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Cloud cover detection combining high dynamic range sky images and ceilometer measurements

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ABSTRACT

This paper presents a new algorithm for cloud detection based on high dynamic range images from a sky camera and ceilometer measurements. The algorithm is also able to detect the obstruction of the sun. This algorithm, called CPC (Camera Plus Ceilometer), is based on the assumption that under cloud-free conditions the sky field must show symmetry. The symmetry criteria are applied depending on ceilometer measurements of the cloud base height. CPC algorithm is applied in two Spanish locations (Granada and Valladolid). The performance of CPC retrieving the sun conditions (obstructed or unobstructed) is analyzed in detail using as reference pyranometer measurements at Granada. CPC retrievals are in agreement with those derived from the reference pyranometer in 85% of the cases (it seems that this agreement does not depend on aerosol size or optical depth). The agreement percentage goes down to only 48% when another algorithm, based on Red-Blue Ratio (RBR), is applied to the sky camera images. The retrieved cloud cover at Granada and Valladolid is compared with that registered by trained meteorological observers. CPC cloud cover is in agreement with the reference showing a slight overestimation and a mean absolute error around 1 okta. A major advantage of the CPC algorithm with respect to the RBR method is that the determined cloud cover is independent of aerosol properties. The RBR algorithm overestimates cloud cover for coarse aerosols and high loads. Cloud cover obtained only from ceilometer shows similar results than CPC algorithm; but the horizontal distribution cannot be obtained. In addition, it has been observed that under quick and strong changes on cloud cover ceilometers retrieve a cloud cover fitting worse with the real cloud cover.

1. Introduction

Clouds play a critical role in the Earth's radiative budget, since they backscatter to space a portion of incoming solar radiation but also re-emit back to the surface a fraction of Earth infrared radiation. Hence, changes on cloud properties like lifetime (and subsequently cloud cover: CC), or albedo could dramatically impact on Earth's climate (Boucher et al., 2013). From the energy production point of view, solar energy systems are strongly affected by cloud presence. Especially in the case of concentration solar power plants and concentration photovoltaic systems, that strongly depend on direct beam solar irradiance, their energy output is highly reduced when the sun is obstructed by clouds (Beyer et al., 1994; Frederick and Steele, 1995; Bartlett et al., 1998; Antón et al., 2011; Cazorla et al., 2015). Both climate and solar energy issues motivate the need for cloud observations.

Cloud cover can be determined by different ways. Visual observations of CC, made by a human observer, are hemispheric “instantaneous” observations that depend on the visible horizon and are subjective observations, prone to human effects due to differences between observers (WMO, 2012). Some authors such as Sánchez-Lorenzo et al. (2009) used this kind of measurements to study long-term CC data series due to the availability of these data in the past. These measurements cannot be automatically done and the time resolution is limited.

It is feasible replacing some of these observations by automated and

Abbreviations: AE, Angström Exponent; AEMet, State Meteorological Agency of Spain (Agencia Estatal de Meteorología); AERONET, AErosol RObotic NETwork; AOD, aerosol optical depth; CBH, cloud base height; CC, cloud cover; CEI, CEIlometer; CPC, Camera Plus Ceilometer; FOV, field of view; HDR, high dynamic range; MABE, Mean Absolute Bias Error; MBE, Mean Bias Error; MDBE, Median Bias Error; RBR, Red-Blue Ratio; RGB, Red Green Blue; SZA, Solar Zenith Angle; SD, standard deviation; SONA, Automatic Cloud Observation System; WMO, World Meteorological Organization

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continuous measurements from a ceilometer, which is an active instrument that emits pulsed laser signals and records with a receiver telescope the vertical signal based on the backscatter of the atmosphere (Tapakis and Charalambides, 2013). Cloud base height (CBH) and CC can be estimated from these measurements due to the strong backscatter of clouds (Martucci et al., 2010; Mittermaier, 2012; Costa-Surós et al., 2013, 2014), however this methods are only based on the vertical information, ignoring the spatial dimensions and excluding some clouds which are not in the vertical line of the ceilometer.

Satellite images can be used to retrieve cloud cover (e.g., Arking and Childs, 1985; Rossow and Schiffer, 1999; Gao et al., 2002; Zhao and Di Girolamo, 2006), but on a global scale, which is not useful to determinate if sun is obstructed by clouds in a particular place. Radiometers, radars, and radiosondes are also used in the retrieval of cloud properties (for a review see: Tapakis and Charalambides, 2013).

Sky cameras are devices that usually provide a hemispherical image of the full sky in the visible range, typically at red-green-blue (RGB) channels. Ghonima et al. (2012) simulated sky images under cloud-free conditions and detected cloudy pixels comparing the measured image with the cloud-free simulated one; to this purpose an aerosol correction is included in the simulations because aerosols can change significantly the sky radiance distribution. Yabuki et al. (2014) presented an algorithm based on the spectral contrast between the RGB channels of the sky image and various constrains. Cazorla et al. (2008) and Linfoot and Alliss (2008) applied neural networks to sky images for detection of cloudy pixels after a previous training. Liu et al. (2015) used the superpixel segmentation technique to locate cloudy pixels in sky images. Some authors combined sky imagery with radiometric data (shortwave or longwave) in order to obtain cloud cover and classification (Martínez-Chico et al., 2011; Alonso et al., 2014; Wacker et al., 2015).

However, most of the sky camera algorithms for detection of cloudy pixels (e.g., Koehler et al., 1991; Long et al., 2006; Calbó and Sabburg, 2008; Kreuter et al., 2009) are based on the whiteness of the pixels quantified by the RBR value: ratio of the red to the blue channel; a threshold value is chosen and the pixels with a ratio below threshold are considered cloud-free (pixel too blue) and for ratio above the threshold the pixel is cloudy (high red channel). This method presents some problems since the commercial cameras usually do not have linear pixel sensitivity (although it can be mitigated by gamma correction), then RBR is not linear, and if their white balance is not fixed it could vary the RBR value. In addition, under large loads of coarse aerosol the cloud-free pixels look whiter than under low aerosol loads; pixels near the circumsolar are usually saturated looking also whiter (Long et al., 2006; Olmo et al., 2008; Heinle et al., 2010; Román et al., 2012); in this way the cloud-free pixels are erroneously classified as cloudy. Saturation and non-linearity problem can be solved taking high dynamic range (HDR) images, which are a composition of various images taken with different exposure times (Debevec and Malik, 1997; Stumpfel et al., 2004; Cazorla et al., 2015; Román et al., 2017).

The main aim of this paper is to develop an algorithm to retrieve the cloud cover and sun condition but removing, or at least reducing, the problems obtained with other algorithms. To this purpose, a sky camera is used and configured to take HDR images (avoiding saturation). HDR images are synergistically combined with information from a ceilometer to improve the cloud detection algorithm. The basis of our cloud detection is partially based on the consideration that a cloud-free sky image presents high symmetry relative to the solar principal plane. Other concepts like variation between two consecutive images or edge detection are considered. The proposed algorithm retrievals are compared with other algorithms and tested against suitable references like those based in trained meteorological observers.

Section 2 presents the locations and data from different instruments used in this work. Relevant information about the configuration of the sky camera to take HDR images can be found in Section 3. The new algorithm developed in this work is explained in detail in Section 4 and Appendix A and B. Section 5 shows the main results of the comparison of the new algorithm and others against reference values and, finally, Section 6 summarizes the main conclusions.

2. Location and instrumentation

Data used in this paper was recorded at stations sited at Valladolid (41.66°N; − 4.71°W; 705 m a.s.l.) and Granada (37.16°N; − 3.61°W; 680 m a.s.l.), both cities located in Spain. The predominant aerosol at Valladolid, sited in North-Central Iberian Peninsula, can be considered as "clean continental" (Bennouna et al., 2013; Román et al., 2014b) but some Saharan dust episodes also happen, especially in summer (Cachorro et al., 2016). These Saharan episodes are more frequent at Granada due to its proximity to North Africa, since this city is located at the South-East of the Iberian Peninsula (Valenzuela et al., 2012). Both stations are equipped with a "CHM-15 k Nimbus" ceilometer (*Lufft* manufacturer), a "SONA" sky camera (*Sieltec Canarias S.L.*) and a "CE318-N" sun/sky-photometer (*Cimel Electronique*).

Both ceilometers belong to the Iberian Ceilometer Network (Cazorla et al., 2017). They provide CC and CBH measurements every 15 s. The cloud cover determined by the ceilometer is described on the Jenoptik CHM15k user manual (Jenoptik, 2013). It is determined using the previously calculated cloud bases heights. First, a time interval is considered and its length depends on the cloud base height, being longer for higher clouds creating a "temporal cone of influence". The frequency of cloud bases is calculated for each time interval. Peaks in the frequency distribution are separated and all cloud bases in the space of a peak will be clustered to one cloud layer. The calculation of the total cloud cover value is done within a rectangle depending on time and altitude. For this purpose the mentioned time interval ("truncated cone of influence") will be divided in a fixed number of small truncated cones. Parts containing cloud bases are counted against the total number of cone parts and the cloud cover value is expressed as a percentage value from this comparison. Finally the percentage value is expressed in oktas.

SONA ("Sistema de Observación de Nubosidad Automático": Automatic Cloud Observation System) sky camera takes hemispherical sky images along the whole day but in this work we only use daytime images. It consists of a surveillance CCD camera, which provides three channels (RGB) images with 8 bit-digitalization providing 256 counts per channel (Cazorla et al., 2015). This camera with a fisheye lens is inside a waterproof case which has a quartz dome and a shadow band in order to block the sun (González et al., 2012). The field of view (**FOV**), zenith (**ZEN**), and azimuth (**AZI**) matrices, representing the angles viewed by each pixel, were obtained correlating the pixel positions of celestial bodies whose coordinates are well known (Román et al., 2017).

The sun/sky-photometers used in this work are integrated in AERONET network (AErosol RObotic NETwork; Holben et al., 1998). The AERONET processed data used in this work are the daily average of *AOD* at 440 nm and the daily Angström Exponent (*AE*) obtained in the spectral range 440–870 nm. All these cloud-screened data (level 1.5) correspond to the AERONET Version 3 algorithm, and are available at http://aeronet.gsfc.nasa.gov.

CC measured visually by trained meteorological observers at two AEMet stations (State Meteorological Agency of Spain) is also available. These measurements are taken three times per day: 07:00, 13:00 and 18:00 UTC, and are given in oktas with a resolution of 1 okta. These AEMet stations are 3.75 km and 4.75 km far away in a straight line for Granada and Valladolid stations, respectively.

Finally, direct beam solar shortwave (SW_b) irradiance data was obtained at each minute as the difference between global and diffuse components recorded by two CM-11 pyranometers (Kipp & Zonen); diffuse is measured using a shadow-ball in a sun-tracker. This kind of data is not available at Valladolid, at least near to the sky camera used in this work. Both pyranometers at Granada presents a relative uncertainty of 1.9% and are frequently calibrated using a reference