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Estimating surface solar irradiance from METEOSAT SEVIRI-derived cloud properties

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ABSTRACT

A satellite retrieval of surface solar irradiance based on METEOSAT SEVIRI-derived cloud properties is presented and validated for the Netherlands with one year of pyranometer measurements from 35 stations. The approach requires two independent steps: 1. Cloud properties are determined from narrow-band satellite radiances. 2. These cloud properties are used together with data on water vapor column and surface albedo to calculate the atmospheric flux transmittance. The retrieved irradiance is biased low by about 3–4 W/m^2 throughout the year, corresponding to an underestimate in atmospheric flux transmittance of about 0.015 in summer and 0.04 in winter. From a least-squares linear regression, residual standard deviations of 56 W/m^2 (0.072, 17.0%), 11 W/m^2 (0.052, 10.8%), and 4 W/m^2 (0.021, 4.2%) are found for hourly, daily and monthly mean irradiance (transmittance, relative error), respectively. These findings indicate that the accuracy of the retrieval is comparable to first-class pyranometers in the summer half year (5% of daily-mean values), but significantly lower in winter. Two aspects requiring further investigation have been identified: 1. For thin clouds, the atmospheric flux transmittance is strongly underestimated. 2. The retrieval accuracy is reduced for snow-covered surfaces.

1. Introduction

The sun is the primary source of energy for the earth's climate system and its five major components, the atmosphere, the biosphere, the cryosphere, the hydrosphere, and the land surface (IPCC, 2007). Hence, solar radiation is a key parameter for our understanding of the climate system, and the processes and interactions taking place within it.

A particularly important component of solar radiation is the surface solar irradiance (SSI), also commonly referred to as surface insolation, e.g. the amount of down-welling solar energy incident on a horizontal surface and integrated over the total solar spectrum. It governs the flux of solar energy at the interface between the atmosphere and the other components of the climate system, and thus determines the partitioning of solar energy between them.

The SSI is modulated by the atmospheric flux transmittance (AFT), which in turn depends on scattering and absorption by atmospheric gases, aerosols, and clouds. Clouds induce the largest changes, and have a high variability in space and time (Rossow & Lacis, 1990). Hence, accurate knowledge of cloud properties and cloud–radiation interactions are an important prerequisite for accurate estimates of the SSI.

Besides our scientific interest in the climate system, there is also a strong socioeconomic interest in spatially and temporally resolved information on SSI. To assess the potential of solar power plants, climatological information on SSI is essential (Robles Gil, 2007). For crop yield prediction and water resource management, the SSI allows to quantify evapotranspiration, plant growth, and soil moisture (Roebeling et al., 2004). Also, the forecasts of numerical weather prediction models can be improved by use of accurate fields of surface fluxes and soil moisture (van den Hurk et al., 1997).

To complement the sparse network of surface measurements, numerous algorithms have been developed to estimate the SSI from satellite radiances (see e.g. reviews by Pinker et al., 1995; Schmetz, 1989). However, the experimental nature of many algorithms in the fairly young field of satellite meteorology, the small number of overpasses of polar orbiting satellite systems, and the coarse spatial and spectral resolution of previous geostationary satellites has limited the adoption of satellite data in applications so far. The launch of the European METEOSAT-8 has changed this situation: satellite images of Europe and Africa are available at high spatial, spectral, and temporal resolution to continuously monitor the physical properties of clouds, and to quantify their influence on solar radiation.

The goal of the Surface Insolation in Cloudy Conditions from METEOSAT SEVIRI imagery (SICCS) project has been the extension and improvement of a retrieval previously developed at the Royal Netherlands Meteorological Institute (KNMI) for the estimation of the AFT and SSI from NOAA–AVHRR (Deneke et al., 2005), to be applicable to the METEOSAT Second Generation Spinning Enhanced Visible and Infrared Imager (MSG SEVIRI) instrument. The SICCS

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retrieval – the SSI retrieval developed during the project – does not directly use radiances as input. Instead, cloud properties from the cloud physical properties scheme (CPP, Roebeling et al., 2006), are used, which is being developed within EUMETSAT's Satellite Application Facility on Climate Monitoring (CM-SAF, see http://www.cmsaf.eu/). Both retrievals are based on lookup tables of detailed 1D radiative transfer calculations. Together, both algorithms provide a set of cloud properties and radiation components which are physically consistent within the framework of 1D radiative transfer theory. This model-based approach allows an easy extension of the algorithm to specific spectral regions (UV, photosynthetically active radiation) or to actinic fluxes.

However, there is also a drawback of this approach versus the more common choice of using empirical narrow-to-broadband conversion and angular distribution models for inferring the SSI. In particular, satellite-retrieved cloud properties are known to contain biases due to 3D radiative effects, which depend on the variability of clouds, and the sun and satellite geometries (Kato et al., 2006). Such effects are implicitly accounted for in empirical relations.

Thus, this study also contributes to the validation of the CPP retrieval, and enables the identification of cases when the model assumptions underlying the retrieval are not met. Ultimately, a reconciliation of both approaches seems desirable, by incorporating 3D radiative effects in both the inversion step of estimating cloud properties, and the forward model for predicting the SSI.

A necessary condition towards this goal is agreement between modeled and empirically determined behavior. As the principle provider of meteorological and climatological data for the Netherlands, KNMI's atmospheric research division has initiated the SICCS project to evaluate the benefits and drawbacks of satellite imager data in general, and the METEOSAT SEVIRI instrument in particular, for current applications relying on ground-based SSI measurements. To enable an objective evaluation, the retrieval accuracy is quantified for the Netherlands by comparison to a one year dataset of ground-based pyranometer measurements of global radiation from 35 meteorological stations.

A summary of required input data is given in Section 2, including the dataset used for validation. The retrieval algorithm is presented in Section 3. Section 4 presents the evaluation and some results of SICCS retrieval. A discussion is given in Section 5, followed by our conclusions and a brief outlook in Section 6.

2. Data

The SICCS retrieval relies on radiance data from the SEVIRI instrument as input. In addition, ancillary information on narrow-band surface albedo are required for the estimation of the cloud properties, on broadband surface albedo, and on the amount of precipitable water for the estimation of the SSI. The MOD43C2 surface albedo product based on the MODIS instrument, and the total precipitable water product generated by the CM-SAF are used for this purpose here. However, both products can easily be replaced by other datasets. An overview of SEVIRI is given first, followed by a description of the ancillary datasets. Finally, a summary of KNMI's pyranometer measurements is given, which are used for the evaluation of the SICCS retrieval.

2.1. METEOSAT-8 SEVIRI

METEOSAT Second Generation is a new series of European geostationary satellites operated by EUMETSAT. METEOSAT-8 is the first MSG satellite and has been launched in August 2002. It carries the SEVIRI and GERB instruments, and provides operational data since January 2004. It is positioned at 3.4°W over the equator. SEVIRI scans the complete disk of the earth 4 times per hour, and provides 12 spectral channels. These are 3 solar channels (0.6, 0.8 and 1.6 μm), 8 infrared channels (3.9, 6.2, 7.3, 8.7, 9.7, 10.8, 12.0 and 13.4 μm), and one high-resolution broadband visible channel (0.3–0.7 μm). The nadir spatial resolution of SEVIRI is 1×1 km^2 for the high-resolution channel, and 3×3 km^2 for all other channels.

2.2. Ancillary input data

The MOD43C surface albedo product is routinely derived from the MODIS instruments on NASA's Terra and Aqua satellites (Schaaf et al., 2002). All cloud-free observations during a 16-day period are aggregated on a 1×1 km^2 resolution sinusoidal equal area grid. If a sufficient number of cloud-free observations are available, the bi-directional reflectance distribution function (BRDF) is estimated for each gridbox. The black-sky albedo, defined as the albedo for a directed beam of radiation at the sun's elevation at local solar noon, and the white-sky albedo, which is applicable for completely isotropic down-welling radiation, are calculated from the BRDF. For the SICCS and CPP retrievals, only the white-sky albedo product is used, because clouds at moderate optical thickness attenuate the direct beam. Thus, most of the energy reaching the ground in cloudy conditions is contained in the diffuse irradiance. However, applying the black-sky albedo for the direct beam reflection has been verified to cause only minor differences even for thin clouds. The estimates of the broad-band visible (0.2–0.7 μm) and near-infrared (0.7–4.0 μm) albedo (Liang, 2001) are used for the SICCS retrieval, while the matching narrow-band channels are used by the CPP retrieval. To limit the amount of data, the 0.05° resolution product is used, which corresponds to a gridsize similar in magnitude to SEVIRI's pixel size.

The total precipitable water (TPW) product generated by the CM-SAF from the Advanced Television and Infrared Observation Satellite Operational Vertical Sounder (ATOVS) is used to account for changes in water vapor absorption. ATOVS is flown on NOAA's polar orbiting satellites and is composed of the AMSU-A and AMSU-B microwave radiometers, and the HIRS/3 infrared radiometer. These data have a resolution of 150×150 km^2. The retrieval algorithm uses an optimum estimation procedure to estimate the atmospheric temperature and humidity profiles (Reale, 2003). The CM-SAF TPW product provides a daily average for all satellite overpasses, and is regridded to 45×45 km^2 resolution.

Gaps in both data products are filled by temporal interpolation, and the data are reprojected to SEVIRI's geostationary satellite view projection (Wolf & Just, 1999) prior to their use in the local processing environment.

2.3. Pyranometer data for validation

KNMI maintains an operational network of 35 meteorological stations which measure the SSI alongside other meteorological parameters. Pyranometers of type *CM11* built by *Kipp en Zonen* are used. Pyranometers are thermoelectric instruments, which measure the differential heating of a black absorbing disc versus the shaded body of the instrument, and translate the temperature difference to the amount of radiation incident on the detector. A glass dome shields the instrument from environmental influences, but also limits the spectral sensitivity to 0.3–2.8 μm. The *CM11* instruments fulfill the accuracy requirements of a secondary standard pyranometer defined in ISO (1990) and WMO (1996), which are specified to be 3%. However, recent investigations suggest that the underlying estimates are likely too optimistic (Bush et al., 2000; Philipona, 2002).

Data loggers record the mean, minimum, and maximum level of irradiance measured by the instruments during 10-min intervals. As the instruments are operated without ventilation and heating, and are checked at rather long maintenance intervals of up to a year, the accuracy of the measurements is somewhat degraded by the deposition of pollution on the instrument's glass domes. Overall, the total error is not expected to exceed 5% (Kuik, 1997).