REMOTE SENSING OF INHOMOGENEOUS CLOUDS WITH MSG/SEVIRI

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ABSTRACT

Clouds are inherently inhomogeneous on all spatial and temporal scales. The neglect of this fact in standard remote sensing techniques introduces uncertainties in form of biases and noise. The quantification of deviations caused by cloud inhomogeneity and possible solutions are of major concern, considering the potential of remote sensing for a global characterisation of clouds and their interaction with the radiation field. We found that, on average, reliable cloud properties are retrieved by a standard method from MSG/SEVIRI data for overcast pixels. However, larger systematic errors occur for partly cloudy pixels. For individual pixels the uncertainties can be considerable. The high resolution visible (HRV) channel of SEVIRI has the capability to improve the normal/low resolution situation, because it provides some sub-pixel inhomogeneity information. In a EUMETSAT case study on the quantitative exploitation of the HRV in synergy with low resolution spectral channels we studied possible improvements for cloud detection and microphysical property retrievals. The accuracy of the derived optical thickness and effective radius were significantly improved when HRV sub-pixel information was included. Future work is planned on more general cloud situations derived from numerical weather model data.

Key words: 3D radiative transfer, cloud, independent pixel error, plane-parallel error.

1. INTRODUCTION

On average about 70% of the earth surface are covered with clouds (Rossow & Schiffer 1999). The observation of cloud characteristics and evolution on a global scale is a principal task of satellite based remote sensing particularly of observations by sensors on geostationary satellites like MSG. Standard passive remote sensing techniques are based on simplifying assumptions on the radiative transport. The possibility of radiative interaction between individual pixels is neglected and clouds are assumed to be plane-parallel and homogeneous throughout each pixel, because below the scale of a sensor’s field of view the cloud inhomogeneity remains unknown.

The first assumption is the so called independent pixel approximation (IPA) and the error caused by the neglect of horizontal transport of radiation between neighbouring pixels is the independent pixel error (Cahalan et al. 1994b). It increases as the pixel size decreases, because the smaller the pixel is the more important becomes the net horizontal photon transport compared to the vertical transport. The neglect of sub-pixel inhomogeneity is the plane-parallel approximation. This assumption leads to a bias in the retrieved cloud properties due to the nonlinear dependence of cloud properties and the related reflected radiance (Figure 1d), the plane-parallel bias (Cahalan et al. 1994a). The bias generally increases with pixel size as the amount of unresolved sub-scale inhomogeneity is increasing.

Apart from several investigations on the impact of a neglect of cloud inhomogeneity and three-dimensional radiative transport on the derived radiative fluxes, e.g. Marshak et al. (1998); Scheirer & Macke (2003) or Di Giuseppe & Tompkins (2003), there have been first attempts to investigate the uncertainties of cloud property retrievals (Loeb et al. 1998; Varnai 2000) and to systematically quantify them (Varnai & Marshak 2001). First approaches to quantitatively consider cloud inhomogeneity
Figure 1. (a) shows the field of optical thickness on which the synthetic high resolution observation (b), simulated with the 3D radiative transfer model MYSTIC, is based on. (c) shows the optical thickness retrievable by a standard remote sensing technique; (e) the satellite resolution observation of the same scene; and (f) the related retrievable optical thickness. (d) is an example of the relationship of optical thickness and reflected radiance: two high resolution “sub-pixel” radiance values will always lead to the derivation of a larger optical thickness than their pixel average value would allow for.
the basis of the investigation (dimensions around 10 km × 1.3 km). Shown is the simulated observation at full resolution of 15 m × 15 m (top) and at the investigated satellite sensor resolution of 13 km² (wavelength band 830 nm).

In retrieval schemes were proposed as well (Faure et al. 2001, 2002; Iwabuchi & Hayasaka 2003).

Similar to the example of Figure 1 most investigations on the impact of a neglect of cloud inhomogeneity and three-dimensional radiative transport are based on predefined 3D cloud structures. Different approaches were used to generate those cloud structures: models using measured statistical cloud properties (as in Figure 1) or numerical cloud resolving models. As the results decisively depend on the realism of predefined cloud inhomogeneity it generally seems desirable to stay as close as possible to observed data. The following investigations are based on 3D cloud structures determined from airborne remote sensing observations. In Zinner et al. (2005) the technique of determination of 3D structures considering the above mentioned radiative transfer caveats is introduced. Three-dimensional distributions of cloud properties of 27 cases of single layer marine stratocumulus were retrieved from high resolution imagery there.

In section 2, for this testbed of realistic cloud structures the natural radiative transport is simulated and a standard remote sensing technique for the retrieval of optical thickness is investigated. Section 3 comments on a EUMETSAT study on the use of the HRV aboard MSG to improve the situation. Future work to extend investigations on more general cloud situations over larger areas is described in section 4.

2. IMPACT OF CLOUD INHOMOGENEITY ON THE RETRIEVAL OF OPTICAL THICKNESS

For the testbed of 27 stratocumulus cloud structures arbitrary solar illumination and sensor settings can be simulated. To investigate a standard cloud property retrieval for clouds observed with SEVIRI over the area of Central Europe, a viewing zenith angle of 55° was simulated for several solar illumination geometries reflecting the typical situations during a day. The sensor was assumed to observe the scene directly from the south. The size of each of the cloud scenes is around 1.3 km × 10 km (cf. Figure 2). Thus each complete scene is assumed to constitute one pixel; its size of 13 km² is between the pixel size of the SEVIRI normal resolution and high resolution channels for Central Europe.

A Lambertian surface albedo of 2.5% (realistic for sea surface outside the sunglint region) is assumed. For all calculations a standard atmosphere for mid-latitude summer was used. Solar zenith angles simulated are 0, 30, 45, and 60°, the solar azimuth angles relative to the south are 0, 45, and 90°. A total number of 10 simulations is thus conducted for each of the 27 cloud situations. With the 3D model MYSTIC realistic reflectance fields are obtained at the maximum spatial resolution of 15 m × 15 m and subsequently these fields are averaged to the desired sensor’s horizontal resolution (Figure 2).

The SEVIRI channels 3 (centred at 830 nm) and 4 (1600 nm) are simulated. Accordingly the standard remote sensing technique investigated is a two channel method to simultaneously retrieve optical thickness and effective radius (Nakajima & King 1990, e.g.). The following analysis concentrates on the results for optical thickness.

In Figure 3 the results are summarised for the solar zenith angles 30 and 60°. The two error components, the independent pixel error and the plan-parallel error, are separated in Figures 3a and b. Figure 3c shows the sum of both, the total error. All errors are given relative to the real optical thickness of the analysed pixels and in dependence on the pixel cloud fraction which is the most important measure of sub-scale inhomogeneity. Shown is the average error (thick solid lines) and the spread of single pixel’s error values (shaded regions). The errors are averaged over all three solar azimuth angles simulated.

Due to the independent pixel assumption the retrieved optical thickness shows a clear underestimation for pixel cloud fraction smaller than 0.5 on average (Figure 3a). Reason is the already mentioned effect of increasing transmission because of the horizontal photon transport. For larger pixel cloud coverage this effect becomes less important. At the same time the impact of effective cloud cover increases: For non-zero solar zenith angle as well as for the non-zero sensor zenith angle the cloud coverage is effectively larger than its nominal value. The incident radiation “sees” fewer cloud gaps the greater the solar zenith angle is and the observed radiance is preferentially reflected by cloud top regions visible at the sensor zenith of 55°. In the case of the investigated cloud type of marine stratocumulus and its distinct vertical profile of microphysics these are more reflective than the lower parts of the cloud structure. This eventually leads to the observed small average overestimation for maximum cloud cover.

The plane-parallel error component is of great importance at the given satellite resolution, especially in situations of medium pixel cloud fraction (Figure 3b). Positive as well as negative plane-parallel biases are visible. The source of negative deviations was already illustrated before (Figure 1d); the positive values occur if small values of optical thickness are involved as it happens for small pixel cloud fractions. At these smallest values a non-linearity of the opposite sense (compared to the effect shown in Figure 1d) is present in the relationship of optical thickness and reflected radiance.

The total error (Figure 3c) reflects a clear underestimation of retrieved optical thickness for all but the greatest class of cloud fractions. Up to cloud fractions of around 0.8 mean underestimation has values of 10% and more for all
Figure 3. Analysis of the impact of cloud inhomogeneity on the retrieval of optical thickness for 27 cases of marine stratocumulus for a mid-latitude geostationary sensor setting (55° viewing zenith angle, pixel size about 13 km²) for two solar zenith angles (30°, 60°; solar azimuth angles – 0, 45, 90° – are not separated): Thick lines give the bias with respect to the real optical thickness, the shaded regions give the spread of single pixel’s errors of all pixels excluding the minimum and maximum 10% of error values. Values are averaged over intervals of pixel cloud fraction (0-0.1, 0.1-0.3, 0.3-0.5, ...). (a) shows the independent pixel contribution to the total error relative to the real cloud optical thickness of each pixel $\Delta \tau_{ip\ rel}$, (b) the plane-parallel contribution $\Delta \tau_{pp\ rel}$, and (c) the sum of both, i.e. the total error $\Delta \tau_{tot\ rel}$. 
solar zenith angles. Thereby it is clear that there is a relevant bias due to cloud inhomogeneity in all cases where a complete cloud coverage of the pixel is not guaranteed. Apart from those mean values the uncertainty of retrieved optical thickness for single pixels is much larger, even for situations of complete cloud coverage. Additional deviations of 20 to 50% are common.

3. USE OF THE HRV CHANNEL

The HRV has a sampling distance at the sub-satellite point of 1 km. This enhanced spatial resolution enables to distinguish small cloud structures like small orographic or convective clouds in a much better way than the low resolution channels, whose sampling distance is limited to 3 km. This offers the unique possibility of determining a high resolution cloud mask and sub-pixel cloud cover, i.e., the internal cloud cover of a low resolution pixel. This additional information can be used to partially account for the plane-parallel error. In fact, each measured low resolution radiance $R_{\text{measured}}$ can be expressed as

$$R_{\text{measured}} = (1 - c) \times R_{\text{cloud-free}} + c \times R_{\text{cloudy}},$$

where $R_{\text{cloud-free}}$ is the mean radiance originating from the cloud-free sub-pixels, $R_{\text{cloudy}}$ is the mean radiance stemming from the cloudy sub-pixels, and $c$ is denotes cloud cover. If the cloud-free radiance is known or can be retrieved, it is possible to solve this equation and compute $R_{\text{cloudy}}$. This quantity can be then used to compute mean cloud properties for the cloudy HRV pixels.

Concentrating on the retrieval of optical thickness by the method described in section 2, it could be shown that mean error and standard deviation improve from -0.274 to -0.093 and from 0.241 to 0.184, respectively. The expected underestimation explained in section 2 can be thus noticeably reduced. It must be noticed however that the presented method cannot account for the sub-pixel variability of cloud properties. These results are based again on simulations of a synthetic stratuscumulus cloud field retrieved from airborne measurements and have been performed in the framework of EUMETSAT ITT No. 03/542 “Study on Quantitative Use of the High Resolution Visible Channel Onboard the Meteosat Second Generation Satellite” (Bugliaro & Mayer 2004). A publication of the results is in preparation.

4. OUTLOOK

The work up to this point concentrated on detailed studies of the physical basis of uncertainties for single layer boundary layer water clouds (section 2) and a case study on potential improvements exploiting the technical possibilities of the new MSG/SEVIRI sensor (section 3). An algorithm accounting for inhomogeneity questions is desirable and seems feasible on the basis of the results obtained. However, such a method has to be based on larger numbers of cloudy pixels and on different cloud types. As already mentioned cloud resolving models or even weather forecasting models could provide common scenes of cloudiness typical for large areas. Especially from the latter ones cloud scenes related to all kinds of meteorological situations as large as whole Central Europe are available on a daily basis.

Consequently we developed a processing scheme to prepare input data for radiative transfer calculations based on cloud water fields from the DWD Lokalmodell (LM). Three-dimensional fields of cloud water, ice water, effective droplet and crystal size as well as water vapour fields are input to our radiative transfer package SIMSAR. This tool, based on libRadtran, is capable of simulating arbitrary satellite sensors taking into account all relevant atmospheric constituents. For large scenes, the radiative transfer simulations were limited to independent column/pixel (1D) computations as the computational effort of 3D radiative transport simulations is tremendous. Two examples of simulated Meteosat-7/MVIRI observations face-to-face with the real satellite data are shown in Figure 4 for the visible channel and the water vapour channel.

The morning situation illustrates the limitations of the 1D approximation: Effects of horizontal radiation transport like the pronounced shadows can not be reproduced. Nonetheless these calculations are a very valuable starting point for test and development of remote sensing techniques. As it was indicated in section 2 the impact of the independent pixel error on the mean reliability of the retrieval is small except for the smallest cloud fractions and the largest sun zenith angles. Nevertheless, we plan the first large-scale 3D simulations in the near future, to correctly account for cloud geometry effects.
For improvements concerning the plane-parallel error, which is of major importance at Meteosat sensors’ fields-of-view, 1D calculations are sufficient. In this case realistic sub-pixel information has to be available as input data. In this respect operational weather models are still limited. The LM has a horizontal resolution of about 7 km × 7 km today and will operate on a resolution of 2.8 km × 2.8 km from 2006 on. In addition, for all numerical atmospheric models the variability on the smallest scales simulated is not realistic for numerical reasons (Bryan et al. 2003). Thus we included a technique to add realistic small scale inhomogeneity into the LM/SIMSAT processing scheme. This task is achieved by well known statistical characteristics of clouds: The variability of cloud microphysics on small scales is given through the large scale variations within the inertial subrange of atmospheric turbulence (Kolmogorov 1941). A simulation for an input field of cloud data from LM with enhanced resolution is shown in Figure 5.

5. SUMMARY AND CONCLUSIONS

The neglect of real cloud inhomogeneity in standard cloud remote sensing techniques causes great uncertainty and noticeable biases. Two independent sources are effective: 3D radiative transport leads to the independent pixel error, unresolved sub-scale variability to the plane-parallel error. For a retrieval of optical thickness utilising synthetic measurements in two MSG/SEVIRI channels these problems have been assessed for the stratocumulus cloud type. Relative biases were small, about ±2% as long as the pixel’s sub-scale cloud fraction is close to 1.0. For broken clouds, biases increase quickly to about 10 to 20% underestimation. The random uncertainty for individual pixels amounts to ±20% for fully covered pixel, ±50% for partially cloud covered pixels. This great uncertainty of a single pixel’s optical thickness is especially posing a problem for the use of remote sensing products with respect to validation or field campaigns when only a very limited number of pixels is evaluated.

In an EUMETSAT study the potential of the high resolution visible SEVIRI channel was evaluated to improve standard retrievals through the additional sub-pixel information. It was shown that a partial account for (low resolution) sub-pixel inhomogeneity is possible and the plane-parallel bias could be reduced.

Starting from these promising results it seems possible to develop remote sensing methods taking into account cloud inhomogeneity. Pre-requisite for such an effort is the availability of 3D representations of all common types of cloud situations, including vertically developed, multi-layer, and mixed phase clouds to investigate their interaction with the radiation field. For this purpose a processing scheme for the provision of 3D cloud structures from a numerical weather model output and a sophisticated (3D and 1D) radiative transfer package for the complete simulation of satellite sensor data (SIMSAT) was introduced.

REFERENCES

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Figure 5. Simulation of the visible channel of Meteosat-7/MVIRI for a resolution enhanced part of the scene in Figure 4 (resolution of 780 m × 780 m).