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The effect of clouds on surface solar irradiance, based on data from an all-sky imaging system

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An all-sky imaging system is deployed to estimate the effect of clouds on incident solar irradiance, for a 2-year period over the city of Thessaloniki, Greece. The minutely cloud radiative effect (CRE) is examined in relevance to the cloud cover and type as well as the percentage of the solar disk covered by clouds and the relative position of Sun and clouds in the sky. CRE increases with the cloud cover and decreases with the solar zenith angle (SZA). The minimum instantaneous values can reach −900 W m^{-2} while enhancement events are found to reach up to +200 W m^{-2}. The greatest cooling effects are caused by thick cumulus clouds, in cases where obstruction of the solar disk is visible and by stratocumulus, stratus-altostratus and cumulonimbus-nimbostratus when accompanied by high values of cloud cover. The enhancement events are mostly found when the clouds are in the vicinity of the Sun and when the clouds are accumulated at the upper part of the sky but the Sun is in a lower position.

1. Introduction

Clouds are a major constituent of the Earth − atmosphere system that affects the incoming solar and outgoing thermal energy and presents complicated interactions with the other atmospheric components. It is very difficult to estimate the radiative effects of clouds with adequate accuracy, due to their high temporal and spatial variability and their complex chemical processes. Even though they inflict the largest impact on the transfer of solar irradiance, their quantitative effects carry the largest uncertainty, when they are produced by models, making their study a continuous challenge in the scientific community [19]. Clouds absorb and scatter radiation in the shortwave part of the spectrum (SW), while they absorb radiation in the longwave (LW) part, which is emitted by Earth's surface and lower troposphere, and re-emit it downwards and into space, thus making a contribution to the greenhouse effect [1,39]. In general, clouds are responsible for a cooling effect in the SW, on a global scale [14,24], although under some circumstances (scattered cloudiness) enhancement effects are observed, leading to a warming outcome [34,35].

In order to study the cloud radiative effect (CRE), the difference in radiation between a clear and a cloudy sky is calculated. New instruments and methods as well as the synergy of ground-based observations, satellite estimations and model results, have been used for this scope [2,6,12,21,25,28]. The radiative effects of clouds depend on various parameters, such as the cloud type [10,22,27], cover [26] and microphysical properties [7,11]. Enhancement events, due to the presence of clouds, have as a result the occurrence of high values of surface irradiance, higher than the ones observed under clear-sky conditions and sometimes even higher than the corresponding values found at the top of the atmosphere [8]. There are two mechanisms that contribute to creating enhancement conditions; the multiple reflection of the direct solar component of radiation at cloud borders and the increased forward scattering by the cloud [5]. These two mechanisms induce an increase of diffuse radiation, but without a decrease of the direct part. According to Ref. [33]; there are three special conditions, regarding the cloud field, that must be met in order for an enhancement event to take place: i) a cumulus cloud field should exist but the solar disk should not be blocked, so the direct radiation can reach the surface; ii) the cloud cover should be a minimum of 50% and a maximum of 90% and iii) the clouds should be very dense so multiple scattering can occur. Enhancement events can last from a few seconds to a few minutes and in extreme cases can have values higher than 1500 W m^{-2}, [3,34,37].

Technological improvements have resulted in the use of sky

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imaging systems for the detection and characterization of clouds with a higher frequency than conventional meteorological observations. Using a commercial compact digital (CCD) camera, the cloud detection process becomes an automated procedure and cloud properties, such as the cloud type and cover can be extracted [9,16,23,31,32]. Feister and Shields [13] studied cloud data, provided by the Whole Sky Imager and compared them with cloud observations at the two sites of Potsdam and Lindenberg, Germany, and in relation to solar irradiance measurements. Enhancement effects, on the diffuse irradiance, were observed in cases with clouds close to the apparent Sun position. Contrails were also found to cause enhancements on the spectral sky radiances, despite the small direct effect they have on global irradiance values. Mateos et al. [29] used a sky imager for the estimation of cloud cover and the consecutive estimation of CRE, in Granada, Spain. CRE was found to increase, in absolute magnitude, at moderate solar zenith angles (SZAs) and decrease, reaching zero, at high values of the SZA. The strongest cloud effect was found in cases where the Sun was obstructed by clouds. Enhancement effects were observed in cases where the sun was partially or not covered at all and the cloud cover was higher than 0.5.

Hanschmann et al. [15] calculated the SW cloud radiative effect (CRE) over ocean, using the ECHAM 5 climate model. The CRE is calculated and evaluated for the input of cloud properties, from ship measurements and satellite data. Ship measurements provide the liquid water path, cloud cover (sky imager), cloud bottom height and temperature and humidity profiles, whereas for the satellite approach, Level-2 products of the Satellite Application Facility on Climate Monitoring (CM SAF) from the Spinning Enhanced Visible and InfraRed Imager (SEVIRI) are used for cloud characterization. For some cases, an improvement is introduced with the use of the satellite estimation of effective radius, but overall, each dataset shows best results for different atmospheric conditions. Kalisch and Macke [20] estimated cloud radiative budgets and radiative effects, over the Atlantic ocean, based on cloud type, with the use of surface radiative flux measurements and cloud type and cover data, obtained by a sky imager. The mean surface net CRE was found to be -33 W m^{-2}, indicating the cooling induced by clouds. Strong negative radiative effects were observed for thick clouds at low SZAs. Using the ECHAM 5 climate model, the CRE was estimated to show a stronger cooling by 17 W m^{-2}, caused by an overestimation of the SW impact of convective clouds. The fluxes, estimated by the model, were found to be close to the observations for clear sky and stratus clouds.

In this study, CRE is estimated from the global horizontal irradiance (GHI) measurements and clear sky values, calculated by a radiative transfer model and aerosol information by a Cimel sun photometer. The effect is examined as a function of cloud cover and type as well as the percentage of the Sun disk that is obstructed by clouds and their relevant position in the sky. This information is derived from a tested processing algorithm applied on images taken by a collocated all-sky imager.

2. Data and methodology

The cloud data are extracted from images taken by a CCD camera (Canon IXUS II), which is set to operate at the Laboratory of Atmospheric Physics, at the Aristotle University of Thessaloniki, Greece. The camera incorporates a fish-eye lens, with a 180° field of view and has the ability to capture an image every 5 min, with a spatial resolution of 640 × 480 pixels. The cloud data that are extracted from the CCD camera are the cloud cover and type. A detailed description of the methodology for the derivation of cloud cover and the classification of cloud types can be found in Ref. [23]. For the identification of cloudy pixels and the subsequent estimation of cloud cover, the intensities of the colors red, green and blue (R, G, B), of the images, are investigated. The methodology takes into account the G intensity for the purpose of decreasing the errors found in cases of broken cloud or overcast situations at large SZAs. With the use of a k-Nearest-Neighbor algorithm, based on statistical color and textural features as well as on the solar zenith angle, the cloud cover, the visible fraction of solar disk and the existence of raindrops in sky images, a total of seven different classes are distinguished (represented by numbers 0 to 6) which correspond to clear sky, cirrus, cumulus, cirrocumulus – altocumulus, stratocumulus, stratus-altostratus and cumulonimbus-nimbostratus clouds respectively (Table 1). The clear sky class corresponds to cloud cover less than 10% due to the limitation of the classifier to define the cloud type with sufficient accuracy when the cloud cover is too low. At the site of this study, the algorithm produces good results: 83% and 94% of the analyzed images agree to within ±1 and ± 2 octas respectively with visual weather observations at a close-by meteorological station and the uncertainties are mainly found in cases of very thin cirrus clouds. The average performance of the classifier is 87.9% and ranges from 78% for cirrocumulus-altocumulus to 95% for clear skies. The algorithm has been also applied on images from a sky camera network comprising four stations in Switzerland [38]. In a comprehensive intercomparison study, the total cloud cover from the sky camera is in 65–85% of cases within ±1 octa with respect to other methods (LW radiation and ceilometers measurements, satellite images and visual observations). The performance of the cloud classifier mainly depends on the atmospheric conditions, site-specific characteristics, the randomness of the selected images, and possible visual misclassifications: the mean success rate is 80–90% when the image only contained a single cloud class but drops to 50–70% if the test images are completely randomly selected and multiple cloud classes occur.

The GHI measurements are taken from a collocated Kipp&Zonen CM-21 pyranometer. The 1-min averaged values of GHI covering a period of two years (2006–2007) are used for this study. Only measurements for SZA<85° are processed in order to avoid the surroundings from obstructing the Sun. According to the manufacturer, the stability of the pyranometer is better than ±0.5% yr^{-1}. Two recalibrations were conducted at the Deutscher Wetterdienst – Meteorologisches Observatorium Lindenberg in 2005 and 2011 and revealed practically no change in its sensitivity; its stability was found to be better than 0.1% during all years of operation. In order to estimate the CRE, modeled values of clear-sky GHI are calculated, using the libRadtran radiative transfer software package [30]. For this purpose, a Look-Up-Table (LUT) is derived, giving the clear-sky GHI as a function of AOD at 500 nm, Angström alpha exponent and SZA. The profiles of the basic atmospheric gases, temperature and pressure, that are used, are typical at mid-latitude sites [4], while the aerosol vertical profile is described by Shettle [36]. Standard and spectrally independent values are assumed for the aerosol single scattering albedo (0.95) and the asymmetry factor (0.7). A collocated Cimel Electronique CE318 multiband sun photometer,

Table 1
The cloud types and class numbers of the classification algorithm.

Cloud type	Cloud class number
Clear sky (cloud cover < 10%)	0
Cirrus	1
Cumulus	2
Cirrocumulus – Altocumulus	3
Stratocumulus	4
Stratus – Altostratus	5
Cumulonimbus – Nimbostratus	6