Evaluation and improvement of mixed-phase cloud schemes using radar and lidar observations

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ABSTRACT

The ability of NWP models to simulate stratiform mixed-phase clouds is assessed and improvements through a parameterization to remove vertical resolution sensitivity and a correction to the ice particle size distribution are examined. Papers further detailing this work will be submitted to QJRMS (Barrett *et al.*, 2013)

1 Introduction

Stratiform mixed-phase clouds are not well simulated by current weather forecast models (and by extension climate models) resulting in erroneous predictions of radiative transfer. Models tend to underestimate the amount of clouds in the mid-levels of the atmosphere (e.g. Illingworth *et al.*, 2007) suggesting a deficiency in the representation of mixed-phase clouds. An absence of these mixed-phase clouds would likely result in excess solar radiation reaching the surface and excess longwave emission at the top of the atmosphere which could result in a warm or cold bias at the surface depending on the time of day. Overall, mixed-phase clouds are likely to have a cooling effect on the planet which may not be captured by current models and this may constitute a missing negative feedback on the climate system in these models.

2 Data, methods and EMPIRE single column model

Observational data and retrieval

Remote sensing retrievals of cloud properties using instruments at Chilbolton, UK are used as observations in this study. A number of days are selected where reliable observations of mid-level mixed-phase clouds have been made. Days are chosen if they contain long-lived liquid layer clouds and at the times when this cloud is present, there is no low level cloud and ideally no cirrus. Times where multiple layers of liquid or mixed-phase cloud are present are also excluded as the liquid water content in each layer can not be retrieved separately. Unfortunately this significantly reduces the number suitable days for analysis relative to the number of days on which mixed-phase clouds occur. In all, 312 hours of data are used from 21 days.

This study makes use of the CloudNet dataset; a full description of the data and processing techniques is available in Illingworth *et al.* (2007) and briefly described below. The radar reflectivity and lidar backscatter are used together with the radar Doppler velocity to determine whether the target is liquid or ice. Because the lidar is sensitive to the numerous small liquid droplets and the radar is most sensitive to the larger ice particles it is possible to determine the phase of the target; this is aided by the radar Doppler velocity which highlights falling ice particles. Liquid water content within the cloud is estimated by

Table 1: Details of the numerical models and their cloud schemes used in later comparisons. Modified from Illingworth et al. (2007).

	UKMO--Meso	UKMO--Global	ECMWF	Météo-France	RACMO	ERA-Interim
Horizontal Resolution (km)	12	60	40 (25)	23.4	18	79
Number of Vertical Levels	38	38	60 (91)	41 (60)	40	60
Grid-box depth at 5 km (m)	615	636	551 (397)	491	523	548
Minimum Liquid Temperature (°C)	−40	−40	−23	−40(−23)	−23	−23
Prognostic Cloud Variables[1]	q_t, q_i	q_t, q_i	q_c, A	q_c	q_c, A	q_c, A

[1]Prognostic cloud variables are q_t – total water mixing ratio, q_c – cloud (liquid + ice) water mixing ratio, q_i – ice water mixing ratio and A – cloud fraction.

calculating the adiabatic liquid water content throughout the liquid layer and scaling it to match the column integrated value retrieved by a microwave radiometer. The ice water content is estimated at each pixel using the empirical relationships of Hogan *et al.* (2006). The high resolution data is averaged in time and height to make the quantities comparable with those from models; different time and height averaging is applied when comparisons are made with each model, giving a range of "observations".

Operational numerical models

A number of numerical weather prediction (NWP) and regional climate models (RCMs) will be compared later and their ability to predict mixed-phase clouds analysed. Table 1 shows details of the model resolution, which ranges between 12 and 79 km in the horizontal and 397 and 636 metres in the vertical at 5 km altitude. As the models are being compared over a long period, where the model has changed, the initial value is given and the most recent value is given in brackets. The table also gives details about the cloud scheme used in each model, the prognostic variables used and the coldest temperature at which liquid water is permitted to exist.

Only two of the models have a cloud scheme where cloud ice is a prognostic variable separate from liquid (UKMO-Meso and UKMO-Global). The other models have a single prognostic variable for total condensed water in the cloud and the ratio of liquid and ice in any grid-box is a diagnostic function of temperature. This simplification does not allow the models with diagnostic ice to capture the liquid over ice structure of mixed-phase clouds that are observed (Marsham *et al.*, 2006).

EMPIRE model

EMPIRE is a new single column model designed to Evaluate Mixed-Phase Importance in Radiative Exchange. It is designed to be similar in structure to GCMs, particularly the Met Office Unified Model including the Wilson and Ballard (1999) microphysics scheme, but with a few notable differences. Firstly, the Lock *et al.* (2000) boundary layer scheme is included both within and outside the boundary layer to drive turbulent mixing created by radiative cooling induced negative buoyancy at cloud top. Secondly, the Edwards and Slingo (1996) radiation scheme is called every 15 minutes, more frequently than typical of a GCM and thirdly the vertical grid spacing is 50 metres by default, approximately an order of magnitude finer resolution than GCMs. The model is initialised from ERA-Interim profiles over Chilbolton and driven using advective tendencies calculated from ERA-Interim. The vertical velocity is also taken from ERA-Interim.

3 Evaluation of operational models

Diagnostics are carefully chosen to compare the model output with the observations of mixed-phase clouds so that they can be equivalently calculated from both model and observational datasets. Three diagnostics are chosen, each a mean quantity of the whole dataset (including zeros) and are divided up into temperature ranges each spanning 5 °C. The data is averaged over particular temperature ranges as it is expected that microphysical processes such as ice nucleation, deposition growth rate and ice particle

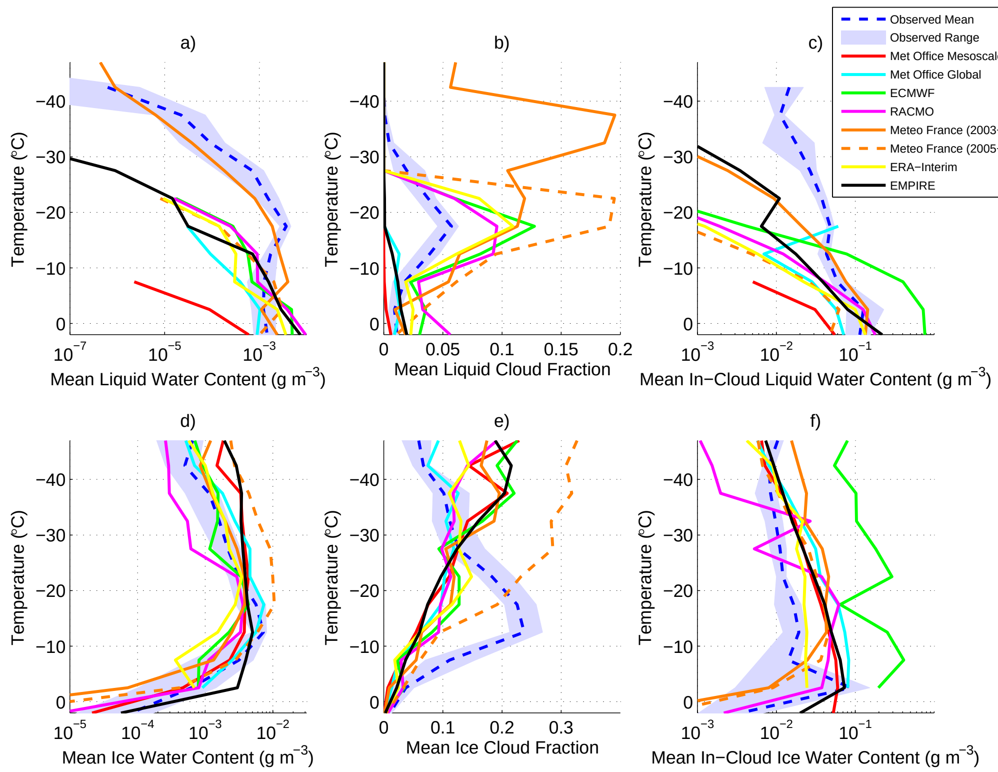

Figure 1: Mean liquid and ice cloud properties from radar and lidar observations and also from a number of NWP forecast models, regional climate models, ERA-Interim reanalyses and EMPIRE. These data are for the selected 21 days where mixed-phase clouds or clear skies are observed, each plotted as a function of temperature.

habit are the important processes in controlling the structure of mixed-phase clouds and these processes are themselves dependent on temperature.

The quantities chosen are the *mean liquid water content*, *mean liquid cloud fraction* and *mean in-cloud liquid water content*. Equivalent quantities are calculated for ice clouds as well as liquid clouds.

Figure 1 shows these three diagnostics for both the liquid and the ice phase from observed cloud derived from radar and lidar observations and also from a number of NWP forecast models, regional climate models, the ERA-Interim reanalyses and EMPIRE. Each of these are plotted as a function of temperature, with the observed quantities being the mean of the observations averaged on to the numerous model grids and the shaded area representing the range of these observations at that temperature.

On average, for the 21 days analysed, the mean liquid water content for temperatures between 0 and -20 °C is roughly constant with temperature with a value between $1.6–2.1 \times 10^{-3}$ g m^{-3} depending on the model grid chosen. For temperatures colder than -20 °C the mean liquid water content decreases exponentially until at -40 °C there is virtually no liquid water. The observed liquid cloud fraction shows a peak at around -18 °C with a maximum cloud fraction of 5.7% whilst the in-cloud liquid water content decreases steadily with decreasing temperature from a value of 0.11 g m^{-3} at 0 °C to 0.011 g m^{-3} at -40 °C.

The observations of the ice phase show a maximum in mean ice water content (7.4×10^{-3} g m^{-3}) and a peak in the ice cloud fraction (23.7%) at -12 °C. This peak in the ice water content is around 5°C warmer than the peak in the liquid cloud fraction as might be expected given the typical structure of mixed-phase clouds with thin liquid layers atop a thicker ice layer. The mean in-cloud ice water content is fairly constant with changing temperature at temperatures colder than -5 °C at around 0.02 g m^{-3}.

All models studied underestimate the mean supercooled liquid water content at temperatures below -15 °C. The worst performing model is the Met Office Mesoscale model which has no liquid at temperatures colder than -10 °C. The Meteo France (2003–5) model is the best performer and lies within the range of observations for temperatures between -15 °C and -40 °C, albeit on the extreme low side of this range and has a mean liquid water content too low by a factor of 2 between -10 °C and -30 °C. This model, like most models, uses a diagnostic scheme to determine the ratio of liquid and ice cloud condensate based on the temperature, but is the only diagnostic scheme that allows liquid to exist at temperatures as cold as -40 °C. Other diagnostic schemes have a different temperature limit beyond which liquid is not able to exist; in this sample all other models with a diagnostic ratio of liquid and ice do not permit liquid at temperatures below -23 °C.

The Meteo France (2003–5) model has a much higher mean liquid cloud fraction than the observations, particularly at the colder temperatures, the worst example being a predicted liquid cloud fraction of 19.5% at -37°C where the maximum of the observations at this temperature is only 0.02%. From 2006 onwards the model changed and the minimum temperature at which liquid can exist changed to -23°C. This brought the model in line with other diagnostic models and improved the prediction of liquid cloud fraction, but this also reduced the total liquid water content and now shows a similar underestimate as other models.

The Met Office mesoscale and global models are particularly interesting as they are the only models in which ice water content is a prognostic variable separate from liquid. At temperatures warmer than -10°C the predicted liquid water content is just 4.5% (mesoscale) and 62.7% (global) of that observed whilst most other models overestimate the liquid water content at these temperatures. Model performance is worse at colder temperatures with no liquid at temperature colder than -10°C in the mesoscale model and -20°C in the global model. The poor performance of these two models is important, as they are the models with a separate prognostic variable for ice. The fact that these models have a severe underestimate of the supercooled liquid water highlights the fact that either these parameterizations are not accurate in the case of mixed-phase clouds or that other processes not included in the model must be involved in their maintainance.

The model predictions of the ice phase are somewhat better than for liquid with the models spanning the range of observations throughout the temperature range analysed. The ice cloud fraction, however, is too large for all models at temperatures colder than -30°C by as much as 0.1, doubling the observed value. At warmer temperatures all models underpredict the ice cloud fraction and at -12°C the mean observed cloud fraction is 23.4% but the multi-model mean is only 7.3% and the largest model value is only 9.5%. The cluster of model predicted ice cloud fractions is remarkably tight given how different they are from the observations. This result likely stems from a poor diagnosis of the cloud fraction from the ice water content, which is the subject of ongoing work.

Figure 2 shows the dominant processes in generating and depleting liquid water from mixed-phase clouds are identified. To do this, an idealised simulation is run with no vertical velocity but otherwise the model contains all the standard physics described in section 2. The vertical resolution for the idealised experiment is improved from 50 to 25 metres. The average tendency for a 60 minute period is shown as a function of height in figure 2 together with the profile of liquid water content after 31 minutes, denoted by the red dashed line. The black line represents the average total tendency over the 60 minute period, a sum of all the tendencies.

During the simulation the radiative cooling at cloud top contributes most to the production of liquid water (+0.45 g kg^{-1} h^{-1}) whilst turbulent mixing near the cloud top reduces the liquid water content significantly (–0.40 g kg^{-1} h^{-1}) by mixing the radiatively cooled air with warmer air lower in the cloud. Lower in the cloud the turbulent mixing acts as a source of liquid water, by enhancing the upward transport of water vapour and the downward transport of radiatively cooled air which increases the total water mixing ratio and reduces the saturation mixing ratio. The radiative impact on the cloud at

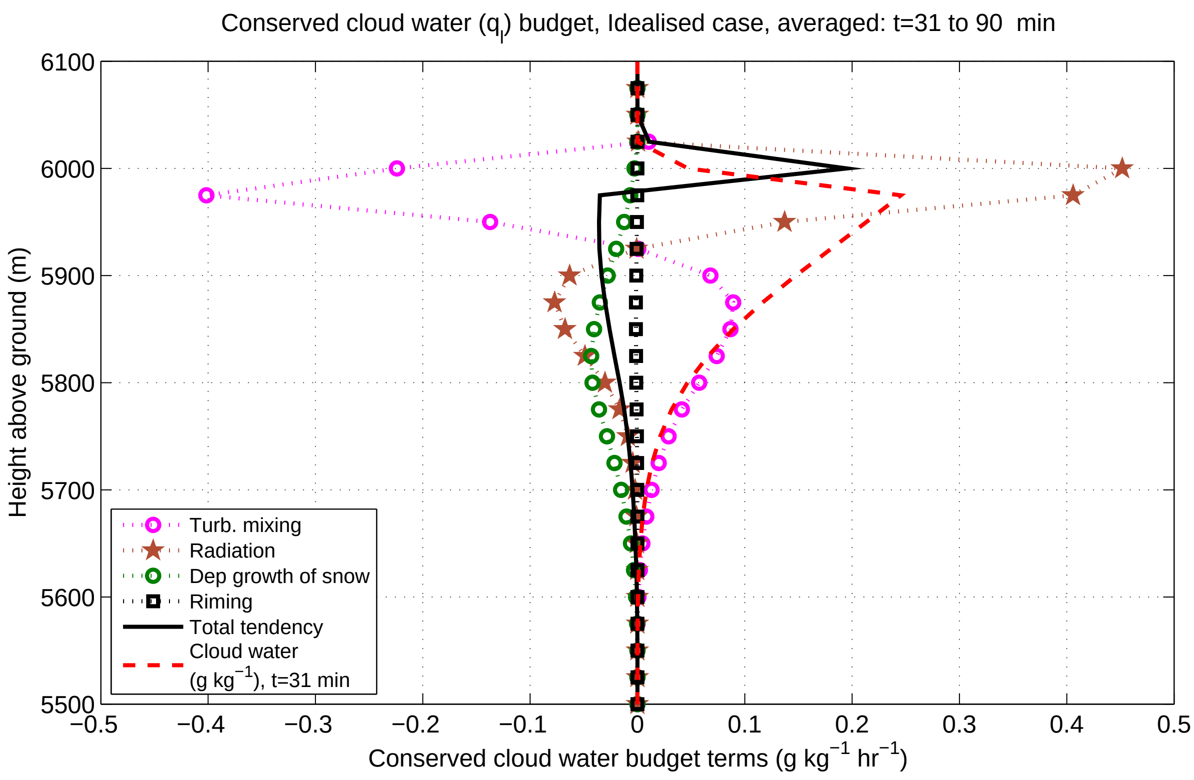

Figure 2: Process rates for EMPIRE simulation of mixed-phase cloud averaged between 31 and 90 minutes from the start of the simulation. The red dashed line shows the liquid cloud water content at the beginning of this time period in units of g kg^{-1}.

this level is a weak warming as the absorption by the ice particles is larger than the cooling, resulting in a negative tendency for liquid water. Ice growth by deposition increases with depth from the cloud top with the growth rate related to the ice water content. The net result of all of these processes is a slight reduction (-0.03 g kg^{-1} h^{-1}) in the amount of liquid water throughout the depth of the cloud, largely related to the depositional growth of ice particles. However, at the cloud top, at and above the height of maximum liquid water content there is an increase in the amount of liquid water ($+0.20$ g kg^{-1} h^{-1}), caused by radiative cooling but unlike lower in the cloud the cooled air is not mixed with warmer air lower in the cloud by turbulent mixing. This results in the increasing tendency at the cloud top and as the simulation evolves this leads to an increase of cloud top height with time. The relative importance of each process shown here is remarkably similar to those from Smith *et al.* (2009) calculated using LEM simulations, increasing confidence in the ability of EMPIRE to simulate these cloud layers.

4 Importance of modelled physical processes

The importance of changes to the physics in EMPIRE is assessed in this section. Changes to the model liquid and ice water contents are assessed, together with the cloud fraction of each phase. Differences in liquid and ice water content between simulations are quoted as changes to the mean at temperatures between -10 °C and -30 °C. At temperatures colder than -30 °C the liquid water content is negligibly small and the ice water content is too large relative to observations, whereas at temperatures warmer than -10 °C the liquid water in greater than observations and shows relatively little sensitivity to change in the ice microphysics as ice is not nucleated until the temperature is -10 °C or colder.

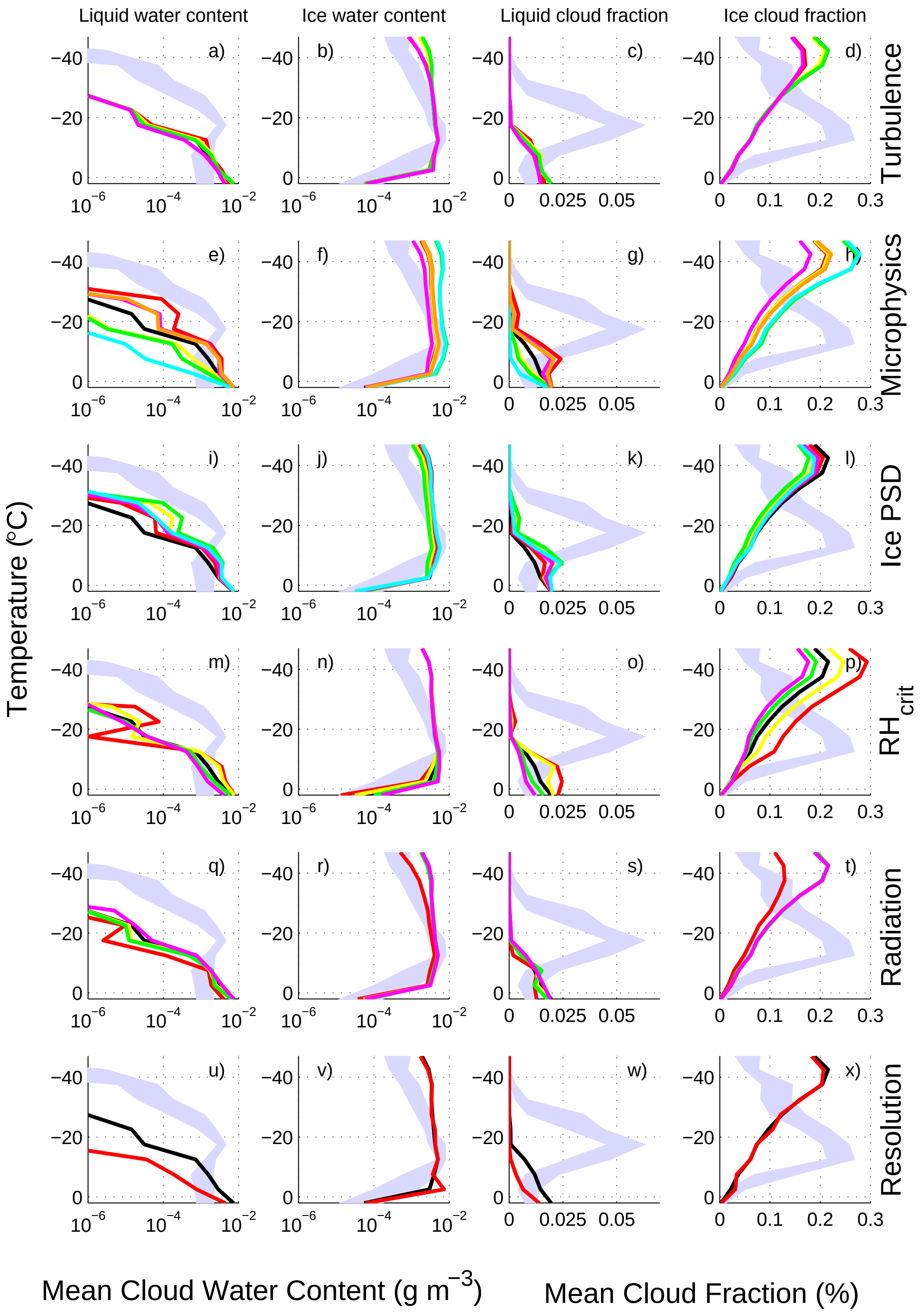

Figure 3: Sensitivities in EMPIRE to changes to the model parameters. Each column is labelled at the top with the diagnostic. Each row represents changes to a family of parameters, the type of which is described on the right of that row. The coloured lines in each row represent the same simulations, but the colours are reused in each row. The lines are deliberately unlabelled, showing only the range of sensitivity within each family of parameters, although some lines are identified in the text. The black line in each figure is the control simulation and the blue shading shows the range of observations, as in figure 1.

Figure 3 shows the sensitivity to many different model parameters. Each row shows changes to one family of parameters, the type described on the right hand side. The blue shaded area shows the range of observed values as in figure 1, the black line shows values from the EMPIRE control simulations and the coloured lines represent the perturbed physics simulations. Same coloured lines on each row relate to the same set of simulations, but colours are repeated on different lines showing different sets of simulations.

The first row of figure 3 shows the sensitivity of cloud properties to changes in the specification of sub-grid turbulence. Sensitivity experiments included reducing the amount of non-local mixing occurring, turning it off completely and letting the local mixing scheme do the work and turning off cloud top entrainment. There is remarkably little sensitivity to the specification of turbulent mixing in EMPIRE, much less than for other model changes described below, which is surprising given the important role the turbulent mixing has on redistributing the liquid, ice and vapour (see figure 2). The biggest increase in the liquid water content occurs when the non local mixing is turned off as this prevents ice being mixed from lower in the cloud towards the cloud top. In contrast the largest decrease in liquid water content occurs when the non local mixing of the total water content (q_t) is turned off as this removes the source of vapour to be condensed at the top of the cloud layer.

The second row details the changes when the microphysics have been altered. This shows the largest sensitivity in terms of mean liquid water content of all the perturbed physics experiments. The largest increases, roughly equal in magnitude, are when the capacitance of the ice particles is reduced by 50% (orange in figure 3e–h)or their fall velocity is increased by 50% (magenta in figure 3e–h). The largest decrease in liquid water content is found when the capacitance is increased or the fall velocity decreased. Changing the assumed particle habit also has a significant effect; where hexagonal plates are assumed, the liquid water content is lowest as hexagonal plates have an increased capacitance and reduced fall velocity relative to the aggregates assumed as default (cyan in figure 3e–h).

The sensitivity of changing the ice particle size distribution is shown in the third row. This also has a large effect in changing the mean liquid water content. The reason for the large sensitivity is because changing the size distribution changes the relative contribution of small and large ice particles in a grid-box and therefore changes the process rates calculated. By reducing the slope of the size distribution, and therefore increasing the relative contribution from the larger ice particles, the total growth by deposition of the collection of particles is reduces and the average mass-weighted fall velocity is increased. As we saw in the above microphysics sensitivities, both of these changes increased the mean liquid water content.

Unsurprisingly, the cloud water contents and cloud fractions can be changed by altering the cloud scheme, as can be seen in the fourth row of figure 3. By varying the critical relative humidity at which cloud forms (RH_{crit}) the amount of cloud present in the simulations modified. Surprisingly, it is an increase in RH_{crit}, and therefore making it more difficult for the cloud to form, that increases the mean liquid water content and reducing RH_{crit} reduces the cloud water content. This is exactly opposite of what would happen if you changed RH_{crit} instantaneously in the model. This curious result can be explained by thinking of a grid box with a mean humidity just in excess of RH_{crit}, with a low cloud fraction and small quantity of condensed water. As ice particles form in the grid box and grow by vapour deposition, they remove much of the liquid water. In a similar simulation with higher RH_{crit} it takes longer for any cloud to form, but when it does, the liquid water content and cloud fraction are higher for the same excess humidity. The ice production and growth by deposition is slightly more efficient as the supersaturation over ice is higher, but overall more liquid survives the timestep and is therefore more likely to be present at the time the radiation scheme is next active. If it is still present then a cloud top cooling will be diagnosed which will aid in the maintainance of the liquid water in the layer.

The sensitivity to radiation is shown in row five. Turning the radiation scheme off completely reduces the mean liquid water content by 85.1% compared to running it every 15 minutes, with a reduction of

10% (hourly) and 34% (three hourly) when the frequency of radiation calls is reduced. The sensitivity to radiation timestep is caused by liquid clouds forming and then glaciating between radiation scheme updates, resulting in the cloud top cooling not being captured. This effect is, however, less important than the sensitivity to ice microphysics as described above.

A significant sensitivity to vertical grid spacing is shown in the bottom row of figure 3 where coarser resolution simulations with 500 metre grid spacing has 95% less liquid water than simulations with 50 metre grid spacing. This is a key reason models with ice water content as a separate prognostic variable fail to simulate enough supercooled liquid water. The current range of model vertical grid spacing is around 350–600 metres in operational NWP models and coarser in climate models. The reasons behind this sensitivity are examined in the next section but pertain to unresolved vertical structure of the cloud layer towards the top of the cloud.

In summary, the EMPIRE model shows there is a sensitivity to many different model parameters, most significantly to the implementation of ice microphysics. There are also sensitivities to RH_{crit}, radiation timestep and turbulent mixing specification although the latter 2 are less significant. The sensitivity to vertical grid spacing is the most striking sensitivity and likely a key reason state-of-the-art forecast models still fail to capture mixed-phase clouds correctly.

5 Ice particle size distribution

As there is considerable sensitivity to the model ice particle size distribution shown in 3i–l, the standard Wilson and Ballard (1999) parameterization is compared with aircraft size spectra data from the EUCREX field campaign. Figure 4 shows a ratio of process rates calculated from the parameterized size distribution to those calculated from the aircraft size spectra. Ice particle growth rates are compared in panels a–c and mass weighted fall velocity is compared in panels d–f. The ratios are plotted as a function of ice water content (IWC) for individual size spectra in dots, and the mean ratio within each IWC bin is shown in the black dashed line. Values in excess of 1 show the parameterization is producing ice growth rates or fall velocities that are too large.

For small ice water contents typical of mixed-phase clouds, the default parameterization shows a large overestimate of the ice growth rate (figure 4a) and a large underestimate of the mass weighted fall velocity (figure 4d). This appears to be as a result of the ice particle size distribution being too steep, with too many small ice particles and too few large ones. The slope of the distribution can be modified by changing the intercept parameter, N_0. Reducing N_0 for small ice water contents and increasing it for large IWC reduces the biases. Following suggestions from the literature, N_0 is modified to be a function of IWC,

$$N_0 = 2 \times 10^6 \times \left(\frac{\mathrm{IWC}}{10^{-2}}\right)^A \quad \mathrm{m}^{-4} \tag{1}$$

where IWC is in g kg^{-1} and A has been set to a value of 0.5 (figure 4b,e) and 0.75 (figure 4c,f). The standard parameterization is obtained with $A = 0$. By modifying the size distribution in this way, biases in the calculated process rates are much reduced, particularly where $A = 0.75$. Including such a modification in EMPIRE simulations results in a 134% increase in the supercooled liquid water content averaged across all simulations.

Although it is likely that the ice particle size distributions calculated from EUCREX data are affected by shattering of large ice particles, preliminary analysis of data where the effects of shattering have been accounted for suggest an even larger bias due to even fewer small ice particles in the observed spectra.

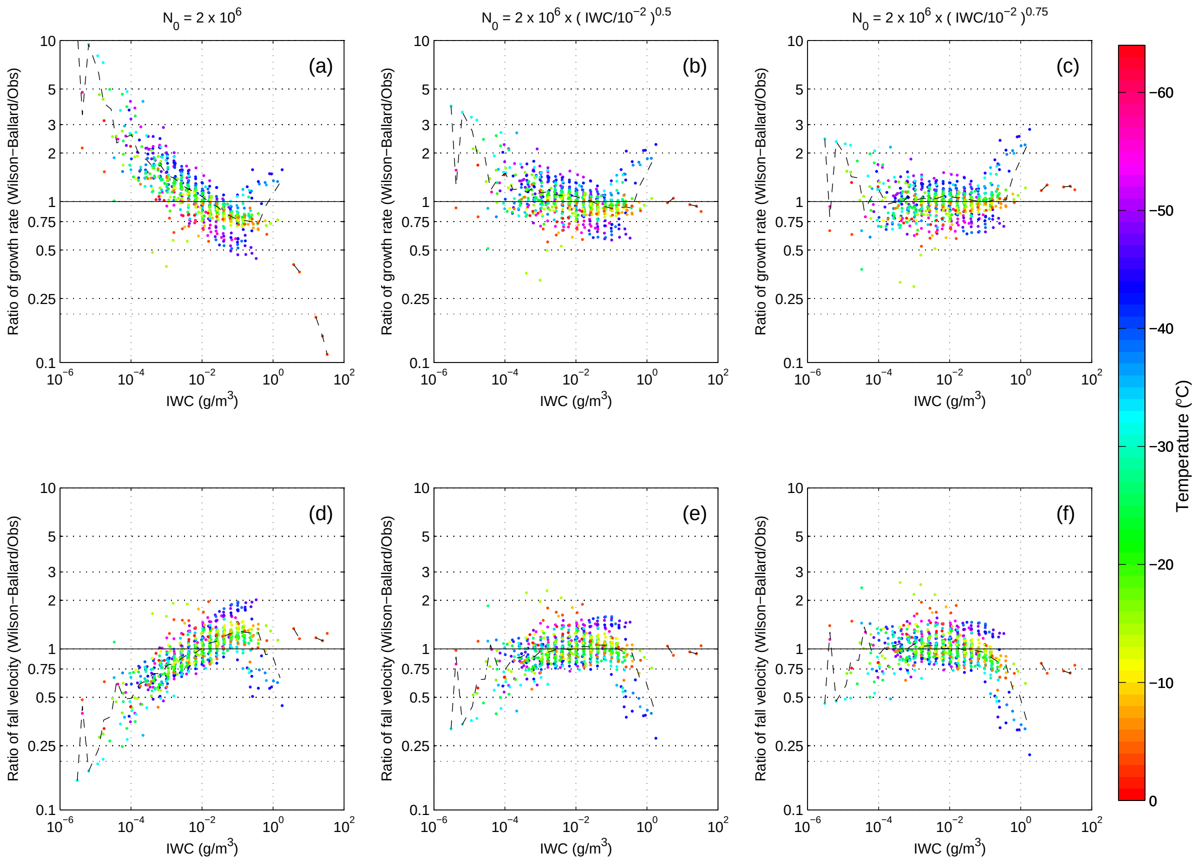

Figure 4: The parameterized process rates from Wilson and Ballard (1999) plotted as a fraction of the true growth rate calculated using size distributions observed during EUCREX. Panels a-c show the growth rates and panels d-f show fall velocities. This is shown as a function of ice water content (x-axis) and temperature (colour) for the standard parameterization (panels a and d) and two modifications of N_0 based on the ice water content (panels b, c, e and f).

6 Resolution sensitivity

To examine the sensitivity to resolution shown in figure 3u–x, the model is run with a vertical grid spacing of 50 metres, as in the sensitivity analysis and at increasing grid spacings up to 500 metres. For these experiments the model is initialised from a idealised profile based on a radiosonde ascent and has vertical velocities set to zero everywhere.

A stark example of the sensitivity to resolution is shown in figure 5 which shows the liquid and ice water contents from simulations at two resolutions, one with 50 metre grid spacing in the vertical (figure 5a-b, coarsened to 500 metre grid spacing in figure 5c-d) and one with 500 metres (figure 5e-f). The liquid water layer persists at the top of the 50 metre grid spacing simulation throughout the duration of the simulation (figure 5b) and has a persistent flux of ice particles falling from this liquid layer, forming an ice only layer below (figure 5a). In the 500 metre simulation the liquid layer decays rapidly at the beginning of the simulation (figure 5f) as the ice is formed in, and then falls from, this layer. The ice water content at the top of the cloud becomes much larger than in the 50 metre simulation after about 30 minutes (figure 5e) due to increased growth of the ice particles by vapour deposition and less sedimentation of the particles from the top of the cloud.

For grid spacings finer than about 200 metres, simulations of this cloud layer converge. At coarser resolutions the liquid water content decreases rapidly with increasing grid spacing. Whilst this single

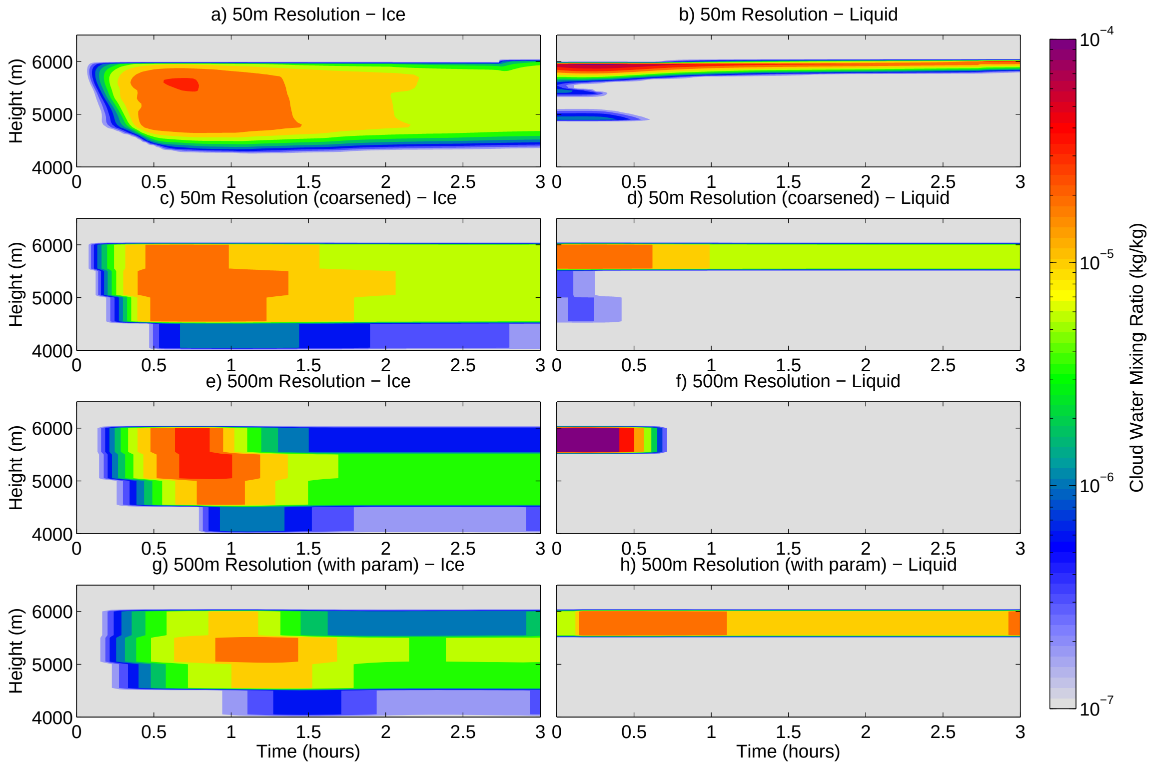

Figure 5: Liquid and ice water contents from simulations with vertical grid spacing of either 50 metres or 500 metres as labelled in the panel title. The top row shows the cloud layer in the 50 metre simulation and the second row shows the same data but coarsened to a 500 metre vertical grid spacing for comparison with the lower panels. The third row shows the cloud layer in the 500 metre grid spacing simulation, with a much reduced liquid cloud lifetime. The final row shows the cloud layer in the 500 metre simulation where the sub-grid parameterization described in this section is included, allowing the liquid layer to persist.

case may not be wholly representative in terms of the point at which the simulations converge it does show that simulations using GCMs with a typical vertical grid spacing of 350 to 600 metres are not able to capture the long lived nature of the liquid layer at cloud top.

There are a number of possible causes of the resolution sensitivity, all of which stem from failing to resolve the vertical structure of some quantity or process near the cloud top in the coarse grid spacing simulations. Simulations performed using 50 metre grid spacing but with one process or quantity coarsened to 500 metre scale identify the importance of resolving the profile of ice water content, liquid water content and temperature, to correctly calculate the microphysical process rates at cloud top, particularly the ice growth rate. Simulations coarsening the resolution of radiation and turbulent mixing processes were shown to be less resolution dependent.

In order for coarse resolution models to correctly simulate the properties of mixed-phase clouds they need to represent the vertical structure at the top of mixed-phase clouds. This could be achieved by a significant increase in the number of vertical levels in the mid-troposphere - which would significantly increase the computational requirements of running a global model - or, more realistically in the short term, by representing the vertical structure within a sub-grid parameterization.

Using knowledge from observations and modelling studies of mixed-phase clouds, the structure at the top of mixed-phase clouds is parameterized. Models currently assume that the grid-box mean value is applicable to the whole vertical span of a grid-box. The next most complex assumption is that these

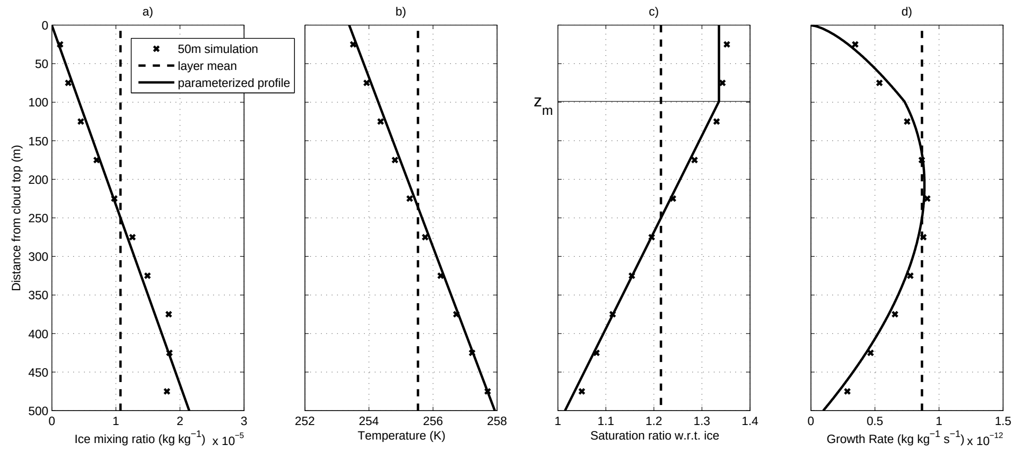

Figure 6: Vertical profiles of cloud properties at cloud top. In panels a–c the crosses show the properties from the 50 metre grid spacing simulation and the dashed line shows the 500 metre layer average (that the 500 metre grid spacing simulation would use). The solid black line shows the parameterized profile of each quantity. In panel d, the lines and crosses have the same meaning, but are the calculated values using the first three panels.

variables vary linearly with height within the grid-box. This assumption is sufficient to construct a parameterization that removes the resolution dependence when simulating stratiform mixed-phase clouds.

Within the parameterization we assume that: a) the model prognostic variables θ_L and q_t are well mixed throughout the layer and are hence constant with height throughout the grid-box. b) the air pressure decreases with height, from which the profile of air temperature can be calculated. c) the ice water content increases linearly with distance down from the grid-box top. A linear fit between the temperature at the top and bottom of the grid-box is calculated that preserves the grid-box mean temperature. From this, the profile of liquid water content and supersaturation with respect to ice can be calculated.

A brief illustration of how the parameterization works is shown in figure 6, where the high resolution data are shown with crosses. The 500 metre layer mean is shown with the dashed line in panels a–c and represents the growth rate calculated using layer means in panel d and the solid lines represent the parameterized profiles of each quantity, except again in panel d where it represents the growth rate calculated using the parameterized profiles. Notice that by using the layer mean values, the growth rate in the layer is maximised, and by parameterizing the profiles of cloud properties within this layer a more representative value is calculated. A similar approach is implemented to resolve the profile liquid water content. Implementing the parameterization in EMPIRE allows the 500 metre grid spacing simulation to maintain the liquid layer at cloud top much longer than the standard version.

In summary, the resolution sensitivity stems from the model not resolving the vertical profile near the cloud top. A sub-grid parameterization of the vertical profile has been created and implemented in EMPIRE and allows the model to maintain the liquid layer at cloud top in the coarse grid spacing model as well as the finer grid spacing models. The results are relatively independent of model resolution and the parameterization now needs to be tested in a GCM to determine the significance of maintaining these cloud layers.

7 Conclusions

This study has found that there is a large under prediction of liquid water content in all models and ERA-Interim on days analysed, by at least a factor of 2 in each model, and that the two models with a physically based parameterization of the mixed-phase microphysics perform worst.

By implementing changes the model physics in EMPIRE, it has been discovered that mixed-phase clouds are sensitive to anything that changes the ice growth rate, whether than be the capacitance or fall speed of ice particles or changes to the size distribution or ice particle habit. Less significant (but not insignificant) sensitivities to the interval between successive calls of the radiation scheme and the critical relative humidity at which cloud forms in the model were also found. No single, physically reasonable, change was enough to increase the simulated supercooled liquid water content to match the observed quantities. EMPIRE showed very little sensitivity to the specification of sub-grid turbulent mixing in the vertical, a surprising result given the importance of the turbulent mixing in controlling the vertical structure of mixed-phase clouds shown in figure 2.

EMPIRE also demonstrated a significant sensitivity to vertical grid spacing and only with grid spacing of finer than 200 metres did simulations of this cloud layer converge. This results from the profiles of cloud properties at cloud top not being resolved in the coarse model simulations. A parameterization of the sub-grid profiles of the cloud top allows the coarse grid spacing simulation to maintain the liquid layer at cloud top similar to the finer grid spacing simulation. There is now a need for this parameterization to be tested in a full GCM and to assess the radiative impact of better representing these mixed-phase clouds in weather and climate simulations.

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