2nd Monitoring Committee Report
THE ROLE OF MIXED-PHASE CLOUDS IN CLIMATE

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1 Introduction

Mixed-phase clouds, that is clouds containing condensate in both liquid and solid form, are currently poorly understood and poorly represented in numerical forecast models (Gregory and Morris, 1996; Mitchell et al., 1989). The difficulty in modelling these clouds is discussed later, but they are important to model correctly for a number of reasons, but primarily due to the relative radiative importance of liquid phase water at cloud top.

Mixed-phase clouds were first observed and measured in the 1950s (Rauber and Tokay, 1991), and since then many mixed-phase clouds have been reported and observed, both convective and stratiform mixed-phase clouds have been recorded. Supercooled liquid is observed to form in narrow layers at the top of ice clouds. This is easier to observe in stratiform clouds with the aid of ground or satellite based remote sensing instruments (particularly lidar and radar) but they also occur in convective clouds. The supercooled layers, a couple of hundred metres deep or less, topping stratiform ice clouds can persist for a number of hours and in some cases days.

Due to their nature, these supercooled layers have a large affect of the radiation budget. The supercooled liquid droplets exist in greater numbers of smaller drops than the equivalent water content in ice phase would. As a result, the liquid layer is much more reflective of solar radiation and thus increases the albedo of the cloud. Climate models have been shown to be sensitive to the model formulation of mixed-phase clouds (e.g. Gregory and Morris, 1996; Li and LeTreut, 1992; Senior and Mitchell, 1993; Sun and Shine, 1995; Mitchell et al., 1989) which can have a large impact on the climate sensitivities of any given model.

A number of current model parameterizations use a simplified temperature dependent split of the liquid and ice water contents in mixed phase clouds (e.g. Tiedtke, 1993). They assume at 0 °C that all condensate is liquid, and that below a threshold temperature it is all ice. Currently the threshold temperature ranges between -15 and -40 °C. Between these two temperatures the ratio of liquid to ice is determined only as a function of temperature. Parameterizations of this type mean that it is impossible for models to represent the vertical distribution of liquid and ice in mixed-phase clouds that matches the distribution we see from observations.

More recently some models have included ice water as a prognostic variable and hence parameterizations have been developed to treat cloud liquid and ice separately (e.g. Wilson and Ballard, 1999; Rotstayn et al., 2000). These parameterizations deal better with mixed-phase clouds, but still struggle to represent them accurately due to the small spatial scales on which they occur.

Ice crystals can grow at the expense of liquid in a cloud through the Bergeron-Findeison mechanism. This occurs because the saturation vapour pressure over ice is lower than that over water. The water vapour in the cloud then preferentially deposits on to the ice crystal instead of the liquid drop. This reduces the water vapour in the air below its saturation value, therefore liquid evaporates to restore the air to saturation. This mechanism therefore suggests that cloud containing both liquid and ice should become totally glaciated on timescales of tens of minutes. This is not generally what we see happening in observations of persistent mixed-phase clouds, and therefore there must be other mechanisms at work. Figure 1 shows an example from earlier this year of persistent mixed-phase clouds over Chilbolton. The lidar sees persistent layers of supercooled liquid between -10 and -20°C throughout most of the day.

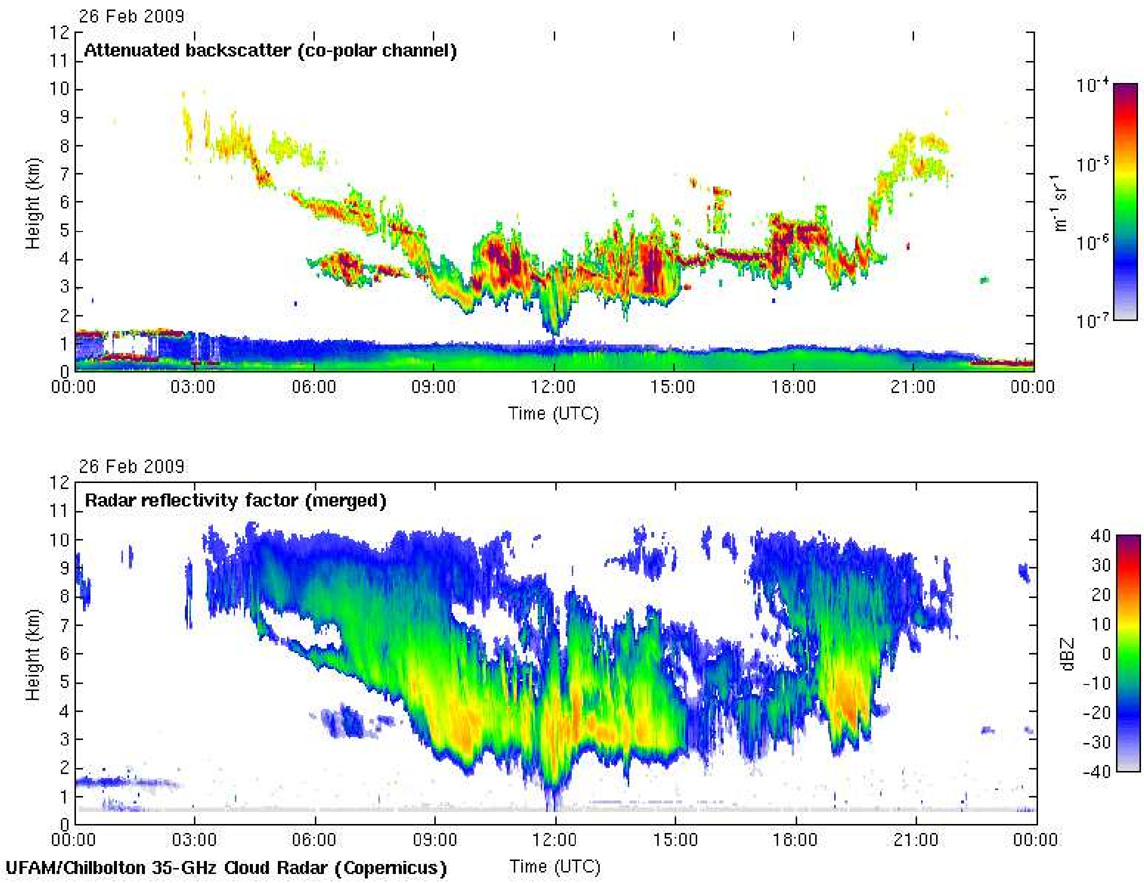

Figure 1: Plots showing lidar and radar returns over Chilbolton on 26 February 2009. The upper figure shows lidar backscatter, and thin layers of strong returns are from liquid water. The lower figure shows the radar returns, which are largely dominated by cloud ice. You can see in the top figure that supercooled liquid is present throughout most of the day. Temperatures range between -10 and -20°C in regions where supercooled liquid was observed.

Reasons for the persistence of supercooled liquid layers have been theorised, and currently accepted in literature are the theories of Rauber and Tokay (1991) and Korolev and Field (2008). Both theories are essentially the same, stating that with sufficiently strong updrafts ($\sim$0.4 m/s) over sufficient vertical distances ($\sim$100-200 m), that air can be brought to liquid saturation despite the preferential growth of ice crystals. This is the same as saying that the vertical transport of moisture must exceed the bulk ice mass growth rate, leading to an excess of liquid water. The mechanisms by which these updrafts form in stratiform cloud are not well understood, but could be as a result of:

- cloud top radiative cooling leading to negative buoyancy at cloud top.
- wind shear driven turbulent mixing.

- gravity waves giving periodic vertical motion sufficient to bring some air to liquid saturation - as is the case in mixed-phase mountain wave clouds (Field et al., 2001).
- a combination of the above or another, unknown, source.

It is also a possibility that the liquid layer persists due to a shortage of ice nuclei in that region. This shortage could be due to a naturally low concentration, or because the ice nuclei have been depleted by prior ice nucleation and the ice crystals which have subsequentally formed have now fallen from the layer. Certainly the ice crystal size at cloud top will be very small and if only a small number of nuclei exist, the growth rate will be limited by their small size. The growth rate of an ice crystal as defined by Rogers and Yau (1988), and used in the Rotstayn et al. (2000) and Wilson and Ballard (1999) parameterizations, is:

$$\frac{\mathrm{d}M_i}{\mathrm{d}t} = \frac{4\pi C(S_i - 1)}{\frac{L_s}{K_a T}\left(\frac{L_s}{R_v T} - 1\right) + \frac{R_v T}{\chi e_{si}}} \quad , \tag{1}$$

where M_i is the mass of a single ice crystal, C is a capacitance term, which depends on ice crystal shape, $(S_i - 1)$ is the supersaturation ratio with respect to ice. L_s is the latent heat of sublimation, K_a is the thermal conductivity of air (= 0.0224 $\mathrm{Jm^{-1}s^{-1}K^{-1}}$ at -20°C), χ is the diffusivity of water vapour (in $\mathrm{m^2s^{-1}}$, at -20°C this is $1.91/p$ where p is pressure in Pascals) and e_{si} is the saturation vapour pressure over ice. The Rotstayn parameterization initialises ice crystals with a mass of 10^{-12} kg and a typical ice nuclei concentration of 10^4 $\mathrm{m^{-3}}$ at -20°C. Using these values, a capacitance based on a flat plate and a pressure of 700 hPa, we find that 0.1 g $\mathrm{kg^{-1}}$ of liquid can become glaciated in 12.5 mins and 1 g $\mathrm{kg^{-1}}$ of liquid will have depleted in favour of ice in 40 mins, yet observations show these liquid layers persisting for much longer.

The aim of this research is to understand when and how mixed-phase clouds form, what their radiative impact is, which of these processes are important in the maintainence of supercooled liquid layers atop ice clouds and how we can improve numerical models and GCMs to better represent this phenomena. A number of questions which I aim to answer in the course of this research have been identified. These are:

1. "When and where do mixed phase clouds form relative to mid-latitude systems?"
2. "What are the most important processes in maintaining layers of supercooled liquid atop ice clouds?"
3. "What, in the large scale, determines if they form or not and can we distinguish between times when mixed-phase clouds form as opposed to times when the clouds remain glaciated?"
4. "How can supercooled layers persist when there is cloud immediately above the supercooled layer?" - as radiative cooling will be inhibited and falling ice crystals should deplete the liquid.
5. "Why are mixed-phase clouds poorly captured in models and how can their representation be improved?"

2 Work to date

2.1 Modelling

As of the last monitoring committee in December, I had started developing a single column model with which I aimed to test the sensitivity of mixed-phase clouds to a number of different physical processes through experimenting with different parameterizations. The model contained two prognostic variables; the first is θ_L, the liquid water potential temperature, which is conserved in reversible wet adiabatic motion (Betts, 1973) and defined as:

$$\theta_L \approx \theta - \frac{L}{c_p}\frac{\theta}{T}q_l \quad , \tag{2}$$

where L is the latent heat of vapourization of water and q_l is the liquid water mixing ratio. The second prognostic variable was q_t, the total water (vapour plus liquid) mixing ratio. The model could advect and diffuse these quantities, but did not yet have the ability at simulate the atmospheric evolution in a physically realistic way.

Since the last committee meeting the model has developed further, so that it can behave in a more physical way. Additions to the model since January include:

1. Three additional prognostic variables. u and v, the horizontal wind speeds which change due to an imposed pressure gradient force, and q_i, the ice water mixing ratio. The model now has five prognostic variables in total: u, v, θ_L, q_t and q_i.

2. A local mixing scheme based on Louis (1979) in included. This determines the local stability through calculation of the local Richardson number and then assigns a vertical diffusivity coefficient based on the Richardson number. This is applied where the model is locally stable (Ri$>$0).

3. Where Ri$<$0 a non-local mixing scheme based on Lock et al. (2000) is used. This parameterization is applied throughout the depth of the troposphere, not just in the boundary layer for which it was formulated. Cloud top radiative cooling destabilises a parcel at cloud top which then descends to its level of neutral buoyancy. A diffusivity profile is determined based on the strength of destabilisation and the depth through which the destabilised parcel sinks. Cloud top entrainment rate has been modified from the original parameterization such that surface heat fluxes and friction velocities are not included. The validity of this alteration still needs to be determined.

4. Calls to the Edwards-Slingo radiation scheme which is called using a Matlab function (I have had no dealings with the radiation coding). The radiation scheme is called regularly (currently between 5-45 timesteps (3-30 minutes), depending on how quickly I wish the model to run). Radiative heating and cooling rates are then applied to the temperature field for all time steps until the next radiation call. The model also has a relaxation term which allows the temperature to tend towards a prescribed temperature to prevent the mid-levels of my model cooling too quickly in clear sky conditions.

5. Ice nucleation parameterization based on Meyers et al. (1992), which at sub-freezing temperatures gives an ice nuclei concentration based on the supersaturation of the air with respect to ice.

6. Ice growth by deposition (Bergeron-Findeison mechanism) based on Rotstayn et al. (2000). This is a physically based scheme very similar to Wilson and Ballard (1999) which is used in the UK Met Office Unified Model, where the rate at which ice mass increases in a grid box is determined by the ice nuclei concentration and pre-existing ice mass. Each ice crystal is assumed to be identical and the individual growth rate is calculated using a well established growth by deposition equation (eq 1).

Figure 2 shows a schematic overview of all the microphysical processes treated by a prognostic cloud scheme. The figure is taken from Rotstayn et al. (2000) and modified such that the solid lines refer to processes in my single column model whereas broken lines are not included. My model has no autoconversion of liquid to rain as the water contents which we look at are not high enough to start any warm rain formation processes. Any falling ice currently does not grow by accretion of liquid water (this will be important when looking at multi layer clouds), and any melting ice is removed (equivalent to assuming it falls to the surface as rain in one time step).

The model can run after being initialised either by model data or from atmospheric soundings and then is currently run for a 24 hour period with a timestep of 40 seconds. It uses GCM forecast model winds (currently ECMWF, although others are also available to use) to infer pressure gradient forces (assuming the model winds

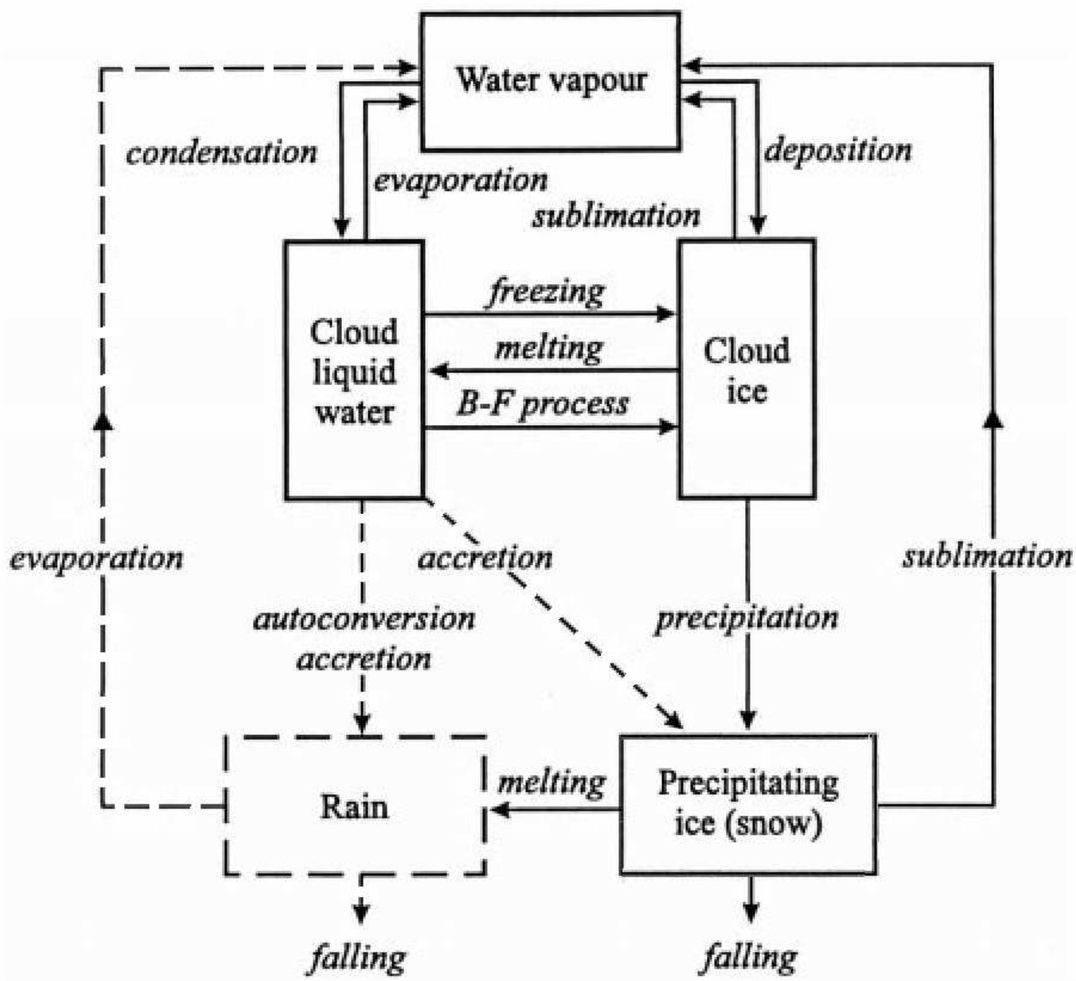

Figure 2: A schematic figure modified from Rotstayn et al. (2000) to show the microphysical processes included in my model (solid lines) and those included in full cloud schemes but not included in my model (broken lines). My model runs with fewer prognostic variables than shown here; the water vapour and cloud liquid water are combined in the q_t term and the cloud ice and precipitating ice are combined in the q_i term.

are geostrophic) but then allows the horizontal winds to vary. The vertical wind is prescribed from the model for each hour. The model outputs variables including cloud liquid and ice water contents.

2.2 Experiments with model

Figure 3 shows an example of model output liquid and ice water content for three different model runs. The runs are based on an idealised situation where a thin layer of air reaches liquid saturation at about 6000 m, where the air temperature is -31 °C. The three simulations vary only the concentration of ice nuclei, with the first simulation (panels a and b) having 1/100th of the ice nuclei concentration from the Rotstayn parameterization. The second simulation (panels c and d) has 1/10th of the parameterized concentration and the third simulation (panels e and f) has an unmodified parameterization. It can be seen in the figures that with fewer ice nuclei, a longer lasting thin layer of liquid water is observed. Fewer ice nuclei mean that the small ice crystals that nucleate cannot deplete all the liquid water before falling from the supercooled liquid layer. The simulation with fewer ice nuclei also have a more persistent ice cloud, although the ice content of the cloud is lower that simulations with higher nuclei concentration. This demonstrates one possible mechanism by which supercooled liquid layers may persist. If ice nuclei are depleted from a layer when nucleated crystals fall, ice may not be able to form so readily later on and will limit the ice growth (and hence liquid depletion) rate.

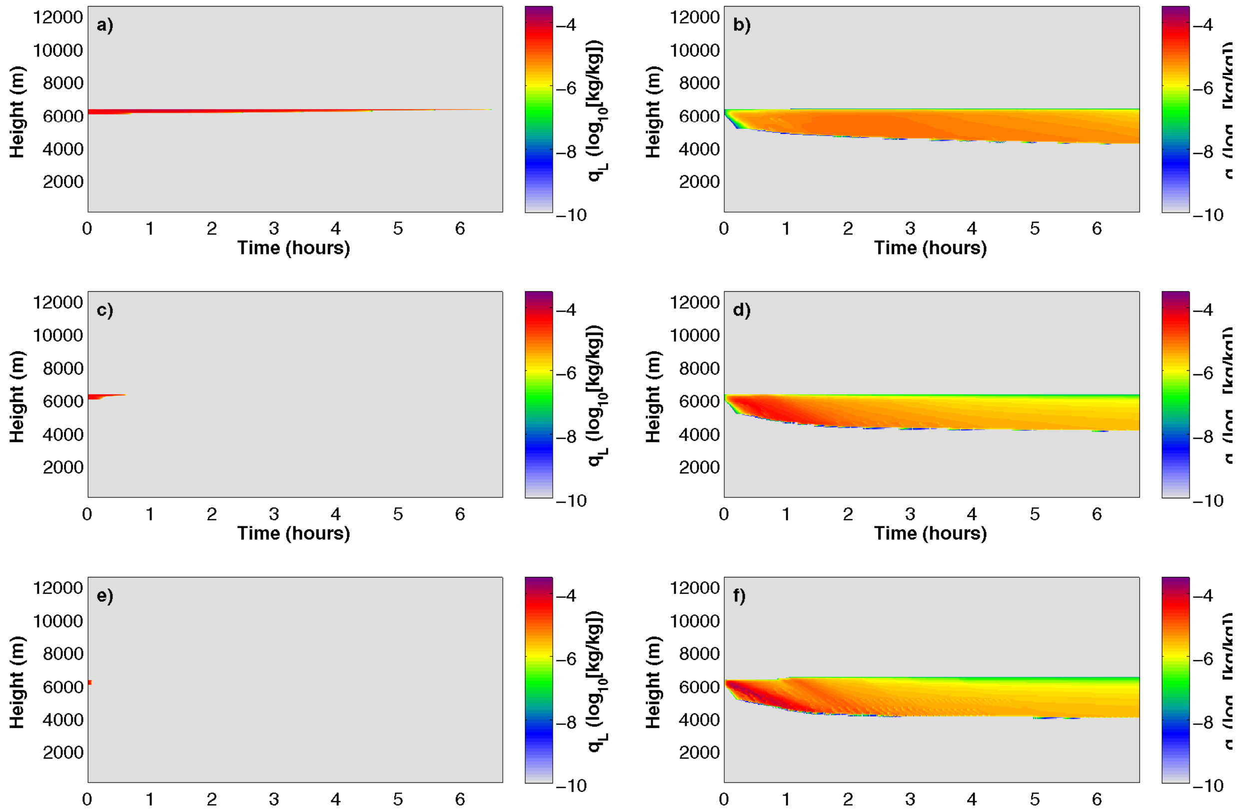

Figure 3: Comparison of model performance for three different formulations of ice nuclei concentration. Panels a) and b) show liquid and ice water mixing ratios for a simulation using the Rotstayn parameterization, but with ice nuclei concentration 1/100th of parameterized value. Panels c) and d) are the same except using 1/10th of the parameterized value and panels e) and f) using unmodified parameterization.

2.3 APPRAISE field campaign

I have spent time helping out with the APPRAISE field campaign between January and March. The APPRAISE project is investigating the initiation and development of ice in mixed phase clouds; how aerosol is important in microphysics, dynamics and precipitation processes and aims to try and reduce the uncertainty in the radiative indirect effect by better understanding mixed-phase clouds. To achieve this improved understanding APPRAISE is using modelling, but also observations using radar, lidar and in-situ aircraft observations. I spent about 5-6 days at Chilbolton operating and scanning the radar whilst the Met Office FAAM aeroplane was taking in-situ observations of mixed-phase clouds. The aeroplane was taking measurements of temperature, liquid and ice water contents, aerosol concentrations and was sampling the ice crystals using a CPI (Cloud Particle Imager) probe, to get an idea of size, shape, concentration and habit. It was good to experience the process of obtaining data by field experiments as well as being part of the decision making process and guiding the plane to specific areas of interest as we identified from the radar scans. Several of the days for which I was at Chilbolton were very interesting days in terms of mixed-phase clouds and should lend themselves to interesting case studies in my future work.

2.4 Paper Submitted

In addition to the work above, I have also completed writing my paper for Geophysical Research Letters on my undergraduate dissertation work entitled “Evaluating forecasts of the evolution of the cloudy boundary layer using diurnal composites of radar and lidar observations”, the paper was submitted on 04 May 2009 and is currently being peer reviewed.

3 Current and Future Work

The model is currently at a stage where all of the required physics is implemented. A couple of quick changes need to be completed before moving on to use the model to conduct a number of experiments. The advection scheme needs a quick change to improve the numerical accuracy. Also, the Rotstayn parameterization for ice growth rates has some strange behaviour when the air is between liquid and ice saturation and needs to be modified.

When this has been completed, I will set up an idealised case where the model is initialised with data that allows mixed-phase clouds to form and persist. The model will then be adapted in a number of ways, by changing parameterizations, time step, resolution, frequency of radiation scheme calls to investigate the sensitivity of the mixed-phase cloud and its persistence to each possible contributing mechanism.

The model will also be used in a similar way but initialised using observed and model data to determine how the model performs and whether, with changes to parameterizations, it can perform better than current GCMs over a well instrumented site. There are a number of ways to determine if my model is performing better, these are:

- 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).
- Creating new metrics for model performance to get objective measures of model performance from long-term model runs.
- 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.
- Comparing radiative fluxes at the surface and top of atmosphere.

To a large extent the future direction of this project will be determined by what is learned from the modelling section. If particular interesting issues are raised by the modelling then they will obviously be pursued further. However, without knowing such things at the present time a number of possibilities for further routes of investigation have been outlined. These include:

Study of observed mixed-phase clouds using long term radar and lidar data from Chilbolton. To answer the question “When and where do mixed phase clouds form?” I will identify times when mixed-phase clouds are observed by the vertically pointing radar and lidar at Chilbolton and see if there is a preference for formation and maintainence in particular weather regimes. I will do this initially by studying synoptic charts and other model output in a subjective way, to get an idea for when and where supercooled layers form. Then a more objective method using large scale variables to better define mixed-phase clouds’ prefered regimes. For instance, are they related to approaching frontal structures, or do they form in calmer times between the passage of fronts? This approach can then be extended to include sites other than Chilbolton. Sites in the United States and Pacific, part of the Atmospheric Radiation Measurement (ARM) programme can be used to provide supporting evidence and also determine if this is a mid-latitude phenomena or whether mixed-phase clouds are also observed in the tropics and further north in Alaska. Mixed-phase clouds have been observed in Alaska as part of the SHEBA field campaign (Shupe et al., 2006) but are often a boundary layer phenomena.

Use of spaceborne radar and lidar to investigate global distrubition of mixed-phase clouds. Previous work by Hogan et al. (2004) using spaceborne lidar found a much greater frequency of occurrence of supercooled liquid layers in the southern hemisphere storm track than in the northern hemisphere. Reasons for this are unclear but may be related to a reduced pollution level or the lack of land in the southern ocean. The global distrubiuton of mixed-phase cloud could be investigated using data from CloudSat and CALIPSO on the A-train of satellites and we could try and answer the question of why this is the case.

Running the model I developed over a long period. By running my model over an extended period ($\sim$1 year), whilst being forced with pressure gradients derived from GCM winds and tendency terms for our other prognostic variables, we can examine whether it provides an improvement upon current GCM formulations. The radar and lidar observations can be forward modelled, given a few assumptions, to produce output similar to what would be seen if the model environment were to be sampled by a radar and lidar. This would then allow an easier method of model evaluation using observed data. It is then hoped that we can demonstrate that my model, with a better representation of the physics, performs better than GCM output over an extended period of time.

Case studies of days with scanning radar and in-situ aircraft observations. An in-depth investigation of one or two days where particularly interesting mixed-phase clouds were present and intensively observed. Once we have knowledge of what the important factors might be from the modelling, we can attempt to explain the formation and evolution of the observed mixed-phase clouds using this understanding and the observations we have obtained.

Running and modifying a large eddy simulation (LES) model. The possibility exists to run a large eddy model to attempt to model mixed-phase cloud persistence over a larger domain. A LES model may give us a new insight in to how these mixed-phase clouds form and persist as the model includes a better representation of the small scale motions and in particular entrainment, which may be important. With turbulent processes likely to be an important part of mixed-phase cloud persistence, large eddy simulations would be a sensible idea. This is currently less likely to be attempted due to the time required to understand large eddy modelling and running the model successfully, although collaboration with John Marsham may be a way around that.

4 Training and Transferable Skills

Since the last committee meeting I have completed writing up my paper on my undergraduate research and submitted to Geophysical Research Letters, I have also given a talk on this research to Chapa Club and will be giving a poster presentation at the RMetS Main Conference.

In addition, I have spent 9 days at the ECMWF on a training course "Parameterization of Diabatic Processes" which was very useful. Over the course of the 9 days I had numerous lectures and problem classes on parameterization subjects such as: radiation, moist processes and clouds, convection, surface and boundary layer, orography, gravity waves, land surface and data assimilation. I found the course very interesting and useful. I now feel that I have a good understanding of how parameterizations are formulated and implemented and why they are necessary. Not much of the course is directly applicable to my current modelling work, but has definitely been useful in understanding parameterization papers that I have read and in discussion with other modellers. Overall the course was excellent, both as a means of learning about parameterizations but also to meet people (both course lecturers and students) who are engaged in similar fields of research and to discuss ideas with them.

I will also be giving a presentation at the RMetS Student Conference on the work I have completed so far. I am also presenting, attending and helping as IT support at the main conference which will hopefully give me further opportunity to network and discuss work with others in a similar field.

I have not formally been assessed on any departmental courses, although I did attend the Remote Sensing course as it was relevant to my work. Additionally, I attended the GSDP course on Effective Time Management and Planning which I found very useful to concentrate the mind on aiming to complete and submit a thesis within 3 years. Furthermore, I have continued attending lunchtime seminars and radar group meetings as a matter of personal interest and keeping up with current research. I also occasionally attend relevant boundary layer group meetings.

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