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Retrieval of surface solar irradiance, based on satellite-derived cloud information, in Greece

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ABSTRACT

Cloud properties derived from the SEVIRI (Spinning Enhanced Visible and Infrared Imager) instrument, on board the MSG (Meteosat Second Generation) satellite, have been used to retrieve the surface global solar irradiance incident on a horizontal surface GHI (global horizontal irradiance) and the DNI (direct normal irradiance) with a temporal resolution of 15 min. The daily amount of solar energy as well as monthly and annual sums, are estimated. Based on a 6-year study period (2008–2013), a monthly climatology is derived. Results are compared with ground-based measurements in Greece. Comparison shows a general good agreement between satellite and ground data, with the highest differences occurring in cases of broken or very thick cloudiness. The highest collected monthly solar energy values are found during summer months, in Southern Peloponnese, Crete and Cyclades islands, and exceed 250 kWh m^{-2}. The annual average energy for GHI is 1400–1500 kWh m^{-2} in Northern Greece and up to 1900 kWh m^{-2} in Southern Peloponnese, Crete and the islands. For DNI, values increase to about 9% in Northern Greece and around 15% in Southern Greece.

1. Introduction

The received solar energy by the Earth–atmosphere system is the critical force responsible for all atmospheric processes and interactions. The knowledge of incident solar energy and Earth's energy budget is of vital importance for climate change studies but also solar energy applications. Many studies are focused on calculating the surface global horizontal irradiance (GHI), as well as the direct normal irradiance (DNI) received on a plane normal to the sun, as related by the equation: GHI = DHI + DNI*cosθ, where DHI is the diffuse horizontal irradiance and θ is the solar zenith angle. As a result, radiative transfer and decomposition models are employed [9,16,21,33]. The interannual variability observed in DNI is higher than GHI [20]; this parameter is more sensitive to aerosol uncertainties [10,12,24]. [35] used 5 different datasets to study DNI in Europe and concluded that, although the uncertainties between different datasets can reach up to 17%, the higher values are observed in Central – Southern Spain, Portugal, Provence (France), Sicily and Sardinia (Italy).

The first efforts to derive the surface shortwave (SW, 280–3000 nm) irradiance budget with satellite data started almost three decades ago [19,27,29,40]. More recently, satellite products have been used in synergy with radiative transfer models in order to estimate SW irradiance [8,13,14,23,36]. [11] derived a climatology of surface radiation budget using satellite data from the ISCCP (International Satellite Cloud Climatology Project) and the ERBE (Earth Radiation Budget Experiment). The annual averages of global downward and net SW fluxes were found 10–20 W/m^2 lower than the ones predicted by general circulation models but in good agreement with other results based on satellite retrievals. [39] proposed a model for the calculation of SW fluxes at the surface, top and in the atmosphere. It was based on products from the MODIS (Moderate Resolution Imaging Spectroradiometer) and, when compared with measurements from the BSRN network, the correlation coefficient was greater than 0.96 and bias ranged between 0 and 6%. [6] used cloud properties provided by the Spinning Enhanced Visible and Infrared Imager (SEVIRI) to estimate surface solar irradiance in Netherlands. Comparisons with measurements at 35 stations showed that the retrieved irradiance is underestimated by 3–4 W/m^2 during the year. The performance of the method is lower when thin clouds or snow-covered surfaces are present. [17] proposed an automatic method for the calibration of

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METEOSAT visible images. The Heliosat–2 method, presented by [31]; used satellite calibrated radiances, instead of digital counts, previously used, in order to estimate the surface solar irradiance with physically-based retrieval methods. [7] studied the uncertainties of the input parameters to the Heliosat–2 method and highlighted the importance of the Linke turbidity factor, terrain elevation, calibration of the satellite sensor and global albedo. [4] studied the conversion of METEOSAT–8 visible channels' radiances to broadband radiances that simulate the ones operationally produced by METEOSAT–7. [18] used the ISCCP – B2 dataset from METEOSAT and the Heliosat–2 method to derive the surface solar irradiance in Europe and Africa. The overall bias was found to be less than 1 W m^{-2} but for individual sites it varied between −15 and + 32 W m^{-2}. METEOSAT images were also used for the estimation of surface solar irradiance in Northern Africa [1], where a dimming was found in the 1985–2005 period. [3] presented the HelioClim project, which processes METEOSAT images to reconstruct the surface solar irradiance back to 1985. A comparison with ground measurements revealed a good agreement with data after 2004 (bias <10 W m^{-2}). The next version of the Heliosat method, Heliosat-3 [34] took advantage of the enhanced capabilities of the Meteosat Second Generation (MSG) satellites and gave emphasis on the influence of clouds, water vapor, aerosols and ozone on GHI. Heliosat-4 method [25] was based on a radiative transfer model and produced, apart from GHI, the direct and diffuse irradiance components and spectral distribution. In the latest version of Heliosat-4 method [28], a new method, developed by the MINES ParisTech and the German Aerospace Center (DLR), made use of the APOLLO (Advanced Very High Resolution Radiometer (AVHRR) Processing scheme Over cLouds Land and Ocean) cloud product for the estimation of GHI. The method included two parts, a clear-sky module (based on the LibRadtran radiative transfer model) and a cloud-ground module (based on two-stream and delta–Eddington approximations). When compared with ground measurements, the method exhibited very good performances and the greatest discrepancies were observed in the presence of partly cloudy conditions.

The HNSE (Hellenic Network for Solar Energy, www.helionet.gr) has been recently developed in Greece to provide information for solar energy applications. Greece is a country with high solar potential, favorable meteorological conditions and long sunshine durations. The purpose of the HNSE is to provide climatic information forecasts at different spatial and temporal scales using satellite and ground-based data, complemented with calculations from radiative transfer and prognostic models.

In this study, data from the MSG satellite are used to derive the CCI (cloud clearness index) which is defined as the ratio of irradiance under real conditions and the corresponding one under clear-sky. This cloud parameter is multiplied with the clear sky DNI and GHI values to calculate the solar irradiance reaching the surface. The study covers the period from 2008 to 2013. The results are compared with ground-based measurements of GHI. Monthly and annual average maps of GHI and DNI are presented for the area of Greece.

2. Data and methodology

MSG satellites were launched on 28/8/2002, 21/12/2005 and 5/7/2012 for MSG-1, MSG-2 and MSG-3, respectively. They are operated by EUMETSAT (European Organisation for the Exploitation of Meteorological Satellites, http://www.eumetsat.int/), positioned over the equator and prime meridian, acquiring imagery of Europe, North Atlantic and Africa and are dedicated to Earth-atmosphere system studies. The main observing instrument is SEVIRI, which acquires data in 12 spectral channels (4 in the visible and near-infrared and 8 in the infrared part of the spectrum). It takes images of the area with a spatial resolution of 3 km at the sub-satellite point (the point on the Earth's surface which is directly beneath the satellite) for 11 channels and 1 km for the HRV (High Resolution Visible) channel.

The parameter used to account for the cloud effect on surface solar irradiance, is cloud clearness index (CCI), which is defined as the ratio of irradiance under real sky conditions and the corresponding one under clear-skies. CCI varies between 0 and 1, with 0 being the theoretical overcast situation where no irradiance is reaching the ground and 1 representing cloudless conditions. The clear-sky DNI and GHI at the surface are calculated by the SBDART model [30], which is included in the LibRadtran radiative transfer package ([22], www.libradtran.org), as a function of solar zenith angle, AOD (aerosol optical depth), surface reflectivity and elevation. The AFGL (Air Force Geophysics Laboratory) midlatitude winter and summer profiles are used for the basic atmospheric gases, pressure and temperature in model calculations [2]. Monthly climatological averages of the Ångström exponent from ground-based measurements and AOD at 550 nm from MODIS, during the period 2000–2012 on-board the Terra satellite were taken into account [24]. The aerosol vertical profile is described by [32]. Surface albedo was set at 0.2 for the SW range [5] and elevation comes from the GTOPO30 world digital elevation model (https://lta.cr.usgs.gov/GTOPO30). CCI is calculated from SEVIRI data, based on a modified version of the original methodology by [37,38]. The SEVIRI channel at 0.6 μm is used for the estimation of cloudiness. The calibration parameters, distributed along with the satellite data, are used for the conversion of the satellite count to on-satellite radiance. In this way, sensor degradation effects are avoided. The radiance incident at MSG is also calculated with the same radiative transfer model code and inputs, as a function of MSG viewing and solar zenith and azimuth angles and CCI. A correction factor, derived empirically from the comparison with ground-based measurements corresponding to cloud-free and overcast conditions is finally applied. To validate the method, the CCI daily averages over Thessaloniki, Greece (40.5°N, 23°E) for the period 2009–2010 were estimated from pyranometer measurements at the SEVIRI overpass times, by using the modeled values of clear-sky irradiance that match the measurement conditions. According to results [41], the overall agreement was quite good (correlation coefficient = 0.94). However, the proposed method underestimates cloudiness and provides higher CCI values in case of heavy clouds.

For the rare case that the land is snow-covered in Greece, an effective surface albedo is calculated by finding the cloud-free pixels in a series of 10 consecutive days. In all cases, the cloudless

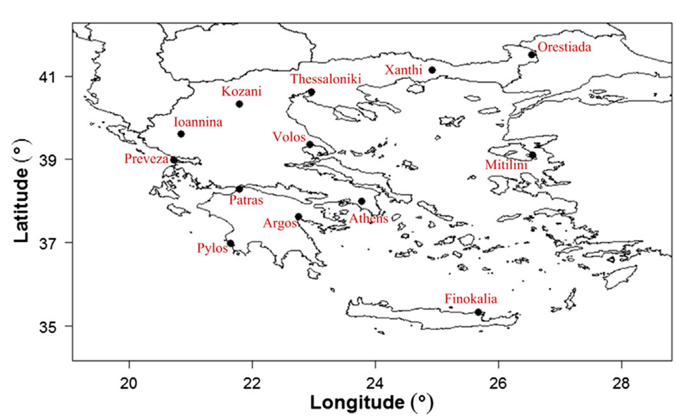

Fig. 1. Map of the ground stations in Greece, used for the evaluation of the satellite-based methodology.