Enhanced formulation of convective cloud cover

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1. Introduction

The parameterization of cloud cover in atmospheric forecast models is difficult for several reasons. The basic problem is to describe for the whole range of atmospheric states how the fractional cloud cover is formulated in terms of known parameters in the model. In principle, cloud cover can be fractional both in the horizontal and in the vertical for a given model grid box. The parameterization challenge becomes more pronounced when the formulation has to be valid over a large range of model resolutions. This is the case for atmospheric forecast models where it is desired to describe the range from typically 50 km down to the scale of cloud resolving models (about 1 km). The parameterization of cloud cover under convective conditions is particularly problematic because of the large possible humidity variation across the grid box associated with moisture exchange over large depths in the atmosphere.

This report provides a brief description of a statistical cloud formulation of convective cloud cover, suggested as an enhancement to an earlier cloud parameterization. A complete documentation of the cloud parameterization is available (Sass, 2002). Only the part relevant for describing convective cloud cover in situations with (shallow) cumulus convection will be studied here. The formulation can be used in connection with many different schemes for describing turbulence and convection.

The cloud parameterization is described in section 2. The potential of the statistical cloud formulation is illustrated in section 3 by showing results of 1-D simulations for two international test cases studying shallow cumulus convection. The first case ('BOMEX') is concerned with shallow cumulus convection over tropical ocean in quasi-stationary conditions. The second case ('EUROCS shallow cumulus') studies the diurnal variation of cumulus clouds in mid-latitudes. The cases have been created for Large eddy simulation studies and 1-D column tests with dynamical forcing specified on the basis of field studies. Tentative conclusions are given in section 4.

2. Parameterization of convective cloud cover

It is natural to describe the humidity variation by a statistical probability distribution function (PDF) which will define both saturated and unsaturated portions of the grid box. By definition, the fractional cloud cover is the saturated fraction of the grid box with cloud condensate in some concentration.

We consider the problem of defining convective cloud cover. For clarity an 'overline' symbol is used in this section for grid box average values, $\overline{q}$ for specific humidity, $\overline{q}_c$ for specific cloud condensate and $\overline{q}_t = \overline{q} + \overline{q}_c$ for total specific humidity. The prognostic moisture variables $\overline{q}$ and $\overline{q}_c$ have known values at a given time step of a model run. Furthermore, the relevant saturation specific humidity to describe supersaturation is $q_s(T_c)$, which is the saturation specific humidity valid for the convective cloud temperature T_c. This temperature is available from the convective cloud ascent model. One may argue that a probability function describing the variation of total specific humidity around the grid box average value will define also the supersaturation in the grid box. In the convective situation the challenge is that the distribution of total specific humidity can vary a lot across the grid box, and the moisture distribution may be quite asymmetric. This is because moisture is exchanged over large depths in the atmosphere. Also temperature varies to some extent. The complexity occurring as the grid box relative humidity approaches 100 % is discussed in a detailed documentation of the scheme (Sass, 2002). Here we consider the situation that $\overline{q}_t < q_s(T_c)$.

The most simple formulation involves 2 rectangular boxes which allows for a simple asymmetric PDF. This type of formulation has been used in the past. The formulation below, however, represents an enhancement consisting of 3 boxes when $\overline{q}_t < q_s(T_c)$. The application of 3 boxes in a rather dry atmosphere is consistent with a simple conceptual picture of convective clouds with a large specific humidity embedded in an environment with a fairly homogeneous humidity. Under these conditions a double-peaked PDF may be expected which fits with a 3-box structure. The 3 boxes have amplitudes, respectively, ψ_1 (box describing low humidities), ψ_* (box describing intermediate humidity interval) and ψ_2 (box describing probability of high humidity values).

The amplitudes are yet unknown, but may be determined by solving the equations (1), (2) and (3) for the situation that $\overline{q_t} < q_s(T_c)$. These equations have a solid basis. Eq.(1) defines that the total integral of the PDF equals 1 when integration is done over the entire humidity spectrum. Eq.(2) expresses that the average value of q_t as determined from the PDF should be equal to the grid box total specific humidity. Eq.(3) is a computation of the grid box mean cloud condensate from the PDF. The integration limits q_{min} and q_{max} have so far not been defined. The development strategy is currently to parameterize q_{min} (see Sass 2002). In this way the lower integration limit is considered a known parameter.

Then the equations (1),(2) and (3) constitute a system of 3 equations with 4 unknowns namely the amplitudes ψ_1,ψ_*, ψ_2 and the integration limit q_{max}. By formally solving the system of 3 equations it is possible to express q_{max} by means of ψ_* and the other known parameters. This solution is specified in (5). At this stage it is possible to specify the amplitude ψ_* with some freedom as a tuning parameter under the restriction that q_{max} is larger than q_s. This leads to a limit ψ_{*l} on ψ_* according to eq.(6). It is noted that the convective cloud cover f_{cv} is obtained by integrating ψ_2 which operates over the saturated part of the grid box.

$$\int_{q_{min}}^{\overline{q}_t} \psi_1 dq_t + \int_{\overline{q}_t}^{q_s} \psi_* dq_t + \int_{q_s}^{q_{max}} \psi_2 dq_t = 1 \tag{1}$$

$$\int_{q_{min}}^{\overline{q}_t} \psi_1 \cdot q_t \cdot dq_t + \int_{\overline{q}_t}^{q_s} \psi_* \cdot q_t \cdot dq_t + \int_{q_s}^{q_{max}} \psi_2 \cdot q_t \cdot dq_t = \overline{q}_t \tag{2}$$

$$\int_{q_s}^{q_{max}} \psi_2 \cdot (q_t - q_s) dq_t = \overline{q_c} \tag{3}$$

$$f_{cv} = \frac{2q_c}{q_{max} - q_s} \tag{4}$$

$$q_{max} = (b_1 + b_2\psi_*)/(b_3 + b_4\psi_*) \tag{5}$$

$$b_1 = (\overline{q}_t - q_{min}) \cdot (q_s + 2q_c) - 2q_s \cdot (\overline{q}_t + \overline{q}_c)$$

$$b_2 = q_s \cdot (q_s - \overline{q}_t) \cdot (q_s + q_{min} + 2\overline{q}_t)$$

$$b_3 = \overline{q}_t + q_{min} - 2\overline{q}$$

$$b_4 = (q_s - \overline{q}_t) \cdot (q_s - q_{min})$$

The limit ψ_{*l} of ψ_* is

$$\psi_{*l} = (b_3 q_s - b_1)/(b_2 - b_4 q_s) \tag{6}$$

Hence the applicable values of ψ_* may be written as

$$\psi_* = \delta_\psi \cdot \psi_{*l}$$

It may be determined whether δ_ψ must be chosen larger than or smaller than 1 by differentiating with respect to ψ_*

$$\frac{\partial(q_{max} - \overline{q}_t)}{\partial\psi_*}$$

in the point ψ_{*l}. In this way it may be concluded that δ_ψ should be smaller than 1 (first case) if

$$b_2(b_3 + b_4\psi_{*l}) - b_4(b_1 + b_2\psi_{*l}) < 0 \tag{7}$$

On the other hand, δ_ψ should be larger than 1 if the sign of the expression in (7) is positive (second case). Tentatively the values $\delta_\psi = 0.07$ (first case) and 1.07 (second case) have been set which appear to give reasonable results. The selection of optimal values, which may be determined from a more involved computation, requires experimentation with a given model.

Hence it is concluded that the above solution allows for some freedom regarding the choice of q_{min} and ψ_*. Having made an appropriate choice the unknowns are then ψ_1, ψ_2 and q_{max}, and the cloud cover f_{cv} may be computed from (4) and (5).

3. Cases with shallow cumulus convection

The new convective cloud parameterization as presented in the previous section is illustrated by means of results from controlled 1-D column experiments allowing for simple model dynamics including also the possibility of specifying advections based on associated field measurements. The focus is only on cloud cover aspects. It is possible to make a validation against Large eddy simulation (LES) results as described below. The vertical model resolution of 1-D HIRLAM runs is corresponding to 14 model levels below about 2000 m above the surface. This resolution is considered high enough to produce meaningful results, but is about 3.5 times coarser than the corresponding resolution (40 m) used in the LES.

3.1. BOMEX case

The origin of this case goes back to a field study over the tropical ocean in 1969. BOMEX stands for the Barbados Oceanographic and Meteorological EXperiment. The field study is involved with an assessment of the heat and moisture budget over the Atlantic tropical ocean (Nitta and Esbensen, 1974). Large-eddy simulations by Siebesma and Cuijpers have been documented in the litterature (Siebesma and Cuijpers, 1995). A case description and the results of LES may be found from the internet page http://www.knmi.nl/~siebesma/gcss/bomex.html A description of the forcing conditions for a 1-D column model is also available.

It is noted that the case applies to quasi-stationary conditions, the so-called BOMEX undisturbed period (22 - 26 June 1969) characterized by non-precipitating cumulus clouds with the highest cloud tops approximately at 1800 m -2000 m. The low troposphere is characterized by subsidence which increases up to about 1500 m and decreases at higher elevations. The surface fluxes of latent heat ($150 - 170 \mathrm{Wm}^{-2}$) and sensible heat ($10 - 20 \mathrm{Wm}^{-2}$) are upward.

Experiments with a HIRLAM column model subject to an appropriated forcing according to the setup outlined above, show that the HIRLAM physics are able to generate quasi-stationary conditions rather well. The results of fractional cloud cover as a function of height are given in figure 1 for LES (dashed line), for an experimental version of the STRACO convection scheme (Sass, 2002) using the new cloud parameterization (dot-dashed), and for a previous cloud parameterization used with the default STRACO convection scheme originating back to 1999 (solid line). The turbulence scheme used is the latest experimental version of the CBR turbulence scheme from Colin Jones at SMHI (personal communication, December 2002). However, the results presented do not critically depend on the use of the latest experimental version of the CBR scheme. The LES results (3 - 6 hour averages) are based on the data presented by P. Siebesma, as mentioned above. These are interpreted as being valid at 4.5 hours. The results for the new and old HIRLAM cloud scheme are instantaneous values valid at this simulation time.

It is seen that the maximum cloud cover ($\sim$ 8 percent) at a vertical model level is fairly realistic for both the new and the old version of the STRACO cloud scheme if the results of LES ($\sim$ 6 percent) is used for validation. However, the new cloud scheme provides a verical cloud cover profile in much better agreement with LES since the cloud cover decrease with height is well described. A much closer agreement can hardly be expected because of the different vertical resolution used in the two experiments. It is noted that the HIRLAM simulations do not generate surface precipitation for this case, in good agreement with observations.

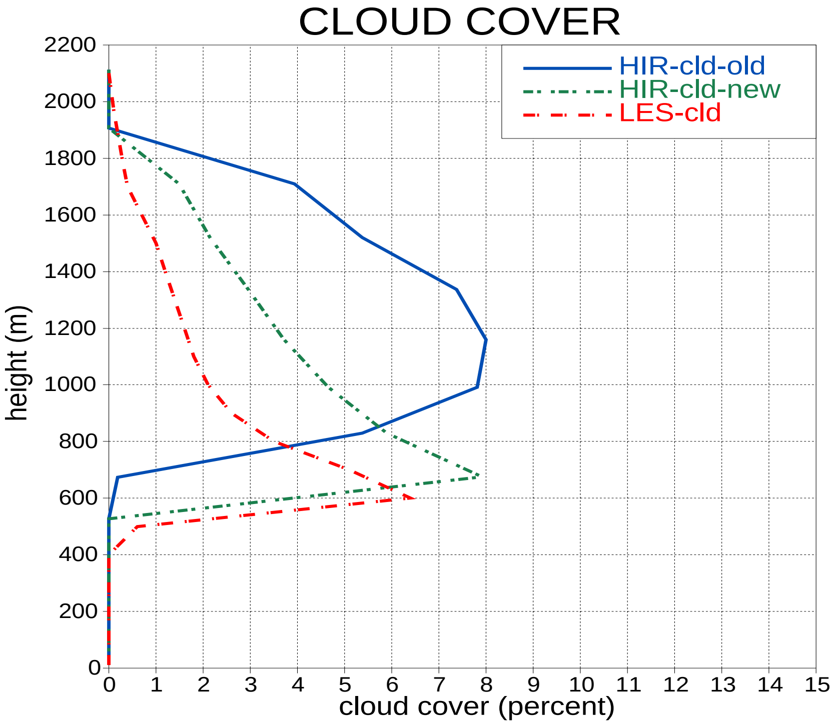

Figure 1: Vertical profile of fractional cloud cover after 4.5 hours of model integration for LES (dashed line), for new proposed HIRLAM cloud formulation (dot-dashed) and for the old formulation (solid line).

3.2. EUROCS shallow cumulus case

The EUROCS project (EUROpean Cloud Systems) is a project funded by the European Community. The project aims at improving the treatment of cloud systems in atmospheric climate models. Idealized test cases based on data from field studies have been established during the project from 2000 - 2003. The project is described from the internet page http://www.cnrm.meteo.fr/gcss/EUROCS. A 1-D test case investigating the diurnal variation of shallow cumulus over land has also been established in the project. The case description including specification of the time varying forcing can also be reached from the above mentioned internet reference page.

In short, this case (6th GCSS WG 1 intercomparison case) is constructed on the basis of data from the ARM (Atmospheric Radiation Measurements) site in the border region between Oklahoma and Kansas. The field data are from 21 June 1997. On this day, non-precipitating cumulus clouds developed on the top of an initially clear convective boundary layer. The clouds started to form at around 8.30 local time and disappeared towards the evening at 17.30 local time. The observed *total* cloud cover amount was about 30 % - 40 % occurring in the morning hours up to noon. The cloud cover generally decreased during most of the time in the afternoon. Moreover, the case is dominated by rather weak synoptic forcing but a significant surface forcing through latent and sensible heat fluxes developing during the day (peak values around 500 Wm^{-2} and 150 Wm^{-2}, respectively). The goal of 1-D model simulations and LES is to reproduce correctly the diurnal evolution of the cloud cover.

Recently, results on this case have been reported (Brown et al., 2002). In this paper simulation results of 8 independent LES models are collected and compared. The forcing boundary conditions for the LES and the 1-D column models represent some idealization of the measured field data for the area. It turns out (Brown et al., 2002) that the definition of initial conditions and forcing for the ARM site is not trivial. This uncertainty explains, at least partly, a slower growth of the convective cloud cover in the morning hours for both the LES and the 1-D model as compared to local observations. The choice is here to compare the results of the HIRLAM 1-D column test, using the new cloud formulation, directly with the results from LES. This is because the imposed forcing is similar, although not identical. Figure 2 shows the highest value of maximum cloud cover in any model layer from the 8 LES as a function of time (dashed curve) and the smallest value of maximum cloud cover in any model layer from the 8 LES (fine dashed curve). The corresponding result for the 1-D HIRLAM run is shown by the solid line. Note that an assumption regarding cloud overlap in the vertical must be made to translate this result into *total* cloud cover which is normally larger than the maximum value from individual levels. Figure 2 applies to a simulation where precipitation release is switched off for both LES and the HIRLAM run. The LES standard results have been obtained using this constraint. In the paper of Andy Brown et al. this condition is termed ‘microphysics switched off’. The article, however, lacks a description of results from LES when ‘microphysics’ is switched on. Figure 3 shows the results of the corresponding HIRLAM column test with microphysics switched on. The LES curves from figure 2 are shown once more in figure 3 in order to facilitate a comparison to standard results from LES. The total precipitation released in this HIRLAM test is slightly less than 0.3 mm.

When estimating the quality of the experimental HIRLAM cloud scheme it is noteworthy that most models participating in 1-D EUROCS comparisons for this case had significant problems to achieve good agreement with LES (see results referenced through the EUROCS internet pages). Several models had substantial problems with overestimation of cloud cover and a lack of cloud dissipation in the evening. On the contrary, the results of the present HIRLAM cloud scheme shown in figure 2 and figure 3 are in remarkably good agreement with LES, since both timing (onset and dissipation), cloud amount and cloud reduction in the afternoon, respectively, are rather well reproduced by the HIRLAM simulation. The effect of allowing precipitation release in the simulation is to decrease cloud cover by up to a few percent during parts of the daytime. This simulation is still in resonably good agreement with the fine dashed ‘minimum’ LES curve. Corresponding results with the old 1999 version of the cloud scheme shows a more oscilating behaviour without a clear trend of cloud reduction in the afternon, although clouds disappear in the evening (not shown).

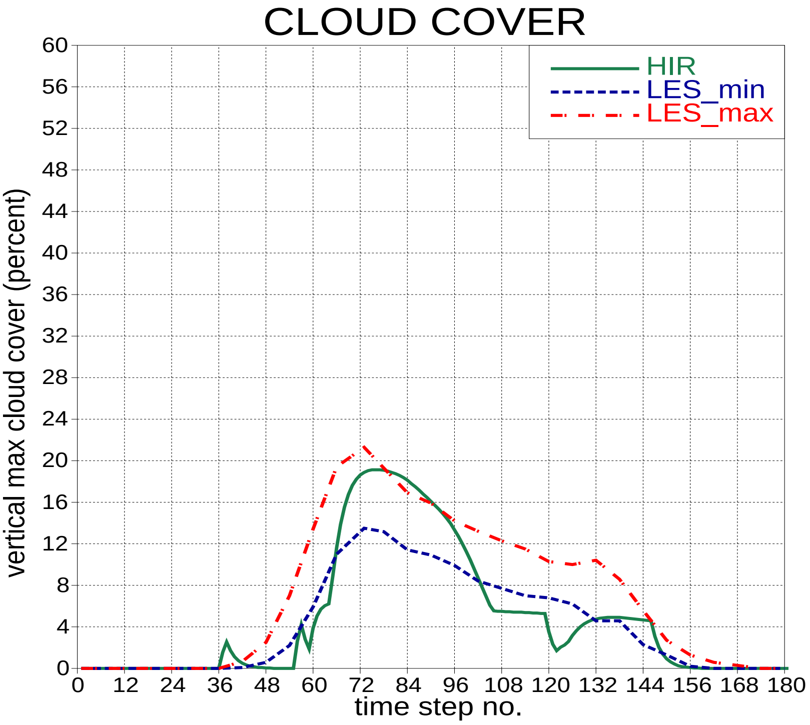

Figure 2: Maximum cloud cover in any vertical level. Dashed line shows largest estimate from LES, fine dashed line shows smallest estimate from LES. Solid line shows result for 1-D simulation with new cloud cover formula

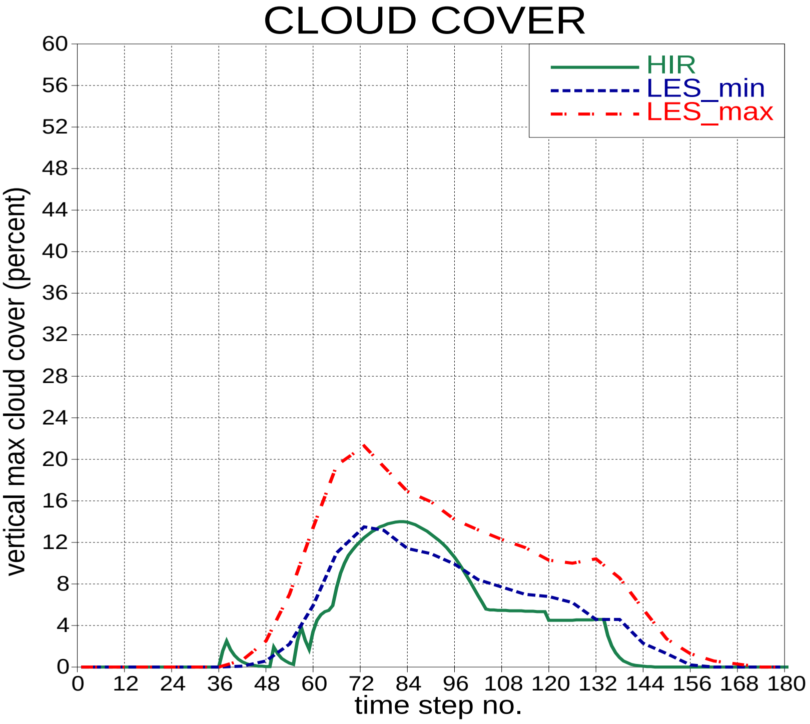

Figure 3: As in figure 2, but allowing for precipitation release in the HIRLAM 1-D simulation (solid line)

4. Conclusions

The results presented above for BOMEX and EUROCS shallow cumulus cases show that the experimental STRACO scheme including the new formulation of convective cloud cover has a good potential for describing convective cloud cover for conditions of shallow cumulus convection. The agreement with corresponding results from LES is remarkable and is better than obtained with an older version of the STRACO cloud scheme. It is natural to repeat the BOMEX and EUROCS shallow cumulus experiments for vertical resolutions comparable (or identical) to the corresponding one used in the LES. Extensive tests in different model setups are clearly needed in order to make more general conclusions concerning the properties of the statistical cloud scheme.

References

Brown, A., Cederwall, R., Chlond, A., Duynkerke, P., Golaz, J.-C., Khairoutdinov, M., Lewellen, D., Lock, A., MacVean, M., Moeng, C.-H., Neggers, R., Siebesma, A., and Stevens, B. (2002). "Large-eddy simulation of the diurnal cycle of shallow cumulus convection over land". *Q. J. R. Meteorol. Soc.* **128**: 1075–1093.

Nitta, T. and Esbensen, S. (1974). "Heat and Moisture Budget Analyses Using BOMEX Data". *Mon. Wea. Rev.* **102**: 17–28.

Sass, B. H. (2002). "A research version of the STRACO cloud scheme". DMI technical report no 02-10, 1 -25, Danish Meteorological Institute.

Siebesma, A. and Cuijpers, J. (1995). "Evaluation of Parametric Assumptions for Shallow Cumulus Convection". *J. Atmos. Sci.* **52**: 650–666.