The impact of a physically based microphysical scheme on the climate simulation of the Meteorological Office Unified Model

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SUMMARY

The predictions of two, large-scale precipitation schemes for a general-circulation model are compared within a development version of the Meteorological Office's climate model. One scheme contains a prognostic ice content and a representation of mixed-phase microphysical processes, whereas the second scheme is a diagnostic scheme where condensate is partitioned into liquid and ice as a function of temperature. Results show that, although the overall near-surface conditions are similar, significant differences occur in the structure of clouds predicted by the two schemes. The total precipitation rate is similar, but the microphysical scheme has less convective activity than the temperature-partition scheme, because of the different subgrid nature of the schemes. Layer-cloud amounts are changed due to both changes in condensate and changes in its diagnosis. More ice is predicted by the microphysical scheme, mainly as a result of reduced fall speeds of ice particles. This shows the need for global measurement methods of ice-water content to be developed.

KEYWORDS: Cloud General-circulation model Parametrization Precipitation

1. INTRODUCTION

The properties of a cloud depend greatly upon its spectrum of water droplets and ice particles. Ice, liquid and mixed-phase clouds behave very differently from each other. It is therefore desirable to make this distinction within a general-circulation model (GCM). It is not known how cloud types will evolve in response to climate change. Hence a parametrization of clouds should be based on physical processes, rather than on an equilibrium situation observed for a particular climate. Such physically based parametrizations should also be advantageous for numerical weather prediction. These requirements to parametrize clouds physically has led to ever more complicated microphysics parametrizations.

All microphysical schemes are best suited to small, if not 'cloud resolving', size grid boxes. However, the use of a microphysical treatment still offers the advantages of being physically based when applied to the scale of climate models. At this scale it is necessary to take into account the effects of partial cloudiness.

Many GCMs now use some form of cloud microphysics parametrization as a method of determining the vertical distribution of amount and phase of condensate in a cloud. Changes to the treatment of microphysics in GCMs often produce large changes in the simulated condensed water paths. These can have large effects on the sensitivity of the model to greenhouse-gas forcing.

Boucher et al. (1995) adjusted microphysical parameters associated with droplet number and threshold droplet size for precipitation production. Increases in droplet number or threshold radius decreased precipitation efficiency, leading to increased water contents and an increase to the albedo of the cloud (above the increase caused by the radiative effect of smaller droplets).

Fowler et al. (1996) included a detailed microphysics scheme, using five water variables. The latent and radiative heating and cooling associated with the altered water contents forced changes to the model's circulation. Sensitivity studies with this scheme, described by Fowler and Randall (1996), showed large changes in water contents and the partitioning between liquid and ice when parameters were altered. This strongly affected

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the radiation characteristics of the simulations. However, no cloud-fraction scheme was used. Since conversion of cloud water to precipitation is strongly dependent upon the cloud water contents, they suggested that the inclusion of a cloud-fraction scheme would be likely to change the results radically.

Del Genio et al. (1996) used a microphysics scheme with a prognostic liquid-water variable. They showed that simulated climate change was sensitive to the parametrization of cumulus anvil. The amount of detrainment from convective cloud to large-scale cloud impacted substantially on the water contents of the clouds. They suggested that parametrizations may need to be dependent upon the type of cloud because different processes are dominant in different clouds, and that a prognostic liquid-water content was necessary for reliable climate-change experiments.

Lohmann and Roeckner (1996) used a microphysics scheme which allowed for a more realistic simulation of supercooled liquid clouds. The scheme produced some liquid-only clouds at temperatures as low as −35 °C. The ice content was sensitive to the specification of the microphysical terms. They also studied the effect of droplet number on the liquid cloud, showing large changes in water path when parametrizations were changed.

Rotstayn (1997) described a mixed-phase microphysics scheme in which the cloud fractions for ice and liquid cloud, and their overlaps both horizontally and vertically, were consistently derived from a method similar to Smith (1990). The water contents were calculated prognostically. The scheme gave large improvements in the cloudiness at high latitudes.

This paper investigates the changes in the climate of a GCM when the large-scale precipitation scheme is changed. Section 2 contains a description of the model and schemes, and section 3 the results of the simulations. Section 4 contains a discussion of some of the sensitivity issues of the schemes, and shows the need for measurements of ice-water content. The mechanisms behind the changes are given in section 5, and a summary of the conclusions are given in section 6. This paper does not assess the sensitivity of climate change under increased greenhouse-gas forcing to the cloud and precipitation parametrization.

2. The Climate Version of the Unified Model

An updated atmosphere-only GCM using the Meteorological Office's Unified Model (Cullen 1993) is currently under development for climate prediction. It is based on the model described by Pope et al. (2000). It is a grid-point model with horizontal resolution of 3.75° longitude by 2.5° latitude. There are 38 vertical levels defined by a hybrid pressure coordinate. The time step is 30 minutes for the physics sections and 15 minutes for the dynamics. The radiation scheme is described by Edwards and Slingo (1996), and the cloud scheme by Smith (1990). The convection scheme is of a mass flux type and is described by Gregory and Rowntree (1990). The model includes a prognostic ice microphysics large-scale precipitation scheme, described by Wilson and Ballard (1999). The reader is referred to this paper for a complete description of the scheme. This is referred to below as the mixed-phase scheme (MPS).

The MPS uses variables representing vapour, liquid, ice and rain. It calculates transfers between these quantities based upon the microphysical equations governing the behaviour of particles in the atmosphere. These transfers represent: condensation and evaporation of liquid water, nucleation of ice, depositional growth or decay of ice, riming, melting, capture of raindrops by ice particles, evaporation of rain, accretion of liquid water by rain, and autoconversion of liquid water to rain. Growth of ice is
principally by deposition. The microphysical method allows glaciation at low levels in deep precipitation systems, whereas shallow layer clouds can remain as supercooled liquid. A summary of such behaviour in observed clouds is presented by Ryan (1996).

In order to assess the impact of this scheme upon the climate simulation of the model, the model was run for ten years of simulation and the results compared with a run where the prognostic ice microphysics scheme was swapped for a Sundqvist (1978) style large-scale precipitation scheme used in previous Meteorological Office GCMs, as described by Senior and Mitchell (1993), with the evaporation of precipitation as given by Gregory (1995). The Sundqvist style precipitation scheme includes a partitioning of condensed water into ice and liquid based upon temperature such that all condensate is ice at temperatures below \(-9 \, ^\circ\text{C}\), all is liquid at \(0 \, ^\circ\text{C}\), and there is a linear transition between these extremes. This is referred to below as the temperature-partition scheme (TPS). Apart from the cloud and precipitation schemes, the runs are identical.

There will be considerable discussion in this paper relating to the subgrid nature of the two schemes. Both use the same formulation for cloud at temperatures greater than \(0 \, ^\circ\text{C}\), that of Smith (1990), which assumes a triangular probability density function of total moisture minus saturation vapour content. Condensation occurs when the local total moisture content exceeds saturation. The TPS also uses the Smith scheme for temperatures colder than \(0 \, ^\circ\text{C}\), with the saturation vapour content representing the value over ice. The method for the MPS is discussed by Wilson and Ballard (1999). Liquid cloud is calculated for all temperatures using the Smith (1990) formulation but with the total water content replaced by the sum of the vapour and liquid, and the saturation vapour content calculated for liquid water. The ice cloud fraction is calculated from the ice content, using a relationship equivalent to that derived from the Smith (1990) scheme between these two quantities, except that saturation with respect to liquid is used. This means that a liquid cloud which freezes does not change its cloud fraction. The supersaturation in the deposition term is replaced by \((q - \alpha q_{\text{sat}})/q_{\text{sat}}\) where \(q\) is the vapour content, \(q_{\text{sat}}\) is the saturation vapour pressure with respect to ice and \(\alpha\) is a value which linearly depends upon the ice cloud fraction. \(\alpha\) equals 1 when the ice cloud fraction equals 1, and \(\text{RH}_{\text{crit}}\) when the ice cloud fraction is 0. \(\text{RH}_{\text{crit}}\) is the critical relative humidity as used in the Smith (1990) scheme.

Tuning has been performed on the MPS in order that the top-of-atmosphere radiation budget balances (such a state is essential for coupled ocean–atmosphere model simulations). Ice fall speeds were increased by 40% relative to the value given by Wilson and Ballard (1999). The autoconversion rates were increased by roughly a factor of two and the lower limit of water content for autoconversion was decreased by a factor of approximately four. The microphysical tuning should reduce amounts of condensate.

The next section assesses the changes to the equilibrium climate of the model. A global overview is presented first. Then the section concentrates upon the cloud and precipitation predicted in three regions: African tropical convection, mid-latitude frontal systems over South America, and summer-time mixed-phase Arctic clouds. Figures shown are for the June, July and August (JJA) season.

3. Changes in the Climate Simulation

(a) Overview

Changing the large-scale precipitation scheme will directly affect the cloud and precipitation fields. These changes are associated with changes in humidity and, through latent heating, temperature. There is also an indirect effect brought about by the different vertical profiles of temperature and moisture causing feedbacks on other physical and
dynamical processes. This paper shows that the indirect feedbacks can be unexpected and complicated.

There is little change in circulation between the two runs, and hence there is little change to the precipitation. A clear difference is obvious, though, when the rainfall is split between convective and large-scale. Very little large-scale rain falls in the tropics in the TPS, but significant quantities fall when the MPS is used. Geographically, the largest increases in the large-scale precipitation rates are where there is convective activity along with significant large-scale precipitation.

The condensed water paths are different. Figure 1 shows comparisons of water contents for June, July and August from the model runs and observations from the National Aeronautics and Space Administration Vapour Project (NVAP) (Randel et al. 1996). The zonal mean layer-cloud liquid-water path is similar between the two runs, except near the poles where there is more supercooled liquid water in the MPS (see the discussion of arctic cloud below). The layer-cloud ice-water path is significantly higher in the MPS at all latitudes. Using sea points only, one can compare the total (large-scale plus convective) liquid-water path against the NVAP estimate of liquid-water path from satellite SSM/I (special sensor microwave imager). Both schemes have similar liquid-water paths over the sea, except at higher latitudes. The model has a general underestimate of liquid-water path compared with NVAP, and variations with latitude are not as great as they should be.

It is difficult to assess the ice-water paths in the model because of the difficulty of producing an observational dataset. Lin and Rosso (1996) obtain estimates of zonally averaged ice-water path for four months for non-precipitating clouds with tops colder than 0 °C. They obtained means of 0.03 to 0.17 kg m⁻² depending upon the season.
and latitude, with an estimated error of 50 to 100%. The model was not conditionally sampled in this way but the observations do not immediately suggest an obvious error in the model’s prediction of ice-water path.

The radiation budgets of the models are very similar because the fall speed of ice particles and the autoconversion terms in the MPS have been tuned, as described in section 2. Large-scale ice cloud fractions are also calculated differently between the schemes. Less ice cloud is diagnosed for the same amount of condensate in the MPS because the scaling saturation vapour content is taken over liquid water rather than ice. However, there are some changes to the radiative fields. There is a decrease in the outgoing long wave in the tropics between 90°E and 180°E, and in the southern hemisphere storm track. This suggests thicker ice cloud. Also, there is a general increase in outgoing short-wave radiation off the western coast of the Americas, suggesting an increase in stratocumulus cloud.

The screen-level temperature shows a warming at high latitudes in the winter. This is due to the diagnosis of cloud at the top of the boundary layer as liquid in the MPS (which does not precipitate) and ice in the TPS (which does precipitate), as discussed by Wilson and Ballard (1999). The resulting increase in cloud with the MPS allows night-time temperatures to be maintained.

The upper troposphere is slightly warmed in the MPS. There is a slight increase in the relative humidity near the tropopause. A decrease in relative humidity occurs in the lower troposphere. Zonal means of zonal wind and meridional wind show very little change. There is a small increase, of about 0.5 m s⁻¹, in the zonal wind associated with the southerly shift of the southern storm track (discussed in subsection (c)).

High cloud has increased in the MPS and low extratropical cloud has decreased (except in the stratocumulus regions).

The changes in moisture fields are summarized in Table 1. Large-scale precipitation has increased at the expense of convective precipitation, and the large-scale condensed water path has increased. These changes result in a characteristic turn-round time for
Figure 2. The total precipitation for June–August (mm day\(^{-1}\)) for the central African region: (a) convective precipitation in the mixed-phase scheme, (b) convective precipitation in the temperature-partition scheme, (c) large-scale precipitation in the mixed-phase scheme, and (d) large-scale precipitation in the temperature-partition scheme. Rates above 0.1 mm day\(^{-1}\) are lightly shaded, rates above 1 mm day\(^{-1}\) are medium shaded and rates above 4 mm day\(^{-1}\) are heavily shaded.

condensed cloud water considerable higher in the MPS than in the TPS, yet the turn-round time for the total moisture is less.

We now present each of the identified regions in turn, for the JJA season.

(b) *African convection*

Convective activity is responsible for most of the precipitation falling on the earth’s surface, and is a major factor in determining the structure of the atmosphere in the tropics. Differences in the moisture content at the grid-scale have the potential to feedback on the modelled convection. This feedback can be investigated by looking at, for example, convective activity over central Africa, where nearly all precipitation is related to convection.

The most striking difference between the two runs is the increase in large-scale precipitation and a corresponding reduction in convective precipitation, shown in Fig. 2. In reality, intense convective cores are associated with large, dynamically (and radiatively) active anvil clouds, which produce widespread precipitation long after the convective updraught has dissipated, as discussed by Tao *et al.* (1991). Whether this model change is an improvement depends upon whether one considers anvil cloud as a large-scale cloud or a convective cloud or neither. Anvil cloud can be maintained after convection has ceased, so may be argued to be a large-scale cloud, but the production of precipitation is via graupel (see, for example, Caniaux *et al.* (1994)), which is not a mechanism parametrized in the MPS. The MPS is not dynamically active either.
Figure 3. A north-south cross-section through the African convection for a ten-year June-August mean. Eta is the ratio of the pressure to the surface pressure. Shown shaded are condensed water contents (kg kg\(^{-1}\)), in dashed lines temperatures (°C), in solid lines relative humidities (per cent), and in thick lines convective cloud fraction for (a) the mixed-phase scheme and (b) the temperature-partition scheme.
A cross-section (Fig. 3) of total condensed water content shows considerably greater water content in the MPS simulation than in the TPS simulation at temperatures colder than 0 °C. This condensate is mostly ice. Profiles for a single point (Fig. 4) show an increase in temperature of over 0.5 degC at pressures less than 200 hPa when the MPS is used, and a considerable increase in the large-scale condensate. The large-scale cloud is reduced.

Mixed phase large-scale cloud is not common in the model for tropical regions. Low-level cloud is similar in both models. The relative humidity and temperature
structure of the boundary layer and free troposphere are generally unchanged, giving similar screen temperatures.

This convective example is further expanded in section 4, where the sensitivity to model parameters is explored, and in section 5, which summarizes the mechanisms involved.

(c) Mid-latitude and orographic precipitation

Stratiform precipitation, modified by orography, represents the most important precipitation process occurring in mid-latitude regions. The method of large-scale precipitation production is considerably different between the two schemes. To investigate these effects we have considered a region across the southern tip of South America, where the Andes mountains force considerable additional ascent to that already present dynamically in the storm track.

A cross-section at latitude 50°S is shown in Fig. 5, and a profile in Fig. 6. Within the MPS the condensate will be nearly all ice at temperatures colder than 0 °C. Significant ice exists in the MPS at much greater altitudes than in the TPS. The cloud fraction is reduced throughout the troposphere. There is a warming at upper levels of nearly 1 degC. There is less build up of condensate around the melting layer in the MPS since this condensate remains as ice in the MPS rather than being diagnosed as liquid (which does not fall).

The orographic enhancement of the surface precipitation is considerably different. This is due to the ways in which the cloud water, formed by the uplift and cooling of the air, can be converted either into ice, and hence rain on melting, or directly to rain. The ice-deposition process in the MPS uses a rate equation, rather than an equilibrium calculation, so adds a delay between uplift and precipitation reaching the ground. Additionally, the enhanced water contents low down in the TPS can create precipitation more efficiently from the lower levels, so less vapour can be carried to the higher altitudes. The time-scale for moisture to be carried an extra 2 km upwards is a few hours, corresponding to a few hundreds of kilometres of horizontal transport. Hence the orographic enhancement of the rainfall rate is reduced, and the rain shadow is slightly less intense. Comparison with observations (Fig. 7), from Xie and Arkin (1997) (without using model data in their analysis), shows that there is too much precipitation within the shadow region of the storm track for both models. The intensity over the mountains is better modelled in the MPS.

There is also evidence that there has been a small southerly shift in the storm track. The direction of the shift is consistent with the radiative warming of nearly 1 degC in the upper levels of the storm track, strengthening the latitudinal temperature gradient to the south of the storm track.

(d) Arctic

The summer arctic provides a region for testing the impact of mixed-phase clouds, as they exist in abundance in this region (see, for example, Hobbs and Rango (1998) or Curry (1986)). The arctic is also predicted to undergo a large rise in temperature under global-warming scenarios, mainly due to changes in sea-ice, so the alteration of the cloud parametrization here could have significant effect in a climate-change simulation.

The rainfall rates are increased in the MPS and the snowfall rates reduced. This is due to some precipitation falling as freezing rain, which the TPS cannot predict (rain falling through a sub 0 °C layer is frozen in the TPS). Modeled liquid cloud (much of it supercooled) is prevalent throughout the arctic in the MPS, with ice concentrations
Figure 5. A cross-section at 50°S plotted like Fig. 3: (a) mixed-phase scheme, and (b) temperature-partition scheme.
increasing towards the surface. The cross-sections in Fig. 8 demonstrate that the MPS, but not the TPS, can maintain a deck of cloud elevated from the surface, even though the temperatures are below 0°C. This is because the TPS will diagnose a significant fraction of the condensate to be ice and will allow it to fall to the 0°C level.

The boundary-layer structure is different, shown more clearly by the profiles in Fig. 9. The MPS has slightly warmer surface temperatures and significantly colder temperatures higher in the boundary layer. This is a similar change to that documented by Wilson and Ballard (1999). In the TPS the falling ice destroys the adiabatic nature of a well-mixed boundary layer. The MPS produces a drier boundary layer with a greater lapse rate. The average boundary-layer top, indicated in the temperature profiles by the
change in lapse rate, is increased in height in the MPS, from 930 to 870 hPa. This, again, is a signal of much reduced precipitation efficiency.

An unexplained feature is the much increased shallow convective activity within the boundary layer for the TPS. This is despite the TPS having a more stable mean profile. The convection is modelled to take place predominately above the height of the 0 °C isotherm. Extra latent heating introduced by the ice (rather than liquid) may play a part in enhancing any instability, or perhaps the shallower boundary layer allows greater instability to be built up by solar heating. Convection is observed to take place over breaks in the sea-ice when previously stable cold air is advected over a relatively warm sea (Curry et al. 1996), but the modelled mechanism may not be correct.

4. SENSITIVITY OF THE MIXED-PHASE SCHEME TO MODEL PARAMETERS

The MPS was tuned to keep a similar radiation balance to the control. This is essential if the scheme is to be used for long integrations of a coupled ocean–atmosphere model. This section investigates some of the large changes that occur for different parameter values.

A group of one month (December) simulations were performed, in which parameters were changed. The runs considered are those where the subgrid model was set to assume no variability within a grid box, and where the autoconversion and ice fall-speed parameters in the MPS were ‘untuned’ back to the specification given by Wilson
Figure 8. A cross-section from Alaska to the north pole plotted like Fig. 3 for (a) the mixed-phase scheme, and (b) the temperature-partition scheme.
and Ballard (1999). This results in reduced fall speeds and reduced autoconversion of liquid to rain. Subsection (a) describes the global results, and (b) considers the results for a single profile within the inter-tropical convergence zone.

(a) Global characteristics

A summary of global characteristics is given in Fig. 10. The large-scale liquid-water path (displayed in (a)) is, as before, reasonably similar for the tuned MPS and TPS. Untuning the MPS results in a much greater liquid-water path, due to the reduction in autoconversion. Setting the subgrid variability to zero significantly reduces the liquid-water path in both schemes, except at high latitudes in the MPS. The reduction is because
Figure 10. Zonal means of water paths and cloud fractions for several one-month simulations for (a) the large-scale liquid-water paths, (b) the large-scale precipitation fraction, (c) the large-scale ice-water paths, and (d) the large-scale cloud fraction. Shown are the mixed-phase scheme; temperature-partition scheme; mixed-phase scheme with no subgrid-scale variability; temperature partition with no subgrid-scale variability, and 'untuned' mixed-phase scheme.

could cannot form unless the grid box reaches saturation on the grid-scale. There is less of a variation in the models when convective water content is added, but all of the models underestimate the true liquid-water path compared with NVAP. There is no directly comparable observation set available for ice-water content or paths.

Figure 10(b) plots the proportion of model precipitation which is large-scale as a function of latitude. The total precipitation rates are similar. The MPS has more large-scale precipitation than the TPS. The TPS produces a similar ratio as the MPS when both have no (so identical) subgrid variability, despite large changes in the ice path and cloud fraction. This suggests that a radiative feedback is not important for the change in large-scale precipitation fraction.

Figure 10(c) shows the large-scale ice-water paths. The 'untuned' mixed phase run has a considerably higher ice-water path than the tuned run, which itself has a larger path than the TPS. Validation of ice content should be seen as part of the validation of the model's climate. One can obtain a similar radiation budget with different ice paths by changing the specification of the cloud fraction. Indeed, the MPS produces less cloud fraction for the same ice content as the TPS, so the long-wave radiation characteristics are similar.

Figure 10(d) displays the changes to the total cloud amount. The tuning has resulted in the cloud amounts for the MPS and TPS being similar, except in the polar regions, where there is more low cloud and fog in the TPS. 'Untuning' the MPS raises the cloud fraction slightly in response to the greater water paths, but the biggest change is when
the subgrid variations are removed (so cloud fraction is unity if ice is present and zero otherwise). This results in much more cloud in the schemes, except in the tropics for the TPS where there is little large-scale cloud compared with convective.

(b) A profile in a convective region

The results of the five simulations can be differenced so as to apportion changes to the change in the tuned microphysics (MPS minus TPS where both have no subgrid model) and changes in the subgrid model (MPS with its subgrid model minus the MPS without the subgrid model, minus a similar difference for the TPS). Also, the effect of untuning the microphysics can be calculated. These results are shown for a profile at 7.5°S, 22.5°E in Fig. 11.

The subgrid-scale change is often the dominant factor in altering the simulation. The change in microphysics tends to produce an opposite effect, although not so large. The moisture reduction at 600–800 hPa is due to the subgrid-scale changes. There is a stabilizing reduction in temperature below 600 hPa due to the subgrid change. The condensate changes at the highest altitudes are due to microphysics (the ice fall speeds have been reduced, hence more ice is maintained) with the tuning having a large effect. It is reasonable to suppose that a similar tuning of the TPS would produce similar magnitude changes to the ice-water contents and other parameters. The upper-level temperatures have increased as a result of untuning the model. Convective cloud is seen to be reduced mainly as a result of the subgrid scheme. Tuning of the microphysics has had very little effect, so it is unlikely that the condensate amounts alone are responsible, via radiative feedbacks, for the convection changes observed. This is confirmed by single-column model runs where the same radiative heating profile is imposed.

5. Mechanisms

The mechanisms behind the changes discussed in sections 3 and 4 are complex.

The increase in ice content of the MPS is primarily due to the reduction in fall speed of the ice, which is more important at colder temperatures. If the downwards flux of ice nearly balances the upwards flux of moisture, and the circulation remains unchanged between the model runs, then a reduction in ice fall speed must lead to an increase in the ice content.

There are two competing effects altering the large-scale cloud amounts. The increase in ice content leads to an increase in the diagnosed cloud fraction, following equations presented by Wilson and Ballard (1999). But a change in the diagnostic relationship used between the two schemes results in less cloud cover diagnosed for the same ice content in the MPS. These changes nearly cancel to give similar large-scale cloud amounts despite significant differences in the ice contents.

The change in relative humidity is again a result of competing effects. The microphysical part of the MPS is not so fast as the TPS at converting changes in vapour to changes in ice. This is because it uses a rate equation to do so rather than converting the moisture instantaneously. Hence supersaturation is required for ice growth, especially at the cloud top where the small amount of ice present produces low depositional growth rates. However, the subgrid formulations of the schemes are different. The TPS has a relationship between vapour and ice condensate from the diagnostic Smith (1990) scheme. The MPS, as described in section 2, uses a deposition term to grow ice, with the supersaturation term modified by the cloud fraction. There is no direct relationship between vapour and ice content, but there is a relationship between equilibrium ice content (where it is not growing or decaying by deposition) and vapour content. For the
Figure 11. A profile at 7.5°S, 22.5°E of changes due to various parts of the parametrizations for (a) relative humidity with respect to ice, (b) total moisture, (c) total condensate, (d) layer-cloud amount, (e) temperature, and (f) convective-cloud amount. Shown are changes attributed to microphysics (thick solid line), changes attributed to the subgrid-scale (thin solid line), and changes due to untuning of the mixed-phase scheme (dashed line).
same equilibrium ice content, there is less vapour required in the MPS. Overall, there is greater relative humidity at the highest levels in the troposphere because of the extra supersaturation, but decreases at mid-levels due to the subgrid changes. The overall specific humidity of the atmosphere is reduced.

The decrease in convective precipitation is primarily associated with the change in the subgrid-scale models rather than the microphysics (shown in Fig. 10(b) by the similarity of the no subgrid-scale simulations whereas the simulations including the subgrid models are different). The same total water content will be composed of more ice and less vapour in the MPS than in the TPS. The increased conversion of vapour to ice will result in a greater flux of ice at the melting layer, and hence greater large-scale rainfall. The convection responds to provide the remaining heat and moisture increments, probably through interactions with the extra latent heat released by the large-scale scheme.

The one-month simulations show that the temperature increase observed in the high troposphere is mainly associated with the microphysical rather than subgrid-scale changes. It may be associated with radiative heating differences due to changes in cloud fraction and ice content, although changes in dynamical circulation and convection could also feedback and effect this. The change in convection is primarily associated with the subgrid model changes, whereas the temperature change is more associated with the microphysical changes, hence it is unlikely that the increase in temperature at high levels has stabilized the convection.

6. CONCLUSIONS

(a) Interaction of convection and large-scale precipitation schemes

The surface precipitation rate is controlled not by the large-scale precipitation scheme but by the upward transport of water vapour in the model. The cloud systems evolve in the model to produce the required amount of precipitation.

The subgrid model in the MPS converts more vapour to ice, increasing the large-scale precipitation and releasing latent heat. The convection is suppressed in response. The greatest increase in the large-scale precipitation is in regions where the large-scale precipitation was already significant. The model is already in a sensitive balance between large-scale and convective precipitation in these regions, and this balance is altered.

Shallow convection in the model often couples with the boundary-layer scheme. An increase in the boundary-layer height, caused by retaining liquid cloud rather than ice in the MPS, can produce a reduction in shallow convection.

(b) Vertical structure of a stratiform precipitation system

A precipitation system strongly forced by ascent has condensed water throughout the troposphere. The MPS produces a profile of ice-water content that slowly increases with decreasing height, until the melting layer is reached. The TPS produces much less ice content at higher altitudes and has a rapid build-up of condensate close to the melting layer. This is due to much of the condensate being diagnosed, incorrectly, as liquid, which does not fall.

At high levels, the fall speed diagnosed in the MPS is less than that in the TPS. This results in an increase in ice content in order to maintain the downward flux at a constant value. More efficient removal of vapour at lower levels can also reduce the ice content at high levels and amplify orographic rain shadows.
Changes in the ice content directly affect the ice cloud fraction and the radiation balance of the system. Hence knowledge of the fall speeds of particles is of great importance in the prediction of the structure of a precipitation system.

The relative humidity is also increased in the MPS at the highest levels in cloud. A time lag imposed by growing ice at a finite rate, rather than instantaneously, produces supersaturations of around 10% at cloud top.

(c) Overall simulation

The boundary layer is, in some cases, deeper in the MPS. This is associated with reduced precipitation of boundary-layer clouds, hence higher cloud fractions at boundary-layer top and greater entrainment of air into the boundary layer. However, except for some winter, high-latitude changes in temperature, associated with radiative effects from supercooled liquid cloud, there is little change in the surface climate of the model. This, in part, is due to the tuning of the MPS in order to keep the radiation budget close to that predicted by the TPS.

(d) Summary

The most significant changes between the two schemes are that of ice fall speeds and that of the subgrid model. The parametrization of the phase of potentially mixed-phase cloud is also important in specific regions, such as the summer arctic. The vertical structure of clouds in the model is considerably different between the two schemes, with no way, at present, to validate the ice content.

The difference in climate sensitivity can only be speculated on at the moment. Del Genio et al. (1996) showed the sensitivity of climate change to anvil cloud. Gregory and Morris (1996) showed that, within the framework of the TPS, the temperature thresholds for defining mixed-phase cloud have a large effect on the sensitivity of the model simulation to changes in greenhouse-gas concentrations. Preliminary results by Senior (personal communication) suggest that the MPS produces much less change in cloud when doubling CO₂.

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