite: SEVIRI	*Application Areas* Climate Modelling and Evaluation

Dissemination Information

Distribution format L3:NetCDF-CF	*Generation frequency* N/A *Generation timeliness* N/A

Spatio-temporal Information

Spatial Coverage L3: Meteosat full disk (includes Europe, Africa, Atlantic Ocean)	*Spatial Resolution* L3:HORIZONTAL:(0.05°)²
Temporal Resolution L3: Hourly Mean L3: Daily Mean L3: Monthly Mean L3: Monthly Mean diurnal-cycle	*Temporal Coverage* 1/1/1983 31/12/2020

Uncertainty Characteristics			Optimum	Target	Threshold
Surface Radiation Budget* – Hourly Mean					
	ACCURACY	MAB	6 W/m²	35 W/m²	45 W/m²
Surface Radiation Budget – Daily Mean					
	ACCURACY	MAB	5 W/m²	25 W/m²	30 W/m²
Surface Radiation Budget – Monthly Mean and Monthly Mean Diurnal-Cycle					
	ACCURACY	MAB	4 W/m²	15 W/m²	20 W/m²
	STABILITY	decadal	0.2 W/m²	1 W/m²	2 W/m²

Verification:
Comparison with BSRN and FLUXNET
Comment:
The defined stability refers to the period 1991 to 2020.

*) Surface Radiation Budget refers to net radiation

Updated requirements for the CM SAF product CM-23811.

CM-23811	Latent and Sensible Heat Flux TCDR R1	LEH_R1_METLAND_TCDR

Type
Dataset

Input Satellite Data Others:Reanalysis	*Application Areas* Climate Modelling and Evaluation

Dissemination Information

Distribution format L3:NetCDF4	*Generation frequency*
	Generation timeliness

Spatio-temporal Information

Spatial Coverage L3:MSG full disk (includes Europe, Africa, Atlantic Ocean)	*Spatial Resolution* L3:HORIZONTAL:(0.05°)²
Temporal Resolution L3:Daily:Mean L3:Hourly:Mean L3:Monthly:Mean L3:Monthly:Mean diurnal-cycle	*Temporal Coverage* 1/1/1983 12/31/2020

Uncertainty Characteristics

			Optimum	Target	Threshold
LE -Daily Mean	ACCURACY	bias	$<0.1xLE_{Obs}$	$<(0.2xLE_{Obs}+10)$	$<(0.4xLE_{Obs}+20)$
LE -Daily Mean	PRECISION	RMS	$<0.1xLE_{Obs}$	$<(0.2xLE_{Obs}+15)$	$<(0.4xLE_{Obs}+30)$
LE -Hourly Mean	ACCURACY	bias	$<0.1xLE_{Obs}$	$<(0.2xLE_{Obs}+10)$	$<(0.4xLE_{Obs}+20)$
LE -Hourly Mean	PRECISION	RMS	$<0.1xLE_{Obs}$	$<(0.2xLE_{Obs}+40)$	$<(0.4xLE_{Obs}+80)$
LE -Monthly Mean	ACCURACY	bias	$<0.1xLE_{Obs}$	$<(0.2xLE_{Obs}+10)$	$<(0.4xLE_{Obs}+20)$
LE -Monthly Mean	PRECISION	RMS	$<0.1xLE_{Obs}$	$<(0.2xLE_{Obs}+10)$	$<(0.4xLE_{Obs}+20)$
LE -Monthly Mean	STABILITY	decadal	<0.1	<4	<9
LE -Monthly Mean diurnal-cycle	ACCURACY	bias	$<0.1xLE_{Obs}$	$<(0.2xLE_{Obs}+10)$	$<(0.4xLE_{Obs}+20)$
LE -Monthly Mean diurnal-cycle	PRECISION	RMS	$<0.1xLE_{Obs}$	$<(0.2xLE_{Obs}+15)$	$<(0.4xLE_{Obs}+30)$
H -Daily Mean	ACCURACY	bias	$<0.1xH_{Obs}$	$<(0.3xH_{Obs}+10)$	$<(0.6xH_{Obs}+20)$
H -Daily Mean	PRECISION	RMS	$<0.1xH_{Obs}$	$<(0.3xH_{Obs}+15)$	$<(0.6xH_{Obs}+30)$
H -Hourly Mean	ACCURACY	bias	$<0.1xH_{Obs}$	$<(0.3xH_{Obs}+10)$	$<(0.6xH_{Obs}+20)$
H -Hourly Mean	PRECISION	RMS	$<0.1xH_{Obs}$	$<(0.3xH_{Obs}+50)$	$<(0.6xH_{Obs}+100)$
H -Monthly Mean	ACCURACY	bias	$<0.1xH_{Obs}$	$<(0.3xH_{Obs}+10)$	$<(0.6xH_{Obs}+20)$
H -Monthly Mean	PRECISION	RMS	$<0.1xH_{Obs}$	$<(0.3xH_{Obs}+10)$	$<(0.6xH_{Obs}+20)$
H -Monthly Mean	STABILITY	decadal	<0.1	<4	<9
H -Monthly Mean diurnal-cycle	ACCURACY	bias	$<0.1xH_{Obs}$	$<(0.3xH_{Obs}+10)$	$<(0.6xH_{Obs}+20)$
H -Monthly Mean diurnal-cycle	PRECISION	RMS	$<0.1xH_{Obs}$	$<(0.3xH_{Obs}+15)$	$<(0.6xH_{Obs}+30)$

Verification:
Comparison with in-situ measurements (FLUXNET stations); comparison with other models (e.g. ERA5, GLDAS Noah) and products (e.g. MOD16-ET, HOLAPS), water budget closure studies over hydrological basins.
Comment: