Sixth Monitoring Committee Report

THE ROLE OF MIXED-PHASE CLOUDS IN CLIMATE

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4pm, Monday 13th June 2011, 1L43

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). More recently, Zhang et al. (2010) used satellite based radar and lidar data and showed that globally "mid-level liquid topped stratiform clouds" occur 7.8% of the time and account for 33.6% of all mid-level clouds. Figure 1 shows the global distribution of these clouds.

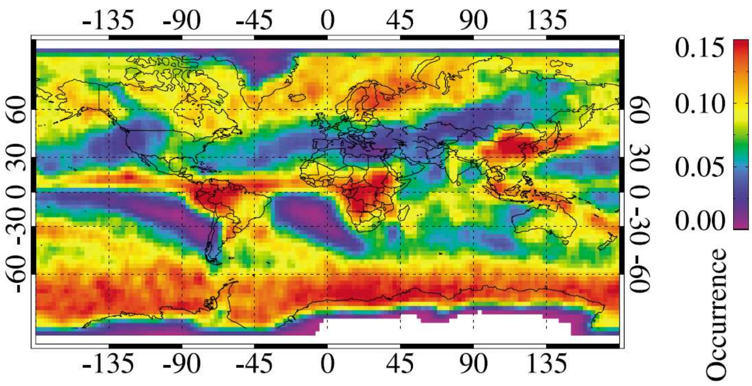

Figure 1: A 2-year averaged occurence frequency of "mid-level liquid topped stratiform cloud" in $2.5° \times 2.5°$ squares. The most common locations for these cloud types are the mid-latitude storm tracks, over land in the tropics and the southern ocean. From Zhang et al. (2010).

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. This has come particularly to our attention with the implementation of the new cloud scheme in the ECMWF model (R. Forbes, personal communication); an absence of night-time supercooled liquid water clouds was correlated with extreme low temperature biases over Scandinavia during January 2011.

At the last monitoring committee meeting it was demonstrated that there was a resolution dependence in EMPIRE for the simulation of mixed-phase clouds and that this may be a significant factor in why GCMs fail to capture many long-lived liquid layers. We suggested that it should be possible to create a parameterization that accounted for the resolution and allowed simulations at all resolutions to have similar results.

In the last 5 months we have furthered the study of the resolution dependence, understanding which processes are contributing most to the resolution dependence and allowing us to create a "superparameterization" to correct for this dependence. Model runs with the superparameterization show an improvement over runs without it but does not completely correct the low resolution simulation. We have also attempted to create an analytic parameterization to achieve the same result, however this is still being developed.

In addition, we have investigated the affect of changing N_0, the intercept parameter in the ice particle size distribution. Changing N_0 showed one of the largest sensitivities in the sensitivity tests previously performed. We compared observed ice particle size distributions from aircraft data with parameterized size distributions. The rate of ice growth by vapour deposition and the mean ice fall velocity are calculated for each observed distribution and compared with the parameterizations. An ice water content dependent bias in both growth rate and fall velocity is discovered; this bias can be corrected for by allowing N_0 to vary as a function of ice water content.

2 Thesis Plan

Chapter	Title/Description	Work Done	Writing Done	Writing Dates
1	**Introduction and project background**	70%	0%	Aug 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%	Aug 2011 - Sept 2011
3	**The EMPIRE model - motivation, formulation and testing** Model formulation and parameterizations and model testing to demonstrate a reasonable performance.	100%	Draft complete	
4	**Important processes in mixed-phase clouds persistence** 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%	July 2011 - Aug 2011
5	**Resolution dependence of the longevity of mixed-phase clouds** 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.	80%	50%	June 2011
6	**Evaluation of Parameterized Ice Particle Size Distributions** Many GCMs assume a distribution of ice particle sizes and use this to calculate the vapour deposition rate and fall velocities. These distributions are evaluated against observed size distributions from aircraft measurements and the impact of the size distribution on mixed-phase clouds and their representation is assessed.	80%	0%	June 2011 - July 2011
7	**Summary and Discussion (Conclusions)**	0%	0%	Oct 2011

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

3 Current Work

Refinement of sensitivity tests

At the last meeting we demonstrated that there was a large difference between the liquid and ice cloud fractions observed by the radar and lidar at Chilbolton and the cloud fractions predicted by the models (including EMPIRE).

Since then the method of calculating the cloud fraction from models and from radar/lidar observations has been slightly modified. In the calculation of the ice cloud fraction from models we now test to see if the ice clouds predicted would have a large enough radar reflectivity to be detected by the radar at Chilbolton. The minimum detectable signal of the radar decreases with the range from the instrument squared and therefore some high cirrus clouds are not detected. By adding this constraint, the model mean ice cloud fraction now agrees much better with observed ice cloud fraction at colder temperatures.

Also, we have compared two methods of calculating the ice cloud fraction from the radar observations. The first method calculates the cloud fraction from the number of radar pixels with reflectivity above -40 dBZ within some time and height range. The second method, analogous to how models compute ice cloud fraction, uses an empirical relationship between grid-box mean ice water content and cloud fraction. We are able to calculate the mean ice water content from the radar reflectivity and therefore calculate a cloud fraction in the same way as the models. There is a large reduction of cloud fraction when calculated using the second method. This poses further questions about the suitability of the empirical relationship between ice water content and cloud fraction in the model, which I will likely not have time to explore.

Developing a parameterization to correct for the resolution dependence

As discussed at the last meeting, EMPIRE shows a resolution dependence for mixed-phase clouds. Figure 2 shows the normailsed integrated liquid water path (NILWP) increasing with decreasing grid-spacing and longer timesteps. This may explain why we do not see many long lived liquid water layers in GCMs. The NILWP is calculated from the integral of the liquid water contents both vertically and in time and normalised by the liquid water path as the simulation begins and also such that the control simulation (Δz=50m, Δt=20s) gives a value of 1. The NILWP increases as a result of the model producing both more persistent layers and layers with greater liquid water contents. Figure 2 shows that the amount of liquid water in the simulations does not converge at high resolutions; although the simulations without non-local mixing do show more sign of convergence at higher resolutions. Since the last meeting we have tested a number of possible resolution dependent processes to discover which is affecting the simulations.

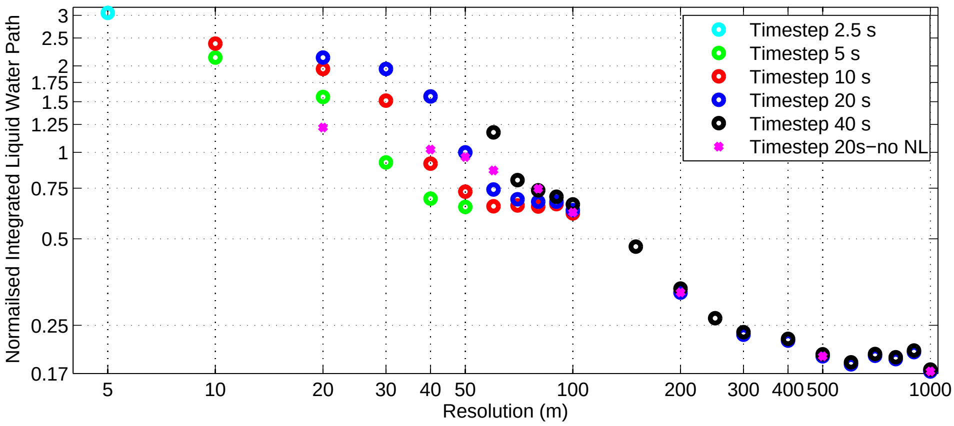

Figure 2: Normalised Integrated Liquid Water Path (NILWP) from the idealised simulations for many vertical resolutions and model timesteps. The NILWP increases with decreased grid spacing due to longer liquid cloud duration and increased liquid water content within the cloud. Longer model timesteps also increase the NILWP at high resolutions. The magenta crosses show simulations that do not include non-local turbulent mixing.

There are five processes in EMPIRE for which resolution may affect the results. These processes are: ice growth by deposition, ice sedimentation, resolving vertical temperature structure of cloud layers, radiation and turbulent mixing. We ran an idealised case in EMPIRE at high (50 m) resolution, and one-by-one degraded these processes to low resolution (500 m). These model runs (not shown) highlighted the importance of the depositional growth and sedimentation processes and also of resolving the thermal structure of the layer. The effect from changing the radiation scheme and turbulent mixing scheme inputs are less significant.

With knowledge of which processes are important, we went about constructing a superparameterization to allow the long-lived liquid layers of high resolution models to exist in a low resolution model. The superparameterization works by finding the top layer of the mixed-phase cloud and subdividing this grid layer into 10 sub-layers. We parameterize the sub-grid profiles of q_i, q and θ to assign values to each of these sub-layers. The process rates for depositional growth and sedimentation are now calculated on the 10 sub-layers, as is the liquid water content. We take an average of the process rates on the 10 sub-layers and apply this to the layer as a whole and use the average liquid water content from the sub-layers as the layer mean liquid water content.

By using this superparameterization we are able to simulate long lived liquid layers in the low resolution model. Figure 3 shows three simulations: 50 m resolution (panels a-b), 500 m resolution (panels g-h) and 500 m resolution with the superparameterization implemented (panels e-f). Panels c-d show the 50 m resolution averaged over 500 m for comparison. The superparameterization run shows that the liquid water layer is sustained at cloud top much longer than without it included, however, the liquid water mixing ratio is lower than the 50 m resolution run. The ice water content in the same layer remains higher than the 50 m resolution run which suggests the parameterization requires further refinement.

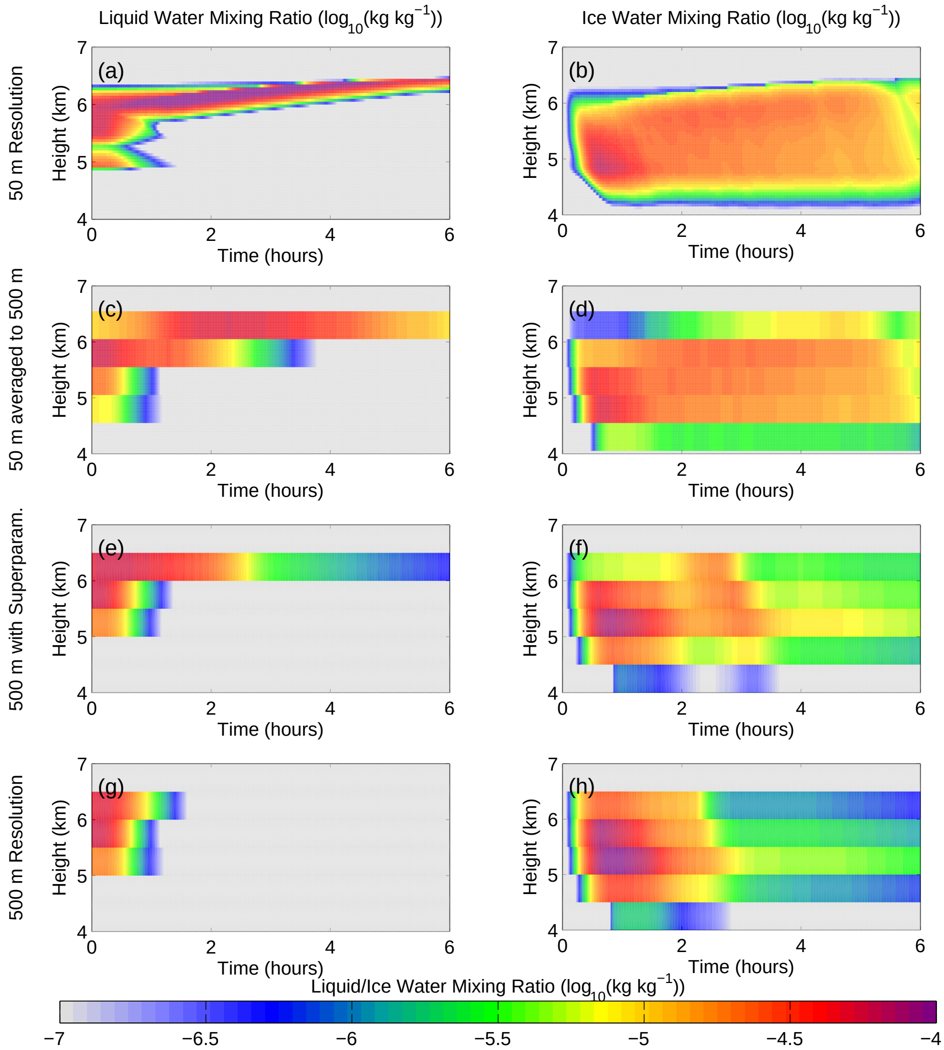

Figure 3: Liquid and ice water mixing ratios from model simulations illustrating the different cloud structure at different resolutions. The 50 m simulation (panels a and b) show a thin liquid water layer throughout the simulation. Panels c and d show the same simulation averaged over 500 m layers for comparison with the 500 m resolution simulations below (panels e-h). Panels e-f show the 500 m simulation including the superparameterization whilst panels g-h do not include this. Including the superparameterization allows the model to maintain a liquid layer at cloud top similar to the high resolution simulation, however, the liquid water mixing ratio is not as large.

Obviously the superparameterization described above is a computationally expensive scheme. It requires subdividing the layer into 10 and calculating the process rates on each sub-grid layer before averaging back to the low resolution grid-box. This method is not scalable to GCMs because the time taken to calculate the new process rates would be prohibitive. However, it is also possible to make the same assumptions within an analytic parameterization and calculate by how much the process rates are altered due to the resolution. Therefore the process rates can be corrected for and the low resolution model will again be able to sustain the liquid layers. This parameterization is nearly complete and early results are very encouraging.

Evaluating parameterized ice particle size distributions (PSDs)
From the sensitivity tests carried out previously we determined that changing N_0, the ice PSD intercept parameter, was one of the most sensitive areas of the model. This led us to question what the correct value of N_0 was and also how well the parameterized PSDs match those observed. One reason why EMPIRE, and probably all GCM schemes, may be so sensitive to the PSD is that both the depositional growth rate and the mean fall velocity are affected by the assumed size of the particles. Large particles grow by vapour deposition faster than small ones; however, they also start off with a larger mass. For a given total ice water content, the total growth rate can be maximised by making the particles small and numerous because in a given time small particles grow by a larger proportion of their initial mass than larger particles. Small ice particles also have a lower terminal velocity, so fall more slowly from the cloud. As such, the large number of small particles that maximise the growth rate also minimises the mean fall velocity. This further enhances the potential to remove liquid from this cloud as the ice particles remain in the liquid layer for longer. Clearly correctly predicting the shape of the size distribution is important because errors in both fall velocity and growth rate act in the same sense.

The parameterized ice particle size distributions from Wilson and Ballard (1999) are compared with observed size distributions from the EUCREX field campaign. Size distributions from Rotstayn (1997) and Thompson et al. (2004) are also in the process of being compared. More than 13,000 observed size spectra are compared with their parameterized equivalents. The parameterized size distributions are described knowing the total ice water content and temperature. The total depositional growth rate for each is calculated, along with the mass-weighted mean fall velocity. The values for each PSD are compared and the results are plotted in figure 4a and d. The figures show the ratio of the parameterized value to the value calculated from the observed PSD and is plotted against the ice water content. The values are coloured by their temperature and the black line shows the mean value for all temperatures. There is a clear ice-water-content dependent error in both the depositional growth rate and the mass-weighted mean fall velocity, which as expected are of opposite sign. The result of this is that for small ice water contents, the parameterized growth rate is too large and the parameterized mean fall velocity is too small. Both of these contribute to an increase in the amount of liquid removed from the cloud by the ice particles.
There has been some previous work which suggests that N_0 is not a constant value (as assumed in these parameterizations), but is in fact a function of ice water content. Figures in both Delanoë and Hogan (2008) and Houze et al. (1979) show an increase in N_0 with increasing IWC. Using these figures an approximate relation of $N_0 \propto \mathrm{IWC}^{0.5}$ is found. Implementing $N_0 \propto \mathrm{IWC}^{0.5}$ removes much of the bias (Figure 4b) and e)), however, using 0.75 for the exponent removed nearly all of the bias in a range that spans at least three orders of magnitude (Figure 4c) and f)). Incorporating $N_0 \propto \mathrm{IWC}^{0.75}$ in to EMPIRE gives, as expected, much less ice produced at the cloud top and consequently more liquid is present throughout the simulations.

Writing up
I have completed a first draft of chapter 3 (EMPIRE model) and am currently revising it after comments from Robin. In addition I have a large proportion of chapter 5 (Resolution dependence) completed.

4 Future Work

Parameterization to account for model resolution
Complete formulation of the analytic parameterization and test it on a number of test cases. Run EMPIRE with the parameterization included across the sensitivity test cases and determine the nature of the changes observed.

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.

Further comparison of ice particle size distributions
To check the generality of the results found so far I will use the additional parameterizations mentioned above and

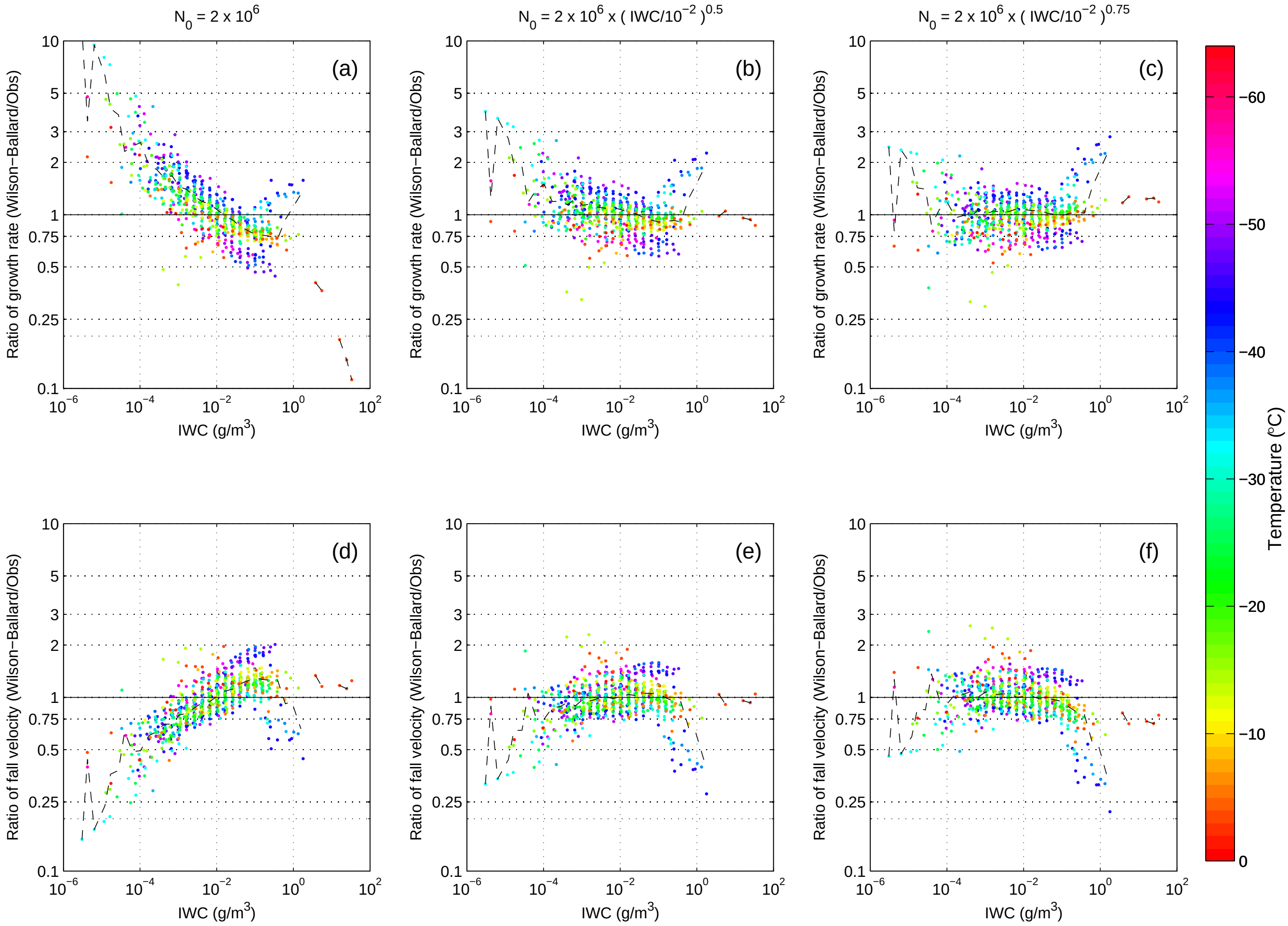

Figure 4: Ratios of calculated depositional growth rates (panels a)-c)) and mass weighted mean fall velocity (panels d)-f)) from parameterized size distributions compared to observed size distributions. The left column uses the standard parameterized value of $N_0 = 2 \times 10^6 \mathrm{m}^{-4}$, the middle column uses $N_0 \propto \mathrm{IWC}^{0.5}$, based on observations and the right hand column uses $N_0 \propto IWC^{0.75}$ which removes almost all the bias.

additional observed data from the APPRIASE field campaign.

Writing up

Obviously the majority of my time in the next few months will be spent writing up.

5 Transferable Skills

I continue to attend Monday and Tuesday seminars and have attended the GSDP courses on “planning and writing a thesis” and “surviving the viva”. I will be giving a department lunchtime seminar on Tuesday 1 November.

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