The effect of sub-pixel clouds on satellite based cloud detection and TOA cloud radiative effect estimations

Timo Hanschmann, Hartwig Deneke, and Andreas Macke
Leibniz Institute for Tropospheric Research, Leipzig

Abstract

The effect of sub-pixel variability and undetected sub-pixel clouds on reflected solar top-of-atmosphere irradiance is investigated. Results are presented which show a brightening of pixels detected as clear by the EUMETSAT/MPEF cloud mask likely attributable to sub-pixel clouds. Furthermore, a peak in the frequency distribution of the shortwave cloud radiative effect (SWCRE) at the top of the atmosphere through small and sub-pixel clouds could be identified and investigated. A distribution of the SWCRE over the whole range was found for these observations taking sub-pixel cloud fraction into account. This change in the distribution of the SWCRE is most likely connected to the different constellation of clouds, sun, and satellite or to the different cloud types and cloud microphysics.

Introduction

The radiation budget represents the balance between the incoming solar radiation on the one hand, and the reflected solar radiation and outgoing thermal radiation on the other hand. Information on the Earth radiation budget (ERB) is important for assessing climate and weather forecast models, for monitoring our climate, and for understanding the interaction of clouds and radiation. Using satellite based estimates of the cloud radiative effect at the top of atmosphere, small clouds and sub-pixel cloud variability causes fundamental problems on spatial scales at or below the resolution of satellite images. Within this paper the effect of sub-pixel variability on the observed outgoing shortwave radiation (OSR) is investigated, especially with respect to its accuracy in the attribution to clear sky and cloudy components. Hereby, the effect of cloud induced sub-pixel variability on the observed CRE is emphasized. Clouds with sizes below this pixel scale are sometimes missed by cloud mask algorithms. Koren et al. (2008) showed a decrease of mean cloud reflectance with decreasing sensor resolution for broken cloud fields. This resolution effect causes uncertainty in the calculation of the shortwave CRE (SWCRE; SWCRE=OSR_{clear}-OSR_{observed}) due to the uncertainty in the OSR as a result of sub-pixel clouds.

Data and Method

Surface dataset

The present study utilizes BSRN measurements from the station Cabauw, the Netherlands (Knap et al., 2006). According to BSRN requirements, measurements of global direct and diffuse shortwave and longwave radiative fluxes are carried out. 14 months from 2009 and 2010 with high sun (April to October) have been investigated. Based on the Radiative Flux Analysis Methodology developed by Long et al. (2000; 2006) the sky fraction covered by clouds and surface clear sky downward solar radiation has been computed with one-minute temporal resolution from these radiation measurements.

Satellite based dataset

At the top of atmosphere the OSR is retrieved from the Spinning Enhanced Visible and Infrared Radiometer (SEVIRI) flown onboard the Meteosat Second Generation (MSG) satellites. The observed narrowband radiances are converted to broadband irradiances by applying a narrow to broadband (N2B) and radiance to flux (R2F) conversion following Clerbaux and Dewitte (2002; 2002b). The N2B conversion is based on a regression utilizing the three solar channels at 0.6µm, 0.8µm, and 1.6µm wavelength. The R2F conversion is based on angular distribution models (ADM) depending on scene type a well as sun and observing geometry. The ADMs used here are based on Loeb et al (2003), and have been adapted by Clerbaux and Dewitte from the CERES to the SEVIRI instrument. For distinguishing between cloudy and clear scenes, the cloud mask derived and distributed operationally by the EUMETSAT Meteorological Product Extraction Facility (Lutz, 1999) is used in this study.

Methodology

Information on the presence and variability of clouds is essential for the goals of our study. The
ground-based sky fraction of clouds derived from Long (2006) is considered as reference for the cloud cover. However, the Radiative Flux Analysis Methodology developed by Long et al. is based on a regression between a cloud fraction dataset and a diffuse cloud effect with special attention directed to nearly clear sky and nearly overcast cases. Thus, this dataset does not represent the truth, but with the high spatial information from the ground-based observations it can serve as suitable reference dataset for the satellite-based observations. In order to compare ground-based measurements and satellite-based observations both datasets have to be averaged to represent similar scales of variability (Deneke et al., 2009). Because in this study hemispheric ground-based observations are used the temporal averaging for the ground-based observations is applied with Gaussian weighting and a full width half maximum of 30 minutes. For the satellite-based observations spatial averaging is applied with Gaussian weighting and full width half maximum of 3x3 pixels. A method to split the reflected solar radiation observed by MSG-SEVIRI into the signal from clouds and from the clear sky atmosphere is applied based on the linear relation
\[ F_{SW} = N F_{SW, CLOUD} + (1 - N) F_{SW, CLEAR} \]  
(Eq.1)

Here \( F_{SW} \) is the broadband solar flux reflected by the earth surface and atmosphere and \( N \) is the cloud fraction. \( F_{SW, CLEAR} \) is calculated from the clear sky TOA albedo and the incoming solar radiation. The clear sky TOA albedo is computed for two week periods for hourly intervals as follows. For each interval all pixels detected within the period as clear sky over a 5x5 pixel array centered at Cabauw and over the 4 SEVIRI-timeslots are considered. The first quartile from the frequency distribution of these reflectances is taken as estimate of the clear sky TOA albedo. As these mostly match with the peak in the frequency distribution of OSR and the spread between the first and third quartile is of a magnitude smaller this seems to be a robust method. A comparison (not shown) to the surface albedo computed from the CM SAF SAL daily mean product (Riihelä et al. (2011)) also indicated reasonable agreement over the whole time series. Based on the clear sky TOA albedo EQ1 can be solved for the unknown which leads to:
\[ F_{SW, CLOUD} = \frac{F_{SW} - (1 - N) F_{SW, CLEAR}}{N} \]  
(Eq.2)

This linear relation is based on the assumption of horizontally homogeneous cloud layers, as the observed clouds are stretched to pixel size. But, also for other single layer clouds this is a good approximation. It has to be taken into account that this equation becomes numerically instable at small cloud fractions, and should not be applied below 5%. For these small cloud fractions \( F_{SW, CLOUD} \) is set to zero.

Result
Within this study the sub-pixel variability is investigated through consideration of the ground-based cloud fraction and its effect on the observed OSR at the top of atmosphere. Hereby it is assumed that the ground-based cloud fraction represents the SEVIRI pixel field of view after spatial and temporal averaging of the dataset. Thus, a small cloud fraction is linked to sub-pixel cloud variability. Within the first part the MPEF cloud mask is compared to the estimated cloud fraction of Long. In the second part the cloud fraction is used to derive a SWCRE independent of the amount of clouds.

1) Cloud fraction comparison
First, the cloud mask is compared to the ground-based estimates of the cloud fraction from the Long algorithm. Therefore, ground-based estimates are split into 12 classes of cloud fraction ranging from clear sky to overcast scenes. The distribution of cloud mask classification results for different cloud fraction classes is shown in the upper panel of figure 1. A small slope is observed which indicates that the relation of cloud mask and cloud fraction is ambiguous. Nevertheless, the performance of the MPEF cloud mask is satisfactory considering the difficulties classifying variable scenes by a binary cloud mask and the effects of averaging. However, this finding can also be used to investigate the propagation of cloud mask uncertainties to clear sky radiances. These radiances are used i.e. to derive the SWCRE

![Figure 1](image)

**Figure 1** Comparison of the MPEF cloud mask for different ground-based cloud fraction intervals (top). The brightening effect due to sub-pixel clouds for different cloud amount intervals is shown for the TOA albedo (middle) and as absolute values (bottom).

<table>
<thead>
<tr>
<th>cloud fraction [%]</th>
<th>&lt;5</th>
<th>5-10</th>
<th>20-20</th>
<th>20-50</th>
<th>&gt;50</th>
</tr>
</thead>
<tbody>
<tr>
<td># data</td>
<td>1677</td>
<td>367</td>
<td>787</td>
<td>2688</td>
<td>9916</td>
</tr>
<tr>
<td>% classified as clear sky by cloud mask</td>
<td>87</td>
<td>73</td>
<td>72</td>
<td>52</td>
<td>11</td>
</tr>
</tbody>
</table>

**Table 1**: The table shows the cloud fraction classes used in figure 1 (middle, bottom) as well, the number of pixels considered for the brightening statistics in the second row. In the third row is shown the percentage of pixels detected as cloud free within these intervals.
and separate observed and clear sky radiance is often performed by cloud mask information. This investigation is shown in the middle and bottom graph of figure 1 and in table 1. Here, it was found that considering an estimated ground-based cloud fraction of 20% to 50%, in 52% of all cases the cloud mask detects the pixel as clear. Comparing the mean TOA OSR with the clear sky TOA OSR, computed as defined above, a positive bias of 33Wm\(^{-2}\) based on clear sky cases contaminated by clouds is found. For this situation an example case is presented to demonstrate the behavior of the cloud mask against the estimated ground-based cloud fraction. On 18.05.2010 around noon, three images captured by the total sky imager at Cabauw are shown in figure 2. The Long algorithm computes the temporally averaged cloud fraction centered at 12:30 UTC as 46%. As seen from the images, small clouds are distributed randomly over the field of view but still effect the observed global radiation as the transmissivity is 0.68 although direct sun is present. The MPEF cloud mask already classifies this scene as clear. Figure 3 shows the diurnal cycle of the global radiation (top panel) and the corresponding cloud fraction (bottom panel). Here a decrease around noon in cloud fraction from the MPEF cloud mask (blue) is shown which is not present in the Long algorithm (red). From the TOA perspective the observed clouds do have a stronger impact on the OSR than in the case of ground-based observations. This results from direct radiation, which increases the global radiation but not the TOA OSR. Also the field of view and the cosine weighting of the pyranometer has to be taken into account, while the satellite sees the scene as plane.

2) SWCRE comparison

Using the ground-based cloud fraction derived by Long to separate the TOA OSR into the portion from the cloudy and the clear part by equation Eq.1 a further formulation of the TOA shortwave cloud radiative effect is gained:

\[
SWCRE = OSR_{\text{clear}} - OSR_{\text{cloud}} \quad (\text{Eq.3})
\]

A direct comparison of results from both formulations is shown in figure 4. The upper graph is a scatter plot with results from the old formulation on the abscissa and results based on Eq.3 on the ordinate. 8 ground-based cloud fraction classes are considered. Positive SWCRE do occur if the OSR\(_{\text{cloud}}\) is set to zero. This was done when the cloud fraction is lower than 5% and equation Eq.2 becomes instable. Also for cloudy periods the TOA clear sky albedo shows inaccuracies due to too little sample quantity. This was observed for only a few periods and results in an overestimated clear sky reflectance, which again can yield a positive SWCRE. For the nearly overcast class (> 87.5% cloud fraction) both formulation yield similar results because the difference OSR\(_{\text{observed}}\) and OSR\(_{\text{cloud}}\) is small. This is not the case for the nearly cloud free class (<12.5%). Here, for the old formulation the SWCRE nearly all observations lie between 0 and -100 Wm\(^{-2}\). Based on the new formulation, values of SWCRE are spread over the whole range. This is also shown in the histogram

Figure 2: This Image shows the cloud condition at Cabauw, the Netherlands, on the 18.05.2010 at 12:30 UTC.

Figure 3: This figure shows the downward shortwave radiation for the 18.05.2010 in the top panel and the cloud fraction from the averaged MPEF cloud mask and the Long algorithm in the bottom. The blue vertical line indicates the time of observation at 12:30 UTC.

Figure 4: Shows the observed SWCRE (abscissa) plotted against the SWCRE corrected for sub-pixel cloud fraction (ordinate) for eight ground based cloud fraction intervals (top) and the relative frequency of the SWCRE in both definitions (bottom).
given as lower graph of figure 4. The density function for the results based on the old formulation (blue) shows a peak only slightly below 0 Wm$^{-2}$ which is absent in the SWCRE obtained from the new formulation (red). The reason for this is the spatial cloud variability and its resulting effect on the detector-cloud-sun constellation which leads to different OSR values at the TOA for similar cloud fraction and cloud types. A further aspect is the effect of the cloud type and its cloud microphysical properties which might affect the albedo of the scene. However, the new formulation is based on assumptions and contains sources of uncertainties. These are mainly the assumption on homogeneous single layer clouds in Eq.2, the instability for low cloud fraction, and the uncertainty in deriving the cloud fraction from radiation measurements within the Radiative Flux Analysis Methodology.

Conclusion
Within this work the effect of sub-pixel variability on the outgoing shortwave radiation at the top of atmosphere induced by clouds and observed by satellite-based instruments has been investigated. This was done based on the assumption that sub-pixel cloud variability is well represented by the ground-based cloud fraction derived by the Long algorithm. A method has been used to split the observed OSR into contributions from the clear and cloudy parts of the atmosphere (Eq.1). For the clear sky contribution, the TOA albedo has been computed by means of a clear-sky composite approach, yielding reasonable agreement with to the CM SAF surface albedo daily mean product s. Within the first part of this paper, the reliability of the cloud mask information has been studied and a diverse response to the estimated ground-based cloud fraction has been found. Furthermore, this cloud mask response leads to a brightening effect in reflectance at the top of the atmosphere for pixels detected as clear, which results most likely from aerosols and sub-pixel clouds. It was shown that if 20% to 50% of the sky is covered by clouds according to Long, the MPEF cloud mask defines the pixel as clear in 52% of all cases. This uncertainty results in a mean clear sky pixel brightening of 33 Wm$^{-2}$. In the second part of this paper the comparison of the SWCRE results from the new and the old formulation yields a strong peak in the frequency distribution of the SWCRE in its old formulation at about 0 Wm$^{-2}$. This peak results from sub-pixel clouds that only cause minor brightening of the pixel due to their small size. When the algorithm accounts for sub-pixel variability, small clouds are weighted more strongly (new formulation) and this peak vanishes. Using the old formulation the SWCRE is limited to a small range 0 to -100Wm$^{-2}$ for small cloud fractions. Using the new formulation a broader range from 0 up to SWCREs of -800Wm$^{-2}$ is found.

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Reference