EUMETSAT Satellite Application Facility on Climate Monitoring

Algorithm Theoretical Basis Document

SEVIRI cloud products

Edition 1

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Fractional Cloud Cover	**CM-06**
Joint Cloud property histogram	**CM-12**
Cloud Top level	**CM-18**
Cloud Optical Thickness	**CM-35**
Cloud Phase	**CM-39**
Liquid Water Path	**CM-44**
Ice Water Path	**CM-46**

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Editor	Rainer Hollmann	Science Coordinator		18/03/2013
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Reference documents

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1 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 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 Service of the United Kingdom (UK MetOffice). 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 (CDR’s) derived from operational meteorological satellites.
In particular the generation of long-term data sets is pursued. The ultimate aim is to make the resulting data sets suitable for the analysis of climate variability and potentially the detection of climate trends. 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 CM SAF is on ECVs associated with the global energy and water cycle.

Another essential task of CM SAF is to produce data sets that can serve applications related to the new Global Framework of Climate Services initiated by the WMO World Climate Conference-3 in 2009. CM SAF is supporting climate services at national meteorological and hydrological services (NMHSs) with long-term data records but also with data sets 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, variability and potential trends for the chosen ECVs. CM SAF ECV data sets also serve the improvement of climate models both at global and regional scale.
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 highest standards and guidelines as lined out by GCOS for the satellite data processing,
- Processing of satellite data within a true international collaboration benefiting from developments at international level and pollinating the partnership with own ideas and standards,
- Intensive validation and improvement of the CM SAF climate data records,
- Taking a major role in data set assessments performed by research organisations such as WCRP (World Climate Research Program). This role provides the CM SAF with deep 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. Here, detailed information about product ordering, add-on tools, sample programs and documentation is provided.

2 Introduction

This CM SAF Algorithm Theoretical Basis Document (ATBD) provides information on the processing algorithms and chain implemented for the generation of the cloud products as part of the CLAAS (CM SAF CLoud property dAtAset Using SEVIRI) dataset. This dataset contains retrieved geophysical parameters from inter-calibrated measurements of the Spinning Enhanced Visible Infra-Red Imager (SEVIRI) mounted on the Meteosat Second Generation (MSG) satellites MSG 1 and MSG 2. The cloud property algorithms applied are the MSG v2010 software package by the NWCSAF (SAF to support to Nowcasting and Very Short Range Forecasting) used to derive cloud fraction and cloud top properties (Derrien and Le Gléau, 2005), and the CPP (Cloud Physical Properties) algorithm (Roebeling et al. 2006), which retrieves cloud thermodynamic phase, cloud optical thickness, cloud particle effective radius, and liquid/ice water path.

The document seamlessly describes all elements of the production of the final CLAAS cloud products which are structured in the following three topics.

1. A description of the data sources and a summary of SEVIRI instrument characteristics are given, including a description of the inter-calibration applied to CLAAS measurements.
2. A report on the derivation of the cloud products by applying CPP v3.9 and MSG v2010 algorithms. Note, significant parts of the MSG v2010 and CPP v3.9 algorithms have already been documented in previous ATBDs, which will be referred to in this document when appropriate.
3. The elaboration on the production of the daily and monthly means (Level-3 data) based on the Level-2 products provided by CPP v3.9 and MSG v2010.

Basic accuracy requirements are defined in the product requirements document [AD 1].

The CLAAS data set contains multiple cloud parameters derived from SEVIRI. The CM SAF release of CLAAS contains the following cloud variables:

Fractional Cloud Cover [CM-06, CFC, section 4.1]

Joint Cloud property histogram [CM-12, JCH, section 4.2]

Cloud Top level [CM-18, CTO, section 4.3]

Cloud Optical Thickness [CM-35, COT, section 4.4]

Cloud Phase [CM-39, CPH, section 4.5]

Liquid Water Path [CM-44, LWP, section 4.6]

Ice Water Path [CM-46, IWP, section 4.7]

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3 Processing of measured SEVIRI radiances (Level-1.5)

3.1 The SEVIRI instrument

SEVIRI is a passive optical imaging radiometer with 12 spectral channels at visible and infrared wavebands. SEVIRI instruments are mounted on the geostationary MSG satellites and measure from 2004 onwards. MSG 1 and MSG 2 measurements were projected so that the subsatellite point appears to be 0°/0° while they are in operational mode. The region, that is seen by a SEVIRI instrument is shown in Figure 4-1. It covers Africa, Europe, partly South America, the Atlantic Ocean and the Middle East. In Figure 3-1 the time-span of CLAAS is displayed together with separation of available MSG 1 and MSG 2 measurements, also indicating gaps during the operation. Both SEVIRI instruments on MSG 1 and MSG 2 respectively are identical in construction. Table 3-1 describes shortly the SEVIRI instrument and its main features while the measurement principle is explained in the following.

An MSG satellite spins around its vertical axis with 100 rpm, the SEVIRI instrument uses this spin to scan the earth line-by-line in east-west direction. After each line, the scan mirror is moved on step in South-North direction and the next line is scanned. The acquisition time of one image is 12 minutes, together with onboard calibration and scan mirror retrace a nominal repeat cycle of 15 minutes is achieved.

For each of the 12 spectral channels three detectors acquire three lines of an image simultaneously. The HRV channel however has 9 detectors and 9 lines are obtained per revolution. In Table 3-2 SEVIRI's channels and their characteristics can be found. After each scan a black body calibration is applied for the infrared channels as well as a measurement of the deep space radiance. The deep space radiance corresponds to zero input radiance and is subtracted from the measured signal. The black body calibration is undertaken by moving a black body into the telescope in the intermediate focal plane. The accuracy of SEVIRI was determined prior to the launch in space. The infrared channels measure brightness temperature with an accuracy of < 1 K for a target of 300 K while the bias for the VIS channels ranges from 0.08 to 0.52 W/(m² sr µm), for more details see Table 3-3.

After acquiring an image, the data are sent to the EUMETSAT ground segment where they are further processed into Level 1.5 data as described in the next section. After this processing step the images are ready to be disseminated to the user.

Table 3-1: *SEVIRI instrument features.*

line-by-line scanning radiometer
12 spectral channels 0.4 -13.4 µm, image every 15 min.
Scan duration 12 min.
blackbody calibration at every scan (15 min.)
spatial resolution: 3 km at sub-satellite point
radiometric bias: <1 K for IR and 1.5 – 11 Wm-2sr-1mm-1 for VIS channels

Table 3-2: *SEVIRI channel characteristics (source: EUMETSAT, 2010)*

Channel ID	Absorption BandChannel Type	Nominal Centre Wavelength (µm)	Spectral Bandwidth (µm)	Dynamic Range	Spectral Bandwidth As % of energy actually detected within spectral band
HRV	Visible High Resolution	Nominally 0.75	0.6 to 0.9	0 - 459 W/m2 sr m (scaled at centre frequency)	Precise spectral characteristics not critical
VIS 0.6	VNIR Core Imager	0.635	0.56 to 0.71	0 - 533 W/m2 sr m	98.0 %
VIS 0.8	VNIR Core Imager	0.81	0.74 to 0.88	0 - 357 W/m2 sr m	99.0 %
IR 1.6	VNIR Core Imager	1.64	1.50 to 1.78	0 - 75 W/m2 sr m	99.0 %
IR 3.9	IR / Window Core Imager	3.92	3.48 to 4.36	0 - 335 K	98.6 % (1)
IR 6.2	Water Vapour Core Imager	6.25	5.35 to 7.15	0 - 300 K	99.0 %
IR 7.3	Water Vapour Pseudo-Sounding	7.35	6.85 to 7.85	0 - 300 K	98.0 %
IR 8.7	IR / Window Core Imager	8.70	8.30 to 9.10	0 - 300 K	98.0 %
IR 9.7	IR / Ozone Pseudo-Sounding	9.66	9.38 to 9.94	0 - 310 K	99.0 %
IR 10.8	IR / Window Core Imager	10.80	9.80 to 11.80	0 - 335 K	98.0 %
IR 12.0	IR / Window Core Imager	12.00	11.00 to 13.00	0 - 335 K	98.0 %
IR 13.4	IR / Carbon Dioxide Pseudo-Sounding	13.40	12.40 to 14.40	0 - 300 K	96.0 %

Table 3-3: SEVIRI channel noise budgets expressed in K for IR channels and W/(m² sr µm) as reported in Schmid, “The SEVIRI instrument”, http://www.eumetsat.int/Home/Main/Satellites/MeteosatSecondGeneration/Resources/index.htm?l=en.

Channel (µm)	HRV	0,6	0,8	1,6	3,9	6,2	7,3	8,7	9,7	10,8	12	13,4
Noise	0,52	0,39	0,36	0,08	0,24	0,4	48	0,15	0,24	0,13	0,21	0,29
Spec.	1,07	0,53	0,49	0,25	0,35	0,75	0,75	0,28	1,5	0,25	0,37	1,8

3.2 The SEVIRI measurement record

The SEVIRI measurement record spans the time-period from 2004 onwards, measurements from the respective instrument on the satellite that was in operational mode was used. During the respective time-span, one operational change took place, from MSG 1 to MSG 2.

Originally, SEVIRI takes an image every 15 minutes, but for CLAAS hourly resolution was applied to balance the benefits from higher accuracy with increased processing time and data amount. The horizontal resolution of a SEVIRI image is 3 x 3 km² at nadir. CLAAS covers the time-span 2004-2011, where MSG1 measurements were processed from 01/2004 – 04/2007 and MSG 2 from 04/2007 – 12/2011. Gaps of more than 24 hours in the MSG 2 time-series were filled with MSG 1 measurements, see Figure 3-1, exact dates with gaps and missing dates in the MSG2 record that could be filled with MSG1 data are listed in Table 3-4.

For the derivation of our cloud products we used the Level 1.5 SEVIRI data provided by EUMETSAT. Level 1 data is image data that was directly transferred to the EUMETSAT’s ground segment. i.e. raw data before any modification has taken place. The Level 1.5 data record comprises image data that has already undergone certain modifications by EUMETSAT: it has been corrected for all unwanted radiometric and geometric effects, has been geolocated using a standardised projection, and has been calibrated and radiance-linearised.

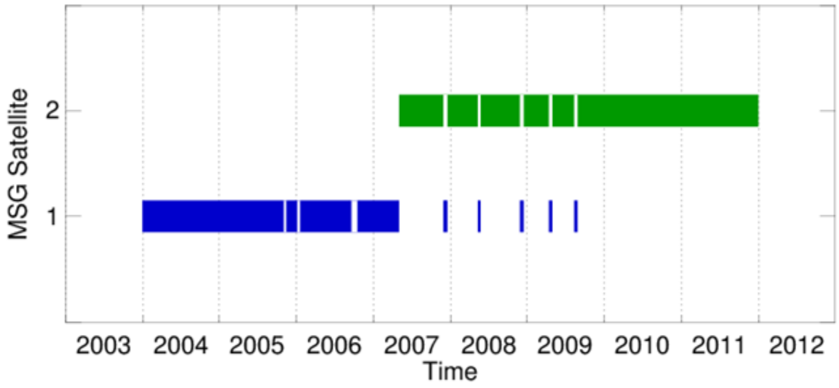

Figure 3-1: Overview of SEVIRI measurements record at CM SAF used as basis for cloud products. Short-term data gaps are shown enlarged due to better visibility. Exact dates can be found in Table 3-4.

Some of the processing steps are described in the following: First, the raw data are projected onto the SEVIRI disk to form a geolocated image. Every image (except for HRV, which will not be described further, since its measurements are not used for CLAAS) consists of 3712 lines by 3712 columns. The space area of the Level 1.5 image is set to a predefined binary value, also the missing pixel will be replaced by this value. The sampling distance is defined to be exactly 3 km by 3 km at the sub-satellite point and the geolocation is centred at 0° latitude and 0° longitude where the centre is situated in the middle of the pixel with the line numbers (1856,1856).

The Level 1.5 images are delivered to the DWD in HRIT format. That means, each time slot or image package respectively consists of header information contained in a so-called prologue file and trailer information included in the epilogue file. All other files contain the image information of the channels. One image is divided into 8 segments, where each segment contains 464 image lines. The header files contains vital information concerning the image acquisition like status of the satellite or the instruments as well as the gain and offset coefficients. In the trailer files information about the geometric and radiometric quality as well as image production status is included.

The image data are stored in a 10 bit integer format, and therefore have been scaled. The user has to apply the gain and offset given in the header to receive the actual radiance values. Please note that EUMETSAT introduced a new radiance definition in 2008 (see EUMETSAT, 2008). The whole SEVIRI Level 1.5 data archive was reprocessed by EUMETSAT and the new files were transferred to the DWD, so the complete CLAAS dataset relies on the reprocessed Level 1.5 radiances.

Table 3-4: *Gaps in SEVIRI measurement record. Gaps of a period shorter than 1 day are not listed.*

Data gap		Reason
from	**to**	
01/08/2005	01/08/2005	no MSG-1 SEVIRI measurements available
10/01/2006	11/01/2006	no MSG-1 SEVIRI measurements available
24/09/2006	10/10/2006	no MSG-1 SEVIRI measurements available
03/12/2007	11/12/2007	no MSG-2 SEVIRI measurements available, replaced by MSG-1 SEVIRI
14/05/2008	15/05/2008	no MSG-2 SEVIRI measurements available, replaced by MSG-1 SEVIRI
01/12/2008	08/12/2008	no MSG-2 SEVIRI measurements available, replaced by MSG-1 SEVIRI
18/04/2009	22/04/2009	no MSG-2 SEVIRI measurements available, replaced by MSG-1 SEVIRI
15/08/2009	20/08/2009	no MSG-2 SEVIRI measurements available, replaced by MSG-1 SEVIRI

3.3 Applied SEVIRI solar channel calibration description

SEVIRI does not carry an on-board calibration device for the solar channels. Therefore, EUMETSAT operates a vicarious calibration system using Earth targets (desert and ocean) as reference. Analyses by Doelling et al. (2004) and Ham and Sohn (2010) revealed that the resulting visible channel nominal calibration, provided in the SEVIRI Level-1.5 data files, has a considerable offset with respect to MODIS, which is thought to be a well-calibrated reference instrument. Meirink et al. (2012) extended these previous analyses to the NIR channels and to longer time periods. They used collocated, ray-matched, atmosphere-corrected, near-nadir SEVIRI and Aqua-MODIS reflectances to derive re-calibration slopes, i.e. multiplicative factors to be applied to SEVIRI nominal reflectance in order to match the MODIS measurements. Results are shown in Figure 3-2. The SEVIRI calibration turns out to be very stable over time, but appears to be off relative to Aqua-MODIS by about -8%, -6%, and +4%, for channels 1, 2, and 3, respectively. For the generation of the CLAAS dataset, the mean re-calibration slopes from Figure 3-2 have been applied to the nominal SEVIRI reflectances.

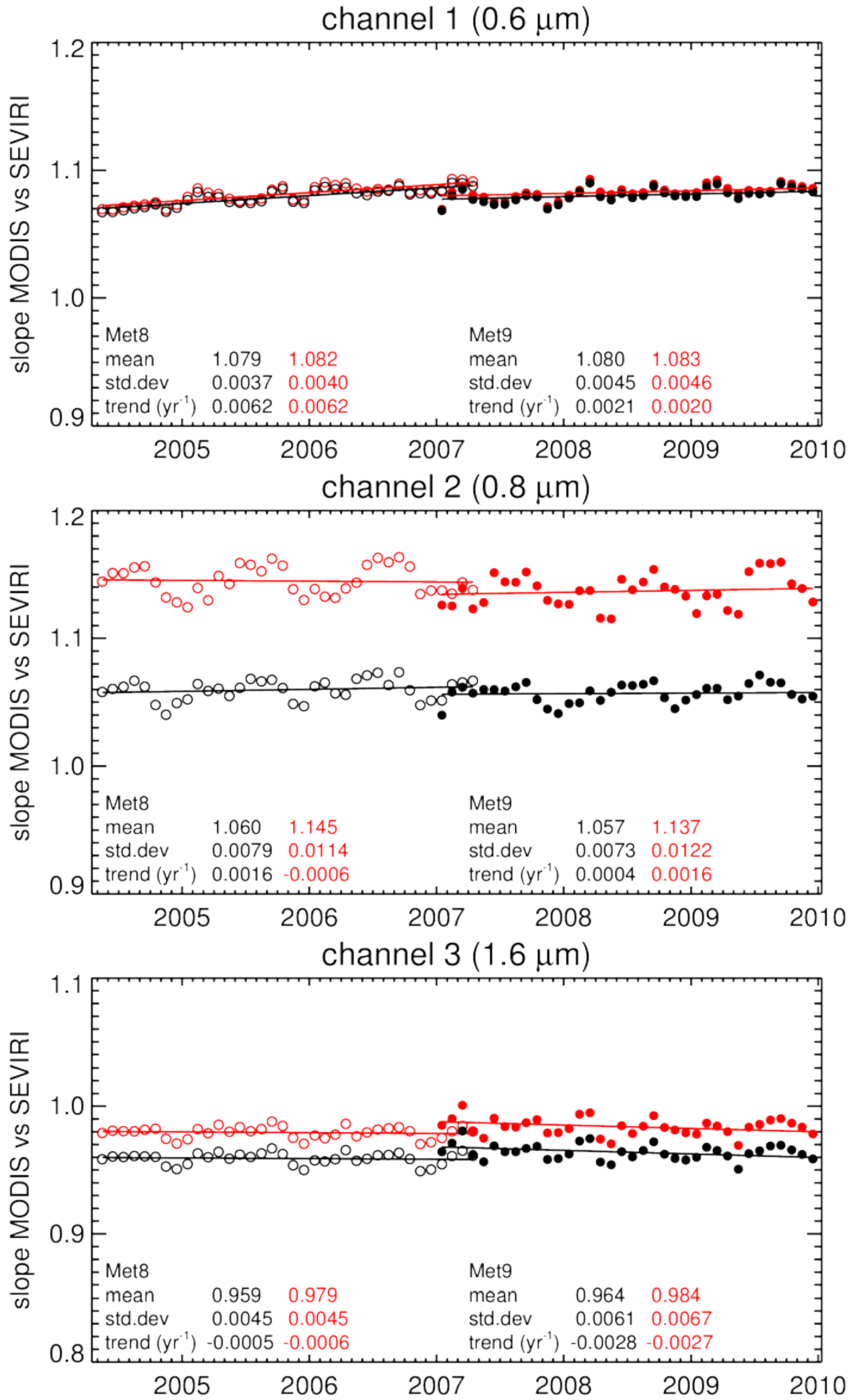

Figure 3-2: Time series of re-calibration slopes for MODIS-Aqua against SEVIRI-Meteosat for three solar channels. The open (filled) circles are the monthly slopes for Meteosat8 (Meteosat9), and the solid lines are linear fits through those monthly slopes. Black (red) symbols and lines correspond to data that have (have not) been corrected for differences in spectral response. Mean, standard deviation, and trend of the re-calibration slopes are indicated in the plot.

4 Retrieval of pixel-based cloud properties (Level-2)

This section provides information on the processing of MSG v2010 and CPP v3.9 to retrieve cloud parameters from inter-calibrated SEVIRI measurements. Each parameter is briefly introduced in the following with the respective detailed ATBD being referred to.

4.1 Fractional Cloud Cover [CM-06, CFC]

This product is derived directly from results of a cloud screening or cloud masking method. The cloud mask comprises 6 categories: Cloud filled, cloud-free, cloud contaminated and non-processed, snow/ice contaminated, undefined. The cloud fractional cover is defined as the fraction of cloudy pixels per grid square compared to the total number of analyzed pixels in the grid square. Pixels are counted as cloudy if they belong to the classes cloud filled or cloud contaminated. Fractional cloud cover is expressed in percent. The cloud screening and cloud masking is performed using the NWC SAF MSG v2010 algorithm, which is described in more detail in [RD 1].

4.2 Joint Cloud property Histogram [CM-12, JCH]

The JCH product is a combined histogram of CTP and COT covering the solution space of both parameters. This two-dimensional histogram gives the absolute numbers of occurrences for specific COT and CTP combinations defined by specific bins, which can be found in section 5.2.2. More details on this product can be found in [RD 3].

4.3 Cloud Top level [CM-18, CTO]

Three versions of the CM SAF Cloud Top product exist: 1. Cloud Top Temperature (CTT), expressed in Kelvin; 2. Cloud Top Height (CTH), expressed as altitude above sea level (m); 3. Cloud Top Pressure (CTP), expressed in pressure co-ordinates (hPa).
Cloud top products are retrieved with the following method:
In a first step, cloudy pixels are separated into three classes depending on cloud type or its opacity respectively: 1) very low, low or medium thick as well as middle level clouds, 2) high opaque clouds and 3) high semi-transparent clouds.
Using RTTOV (http://research.metoffice.gov.uk/research/interproj/nwpsaf/rtm/) the corresponding radiances and brightness temperatures for overcast and clear sky are simulated for each pixel, with vertical profiles of temperature and humidity analysis from ERA-Interim (Dee et al., 2012) as ancillary input. The SEVIRI channels used are: 6.2, 7.3, 13.4 10.8, 12.0 µm.
For very low, low or medium thick clouds as well as opaque clouds the cloud top pressure is retrieved as the best fit between the simulated and the measured 10.8µm brightness temperatures. Also the possibility of a low level thermal inversion is taken into account with the help of the ERA-Interim temperature profile at the respective pixel . In that case the very low, low or medium clouds are assumed to form at the inversion level, while they can also rise above that level if their brightness temperatures are colder than the air temperature below the thermal inversion. The type of the inversion (dry air above the inversion level or not) is included by subtracting a variable offset.
In case of semitransparent clouds the radiance rationing method is used, in which the ratio of radiances from 2 channels is compared to simulated radiances at clear sky conditions for a fixed temperature profile or H2O/IRW intercept method. For the latter a linear relationship of radiance between 2 spectral bands is assumed, but a curve for a window and a sounding

channel. For opaque clouds this technique is always applied as preceding test, in order to remove any pixels that are semitransparent but where in fact falsely labeled as opaque by the cloud type test.
The retrieval algorithms are part of the NWC SAF MSG v2010 package, details can be found in [RD 1].

4.4 Cloud Optical Thickness [CM-35, COT]

The Cloud Optical Thickness (COT) is defined at 0.6 μm under the assumption of a plane parallel atmosphere with reference to a vertical transect. COT is retrieved from a comparison of the measured 0.6 μm reflectance to pre-calculated Lookup Table (LUT) values. The LUTs were obtained using radiative transfer calculations from the Doubling Adding KNMI (DAK) model. COT is simultaneously retrieved with cloud particle effective radius in an iterative manner.
During the iteration the retrieval of COT at the 0.6-μm channel is used to update the retrieval of cloud particle effective radius at the 1.6-μm channel. This iteration process continues until the retrieved cloud physical properties converge to stable values. Since the particle sizes become unreliable for optically thin clouds, the retrieval is weighted with climatologically averaged effective radii of 8 μm and 26 μm for water and ice clouds, respectively, for clouds with $\tau < 8$.
For more details on the radiative transfer modelling and retrieval scheme details we refer to [RD 2].

4.5 Cloud Phase [CM-39, CPH]

The cloud thermodynamic phase (CPH) is determined as follows. The iterative process described above is first applied using the ice cloud LUT. If convergence is achieved and the cloud-top temperature ($T_{c,}$ obtained from measured 10.8-μm brightness temperatures) is lower than 265 K, the phase ‘ice’ is assigned. If not, the phase ‘water’ is assigned. Details can be found in [RD 1]

4.6 Liquid Water Path [CM-44, LWP]

Liquid water path is computed from the retrieved COT and cloud particle effective radius (r_e) values by (Stephens et al., 1978):

$$LWP = \frac{2}{3} COT \rho_l r_e \,,$$

in which ρ_l represents the density of liquid water (1000 kg m^{-3}).
For the radiative transfer calculations droplets are considered to be spheres, the droplet size distributions have effective radii between 1 and 24 μm and an effective variance of 0.15.
More details can be found in [RD 2].

4.7 Ice Water Path [CM-46, IWP]

The Ice Water Path (IWP) is calculated using the same formula as for LWP using the retrieved effective radius of ice crystals and the density of ice (930 kg m^{-3}). For the ice crystals, volume equivalent effective radii are 6, 12, 26, and 51 μm. These radii are based on 4 types of imperfect hexagonal columns defined by Hess et al. (1998). See [RD 2] for more details.

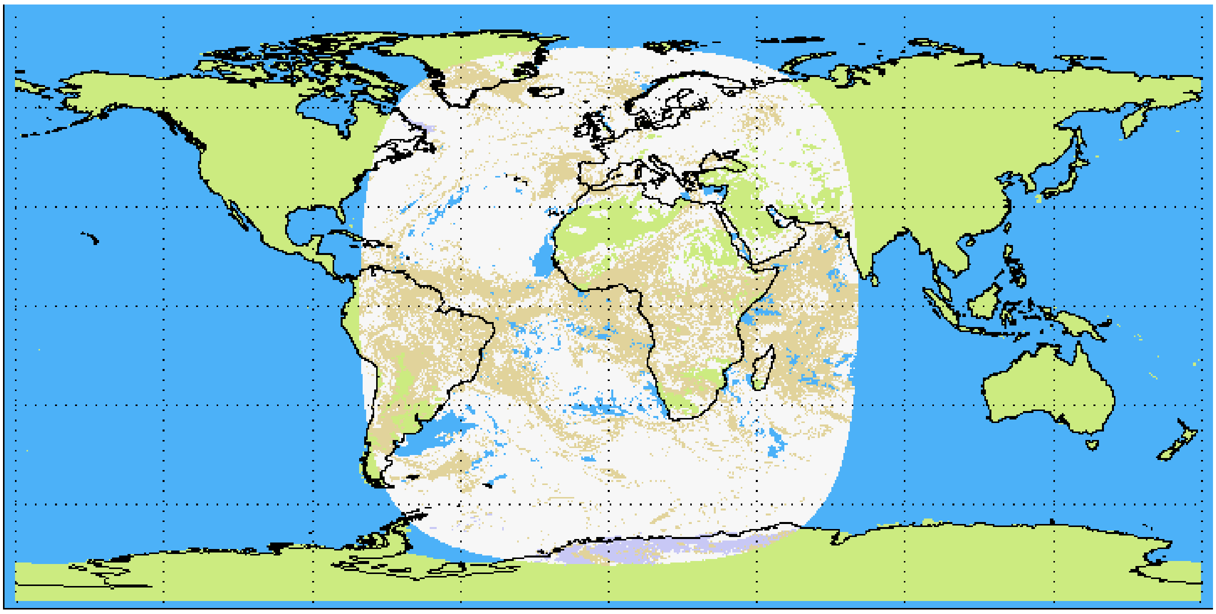

Figure 4-1: Area seen be SEVIRI, example for cloud fractional cover.

5 Generation of daily and monthly means, and histograms (Level-3)

In addition to the Level 2 pixel-level products, which are on native SEVIRI projection and resolution, CLAAS also contains Level 3 products of various parameters and parameter combinations. The pixel level retrieval results of the Level 2 algorithm software of CPP v3.9 and MSG v2010 are input to the L2/L3 processing. The final L3 outputs produced are fields of daily and monthly averages with specification defined in [AD 1]. These specifications are summarized in section 5.1. The covered geographic area is shown in Figure 4-1. The Level-3 data (daily and monthly means) are aggregated and averaged on the original SEVIRI resolution. Building on that, that data is re-projected onto a regular latitude/longitude grid with a resolution of $(0.05°)^2$. An exception are the JCH which are determined for 6x6 SEVIRI pixel boxes before being re-projected onto a regular latitude/longitude grid with a resolution of $(0.25°)^2$.

5.1 Definition of product specifications

The CLAAS cloud data set provides a number of cloud parameters on the area indicated in Figure 4-1. Instantaneous retrievals with a temporal resolution of 1 per hour at original spatial resolution are used to derive the spatio-temporally averaged data sets. The products are available as daily and monthly composites on a regular latitude/longitude grid with a spatial resolution of 0.05° × 0.05° degrees. Also monthly mean diurnal cycles are available consisting of 24 time-steps with a spatial resolution of 0.25° × 0.25° degrees.

Acknowledging the different observation capabilities during night and during day and also taking into account existing diurnal variations in cloudiness, a further separation of results into daytime and night-time portions has also been done (currently only for fractional cloud cover and cloud type). Here, all observations made under twilight conditions (-3° < solar elevation < 10°) have been excluded in order to avoid being affected by specific cloud detection problems occurring in the twilight zone.

In addition to the mean values, histograms are provided on monthly time scales. The Joint Cloud property Histograms are two-dimensional histograms of COT and CTP are composed with a spatial resolution of 0.25° x 0.25° degrees. (See Section 5.3.2 for more technical details). For CTP, COT, LWP and IWP one-dimensional histograms are constructed on a monthly basis with a spatial resolution of 0.05° × 0.05° degrees (see Sections 5.3.3, 5.3.4, 5.3.6 and 5.3.7 for more technical details.).

The temporal coverage of the data sets ranges from 19 January 2004 to 31 December 2011. Notice again (as mentioned in Section 3 and visualised in Figure 3-1) that until 11th of April 2007, 11:45 a.m. MSG-1 SEVIRI was the data source, while after that MSG-2 SEVIRI data was received and processed, unless MSG1 SEVIRI was used for gap filling when MSG2 SEVIRI was undergoing maintenance procedures..

5.2 Calculation of Level 3 products

For the daily and monthly averages all data fields with original SEVIRI pixel size and in hourly resolution are temporally averaged. Here, all values are considered equally valid, thus no weighting is applied. Note that unlike in the operational version of SEVIRI cloud parameters, the monthly averages are also created from averaging all available instantaneous data, NOT by averaging the daily mean values!
To achieve the final spatial product resolution of (0.05°)², the temporal averaged fields are remapped as described in section 5.4
It is important to note that different quality checks are applied for filtering valid numbers for each parameter. This is motivated by the fact that not in all cases where a cloud mask is available all cloud retrieval results of CPH, CTO, COT, LWP and IWP are available. Please note that due to to large file size the joint cloud property histogram as well as the monthly mean diurnal cycle of the respective parameters are provided only on a (0.25°)² grid.

5.2.1 Fractional Cloud Cover [CFC]

The daily and monthly mean fractional cloud cover is calculated from the aggregation of the instances of the binary cloud mask information as follows:

$$CFC(i,j) = \frac{N(i,j)_{Cloudy}}{N(i,j)_{Cloudy} + N(i,j)_{Clear}} \qquad (1)$$

with i and j being the indices of the original field projection, $N(i,j)_{Cloudy}$ the number of cloudy cases and $N(i,j)_{Clear}$ the number of clear cases. Acknowledging the different cloud detection capability during day and night time, an additional separation is done leading to $CFC(i,j)_{Night}$ and $CFC(i,j)_{Day}$, separate day time and night time averages. Here, the solar zenith angle of ≤80° and ≥103° are used to define day and night, respectively. Cases with solar zenith angles between 80° and 103° are excluded due to specific problems occurring in twilight conditions.

5.2.2 Joint Cloud property Histogram [JCH]

Differing from CFC, CPH, COT, LWP and IWP product derivation, the JCH does not include a classical mean of a specific cloud property but covers the solution space for the 2 cloud parameters: COT and CTP. Thus these products are described in four-dimensional fields $JCH(i, j, t, p)$. Indices i and j refer to location space, while t and p being the indices for specific bins of the range of occurring COT and CTP values.
Each specific field entry contains the absolute number of occurrences of cloud pixel falling into the COT bin t and the CTP bin p being. The following values bordering the bins of COT and CTP (given in hPa) have been defined:

COT: {0, 0.3, 0.6, 1.3, 2.2, 3.6, 5.8, 9.4, 15, 23, 41, 60, 80, 100, 257}
CTP: {0, 37.5, 87.5, 137.5, 187.5, 237.5, 287.5, 337.5, 387.5, 437.5, 487.5, 537.5, 587.5, 637.5, 687.5, 737.5, 787.5, 837.5, 887.5, 937.5, 987.5, 1012.5, 1087.5}

The CTP binning is done in order to properly account for the vertical resolution of CTP which is 25hPa. In a second step, the histograms are remapped onto ISCCP like binning, but with doubled resolution in CTP and COT. Thus the final and provided binning of the JCH is as follows:

COT:{ 0, 0.3, 0.6, 1.3, 2.2, 3.6, 5.8, 9.4, 15, 23, 41, 60, 80, 100} and
CTP:{ 1, 90, 180, 245, 310, 375, 440, 500, 560, 620, 680, 740, 800, 875, 950, 1100} [hPa].

These histograms are calculated for liquid and ice clouds separately, thus:

$$JCH(i, j, t, p)_{ice} = N(i, j)_{COT \varepsilon COTbin; CTP \varepsilon CTPbin; CPH = ice} \quad (2)$$

and

$$JCH(i, j, t, p)_{liquid} = N(i, j)_{COT \varepsilon COTbin; CTP \varepsilon CTPbin; CPH = liquid} \quad (3)$$

5.2.3 Cloud Top Level [CTO]

The CTO product contains daily and monthly means for CTH, CTP, and CTT. For these parameters all valid entries of the original fields are aggregated and then weighted by the number of used entries.

$$< x(i, j) >= \frac{1}{N(i, j)_{Cloudy}} \sum_{k=1}^{N(i,j)_{Cloudy}} x_k(i, j) \quad (4)$$

with $x(i, j)$ being a general expression for CTH, CTP and CTT at a specific original grid cell. After temporal averaging, the fields are remapped to the final resolution as described in section 5.4

For CTP, an alternative way of averaging is followed and additionally calculated and provided as geometrical mean where the variables are averaged in logarithm space:

$$< ctp(i, j) >_{\ln} = \exp(\frac{1}{N(i, j)_{Cloudy}} \sum_{k=1}^{N(i,j)_{Cloudy}} \ln(ctp_k(i, j))) \quad (5)$$

Geometrical mean is added to keep consistency between CTH and CTP. CTP depends logarithmically on CTH, so if CTH is averaged linearly, CTP has to be averaged logarithmically to preserve the relation. One-dimensional histograms are generated for CTP on the same spatial resolution, but only on monthly basis. The CTP bin borders for these histograms are:

CTP:{ 1, 90, 180, 245, 310, 375, 440, 500, 560, 620, 680, 740, 800, 875, 950, 1100} [hPa].

5.2.4 Cloud Optical Thickness [COT]

Similar to CTT and CTH and the arithmetical mean of CTP, the daily and monthly mean of COT $< COT(i,j) >$ is calculated following Equation (4). Additional, ice and liquid cloud specific values are calculated: $< COT(i,j) >_{ice}$, $< COT(i,j) >_{liquid}$ using CPH as identifier.
As an upper limit for realistic COTs the value of 100 was defined.
One-dimensional histograms are generated for COT on the same spatial resolution, but only on monthly basis. The COT bin borders for these histograms are:

COT:{ 0, 0.3, 0.6, 1.3, 2.2, 3.6, 5.8, 9.4, 15, 23, 41, 60, 80, 100}.

5.2.5 Cloud Phase [CPH]

Similarly to CFC, the daily and monthly averages of CPH are calculated by temporal averaging of retrieval results on original pixel basis and subsequent remapping. CPH is expressed as fraction of liquid water clouds by calculating the ratio of number of detected liquid clouds $N(i,j)_{Cloudy}$ with respect to the total number detected clouds $N(i,j)_{Cloudy}$:

$$CPH(i,j) = \frac{N(i,j)_{liquid}}{N(i,j)_{Cloudy}} \quad (6)$$

5.2.6 Liquid and Ice Water Path [LWP]

Daily and monthly mean LWP is calculated for each grid cell $< LWP(i,j) >$ as given in Equation (4). If collocated COT values exceed 100, the LWP is scaled down accordingly.
One-dimensional histograms are generated for LWP on the same spatial resolution, but only on monthly basis. The LWP bin borders for these histograms are:

LWP: {0, 5, 10, 20, 35, 50, 75, 100, 150, 200, 300, 500, 1000, 2000, inf} [g/m²].

5.2.7 Ice Water Path [IWP]

Daily and monthly mean IWP is calculated for each grid cell $< IWP(i,j) >$ as given in Equation (4). If collocated COT values exceed 100, the IWP is scaled down accordingly.
One-dimensional histograms are generated for IWP on the same spatial resolution, but only on monthly basis. The IWP bin borders for these histograms are:

IWP: {0, 5, 10, 20, 35, 50, 75, 100, 150, 200, 300, 500, 1000, 2000, inf} [g/m²].

5.3 Additional statistical parameters

In addition to the daily and monthly mean values, the standard deviations s over all valid and used values is calculated for CTO, COT, LWP and IWP for each grid box with

$$s(x(i,j)) = (< x^2(i,j) > - < x(i,j) >^2)^{0.5}$$

5.4 Re-projection onto final lat/lon grid

While the Level 2 products are provided on native SEVIRI projection/resolution, all Level 3 products are, after creation, mapped onto a latitude-longitude grid with a spatial resolution of 0.05° (0.25° for the histograms). This resolution was chosen with respect to the similarity to the native SEVIRI resolution (reduced spatial resolution of histograms is due to file size limitations).
The remapping (reprojection) is performed using the Climate Data Operator (CDO) tools (available at https://code.zmaw.de/projects/cdo). Spatial transfer pointers are inferred for the chosen nearest-neighbour approach and the CDO command call is used as follows:

```
> cdo gennn,FINAL_GRID -setgrid,SEVIRI_LAT_LON_FILE &
    -import_cmsaf IN_FILE WEIGHTS_FILE
```

in which SEVIRI_LAT_LON_FILE contains the latitude and longitude information in SEVIRI projection/resolution and IN_FILE data on SEVIRI projection/resolution. FINAL_GIRD is an ASCCI file grid information:

```
gridtype = lonlat
xsize = 3600
ysize = 3600
xfirst = -89.975
xinc = 0.05
yfirst = -89.975
yinc = 0.05
```

For histogram data `xinc` and `yinc` are specified with 0.25. Due to computational cost the CDO call is avoided for most products, and the transfer pointers (one they were stored in WEIGHTS_FILE) are used in an external remapping script to perform the remapping. The reader is referred to CDO (2009) for more information on CDO.

5.5 Monthly mean diurnal cycles

To facilitate the assessment of monthly mean diurnal cycle for the user not only daily and monthly means are created but also monthly mean diurnal cycles from the quantities CFC, CTO, COT, LWP, IWP and CPH. For a monthly mean diurnal cycle, all fields of a specific slot are considered and averaged hour wise, the result is a file with 24 fields. Each field contains the monthly average of all input fields of a specific hour. Please note that the time axis refers to UTC, for a depiction in local time the pixel will have to be sorted with respect to the time zones.

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6 Glossary

ATBD	Algorithm Theoretical Baseline Document
AVHRR	Advanced Very High Resolution Radiometer
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarisation
CDO	Climate Data Operators
CDOP	Continuous Development and Operations Phase
CFC	Fractional Cloud Cover
CFOT	Cloud Feature Optical Depth
CLARA-A1	CM SAF cLoud, Albedo and Radiation products, AVHRR-based, Edition 1
CLAAS	CM SAF CLoud property dAtaset Using SEVIRI
CM SAF	Satellite Application Facility on Climate Monitoring
CPH	Cloud Phase
CPR	Cloud Profiling Radar
COT	Cloud Optical Thickness
CTH	Cloud Top Height
CTO	Cloud Top product
CTP	Cloud Top Pressure
CTT	Cloud Top Temperature
CPP	Cloud Physical Properties
DRI	Delivery Readiness Inspection
DWD	Deutscher Wetterdienst (German MetService)
ECMWF	European Centre for Medium Range Forecast
ECV	Essential Climate Variable
ERA-Interim	Second ECMWF Re-Analysis dataset
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FCDR	Fundamental Climate Data Record
GAC	Global Area Coverage (AVHRR)
GCOS	Global Climate Observing System
IWP	Ice Water Path
ISCCP	International Satellite Cloud Climatology Project
JCH	Joint Cloud properties Histogram
KNMI	Koninklijk Nederlands Meteorologisch Institut
LWP	Liquid Water Path
MODIS	Moderate Resolution Imaging Spectroradiometer
MSG	Meteosat Second Generation
NOAA	National Oceanic & Atmospheric Administration

NWC SAF	SAF on Nowcasting and Very Short Range Forecasting
NWP	Numerical Weather Prediction
PRD	Product Requirement Document
PUM	Product User Manual
SEVIRI	Spinning Enhanced Visible and InfraRed Imager
SAF	Satellite Application Facility
SMHI	Swedish Meteorological and Hydrological Institute
SYNOP	Synoptic observations