Abstract

Most numerical climate models use the plane parallel homogeneous (PPH) approximation when computing the interactions of radiation and clouds. The latter actually means that clouds are seen as boxes stretching over the complete vertical extension of a model layer and horizontally cover an area according to their cloud fraction. Ice and liquid water content within the cloud are constant. This is of course in contrast to real clouds revealing structures on scales much smaller than the typical grid size of a climate model. It can be shown that neglecting this sub-grid scale variability leads to a systematic error, such that the reflectivity (transmissivity) of clouds is overestimated (underestimated). This is called PPH-bias.

Two different correction approaches are tested in this study: The effective thickness approach (ETA) and the statistical approach of weighted two-stream approximation. In the former, empirical reduction factors $\chi < 1$ are determined such that the effective optical thickness of clouds becomes $\tau_{\text{eff}} = \chi\overline{\tau}$, where $\overline{\tau}$ is the mean cloud optical thickness in a single level of a model grid cell. When the sub-grid scale statistics of the distributions of cloud liquid and ice water and therefrom of optical thickness are known, expressed by the probability distribution function $p(\tau)$, the refelectivities and transmissivities may be computed by weighting the standard two-stream formulas with p. When this approach is to be applied to multiple layers, one has to account for the correlation of the PDFs in adjacent layers.

In order to test the correction approaches, spatially highly resolved data from two large eddy simulations are used: A nocturnal stratocumulus and a shallow trade wind cumulus. By taking the independent column approximation (ICA) as reference and comparing the ICA fluxes to the PPH analogues, the PPH-bias can clearly be identified. It is relatively small for the stratus cloud ($\sim 5\%$), while it is tremendous for the trade wind cumulus (up to 100%). The ETA shows good agreement with the ICA calculation with $\chi = 0.9$ for the stratus cloud and $\chi = 0.4$ for the trade wind cumulus. Clearly, the reduction factor is no unique constant, but rather crucially depends on the cloud type and thus variability. For the statistical approach, Gamma distributions are fitted to the cloud data and the

Gamma-weighted two-stream approximation is applied. In both cloud cases, the GWTSA including a correlation correction remarkably underestimates the reflectivity. This is in contrast to other studies and is likely to be due to misfits of the distributions in the small model domains. The effect of correlation is of similar order as purely weighting the two-stream functions with the PDF.

Finally, the two correction approaches are also implemented into the ECHAM5 climate model. The ETA is realized in various fashions: using a single reduction factor $\chi = 0.7$ for all clouds or only for liquid clouds, while ice clouds remain unchanged, applying $\chi_{\text{conv}} = 0.4$ to convective clouds and $\chi = 0.9$ to stratiform clouds and disinguishing between ice clouds ($\chi_{\text{ice}} = 0.9$) and liquid clouds ($0.4 \leq \chi_{\text{liq}} \leq 1.$, depending on liquid water path), where thick clouds are assumed to be more variable and thus a smaller reduction factor has to be used. The latter is the standard scheme of the ECHAM5 model. A statistical approach is realized as a Beta-weighted two-stream approximation (BWTSA), making use of the Beta-shaped distribution of total water mixing ratio as it is supplied by the cloud cover scheme. The effect of correlation is not accounted for. Comparing the various schemes, one can identify the huge impact of ice clouds, when a small reduction factor as $\chi = 0.7$ is applied to them. Their influence is remarkably reduced by using $\chi = 0.9$, as it has been deduced empirically. The albedo correction patterns of the BWTSA and the ECHAM5 standard ETA are very similar, but the BWTSA corrections are only half that of this ETA variant. Including the correlation effect into the BWTSA will increase the corresponding corrections, but is unlikely to reach the values of the ETA. Due to the lack of suitable observational data, the albedo corrections cannot be validated yet. It should be noted that the BWTSA does not introduce any empirical parameterizations like the distinction between ice and liquid clouds in the ETA, but treats clouds consistently with the cloud cover scheme.