EUMETSAT Satellite Application Facility on Climate Monitoring

Algorithm Theoretical Basis Document

ICDR AVHRR, based on CLARA-A2 methods

Surface Radiation

Surface Incoming Shortwave Radiation **CM-6210**

Reference Number:	SAF/CM/DWD/ICDR/CLARA/RAD/ATBD
Issue/Revision Index:	2.1
Date:	01.02.2021

Document Signature Table

	Name	Function	Signature	Date
Author	Jörg Trentmann	CM SAF scientists		13.11.2020 29.01.2021
Editor	Rainer Hollmann	Science Coordinator		20.11.2020 01.02.2021
Approval	CM SAF Steering Group			
Release	Rainer Hollmann	Project Manager		

Distribution List

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Document Change Record

Issue/ Revision	Date	DCN No.	Changed Pages/Paragraphs
2.0	16/11/2020	SAF/CM/DWD/ICDR/CLARA/RAD/ ATBD	First Version
2.1	01/02/2021	SAF/CM/DWD/ICDR/CLARA/RAD/ ATBD	Update implanting the Review comments and RIDs. Layout revision and barrier free conversion

Applicable documents

Reference	Title	Code
AD 1	CM SAF Product Requirement Document	SAF/CM/DWD/PRD/3.7

Reference documents

Reference	Title	Code
RD 1	Product User Manual, CLARA-A2.1, Surface Radiation Products	SAF/CM/DWD/PUM/GAC/RAD /2.3
RD 2	Algorithm Theoretical Baseline Document, CLARA-A2.1, Surface Radiation Products	SAF/CM/DWD/ATBD/GAC/RA D/2.5
RD 3	Algorithm Theoretical Basis Document ICDR AVHRR – based on CLARA-A2 methods, Cloud Fraction	SAF/CM/SMHI/ICDR/CLARA/C LD/ATBD_CMA/2.0

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The EUMETSAT SAF on Climate Monitoring

In 2000 the EUMETSAT Member States 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". Already in 1999, recognizing the importance of climate monitoring with satellites, 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), the Meteorological Service of the United Kingdom (UK MetOffice), and the Centre National de la Recherché Scientifique (CNRS). 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 Thematic Climate Data Records (TCDRs) for 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 records 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, i.e. FCDRs and TCDRs, but also with data records produced close to real time that can be used to prepare monthly/annual updates of the state of the climate, i.e. Interim Climate Data Records (ICDRs). 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 within research programmes such as WCRP. 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.

1 Introduction

This CM SAF Algorithm Theoretical Basis Document (ATBD) provides information on the processing algorithm implemented for the retrieval of the surface solar radiation from the AVHRR Global Area Coverage (GAC) data as part of the ICDR Global AVHRR, based on CLARA-A2 methods.

More information on the basic accuracy requirements are defined in the product requirements document [AD 1]. The ICDR AVHRR surface radiation data set contains only one parameter:

Surface Incoming Shortwave Radiation [CM-6210].

Please note that the corresponding CM SAF climate data record, i.e., CLARA-A2.1, does contain two additional surface radiation parameters, namely the surface downwelling radiation (SDL) and the surface upwelling longwave radiation (SOL). These two parameters are not part of the CLARA-A2 ICDR, which is documented here, because of limited user requests as well as their strong dependence on data from auxiliary sources, namely atmospheric reanalysis.

2 Retrieval Algorithms of the ICDR AVHRR Surface Radiation Product

In the following the retrieval algorithm used to generate the surface solar radiation product in the CM SAF ICDR AVHRR data set will be described.

2.1 Shortwave Surface Radiation

The retrieval algorithm of the surface shortwave radiation (i.e., the surface radiation in the wavelength region between 200 nm and 4000 nm) used for the near-realtime processing of the AVHRR GAC data is based on the algorithm used for the generation of the CLARA-A2.1 climate data record [RD 1,RD 2].

The underlying fundamental assumption of retrieving the surface solar irradiance from satellite observations is that the reflected radiance, as measured by the satellite instrument, is related to the broadband atmospheric transmission, T. From the atmospheric transmission the surface incoming solar radiation, SIS, can be derived:

$$SIS = E_0 \cos(\Theta_0)\ T \qquad (1)$$

where E_0 is the incoming solar flux at the top-of-the-atmosphere (E_0 = 1361 W/m^2) and Θ_0 the solar zenith angle. The solar flux is assumed to vary only with the Earth distance from the sun; changes in the solar flux due to the solar activity are considered to be very minor for the satellite-based estimation of the surface irradiance and are neglected here.

2.1.1 SIS Algorithm

The algorithm used here to derive SIS from the AVHRR GAC data set is based on the application of a look-up-table to derive the atmospheric transmission and the surface incoming solar radiation *Pinker and Laszlo, 1992*. The details of the algorithm are given in *Mueller et al.*, 2009]. Here, the basic layout and the fundamental assumptions of the algorithm are presented.

The solar surface irradiance is mainly determined by the solar zenith angle, the cloud coverage, the vertically-integrated water vapour and the aerosol optical depth.

The solar zenith angle (SZA) is determined by the rotation of the Earth, the tilting of the Earth axis and their movement around the sun; the SZA can be accurately calculated. While satellite-based information on the integrated water vapour is available from microwave instruments (e.g., the ATOVS package), these instruments / satellite channels are not available from the AVHRR GAC data set. Also no suitable data set of the aerosol optical depth is available from the AVHRR GAC data. For these two parameters, external data sources have to be consulted to calculate the transmissivity and the surface solar incoming radiation. The main information that is used from the AVHRR GAC satellite data is the information on cloud coverage.

The retrieval algorithm used to derive the surface incoming solar radiation consists of two steps. First, the full spectral information of the satellite instrument is used to derive information on cloud coverage for each pixel using the Nowcasting SAF (SAFNWC) software [RD 3]. In case, no cloud is detected (i.e., the satellite pixel is considered '*cloud-free*'), the surface solar irradiance is calculated by radiative transfer modelling using information on the integrated water vapour and the aerosol optical depth from auxiliary sources without the use of additional satellite observations. In the case the cloud retrieval algorithm detects the presence of a cloud (i.e., the pixel is classified by the SAF NWC software either as 'cloud-contaminated' or as 'fully cloudy'), the pixel is considered '*cloudy*' and the atmospheric transmissivity and subsequently the surface solar irradiance is derived using the method described in Section 2.1.1.2.

2.1.1.1 Cloud-free conditions

The calculation of the surface solar irradiance under cloud-free conditions does not require any additional information from satellite, but is performed using the clear-sky Mesoscale Atmospheric Global Irradiance Code (MAGIC, https://gnu-magic.sourceforge.net/), which is described in more detail in *Mueller et al* [2009].

2.1.1.1.1 The MAGIC clear sky model

Figure 2-1 presents the flow-chart of the calculation of the surface incoming solar radiation under clear-sky conditions using MAGIC. Look-up tables (LUTs) form the core of the MAGIC clear-sky model. They have been pre-calculated for several aerosol optical depths (10 values) and aerosol types (3 values for the single scattering albedo, 2 values for asymetry parameter), 2 sun zenith angles (0 and 60 degree) with fixed values of surface albedo (0.2), integrated water vapour column (15 mm) and ozone (345 DU) using the RTM model libRadtran [*Mayer and Kylling*, 2005].

In a first step the pre-calculated clear sky fluxes from the LUTs are interpolated towards the actual optical aerosol information derived for the location and the time under investigation. Subsequently, correction formulas are applied that consider the difference between the reference values (i.e., the values used to derive the look-up-table) of the other atmospheric parameters (i.e, SZA, water vapour, ozone, albedo) and the current values of the parameter. The sensitivity of the clear-sky surface irradiance to the surface albedo is small, i.e., a change of the surface albedo by a factor of 2 (e.g., from 0.2 to 0.4) induces only a 2% change on the surface downwelling clear-sky irradiance [*Mueller et al.*, 2009, Figure 2-4]. The Modified Lambert-Beer (MLB) function is used to derive the dependency of the surface solar radiation from the solar zenith angle based on only 2 pre-calculated solar-zenith angles [*R W Mueller et al.*, 2004]. These optimisations reduce the number of required radiation transfer calculations substantially by a factor of 10.000 compared to 'traditional' look-up table approaches without any loss in the accuracy. The computational efficiency of the algorithm makes it perfectly suited for the satellite retrieval of the surface solar radiation under clear-sky conditions. No additional information (e.g., the top-of-the-atmosphere reflectance) is used from the satellite measurement.

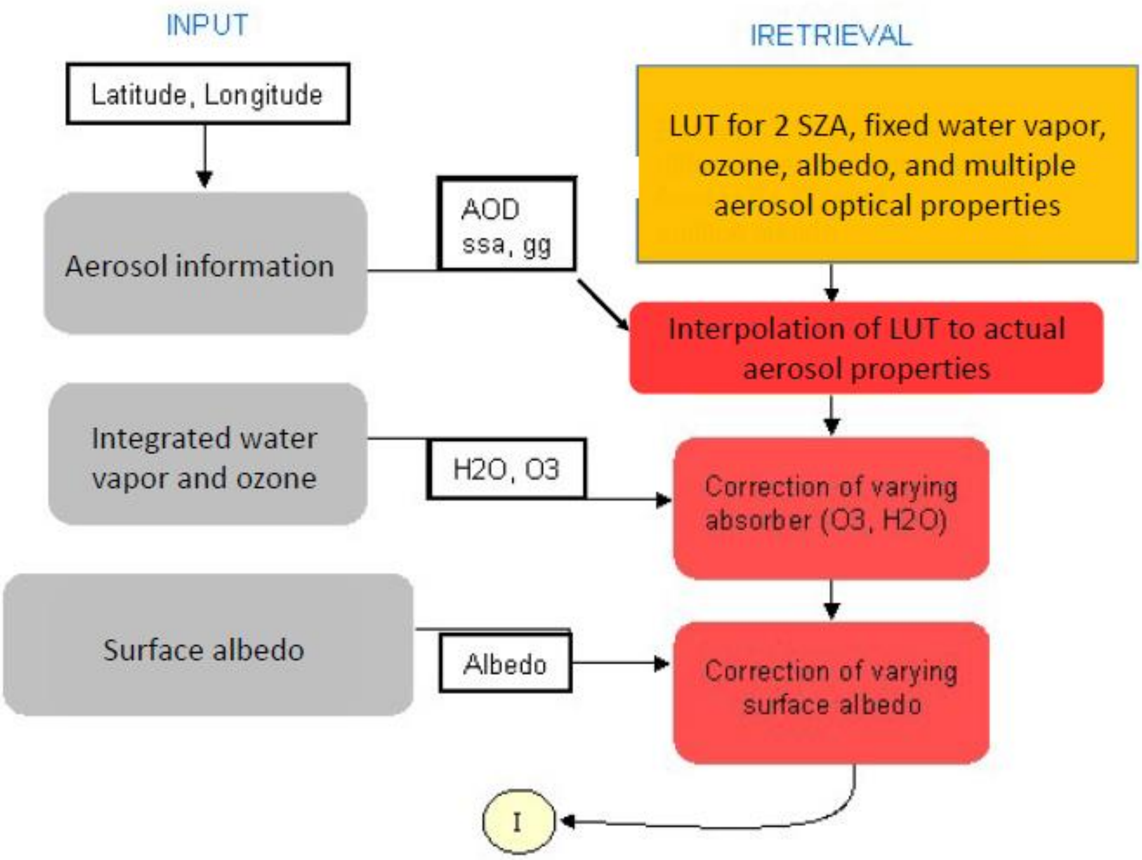

Figure 2-1: Flow-chart of the calculation of the surface incoming solar radiation under clear-sky conditions. The required input data is shown on the left side of the diagram, the right part represents the calculation of the surface solar irradiance using the MAGIC clear-sky model. The figure is adopted from RW Mueller et al. [2009].

2.1.1.1.2 Auxiliary data

As input parameters, aerosol information (i.e., aerosol optical depth, single scattering albedo, backscattering coefficient), vertically-integrated water vapour and ozone, as well as the surface albedo are required.

2.1.1.1.2.1 Aerosol

For the aerosol information, a modified version of the monthly mean aerosol fields from the GADS/OPAC climatology [*Hess et al.*, 1998] has been used. Based on the study of *Mueller et al.* [2015] we reduced the maximum AOD values of the original GADS/OPAC climatology to account for the detection of thick aerosol clouds by the cloud retrieval algorithm.

2.1.1.1.2.2 Water vapour and ozone

The integrated water vapour is taken from the operational analysis provided by the ECMWF (https://confluence.ecmwf.int/display/FUG/2+The+ECMWF+Integrated+Forecasting+System+-+IFS; accessed 29.01.2021); the vertical ozone column, which has a negligible impact on the calculated global radiation, has been set constant to 335 DU. Note that the value for the total ozone column used in the retrieval differs from the value used for the generation of the look-up-table (Section 2.1.1.1).

2.1.1.1.2.3 Surface albedo

The surface albedo information is calculated based on the spatial distribution of 20 surface types. The Surface and Atmospheric Radiation Budget (SARB) working group, part of the Clouds and the Earth's Radiant Energy System (CERES) mission, provides global digital information on land cover based on scene types from the International Geosphere/Biosphere Programme (IGBP) on a 1/6 deg grid (https://ceres.larc.nasa.gov/data/general-product-info/). Using the broadband albedo for each surface type, a constant global surface albedo map is generated (see Figure 2-2). The use of the temporally constant surface albedo map implies that changes in the surface albedo due to snow and sea ice coverage are not considered in the calculation of the clear sky surface radiation. However, since the impact of the surface albedo on the incoming solar radiation is only moderate, no substantial degradation of the accuracy are expected under clear sky conditions.

This auxiliary information is used in the MAGIC clear-sky solar radiation transfer code to derive the surface solar irradiance when clouds are absent.

It is worth noting at this stage that all data pixels where the monthly climatological surface albedo derived from the CLARA-A2.1 SAL data set differs by more than 35 % from the surface albedo used in the retrieval and described here are set to missing values in the final product to avoid unrealistic irradiance values oin the final product; see also Section 2.1.1.3.

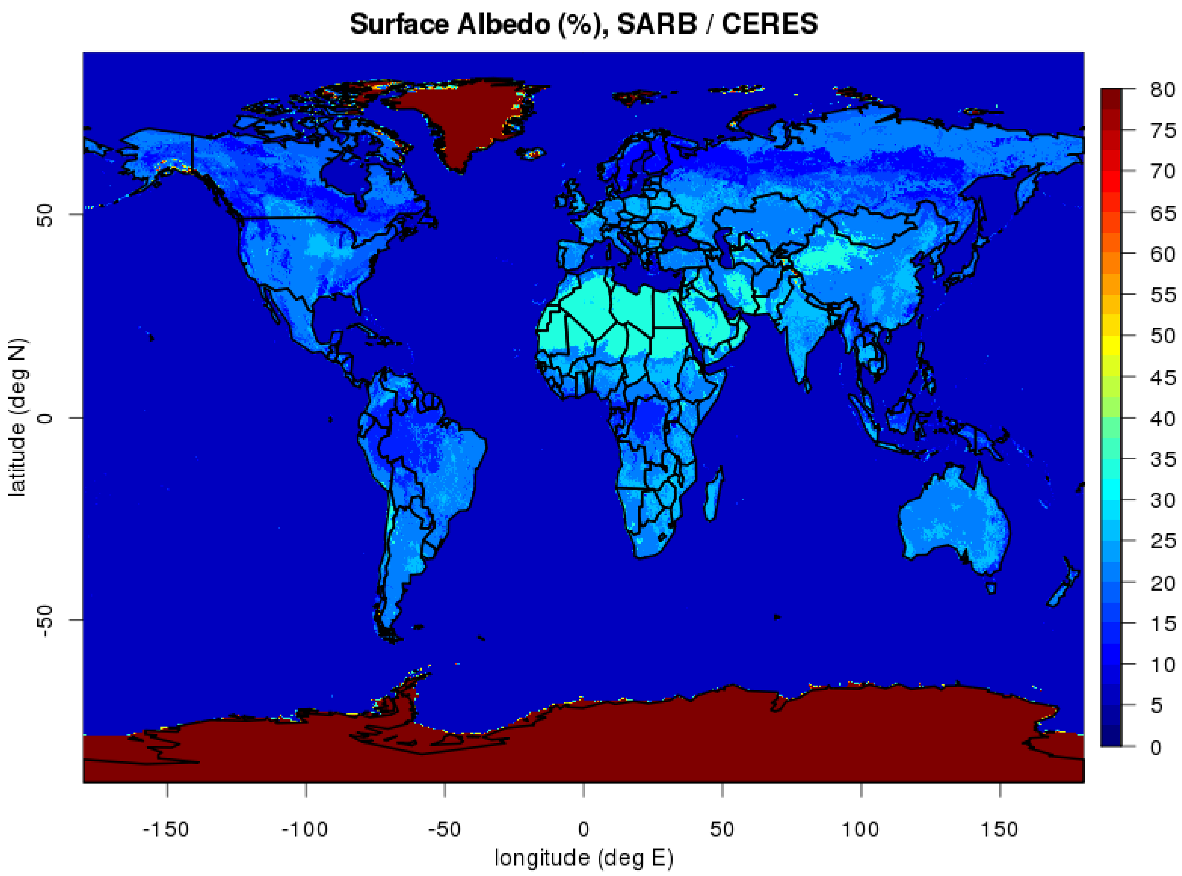

Figure 2-2: Spatial distribution of the surface albedo used in the calculation of the clear-sky surface radiation.

2.1.1.2 Cloudy Condition

Under cloudy conditions (i.e., the pixel is classified as 'cloud-contaminated' or 'fully clouded' by the Nowcasting SAF (SAFNWC) software) a different approach is taken to derive the surface solar radiation. Figure 2-2 presents the diagram of the retrieval of the surface solar incoming radiation under cloudy conditions, which follows the ideas of [*PINKER and LASZLO*, 1992]. The auxiliary input data is identical to the input data used to calculate the clear-sky surface radiation, i.e., surface albedo, vertically-integrated water vapour and ozone, and aerosol information. In addition to this auxiliary input data, also satellite data is used to derive the surface radiation under cloudy conditions.

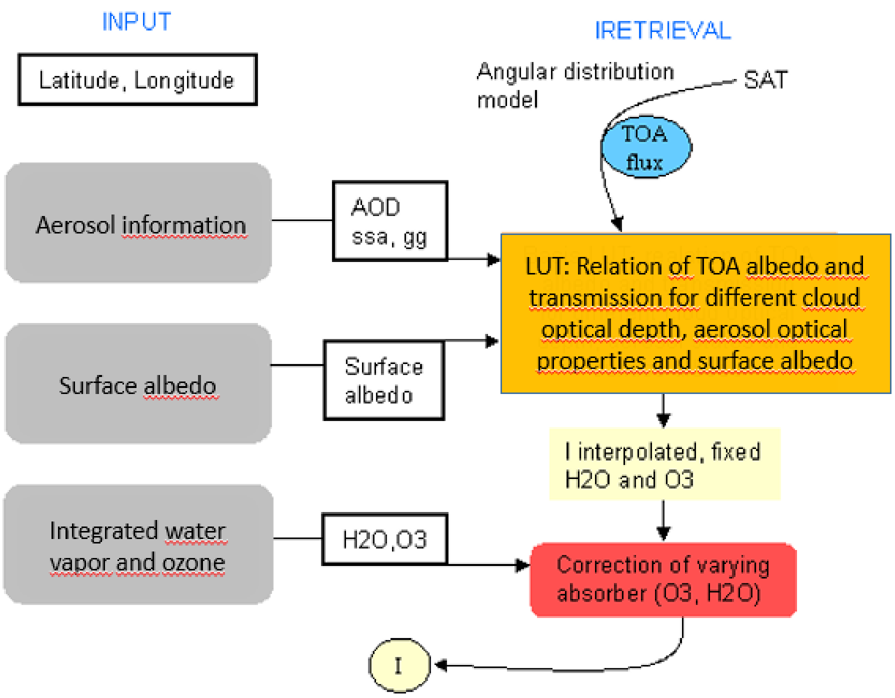

Figure 2-3: Diagram of the calculation of the surface solar incoming radiation under cloudy conditions. The required input data is shown on the left side of the diagram, the right part represents the calculation of the surface solar irradiance using the look-up tables for the TOA albedo. The figure is adopted from [RW Mueller et al., 2009]

2.1.1.2.1 Broad-band ToA albedo

The algorithm requires the satellite-derived top-of-the-atmosphere broadband albedo in the shortwave spectral region as input parameter (see Figure 2-4). However, this quantity is not measured directly by the AVHRR instrument, but has to be inferred from measurements in the two visible channels. As a first step, the calculation of the broadband reflectance is conducted based on the measurements of the reflectance in the two visible channels of the AVHRR instruments (see Figure 2-4) following [*Hucek and Jacobowitz*, 1995]. The derived broadband reflectance for each pixel is then transferred to broadband fluxes using the bidirectional reflectance distribution function (BRDF, also termed Angular Dependence Model (ADM)) derived for ERBE [*Suttles et al.*, 1986].

2.1.1.2.2 Look-up tables

The broadband top-of-the-atmosphere albedo is used in a look-up-table approach to derive the atmospheric transmissivity and, subsequently, the surface solar radiation. In addition to the clear-sky approach, under cloudy conditions, also cloud information (in this case the cloud optical depth) has to be taken into account when generating the look-up-tables. To retrieve the relationship between the atmospheric transmissivity and the top-of-the-atmosphere albedo from the look-up-tables, the information on the aerosol optical properties and the surface albedo is taken from the auxiliary data. Based on the measured top-of-the-atmosphere albedo, the corresponding atmospheric transmissivity is extracted from the look-up-tables. As for the clear-sky case, the look-up tables for the cloudy case have been generated for fixed values of vertically-integrated water vapour and ozone. The required correction of the atmospheric transmissivity due to the contribution of these two atmospheric absorbers are applied subsequently (see *Mueller et al.* [2009]).

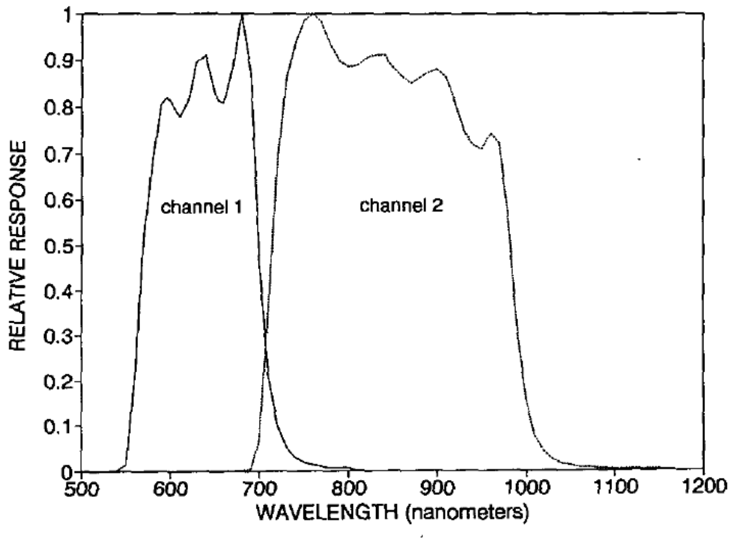

Figure 2-4: NOAA 9 AVHRR spectral response functions for the visible (channel 1) and the near-infrared (channel 2) detectors. Figure taken from [Hucek and Jacobowitz, 1995]

In the case of thin clouds over snow-covered surfaces, the use of the constant surface albedo information can lead to an underestimation of the atmospheric transmissivity and subsequently an underestimation of the surface solar radiation. The underestimation of surface solar radiation is correlated to the difference between the actual surface albedo and the assumed climatological value. These differences are expected to be largest under conditions with snow-covered surfaces and, in particular, in the presence of sea ice. It is likely that the accuracy of the CLARA SIS data set will not meet the target accuracy under these conditions.

Based on the retrieved atmospheric transmissivity, the surface solar irradiance is calculated using Equation 1 for each satellite pixel.

2.1.1.3 Calculation of gridded averages

The CM SAF ICDR AVHRR SIS data set based on AVHRR satellite measurements is generated and provided on a regular lon-lat grid with a grid point spacing of 0.25° as daily and monthly averages. To generate this data from the satellite observations, the information from the satellite retrieval (clear-sky and cloudy-sky solar surface radiation) for each pixel is remapped to a regular lon-lat grid with a spatial resolution of 0.05° using the nearest-neighbour remapping. This resolution is comparable to the spatial resolution of the AVHRR instrument, so no spatial or temporal averaging is performed in this step.

In the next step, the daily mean is calculated following the method by [*MOSER and RASCHKE*, 1984]:

$$I_{dm} = I_{clr,dm} * \frac{\sum I_i}{\sum I_i^{clr}} \tag{2}$$

here I_{dm} is the daily mean of the surface solar irradiance, $I_{clr,dm}$ is the daily mean of the clear sky surface solar irradiance, I_i is the retrieved surface radiation from the satellite retrieval and I_i^{clr} is the clear-sky surface solar radiation that corresponds to I_i. I_i^{clr} is calculated for each satellite pixel during the processing of the satellite data using the MAGIC clear-sky radiation transfer model. The daily mean of the clear-sky surface solar irradiance, $I_{clr,dm}$, is calculated on the 0.05° grid using the MAGIC radiation transfer model. This method to calculate the daily means of the surface radiation substantially reduces the error introduced due to the limited number of observations per pixel per day [*MOSER and RASCHKE*, 1984].

The daily mean surface radiation on the 0.25°-grid is obtained by averaging the corresponding 25 high-resolution grid boxes. To limit the uncertainty of the calculation of the daily averages due to limited number of observations, all daily mean values of the surface solar irradiance that are based on less than 20 observations on the 0.25°-grid are set to missing value.

The monthly mean data of the surface solar irradiance are calculated as averages from the daily mean values. Only those grid boxes are considered that have more than 20 valid daily means of the surface solar radiation. The remaining grid boxes are considered missing data.

To account for the known inaccuracy of the surface solar irradiance data record under conditions of snow-covered surface, the corresponding grid points have been set to missing data on the daily and the monthly mean data files. To identify these grid points the monthly climatology of the difference between the CLARA-A2 SAL data record and the surface albedo used in the processing of the SIS data record has been calculated for the full CLARA-A2 time series, i.e,, from 1982 to 2015. All data points in the ICDR AVHRR SIS data record with a climatological difference exceeding 35 % have been set to missing data. The same holds for all polar pixels.

2.1.1.4 Known Limitations and their Implications

Known limitations and shortcomings of this algorithm to derive the surface solar irradiance:

- The application of the temporally-constant SARB/CERES surface albedo map limits the quality of the data set in regions with varying surface albedo, i.e., in Canada, Alaska, Russia, Scandinavia, and regions with sea ice, during the times when the surface albedo is greatly different from the value assumed in the SARB/CERES albedo map. Even though the impact of this effect has been reduced by masking out the corresponding grid points, however it cannot be completely excluded that the accuracy of the CM SAF ICDR AVHRR SIS data record in snow-covered areas is outside the target accuracy.

- The algorithm requires broadband solar fluxes at the top-of-the-atmosphere to retrieve the atmospheric transmissivity and subsequently the surface solar radiation. The conversion of the satellite-observed radiances at two wavelengths into broadband solar fluxes requires assumptions on the spectral responses of the satellite channels and the bidirectional reflectance distribution function (BRDF), which can introduce large uncertainty into the satellite retrieval under cloudy conditions.

- The algorithm depends on the ability of the cloud-detection software to detect clouds. Misclassification of pixels by the cloud-detection algorithm enhances the uncertainty of the retrieved surface solar radiation.

- The application of monthly climatological aerosol information limits the accuracy of the data set, especially in regions with high interannual and sub-monthly aerosol variability, e.g., desert regions. The same applies for the analysis of long-term changes and trends of surface irradiance, which are also not represented in the aerosol data set. It is, however, in general not recommended to use the CLARA-ICDR data record for any long-term studies (e.g., for trends) due to limited satellite data calibrations and other effects that degrade the temporal stability of this 'near-realtime' satellite data record.

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4 Glossary

ADM	Angular Dependency Model
AOD	Aerosol Optical Depth
ATBD	Algorithm Theoretical Baseline Document
ATOV	Advanced TIROS Operational Vertical Sounder
AVHRR	Advanced Very High Resolution Receiver
BRDF	Bidirectional Reflectance Distribution Function
CDR	Climate Data Record
CERES	Clouds and the Earth's Radiant Energy System
CLARA-A	CM SAF cloud, Albedo and Radiation products, AVHRR based
CM SAF	Satellite Application Facility on Climate Monitoring
CNRS	Centre National de la Recherché Scientifique
DWD	Deutscher Wetterdienst (German MetService)
ECMWF	European Centre for Medium Range Forecast
ECV	Essential Climate Variable
ERA	ECMWF Re-analysis
ERA-Interim	Second ECMWF Re-Analysis dataset
ERBE	Earth Radiation Budget Experiment
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FCDR	Fundamental Climate Data Record
FMI	Finnish Meteorological Institute
GAC	Global Area Coverage (NOAA)
GADS	Global Aerosol Data Set
GCOS	Global Climate Observing System
GFCS	Global Framework for Climate Services WMO
ICDR	Interim Climate Data Record
IGBP	International Geosphere/Biosphere Programme

KNMI	Royal Netherlands Meteorological Institute
LipRadTran	Library for Radioactive Transfer
LUT	Look-up Tables
MAGIC	Mesoscale Atmospheric Global Irradiance Code
MeteoSwiss	National Weather Service of Switzerland
MLB	Modified Lambert-Beer function
NMHS	National Meteorological and Hydrological Service
NOAA	National Oceanic & Atmospheric Administration
NWCSAF	SAF in Support to Nowcasting and Very Short Range Forecasting
OPAC	Optical Properties of Aerosols and Clouds
PRD	Product Requirement Document
PUM	Product User Manual
RAD	Radiation
RMIB	Royal Meteorological Institute of Belgium
RTM	Radiative Transfer Model
SAF	Satellite Application Facility
SARB	Surface and Atmospheric Radiation Budget
SAL	Surface Albedo
SCOPE CM	Sustained Coordinated Processing of Environmental satellite data for Climate Monitoring
SIS	Surface Incoming Shortwave Radiation
SMHI	Swedish Meteorological and Hydrological Institute
SSA	Single Scattering Albedo
SSI	Surface Solar Irradiance
SZA	Solar Zenith Angle
SZW	Ministry of Social Affairs and Employment
TIROS	Television Infrared Observation Satellites
TOA	Top of the Atmosphere

UK MetOffice	United Kingdom Meteorological Office
WCRP	WMO World Climate Research Programme
WMO	World Meteorological Organisation