Estimating the PPH-bias for simulations of convective and stratiform clouds

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Abstract

The plane parallel homogeneous (PPH) approximation is known to generate systematic errors in the computation of reflectivity and transmissivity of a horizontally inhomogeneous cloud field. This PPH-bias is determined for two cloud fields, a stratocumulus and a shallow convective cloud scene, which have been simulated using a cloud resolving model. The independent column approximation has been applied as reference and a PPH analogue has been interpolated from the original cloud data. In order to correct for the bias the effective thickness approach (ETA) has been employed. For the two cloud simulations, the corresponding reduction factors have been determined.

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1. Introduction

Clouds show variability of liquid water path (LWP) on many different scales (Davis et al., 1999). In current general circulation models (GCMs) with typical horizontal resolution of some 100 km only the very coarse structure of these cloud fields can be resolved. On the sub-grid scale the only distinction is made between clear and cloudy sky. The latter is assumed to fill the whole vertical extent of the layer and is plane parallel and homogeneous in the horizontal. This is called plane parallel homogeneous (PPH) approximation. Due to the non-linear dependency of optical properties like reflectivity on LWP, neglecting sub-grid scale features leads to systematic errors as a direct consequence of Jensen’s inequality (Jensen, 1906): Cloud reflectivity is overestimated,
transmissivity underestimated. This PPH-bias has received considerable attention over the last years. Cahalan et al. (1994) developed the effective thickness approach (ETA) to correct for this error. Basically, it uses an effective cloud optical thickness in the radiation computation, which is smaller than the thickness derived from mean cloud properties directly. However, the reduction factor has to be determined empirically.

The ETA is the most widely applied correction method in current GCMs, because it can be implemented easily into standard two-stream radiation schemes (see e.g. Roeckner et al., 2003). However, the reduction factor has to be deduced empirically. In this study, we use data from a cloud resolving model in order to determine the PPH-bias and find appropriate reduction factors for convective and stratiform clouds.

A different approach based on probability density function (PDF) of liquid water content on the sub-grid scale has been introduced by Barker (1996). He assumed the PDF as a Gamma distribution, while Bäuml and Roeckner (submitted) start from a Beta distribution. For the small domain size of the cloud simulations we use in this study, the statistics are not good enough for fitting an appropriate distribution, thus, these statistical schemes cannot be applied.

2. Cloud data

The simulations have been performed with a Cloud Resolving Model (CRM) developed at the Max Planck Institute for Meteorology in Hamburg. It is based on the idea of Large Eddy Simulation (LES). LES means that all spatial scales, which represent the dominant large-scale turbulent motions, are explicitly resolved, while the effects of smaller scale turbulence on the resolved flow are parameterized. Therefore, the dominant cloud structures are explicitly calculated. An extensive description of the LES model can be found in Chlond (1992, 1994) and Müller and Chlond (1996).

The first case study is based on a situation encountered during flight RF06 in the framework of the Atlantic Stratocumulus Transition Experiment (ASTEX). The flight path followed a stratocumulus cloud over the North Atlantic (37°N, 24°W) in its transition state. An initially horizontally homogeneous cloud layer developed into a decoupled boundary layer with cumulus penetrating the stratocumulus deck from below. Further details of the ASTEX experiment and especially of the flight RF06 can be found in de Roode and Duynkerke (1997) and Duynkerke et al. (1999), respectively.

In their LES study Chlond and Wolkau (2000) tried to simulate the observed cloud field. The data used for the radiation computation in this work are labeled REFERENCE in their article. The first 30 min are neglected as LES model spin-up time, leaving 49 snapshots with an time interval of 3 min between them. For the REFERENCE-case the model domain was $28.8 \times 3.2 \times 1.5 \text{ km}^3$ with a horizontal resolution of $\Delta x = \Delta y = 50 \text{ m}$ and a vertical grid spacing of $\Delta z = 25 \text{ m}$. Fig. 1 gives an impression of the evolving cloud field. Cloud cover was 1 throughout the whole integration.

For the second case study initial and boundary conditions are applied, which have been derived from data collected during the Atlantic Trade Wind Experiment (ATEX) (Brümmer et al., 1974). This case was used as an intercomparison project of the GCSS program (Stevens et al., 2001). The experiment took place in the Atlantic northeast trade
wind region (near 12°N, 35°W). The model domain for this integration is 6.4 × 6.4 × 3.0 km³, where the horizontal grid spacing is Δx = Δy = 100 m and the vertical Δz = 20 m. Output is written every 5 min. The first 2 h of model integration are discarded as model spin-up time, leaving data of 5-h simulation time. Fig. 2 gives an example of the general structure of the simulated cloud field. Cloud fraction and liquid water path (LWP) vary substantially during the simulation.
Fig. 2. Snapshot of the trade wind cumulus simulation (ATEX). Shown are volume surface plot, colored by LWP (top), LWP (middle) and vertical profile of mean liquid water content (right).
3. Methods

All radiation computations are performed using a two-stream scheme, as it is implemented in the ECHAM4 climate model (Roeckner et al., 1996). It has been developed by Fouquart and Bonnel (1980) and has been slightly modified (Morcrette, 1989; Gregory et al., 1998). The simulations shown below are performed assuming no aerosol loading. Therefore clouds are the only scattering objects (apart from Rayleigh scattering), which simplifies interpretation. The droplet number density is parameterized for sea surface conditions (see also Roeckner et al. (1996)) and the ground albedo is set to zero, i.e. there are no surface effects. Since both cloud simulations are for maritime cloud systems and the observed ocean albedo is low, these parameter settings are consistent with LES case studies.

In order to determine the PPH bias, a reference computation accounting for the horizontal inhomogeneities has to be compared to an analogue PPH calculation. As a reference we use the independent column approximation (ICA) (Chambers, 1997), i.e. the radiation code is called for each LES cloud model column individually and the fluxes are averaged for each scene. The ICA assumes that the net horizontal photon transport is zero, i.e. there are as many photons leaving a column as entering it through its sides. For an individual column this assumption has been shown to be completely wrong, but the average fluxes over a cloud domain are a good measure from an energetic point of view (Titov and Kasjanov, 1996). The ICA can be implemented quite easily: The data from the cloud resolving model, as described in the previous section, are read column by column. The cloud fraction for each pixel \( i \) is

\[
A_c^i = \begin{cases} 0, & \text{if } q_l < q_{l,\text{thresh}} \\ 1, & \text{if } q_l > q_{l,\text{thresh}} \end{cases}
\]

For the following analysis this threshold has been set to \( q_{l,\text{thresh}} = 10^{-3} \text{ g/kg} \) in accordance with Petch and Edwards (1999). The effective radius \( r_{\text{eff}} \) and the optical properties \( \tau, \omega \) and \( g \) are computed as discussed in Roeckner (1995). Since \( r_{\text{eff}} \) is a function of the liquid water content, liquid water content as well as effective radius are horizontally inhomogeneous fields and both influence the variability of the optical thickness, single scattering albedo and asymmetry factor. Setting the effective radius to a constant value of 10 \( \mu \text{m} \) does not change the results noticeably. Therefore, this variability can be neglected in this study. A standard two-stream radiation computation is then performed for each column. Finally, the fluxes for the individual columns are added up and divided by the number of columns to obtain the scene averages.

The plane parallel counterpart is constructed by reading in the data of each model layer and work out the algebraic mean of the atmospheric state variables. The cloud fraction is determined similarly as for the ICA experiment: All pixels with liquid water mixing ratio \( q_l > q_{l,\text{thresh}} \) are counted as cloudy. The cloud fraction in level \( i \) then simply is

\[
A_c^i = \frac{n_{\text{cd}}^i}{n_{\text{tot}}^i}
\]

where \( n_{\text{cd}}^i \) is the number of cloudy pixels in level \( i \) and \( n_{\text{tot}}^i \) is the total number of pixels per level. For partial cloudiness the maximum-random overlap assumption is applied. A single two-stream radiation computation, identically to the one performed for an individual column in the ICA, is carried out, immediately supplying the PPH fluxes.

The ETA may be applied easily to the PPH dataset by using an effective optical thickness \( \tau_{\text{eff}} = \chi \tau \) with the reduction factor \( \chi < 1 \). In order to closely resemble the conditions of using the ETA in a GCM we employ the same \( \chi \) for each layer. From the
characteristics of a fractal cloud model, Cahalan et al. (1994) derives a relation between $\chi$, the mean of the logarithm of liquid water path (LWP), $\bar{W}$, and the mean of the logarithm:

$$\chi = \frac{\exp(\log W)}{\bar{W}}.$$ (1)

However, for broken cloudiness like in the ATEX simulation, Eq. (1) cannot be applied immediately, because $\log(W)$ for $W=0$ is not defined. Therefore, we define a threshold for the lowest LWP that is regarded as cloudy. The threshold for liquid water mixing ratio in the ICA computation, $q_{\text{thresh}}^{\text{LWP}} = 10^{-3}$ g/kg, results in a threshold for LWP of $W_{\text{thresh}} = 22 \times 10^{-3}$ g/m². A more empirical approach is to systematically vary the reduction factor from 0 to 1 and compare the results with the ICA calculations, thereby determining the proper value for $\chi$.

All radiation computations are performed for an intermediate solar zenith angle of 45° and thus represent mean values of the diurnal cycle. To investigate the zenith angle dependence in detail, realistic three dimensional calculations, like Monte Carlo techniques, would be more appropriate, because they also account for other effects such as side illumination, etc. (O’Hirok and Gautier, 1998).

4. Results

For both cloud simulations, the reflectivity, transmissivity and absorptivity, which result from the various methods described above, are collected in Figs. 3 and 4. For an overview of the labels, see Table 1. Fig. 5 shows the reflectivity as a function of model time. For the stable ASTEX cloud case the corresponding values are nearly constant for all snapshots.

First, we may identify the PPH-bias by comparing PPH and ICA. For both cloud cases, obviously, the reflectivity computed with the PPH approximation is larger than the corresponding ICA value, while the transmissivity is smaller. Comparing the results for the trade wind cumuli of the ATEX simulation with the ones for the stratocumulus in ASTEX the PPH-bias is substantially larger in the inhomogeneous ATEX case than in the rather homogeneous ASTEX cloud: The error is around 0.01 for ASTEX and 0.05 for the ATEX cloud, i.e. the relative error defined as $(R_{\text{PPH}} - R_{\text{ICA}})/R_{\text{ICA}}$ comes close to 100% for ATEX, while it is only around 5% in the ASTEX case. This could be expected qualitatively from the variability of the liquid water path displayed in Fig. 2, where the ASTEX cloud looks very much like a plane parallel homogenous slab of cloud, while the ATEX clouds are highly variable in shape and thickness with a much broader range of LWP-values. From Fig. 5 it can be seen that the reflectivities, PPH and ICA, vary from snapshot to snapshot. Nevertheless, the albedo bias is always of the same order of magnitude.

We may now try to apply the ETA in order to correct for the PPH-bias. First, we will use Eq. (1) directly. For the ATEX stratocumulus cloud this yields reduction factors between $\chi_f = 0.93$ and $\chi_f = 1.0$ for the individual timesteps with a mean of $\chi = 0.94$. If we take all time-steps as representation of a bigger cloud field corresponding to different stages of a stratocumulus cloud at the same time, resulting in a virtual domain size of
Fig. 3. Reflectivity, transmissivity and absorptivity of the stratocumulus simulation (ASTEX) using different schemes. All values are computed for an incident zenith angle of 45° and are averages over all time-steps. The labels are explained in Table 1.
Fig. 4. Same as Fig. 3 for the trade wind cumulus simulation (ATEX).
28 × 195 km², we obtain \( \chi = 0.90 \), which is smaller than that for the individual time-steps since the overall variability is larger. Whatever value we choose, the reduction factor is substantially larger than the value of 0.7 suggested by Cahalan et al. (1994) for stratocumulus. Fig. 3 shows the corresponding radiative properties for \( \chi = 0.7 \) and \( \chi = 0.9 \) labeled ETA.7 and ETA.9, respectively.

In the case of the broken cloud field of the ATEX simulation the threshold value \( W_{\text{thresh}} \) for cloudy cells has to be used. Since \( W_{\text{thresh}} \) is not physically based, it is interesting to ensure that \( \chi \) does not depend on the choice of this threshold value. Fig. 6 shows the reduction factor (again the mean over all time-steps). The reduction factor computed by Eq. (1) is far from being independent of \( W_{\text{thresh}} \). For \( W_{\text{thresh}} < 10^{-4} \) m\(^{-2}\) the curve saturates at \( \chi = 0.15 \). Fig. 7 depicts the reflectivity for the ATEX cloud simulation as a function of reduction factor. The vertical line marks the ICA value. Clearly, the \( \chi = 0.16 \) is much too small, but \( \chi = 0.42 \) seems to be more adequate. Similar results have been obtained by Kogan et al. (1995), who found a reduction factor of \( \chi = 0.5 \) for an LES simulated cumulus cloud field. In Fig. 4, the values corresponding to \( \chi = 0.4 \) and \( \chi = 0.7 \)

### Table 1

<table>
<thead>
<tr>
<th>Label</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>ICA</td>
<td>ICA computation; full vertical resolution</td>
</tr>
<tr>
<td>PPH</td>
<td>PPH computation; full vertical resolution</td>
</tr>
<tr>
<td>ETA.4</td>
<td>ETA computation; reduction factor ( \chi = 0.4 )</td>
</tr>
<tr>
<td>ETA.7</td>
<td>ETA computation; reduction factor ( \chi = 0.7 )</td>
</tr>
<tr>
<td>ETA.9</td>
<td>ETA computation; reduction factor ( \chi = 0.9 )</td>
</tr>
<tr>
<td>S-ICA</td>
<td>ICA computation; single cloud layer</td>
</tr>
<tr>
<td>S-PPH</td>
<td>PPH computation; single cloud layer</td>
</tr>
<tr>
<td>S-ETA.4</td>
<td>ETA computation; single cloud layer, ( \chi = 0.4 )</td>
</tr>
</tbody>
</table>

![Fig. 5. Reflectivity for ATEX cloud simulation as function of model time for PPH, ICA and ETA computation using \( \chi = 0.4 \).](image-url)
are shown. The reduction factor of $\chi = 0.4$ also reveals good results for each snapshot scene individually, as can be seen from Fig. 5.

All radiation computations are performed using maximum-random overlap assumption. For the ASTEX case stratus with cloud cover being 1 in nearly all cloudy layers, the overlap assumption does not matter. In contrast, for the ATEX case overlap is likely to influence the radiative properties. In order to avoid this inconsistency between CRM clouds and GCM simulation, we interpolated the ATEX data to the much coarser vertical resolution of current GCMs. The levels are 20, 40, 500 and 3000 m. The whole cloud resides in a single layer in this interpolated data set. Thus, cloud overlap assumptions no longer have any effect. The corresponding optical properties are shown in Fig. 4 labeled S-PPH, S-ICA and S-ETA.4. There are only little differences between the full resolution and interpolated data sets for ICA, PPH and ETA, confirming the finding of the full resolution

![Graph](image1)

Fig. 6. Scaling factor $\chi$ of the ETA computed for the ATEX cloud data using Eq. (1) vs. the threshold value $W_{\text{thresh}}$ of the LWP. Pixels with $W < W_{\text{thresh}}$ are regarded clear sky.

![Graph](image2)

Fig. 7. Reflectivity of the ATEX cloud data, averaged over all time-steps, as a function of the scaling factor $\chi$ for a solar zenith angle of 45°. The values of the reference ICA computation are marked by a horizontal line. From the intersection of the ICA line with the ETA curve, the best fit scaling factor can be extracted.
analysis that $\chi = 0.4$ corrects for horizontal inhomogeneities quite well. For the sake of completeness one should mention, that the absorption is of course smaller in the ETA computation than it is in the PPH case, because the clouds are virtually thinned out. It is even smaller than, but comparable to the ICA case.

5. Conclusion

Using the data from two cloud resolving simulations, a nocturnal marine stratocumulus case and a trade wind cumulus field, we determined the PPH-bias by comparing the independent column approximation and the corresponding plane parallel homogeneous computations. While the bias in reflectivity and transmissivity is only about 0.01 for the stratus case, it is nearly 0.05 for the broken cumulus cloud case. Absorption seems only slightly affected. For both cloud types the effective thickness approximation has been applied. While for the overcast stratus cloud, a reduction factor of $\chi = 0.9$ could be extracted directly from the variability of the liquid water path, this factor could not be derived for the broken cloud field in the cumulus simulation. Nevertheless, a reduction factor of $\chi \approx 0.4$ has been deduced empirically. Therefore, the reduction factor $\chi = 0.7$ suggested by Cahalan et al. (1994) for stratus clouds, may not be regarded as a representative value. We demonstrated that $\chi$ depends strongly on the cloud type. This should be accounted for when the ETA is implemented into GCMs (Tiedtke, 1996; Bäuml and Roeckner, submitted for publication).

References


