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Operational generation of AVHRR-based cloud products for Europe and the Arctic at EUMETSAT's Satellite Application Facility on Climate Monitoring (CM-SAF)

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Abstract. The Satelite Application Facility on Climate Monitoring has implemented a new processing environment for AVHRR-based climate monitoring products. AVHRR measurements from NOAA-17, NOAA-18 and MetOp-A are utilized to generate daily and monthly means of several cloud parameters for Europe and the Inner Arctic: Cloud fraction, cloud types, cloud phase, cloud top height, cloud optical thickness and cloud liquid water path.

1 Introduction: climate monitoring with satellites

Satellite data provide information on the climate system that are not available or difficult to measure from the Earth's surface like top of atmosphere radiation, cloud properties or humidity in the upper atmosphere. In particular over ocean and sparsely populated areas space-based observations are largely the only data source. Following this idea, EUMETSAT's Satellite Application Facility on Climate Monitoring (CM-SAF) is dedicated to the long-term monitoring of the climate system's state and variability (Schulz et al., 2009). The EUMETSAT Satellite Application Facilities (SAF) are dedicated centres of excellence for processing satellite data, and form an integral part of the distributed EUMETSAT Application Ground Segment (http://www.eumetsat.int). CM-SAF is a consortium with contributions of several European meteorological services (FMI, KNMI, MeteoSwiss, RMI, SMHI) with Deutscher Wetterdienst (DWD, Germany) as the leading entity.

It supports the analysis and diagnosis of climate parameters in order to detect and understand changes in the climate system. For this purpose CM-SAF exploits several sensors on geostationary (SEVIRI and GERB instrument on-board Meteosat Second Generation) as well as polar-orbiting meteorological satellites (AVHRR, ATOVS and SSM/I instruments). CM-SAF provides data sets of several cloud parameters, surface albedo, radiation fluxes at the top of the atmosphere and at the surface, atmospheric temperature and water vapour profiles as well as vertically integrated water vapour (total, layered integrated).

For recent years a product suite of these parameters is already available. Starting with January 2009, new products for the Inner Arctic will be included into the product suite. These products are derived from measurements of the Advanced Very High Resolution Radiometer (AVHRR). In that context the processing environment for several other AVHRR-based products has also been significantly improved. Here we describe the new operational AVHRR processing scheme with focus on the new Arctic products.

2 The operational AVHRR processing chain

2.1 Overview

CM-SAF provides operational AVHRR-based products since January 2004. These were produced for the so-called CM-SAF baseline area, that includes Europe and parts of the North Atlantic (30° N to 80° N, 60° W to 60° E). Starting with beginning of 2009 a new processing chain for AVHRR measurements is set into operational status. Compared to the previous version this brings several significant improvements and new features:

– Data from the MetOp-A satellite are considered, which is in operational mode since May 2007.

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– Processing is not based on locally received data any more, but utilizes data streams with a better spatial coverage. In case of MetOp-A the data stream provides full global coverage at full sensor resolution.

– The product suite is extended to cloud products and surface albedo for the Arctic (so-called CM-SAF Inner Arctic region, see Figs. 1 and 2).

– Processing is done on original satellite overpasses instead of remapping the input data. Intermediate products are therefore available at original satellite projection.

Large parts of this operational environment are based on the updated version of the "Polar Platform System Software" (version 2008) that was provided by the NWC-SAF (SAF on Support to Nowcasting and Very Short Range Forecasting; http://nwcsaf.inm.es). This package provides the algorithms for retrieval of the cloud mask, cloud type, cloud top height and cloud phase products. As the underlying algorithms are described elsewhere (e.g. Dybbroe et al., 2005a; Dybbroe et al., 2005b), we focus on the operational implementation at CM-SAF and the generation of CM-SAF's climate monitoring products. Compared to NWC-SAF's activities, CM-SAF focuses on calculation of daily and monthly means and long-term archiving. In this paper, we therefore focus on the operational procedure for generation of these averaged products and the new Arctic products.

2.2 AVHRR input data

The Advanced Very High Resolution Radiometer (AVHRR) measures the reflectance of the Earth in 5 relatively wide spectral bands (sensing in the visible, near-infrared, and thermal infrared portions of the electromagnetic spectrum). Each pass of the satellite provides a swath width of 2048 pixels with a ground resolution of approximately 1.1 km at the satellite nadir (degrading to several kilometers at the swath edges). The sensor is on-board NOAA's polar-orbiting satellites and EUMETSAT's polar-orbiter MetOp-A. Each of these satellites orbits the Earth with a period of approx. 101 min at a height of approx. 830 km above its surface.

In the new processing environment, CM-SAF utilizes AVHRR data from MetOp-A, NOAA-17 and NOAA-18. MetOp-A data are received via the EUMETCast dissemination system that provides a continuous high-resolution global coverage. Data from NOAA-17 and NOAA-18 are obtained via the EUMETSAT Advanced Retransmission Service (EARS), which is based on a combination of data that are received by several ground reception stations. This results in a Europe-wide coverage and also includes parts of the North Atlantic and Greenland.

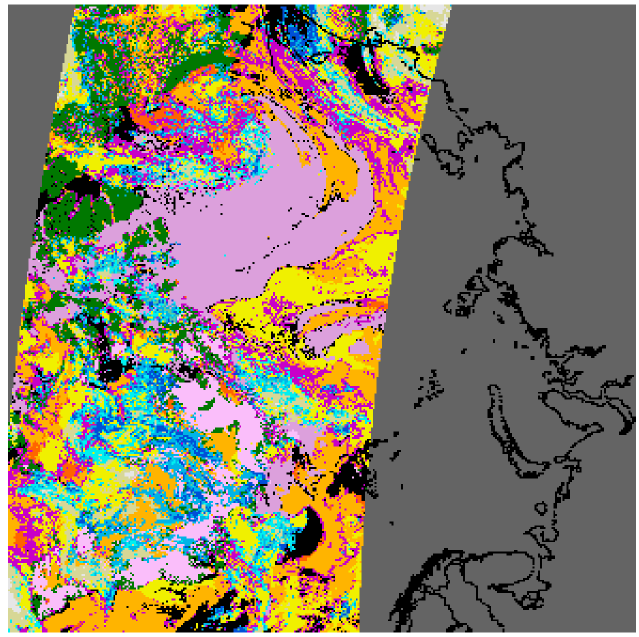

Figure 1. Cloud types as detected by NWCSAF's PPS-software for one selected satellite scene: MetOp overpass from 16.07.2007, scene starting at 21:52 UTC. The figure shows the CM-SAF Inner Arctic region (square with a size of 5010 km×5010 km centered to the pole with grid cells oriented parallel to the 0° and 90° meridians) at a spatial resolution of 15 km×15 km. The figure also illustrates the swath-based processing. See Table 1 for a colour legend.

2.3 The NWC-SAF Polar Platform System Software (PPS)

The new version (2008) of the PPS software operates on satellite swaths (as illustrated in Fig. 1). For each AVHRR pixel, the following products are derived:

– **Cloud mask:** The Cloud Mask scheme attempts to delineate all absolutely cloud-free pixels with a high confidence. It is a thresholding algorithm, utilising all channels of the AVHRR sensors, short range forecast data from numerical weather predictions (NWP) and auxiliary data (1km digital elevation and land use). The scheme makes use of off-line radiative transfer simulations of cloud free atmospheres to estimate the optimal thresholds valid for the given scene.

– **Cloud type:** The main objective is to distinguish between thin and opaque clouds, to provide a rough estimate of the cloud top height, and try to distinguish between water clouds and ice clouds. The algorithm also delineates stratiform and cumuliform clouds. Highest priority is given to reliable identification of the major cloud categories: low, medium, high and semi-transparent cirrus. The Cloud Type algorithm takes the Cloud Mask output as input and utilises the same input as described for the Cloud Mask algorithm. The algorithm distinguishes different cloud types using thresholds defined by off-line radiative transfer calculations and a database of interactively collected training targets. Figure 1 shows an example of the PPS cloud type products of one MetOp-A overpass mapped to the CM-SAF Inner Arctic region. The algorithm also distincts between water and ice clouds which is used as the basis for CM-SAF's cloud phase product.

– **Cloud top:** The algorithm takes the Cloud Type as input and utilises the 11 and 12 micrometer channels of the AVHRR sensor as well as NWP short range forecast data and the same auxiliary data as for the Cloud Mask. Radiative transfer calculations and NWP short range forecast output (vertical temperature and humidity profiles) are used to compensate for the atmospheric attenuation above the opaque clouds and for the semi-transparency correction. The cloud top product is provided in three alternative versions: Cloud top temperature (CTT) [K], cloud top height (CTH) [m] relative to the topography and cloud top pressure (CTP) [hPa].

2.4 Surface radiation components and cloud physical parameters

Additonal products are derived for the Baseline region: These are components of the surface radiation budget and cloud physical parameters (cloud optical thickness and cloud liquid water path). Retrieval of these parameters is based on the same algorithms as used in the previous operational environment (Schulz et al., 2009), but are now also applied in a swath-based mode and additionally utilize data from MetOp-A. These products are not produced for the Arctic, except for surface albedo.

The retrieval of cloud physical properties is based on the principle that the reflectance of clouds at a non-absorbing wavelength in the visible region is strongly related to the optical thickness and has very little dependence on particle size, whereas the reflectance of clouds at an absorbing wavelength in the near-infrared region is primarily related to particle size (see Roebeling et al. (2006) for details).

2.5 Operational implementation of PPS

CM-SAF utilizes the NWC-SAF Polar Platform System Software (PPS) as described above on a day-to-day basis to process all AVHRR data that is available for the product region via the EARS (NOAA-17 and NOAA-18) and the EUMETCast (MetOP-A) data dissemination systems.

The processing is done on full pixel resolution and all parameters are retrieved for each pixel. These instantaneous intermediate results are the basis for the daily and monthly means of CM-SAF, which are calculated as described in the following section.

2.6 Product averaging

The final products are provided in equal area projections at a spatial resolution of 15 km×15 km for both product regions: A sinusoidal projection is used for the Baseline region and a Lambert azimuthal equal-area projection is used for the Inner Arctic.

Calculation of these averaged fields is based on the following steps:

– Each individual pixel of the "instantaneous" product is first remapped from the original satellite view to a grid in the selected projection at high spatial resolution of 1 km^2. With an AVHRR-resolution of approximately 1.1 km at nadir, this results in an almost completely filled destination grid close to the nadir line. Due to the coarser resolution of the sensor at the swath edges, the density of remapped pixel is coarser in these regions and not all pixels get a value in this step.

– A nearest neighbour search is used to fill the remaining empty pixels inside the swath.

– These remapped "instantaneous" data are then averaged to the final product area by averaging squares of 15×15 pixels (resulting in a spatial resolution of (15 km)^2). In the same step all available instantaneous values for that day are averaged to the daily mean. The method for this averaging is product-dependent (see below). For non-continuous data as, e.g. cloud types, this step also includes a reclassification to aggregated categories.

– Averaging of monthly products is based on the daily values in order to guarantee an equal weighting of each day.

The product-dependent averaging for the daily means is done as follows:

– **Fractional cloud cover (CFC) [%]:** The input to the averaging routine is the cloud mask as generated by PPS. Pixels identified as either "cloud filled" or "cloud contaminated" are considered when the fractional cloud cover is calculated as the percentage of cloudy pixels (with full weight on both categories). Figure 2 shows an example of the CFC product.

– **Cloud type (CTY) [%]:** PPS detects 19 cloud types (including four categories of cloud-free pixels). These are aggregated to five categories according to the list as shown in Table 1. The final product contains the fraction of each category in a region of 15×15 km^2 relative to all cloudy pixels in the square. See Fig. 3 for an example.

– The **Cloud top product** gives three representations of the cloud top: height, pressure and temperature (CTH/CTP/CTT) [m/hPa/K]: Cloud-top temperature

Table 1. Cloud types categories as used by NWC-SAF and aggregation to CM-SAF cloud type product.

NWC-SAF cloud type category (i.e. CM-SAF intermediate product)	CM-SAF cloud type category (i.e. daily and monthy means)	Colour legend for Fig. 1
cloud free land	cloud free	green
cloud free sea	cloud free	black
land contaminated by snow	cloud free	light pink
sea contaminated by snow/ice	cloud free	pink
very low stratiform clouds (incl. fog)	low clouds	red
very low cumuliform clouds	low clouds	dark orange
low stratiform clouds	low clouds	orange
low cumuliform clouds	low clouds	light orange
medium level stratiform clouds	middle level clouds	yellow
medium level cumuliform clouds	middle level clouds	light yellow
high stratiform clouds	high opaque	dark beige
high cumuliform clouds	high opaque	light beige
very high stratiform clouds	high opaque	grey
very high cumuliform clouds	high opaque	white
high semi-transparent very thin cirrus	high semitransparent	dark blue
high semi-transparent thin cirrus	high semitransparent	blue
high semi-transparent thick cirrus	high semitransparent	light blue
high semi-transparent cirrus above low or medium level clouds	high semitransparent	light green
fractional clouds	fractional clouds	purple

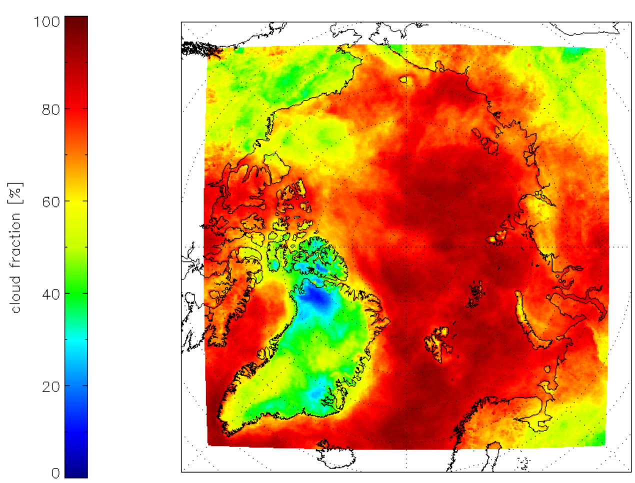

Figure 2. Monthly mean cloud fraction in the Inner Arctic [%] for August 2007.

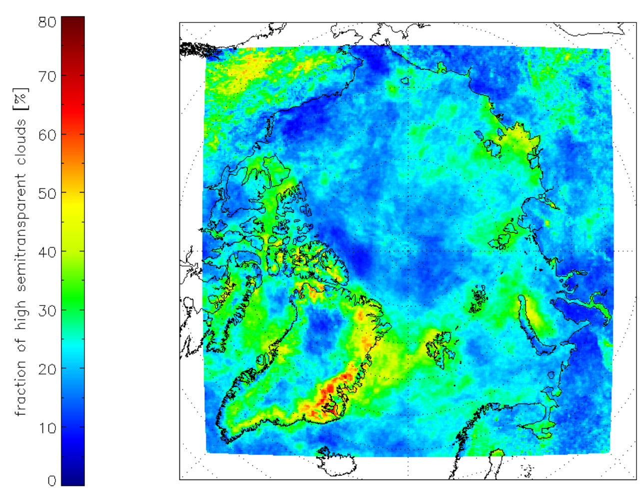

Figure 3. Monthly mean fraction [%] of high semitransparent clouds in the Inner Arctic in August 2007 as an example for one category in the CM-SAF cloud type product.

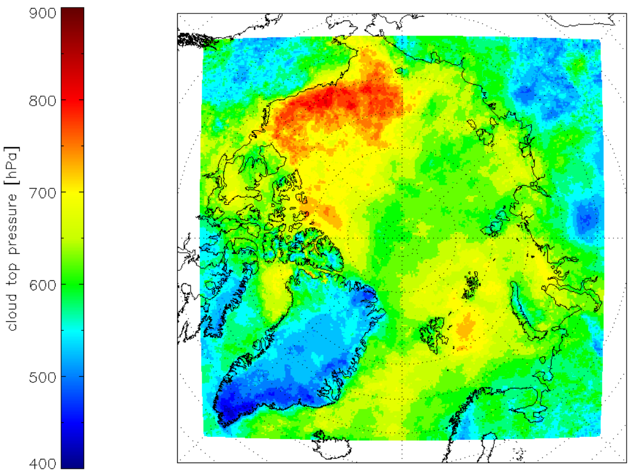

Figure 4. Monthly mean cloud top pressure [hPa] for August 2007.

and height are averaged linearly while cloud-top pressure is averaged logarithmically. The logarithmic averaging is motivated by the desire to keep consistency between the three different cloud top products. For example, linearly averaged geometrical cloud top height in meters does not correspond to the same geometrical height as the corresponding linearly averaged cloud top pressure. Since pressure decreases exponentially as a function of the geometrical height, logarithmic averaging will reduce these differences. Averages are calculated using only pixels classified as cloudy. Figure 4 shows an example of the CTP product.

– **Cloud phase (CPH) [%]:** For each of the three classes (water/ice/mixed phase) the relative fraction of pixels within that class in each square of 15×15 km^2 is calculated. The fraction refers to cloudy pixels only, i.e. all three classes sum up to 100%.

– **Cloud optical thickness (COT) [–]:** The Cloud Optical Thickness product is defined as the vertically integrated optical thickness. The final daily average product is calculated by logarithmic averaging of the original algorithm output in one kilometer resolution over 15×15 km^2 sub-areas. Pixels where the retrieval failed for any reason are excluded from averaging. Due to the logarithmic averaging only cloudy pixels are considered.

  The COT product requires availability of data from the visible channel and can therefore only be retrieved during daylight. In addition, the product cannot be produced for NOAA-18 measurements, as channel 3a is discontinued on this satellite. The averaged product is therefore based on measurements of NOAA-17 and MetOp-A under daylight conditions.

– **Cloud liquid water path (CWP) [kg/m^2]:** The CWP is calculated as a function of the Cloud Optical Thickness and the estimated droplet effective radius. Consequently, for the same reasons as described for COT, the CWP product is only produced for measurements of NOAA-17 and MetOp-A under daylight conditions.

  Two versions of the mean are included into the product: One is calculated based on all available pixels and therefore represents the daily mean liquid water path. However, for some studies it is of interest to have a CWP product, that is consistent to the COT product. As COT is calculated for cloudy pixels only, a consistent CWP is calculated containing the average liquid water path of clouds only.

2.7 Monthly means

The monthly averages are calculated as average values of these daily values. They are not calculated as average of the instantaneous data in order to avoid giving different weights to days with different availability of satellite overpasses. Monthly means of CTP and COT are calculated logarithmically, all other cloud products are averaged linearly.

2.8 Satellite-specific averages

Averages for the Baseline area and the Inner Arctic are based on all utilized polar-orbiting satellites (NOAA-17, NOAA-18 and MetOp-A). For the Arctic an additional average is provided based on MetOp-A measurements only. Due to the different ways of dissemination of the input data, the Arctic area is not fully covered in case of the NOAA-based products, but for MetOp-A. The average based on MetOp-A only has a comparable data density over the complete area. For some applications, e.g. validation of climate models, a product with such a better spatial homogeneity could be preferable.

3 Validation and monitoring of product quality

Continuous validation is performed on an annual basis in order to maintain high quality of the products. Annual validation reports are available at www.cmsaf.eu (e.g. CM-SAF, 2009a). They give comprehensive information on the accuracy of the operational monitoring products of CM-SAF. The majority of validation results is based on comparions with insitu observations from meteorological networks, e.g. synoptic station data or radiosonde data, as well as comparions to other satellite products, esp. the more sophisticated and spectrally superior MODIS instrument in case of cloud products.

Figure 5 shows an example from the validation for 2008. The example refers to the cloud coverage as it was produced by the previous version of the AVHRR processing environment that utilized locally received AVHRR data only. The

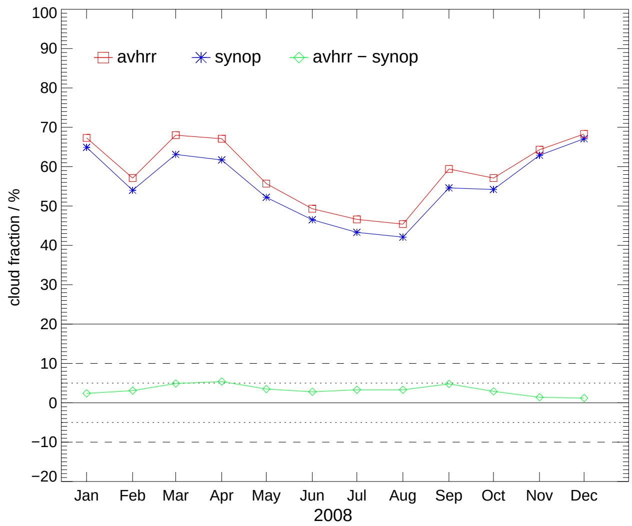

Figure 5. Annual cycle of cloud fraction in 2008. Values are averaged over all locations with synoptic observations within the central portion of the Baseline area that is covered by the locally received AVHRR data.

validation in this example is therefore limited to the central portion of the Baseline area. As the figure illustrates, there is generally good agreement and the product is within the required accuracy of 5%. The product is also in good agreement compared to MODIS-derived cloud fraction and the overall difference between both products is within 1% except for the winter months where CM-SAF cloud coverage is about 5% lower. The validation for 2008 also showed that the required accuracy is met for the cloud type, cloud phase and cloud top products. The cloud optical thickness and cloud liquid water paths products show an underestimation of around 30% with respect to MODIS. See CM-SAF (2009a) for details.

First comparisons have also been done for the new Arctic products. They have also shown that the monthly mean cloud cover products of polar summer 2007 are capable of reproducing similar results as those based on the MODIS instrument. Validation against ground-based measurements also shows that the Arctic CFC product is within the required accuracy. More details can be found in CM-SAF (2009b).

4 Product availability, data formats and processing tools

CM-SAF products can be ordered free-of-charge at www.cmsaf.eu. AVHRR-based cloud products have been generated by CM-SAF for the Baseline Area since 1 January 2004, but were generated with a different processing environment and based on different input data until 31 December 2008.

CM-SAF's climate monitoring products are provided as HDF5 (Hierarchical Data Format, release 5). Reasons for selecting HDF5 were its high compression efficiency and the features to include several data models and self-describing datasets. Many users are interested to receive the data in different formats or projections. CM-SAF has therefore supported the integration of its data formats into the "climate data operators". The "climate data operators" (CDO) are a collection of command line operators that were originally developed for processing and analysis of data produced by a variety of climate and numerical weather prediction models (e.g. for file operations, simple statistics, arithmetics, interpolation or the calculation of climate indices). Supported file formats are NetCDF, GRIB and several binary formats. Besides the pure conversion of CM-SAF HDF5-files to other formats, the package also offers opportunities for interpolation to other grid types, selection of regions, etc. The package was developed at the Max-Planck-Institute for Meteorology (Hamburg, www.mpimet.mpg.de/cdo) and is a widely-used tool within the climate modelling community.

5 Conclusions

CM-SAF provides AVHRR-based climate monitoring products for several cloud parameters. The product suite has been extended to the Inner Arctic.

One potential application of these datasets is the monitoring of processes that could be responsible for changes in the Arctic sea ice. Kay et al. (2008) discussed whether the low cloud amounts in summer 2007 could be a contributing factor to the unprecedented rapid melting of sea ice during the polar summer of 2007. The new CM-SAF products for the Arctic offer additional opportunities for such analyses and continuous monitoring of such processes.

Another application is the validation of regional climate simulations. Satellite-derived datasets have the strong advantage of consistent measurements and processing methodologies across regions.

CM-SAF currently prepares the reprocessing of historic AVHRR data from 1982 until present.

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