REMOTE SENSING OF WATER AND ICE CLOUDS FROM MSG/SEVIRI

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ABSTRACT

Clouds and their interaction with radiation are still one of the main uncertainties in our understanding of present and the prediction of future climate. MSG/SEVIRI - with its unique combination of time and spatial resolution and spectral information - has the potential of contributing significantly to the reduction of this gap. We have developed a new water and ice cloud detection and microphysical properties remote sensing algorithm. Cloud detection and classification is based on a prototype version of the EUMETSAT Scenes Analysis scheme, with a particular emphasis on the detection of thin ice clouds. Cloud microphysical properties are retrieved using tabulated forward calculations by a detailed radiative transfer code, libRadtran, which takes into account cloud phase, microphysical properties as well as a complete description of the background atmosphere and surface. Particular attention is given to the treatment of inhomogeneous clouds where we aim at combining the spectral information of the low-resolution channels with the higher spatial resolution of the HRV channel, in order to directly consider sub-pixel cloud inhomogeneity in the retrieval to reduce potential biases.

Key words: radiative transfer, cloud, cirrus.

1. INTRODUCTION

According to Houghton et al. (2001) probably the greatest uncertainty in future projections of climate arises from clouds and their interaction with radiation. A better understanding of clouds and their microphysical and optical properties is therefore crucial for improving the accuracy of climate predictions. The new spectral channels and the absolute calibration of MSG/SEVIRI allow the quantitative determination of cloud optical and microphysical properties. In addition to snapshots, which can also be obtained from polar orbiting satellites with even higher spatial resolution, the high repetition rate of MSG/SEVIRI allows to study diurnal variation of clouds as well as their formation and dissipation and their average lifetime. This will certainly help to gain better insights into the relevant processes required to better represent clouds in general circulation models. Also, the improved detection capability of MSG/SEVIRI will allow a better validation of the parameterization of clouds and in particular their interaction with radiation in general circulation models. Long time series are required for this purpose and we plan to extend our 15 year European Cloud Climatology (ECC) (Meerkötter et al. 2004) into the future using MSG/SEVIRI data. While the 15 year time series is subject to the orbital drift of the NOAA satellites which causes a slow shift in the overpass time, this is completely avoided when we make use of the data which are available every 15 Minutes.

In the following, the remote sensing methods developed in our group are described, including a brief outline of the libRadtran radiative transfer model which forms the basis of all these methods, a description of our satellite radiance simulator SIMSAT, as well as our water and ice cloud retrievals.

2. CLOUD REMOTE SENSING

Our group currently focusses on MSG/SEVIRI for water and ice cloud remote sensing. We are developing a cloud classification scheme based on a prototype of the Scenes Analysis Software provided by EUMETSAT, based on our long experience with the APOLLO (AVHRR Processing Over cLouds, Land, and Ocean) package (Kriebel et al. 2003). A retrieval scheme has been developed to quantitatively derive water and ice cloud microphysical properties (optical thickness and effective particle size). The development of classification and retrieval schemes is based on radiative transfer simulations with our libRadtran package (Kylling & Mayer 1993-2004). To this end, we have developed a simulator, SIMSAT, which allows us to simulate MSG scenes for given clouds, for all 12 spectral channels. Finally, we try to exploit the high spatial resolution of the HRV channel to improve the retrieval of inhomogeneous pixels which are rather frequent at the spatial resolution of the MSG field-of-view.
2.1. Radiative transfer simulations

libRadtran (Kylling & Mayer 1993-2004) is a flexible and user-friendly model package to calculate radiance, irradiance, and actinic flux for arbitrary input conditions which has been jointly developed by Arve Kylling (NILU, Norway) and one of us (Bernhard Mayer) since about 10 years. The model handles absorption and scattering by molecules and aerosols, as well as water and ice clouds. The underlying surface may be described in terms of a Lambertian albedo or a bi-directional reflectance distribution function (BRDF): Angular models for vegetation (Rahman et al. 1993a,b) and water surfaces including waves and whitecaps (Cox & Munk 1954a,b; Nakajima & Tanaka 1983) are implemented. libRadtran provides a choice of radiative transfer solvers, including the discrete ordinate code DISORT by Stamnes et al. (1988), a fast two-stream code, a polarization-dependent solver, polRadtran (Evans & Stephens 1991), and even a three-dimensional radiative transfer code, MYSTIC (Mayer 1999; Cahalan et al. 2004) which is our benchmark tool for radiative transfer under cloudy conditions. To simulate satellite radiances, we usually employ the DISORT solver, version 2.0, which is ideally suited to accurately handle the highly detailed phase functions of water and ice clouds.

libRadtran allows different choices for spectral calculations, including a line-by-line option, different correlated-k distributions, as well as a pseudo-spectral option based on the LOWTRAN three-term exponential sum fit with a spectral resolution of 20 cm$^{-1}$, adopted from the SBDART code (Ricchiazzi & Gautier 1998). For the simulation of satellite radiances we currently use the latter, with 15 spectral grid points for each MSG/SEVIRI channel. In future we plan to optimize the spectral grid and to develop correlated-k distributions specifically for the SEVIRI channels. An example of the simulation is shown in Fig. 1.

The optical properties of water clouds are calculated using Mie theory and tabulated as function of the effective droplet radius. For ice clouds where the assumption of spherical particles is not applicable parameterizations are used: For the solar spectral range, the single scattering properties are provided by Key et al. (2002); Yang et al. (2000) while for the thermal channels the parameterization by Fu et al. (1998) is used. The further uses a double-Henyey-Greenstein approximation of the phase function which has been shown to be a good approximation of theoretical and observed scattering phase functions of non-spherical ice particles (Gonzalez et al. 2002), even for the calculation of radiance. The parameterization for the longwave range uses a one-parameter Henyey-Greenstein phase function defined on a relatively coarse wavelength grid. As scattering is less important in the longwave range, this may serve as a first approximation, but for the future it is planned to setup a consistent database of ice cloud optical properties throughout the whole shortwave and longwave spectral ranges.

Figure 1. (Left) line-by-line calculation of the atmospheric transmittance in the MSG/SEVIRI 3.9 μm channel; the absorption bands are due to H$_2$O, CO$_2$, N$_2$O, and CH$_4$; (right) libRadtran simulation of the filter-weighted nadir radiance for the 3.9 μm channel for a homogeneous cloud, embedded in the midlatitude summer atmosphere; LOWTRAN parameterization of the absorption coefficient (thin line) and the 15 bands which we routinely use for the simulation of MSG/SEVIRI channels (thick line); the spectral radiance is modulated by the wavelength dependence of the optical properties of the cloud.
2.2. Simulation of MSG scenes

Using libRadtran, MSG/SEVIRI observations can in principle be simulated. libRadtran is designed to calculate single spectra for a given wavelength setting, sun and satellite geometry, atmospheric profile, and surface properties. Calculation of realistic satellite scenes can therefore be a rather tedious task, as the sun and satellite geometry, the atmospheric profile (in particular clouds) and the surface properties vary from pixel to pixel. Therefore, a user-friendly front-end has been developed for libRadtran: SIMSAT allows to simulate scenes for different satellite instruments including MSG/SEVIRI, requiring minimum input by the user: For given location, time, scene size, and cloud properties a field of pixel radiances is automatically calculated for selected satellite channels. Fig. 2 shows an example of such a scene, using a three-dimensional cloud distribution generated by one of our stochastic models. The top shows the horizontal distribution of optical thickness, the middle plot the simulated HRV radiance, and the bottom plot the 10.8 µm radiances as an example for the low-resolution thermal channels. The resolution of the images is the actual MSG/SEVIRI resolution and the scene size in this case is about 40 x 40 km$^2$. These simulations can be done with the usual one-dimensional independent pixel approximation, but a three-dimensional radiative transfer calculation is also possible in principle. It is immediately clear that SIMSAT is an invaluable tool for developing and testing remote sensing algorithms: Different from an actual observation, not only the radiances are known but also the underlying cloud properties. As the radiative transfer simulation uses our best knowledge of the optical properties of water and ice clouds, the results are probably very realistic and hence ideally suited for testing the ability of remote sensing algorithms to retrieve certain cloud properties.

An essential element of these calculations is a realistic description of clouds. Within the framework of our studies of radiative transfer in inhomogeneous clouds, we have developed several ways to create realistic three-dimensional cloud structures, either from statistical assumptions or from satellite or aircraft observations (Zinner 2004; Scheier & Schmidt 2004). In both cases, vertical profiles of the optical properties are derived using assumptions about cloud physics. With this combination, realistic three-dimensional cloud structures and SIMSAT, we are able

- to develop and optimize cirrus cloud tests,
- to quantify the detection limit for optically thin clouds,
- to determine the accuracy of optical thickness and effective size for thin ice clouds,
- to study the influence of sub-pixel inhomogeneity on the retrieval of cloud properties at the MSG/SEVIRI resolution,
- to quantify the accuracy of the CO$_2$ slicing method in determining cloud altitudes,
- and many other applications.

Figure 2. A simulated MSG scene. (Top) Cloud optical thickness, generated by a stochastic model. (Middle) HRV radiances. (Bottom) 10.8 µm radiances.
2.3. Retrieval of cloud optical properties

Cloud classification is based on a prototype of EUMETSAT’s scenes analysis software. For cloud detection we use a classical threshold method combining various channels. To retrieve the optical properties of water and ice clouds, a two-channel retrieval scheme has been developed, exploiting a channel with zero cloud absorption (0.6µm) and one with cloud absorption (1.6µm). The method follows the traditional approach by Nakajima & King (1990); Nakajima et al. (1991), with the major difference that for the absorbing channel we selected the 1.6µm channel instead of the 3.9µm channel. While the sensitivity to water clouds is smaller at 1.6µm than at 3.9µm, (1) the 1.6µm channel is not affected by thermal emission; hence the knowledge of cloud top temperature is not required which redundancies the use of a third, thermal, channel; (2) the 3.9µm channel includes overlapping absorption bands by CO2, H2O, N2O, and CH4 which make the simulation more uncertain (see Fig. 1). The algorithm is based on a lookup-table, calculated with libRadtran as described above. As an example, results for ice clouds are shown in the next section.

2.4. Quantitative cirrus cloud detection

Cirrus clouds are an important component of the climate system: Despite their usually small optical thickness, their location close to the cold tropopause results in a large greenhouse potential, and in contrast to water clouds, cirrus tends to warm the surface. One of the important open questions in the last IPCC reports (Penner et al. 1999; Houghton et al. 2001) was the contribution of air traffic to climate forcing: While the impact of linear contrails is reasonably assessed, the indirect effect of aircraft on natural cirrus is an open question with the potential of making a significant contribution to global warming. Hence there is particular interest to quantitatively derive cirrus clouds and their microphysical properties on a global scale.

Cirrus clouds are different from water clouds in several respects: First, their optical thickness is usually smaller than that of water clouds. Second, the particle shape is non-spherical for which reason an a-priori assumption of the particle shape is necessary (Gonzalez et al. 2002). Third, their top is usually much higher in the atmosphere, close to the tropopause. Fourth, their top temperature is usually much lower than that of water clouds. While the first two points cause higher uncertainty in the determination of the optical thickness, the third and fourth properties can be used to detect cirrus clouds using infrared channels which has the big advantage of being applicable during day- and nighttime. Our ice cloud detection algorithm is based on a combination of water vapour channels (6.2 and 7.3µm) and IR channels (8.7, 10.8, 12.0, and 13.4µm) using thresholds for different combinations of these channels. Alternatively, we use morphological tests to separate the variable cirrus clouds from the slowly varying background in the water vapour channels. Fig. 3 shows as an example a noontime image for May 17, 2004. The top shows a false-color composite (red: 0.6µm; green: 0.8µm; blue: 10.8µm inverted). The second image is the cirrus cloud mask, and the lower panels show optical thickness and effective particle radius. The optical thickness reaches very high values in some areas, indicating that the cirrus cloud lies above a lower water cloud. As has been shown by Gonzalez et al. (2002), optically thin water clouds may be quantitatively separated from lower water clouds using a combination of the different viewing geometries of ATSR, ATS/2, or AATSR. The available single viewing geometry of MSG/SEVIRI does not allow such a separation, at least not when using shortwave channels for the determination of the optical thickness.

2.5. Exploitation of the HRV channel to improve cloud property retrieval

In a study, partly funded by EUMETSAT, we explore the use of the HRV channel, in particular for the detection of clouds and the retrieval of their microphysical properties. Due to the inherent inhomogeneity of clouds at all spatial scales, a considerable fraction of MSG/SEVIRI pixels (estimated to about 30%) is classified as “partly cloudy”. Even those pixels classified as “fully cloudy” show certainly a varying degree of inhomogeneity over the field of view of the instrument. In a study currently summarized by Zinner (2004), it has been shown that sub-pixel inhomogeneity and the variability between neighbouring pixels may cause considerable uncertainty in the derived cloud properties. As has been shown by Cahalan et al. (1994), the neglect of sub-pixel inhomogeneity leads to a systematic under-estimation of the derived optical thickness. The work of Zinner (2004) shows that the error in the optical thickness is partly cancelled when averaged over larger areas or longer times, while the uncertainty in the derived effective radius may be considerable, even after averaging.

To avoid such errors, we started using the high-resolution information of the HRV channel. In a first step, sub-pixel cloud fraction is determined, which is then used as extra information in the retrieval. Preliminary results show that the uncertainty in the retrieved properties may be reduced considerably.

3. SUMMARY AND CONCLUSIONS

The purpose of this paper was to give an overview of the methods and tools developed in our group. Details about the individual methods have been and will be described elsewhere. MSG/SEVIRI proofs to be a unique tool for the remote sensing of water and ice clouds which we will heavily employ during the following years. In particular, we plan to study the life cycle of contrails and cirrus clouds, to extend our 15 year European Cloud Climatology (ECC) into the future using MSG/SEVIRI data. Using the HRV channel we try to reduce the uncertainty of cloud retrievals, due to the unavoidable cloud inhomogeneity within the field of view of the satellite.
Figure 3. Ice cloud classification and properties retrieval. (a) MSG/SEVIRI scene, May 17, 2004, 12:00; false-color composite; (b) cirrus cloud mask; (c) optical thickness; (d) effective particle radius.
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