Fifth Monitoring Committee Report

THE ROLE OF MIXED-PHASE CLOUDS IN CLIMATE

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12pm, Friday 14th January 2011, 2L41 (Stephen's Office)

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.

At the last monitoring committee meeting, experiments using the EMPIRE model had been conducted. These experiments showed sensitivity of the model to frequency of radiation scheme calls, turbulent mixing specification and assumed ice properties (fall speed, crystal habit, growth rate and concentration). Statistics for liquid and ice in EMPIRE were compared with observations from Chilbolton and GCMs. EMPIRE appeared similar to other GCMs, however, both GCMs and EMPIRE were far from the observations of liquid occurrence for the 39 cases of interest. Some doubt existed about how reliable the comparison of the three data sources was, because of the different temporal and spatial scales of the data, most notably the observations. EMPIRE also showed a large sensitivity to the vertical resolution chosen. This was explained using the argument that at higher resolution a larger fraction of the ice in a grid-box would fall out in a given timestep. If this ice is not replaced from the grid-box above then the ice mixing ratio is very low when the growth rate is calculated. This resulted in low ice concentrations at the cloud top and allowed the liquid to persist for longer in the higher resolution model.

Since the last meeting I have further investigated the sensitivity tests and developed a better understanding of the resolution dependence and how it might be corrected for. A new method using cloud fraction rather than cloud occurrence has been used for comparing liquid and ice cloud properties across multiple sources of data. This means that we no longer need to assume an arbitrary "grid-box size" for the observations and the EMPIRE model. Aircraft data have been examined to look in greater depth at the mixed-phase cloud structure and to understand the relation between sub-grid variability and turbulence. This resulted in implementing a parameterization for the sub-grid variance of water vapour in EMPIRE based on boundary-layer similarity relationships. This is all discussed in greater depth in section 3.

2 Thesis Plan

I include my thesis plan at this point so as to put the current and future work sections into context.

Chapter	Title/Description	Work Done	Writing Done	Writing Dates
1	**Introduction and project background**	70%	0%	Apr 2011 - Sept 2011
2	**Literature Review: Observations, global distribution and radiative impacts** Including summary of observations from Chilbolton, frequency of mixed-phase clouds globally and the local radiative influence of mixed-phase clouds.	50%	0%	Apr 2011 - Sept 2011
3	**The EMPIRE model - motivation, formulation and testing** Model formulation and parameterizations and model testing to demonstrate a reasonable performance.	90%	5%	Nov 2010 - July 2011
4	**Sensitivity testing of EMPIRE for mixed-phase clouds** Summary of sensitivity tests and the change to the modelled clouds, which parameters are most sensitive and why, what we need to change to allow simulated clouds to match observations.	80%	0%	Feb 2011 - July 2011
5	**Resolution dependence in EMPIRE model** Exploring the resolution and timestep sensitivity shown by EMPIRE, showing how large the effect is, explaining why it's there, developing a parameterization to account for it, demonstrating improvement with parameterization.	50%	0%	Jan 2011 - May 2011
6	**Formation of multiple layers of mixed-phase clouds** Most literature implies mixed-phase clouds are radiatively driven, however sometimes we see multiple layered clouds which cannot be. EMPIRE shows multiple layers in some cases, this chapter will examine how and why.	0%	0%	July 2011 - Aug 2011
7	**Summary and Discussion (Conclusions)**	0%	0%	Sept 2011

Table 1: Thesis plan including chapters with descriptions, amount of work done so far and likely writing and completion dates.

3 Current Work

Analysis of radar and lidar observations of mixed-phase clouds

Previously, radar and lidar observations from Chilbolton were averaged to GCM model resolution before the liquid cloud frequency was calculated. This showed a high frequency of occurrence of liquid cloud because the presence of a single liquid cloud within the averaging window resulted in the whole averaging time being counted as "cloudy". I have adapted existing code to calculate the liquid cloud fraction from these observations and used this to recalculate the liquid cloud statistics for a fair comparison between modelled cloud and observations.

Figure 1 shows the comparison of this new metric derived from radar/lidar observations and taken from model fields. Notice how only the ECMWF model has liquid cloud fractions that match or exceed the observed values at temperatures below freezing and how the peak in the ice cloud fraction is at much colder temperatures for all models than observations. This peak in observed ice cloud fraction is at a slightly warmer temperature than the peak for the liquid cloud fraction, as expected.

This metric can also be used to assess the sensitivity of the EMPIRE to model changes. This is shown by the grey lines. None of the sensitivity tests, except one, is able to capture as much supercooled liquid cloud. The only one to match or exceed the observed liquid cloud fraction is where we turn off all ice production in the model. However, there are still regions of the temperature profile where the model liquid cloud fraction is lower than observed. This implies that there must be something wrong with way we are forcing the model.

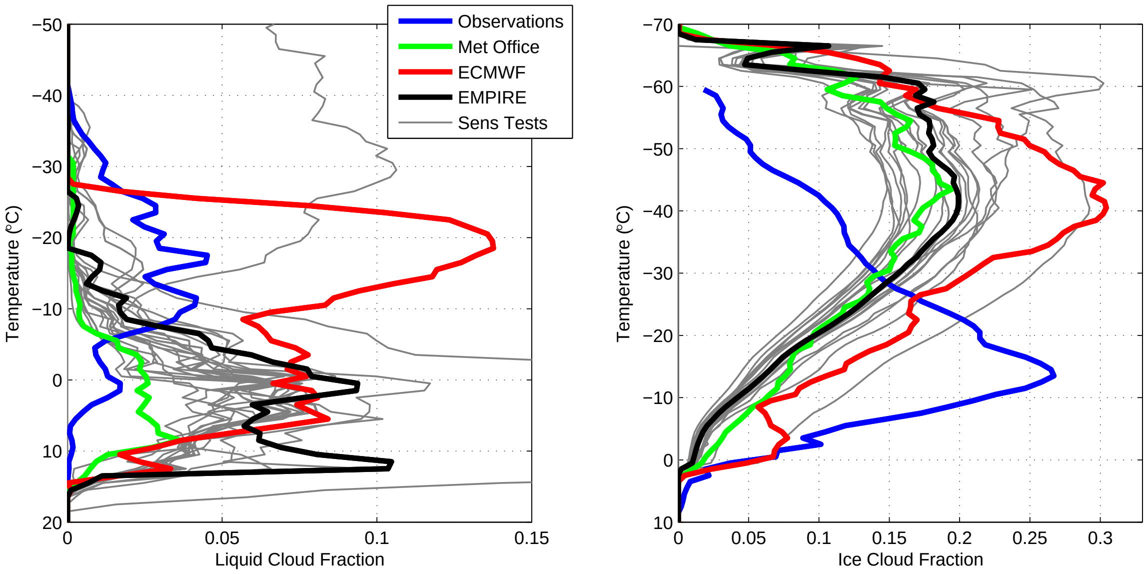

Figure 1: Mean liquid and ice cloud fraction from radar/lidar observations and from 3 models for the 39 days used for sensitivity testing. Note how only the ECMWF model has as much supercooled liquid cloud as observations and that the ice cloud fraction peak is far too cold for all models. The mean liquid and ice cloud fractions from the sensitivity tests are plotted in grey. Note how even the most extreme model changes (no ice production and increased RH by 30%) fail to match the observed liquid cloud fraction.

Figure 2 shows the mean liquid and ice water contents in the same way that figure 1 shows mean cloud fraction. Again we see that the models have less cloud water present than the observations, the same is also true for cloud ice water content. The EMPIRE liquid water content is closer to the observations than either ECMWF or Met Office models, however, the sensitivity tests span much of the range between models and observations. Again the two sensitivity tests that exceed the observed liquid water content are the increased RH and no ice simulations. The mean ice water content is much less sensitive to changes in model specification than the liquid water content.

As we are missing a large amount of liquid water from our model simulations, it is possible that our forcing data (ERA-interim) is too dry. To test the hypothesis that there is a dry bias in this data set, the water vapour field has been compared to that from radiosondes. Whilst it is known that radiosonde humidity sensors perform poorly at cold temperatures, there are no other reliable observations to compare with. Figure 3 shows the difference in the mean and RMSE of the a) water vapour and b) relative humidity from radiosondes for ERA-interim, Met Office and EMPIRE for the 39 days we run the model on. This shows that the mean quantity is about right, and perhaps slightly high in ERA-interim at colder temperatures whilst the Met Office has a dry bias throughout the troposphere. We also need

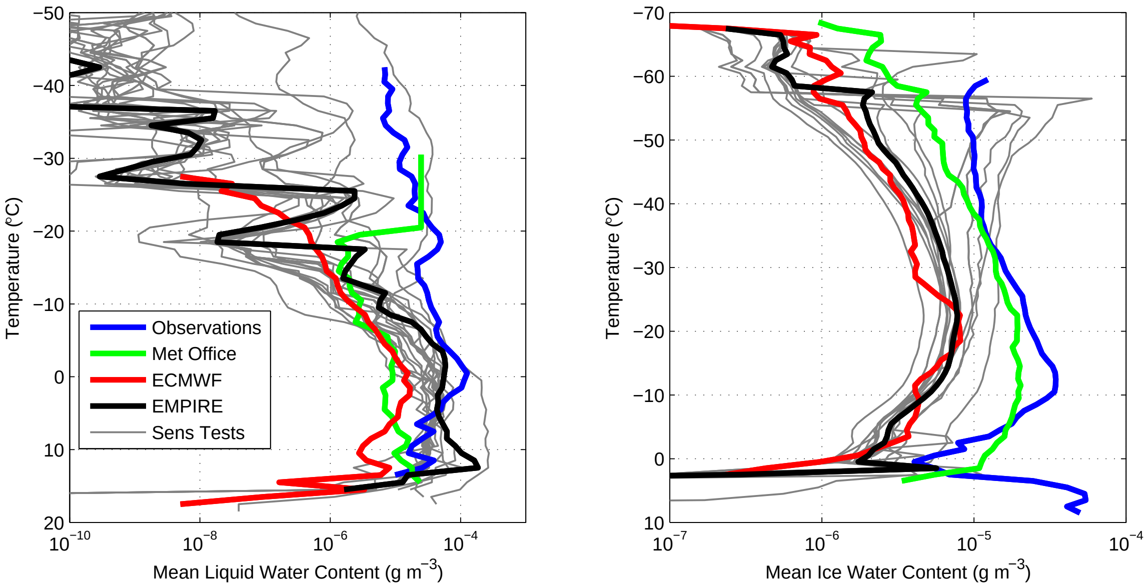

Figure 2: Mean liquid and ice water contents, where the respective water content was non-zero, for the 39 days. Observed liquid and ice water contents are higher than seen in the models for all sub-freezing temperatures. The sensitivity tests span much of the range between models and observations for liquid water content but not for ice water content.

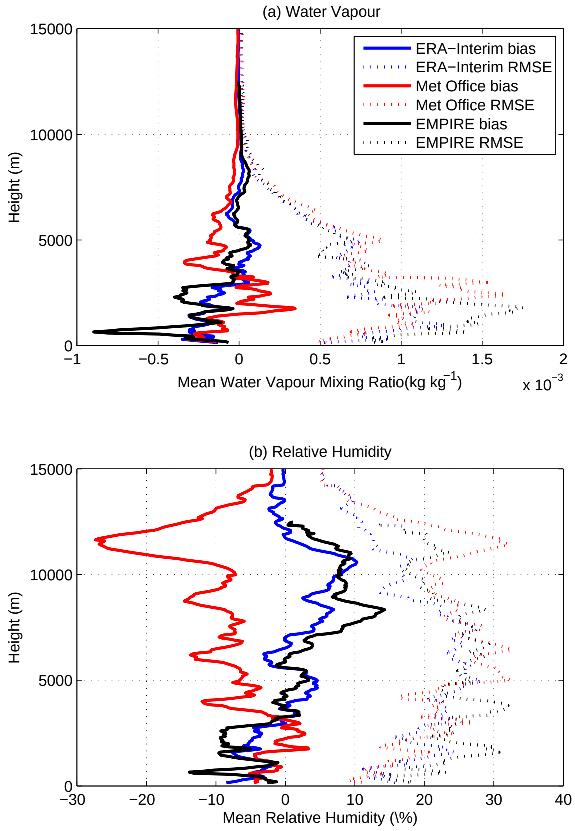

Figure 3: Bias and root mean square error (RMSE) compared to radiosondes for a) Water Vapour and b) Relative Humidity. The Met Office model shows a consistent dry bias throughout the troposphere whereas ERA-Interim and EMPIRE both have a bias which changes sign in the mid troposphere with smaller bias.

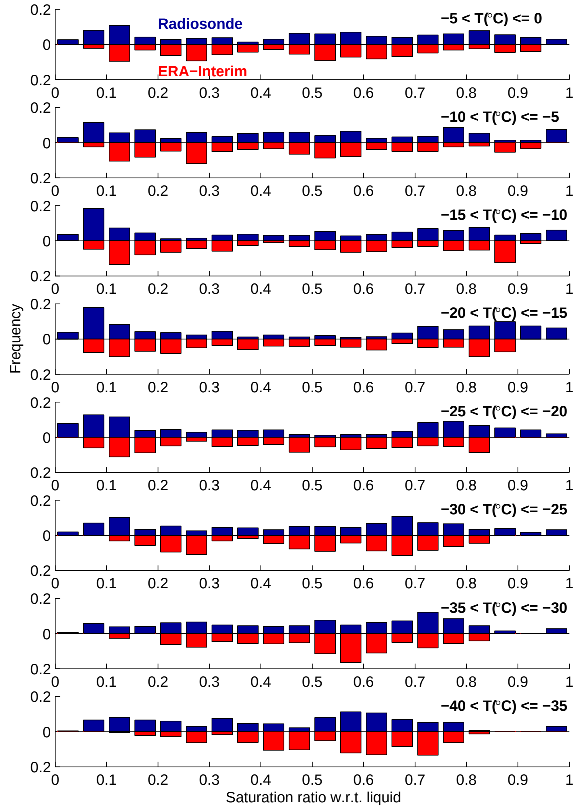

Figure 4: Histograms of model and radiosonde values of saturation ratio in 5°C temperature bins, plotted back-to-back for clarity. Notice the absence of high saturation ratio values for ERA-Interim compared to radiosondes particularly between -15 and -30°C. ERA-Interim seems to struggle to maintain water vapour in excess of ice saturation values.

to compare the PDFs of these quantities, this is shown in Figure 4. This shows that ERA-interim misses many of the times where high relative humidity is observed. This follows through to EMPIRE which also shows a similar lack of high RH values, as indeed do the Met Office models (not shown).

Use in-situ aircraft and surface based radar observations investigate sub-grid moisture variability

Sensitivity tests have previously shown that the specification of the sub-grid moisture field is important for the formation of mixed-phase clouds. Specifying a larger variance of the sub-grid moisture field allows the model to bring part of a grid-box to saturation more easily. Current GCMs use either a fixed variance scheme (Smith, 1990) or a prognostic variance scheme (Tompkins, 2002). A scheme of intermediate complexity may be helpful, using diagnostic variance. Moeng and Wyngaard (1984) showed that a conservative tracer (such as q_t, the total (liquid + vapour) water mixing ratio) has a greater variance in turbulent air. Using the relationship shown in their paper it is possible to create a parameterization for the variance of q_t based on the turbulence in the cloudy regions. The variance is calculated as:

$$\overline{c^2} = \left(\frac{\overline{c'w'}}{w_*}\right)^2 f(z) \;; \qquad f(z) = 2.1\left(1 - \frac{z}{z_i}\right)^{-\frac{2}{3}} \tag{1}$$

where $\overline{c'w'}$ is the flux into the turbulent mixed layer and w_* is the convective velocity scale, $f(z)$ scales the variance throughout the depth of the mixed layer.

Using the Moeng and Wyngaard (1984) relationships I developed a parameterization for the variance of q_t and implemented this into EMPIRE. With this parameterization included EMPIRE demonstrated a much larger variation in time of the cloud properties, which looked more realistic than simulations without the parameterization. However, comparing the full set of model runs with the control case and observations, this change results in less liquid cloud water on average. In some cases diagnostic variance seems to provide longer lived liquid clouds with higher water contents, so some further work is needed to understand this differing behaviour.

Addressing Ice Deposition and Sublimation problems

Problems previously mentioned, whereby ice appears to "melt" at temperatures of around -10 or -15 °C (depending on RH_{crit}) have been addressed. This is done following the methods described in the Met Office UM Documentation (Wilkinson et al., 2009) which splits each grid-box into regions of 'liquid saturation', 'ice cloud', 'mixed phase' and 'clear air' and prescribes the value of q_t in each region. Using this method prevents the unphysical melting problem at subfreezing temperatures.

Further exploration of the resolution and timestep dependence of EMPIRE

At the last meeting I had established that EMPIRE showed a potentially important dependence on the model's vertical resolution. I proposed at the time that this was because the sedimentation of ice from the grid-box was emptying small (high resolution) grid-boxes whilst large (low resolution) grid-boxes retained larger amounts of ice. As the ice growth rate (and hence liquid depletion rate) is dependent on the amount of ice at the start of the timestep then this resulted in divergence of the model simulations at different resolutions.

This vertical resolution dependence will likely be a reason why we don't see long lived supercooled liquid clouds in models as typical vertical resolutions in the mid-troposphere are 500 - 1000 m. As a result much more work looking at this has taken place in the last 6 months.

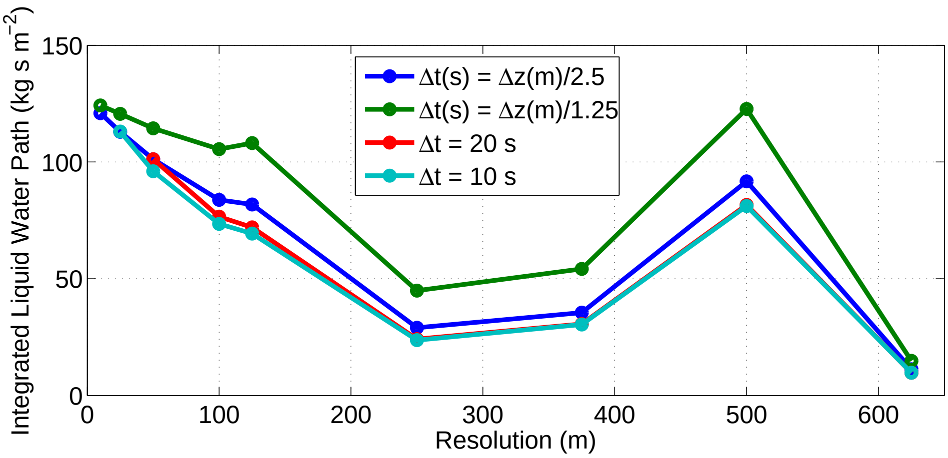

Figure 5: Liquid water path integrated vertically and in time for varying model vertical resolution and timestep. The change in this quantity for high resolution is clear. The peak at 500 m resolution is because the modelled cloud is 500 m deep.

Figure 5 shows how the total simulated liquid water (integrated vertically and in time) varies with model resolution and timestep. Even at very high resolution (Δz = 10 m) the integrated liquid water content has not converged, although there seems to be less sensitivity to timestep at higher spatial resolution.

A high resolution (Δz = 50 m) model simulation was performed where the rates of ice growth and liquid depletion were dependent on the 500 m mean quantities, rather than on the local grid-box values. This was designed to represent the growth rates of the lower resolution model whilst retaining the structure of the more highly resolved fields. This simulation is very similar, in terms of ice and liquid water amounts, to the low resolution (Δz = 500 m) run previously. This implies that it is the averaging of these quantities over a large scale (larger than the cloud depth in many cases) that is causing the rapid glaciation of these clouds at low resolution. This result offers hope that we may be able to help low resolution models to retain some liquid water in these clouds if we were to assume some vertical structure to these clouds and calculate the growth rates accordingly. This would form the basis for a new parameterization which is under development and discussed more in the Future Work section.

4 Future Work

Parameterization to account for model resolution

As shown above the model vertical resolution has a large effect in EMPIRE and shows a key reason why these clouds cannot be modelled using a current GCM setup. We believe it should be possible to account for the effect of resolution by parameterizing variation of q_i and q_l as piecewise linear within a grid-box, rather than constant. The parameterization would identify whether a cloud is suitable for applying the parameterization and then scale the ice growth rate based on an assumed vertical distribution and overlap of liquid and ice. This parameterization would then be tested in the EMPIRE model.

Completion of sensitivity testing with EMPIRE
Much of the sensitivity testing has already been done; however, the model does not perform at all well in some situations caused by erroneous forcing. These cases need to be removed from the sensitivity test statistics. Also, the control simulation does not well match observations, so we would like to improve this simulation by using more realistic values for ice properties (capacitance, fall speed and mass-diameter relationship) based on more recent observations than those currently used.

Looking at multi-layered mixed-phase cases
Multi-layered mixed-phase clouds are still a great puzzle. Much of the literature on mixed-phase clouds suggests that the radiative cooling at cloud top is the primary reason for their long lifetimes. In cases with multiple layers, the layers are often quite close in proximity and as a result the radiative cooling of the lower layers is greatly reduced. Despite this, these multi-layered systems are still observed to persist for a long time. In some cases EMPIRE suggests the presence of multiple layers. We would like to understand what conditions enable the model to produce multiple layers.

Comparison with Marsham et al. (2006)
Marsham et al. (2006) looked at a particular mixed-phase altocumulus cloud and compared observations from radar, lidar and microwave radiometer with a LES model run. We are able to run EMPIRE on the same case using the same model forcing. This will give us another source of comparison with EMPIRE.

Writing up
I would like to start writing up soon, to enable this I plan to complete work in sections according to the thesis plan, so that I can start writing up complete chapters.

5 Transferable Skills

I continue to attend Monday and Tuesday seminars and I am demonstrating on BSc and MSc courses. I have presented my work at the department poster session (October) and at the AMS Clouds and Radiation Conference (July). I continue as chair on the HDR forum and I have attended the GSDP course on planning and writing a thesis.

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