Characteristics of CBR and STRACO versions.

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1 Introduction

The developments on the Hirlam vertical diffusion scheme are moving along quite rapidly. The current reference, dry version of CBR (Cuxart et al, 2000, Lenderink, 2002) has been adapted to provide stronger mixing in stable regions of the atmosphere, as it was felt that the current reference version of CBR underestimated the mixing in stable conditions. These updates are developed by Colin Jones. We will call the CBR version with these updates CBRcj in the remainder of this article. Preliminary 3-D tests show that these updates result in a reduced PMSL bias.

Separately, a moist version of CBR has been developed. Under certain conditions the dry version of CBR generates dry adiabatic vertical temperature profiles, while the grid box profile is saturated (see figure 1). This means that vertical mixing is underestimated by the model in saturated regions. To improve the behaviour of CBR under these conditions, the buoyancy production of TKE and the vertical mixing are (among others) based on the liquid water potential temperature instead of the dry potential temperature. In this way the effects of heat release/consumption by condensation/evaporation are taken into account. In the remainder of this article we will call the moist version of CBR CBRm.

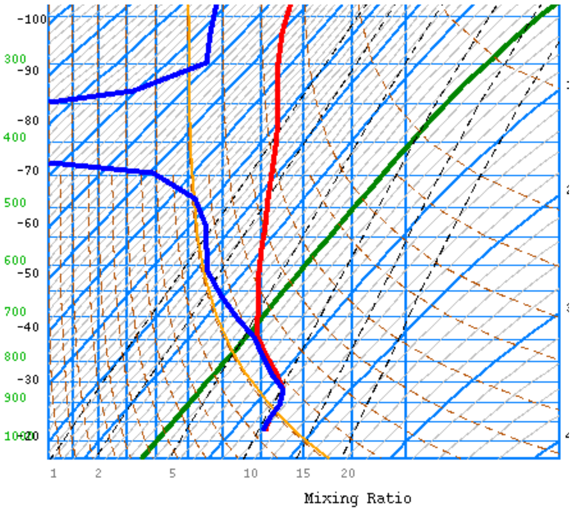

Figure 1: An example of a vertical profile from a Hirlam forecast that shows a dry-adiabatic lapse rate in a saturated environment. The diagram is a so called θ_s-p diagram, where the wet adiabats are the straight vertical lines. The curved dashed lines are the dry adiabats.

As CBRcj improves the PMSL scores, this version probably will become the reference vertical diffusion scheme in Hirlam. It is therefore best to base the moist version of CBR on the CBRcj. We therefore also introduced a version of CBRm that includes the updates of Colin Jones. We will call this version of CBR CBRm_cj.

In this article we will look at the differences in behaviour of three versions of the vertical diffusion scheme, namely CBR, CBRcj and CBRm_cj. We will look at three different cases that are included in the 1-D model, namely a dry boundary layer, a cumulus topped boundary layer and a stratocumulus topped boundary layer.

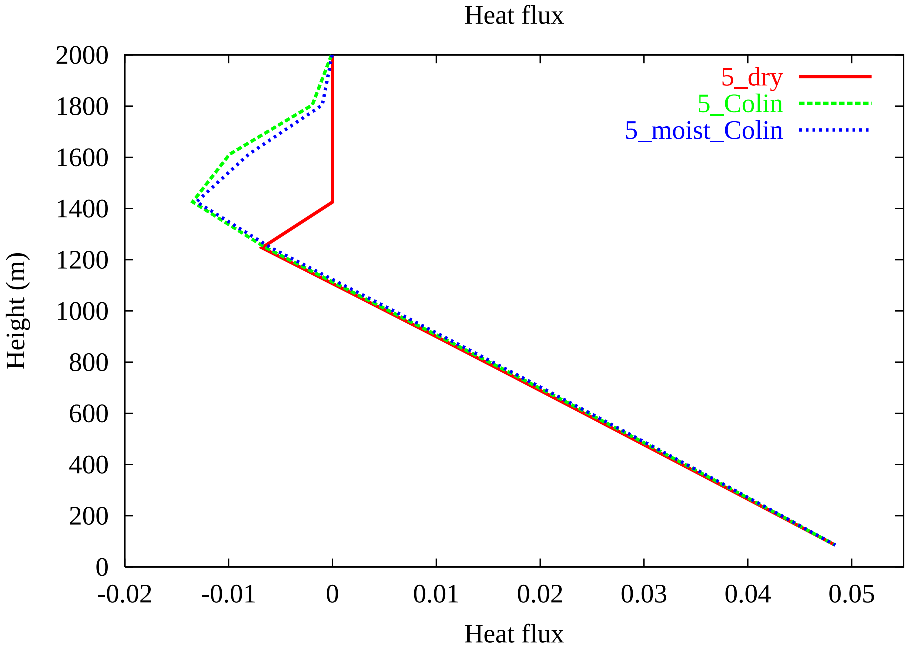

Figure 2: The averaged heat flux profiles with CBR, CBRcj and CBRm_cj between hours 10 and 11 in the integration of the dry boundary layer case.

A second part of Hirlam that is undergoing changes is the STRACO scheme. In the 1-D tests that are described in this article, we also tested the STRACO scheme to see if the turbulence scheme behaves correctly, not only in cooperation with the Kain Fritsch scheme, but also when the STRACO scheme is used as convection and condensation scheme. In this study we look at three different versions of STRACO, the 1999, 2002 and 2003 versions.

2 The dry boundary layer

One of the cases build into the 1-D hirlam model is a dry boundary layer case. At the surface, this boundary layer is forced with relatively small fluxes. The surface sensible heat flux is about 60 Wm^2. Initially, the boundary layer has a depth of about 1000 m. Due to the relatively small surface fluxes, the boundary layer only grows very slowly and as the boundary layer capping inversion is not too strong, the different evolutions of the boundary layer between the different CBR versions are clear.

Figure 2 shows the averaged heat flux profiles with the three versions of the vertical diffusion scheme. The profiles are very similar up to the level of the boundary layer top. There, the new versions of CBR show a much larger entrainment than the reference CBR. Where CBR has an entrainment of about 15% of the surface heat flux, CBRcj and CBRm_cj have an entrainment of about 30% of the surface heat flux. This can have a significant impact on the evolution of the boundary layer when surface heat fluxes are large.

Figure 3 shows the potential temperature profiles between hours 12 and 13 in the experiment for the three CBR versions together with the initial potential temperature profile. The boundary layer top initially lies at around 800 m. After 12 hours of integration the boundary layer has grown to about 1300 m in the reference CBR while the boundary layer top lies about 100 m higher in the integrations with CBRcj and CBRm_cj. Also, the potential temperatures in the boundary layer are higher with the two new versions of CBR while the temperature is lower above the boundary layer. This is caused by the larger entrainment, due to the adjustments of Colin Jones. CBRm (without the CJ updates) behaves more like CBR. Note that the surface fluxes are quite small in this experiment. Larger fluxes will lead to larger differences between the different CBR versions.

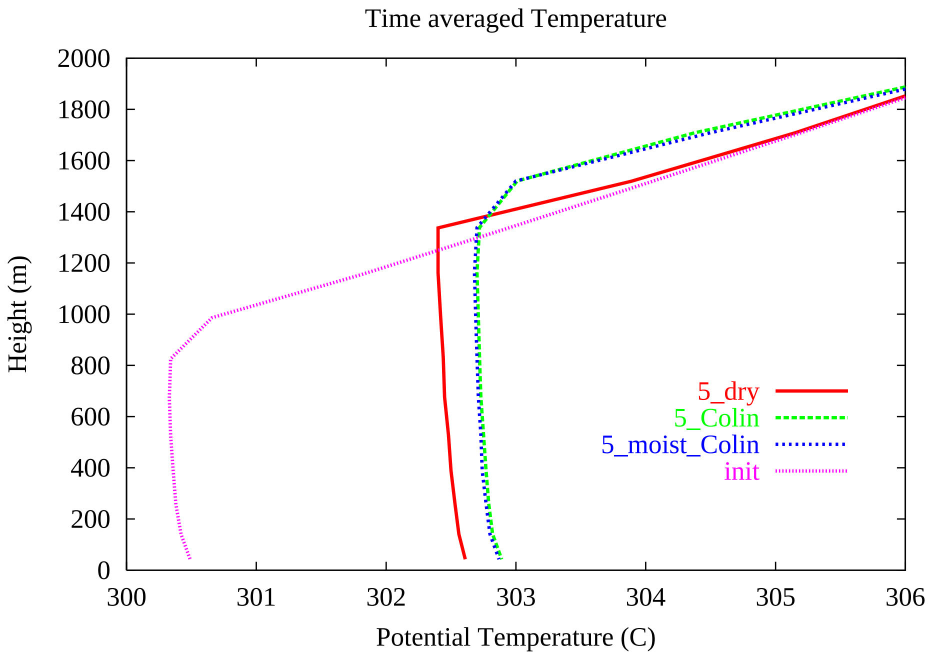

Figure 3: The potential temperature profiles with the three versions of CBR between hours 12 and 13 in the integration of the dry boundary layer case. Also shown is the initial profile (init).

The differences between the dry version of CBR and the other two versions may be quite small, but they can be quite important. A convective inhibition can be mixed away due to the stronger mixing at the boundary layer top with the two new versions of CBR. This may result in an earlier onset of convection. Also, the temperature in the boundary layer is higher with the new CBR versions. This may also result in an earlier onset of deep moist convection. The stronger entrainment will also result in more mixing of dry, free tropospheric air into the boundary layer. This may reduce the moist bias that was a persistent feature in the earlier Hirlam versions.

3 Shallow convection experiment

The second experiment that is used in the comparison between the different CBR-versions and with the different STRACO versions is an experiment with cumulus at the top of the boundary layer (and above). With this case we look at two different things. First: what is the impact of the moist version of CBR on shallow convection, can it resolve the shallow convection on its own or is a separate shallow convection parameterization still necessary. Second, we look at the precipitation production of different versions of STRACO and the Kain Fritsch scheme (Kain and Fritsch, 1990) as precipitation release by shallow clouds was one of the problems of earlier versions of the STRACO scheme.

One of the concerns with a moist turbulence parameterization is that this parameterization and the (shallow) convection parameterization are doing the same job twice. To see if the moist CBR is capable of representing cumulus convection we turned the shallow convection parameterization in the Kain Fritsch scheme off. This results in cloud water profiles that are shown in figure 4.

The experiment with the shallow convection turned on shows a cloud that extends from about 800 metres to 2700 metres. Near 1000 metres the maximum cloud water content can be found. This cloud layer vaguely resembles a stratocumulus cloud, but the cloud water content is much lower than with a stratocumulus cloud as will be shown in the last experiment. The experiment where the shallow convection of the Kain Fritsch scheme is

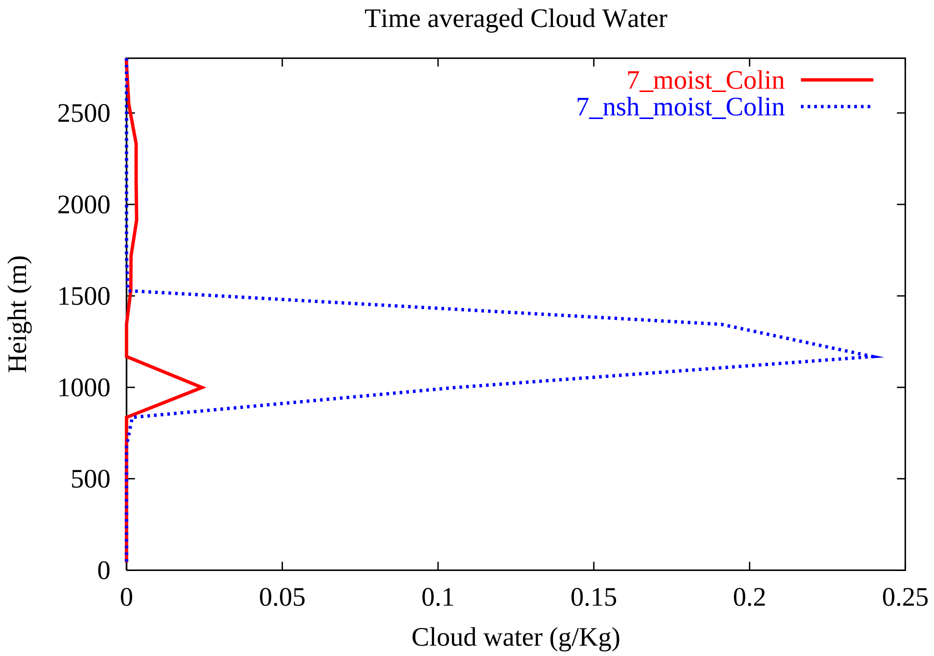

Figure 4: The one hour average cloud water profile between hours 7 and 8 in the experiment in the case with shallow convection parameterization (7_moist_Colin) and without shallow convection parameterization (7_nsh_moist_Colin).

turned off shows a much different picture than the first experiment. Now there is only one cloud layer, with a rather high value for the cloud water content. This cloud more closely resembles a stratocumulus cloud. The conclusion from this experiment must be that the moist version of CBR is not capable of producing shallow convection, probably because there is too little cloud water present in the cumulus to have a large impact on the liquid water potential temperature, causing the moist vertical diffusion to closely match the dry vertical diffusion.

This can also be seen in a comparison of the temperature tendencies caused by dry and moist vertical diffusion in this case. The differences between CBRcj and CBRm_cj are very small, similar to the differences found in the dry case, so the moist vertical diffusion does not interact (heavily) with the shallow convection parameterization in the Kain Fritsch scheme. The same conclusion can be drawn from experiments with the STRACO scheme.

Another difference between the moist and dry versions of CBR is the vertical diffusion of cloud water. In the dry version cloud water itself is mixed by CBR, while the moist version only mixes total water and lets the large scale condensation sort out if there can be cloud water or not. This results in some differences that may also explain why low stratocumulus and stratus clouds have the tendency to grow to the surface in Hirlam with the dry CBR's.

Figure 5 shows the bottom half of the boundary layer for the experiment with CBRcj (dry) and CBRm_cj (moist). There is a very clear difference. With CBRcj the cloud water extends to the surface, while with CBRm_cj the cloud water is zero below the significant clouds. This difference is caused by the vertical diffusion of cloud water in the CBRcj. With CBRm_cj the condensation part of the moist physics decides that no cloud water can exist with the existing relative humidity profile (relative humidity below 80%).

A very important problem (for weather forecasters) is the tendency of (old) Hirlam versions to produce convective precipitation from shallow cumulus clouds. In this case the cloud has a depth of about 1500 to 2000 metres. As the temperature in the cloud is far above 0°C this cloud should produce (almost) no rain. Only when a water cloud is deeper than about 3000 metres it has a significant chance of producing rain.

Figure 6 shows the precipitation production with three different versions of STRACO and with Kain Fritsch. The two older STRACO versions and Kain Fritsch all produce a

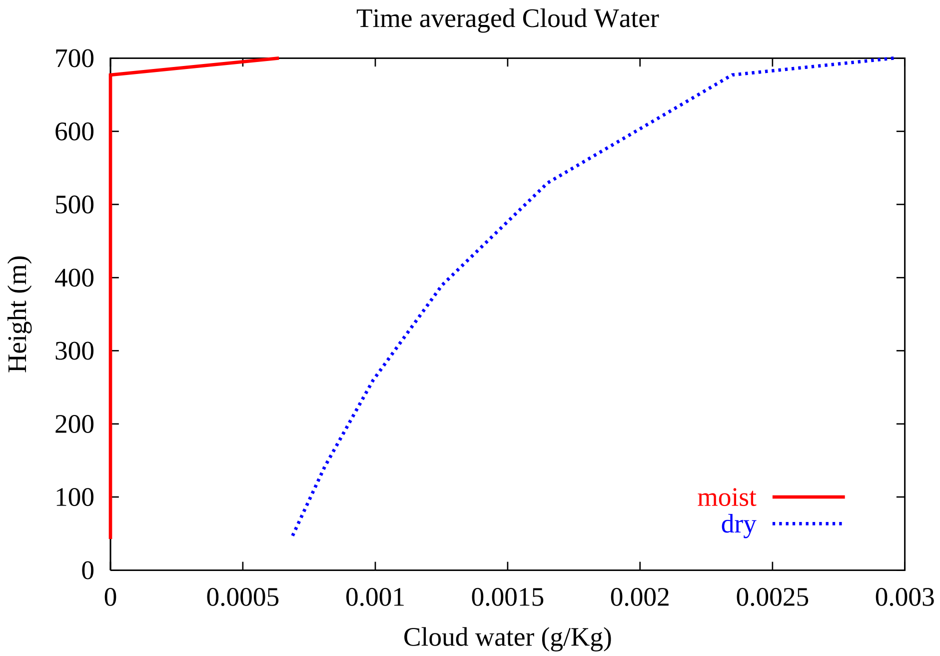

Figure 5: The one hour average cloud water profile between hours 5 and 6 in the experiment in the case with shallow convection with CBRcj and CBRm_cj.

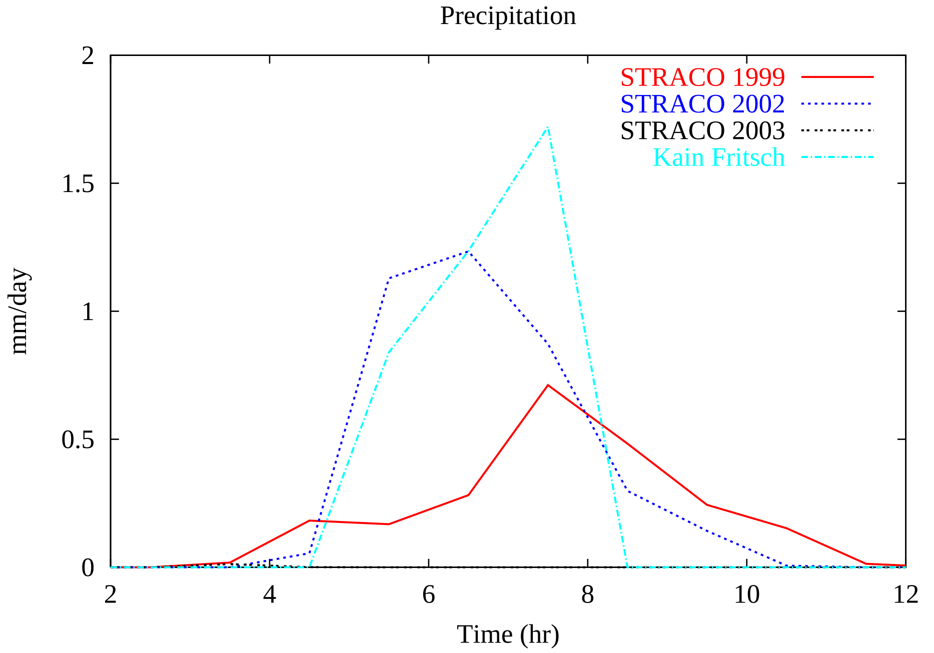

Figure 6: The hourly average precipitation as a function of time for 4 different experiments, three STRACO versions and Kain Fritsch.

significant amount of precipitation. Only the 2003 STRACO version produces almost no precipitation. In a reaction to the smaller or absent cloud water release in the form of precipitation, the liquid water path is larger in the 2003 version of STRACO than in the older versions. This reduces the short wave radiation reaching the surface by a few percent.

4 Stratocumulus case

4.1 Moist CBR

The third experiment that is used to explore the behaviour of the different CBR versions is a stratocumulus case. To check the moist part of the scheme we ran this case with prescribed surface fluxes and without large-scale forcing (subsidence). The results of this case are promising if we look at the temperature profile. Figure 7 shows the average profile of θ_l between hour 2 and 3 in the integration for the original CBR and CBRm. The difference is clear. In CBR θ_l decreases with height in the cloud that extends from about 100 m to about 400 m, as θ remains constant up to the top of the stratocumulus cloud. With CBRm the liquid water potential temperature is almost constant in the cloud layer, which means that the dry potential temperature increases with height in the cloud.

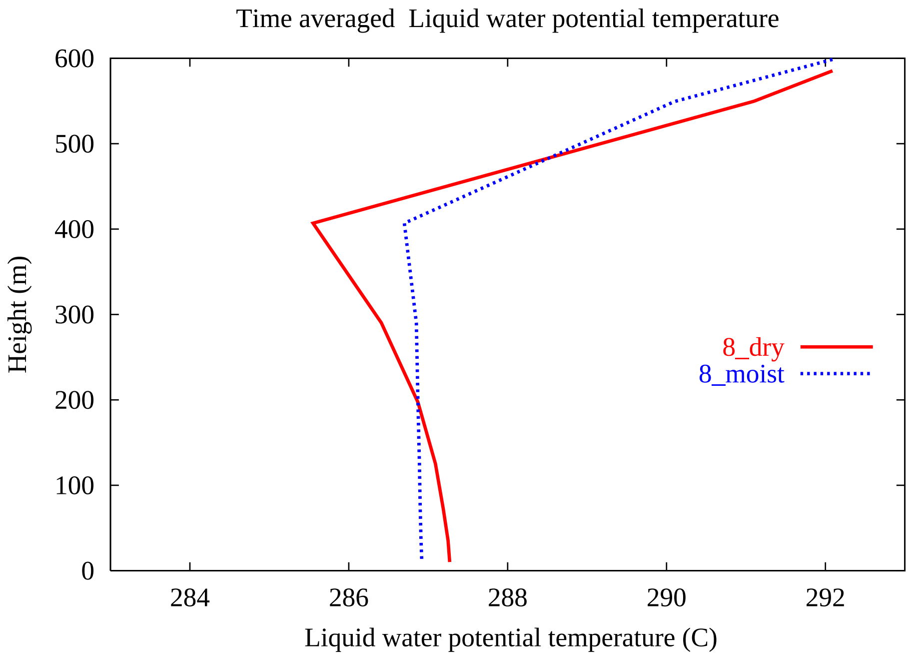

Figure 7: The vertical θ_l profiles with the dry and moist versions of CBR after 2.5 hours in the integration of the stratocumulus case.

While the new scheme works very well for the temperature profiles, the cloud water behaves badly. Figure 8 shows the average cloud water profile of the two experiments with CBR and CBRm after 6.5 hours in the experiment. The comparison with the initial profile (init) shows that the amount of cloud water increases considerably during the integration period with CBR as well as with CBRm. A second unwanted phenomenon is the descend of the cloud top during the integration period as LES show a slowly rising cloud top. In this experiments the cloud also extends to the surface. something that is not found in LES.

4.2 High vertical resolution

The negative aspects of the first experiment question the correctness of the moist version of CBR. Cloud top entrainment should mix enough warmer and dryer air in the stratocumulus topped boundary layer to keep the cloud at the same level or let it grow upwards, and to prevent the increase in cloud water that can be seen in both experiments. To test the validity of CBRm we tried it at a very high (30-40m) vertical resolution with 150 levels in the 1-D model.

The results of these runs are shown in figure 9. Now clear differences are found between the moist version of the scheme and the dry version. The dry version again tends to extend

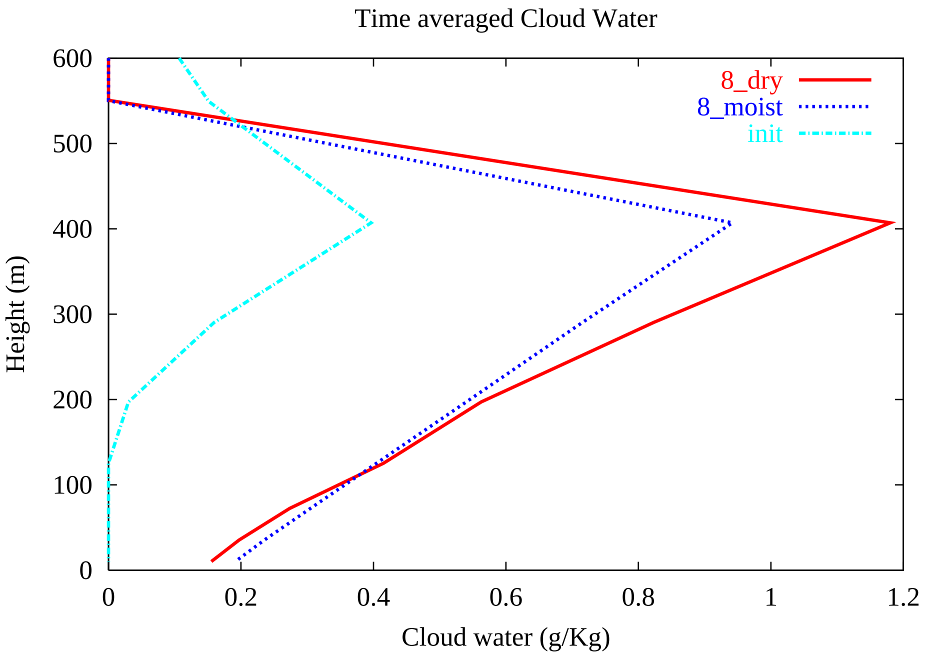

Figure 8: The cloud water profiles with the dry and moist versions of CBR after 6.5 hours in the integration of the stratocumulus case. Also shown is the initial cloud water profile (init).

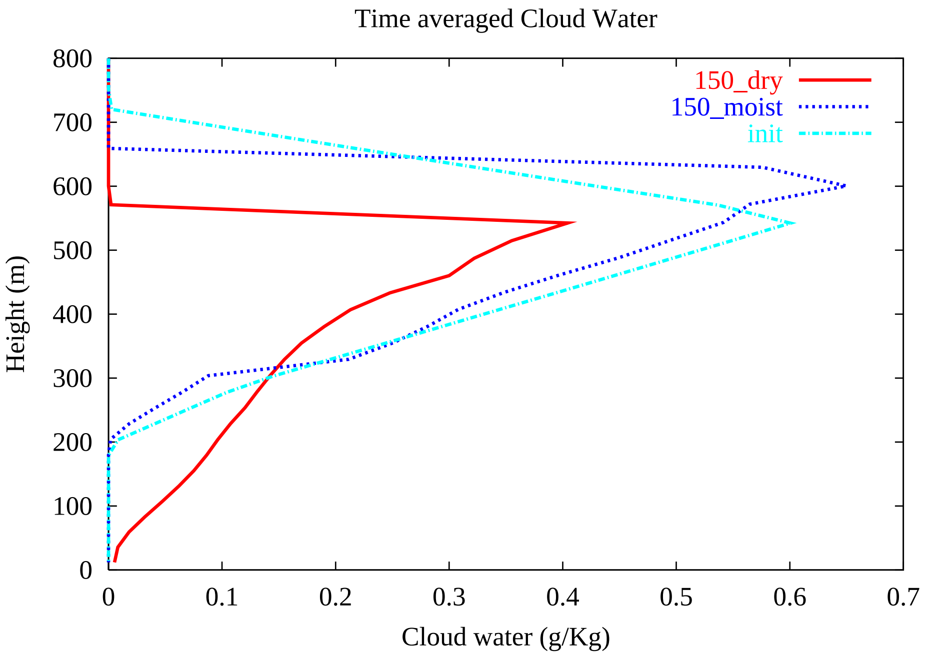

Figure 9: The cloud water profiles with the dry and moist versions of CBR after 8.5 hours in the integration of the stratocumulus case with 150 levels. Also shown is the initial cloud water profile (init).

the cloud to the surface, although the level at which the cloud water is maximum is retained. The total cloud water is somewhat lower than the initial value. The moist version now behaves beautifully. The cloud water maximum is retained and has shifted upwards, the

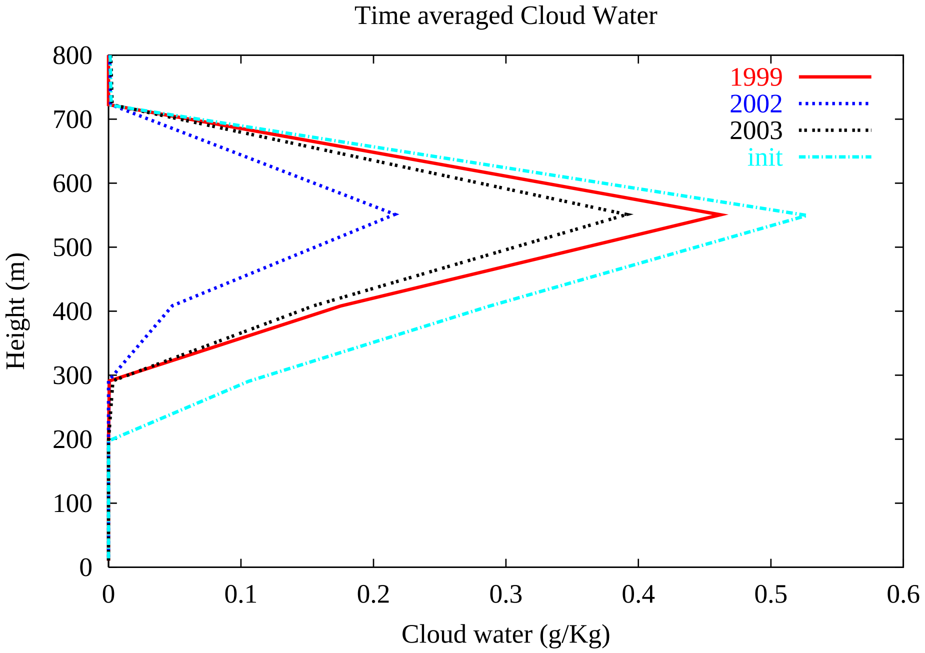

Figure 10: The hourly average cloud water profiles between hours 7 and 8 in the stratocumulus case with three different STRACO versions.

cloud does not extend to the surface any more and the total cloud water also is retained.

This experiment shows that the moist version of CBR works correct in principle, however, the coarse resolution of 40 (or 31) levels clearly is not enough to describe the processes in the stratocumulus correctly with the setup of the model as it is. The increase in cloud water in the coarse resolution runs indicates that the cloud top entrainment is not described correctly. Therefore we can conclude from these experiments that CBRm with KF-RK does not work correctly at the normal vertical resolutions and that a parameterization for the cloud top entrainment (vertical resolution dependent) is necessary.

4.3 STRACO

Above we showed the behaviour of the Kain Fritsch scheme for a case with stratocumulus clouds. One of the conclusions was that a the current vertical resolution (31 or 40 levels) stratocumulus cannot be resolved adequately. A much higher resolution is necessary to get the correct behaviour (no extension of the cloud to the surface, no drop in the cloud top and cloud water levels that remain almost constant). Here we will look at the behaviour of the different STRACO versions in this case and with the different versions of CBR.

One feature that the experiments with the different STRACO versions do not show at 40 vertical levels and that the Kain Fritsch scheme does show is the increase in cloud water during the integration period. Figure 10 shows the cloud water profiles between hours 7 and 8 in the integration with CBRm_cj. Compared to the initial profile, all profiles contain less cloud water. The 1999 version is closest to the initial profile, the 2002 version has the least cloud water.

The decrease in cloud water levels also has consequences for the cloud cover and the amount of short wave radiation that is able to reach the surface during the day time. The cloud cover should be near 100% in this case. Figure 11 shows the cloud cover with the three different versions of STRACO. Where the cloud water profiles already show significant differences, these differences are even more clear in the cloud cover. The 1999 version of STRACO, which has the most cloud water, has a cloud cover that stays near 100% for the first 7 hours of the integration period. The other two versions of STRACO have an initial cloud cover of around 50% that quickly increases to 75% and then slowly decreases to values

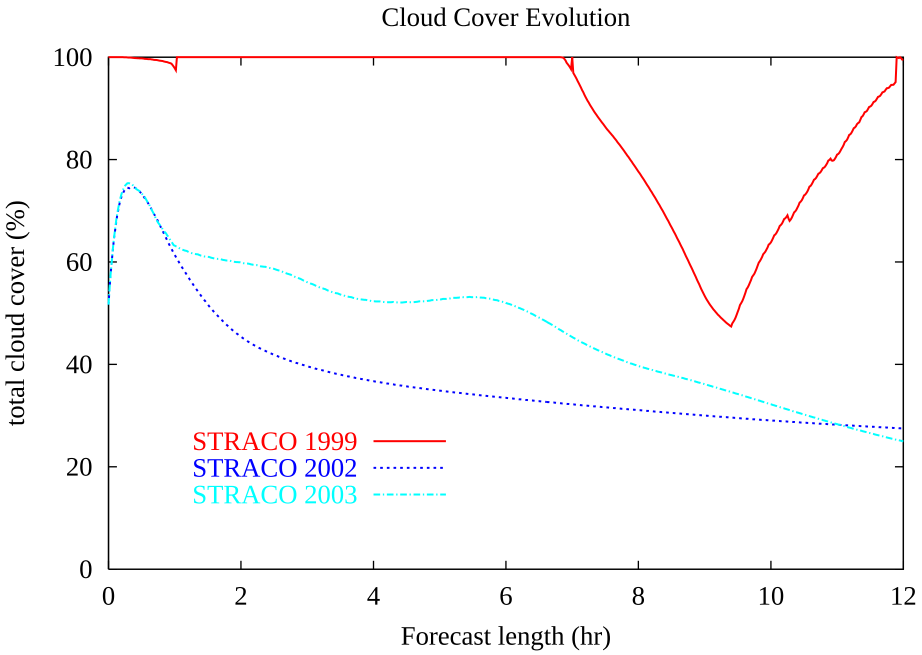

Figure 11: The cloud cover as a function of time for the three different STRACO versions.

around 30% after 12 hours. So the new STRACO versions are not capable of maintaining the cloud water levels and a 100% cloud cover for a 300 to 400 metres thick stratocumulus layer.

This is probably caused by a parameterization of the entrainment/detrainment flux at the top of the cloud. The cloud top detrainment may be a little to enthousiastic, causing a too strong mixing of dryer air from above in the stratocumulus layer. The too large detrainment is also apparant if we perform the same experiment at a very high resolution. At a vertical resolution of 30 to 40 metrest the detrainment at the cloud top becomes too strong and it takes over from the vertical diffusion scheme. In the high resolution runs with Kain Fritsch the vertical diffusion takes care of the entrainment of warm, dry air into the boundary layer.

5 Conclusions and discussion

The updates of Colin Jones that increase the mixing in stable conditions cause the boundary layer to become deeper and warmer. This is due to the larger entrainment of relatively warm air that overlies the boundary layer. Due to the larger entrainment, the air directly above the boundary layer becomes colder. This can lead to an earlier removal of a boundary layer capping inversion and the earlier onset of shallow or deep moist convection. Also the air in the boundary layer will become dryer due to the entrainment of dry air into the boundary layer.

The current version of moist CBR is not capable of handling shallow cumulus convection. Due to the low cloud water content of shallow cumulus, the impact of the moist part of the scheme is small. Therefore the scheme will not be capable of handling shallow convection by itself and a shallow convection parameterization will remain necessary. As for the double counting of the moist convection and the shallow convection, this usually will be no problem. Experiments show that when this may be a problem, the process involved will usually be performed by the turbulence scheme or the convection scheme and not by both at the same time.

Cloud water is mixed in the vertical by the dry version of CBR. This causes low cloud water levels down to the surface when clouds are present in the lowest two kilometers of the atmosphere. This will moisten and cool the lowest layers of the atmosphere and may be another possible source of systematic model errors.

The moist version of CBR fixes the wrong behaviour of the potential temperature in clouds. The liquid water potential temperature is conserved in these area's causing the temperature to follow the wet adiabat in clouds instead of the dry adiabat as can be the case with the dry version of CBR.

At the vertical resolutions that are currently used in the operational setups of Hirlam (31 and 40 levels), stratocumulus clouds are not represented correctly in combination with KF. The cloud top entrainment is too weak causing the cloud water to increase and the cloud to extend to the surface. This behaviour does not occur at a very high vertical resolution of around 30-40 metres. Therefore a vertical resolution dependent cloud top entrainment parameterization is necessary. The high vertical resolution result poses the interesting question: what resolution increase gives the largest benefit, horizontal or vertical?

The Kain Fritsch part of this study was performed with the Xu-cloud diagnostics scheme. This scheme causes a very different behaviour of the stratocumulus than the current 'reference' setup of KF-RK. Without the Xu-diagnostics the stratocumulus bounces up and down, never reaching an equilibrium state and it does not show the build up of cloud water.

The new version of STRACO is not capable of representing a shallow, closed stratocumulus layer. A too strong prescribed cloud top detrainment may be the cause of the slow dissolving of the stratocumulus. Cloud top detrainment and entrainment of free tropospheric air can be handled by moist CBR as shown in the vertical resolution experiment. The cloud top detrainment in STRACO may have to be made vertical resolution dependent and tuned down a little for stratocumulus clouds.

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