Application of CM-SAF cloud and radiation products to verify surface cloud radiative effects in climate models over ocean

Timo Hanschmann¹, Andreas Macke¹, Rob Roebeling², Hartwig Deneke¹

¹ Leibniz Institute of Tropospheric Research (IFT), Leipzig
² The Royal Netherlands Meteorological Institute (KNMI), Utrecht

Abstract

We investigate the question whether the radiative transfer scheme of the ECHAM-5 climate model can reproduce the shortwave cloud radiative effect (CRE) at the surface, given a detailed characterization of atmospheric state based on measurements. For this purpose, we use two different datasets of cloud properties obtained from ship instruments, in particular a microwave radiometer, as well as from the Meteosat SEVIRI satellite imager. Three different experiments have been defined and applied to five different synoptic situations to model the downward shortwave radiation (DSR) at the surface, and to compare their accuracy to radiation measurements.

Overall, we find that using satellite based estimates leads to a comparable accuracy of modeled DSR to that using ship based data. Due to their different measuring characteristics, however, each dataset shows best results for different atmospheric conditions. In particular, the satellite based estimates have problems in broken cloud situations with small cloud cover, likely caused by the coarse pixel resolution, but lead to the best results for homogeneous overcast situations. Furthermore we demonstrate the improvement obtained through including the effective radius as additional information from satellite to describe the model atmosphere.

Introduction

Clouds strongly influence the energy budget of the earth’s atmosphere. Because of their high degree of temporal and spatial variability, and the complexity of cloud processes, it is challenging to predict and model the effect of clouds on the energy budget. The representation of clouds in global circulation models (GCM) are therefore identified by the International Panel on Climate Change (IPCC, Solomon et al., 2007) as the largest source of uncertainty for predicting future climate change. Especially the CRE, defined as the difference between the net radiative fluxes of the cloudy and clear atmosphere, often is not represented satisfactorily. The reason for this is the high diversity of the CRE itself, and its dependence on a large variety of cloud parameters and their distribution inside the cloud. These parameters include the profiles of ice and liquid water, effective radius, and cloud droplet number concentration. To evaluate this source of uncertainty in GCMs, it is important to identify those situations in which the model can reproduce the CRE well and badly. For this purpose, ground based measurements as well as satellite based estimates can be used (Macke et al., 2011). Ground based measurements are also needed to verify the accuracy of satellite products, which are generally based on indirect
retrieval techniques. Over the ocean, however, which covers nearly 2/3 of the earth, ground based measurements of cloud properties and radiative fluxes are rare. It is thus also of interest to find out whether satellite-based estimates of cloud properties can represent the atmosphere as well as ground based observations.

Data, Model, and Methods

To understand why GCMs cannot reproduce the CRE accurately in specific situations, it is important to compare measurements with model outputs on a high temporal and spatial resolution. This is necessary because cloud processes of relevance for the energy budget also take place on very small scales. These effects are no longer present, or cannot be attributed to their origin if datasets are averaged over longer times. OCEANET is a project on an independent measurement platform for the ocean and atmosphere exchange of energy and matter. In the context of the project, seven cruises between the northern and southern hemispheres have been done with the research vessel POLARSTERN (Macke, 2009). OCEANET provides ship based measurements of cloud properties and radiative fluxes in a high temporal resolution. Following data are used in this study to describe the model atmosphere by ship based measurements. Liquid water path (LWP), temperature and humidity profiles are derived from a HATPRO microwave radiometer (Rose and Czekala, 2009). The microwave radiometer uses a statistical retrieval, which relies on a trainings dataset to compute LWP and T+H-profiles from received radiances. A pyranometer CMP21 (Kipp&Zonen, 2006) measures the global radiation. This is done by measuring the differential heating of an absorbing disk exposed to radiation relative to a shaded reference, which is converted into a voltage by a thermopile. These data are provided in two second resolution. A total sky imager is used for capturing images of the whole sky every fifteen seconds. An algorithm is used to compute the cloud fraction for each image using the difference between the red and blue information from the RGB colorspace. The instruments are shown in figure 1, 2, and 3.

The Satellite Application Facility on Climate Monitoring, initiated by EUMETSAT, provides a large variety of level-3 products corresponding to hourly, daily, and monthly means on a 15kmx15km sinusoidal grid (CM-SAF, 2008). In particular, several products on cloud properties and radiative fluxes are derived based on Meteosat SEVIRI. To evaluate a radiative transfer scheme and its ability to resolve the CRE, we have found it beneficial to use products at highest possible temporal and spatial resolution. Instead of the level-3 products, we have therefore used level-2 products calculated with the CM-SAF retrievals to obtain cloud properties.
(liquid water path, optical depth, and effective radius) on the temporal and spatial resolution of SEVIRI. For the surface solar irradiation, we have used hourly data with SEVIRI’s full spatial resolution. The method of Nakajima and King (1990) is applied to estimate cloud optical thickness (COT) and effective radius ($R_{\text{eff}}$). This is done using SEVIRI’s 1.6µm channel for the absorbing wavelength, and the 0.6µm channel as non-absorbing wavelength. From COT and $R_{\text{eff}}$, the liquid water path (LWP) is estimated with the following equation (Roebeling et al., 2008).

$$LWP = \frac{2}{3} \text{COT} R_{\text{eff}} \rho$$  \hspace{1cm} \text{Eq.1}

Only LWP and COT are official CM-SAF products, but equation 1 allows us to obtain the effective radius from the official CM-SAF products. The surface solar irradiation is computed using look up tables with transmittances (CMSAF, 2008 and Macke et al., 2010).

Both the ship based and satellite based datasets are available with different temporal and spatial resolution. Additionally, the different instruments sample different volumes of the atmosphere, and are thus sensitive to different scales of variability. For our comparison, both datasets have been matched in space and time, and averaged to remove small scale variability not resolved by the satellite measurements. Following Greuell and Roebeling (2009) and Denek et al. (2009), averaging has been applied both in space and time. Spatial averages has been obtained for satellite estimates using a Gaussian weighting function with a full width half maximum of 3x3 pixels. For averaging of the ship based time series, we found that Gaussian averaging over 30 minutes leads to the best results. This roughly corresponds to the time it takes the ship to cross the hemispheric field of view of the pyranometer. With these averaging techniques, we obtain time series of both datasets representing similar scales of variability. This is shown in figure 4 for the liquid water path for November the 3r, 2007, where light grey stands for the non-averaged microwave radiometer LWP (MWR-LWP), blue for the averaged MWR-LWP, and dark grey for the CM-SAF LWP.

We use both datasets to describe the atmosphere as input for the radiative transfer scheme of the ECHAM-5 climate model, which is used in single column mode for this study. This implies that only the radiative transfer scheme is run for each model column separately. Like other GCMs, ECHAM-5 is based on the assumption of plane parallel clouds, which assumes a homogeneous distribution of LWP and cloud droplet number concentration within one grid cell.
The radiative transfer scheme is based on the two stream Eddington approximation. Scattering at cloud droplets and ice crystals are computed by Mie theory and molecular scattering is taken into account by Rayleigh scattering. Aerosols are considered in scattering and absorption. For our purpose the single column model (SCM) is only used for single timesteps. Through this, no evolution of cloud droplets takes place such as particle growth or precipitation.

**Experiments and Results**

For this study, we computed the daily cycle of the downward shortwave radiation (DSR) at the surface with the SCM, and compared it to the ship based radiation measurements. We defined three different experiments for testing the sensitivity of the model to the input atmosphere, and for understanding the processes and mechanisms leading to differences between the different model experiments and the ship based measurements.

Table 1 gives an overview of all three experiments. For experiment PS, the atmosphere in the model is only described by ship based measurements. In experiment CM-SAF, CM-SAF data are used to describe the cloud properties. We use the LWP to calculate the mixing ratio of liquid water, and the effective radius to obtain the cloud droplet number concentration. For evaluating the benefit of the effective radius information on the radiative transfer calculations, we also defined the experiment MIX. This experiment uses the CM-SAF LWP together with the standard profile of cloud droplet number concentrations, as is used by the model for maritime clouds.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Experiment PS</th>
<th>Experiment CMSAF</th>
<th>Experiment MIX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixing Ratio of Liquid Water</td>
<td>OCEANET</td>
<td>CMSAF</td>
<td>CMSAF</td>
</tr>
<tr>
<td>Temperature Profile</td>
<td>OCEANET</td>
<td>OCEANET</td>
<td>OCEANET</td>
</tr>
<tr>
<td>Humidity Profile</td>
<td>OCEANET</td>
<td>OCEANET</td>
<td>OCEANET</td>
</tr>
<tr>
<td>Cloud Cover</td>
<td>OCEANET</td>
<td>OCEANET</td>
<td>OCEANET</td>
</tr>
<tr>
<td>Surface Pressure</td>
<td>OCEANET</td>
<td>OCEANET</td>
<td>OCEANET</td>
</tr>
<tr>
<td>CDNC</td>
<td>Standard marine profile</td>
<td>CMSAF</td>
<td>Standard marine profile</td>
</tr>
<tr>
<td>Cloud height</td>
<td>OCEANET</td>
<td>OCEANET</td>
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</tr>
</tbody>
</table>
We selected five situations for the study, ranging from clear sky conditions without any influence of clouds to overcast conditions with optical thick and thin clouds. We also examined separately days with broken clouds with smaller and larger cloud fraction. For each situation, we modeled the daily cycle of the shortwave CRE at the surface (SWCRE) in a temporal resolution of 15 minutes corresponding to the SEVIRI repeat cycle.

Equation 2 defines the SWCRE at the surface as is used in this study, with $\alpha$ denoting the surface albedo.

$$SWCRE = (1 - \alpha) \ (DSR_{\text{all sky}} - DSR_{\text{clear sky}}) \quad \text{Eq. 2}$$

Figures 5 and 6 show the daily cycle of the SWCRE for two different situations. In both figures, the black curve corresponds to the pyranometer measurements and the shaded area around it indicates the variability during each averaging period. A large shaded area indicates strong fluctuations in the DSR at the surface within the 30 minutes averaging period. The other curves show the model results for the different experiments (blue for experiment PS, red for experiment
CM-SAF and orange for experiment MIX). The light grey bar indicates problems in the input data such as rain for the microwave radiometer (defective input), sunglint for CM-SAF data etc.

Broken cloud conditions dominate the situation displayed in figure 5. This is shown by the large variability of the measured DSR. At 14:00 UTC a negative peak occurs for all modeled DSRs, which is not observed by the pyranometer. The corresponding cloud field is shown in figures 7 and 8, corresponding to the images of the total sky imager (TSI) at 14:00 UTC and 14:15 UTC, combined with the DSR from the pyranometer and model experiments. The general situation is similar, with the direct sun contributing a large part to the DSR, and a cloud covering the left part of the sky. But the difference is in the right hand side of the image where many small clouds are present at 14:00 UTC and are gone at 14:15 UTC. These clouds enhance the cloud cover, N, which controls the DSR in the model by Eq. 3.

\[
DSR = N \cdot DSR_{\text{cloudy}} + (1-N) \cdot DSR_{\text{clear}} \quad \text{Eq. 3}
\]

The cloud cover has a large influence on how direct and diffuse radiation in the model is combined. Direct sun cases cannot be resolved by the model, what is another consequence from the plane parallel assumption.

In figure 6 an overcast day is shown with mostly homogeneous optically thin clouds. For this case experiments CM-SAF and MIX show particularly good results that are close to the ground based measurements. During noon all modeled fluxes show significant underestimation of the SWCRE. This corresponds to a positive measured SWCRE during this time, which implies a larger measured DSR than in the clear sky case (see Eq.2). In this case it is because of the broken cloud effect during noon, which is also indicated by the enhanced variability during this time. Broken cloud effects occur when direct radiation and diffusive radiation are both strong and superpose to enhanced DSR.

Table 2 gives an overview of the results for all experiments and all cases. Shown is the deviation of the modeled DSR to the measured DSR in percent. The best results are highlighted in bold. The clear sky case deviations show that the SCM can reproduce the DSR at the surface accurately in the absence of clouds. For the overcast thick case it has to take into account that

<table>
<thead>
<tr>
<th>Case</th>
<th>Experiment PS</th>
<th>Experiment CMSAF</th>
<th>Experiment MIX</th>
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</thead>
<tbody>
<tr>
<td>Clear sky</td>
<td>-0.6</td>
<td>-0.5</td>
<td>-0.5</td>
</tr>
<tr>
<td>Broken cloud 25 %</td>
<td>+13.4</td>
<td>+16.1</td>
<td>+11.5</td>
</tr>
<tr>
<td>Broken cloud 25 %</td>
<td>-0.3</td>
<td>+0.08</td>
<td>-0.2</td>
</tr>
<tr>
<td>Broken cloud 75 %</td>
<td>-13.2</td>
<td>-6.4</td>
<td>-17.7</td>
</tr>
<tr>
<td>Broken cloud 75 %</td>
<td>-8.8</td>
<td>-11.8</td>
<td>-17.8</td>
</tr>
<tr>
<td>Overcast thin</td>
<td>+11.5</td>
<td>-0.06</td>
<td>-7.4</td>
</tr>
<tr>
<td>Overcast thick</td>
<td>-5.4</td>
<td>-10.5</td>
<td>-26.4</td>
</tr>
</tbody>
</table>
this day was partly influenced by sunglint, which is excluded in the comparison but still might contribute to the enhanced deviation of experiment CM-SAF.

In summary the results in table 2 show no general difference in using ship based measurements or satellite based estimates for describing the atmosphere in the SCM. Both experiment CM-SAF and PS show good results for different cases. In particular, the experiment CM-SAF shows good results for the homogeneous cloud case and for the broken cloud case with large cloud fraction, but poor results for the broken cloud case with a small cloud fraction. This results from the fact that satellite retrievals of cloud properties have more problems to see clouds that are smaller than their spatial resolution.

**Conclusion**

In order to evaluate the SWCRE modeled by the radiative transfer scheme of the ECHAM-5 model, we have conducted three different experiments, and analyzed their results for five specific cases. Here, the main focus was put on the question if satellite based estimates of cloud properties can be used as input for the model, and if the modeled SWCRE can match that obtained with ship based measurements in terms of accuracy. For this purpose, all data were averaged to a common temporal and spatial resolution. Generally, using CM-SAF data does not result in a loss of accuracy, but this depends on the atmospheric situations. Satellite estimates show problems under broken cloud situations, which is likely due to problems with broken clouds and to distinguish between cloudy and clear sky scenes within pixels. On the other hand, we find that satellite estimates give better results for the overcast situation. This is likely due to the fact that satellites measure the spatial mean over the pixel area, while ship based instruments only measure a one dimensional cross section along their course. The pyranometer measures the radiance with a hemispheric field of view, so that satellites can possibly resolve the relevant atmospheric conditions better than the ship based microwave radiometer, which only has a narrow field of view.

The high variability of DSR in broken cloud situations causes fundamental problems in the comparison of model results and measurements. In particular the broken cloud effect, which enhances the radiation above clear-sky levels, cannot be reproduced by climate models. This is due to the plane parallel assumption made in the radiative transfer scheme, which does not consider horizontal transport of radiation from cloudy into clear-sky columns. For overcoming this issue, three dimensional radiative transfer models are needed together with realistic cloud fields. Cloud resolving models nested inside individual grid cells (Bretherton and Hartmann, 2009) could provide this information, and resolve the small scale cloud distributions. Also, the model output is given as grid box average of the clear-sky and cloudy fractions of the grid-box, which does not resolve the sharp transition from shaded conditions to direct sun observed for point measurements.

This study has shown the importance of using level-2 CM-SAF data for understanding deviations between modeled and measured irradiance. In several cases, mechanisms responsible for the differences between the experiment PS and the pyranometer measurements could only be identified because of the high temporal and spatial resolution of the level-2 data.
Through experiment MIX we also could show the importance of using the effective radius for modeling the SWCRE. As an additional factor for describing the cloud microphysics the effective radius is essential.

Acknowledgment

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