A comparison of two bulk microphysical schemes and their effects on radiative transfer using a single-column model

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SUMMARY

Increasingly, numerical models in climate studies are using prognostic bulk microphysical schemes to predict grid-scale cloud cover and properties. These schemes provide information which can lead to improved calculations of radiative transfer, and a better understanding of the interaction of radiation with cloud microphysics on the large scale. In this study a one-dimensional, hydrostatic column model with fixed vertical velocities includes two different bulk microphysical schemes to investigate how the type of scheme influences the hydrometeor content in a cloud, and the effect of this on the radiative heating rates through the cloud.

Two test cases are performed, one representing the stratiform region of a tropical cloud cluster, the other a dissipating tropical cirrus cloud. Each test is first performed using a microphysical scheme that carries only one variable for solid water (MS1), and then using a scheme that separates solid water into ice crystals, snow, and graupel (MS2). Further sensitivity tests are made using MS2 to examine the effects of excluding graupel, and of allowing the ice crystals to fall. The influence of these modifications on the hydrometeor contents of the clouds and the corresponding radiative heating rates is considered.

In a simulation of the stratiform region of a tropical cloud cluster, MS1 is shown to produce significantly larger hydrometeor contents than MS2. However, in the simulation of a dissipating cirrus cloud, the ice content predicted by MS2 remains much larger than the ice content predicted by MS1, throughout a 24-hour integration. This is because there is a non-precipitating ice category in MS2 which is very slow to convert to snow at low ice-water contents. The use of a non-precipitating ice variable is shown to have a major impact on both the solar and the infrared radiative heating rates at the cloud top, and in some cases to give unrealistic predictions of cloud ice contents.

KEYWORDS: Cirrus cloud Ice microphysics Parametrization Tropical cloud clusters

1. INTRODUCTION

Clouds are a product of complicated interactions involving dynamics, radiation and microphysical processes. Apart from their importance in the prediction of precipitation, clouds have a large influence on the radiation balance both at the top of the atmosphere and at the surface. They are important on the time-scales used for numerical weather prediction and forecasting climate change.

Numerical modelling is one of the most important methods of predicting the future climate, and it has been recognized that the role of clouds and their interaction with radiation is a key uncertainty (e.g. IPCC 1990). Numerical models used in climate prediction usually include either diagnostic or prognostic parametrization schemes to represent clouds. As computers become faster, more and more numerical models of various weather and climate systems are using prognostic microphysics (e.g. Dudhia 1989; Ghan and Easter 1992; Chin 1994; Xu and Randall 1995; Fowler et al. 1996). The most common types of prognostic microphysics are bulk microphysical schemes. In these, water contents and size distributions of various types of hydrometeors such as ice, snow, graupel, rain and cloud droplets may be predicted. This is far more information than is available from typical diagnostic cloud schemes and can be used to improve radiative-transfer calculations in numerical models.

The number of water variables carried in a microphysical scheme is a trade-off between accuracy and computational efficiency. For example, increasing the number of categories of solid water particles allows a more detailed representation of the microphysics of cold and mixed-phase clouds. This paper considers whether extra complexity in a

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microphysical scheme significantly affects hydrometeor contents and the corresponding radiative-transfer calculations. As bulk microphysical schemes were originally designed for mesoscale models, many assumed the fall speed of ice crystals was negligible. This approximation may not be very suitable for experiments involving longer integrations, such as climate modelling. The effect of including a fall speed for ice is also considered in this paper.

A simple column model, described in section 2, is used to investigate how different bulk microphysical schemes influence hydrometeor contents and radiative heating rates through a cloud. Section 3 contains a description of the simulation of the stratiform region of a tropical cloud cluster, and section 4 the dissipation of a tropical cirrus cloud. Section 5 contains the main conclusions.

2. THE COLUMN MODEL

(a) Introduction

The column model is a one-dimensional model in the vertical which provides a simple framework for testing complex cloud microphysical and radiative parametrizations that could be used in large-scale models. By using the column model, the interaction of radiation with cloud microphysics can be separated from dynamical feedbacks.

The model domain extends from the surface to 18 km; above this a standard tropical atmosphere (based on McClatchey et al. (1972)) is used for the radiation calculations. The vertical resolution is 500 m, which is typical for models used in the investigation of the interaction of clouds and radiation using bulk microphysical schemes (e.g. Chen and Cotton 1988; Churchill and Houze 1991). The model is in hydrostatic balance and has a prescribed vertical-velocity profile which is fixed in time.

The model carries up to six different variables to represent water, the actual number depending on which microphysical scheme is being used. The different water species are:

- water vapour mass mixing ratio—$q_v$
- cloud liquid-water mass mixing ratio—$q_l$
- rain mass mixing ratio—$q_r$
- ice mass mixing ratio—$q_i$
- snow mass mixing ratio—$q_s$
- graupel mass mixing ratio—$q_g$

The equations used to calculate the rate of change of the various water species, $q$, and potential temperature, $\theta$, are:

\[
\frac{\partial q}{\partial t} + \frac{w}{\rho} \frac{\partial (\rho q)}{\partial z} = S_q + D_q, \tag{1}
\]

\[
\frac{\partial \theta}{\partial t} + \frac{w}{\rho} \frac{\partial (\rho \theta)}{\partial z} = \frac{\mathcal{R}}{\pi} + S_\theta + D_\theta. \tag{2}
\]

In these equations $\rho$ is the air density, $w$ is the vertical velocity, $t$ is the time, $z$ is the height, and $\mathcal{R}$ is the heating rate due to radiative processes (discussed in section 2(c)). $S$ represents source and sink terms due to microphysical processes (discussed in detail in section 2(b)). The Exner pressure, $\pi$, is defined by

\[
\pi = \left( \frac{p}{p_{\text{ref}}} \right)^{\frac{\kappa}{\kappa - 1}}, \tag{3}
\]
where $p$ is the dimensional pressure with the same units as $p_{ref}$, a reference pressure (i.e. 1000 mb), $R$ is the gas constant for dry air and $c_p$ is the specific heat of dry air at constant pressure.

The changes caused by turbulent fluxes, $D$, are given by

$$D_q = \frac{\partial}{\partial z} \left( k \frac{\partial q}{\partial z} \right) \quad \text{and} \quad D_\theta = \frac{\partial}{\partial z} \left( k \frac{\partial \theta}{\partial z} \right),$$

where $k$ is the eddy diffusion coefficient calculated using a Richardson number dependent turbulence parametrization (e.g. Mason 1994), with a minimum value of 5 m$^2$s$^{-1}$ used to ensure numerical stability. At the surface the turbulent fluxes of heat and water vapour are calculated using bulk aerodynamic formulae taken from Rotunno and Emanuel (1987) and drag coefficients for heat and water vapour from Smith (1988). Further details of the formulation of all the equations in the column model, including the numerical method used, can be found in Petch (1995).

(b) Microphysical parametrizations

A bulk microphysical scheme uses the mixing ratio of different categories of hydrometeor to describe a cloud. In the column model the parametrization of the cloud microphysics uses two different bulk microphysical schemes. Conversions are calculated between the different categories to represent various microphysical processes. These exchanges are related to temperature, humidity and the mixing ratios of the various hydrometeors included in the scheme.

The purpose of the work described in this paper is not to develop new cloud microphysical parametrizations, but to use information from existing schemes in radiative-transfer calculations. The microphysical schemes chosen for this work are first that described by Cox (1988), hereafter MS1, which is used in a research version of the UK Meteorological Office non-hydrostatic model (Golding 1992, 1993) and second that described by Swann (1994), hereafter MS2, which is currently used in the UK Meteorological Office large-eddy model (Shutts and Gray 1994).

MS1 uses four water variables—water vapour, cloud droplets, rain, and ice particles, although some schemes use more (e.g. Lin et al. 1983), and others carry only water vapour and liquid water (e.g. Sundqvist 1978). Ice particles and rain have a non-zero fall velocity, but cloud droplets are assumed to have a negligible terminal velocity and can only move by advection due to the mean wind and diffusion. Conversions within MS1 are based on the schemes of Rutledge and Hobbs (1983) and Tripoli and Cotton (1980), simplified to have a combined ice and snow variable and no graupel. The exchanges between the various water categories in MS1 are shown in Fig. 1; the rates of these conversions are described by Cox (1988).

The conversions in MS2 are based on the schemes of Rutledge and Hobbs (1983) and Lin et al. (1983). The main difference from MS1 is that solid water is divided into three categories—ice crystals, snow and graupel. This kind of bulk microphysical scheme is very common in many types of numerical simulations where cloud microphysics is important (e.g. Churchill and Houze (1991) in a simulation of a tropical cloud cluster, Chin (1994) in a simulation of a midlatitude squall line, and Xu and Randall (1995) in cumulus ensemble simulations).

The ice crystals category in MS2 represents small crystals with the density of solid ice. The fall speed of the ice crystals is assumed to be ‘insignificant’, although this depends very much on the purpose for which the microphysical scheme is being used (see section 4(c)). The snow category represents larger ice crystals, dendrites and aggregates,
which are assumed to have a significant fall speed. The bulk density of the snow category is 100 kg m$^{-3}$. The graupel category represents heavily rimed ice crystals and heavily rimed snowflakes with a bulk density of 500 kg m$^{-3}$; consequently it has a larger fall speed than the snow. The exchanges between the various water categories in MS2 are shown in Fig. 2; the rates of these conversions are described in Swann (1994).

(c) Radiative-transfer parametrization

The radiation scheme used is a flexible radiation code, described by Edwards and Slingo (1996), which enables it to be used at different spectral resolutions in both the solar and the infrared spectrum. It also allows the choice between including or ignoring various processes important in radiative-transfer calculations, such as absorption and scattering by cloud, Rayleigh scattering, etc. Here the radiation scheme is included with nine spectral bands across the solar and six spectral bands across the infrared spectrum. In all the solar and infrared regions absorption by carbon dioxide, ozone and water vapour is included. The effects of Rayleigh scattering in the solar spectrum, and the water vapour continuum in the infrared spectrum, are also included. Further details of the configuration of the radiation scheme can be found in Petch (1995).

Hydrometeors are included in radiative-transfer calculations using the method of Slingo and Schrecker (1982). Mie theory is used to calculate the single-scattering parameters, over all wavelengths, for a range of typical size distributions of ice crystals and cloud droplets. These are then averaged over each band and weighted by the incident flux in the short wave, and the thermal source function in the infrared. The single-scatter properties are then parametrized in terms of the effective radius and the liquid- or ice-water content. This investigation concerns differences in radiative heating due to the type of microphys-
1. Evaporation of cloud water. (Liquid to gas)
2. Condensation. (Gas to liquid)
3. Autoconversion of cloud water to rain. (No phase change)
4. Capture of cloud water by rain. (No phase change)
5. Evaporation of rain. (Liquid to gas)
6. Contact nucleation of ice crystals. (Liquid to solid)
7. Deposition of vapour onto ice crystals. (Gas to solid)
8. Sublimation of ice crystals to vapour. (Solid to gas)
9. Melting of ice cloud to liquid cloud. (Solid to liquid)
10. Nucleation of ice crystals by the Hallet and Mossop effect. (Liquid to solid)
11. Rain accreted by ice crystals to form snow. (Liquid to solid)
12. Rain accreted by ice crystals to form graupel. (Liquid to solid)
13. Fletcher nucleation of ice crystals. (Gas to solid)
14. Ice crystals accreted by rain to form graupel. (None)
15. Ice crystals accreted by rain to form snow. (None)
16. Collection of snow by rain to form graupel. (None)
17. Melting of snow to rain. (Solid to liquid)
18. Collection of rain by snow to form graupel. (Liquid to solid)
19. Collection of ice crystals by snow. (None)
20. Autoconversion from ice crystals to snow. (None)
21. Collection of liquid cloud by snow. (Liquid to solid)
22. Deposition of water vapour to snow. (Vapour to solid)
23. Sublimation of snow to water vapour. (Solid to vapour)
24. Autoconversion of snow to graupel. (None)
25. Freezing of rain to form graupel. (Liquid to solid)
26. Collection of cloud water by graupel. (Liquid to solid)
27. Collection of ice crystals by graupel. (None)
28. Collection of rain by graupel. (Liquid to solid)
29. Collection of snow by graupel. (None)
30. Sublimation of graupel to vapour. (Solid to gas)
31. Melting of graupel to form rain. (Solid to liquid)
32. Liquid water shed by graupel to form rain. (None)

Figure 2. A schematic of the various exchange processes involved in MS2 (see text) (Swann 1994). The exchanges are numbered with the phase change given in brackets.

Numerical scheme, hence the solid water in MS2 (i.e. ice, snow and graupel) is treated in the same way as the ice in MS1. Petch (1997) investigated the way information from a more sophisticated microphysical scheme, such as MS2, can be used to improve the radiative-transfer calculations by incorporating a separate treatment of the radiative properties of each hydrometeor.

The surface emissivity in the infrared scheme was set to 1.0. In the solar scheme the solar zenith angle was fixed at 60°, the solar constant was taken to be 1370 W m⁻² and the surface albedo was taken to be 0.1. For both the solar and the infrared radiation scheme the cloud water droplets, rain drops and ice particles were assumed to have fixed effective radii of 18 μm, 750 μm and 60 μm respectively.
3. THE SIMULATION OF THE STRATIFORM REGION OF A TROPICAL CLOUD CLUSTER

(a) Initial conditions

In the simulation of the stratiform region of a tropical cloud cluster experiment the model is forced with a fixed vertical velocity and run until a steady state is reached. Steady state is defined to be when the hydrometeor fields and precipitation rate are changing by less than 1% per hour, and the total temperature tendency at all model levels has an absolute value less than 0.1 K day\(^{-1}\). It should be noted that the hydrometeor fields and precipitation reach a steady state much quicker (~ 24 hours) than thermal equilibrium (~ 100 hours) for the chosen initial conditions. The time to reach steady state may seem large but is due to the very strict criteria required. The type of microphysical scheme included in the model has very little influence on the time taken to reach equilibrium.

The vertical-velocity profile used in this simulation is shown in Fig. 3; it is representative of a vertical section from the data used in the model of Churchill and Houze (1991), taken from a case study of a squall line on 12 September 1974 described by Gamache and Houze (1985). In common with much previous work, no consideration is made of the effects of turbulent variations in the vertical velocity, although these may have an important influence on cloud microphysics.

The surface temperature, which is required for both the infrared radiation scheme and the parametrization of surface fluxes, was fixed at 293 K, and is consistent with the conditions used by Churchill and Houze (1991).

(b) Comparisons of microphysical schemes

Figures 4 and 5 show the steady-state hydrometeor contents for MS1 and MS2 respectively, for runs excluding radiation. In Fig. 5, the total solid water shows the sum of ice, snow and graupel and is equivalent to the ice variable in MS1. The total solid water content in MS2 has a peak value of around 0.5 g kg\(^{-1}\) at a height of 7.5 km, with values remaining above 0.4 g kg\(^{-1}\) up to an altitude of 13 km. This is considerably different to the ice content for MS1 which peaks at just over 1.5 g kg\(^{-1}\) at 6 km. The rain contents have a
Figure 4. Steady-state hydrometeor profiles for MS1 (see text) simulation of the stratiform region of a tropical cloud cluster with no radiation included. Very little cloud water (< 0.04 g kg$^{-1}$) was present and is not shown.

Figure 5. Steady-state hydrometeor profiles for MS2 (see text) simulation of the stratiform region of a tropical cloud cluster with no radiation included. Very little cloud water (< 0.02 g kg$^{-1}$) was present and is not shown. Total solid water is the sum of ice, snow and graupel.

similar shape and extend through a similar depth for both schemes, but the values between 0.2 g kg$^{-1}$ and 0.3 g kg$^{-1}$ for MS1 are approximately double those for MS2. The surface rain water content corresponds to a rainfall rate of 75 mm day$^{-1}$ in MS1 and 34 mm day$^{-1}$ in MS2.

The peak ice content close to the cloud top for MS2 can be explained by the fact that the ice is non-precipitating and can build up in this region. The smaller total solid water and rain contents in MS2 suggest that the mechanisms that remove water from the atmosphere are more efficient in this scheme. It may appear surprising that, although MS2 is more
efficient at removing water from the atmosphere, the precipitation rate for this scheme is much lower. The reason for this is that the steady-state precipitation rate is directly related to the convergence of the total water in the column. As the model is assumed to be representing an infinite horizontal domain, then the convergence of water at any level is related to the amount of water already present at that level. Because MS1 has larger ice contents, the convergence of ice is greater and thus also the surface precipitation.

Figures 6 and 7 show the steady-state temperature profiles and heating rates respectively for MS1 and MS2. The temperature profiles (Fig. 6) and the heating balance are very similar through the cloud for MS1 and MS2, despite the fact that the precipitation rates and hydrometeor contents differ by a factor of two. This implies that the larger precipitation rate in MS1 is connected with the increased horizontal convergence of ice and not with an increase in the condensation rate.

The most notable difference between the temperature profiles of the two schemes is the lack of a pronounced isothermal layer (Fig. 6) at the freezing level (3.5 km) with MS2. This is because the graupel in MS2 has a much higher fall speed than the ice in MS1 and thus the melting is spread over more than one layer. This is also reflected in the heating terms (Fig. 7) where the sharp spike in latent cooling seen in MS1 is much weaker in MS2 and 500 m lower. The difference in temperature above the cloud top between the two schemes is related to the background diffusion included for numerical stability and has no physical significance.

(c) Effects of excluding graupel

MS2 has the option of graupel being “switched off”, whereupon all conversion terms in the scheme that involve graupel are set to zero. This represents a microphysical scheme where there are only ice and snow as the solid water particles; this type of scheme has been used in some numerical simulations (e.g. Dudhia 1989; Heckman and Cotton 1993). As graupel is not common in weak vertical velocities (i.e. 2 cm s$^{-1}$) excluding it may give
Figure 7. Steady-state heating rates for simulations of the stratiform region of a tropical cloud cluster with no radiation included: (a) MS1 and (b) MS2 (see text).

Figure 8. Steady-state hydrometeor profiles for MS2N (see text) simulation of the stratiform region of a tropical cloud cluster with no radiation included.

A more realistic simulation, and allows the effect of graupel on the total ice content and precipitation rate to be investigated. Runs including MS2 with graupel 'switched off' will be referred to as MS2N.

Figure 8 shows the steady-state hydrometeor contents for MS2N which can be compared with the hydrometeor contents for MS2 (Fig. 5). In the case of MS2N the snow content is considerably larger through much of the cloud than the total solid water in MS2.
The rain water content of MS2N is also larger than that of MS2. This confirms that the formation and precipitation of graupel is an efficient method of removing water from the cloud. The hydrometeor contents of MS2N are closer to those of MS1 (Fig. 4) but are still smaller. This suggests that although graupel plays a major role in the removal of water from the cloud, the snow in MS2 is still more efficient at removing water than the ice in MS1.

(d) \textit{Effects on radiative heating rates}

The effects of radiation on the temperature profile and hydrometeor contents of both MS1 and MS2 are small ($< 1\%$), and therefore the hydrometeor contents with radiation included are very similar to those shown in Fig. 4 and Fig. 5. Figure 9 shows the steady-state radiative heating rates obtained using MS1 and MS2 when only infrared radiation was included. It is clear that there are very large differences in the heating rates for the two microphysical schemes, particularly in the region of the cloud top. For MS1 the cloud-top cooling has a peak value of 11 K day$^{-1}$ at a height of 11.5 km, whereas for MS2 the peak cloud-top cooling is 35 K day$^{-1}$ at a height of 13 km. In the case of MS2, cooling is confined mainly to two model layers (i.e. the top 1 km of the cloud) whereas cooling for MS1 extends through the top 3 km of the cloud. The large difference in the infrared heating rates for MS1 and MS2 is due to the large ice content close to the cloud top in MS2 (see section 3(b)).

The differences in the cloud-base warming for the two schemes are smaller for MS2, 1.5 K day$^{-1}$, than for MS1, 3 K day$^{-1}$. The greater warming for MS1 is connected with the sharper increases in ice content at the cloud base. This feature would have a larger influence but is being counteracted to a small extent by the larger rain content in MS1 reducing the warming.

Figure 10 shows the steady-state radiative heating rates of MS1 and MS2 for the experiment with both infrared and solar radiation included. As in the case when only infrared radiation is included, there are very large differences between the heating rates
for the two microphysical schemes. For MS1 there is cooling between 11 km and 12.5 km, with a peak value of 5 K day\(^{-1}\) at 11.5 km. There is then warming through the rest of the cloud with a peak value of 5 K day\(^{-1}\) at 9.5 km. For MS2 there is cooling of 13 K day\(^{-1}\) confined to the top layer of the cloud (13 km) and warming through the rest of the cloud with a peak value of 7 K day\(^{-1}\) at 12 km.

The reason for the large difference in the combined infrared and solar heating rates between MS1 and MS2 is the same as for the infrared only experiment. The well defined cloud top in MS2 means that most of the infrared emission is taking place from the top 1 km of the cloud and most of the solar absorption in the top 3 km. This leads to larger heating and cooling rates, and larger gradients in the heating. With MS1 the slow increase in ice content causes the heating terms to be smaller and spread through a greater depth.

The radiative heating rates for the experiment using MS2N were also considered, but they are not shown as they were very similar to MS2. The main difference was for infrared heating at the cloud base where there was a slightly larger warming for MS2N (increased by 0.5 K day\(^{-1}\)) due to the larger total ice content at the cloud base.

4. THE SIMULATION OF THE DISSIPATION OF A CIRRUS CLOUD

(a) Initial conditions

The simulation of the dissipation of a cirrus cloud experiment is similar to one used by Dudhia (1989) to test an ice-phase parametrization; it has an initial prescribed ice content and no forced vertical motion. This allows the ice crystals or snow (in the case of MS2) to fall into the layers below and evaporate. The radiative heating rates are dominated by the effects of ice crystals, and large enough to have a significant effect on the hydrometeor content.

Two different sets of initial conditions were used and the model was integrated for 24 hours. The first set involved initializing the model with a fixed ice content of 0.5 g kg\(^{-1}\)
Figure 11. Hydrometeor profiles after 24 hours for the dissipation cirrus experiment with no radiation included and an initial ice content of 0.5 g kg$^{-1}$ between 9 and 13 km. Shown are the ice content and snow content of MS2 and the ice content of MS1 (see text).

between 8.75 km and 13.25 km. The second set used a fixed ice content of 0.2 g kg$^{-1}$ between the same heights. For both experiments the humidity was initially taken to be 90% with respect to ice within the ice cloud, and 60% in all regions outside the cloud. This humidity profile allows some evaporation within the cloud. The initial temperature profile is the same as that used in the simulation of the stratiform region of a tropical cloud cluster in section 3.

(b) Comparisons of microphysical schemes

Figures 11 and 12 show the ice and snow contents after 24 hours for MS1 and MS2; in Fig 11 the initial ice content is 0.5 g kg$^{-1}$ and in Fig. 12 it is 0.2 g kg$^{-1}$. It is clear that there are very large differences between the total ice contents for MS1 and MS2 after 24 hours. Since ice has a non-zero fall speed in MS1 almost all of it has fallen below the cloud base and evaporated. In the case of MS2, however, the removal of the ice requires autoconversion to snow, and possibly the collection of ice by snow, before it can fall and evaporate. This mechanism is inefficient particularly at low ice mixing ratios; with an initial ice content of 0.2 g kg$^{-1}$ very little ice is converted to snow.

The main removal of the ice in MS2, particularly in the case with an initial ice content of 0.5 g kg$^{-1}$, occurs lower in the cloud. A possible explanation for this is that the rate of autoconversion from ice to snow is greater at higher pressures, i.e. lower in the cloud. However, investigation of the conversion rates showed it is due to the collection of ice by snow, which is greater lower in the cloud, because this is where snow contents are larger.

Amounts of ice remaining in the cloud with MS2 are much larger than would be expected. Even if the ice crystals are small (20 µm), in the absence of vertical air motion they will fall a considerable distance (2 km) in 24 hours. This problem could be solved by either adjusting the autoconversion term or allowing the ice crystals to fall. The effect of falling ice crystals in MS2 is considered in the following subsection.
Figure 12. Hydrometeor profiles after 24 hours for the dissipating cirrus experiment with no radiation included and an initial ice content of 0.2 g kg$^{-1}$ between 9 and 13 km. Shown are the ice content and snow content of MS2 and the ice content of MS1 (see text).

(c) Effects of falling ice crystals in MS2

The effect of allowing the ice crystals to fall is likely to be important in simple models such as the one used here, where, in the absence of vertical motion and radiation, falling ice and snow are the only means of removing the ice crystals if the air is saturated in the cloudy region. The problem with having a zero fall speed of ice can also be seen in models with more detailed dynamics (e.g. Craig and Clough 1993). As seen in the previous subsection this can lead to large ice contents remaining after long integration times (Figs. 11 and 12).

In MS1 the fall speed of the ice category (which encompasses all solid water) is always included. It is based on an empirical relation derived from observations by Heymsfield (1977) and is given by

$$v_i = 3.23(q_i)_{0.17}, \quad (5)$$

where $v_i$ is the fall speed of the ice (in m s$^{-1}$), $q_i$ is the ice mixing ratio and $\rho$ is the density of the air (in kg m$^{-3}$). For this work, the method of calculating the fall speed of the ice crystals in MS2 has been taken from Cotton et al. (1982) and is based on the fall speeds of hexagonal plates taken from laboratory measurements of Hobbs et al. (1972). The maximum distance, $D$ (in metres) across the face of an unrimed hexagonal plate is given by

$$D = x_1m_1^{0.5}, \quad (6)$$

where $x_1$ is related to the size of the crystal and $m_1$ is the mass of the ice crystal in grams.

The fall speed of the ice can then be expressed in terms of the diameter $D$ by

$$v_i = x_2D \left( \frac{p_\infty}{p} \right)^{0.5}, \quad (7)$$

where $x_2$ is related to the size of the crystal, $p$ is the pressure at the model level and $p_\infty$ is standard atmospheric pressure. According to Hobbs et al. (1972) there exists two regimes for different sized ice crystals which determine the values of $x_1$ and $x_2$. These are

$$x_1 = 0.515 \text{ m g}^{-1/2} \text{ and } x_2 = 304 \text{ s}^{-1} \text{ for } m_1 < 1.7 \times 10^{-7} \text{ g}, \quad (8)$$
Figure 13. Ice contents after 24 hours for the dissipating cirrus experiment with an initial ice content of 0.2 g kg\(^{-1}\). Shown are the ice contents of MS2 (see text) using the fall speed of Cotton et al. (1982), and zero fall speed.

\[ x_1 = 0.192 \text{ m g}^{-1/2} \text{ and } x_2 = 1250 \text{ s}^{-1} \text{ for } m_i \geq 1.7 \times 10^{-7} \text{ g}. \]  

(9)

It should be noted that there is a discontinuity in the expression for the fall speed of an ice crystal at a mass of \(10^{-7}\) grams. This is because the coefficients shown are from laboratory experiments where both unrimed and lightly rimed hexagonal plates were investigated; the coefficients in (8) are for unrimed hexagonal plates whilst those in (9) are for lightly rimed hexagonal plates. Using these equations a typical mass for an ice crystal with a radius of 30 \(\mu\text{m}\) is around \(10^{-8}\) g and it will have a fall speed of 5 cm s\(^{-1}\).

The tropical cirrus experiment was run using an initial ice content of 0.2 g kg\(^{-1}\) and the fall speed for the ice crystals given above. Figure 13 shows the ice content through the cloud after 24 hours using the fall speed of Cotton et al. (1982) (Eq. 7). It can be seen that allowing the ice crystals to fall has a significant impact on the ice remaining in the cloud after 24 hours, with the cloud base \(\sim 1.5\) km lower. Although not as much ice is removed as with MS1 (Fig. 12), mainly due to the different expressions for the fall speed that are used, there is significantly less ice than with zero fall speed. Another important effect of allowing the ice to fall, particularly when considering radiative heating, is that the cloud top becomes less well defined.

Figure 14 shows the column ice content throughout the 24-hour integration from the same experiment. It is clear that the effect of the ice falling becomes more significant in time, particularly when the fall speed is calculated using Eq. (7). After 10 hours the difference between the column ice content for zero fall speed and that for falling ice calculated using Eq. (8) is \(\sim 80\) g m\(^{-2}\) (35%), whereas after 24 hours the difference is \(\sim 110\) g m\(^{-2}\) (65%).

(d) Effects on radiative heating

Figure 15 shows the radiative heating rates of MS1 after 24 hours, and MS2 after 20 minutes and 24 hours. Infrared radiation only is included, with an initial ice content of 0.5 g kg\(^{-1}\) and zero fall speed for the ice. Figure 16 shows the same as Fig. 15 but with combined infrared and solar radiation. Heating rates are shown for MS2 with zero
Figure 14. Variation of column ice contents with time for the dissipating cirrus experiment with an initial ice content of 0.2 g kg\(^{-1}\). Shown are the column ice contents of MS2 (see text) using the fall speed of Cotton et al. (1982), and zero fall speed.

Figure 15. Infrared heating rates for MS2 after 20 min, and for MS1 and MS2 (see text) after 24 h, for the dissipation cirrus experiment with an initial ice content of 0.5 g kg\(^{-1}\). The heating rates for MS1 after 20 min are very similar to those of MS2 and are not shown.

fall speed for the ice, because this is the most common assumption in bulk microphysical schemes and the basic form for MS2. This means the heating rates shown are a worst-case scenario for MS2 due to the false assumption that the fall speed of the ice crystals may be neglected.

For MS2 it can be seen from Fig. 15 that after 20 minutes there is a very large cooling rate at the cloud top (45 K day\(^{-1}\)), and a very large heating rate at the cloud base (39 K day\(^{-1}\)). The same is true for MS1 (not shown). This is because the cloud top and base are very well defined at this time for both MS1 and MS2. After 24 hours there is still
a large cooling at the cloud top for MS2 but the cloud base is less well defined (Fig. 11) and thus the heating is spread through more layers. For MS1 the heating rates are very close to zero after 24 hours because there is very little ice left.

The effect of radiation on the cloud ice contents can be seen in Fig. 17 with initial ice content 0.5 g kg\(^{-1}\), and Fig. 18 with initial ice content 0.2 g kg\(^{-1}\). It is clear that infrared radiation has a larger effect when the ice contents are lower (Fig. 18). In this case cooling at the cloud top is causing more condensation of ice, and cloud-base heating is causing ice to evaporate and thus the cloud becomes less deep. There is also an increase in the cloud ice content between 11.5 km and 12.5 km where there is very little radiative cooling.
or heating; this is due to increased instability from cloud-top cooling and possibly cloud-base warming, producing more overturning and mixing the larger ice contents to lower regions in the cloud. The overall effect of including infrared radiation is a reduction in the column ice content of 32 g m^{-2} (20%) compared with the run with no radiation. When solar and infrared radiation are included there is still cooling at the cloud top which causes an increase in the ice content in this region, but warming through the rest of the cloud causes a significant reduction in ice content. The column ice content through the cloud is 76 g m^{-2} (46%) less than when no radiation is included.

When more ice is present (Fig. 17) the autoconversion term removes any ice that is formed by condensation due to infrared cooling. In this case the main effect of the infrared radiation is to make the lapse rates through the cloud less stable and thus cause more mixing of the ice. The difference in the column ice content when infrared radiation is included is very small, 4 g m^{-2} (< 2%). There is also a more unstable lapse rate and increased mixing through the cloud when solar radiation is included, but in this case the heating causes a reduction in the column ice content of 28 g m^{-2} (13%). Hence the degree of interaction between the cloud microphysics and radiation appears to be dependent on the representation of a single process (autoconversion) in the model.

5. Conclusions

Differences in cloud hydrometeor contents produced by two different microphysical schemes were investigated using two simple experiments: the simulation of the stratiform region of a tropical cloud cluster and the dissipation of a tropical cirrus cloud. The influence of the different hydrometeor profiles on radiative heating through the clouds, together with the effects of allowing ice to fall, and of excluding graupel using the microphysical scheme of Swann (1994), were also considered.

The experiments involving the simulation of the stratiform region of a tropical cloud cluster showed that, although the two different microphysical schemes (Cox 1988; Swann 1994) have little effect on the steady-state heat balance of the system, they do produce very different hydrometeor contents and corresponding precipitation rates. This has a major
impact on the radiation scheme, particularly infrared radiation at the cloud top. The well defined cloud top using the scheme of Swann (1994) caused large cooling rates, whereas the scheme of Cox (1988) had a less well defined cloud top and smaller cooling rates. The peak infrared cooling rate was 11 K day\(^{-1}\) for the scheme of Cox (1988), and 35 K day\(^{-1}\) for the scheme of Swann (1994).

Experiments involving the simulation of the dissipation of a tropical cirrus cloud confirmed that the two microphysical schemes produce very different hydrometeor contents; sensitivity tests showed that the zero fall speed of the ice played a major role in this. Cirrus cloud simulated in the experiment almost completely dissipated using the microphysical scheme of Cox (1988), but very little ice was removed using the microphysical scheme of Swann (1994). Radiation had a significant effect on ice content and distribution in the cirrus cloud, particularly when the initial ice content was small.

We have shown that different bulk microphysical schemes produce very different profiles of hydrometeor content. A major difference between the two schemes investigated was the ice content at the cloud top, and this region has the most significant impact on the radiative heating profiles in both the solar spectrum and the infrared spectrum. Although observations of the vertical profiles of the microphysical properties of high and deep clouds are rare, particularly in the tropics, it is clear that a non-precipitating ice variable in a bulk microphysical scheme can give unrealistic predictions of cloud ice contents. This is likely to be most important in large-scale models where vertical velocities are small and time steps large.

To summarize, several points can be made from this work concerning bulk microphysical schemes:

(1) More complexity in a microphysical scheme does not necessarily lead to more realistic hydrometeor profiles.

(2) Small changes in hydrometeor distributions (well within the errors in knowledge of microphysics) can produce large changes in the radiative heating rates.

(3) The feedback of radiation on microphysics is most important in cold clouds with low ice-water contents.

(4) The degree of dependence of the modelled hydrometeor contents on radiation is likely to be determined by the way in which microphysical processes are represented in the model. Uncertainty in the representation of any of the microphysical processes may influence the effect of radiation on microphysics.

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