THE BEHAVIOUR OF DIFFERENT CLOUD PROCESS PARAMETRIZATIONS IN A LARGE-SCALE MODEL

Damian R. Wilson, Amanda M. Kerr-Munslow, Andrew C. Bushell
Met Office, Exeter, EX1 3PB, UK

1. INTRODUCTION[*]

In this paper we compare the results from two, very different, general circulation model (GCM) large-scale cloud schemes. These are run in the Met Office Unified Model (UM). The first scheme is a diagnostic cloud scheme, based on Smith (1990) and Wilson and Ballard (1999). The second scheme is a prognostic cloud scheme, following on from the work of Gregory et al (2002). We briefly describe the essential differences between the schemes, then present more detailed analysis of simulations of tropical convective cloud and mid-latitude stratocumulus cloud. We note that:

a) the simulation of high tropical cirrus cloud is primarily determined not by the phase or cloud fraction parametrization of the detrained water, but simply by the amount of water detrained. It is the large-scale scheme that controls the cloud fraction and ice content of the cloud;

b) the simulation of stratocumulus cloud is much improved by allowing the width of the assumed, underlying probability density function (PDF) of moisture to vary. Specifically, the width should decrease as cloud fraction increases, and this can be achieved through parametrization of the physical processes involved.

2. THE LARGE-SCALE MODEL CLOUD SCHEMES

2.1 The diagnostic (control) scheme

The control scheme represents the condensation and evaporation of liquid water with the PDF method of Smith (1990). Here a specified distribution of total moisture (q_T=q+l) and liquid water temperature (T_L=T – l L/c_p) is assumed across a gridbox, with the mean values given by the large-scale prognostic variables. q represents vapour, l represents liquid water, T, the dry-bulb temperature, L is the latent heat of condensation and c_p is the heat capacity of air. The width of this distribution is specified, and does not change with the action of cloud processes. Instantaneous condensation is assumed so that, at any point in the gridbox,

$$l = \max\{ q_T - q_{sat\ water}(T),\ 0 \}$$

where $q_{sat\ water}$ is the saturation specific humidity with respect to liquid water. Integrating across the PDF will retrieve the gridbox mean values of q and l from q_T.

The rest of the parametrized microphysics uses the scheme of Wilson and Ballard (1999), which represents the transfer of water between four categories: ice; liquid water; vapour and rain. Within this scheme there is an implicit subgrid-scale parametrization of the deposition / sublimation process that allows deposition to start occurring before the gridbox becomes completely saturated.

2.2 The PC2 (Prognostic Cloud, Prognostic Condensate scheme).

The PC2 scheme describes liquid and ice contents and cloud fractions in a prognostic way. This is similar in concept to Tiedtke (1993), although the formulation of each term is different. Condensation is represented by formulating equations for dq/dt. dl/dt and dC_l/dt, where C_l is the liquid cloud fraction, for each process that is represented in the model. For l, for example,

$$dl/dt = dl/dt|_{advection} + dl/dt|_{adiabatic\ warming}\ dl/dt|_{radiation} + dl/dt|_{boundary\ layer} + dl/dt|_{convection} + dl/dt|_{microphysics}\ .$$

The formulation for the convection is discussed in Bushell et al (2003). Condensation can also be forced by adiabatic warming or cooling as a result of the advection, the radiative warming or cooling and the change in temperature and moisture due to the boundary layer. This is currently represented as if the forcing was uniform across the gridbox, described in more detail by Wilson and Gregory (2003).

The microphysics scheme is that of Wilson and Ballard (1999) and is modified to give liquid cloud fraction and ice cloud fraction changes as well as changes to liquid and ice contents (as in the control). In particular, the autoconversion parametrization (representing the collision coalescence mechanism of warm rain production) does *not* alter the cloud fractions, but does adjust the liquid water content. This may allow optically thin, but extensive, layer clouds to exist more readily.

3. HIGH ICE CLOUD

Typically, deep convection detrains moisture at high levels in the troposphere. This behaviour is modelled by convection schemes, for example, the mass-flux based convection scheme used in the UM. The detrained moisture causes large anvil clouds to form, which may extend over hundreds of kilometres and persist long after the convective source of the moisture

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[*] Corresponding author's address: Damian R. Wilson, Met Office, FitzRoy Road, Exeter, EX1 3PB, UK;
E-Mail: Damian.Wilson@metoffice.com

has declined. Aircraft observations of ice particles in these anvil clouds demonstrate that the ice particles have usually not been detrained from the convective core, but have formed and evolved as a result of circulations in the moist anvil itself.

In the control simulation considered here, detrainment is entirely in the form of vapour, and it is the microphysics scheme that determines its conversion into ice, which will persist over several timesteps. Figure 1 shows a slice of instantaneous large-scale cloud fraction through convection. The control also has a representation of convective tower and anvil cloud directly linked to the convection scheme, when convection is active this cloud will be diagnosed.

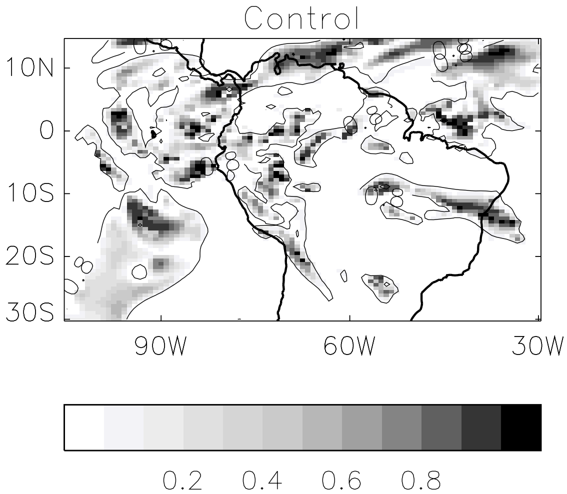

Figure 1. Cloud fraction at 12.5 km altitude for a T+6 run of the control scheme, VT 12Z 19/3/02. The solid line is the 0.8 relative humidity wrt ice contour.

The equivalent PC2 simulation (figure 2) allows convection to directly detrain (and entrain) condensate and cloud fraction. Hence we might expect significant differences between the two simulations. Although there are differences on the grid-points in the immediate vicinity of a convective core, the phase of the detrainment (vapour or ice) does not give significant differences further away, although we note that low values of cloud fraction are more extensive (see next section). In particular, the highest cloud, which is fed by moisture from only a few, very strong, convective sources, shows almost no sensitivity to the phase of the detrained moisture. *It is simply the amount of moisture detrained and the details of the microphysics scheme that affect the predicted cloud.*

3.1 The subgrid-scale ice microphysics model.

The representation of the distribution of vapour across a gridbox is, not surprisingly, a key factor in the simulations. In a prognostic ice microphysics scheme (used in both the control and PC2), it is not possible to use the concept of instantaneous condensation, since the timescale for the depositional growth or sublimation of ice is significant (of order 30 minutes). Notably, an assumption of instantaneous condensation for ice will preclude the existence of any liquid water.

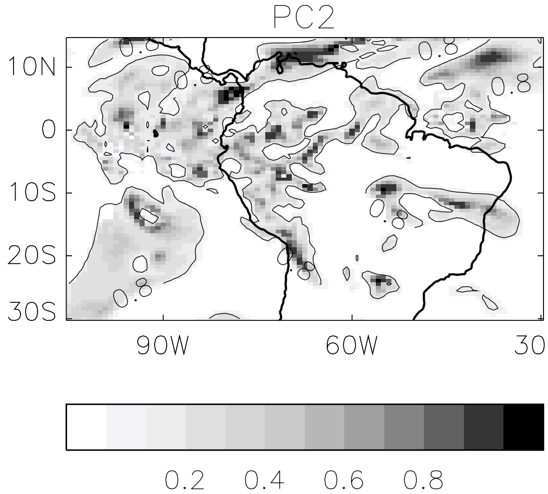

Figure 2. Like figure 1 but for the PC2 scheme.

For PC2 we have proceeded by first calculating the mean vapour content across the part of the gridbox covered by ice cloud (but not by liquid cloud). We now assume that the vapour in this partition of the gridbox has a uniform distribution. By specifying its width and assuming that the ice is located where the vapour content is largest, we are able to calculate the average deposition rate across the whole gridbox. Figure 3 demonstrates the effect of applying this change *on its own* to the control simulation shown in figure 1. *Small cloud fractions are now closer to those predicted by the PC2 scheme.*

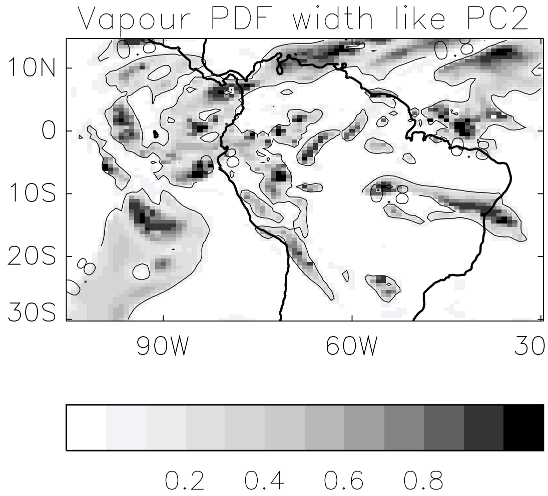

Figure 3. Like figure 1 but for the adjusted width of the vapour distribution in ice-cloud.

This change in this parametrization of vapour distribution gives very significant differences in results of a full atmospheric GCM. Notably, the cold and moist bias in upper levels in midlatitudes is removed when a large width is chosen for the parametrization. Figure 4 shows the difference between PC2 (which includes, amongst others, the change that is demonstrated in figure 3) and the control simulation for zonal mean temperature and relative humidity (RH). The change in the midlatitudes (but not the tropics) can be shown to be attributable to the parametrization of the vapour distribution by running an equivalent simulation to that shown in figure 3.

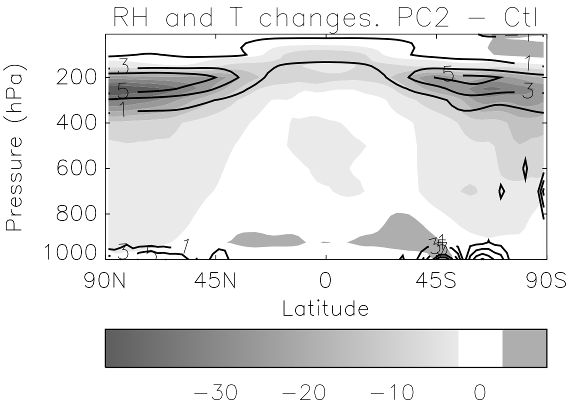

Figure 4. Annnual mean relative humidity changes wrt ice (shaded) and temperature changes (contours) between the PC2 and control simulations for a 5 year simulation.

These changes are a significant improvement in the simulation of mean temperature and relative humidity. Figure 5 shows the mean errors of the PC2 simulation when it is compared with ECMWF reanalysis data.

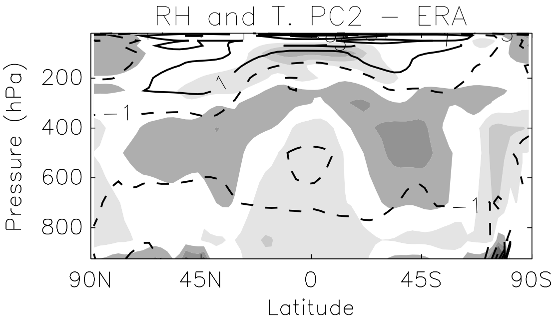

Figure 5. Zonal mean annual differences between PC2 and ERA for temperature (contours, values +1 and +3 are solid, -1 and -3 are dashed) and relative humidity (shaded as in figure 4).

We hypothesize that the changes in RH are caused by more ice being produced when the parametrized width of the vapour distribution is greater. This ice can fall to lower levels, so drying the upper troposphere. The temperature change is a radiative response to the drying; although the relative humidity response in the model is immediate, the temperature response requires several months to appear in full.

4. STRATOCUMULUS CLOUD

The ready breakup of stratocumulus sheets over land in operational models is a principal reason for developing the PC2 scheme. Figure 6 shows a satellite image of a typical UK stratocumulus case.

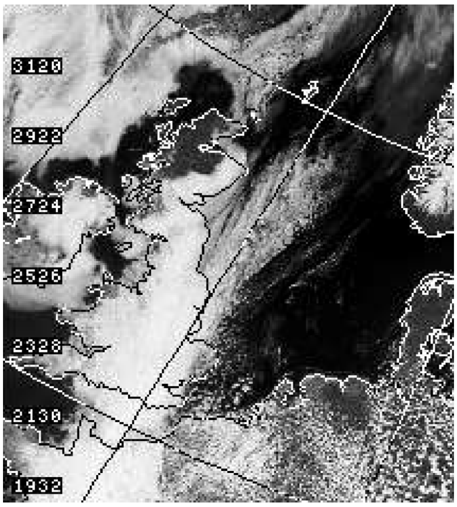

Figure 6. Visible satellite image, 1209Z 6/4/03.

The representation of autoconversion (representing the collision coalescence mechanism of drizzle production) should remove water from the moistest parts of a gridbox. In a scheme (like PC2) where cloud fraction is not reduced in response, this will effectively reduce the width of the underlying PDF of moisture (although the scheme does not need to know this width). In contrast, removal of liquid content by autoconversion in the fixed PDF-width control (Smith, 1990) scheme, will, in general, result in the reduction of cloud fraction and some extra condensation.

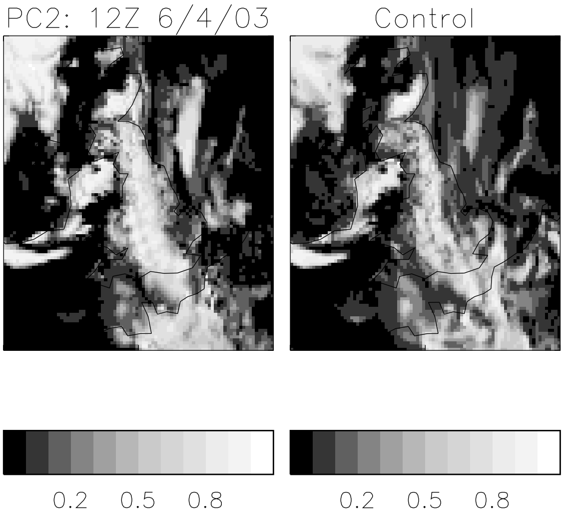

Figure 7. Liquid cloud fractions (looking down) for a T+11 run, VT 12Z 6/4/03. PC2 (left) and control (right).

The narrowing the PDF, as PC2 allows, will result in cloud fractions of 1 being reached for lower gridbox mean relative total humidities. This allows stratocumulus to be more prevalent in PC2, as shown in figure 7.

The satellite image (figure 6) shows that the sheet of cloud exists in an almost unbroken state across most of the UK, more in accordance with the PC2 predictions. Note that, in this example, the PC2 cloud scheme has produced substantial icing of the sheet in its eastern part (probably due to the greater overlap of ice and liquid cloud in PC2), which may have contributed to thinning of the liquid cloud in this region.

Wood and Field (2000) presented aircraft data from decoupled and coupled stratocumulus cases and showed relationships between cloud fraction and water contents that were not consistent with currently used cloud parametrization schemes. In particular, cloud fractions reached 1 for gridbox mean moisture only a little above saturation. Figures 8 and 9 show that the PC2 results compare favourably with the Wood and Field relationships.

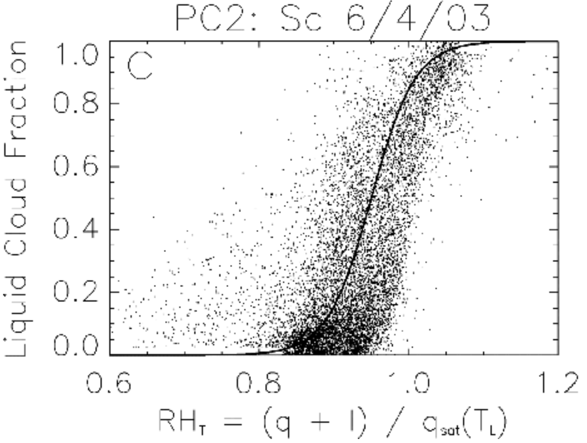

Figure 8. Liquid cloud fraction against total water content normalised by the saturation specific humidity for the PC2 simulation. The solid line is the WFI relationship from Wood and Field (2000).

Relationships from a Smith-like scheme for the RH_T – C_l plot will always be anti-symmetric, passing through the point $RH_T = 1$, $C_l=0.5$.

Climate simulations with PC2 show that the increased stratocumulus cloud is also visible in the semi-permanent stratocumulus sheets off western continental landmasses.

5. SUMMARY

The representation of clouds by a prognostic scheme can offer considerable advantage over a diagnostic scheme, but improvements may come for reasons that are quite subtle. In this paper we have seen that the PC2 scheme improves the simulation of stratocumulus cloud by effectively decreasing the width of the underlying PDF of moisture. The behaviour of the high ice cloud, even in strongly convective regions, is more affected by the parametrization of the PDF of moisture than by the details of the detrainment of ice cloud fraction.

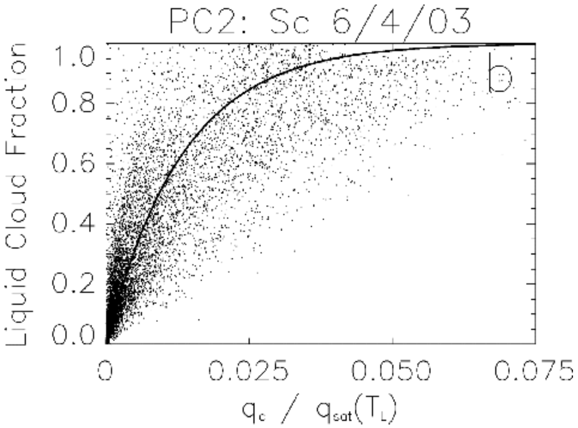

Figure 9. Liquid cloud fraction against liquid water content normalised by the saturation specific humidity for the PC2 simulation. The solid line is the WFII relationship from Wood and Field (2000).

6. ACKNOWLEDGEMENTS

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