3rd Monitoring Committee Report
THE ROLE OF MIXED-PHASE CLOUDS IN CLIMATE

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1 Introduction

Mixed-phase clouds are important in the climate system, yet are poorly represented in NWP models (Vaillancourt et al., 2003; Hogan et al., 2003) and mid-level clouds (where mixed-phase clouds are frequently observed) are underestimated in many models (Illingworth et al., 2007). My research is aiming to answer the question of why mixed-phase clouds are poorly modelled and how we can improve their representation in large scale models.
In the 6 months since the last meeting I have been further developing and running the single column model as discussed in the previous meetings. The sensitivity of mixed-phase clouds to many influences has been tested in my model, and the performance of the model assessed across a number of cases. In addition, the paper on my undergraduate work has been revised and is now in print (Barrett et al., 2009).

2 Current Work

2.1 Model Development

Since the last monitoring committee meeting the model has been developed a little further, and many small bugs have been fixed.

- The model now uses a TVD (Total Variation Diminishing) advection scheme, which has high accuracy and low numerical diffusivity, this is used largely to allow the falling of ice crystals to be represented by an advection scheme without excessive numerical diffusion or giving negative values.
- The issues with the Rotstayn ice scheme (Rotstayn et al., 2000) not allowing ice to grow in air subsaturated with respect to liquid have been fixed.
- A new ice scheme based on Wilson and Ballard (1999) is now implemented. Advantages of this scheme include the use of a particle size distribution for ice and fall speeds based on particle size.
- Radar and Lidar forward models have been implemented using relations from Hogan et al. (2006) and Marsham et al. (2006).

2.2 Model Performance

I have run the model over an extended period - up to about 2 weeks - to assess the general performance. In doing so, the results of which can be seen in Figure 1, we discovered that the model, whilst being able to capture fairly well the existence and development of mixed-phase stratiform clouds, had more serious problems in representing other features. The main such concern was the inability to in any way capture the passage of

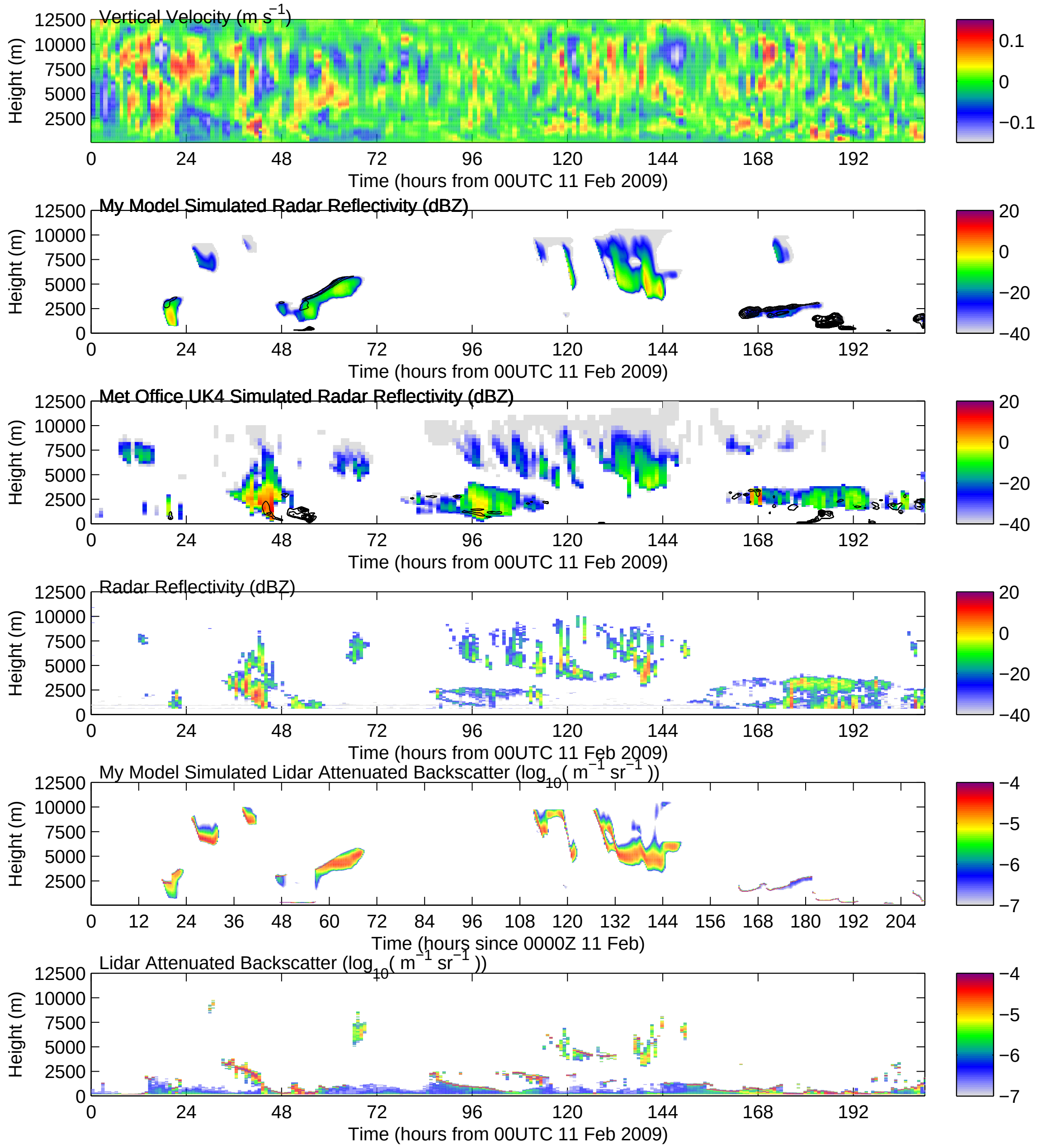

Figure 1: A comparison of simulated radar reflectivity and lidar backscatter from my model, the Met Office UK4 model and observations from Chilbolton. Model Radar Reflectivity plots show liquid water content contoured as liquid is not included in the reflectivity forward model currently.

synoptic scale frontal systems (as can be seen in Figure 1 between 36-60 hours). We suspect two deficiencies in the model which may cause such a result and are working towards fixing these before running the model over a longer period of up to 1 year. The two issues are the lack of moisture and temperature advection in the model (a relaxation to GCM values is used to stop large drifts from reality, but with a timescale of 6 hours, advective features such as fronts are poorly captured). The other issue is the lack of a cloud scheme at present. This means that air must reach liquid saturation before producing liquid water in cloud, whereas GCMs often produce cloud in air once relative humidity exceeds some threshold value (for instance, 85%). Steps have been taken to resolve these issues, outlined in my future work section.

2.3 Sensititvity Testing

The model is able to simulate mixed phase clouds in a manner similar to those which we observe. As this is the case we are now able to test the sensitivity of the existence and nature of these clouds in the model by changing various parameters. Table 1 summarises the sensitivity tests we have done and shows the changes to mixed phase cloud structure that results. These results are expanded upon in the text beneath.

2.3.1 Control Simulation

The case for the control simulation is the day of the last monitoring committee meeting (25 June 2009), where mixed-phase clouds (glaciating Altocumulus) were observed throughout much of the day at a height of about 5 km, where the temperature was about -15°C. The model is initialised with a Larkhill sounding from 6Z and is run for 18 hours. The model slowly relaxes towards the Meteo-France model forecast for that day, so as to evolve the temperature and moisture fields, and the vertical winds from the Meteo-France model are applied directly to my model.

The radiation scheme is called every 13.3 minutes (40 timesteps) and all parameterization settings are set to their default values. Ice growth rate and fall speeds are from the Wilson and Ballard (1999) ice scheme.

In this standard set up the model produces a liquid cloud that persists for 9 hours with a peak liquid water path (LWP) of 48 g m^{-2}.

Parameter	Change from Control Run	Peak LWP (g m^{-2})	Liquid Duration (hours)
Control	-	48	9
Solar Radiation	Turn Off	125	15
All Radiation	Turn Off	5	1
All Radiation	every 4 hours	40	18+
All Radiation	every hour	50	10
All Radiation	every 4 minutes	48	9
Entrainment	Turn Off	48	12
Entrainment	Double	40	8
Turbulence (eddy diffusivity)	Turn Off	45	13
Turbulence (eddy diffusivity)	Local Mixing Only	40	8
Turbulence (eddy diffusivity)	Non-Local Mixing Only	45	9
Turbulence (eddy diffusivity)	Non-Local, No Entrainment	48	9
Turbulence (eddy diffusivity)	Entrainment Only	45	13
Ice Scheme	Rotstayn	30	8
Crystal Shape	Hexagonal Plate	20	7
Ice Crystal Fall Speed	Doubled	48	9
Ice Crystal Fall Speed	Halved	45	9
Ice Crystal Fall Speed	Quartered		
Ice Crystal Fall Speed	Zero	10	1
Ice Nuclei Mass	x1000	48	9
Ice Nuclei Mass	x0.001	48	9
Ice Nuclei Number	x1000	48	9
Ice Nuclei Number	x0.001	48	9
Vertical Velocity	Doubled	100	9
Vertical Velocity	x4	358	7

Table 1: Table showing model sensitivity to different parameter changes

2.3.2 Ice Nuclei Mass

Increasing or reducing the ice nuclei mass by up to three orders of magnitude has very little effect on the cloud structure. This is because after the ice has been nucleated it grows by vapour diffusion which is a much larger affect. After the ice has been nucleated no knowledge about the initial size or number is retained, the ice size distribution is inferred from ice mass, temperature and humidity.

2.3.3 Ice Nuclei Number

Increasing the number of ice nuclei effectively has the same consequence as increasing the ice nuclei mass in the Wilson and Ballard Ice scheme. In the Rotstayn scheme the ice nuclei number is used to define the ice crystal concentration, reducing this number results in bigger ice crystals which grow faster hence producing more ice and less liquid. In the Wilson and Ballard scheme, the ice crystal number is fixed, although it could be changed in my model.

2.3.4 Ice Fall Speeds

Doubling the fall speeds results in ice falling from the layer of liquid water more quickly, and therefore being able to deplete the liquid present for a shorter period of time. With faster fall speeds the cloud characteristics did not change hugely. Halving the fall speeds has the opposite effect. Slower fall speeds result in higher ice water contents and lower liquid water contents, however the liquid water contents change by only about 10% when changing the fall speeds by a factor of 4. Ice water contents can change by an order of magnitude in the cloud below the liquid layer, but this is relatively unimportant for radiation so long as the liquid layer still exists.

2.3.5 Ice Crystal Habit

The specification of the ice crystal shape is important in determining the rate at which vapour deposition occurs. The capacitance which determines this rate is very dependent on the chosen mass-diameter relationship. Using the Rotstayn ice scheme, liquid layer clouds which can persist for up to 12 hours if ice crystals form as spheres are depleted within 1 hour if the ice crystals instead form as hexagonal plates. In the Wilson and Ballard scheme the effect is smaller, but the liquid water path when hexagonal plates form is less than half that of the simulation with spheres.

2.3.6 Shortwave Radiation

By turning off the shortwave radiation part of the radiation scheme, liquid cloud layers can be allowed to persist longer than if the shortwave radiation is included. The cloud persists nearly twice as long with 250% of the liquid water path. The warming effect of the solar radiation in the cloud layer means that the air is less able to sit at liquid saturation, due to the requirements for additional vapour to maintain saturation at warmer temperatures.

2.3.7 Longwave Cooling

Longwave cooling from the liquid layer is a very important process in maintaining liquid cloud layers. Not only does the cooling of the cloud top reduce the moisture required to maintain saturated air, it also destabilises the layer which in turn drives turbulent mixing throughout the cloud, supplying further moisture to cloud top.

2.3.8 Turbulence (eddy diffusivity)

Turbulence is applied in my model as a diffusivity, and calculated based upon Richardson number in the local scheme and radiative flux divergence at cloud top in the non local scheme. It is thought to be an important process in supplying water vapour to cloud top. My simulations are not hugely sensitive to the mixing specification, although less liquid is present if the non local shceme is turned off. The liquid layer clouds can persist for a longer time in simulations with no turbulent mixing at all, although this allows unrealistic instability to be present in a single layer for a long period.

2.3.9 Entrainment

Entrainment allows the cloud layer to mix with warmer/drier air above the cloud layer, acting to reduce the liquid water content at cloud top. Entrainment is almost always small (at most a few centimetres per second) and so turning this off has little effect. However increasing it causes mixing with cloud free air more quickly and thus reducing the liquid content.

2.3.10 Timestep

The model is not sensitive to changes in timestep - this is good!

2.3.11 Radiation Timestep

The effect resulting from changing the frequency of radiation calls is almost nil in a steady state case. In the case of forming or dissipating liquid layers, if the radiation scheme is called less frequently, the start or end of a liquid layer may not have the correct radiative response, or may be continued too long. This may in turn allow or prevent subsequent liquid layers forming which may otherwise not have been the case. For the chosen case, the model simulation is convergent with radiation timesteps smaller than about 15 minutes, although this may not generally be the case.

2.3.12 Vertical Velocity

The model is very sensitive to the specification of vertical velocity. Larger vertical velocities can obviously bring air to saturation more quickly and therefore result in significantly more liquid within the cloud. Currently vertical velocities from NWP models are used to force my model, but this raises questions about what horizontal extent my model has.

2.3.13 Vertical Resolution

Yet to be verified

2.4 Evaluating Model Performance

At my last monitoring committee meeting I stated that the performance of my model could be assessed by:

1. **Using observational forward models on the output from my 1D model for comparison with observed radar and lidar data, similar to the methods used in Marsham et al. (2006).** Observational forward models for radar and lidar have been implemented as a standard way of analysing what the model is doing and comparing it with NWP models and with observations. An example of this is shown in Figure 1. These provide a good way or comparing whether the model is performing well or not. Additional forward models will be created, to include radar Doppler velocities to assess the ice fall speed parameterization.

2. **Create new metrics for model performance for long-term model runs.** A number of new metrics have been chosen that will allow an objective comparison between model and observations. These will allow us to see if we are better capturing the distribution of mixed-phase clouds than standard GCMs. An example of one such diagnostic is shown in Figure 2, which shows the combined frequency of occurence

of liquid water mixing ratio and temperature. A frequency of 0.1 means that of all data points with that temperature 10% contain liquid water between the upper and lower bounds of that 'bin'. Figure 2 shows my model is better able to capture the peak liquid water contents, but not the spread - although the statistics are particularly poor as only a single day of data are used currently. Other metrics of a similar nature can also be used - e.g. Liquid water content-height, Ice water content-temperature, cloud fraction-temperature.

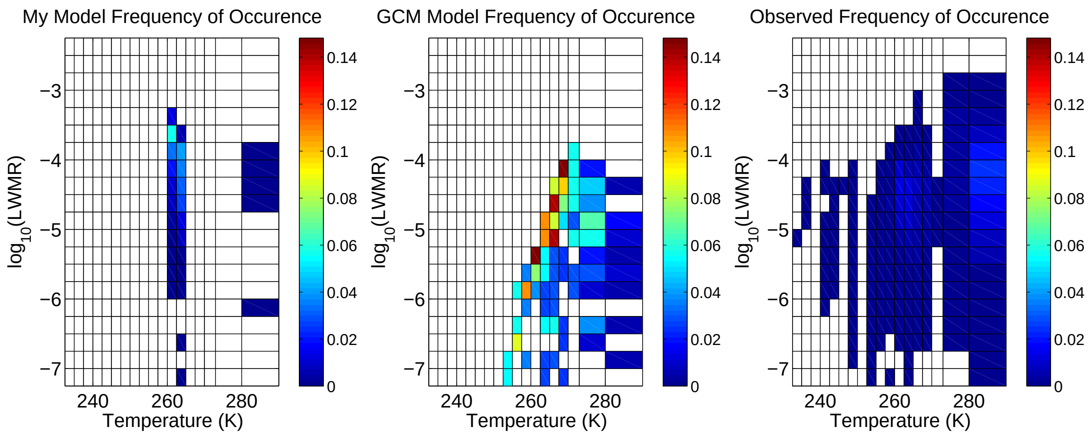

Figure 2: A comparison of the frequency of occurence of liquid water mixing ratio (LWMR) at a given temperature between my model, the Meteo-France model and observations for 25 June 2009. My model better captures the peak liquid water contents although does not show the spread seen in the Meteo France model or observations.

3. **Comparison of cloud liquid and ice water contents between my model, large scale models and with derived values from surface remote sensing instruments (e.g. radar, lidar and microwave radiometer) as gathered from the Cloudnet project.** By doing a three-way comparison with my model output, GCM output and processed remote sensing data of parameters like liquid water path, the performance of my model relative to other models can and has been assessed.

4. **Comparing radiative fluxes at the surface and top of atmosphere.** A comparison of radiative fluxes at the surface and top of atmosphere has yet to be performed. It is my intention to use the radiative fluxes from my model - which are already calculated when the radiation scheme is called - and compare them with GERB measurements of the days being modelled. This will allow us to see whether the improvement in mixed-phase cloud representation that we are demonstrating helps to bring the radiation budget closer to reality compared with current representations of mixed-phase clouds.

2.5 Observational Data Exploration

I have started work looking at mixed-phase clouds in the real atmosphere. By looking through the Cloudnet dataset of radar and lidar observations from Chilbolton, the presence of mixed-phase clouds can be assessed fairly quickly by eye. In cases where persistent mixed-phase clouds further analysis of the large-scale conditions was performed, by looking at synoptic charts, satellite images and radiosonde ascents. I done this on about 2 years of data so far, with about 4 more years to look at. I can also look at observations from two other european sites. So far I have identified a few different regimes under which persistent mixed phase clouds are commonly observed.

1. Ahead of an approaching and/or stalled warm front

2. In a high pressure situation, when an upper level disturbance is marked on the synoptic chart in the vicinity of the mixed-phase cloud - especially in association with dry upper level air which prevents cirrus formation.

3. At times when heavy rain from a cold front or convective storm has recently passed.

3 Future Work

Work in the next 6 months will largely be a continuation of current work. Of primary importance is to change the model to account for the two problems causing poor performance in advective situations. I will add a cloud scheme to the model, which hopefully will be a simple task. Secondly, we will obtain single column model forcing data from Roel Neggers, which will remove our need to use tendancies. I will identify more cases over which to run the model and the same sensitivity tests will be carried out on these cases in order to get better statistics of the cloud changes resulting from the model changes. From this we will try to infer what the most important processes in mixed-phase cloud formation and persistence are and then understand why models can't represent them and how this can be improved.

The observational work will be extended so as to look at more of the available data. This will then be extended to include a more objective measure of the conditions rather than the subjective approach currently used.

Use spaceborne radar and lidar to investigate global distribution of mixed-phase clouds.
After investigating the possibility of using the spaceborne radar and lidar on the A-train, CloudSat and CALIPSO, it now seems unlikely that this will make up any part of my PhD work. Much of the analysis that I had planned to do, including looking at the global distribution of mixed-phase clouds, has or is being performed by Julien Delanoe here in the Department. However, I may still look at why the global mixed-phase cloud distribution is as it is.

Case studies of days with scanning radar and in-situ aircraft observations.
This has not yet been performed - I still plan to look at this in the future, maybe when I have more specific questions that I would like to be answered by doing so.

Running and modifying a large eddy simulation model and other single column models.
The idea of modifying and running a large eddy simulation model has not progressed since the last meeting. At present it seems the time and effort involved in doing such a task may not be the best use of my time. We currently do not have a particular hypothesis which we are trying to test by doing this. Instead of running LES models, a preferable option is to run other single column models based on GCMs. Probably we will run the Met Office Unified Model Single Column Model and there is also the possibility of spending some time at the ECMWF running their Single Column Model. This will give us the opportunity to test the performance of my model in a fairer way - if we can use the same forcings - rather than testing against full GCMs which have the advantage of having a 3D domain and advection. Also we can try to modify these Single Column Models to get a better representation of mixed phase clouds and to see what affect changing important parameterisations has on the cloud scheme. This potentially provides a quick way into full GCM experiments.

4 Transferable Skills

In the past 6 months I have attended both the RMetS main conference and student conference. At the main conference I presented a poster on work from my undergraduate project - which has since been published in GRL (Barrett et al., 2009). I have given talks in both Chapa Club and Radar Group this term about my work so far and have also attended collaboration meetings for the APPRAISE-Clouds project and for model evaluation using remote sensing. Both of these meetings enabled me to discuss my work with others in the field and to meet other people doing similar work to myself. I have continued attending external and departmental seminars; however, have missed a number of external seminars this term due to clashes with demonstrating. In addition, I am on the organising committee for Kerry Emanuel's visit in January, I continue to be a 2nd year representative at the HDR forum. I have also improved my time and people management skills by directing the Met Department Pantomime.

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