Fourth Monitoring Committee Report

THE ROLE OF MIXED-PHASE CLOUDS IN CLIMATE

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1 Introduction

Mixed-phase clouds, specifically glaciating mid-level liquid stratiform clouds, are important in the climate system. Observational studies have shown altocumulus and altostratus to cover 22% of the Earth's surface (Fleishauer et al., 2002) and mixed-phase clouds were observed 46% of the time during the Third Canadian Freezing Drizzle Experiment (Cober et al., 2001). The complex three-way interactions between vapour, liquid and ice is unique to mixed-phase clouds (Shupe et al., 2008) and makes them a challenge to understand and to model. Additionally they are radiatively important, with the liquid present at cloud top scattering solar radiation away from the Earth's surface whilst cooling the cloud region due to longwave emission. An accurate representation of mixed-phase clouds is therefore important in a climate context, but is also important for weather forecasting. Smith et al. (2009) noted that icing on unmanned military vehicles is problematic in Afghanistan and Fleishauer et al. (2002) suggest mid-level cloud reduces effectiveness of military reconnaissance and bombing flights because models are generally poor at capturing the areal coverage or longevity of mid-level clouds, a conclusion also reached by Illingworth et al. (2007).

At the last monitoring committee meeting, a model, now named EMPIRE (Evaluating Mixed-Phase Importance in Radiative Exchange), had been developed to assess the important processes involved in the maintenance of mixed-phase clouds. There were two main problems with the model at this time, firstly a underestimate of total cloud amount and secondly poor performance in situations with large advective influences.
Since that last meeting the above issues have been addressed. The model now has a cloud fraction scheme which allows partial cloudiness to occur once the grid-box mean humidity reaches RHcrit (typically 85%). Advective forcing data has been acquired from Roel Neggers which uses ERA-interim data to provide 3-hourly advective changes in temperature, moisture and wind fields. These two additions have significantly improved the model performance and representation of mixed-phase clouds, although some other model issues still exist (in particular with respect to ice sublimation and the cloud fraction scheme, more later). Thirty-nine days have been chosen where good observations of long-lived mixed-phase clouds exist. The model is run for these days to allow a quantitative comparison with observations and other GCMs using a number of metrics. Many changes to the model have been tested and a selection of the more significant sensitivities are discussed in section 3.1.

2 PhD Key Questions

This section outlines the key questions to be answered, and outlines a strategy for finding the answers.

1. **When do mixed-phase clouds form and why?**
    - Use surface based radar and lidar observations to detect mixed-phase clouds. **DONE**
    - Use synoptic charts, satellite images and radiosonde soundings to understand favourable conditions for mixed-phase cloud formation. **DONE**

- Find large scale properties that predict the existence of mixed-phase clouds and use GCM properties to generate statistics of cloud existence.
- Use Cloudsat and CALIPSO from the A-train of satellites to assess the global coverage of mixed-phase clouds.

2. **Why do GCMs fail to capture the existence of mixed-phase clouds?**
   - Build a simplified one-dimensional model similar in formulation to a GCM. **DONE**
   - Increase to complexity of the model and change parameterization settings to get an adequate representation of clouds. **DONE**
   - Test sensitivity to numerous model settings to understand what processes are crucial for GCMs to capture mixed-phase clouds. **IN PROGRESS**
   - Use aircraft data to understand sub-grid variations in water vapour content for use in models

3. **How can multi-layer mixed phase clouds exist simultaneously?**
   - Use aircraft observations to understand the microphysical make up of mixed-phase clouds where radiative cooling is and is not important.
   - Test hypothesis that a limited number of large, fast falling ice crystals would not deplete all liquid water from a thin layer.

4. **What is the radiative significance of models not capturing these clouds?**
   - Use the Edwards-Slingo radiation scheme to calculate the top of atmosphere and surface radiative fluxes and to compare these with GERB data and surface observations.
   - Compare radiative fluxes from model simulations that capture mixed-phase clouds well with those that do not. Assess the difference in fluxes and infer the importance of capturing these clouds in GCM climate simulations.

3 Current Work

3.1 Sensitivity Testing

The aim of the sensitivity tests is to see which processes are important in the model simulations of mixed-phase clouds, and also to what extent missing, or overly complex, physics in GCMs may inhibit their production of mixed-phase clouds. 39 cases were selected from Chilbolton radar and lidar observations based on the quality of these observations and the absence of low level clouds (which attenuate the lidar signal, meaning mid-level clouds are poorly sampled).

The sensitivity tests results can be seen in figure 1. The control case shows EMPIRE performing comparably with GCMs, although is still some way from the observed cloud frequency. It is, however, likely that the observed frequency is an overestimate of the true frequency because of the algorithm used to average quantities to a GCM grid scale - this is to be corrected, see Future Work. The sensitivity test results show significant changes in liquid presence and amount to: radiation scheme call frequency, ice fall speed, ice crystal habit, ice growth rate, ice crystal number concentration and turbulent mixing specification (for clarity, not all are shown). Surprisingly, the sensitivity tests showed a relatively small dependence on model vertical velocity (not shown), with cloud formation seemingly dominated by the advection of heat and, more importantly, moisture in to the model domain. The most notable sensitivities, however, are to non-physical model settings. A large dependence to RHcrit was found, which is a measure of the width of the sub-grid PDF of water vapour, and a small but important decrease in liquid amount for poorer vertical resolutions. These findings required additional attention, see sections 3.2 and 3.3 below.

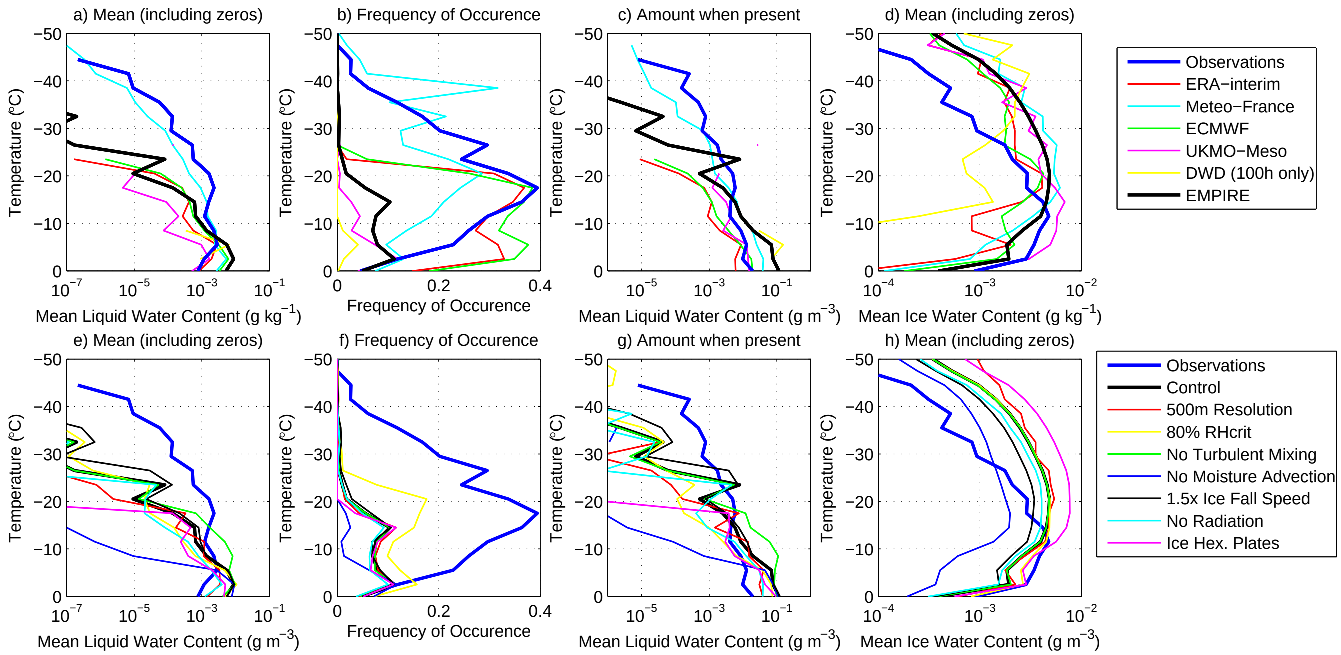

Figure 1: Liquid water statistics from from the sensitivity testing on 39 days. Panels a) to d) show the control run from EMPIRE compared with observations and other models. Panels e) to h) again show the control run and observations with results from sensitivity tests with changed parameters.

3.2 Idealised Simulation

To understand why vertical resolution is important, an idealised simulation was set up. The simulation was initialised with a mid-level liquid cloud, which then glaciated. EMPIRE was run with vertical resolutions of 50 m (high resolution) and 500 m (typical GCM resolution). The difference in results between these runs was remarkable, and can be seen in figure 2. The liquid cloud in the 50 m simulation persists for at least 24 hours, whilst the liquid at 500 m resolution lasts only 80 minutes. Also the cloud ice content is greater in the 500 m resolution run.

The results can be explained by thinking about the ice growth and fall speed implementation - both of which are similar to many GCM ice schemes. Our prognostic ice variable is the grid-box mean ice mixing ratio, q_i (in kg kg^{-1}). The rate of change of this with time is dependent on rate of ice growth (Deposition), the rate of nucleation and the difference between ice falling in to and out of the grid-level (Sedimentation). Neglecting the small contribution from nucleation (when compared to deposition), the remaining two terms are dependent on the current ice mixing ratio (q_i), temperature (T) and supersaturation of the air with respect to ice ($S_i - 1$). In the absence of ice falling in to the layer from above then the growth rate and fall speed alone control the ice mixing ratio.

$$\frac{dq_i}{dt} \approx \frac{dq_i}{dt}_{Deposition} + \frac{dq_i}{dt}_{Nucleation} + \frac{dq_i}{dt}_{Sedimentation} \tag{1}$$

$$\frac{dq_i}{dt}_{Deposition} \approx A(T)(S_i - 1){q_i}^{\frac{1}{3}} \tag{2}$$

$$\frac{dq_i}{dt}_{Sedimentation} \approx \frac{d}{dz}\left(\frac{w(q_i, T, N_0)q_i}{\Delta z}\right) \tag{3}$$

The above equations describe the single-layer evolution of the ice mixing ratio q_i in terms of the contribution by depositional growth, nucleation and sedimentation. A is a collection of constants and weakly temperature dependent terms, w is the grid-box mean ice fall speed and Δz is the model layer depth. All other terms are described above and nucleation is neglected as it is many orders of magnitude smaller than either of the other rates.

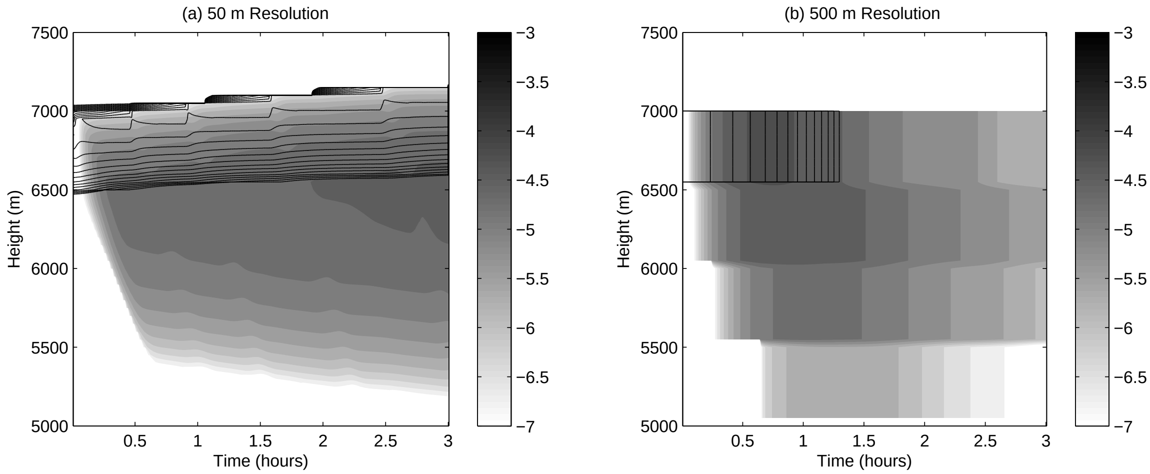

Figure 2: Comparison of idealised runs at 50 m and 500 m resolutions. The filled contours show ice water mixing ratio ($\log_{10}$(kg kg^{-1})) and the black contours show liquid water mixing ratio ($\log_{10}$(kg kg^{-1})). Note the much shorter liquid water persistence and the greater values of ice water in panel (b) compared to panel (a). See text for explanation.

The resolution dependence occurs when we consider the sedimentation term. Take two grid boxes, one of 50 m depth and the other 500 m depth, and assume they have the same values of ice mixing ratio, temperature, etc. The amount of ice falling through the lower surface of this box will be the same for both simulations as they have the same ice mixing ratio and fall speed. However, the 50 m box loses a greater fraction of its initial ice solely because it is smaller. Hence, the ice mixing ratios in the two boxes are now not equal, and as the next growth rate depends on the ice mixing ratio the inequality will be increased.

We need to remember that when ice and liquid coexist in a volume of air that the ice grows at the expense of the liquid by the Bergeron-Findeison mechanism. So near cloud top, where liquid exists, this difference in ice growth rate (and hence liquid depletion rate) results in longer lived liquid clouds at higher resolution.

This result is most important near cloud top. Further into the cloud, ice falling from the layer above helps increase the model level ice content and hence the growth rate. However, it can be seen from figure 2 that the 50 m resolution simulation has less ice throughout the cloud. The extent to which this effect is present in other models is currently unknown, although we see no reason for it to behave differently with the same specification for ice growth rates and fall speeds.

3.3 Importance of RHcrit

The other issue from the sensitivity tests was the large dependence on RHcrit. RHcrit is the relative humidity at which the model starts to form cloud within a grid-box. EMPIRE's typical value for sensitivity testing was 85%; the Met Office use 80% in their NAE model. However, "there is no systematic way of choosing RHcrit, it is chosen by trial and error at each resolution to roughly maintain radiative balance" (Pope and Stratton, 2002). GCMs often have higher RHcrit values in the boundary layer, where it is moister, to prevent excessive cloud. A normal value in the boundary layer would be 90-95%.

RHcrit arises from assumptions made about the sub-grid variability of moisture. In the cloud scheme currently implemented (Smith, 1990), a distribution of water vapour mixing ratio is assumed, based on the temperature alone. As stated above there is no systematic way for choosing RHcrit, but is the assumed variability correct? I have started looking at aircraft observations from APPRAISE cases to look at horizontal variability of water vapour and temperature in, below and above altocumulus to try and answer this question. Is there a better way to represent the sub-grid moisture variability? See Future Work for details on how we might answer this.

3.4 Ice Sublimation

Since adding the cloud scheme to EMPIRE, an odd effect has been discovered where ice appears to start melting at $-15°C$. The Smith (1990) cloud scheme assumes a triangular distribution of water vapour, the width of which is $(1 - RHcrit)q_{sat}$ where $RHcrit$ is the critical relative humidity and q_{sat} is the saturation mixing ratio. Two example distributions are shown in figure 3. In both cases liquid water will be present, as the extreme right of the distribution is greater than q_sat_liq. However, with temperature of $-10°C$ the grid-box mean vapour mixing ratio is below q_sat_ice and hence the grid-box is subsaturated with respect to ice.

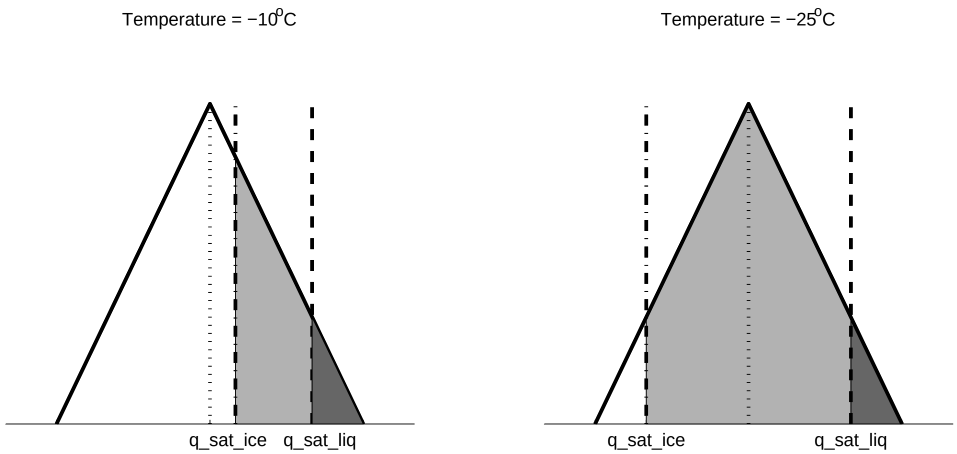

Figure 3: An illustration showing the PDF of water vapour mixing ratio, q_t, at -10°C and -25°C. In both cases liquid water is present, as the extreme right of the PDF is greater than the point of liquid saturation. In the colder case the grid-box is, on average, supersaturated with respect to ice (shown by the shaded region) leading to ice growth. The warmer case, however, is on average sub-saturated w.r.t. ice, and hence ice evaporates despite liquid being present in the grid-box. This evaporation increases the vapour and pushes the PDF to the right, thus the net result is an apparent melting of ice at -10°C.

This paradox, where the air is moist enough to support liquid cloud (at least in part of the grid-box) but is dry enough to permit ice to sublime exists for temperatures warmer than $-15°C$ (for RH_{crit} of 85%). This ice sublimation increases the vapour content of the grid-box, and hence also increases the liquid water content. The net effect is an apparent melting of ice at $-15°C$. This effect explains the lack of sensitivity found at temperatures warmer than $-15°C$; the frequency of occurrence of liquid is almost unchanged for most model changes in this temperature range. This occurs because growth of ice is the primary mechanism for liquid removal, but because of this melting any change to the ice growth rate does not affect the model.

4 Future Work

My future work is designed to further investigate problems mentioned above and to find answers to the questions posed in Section 2.

Re-analyse radar and lidar observations of mixed-phase clouds
Radar and lidar observations from Chilbolton, averaged to GCM model resolution, currently show high frequency of occurrence due to the lack of an observed liquid cloud fraction. I will adapt existing code to recalculate liquid cloud statistics to enable a fair comparison between modelled cloud and observations.

Use in-situ aircraft and surface based radar observations to look at sub-grid variability
The sensitivity tests have shown that the specification of the sub-grid moisture field is important for how much mixed-phase cloud the model forms. The current specification in EMPIRE and other GCMs is based on a fixed moisture variance, which to some extent is chosen arbitrarily. Other possible schemes are more complex (e.g. diagnostic or even prognostic variance) but before implementing either in EMPIRE an understanding of the

moisture variance in the atmosphere would be advantageous. To assess this, in-situ aircraft measurements of moisture and temperature from numerous flight campaigns will be analysed. If we can form a coherent picture of the profile of variance and its relation to mixed-phase cloud occurrence then this will give direction for further model modifications.

Addressing Ice Deposition and Sublimation problems

The ice sublimation problem mentioned above has been encountered before by modellers, however, there is a lack of literature addressing this problem. Again, this problem comes down to the sub-grid distribution of moisture and ice, and more importantly their overlap. Many models in practice use schemes based on assumptions which have little or no basis in reality. Radar observations of liquid and ice cloud overlap together with some thought could be used to address this problem. The exact method of addressing this has yet to be defined, but it could lead to some valuable results.

ECMWF visit / GCM experiments

After discussion, we have decided that now would not be the most beneficial time to visit the ECMWF. We don't yet have an alternative 1D cloud scheme ready to be implemented in a GCM. It would still be beneficial to visit the ECMWF at a later time to implement such a scheme, run their model and assess any changes in model performance.

AMS Clouds and Radiation Conference

I am attending and presenting a poster at the AMS Clouds and Radiation conference in Portland, Oregon at the end of June. I hope to use the opportunity of a specialist international conference on clouds to meet and discuss my work and ideas with a number of people who also work in a similar field.

5 Transferable Skills

In the last 6 months I have continued attending Monday and Tuesday seminars. I have also taken part in Quo Vadis and will talk again in Radar Group before the end of term. I will be presenting at the AMS Clouds conference in June and to ready myself for this experience I have attended GSDP courses on presenting conference papers. I continue my role on the HDR forum, taking over as forum chair from September, as well as continuing with demonstrating and exam invigilation.

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