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THE MICROPHYSICS OF DEEP FRONTAL CLOUDS OVER THE UK

T. W. Choularton[1]*, Vaughan T. J. Phillips[1+], P. Clark[1], K.N. Bower[1], A.J. Illingworth[2], R.J. Hogan[2] , P.R.A. Brown[3] and P.R. Field[3]
[1] Physics Department, UMIST, Manchester, UK
[2] Department of Meteorology, University of Reading, UK
[3] The Met office, UK

1. INTRODUCTION

An investigation into the nature of glaciation in mixed-phase stratiform layer-cloud is presented in this paper. The glaciation in stratiform cloud is an important process to parametrise accurately in global climate models for several reasons. Glaciation in such cloud appears to be fundamental to the production of precipitation. Most of the surface precipitation in mid-latitudes falls from frontal layer-cloud. The Bergeron-Findeisen process promotes the efficient formation of precipitation embryos in mixed-phase layer-cloud. This mechanism involves the deposition onto ice crystals of vapour evaporated from cloud-water. Also, the optical depth and effective particle radius influence the radiative properties of a cloud, depending on rates of nucleation and growth of ice crystals. Finally, the release of latent heat during glaciation has a marked effect on the dynamical evolution of layer-cloud.

Bower *et al.* (1996) observed high concentrations of ice crystals near the -6 ^{o}C and -15 ^{o}C levels in extra-tropical frontal stratiform cloud. These concentrations exceeded the expected concentrations of primary ice nuclei (IN) by orders of magnitude. The Hallett-Mossop (H-M) process of ice particle multiplication (Hallett and Mossop 1974) is one possible mechanism that has been proposed to account for such high crystal concentrations. During the riming of large droplets onto ice particles, fragments of ice are seen to be emitted at temperatures within the range of -3 to -8 ^{o}C in laboratory experiments.

The efficiency of the H-M process depends on the abundance of supercooled cloud-water. Very low values of vertical air velocity of a few cm sec^{-1} prevail over most of the area of a typical frontal cloud. Such a low rate of ascent is insufficient to support large cloud-water contents because the low rate of supply of vapour to subzero levels does not maintain a supersaturation that is high enough for much condensation to occur. However, there are usually cells of convection embedded within stratiform layers. Ascent of cloudy air in these cells augments the supply of cloud-water for riming and H-M splinter production.

Mixed-phase stratiform cloud is often characterised by high rates of production of snow from the aggregation of ice over long time-scales. Slow-falling snowflakes have not been given much focus in laboratory studies of the H-M process hitherto. Saunders and Hosseini (2000) have observed H-M splinter production at terminal velocities > 2 m s^{-1}; much less is known about the H-M process at lower fall-speeds than this. Snow generally has fall-speeds of less than 2 m s^{-1} (see Rogers and Yau, 1991). In this paper a number of cases of mixed-phase stratiform over Chilbolton in the UK that were observed by aircraft and polarisation-diversity radar (Hogan *et al.* 2002) are utilised for dynamical and microphysical simulations using the Met Office Cloud Resolving Model (Derbyshire et al 1994) using parameterised microphysics. In one case a detailed simulation of the microphysicalprocesses was performed using an Explicit Microphysics Model (EMM). This latter model includes a detailed representation of the H-M process and of the trajectories and growth of ice particles. The model predicts some radar properties of the cloud for comparison with observations. Simulated radar properties include the differential reflectivity, Z_{DR}. This quantity increases monotonically with the non-sphericity, bulk density and degree of alignment of the scattering particles.

The overall aim for the microphysical modeling in the present paper is:- (1) to define a dynamical environment which is a realistic representation of what was observed and to investigate the effects of the cloud microphysics on the cloud dynamics; (2) to examine whether certain combinations of microphysical processes acting within this dynamical framework are capable of reproducing some of the key microphysical characteristics as

* *Corresponding author address*: Tom Choularton, Physics Department, UMIST, P.O. Box 88, Manchester M60 1QD, UK ; email T.W.Choularton@umist.ac.uk

observed by aircraft and dual-polarization radar; and (3) to outline the salient dependences of the mixed-phase microphysics on important characteristics of the large-scale environment.

2. THE EXPLICT MICROPHYSICS MODEL

The EMM developed by Phillips (2001) is an extension to the 1-D Multi-Thermal Model (MTM) of cumulus glaciation by Blyth and Latham (1997). Fully interactive components for vapour, cloud-water and rain, as well as aggregation of ice, heterogeneous and homogeneous freezing, melting, simulated radar properties and the evolution of crystal shape (or 'habit') during particle growth are some of the new processes incorporated into the EMM by Phillips.

A detailed representation of the cloud dynamics is prescribed as an input for the prediction by the EMM of the microphysical development of the cloud. For the present study, the EMM has been further modified to incorporate a representation of the surrounding cloudy region (SCR) of weak ascent outside the single updraught. In contrast with previous EMM simulations of glaciated cumuli, raindrop production by coalescence is prohibited. Both the observations and the runs with the Cloud Resolving Model suggest that this is an appropriate assumption for the clouds studied.

3. REALISTIC DEFINITION OF CLOUD DYNAMICS AND ENVIRONMENT FOR MODEL

The case simulated by the EMM control simulation is a lightly precipitating stratiform cloud observed by the 3-GHz polarisation-diversity radar at Chilbolton in England on 30 March 1999 (see Hogan *et al.* 2002). *In situ* measurements were made at 12:14-12:44 UTC on the UK Met Office C-130 aircraft. During this time period, Lagrangian figure-of-eight patterns were flown between the –5 and –11 ^{o}C levels following a region of embedded convection that was being advected towards the north east. The aircraft sounding shows that cloud top was near the -15 ^{o}C level, which corresponds to a Mean Sea Level (MSL) altitude of about 4.3 km. The cloud base is located at about 1 km MSL, not far below the freezing level at 1.8 km MSL.

The radar velocity data indicate a uniform vertical shear of the horizontal wind of 5 m s^{-1} km^{-1} for this case. Maxima in radar reflectivity (*Z)* above the freezing level were seen to be advected by a mean flow with an average horizontal velocity of about 1 km min^{-1}. Such *Z*-maxima ascended through the frontal cloud as maxima of vertical air velocity inside thermals. These vertically elongated `turrets' were about 1 km in size. The intensity of the bright-band at 1.8 km MSL suggests that the high *Z* values seen in thermals at subzero levels were caused by the presence of low-density, aggregated snowflakes.

The C-130 aircraft measured vertical air velocities with peak values of 1 - 2 m s^{-1}. The Particle Measuring System (PMS) probes on the aircraft were the Forward Scattering Spectrometer Probe (FSSP), and the 2D cloud and precipitation probes (2D-P and 2D-C) probes. The FSSP probe provided only an approximate estimate of the droplet concentration since over-counting of droplets may occur when large ice particles are present (see Gardiner and Hallett 1985). High concentrations of small ice crystals were observed with these probes in and above the turrets. Supercooled cloud-water and rimed ice particles were observed in the turrets, reflecting the possibility of an active H-M process.

The area surrounding the turrets was seen to consist of:- (1) one or two slanted streaks of high differential reflectivity (Z_{DR}) of about 3 dB in which high concentrations of pristine columns with Axial Ratios (AR) of *5* were observed *in situ*; (2) ubiquitous low-Z_{DR} values later on owing to the presence of large quasi-spherical aggregates. Radar data only yields information about the largest particles present in a given region (Rogers and Yau 1991). The aggregates are also expected to have depleted the pristine columns by aggregation. Near cloud top, plumes of very high-Z_{DR} of up to 7 dB were seen to spread out into horizontal layers due to the growth of planar crystals; columnar crystals can never attain values higher than 4 dB.

The UK Met Office analysis for 1200 UTC on this day is presented by Hogan *et al.* It shows that the low-level isobars near the cold front over southern England are oriented in the south-westerly direction, extending from the Atlantic ocean towards Scandinavia. These isobars are to the south of two cyclonic minima in pressure. The geostrophic component of the low-level flow is south-westerly. Indeed, the mean wind observed by the aircraft was from the 215^{o} direction. Although no *in situ* observations of the CCN concentration were performed at Chilbolton, the synoptic observations suggest that the airmass sampled in this observed case was probably maritime.

4. MAIN RESULTS

Applying the Met office cloud resolving model to this cloud showed that the convective turrets were due to conditional instability prevailing in the cloud. The EMM was run using the observed dynamical framework.

The purpose of the EMM is to provide a detailed representation of the evolution of crystal properties as particles grow from a pristine state into either graupel, snow or rimed aggregates. This representation is possible because the trajectories of individual particles spanning a spectrum of sizes are traced through the cloud. Essentially, it allows the differential reflectivity - a function of both particle shape and bulk density - to be predicted explicitly. Either the observed dynamical framework or that predicted by the Cloud Resolving Model can be used

Satisfactory agreement was generally found between the EMM control simulation and observations of the stratiform cloud case with radar and aircraft data. The predicted properties of ice particles are explicable in terms of:- (1) the sequence of temperature-dependent habits for vapour depositional growth encountered by individual particles; and (2) their history of growth by accretion and riming. Predicted values for the crystal properties of bulk density and axial ratio are consistent with results from laboratory studies summarised by Pruppacher and Klett (1997). The instantaneous maximum value of the ice concentration near the centre of the H-M region is correctly predicted to be between two and three orders of magnitude higher than the primary ice concentration near cloud top. The time-averaged total ice concentration displays a maximum average value of 200 L^{-1} at this level in the EMM control, which is of the correct order of magnitude. Thermals are predicted to be radar-visible as ascending maxima and minima of Z_H and Z_{DR} respectively, as is seen in the polarisation-diversity radar observations. Scarcely any adjustment of input parameters had been performed prior to performing this preliminary control simulation.

Naturally, the agreement between microphysical predictions and observations is not expected *a priori* to be quantitatively exact in all respects. It suffices to predict correctly the order of magnitude for quantities such as the concentration of a microphysical species. Firstly, it was not possible to measure absolutely all the properties of the environment and cloud dynamics during observations for the case study at Chilbolton. Estimates have necessarily been made of the concentrations of CCN and IN by applying standard literature values. Only the order of magnitude of nucleus concentrations at mid-day on 30 March 1999 at Chilbolton may be inferred with such estimates, since such quantities tend to vary widely for any given type of airmass. Additionally, the updraught strength at cloud base was not observed on this day. The value of vertical air velocity in the SCR is so close to zero that only its order of magnitude may be inferred from the aircraft observations. Furthermore, a high value of the vertical wind shear was measured in the environment for this case. The physical dependences of thermal entrainment on the shear and stratification of the ambient fluid appear not to have been fully quantified in laboratory studies in the literature. Hence, it appears that only the order of magnitude of b_E in the real cloud may be inferred reliably from laboratory data. Secondly, multiplicative processes and positive feedbacks are expected to be present in a complex web of microphysical interactions occurring within real mixed-phase cloud.

The peak in average ice concentration seen near the centre of the H-M region in aircraft observations of the Chilbolton case is accounted for by the detailed representation of the H-M process in the EMM control simulation. Similarly, a peak of the ice concentration in the H-M region was seen in aircraft observations by Bower *et al.* (1996). Overall, the H-M process in the EMM control simulation was found to be more active in thermals than in the SCR due to a higher cloud-water content supported by the more rapid ascent. In particular, the hypothesis that slow-falling snow and aggregates may produce H-M splinters appears to have produced a satisfactory control simulation.

Mason (1996) suggested that a different peak in ice concentration observed by Bower *et al.* at the -15 ^oC level was caused by the accumulation of H-M splinters near the cloud top following their formation in the H-M region. The present study shows that Mason's hypothesis is at least plausible, although no such peak is predicted in the particular cloud simulated in the EMM control. In the dynamical framework of this particular simulation, H-M splinters ascend and then fall out of thermals before the cloud top is attained. Fragmentation of fragile dendritic crystals - either mechanically or during sublimation - seems difficult to eliminate as a possible alternative explanation for the peak at -15 ^{o}C observed by Bower *et al.*

Primary ice was found to dominate the simulated radar properties of the model cloud. Realistically high values of Z_{DR} of up to almost 4 dB were predicted by the EMM near the cloud top in the SCR of the control simulation. This peak was caused by primary crystals growing in the dendritic (planar) regime by vapour deposition in the model. Such crystals are highly non-spherical. Similarly, high values of Z_{DR} of up to 4 dB were observed near the cloud top level and were attributed to large dendritic crystals in observations of another case of precipitating stratiform by Bader *et al.* (1987). The accumulation of supercooled cloud-water in the highest 200 m just below the cloud top in the EMM control simulation is typical of supercooled layers reported in observational studies of stratiform cloud. Such cloud-water aloft promotes the dendritic growth of crystals by vapour deposition in the simulation by maintaining water saturation.

Individual slanted regions of high total $Z_{DR} > 1$ dB are sometimes seen extending within the supersaturated environment towards the freezing level near turrets in radar observations of the real cloud (Figure 5, Hogan *et al.*, 2002). Such high-Z_{DR} regions are observed within only a limited fraction of the total volume of SCR and appear to be transient features. They are seen in the radar data partly because small H-M columns of high intrinsic Z_{DR} can avoid depletion by aggregation within gaps in the 3-D fall-out of large aggregates. Indeed, an anti-correlation between the total ice concentration and Z_H is evident in the EMM control at the base of the H-M region of the SCR, which is qualitatively consistent with this explanation. Also, such gaps in the real cloud might tend to `unmask' temporarily the intrinsic high-Z_{DR} signal from any small crystals such as H-M splinters that are present. The regions of high total Z_{DR} seen in the radar observations are not resolved in the SCR of the EMM control: the EMM treats the SCR as a 1-D channel and does not directly simulate in 3-D the inhomogeneous, turbulent flow of the real cloud. Nevertheless, the hypothesis by Hogan *et al.* (2002) that `high-Z_{DR}' features in the centre of the cloud may be caused by H-M splinters is qualitatively consistent with the model results. The EMM predicts fall-streaks of intrinsic Z_{DR} from H-M splinters with instantaneous values of up to about 2 dB in the H-M region of the supersaturated environment. H-M splinters are present in much of the SCR and almost all of the updraught in the control simulation. Their concentrations are orders of magnitude higher than the primary ice concentration.

Sensitivity studies were conducted by varying the concentrations of IN and CCN entering cloud base. These generally indicate that the concentration of aerosol particles in the environment has a major impact on the glaciation of the frontal cloud. Increasing the concentration of either IN or CCN acts to restrict the growth rates of droplets, diminishing the efficacy of the H-M process. Similarly, in previous EMM simulations of deep cumuli by Phillips (2001) and Phillips *et al.* (2001a,b) the CCN concentration was found to determine whether the droplet-size dependent H-M process is activated. In the present study, the total ice water content is reduced by lower rates of H-M splinter production in the continental case relative to the control; the suppression of the H-M process is more than counteracted by the growth of extra primary ice in the response of the ice water content when IN concentrations are augmented. Also, the precipitation rate below the cloud is found to increase markedly with the atmospheric IN concentration.

A key conclusion from the CCN and IN tests described here is that the liquid and ice water paths are significantly sensitive in the SCR to the environmental aerosol concentration. Furthermore, the peak in cloud-water content found near cloud top in the control simulation is completely eliminated by extra deposition of vapour onto ice when the IN concentration is increased by an order of magnitude. The total ice concentration is similarly sensitive to nucleus concentrations at upper levels. The cloud albedo and emissivity would be affected by such changes in particle concentration, effective particle size and water path for ice and cloud-water. In particular, the cloud albedo would be expected to be highly dependent on the intensity of the IN-sensitive peak in cloud-water content predicted near cloud top in the EMM control simulation. A major contribution to the global radiation budget comes from spatially extensive SCR regions of stratiform cloud. The appreciable sensitivity of mixed-phase microphysics in EMM simulations of frontal cloud is clearly of paramount importance for the cloud property feedback in global climate change.

In some other case studies use of the Cloud Resolving Model showed that vertical windsheer produced Kelvin –Helmholz billows that were responsible for the considerable spatial inhomogeneity of the cloud. The updrafts produced by the billows resulted in supercooled liquid water extending up to –10C . The cloud structure predicted by the model produced a predicted radar reflectivity pattern very similar to that observed. The cloud microphysics is found to strongly affect the distribution of ice and liquid water in the cloud. This in turn determines the pattern of latent heat release, which is very important in the cloud dynamics in all the cases studied

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