EVALUATION OF METEOSAT-8/SEVIRI RETRIEVED CLOUD DEPTH FOR WATER CLOUDS USING CLOUDNET SITES

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Abstract

In order to monitor the first indirect aerosol effect new algorithms have been implemented to retrieve information about cloud depth and cloud droplet number concentration from passive satellite observations. These algorithms determine the latter two cloud properties starting from satellite retrieved information on cloud optical thickness and effective radius.

The algorithm “Satellite monitoring of the first indirect aerosol effect: Retrieval of the droplet concentration of water clouds” (Boers et al., 2006) has been implemented and applied to Meteosat-8/SEVIRI observation data. This algorithm uses a single-layered water cloud model with quasi-adiabatic vertical profiles of the liquid water content.

After a sensitivity analysis of the described algorithm, this work investigates the ability of the algorithm to correctly retrieve the cloud depth from the Spinning Enhanced Visible and Infrared Imager (SEVIRI) onboard METEOSAT-8. The satellite retrieved cloud depth is compared with the ground-based measurements obtained during CloudNet project. The ground-based cloud depth is calculated using a combination of radar and lidar (R&L) data.

The results show an excellent agreement between ground-based and SEVIRI induced cloud depth values. The correlation factor between SEVIRI and R&L retrieved cloud depths is about 0.73 for six selected days when single-layered water clouds overpass CloudNet sites. For daily mean values of the cloud depth, the correlation increases up to 0.80, but the important feature to note is that the mean values of the cloud depths differ only for about 4 meters. The consistency of cloud depth retrieval with ground-based observations suggests that SEVIRI may be used to study the first indirect aerosol effect from space.

1. INTRODUCTION

Monitoring of the first indirect aerosol effect is an important achievement to better understand cloud formation and distribution. Passive satellites measuring the cloud’s reflectances can only retrieve microphysical properties such as cloud optical thickness (COT), effective radius (Reff), Liquid Water Path (LWP) and cloud phase. Conversely, cloud geometrical properties are difficult to retrieve using only passive satellite measurements. However, a correct retrieval of cloud depth (DCLD) and droplet concentration (CDNC) from the geostationary satellite Meteosat-8/SEVIRI would give the opportunity to describe the first indirect aerosol effect with high temporal and spectral resolution.

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Lately, new algorithms have been implemented to retrieve cloud depth (DCLD) and cloud droplet number concentration (CDNC) from passive satellite observations in order to monitor the first indirect aerosol effect.

Several authors implemented models of vertical distribution of cloud microphysical and optical properties to simulate cloud depth and droplet concentration using satellite retrieved COT and Reff. Some authors in their models assume water clouds to be simply adiabatic (Brenguier et al., 2000; Szczodrak et al., 2001), while others apply a quasi-adiabatic water cloud model taking into consideration the effects of mixing and entrainment (Boers et al., 2006). Apart from those methods, Schuller et al., 2003, retrieves cloud depth and droplet concentration directly from satellite radiances, performing the radiative transfer calculations for clouds using prescribed Look-Up Tables for droplet concentration and liquid water content profiles.

In this work, the algorithm implemented by Boers et al., 2006 has been applied to Meteosat-8/SEVIRI observations. In fact, Meteosat-8 gives very good time coverage with its 15 minutes sampling frequency. The essential feature of the algorithm is that satellite retrieved effective radius and optical thickness are functions of the droplet concentration and the cloud depth.

A correct evaluation of the retrieved cloud depth gives the opportunity to reduce the number of unknowns considered in the presented algorithm so that the accuracy for the droplet concentration retrieval can be increased. The algorithm has been already applied to the Moderate Resolution Imaging Spectroradiometer (MODIS) in Cape Grim, Tasmania, and it was found that the CDNC correlates well with the Cloud Condensation Nuclei (CCN) numbers for marine stratocumulus (CF ~ 0.9) (Boers et al., 2006; Twohy et al., 2005). Conversely, the cloud depth was not validated and its retrieval was very uncertain. Furthermore, uncertainties and errors in the algorithm were not completely quantified.

For these reasons, before the algorithm validation, in order to quantify the uncertainties of the cloud depth and CDNC retrievals, the sensitivity analysis of the quasi-adiabatic cloud model to errors in COT and Reff has been studied.

This work shows the validation of the cloud depth retrieval algorithm by comparing the Meteosat-8/SEVIRI retrieved cloud depth with the observations carried on at three CloudNet sites. CloudNet project (www.cloud-net.org) observations give a statistically significant set of measurements that can be used for collocated and synchronized validation of satellite retrievals for all the three ground-based remote sensing stations. The outline of the paper shows in section 2 the description of the datasets used during the work: the satellite retrievals and its sensitivity analysis and the ground-based cloud depth retrieval. Section 3 shows the method for comparison of the two datasets and the comparison results. Finally, concluding remarks are written along with some more future works in section 4.

2. DATASETS

Satellite Retrievals

Cloud Properties, such as COT, Reff and LWP, are retrieved from METEOSAT-8/SEVIRI using the Cloud Physical Properties (CPP) algorithm as part of the Satellite Application Facility on Climate Monitoring (CM-SAF) project (Roebeling et al., 2006). COT and Reff are retrieved in an iterative manner by simultaneously comparing satellite observed reflectances at visible and near-infrared wavelengths (0.6 and 1.6 µm) to reflectances simulated with the Doubling Adding KNMI (DAK) radiative transfer model. DAK is developed for line-by-line or monochromatic multiple scattering calculations at UV, visible and near-infrared wavelengths in a horizontally homogeneous (plane parallel) cloudy atmosphere using the doubling-adding method (De Haan et al., 1987; Stammes, 2001). The phase “ice” is assigned to pixels with Cloud Top Temperature (CTT) lower than 265 K. The remaining cloudy pixels are considered water clouds. When a fixed vertical profile of liquid water content is assumed, the LWP can be computed using COT and Reff according to the formula from Stephens et al., 1978:

\[
LWP = \frac{2}{3} COT_{vis} r_i \rho_l \quad (1)
\]

where \( \rho_l \) is the density of liquid water and \( r_i \) is the Cloud Effective Radius (Reff).
The quasi-adiabatic cloud model of Boers et al. [2006] is used to calculate the cloud depth and the cloud droplet concentration. This model parameterizes the vertical variation of cloud microphysical and optical properties. The essential point of the cloud model is that COT and Reff are explicit functions of DCLD and CDNC, which are computed with the following equations:

\[
CDNC = A_1 COT^{\frac{1}{2}} r_e^{-\frac{5}{2}}
\]  

(2)

\[
DCLD = A_2 COT^{\frac{1}{2}} r_e^{-\frac{1}{2}}
\]

(3)

Where, the factors \( A_1 \) and \( A_2 \) are derived from implicit assumptions about the nature of four thermodynamic and microphysical conditions, i.e. (a) the sub-adiabatic behaviour of the cloud, (b) the shape of the vertical liquid water content profile, (c) the relationship between effective radius and volume radius of the size distribution, and finally (d) the mixing model that describes the vertical variations in liquid water content as function of the vertical profiles of CDNC and volume radius. Boers et al. [2006] found that the major source of uncertainty in the retrieval is the sub-adiabatic behaviour of the cloud, which is expressed by the sub-adiabatic fraction \( Fr \). The \( Fr \) values vary between 0.3 and 0.9, due to turbulent entrainment and vertical mixing in cloud. Deviations from adiabatic clouds \( (Fr = 1) \) lead to an increase of DCLD and a decrease of CDNC. The shape of the liquid water content profile, which Boers et al., 2006 indicate with \( \alpha \), varies between 0 for a linear profile and 1 for a C-shaped profile.

Sensitivity of the Algorithm

The algorithm, containing implicit assumptions about the nature of four basic thermodynamic and microphysical points, needs to be studied with a sensitivity analysis able to describe the accuracy of the cloud depth retrieval. Each of the four issues may introduce uncertainties in the retrieved products. However, while the last three issues can be set constant referring to previous studies (Boers et al., 2006), the adiabatic character of the cloud is the only variable parameter to take into consideration when calculating the errors.

Figure 1 presents the sensitivity of DCLD and CDNC retrievals to errors in DCLD and Reff. The sensitivities were determined with random and normally distributed errors of ±10% on the COT and Reff values, which is comparable to the errors Roebeling et al. (2007) found in validation studies. The cloud model was run with a fixed sub-adiabatic fraction of 0.7.

The graphs show that the retrieval of DCLD has not high sensitivity to changes in both COT and Reff. In general, the errors in DCLD retrievals increase with increasing COT and Reff, but only until a maximum value of 75 m, even for the largest COT and Reff. This value, actually, is close to the accuracy of the ground-based DCLD retrievals (50 m). On the other hand, the errors in CDNC increase with increasing COT, and become as large as 150 cm\(^{-3}\) for optically thick clouds (COT > 20). However, the CDNC retrievals are most sensitive towards changes in Reff. The sensitivity of the CDNC retrievals increases rapidly for droplets smaller than 5 µm, and becomes unacceptably large for droplet smaller than 4 µm. Since the values for droplet concentration start becoming very high for droplets smaller than 5 µm, the retrievals for points where the droplets are smaller than 5 µm should be and are omitted from the analysis.

After the sensitivity analysis, the cloud model was run with a sub-adiabatic factor set to 0.72, being this value the one that gives the closest cloud depth retrieval to the ground-based observations and an almost linear vertical liquid water profile equal to \( \alpha = 0.3 \).
Figure 1: Sensitivity of Cloud Depth (CGT) and Cloud Droplet Number Concentration (CDNC) retrievals to effective radius (Reff = 8 µm ± 10%) as function of COT (left panel) and to COT (COT =16 ± 10%) as function of effective radius (right panel). The sub-adiabatic cloud model was run with Fr=0.7.

Ground-based measurements with CloudNet sites

The ground-based measurements of the CloudNet project (www.cloud-net.org) were collected at Chilbolton in the United Kingdom (51.14°N, 1.44°W), Cabauw in The Netherlands (51.97°N, 4.927°E) and Palaiseau in France (48.71°N, 2.21°E). These sites were equipped with a suite of active and passive instrumentation.

The active instruments (lidar and cloud radar) were used for the observation of cloud depth. In fact, the cloud depth can essentially be calculated from the difference between the cloud top height measured by the cloud radar, more sensitive to particle diameter, and the cloud base height measured by the lidar, more sensitive to droplet number concentration, with a vertical resolution of about 90 meters for Cabauw and 60 meters for the other two sites (Illingworth et al., 2007).

Figure 2: Location of the 3 remote sensing sites belonging to the CloudNet project.
3. COMPARISONS AND RESULTS

Following the sensitivity analysis and a re-run of the SEVIRI cloud depth retrieval with the sub-adiabatic fraction set to 0.72, the comparison process with the ground-based data started. The presence of clouds was diagnosed from the ground-based observations using the CloudNet target categorization data. These data include information on the presence of liquid water or ice crystals, which is derived from an algorithm that uses integrated observations from radar, lidar, model temperature data and rain gauge observations (Illingworth et al., 2007). Figure 3 shows the time series of the cloud depths for six days where single layers water clouds were present in the CloudNet measurements.

As we can notice, the courses of the two cloud depths are very similar and the temporal variations in the observed cloud depths are well reproduced by SEVIRI.

For these six selected single layer days, the correlation factor between the two cloud depths is 0.73. A better description of the validity and accuracy of the algorithm is given by the mean values of the measurements. In fact, the mean value measured with R&L (336.71 m) is about 26 m higher than the one retrieved from SEVIRI (310.22 m). Furthermore, the median values of the cloud depths differ only for 3 m, while the standard deviations are 148.72 m for R&L and 140.62 m for SEVIRI retrieval.

Figure 3: Time Series of the Cloud Depth retrieved from METEOSAT-8/SEVIRI (MSG, dashed-point line) and from ground-based measurements with Radar and Lidar (R&L, solid line) for six selected days with single-layered water clouds over the CloudNet sites. The gray shading around the SEVIRI retrievals indicates the estimated range of errors in cloud optical thickness and effective radius calculated during the sensitivity analysis. The ground-based measurements have been assumed to have constant error bars of ± 50 m.

Figure 4 shows the scatter plot of 768 instantaneous points of collocated observations for Radar&Lidar on the x-axis and for Meteosat-8/SEVIRI on the y-axis. The scatter plot shows that most of the points are below the 800 meters confirming the theory of the geometrical thickness of water clouds. The correlation factor between the instantaneous points is not very high, CF = 0.59, due to the differences on the geometry of the Fields of View. In fact, Meteosat-8 has a footprint of about 3x6 Km for the pixels in the Northern Europe, while the ground-based instruments have smaller beams. However, the mean values of the retrieved cloud depths are very close to each other, 286.43 m for SEVIRI and 290.50 for Radar&Lidar. The standard deviations of the instantaneous observations are 127.85 m for the Meteosat-8 (MSG) and 143.20 m for the ground-based measurements.

The problem of the different fields of view is overcome when the daily mean values of the observations are considered. Figure 5 shows the scatter plot of the cloud depths retrieved daily mean values for 29 days. It can be noted that the correlation factor increases up to 0.80. The correlation for daily mean...
values increases since the limitations matching satellite passive observations fields of view with ground-base active measurements are no longer influencing the comparison. At the same time the mean values differ of less than 3 m to each other. The standard deviations of the SEVIRI retrieval is 81.28 m, while for the Radar&Lidar is 86.20 m. Another important figure is the standard deviation of the differences of the two cloud depths; it has been calculated in 52.80 m.

**Figure 4:** Scatterplot of the instantaneous cloud depth values retrieved from SEVIRI (MSG) and ground-based Radar&Lidar observations.

**Figure 5:** Scatterplot of the daily mean cloud depth values retrieved from SEVIRI and ground-based Radar&Lidar observations. The data points correspond to collocated and synchronized cloud depth retrievals at the three different CloudNet sites as the legend shows.
4. CONCLUSIONS

Cloud droplet concentration is a very important parameter for the monitoring of aerosols indirect effects. However, no global observation is available because it is not straightforward its retrieval by current satellite remote sensing techniques. The main purpose of the presented algorithm is to further strengthen the idea that consistent and reasonably accurate retrievals of cloud droplet concentrations and cloud depths for water clouds are achievable with current satellite instruments in support of long term global indirect aerosol effect studies. The retrievals rely on a model for the vertical variation of cloud microphysical and optical properties which contain a number of assumptions. The main assumption is that the cloud is single-layered, quasi-adiabatic with a smooth liquid water profile.

This work shows the ability and the accuracy of the described algorithm to retrieve consistently the cloud depth from passive satellite, starting from satellite derived information on cloud optical thickness and effective radius. In fact, ground-based and satellite retrieved cloud depths show very good agreements. The instantaneous comparison shows fairly good agreement between cloud depth from satellite and ground-based observations (CF = 0.73). Both satellite and ground-based retrievals span a wide range of cloud depth values. The agreement between ground-based and satellite retrievals improves when daily means are used instead of instantaneous retrievals (CF = 0.80). The mean values retrieved from SEVIRI are very close to the ones measured from the ground active instruments, showing that the algorithm can robustly describe the cloud depths.

During this work, the algorithm has been improved in setting the best value for the adiabatic factor that introduced the most uncertainties and errors in the retrievals. The adiabatic factor was set to 0.72, being the best values to obtain very good agreement with the ground-based measurements. The setting of Fr to 0.72 shows that water clouds over Northern Western Europe deviate from an adiabatic behaviour.

The correct retrieval of cloud depth leads to a better calculation of the cloud droplet concentration. The latter cloud property cannot be validated since the lack of direct ground based or in-situ measurements. However, a comparison of the obtained results with the values present in the literature shows that the SEVIRI retrieved droplet concentrations are in the same interval of values of the other findings. (Brenguier et al., 2003, Schuller et al., 2005).

A direct validation of the satellite retrieved droplet concentration will be possible in 2008 when Cabauw site will be fully equipped with instrumentations for remote sensing purposes. At that time, the SEVIRI droplet concentration retrieval can also be validated and it can be stated exactly with which accuracy and precision SEVIRI can be used to study the first indirect aerosol effect. Further validation studies of the presented algorithm are described in a paper submitted to the Geophysical Research Letters by Roebeling et al., 2007a where simultaneous validation of liquid water path and cloud depth retrieved from SEVIRI are addressed along with the back trajectories to study where the air masses have been originated and study the relations between anthropogenic activities, aerosols loads and cloud droplet number concentration.

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6. REFERENCES


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