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Abstract

Forecasts of supercooled liquid water content produced by the new cloud and precipitation scheme in the mesoscale version of the Unified Model have been compared with in-situ observations made with the MRF C-130 aircraft. The purpose was to evaluate their applicability to the production of aircraft icing forecasts. Five flights were analysed from frontal cases and one made in supercooled stratocumulus. In the frontal cases, the forecast supercooled liquid water was confined to temperatures above –5°C, whilst it was observed down to lower temperatures. When supercooled liquid water was forecast it was nearly always observed. The extent of supercooled liquid water was underestimated even ignoring the temperature at which it was forecast.

In the stratocumulus case, with cloud-top temperature –5°C, the model forecast extensive supercooled liquid water because ice is not initiated by the new cloud scheme until the cloud-top temperature is below –10°C. Significant icing was observed on this occasion. It was concluded that the supercooled liquid water content forecasts could not be used alone to forecast aircraft icing. They could be used to delineate areas with a higher probability of icing. The temperature at which supercooled liquid water is forecast should be ignored and the maximum forecast value assumed to occur anywhere between zero and –16 to –20°C.

Contents

1. Introduction

Little work has been devoted to R&D into aircraft icing, especially forecasting for many years prior to the nineties. One reason may have been the introduction of large jets which are not particularly susceptible to icing because of their high cruise altitude and large reserves of power for anti-icing or de-icing measures. However, smaller aircraft and helicopters remain susceptible to icing and this motivated some mainly climatological studies in the 1980s. Although the increased sophistication of NWP models during the eighties led to forecasts of more weather elements being available directly from the models, little progress was made on icing.

During the nineties, the description of clouds in Numerical Weather Prediction (NWP) models has evolved from inferring the presence of cloud from relative humidity, to carrying total cloud water content (TWC), ie liquid + ice, as a prognostic variable. One method of diagnosing the separate supercooled liquid water content (SLWC) and ice water content (IWC) based on aircraft measurements (Moss and Johnson, 1994) is to assume that the ratio of liquid to ice is a function of temperature. The temperature-based UM scheme assumed the cloud is all water at 0^{o}C and all ice at -9^{o}C, with a linear variation between. More detailed cloud schemes are just starting to be introduced which produce explicit forecasts of IWC and SLWC eg Tremblay et al. (1995), Reisner et al. (1998), Wilson and Ballard (1999).

The techniques for deriving icing forecasts from NWP output have lagged behind the developments in model cloud schemes and current methods are based upon temperature and relative humidity thresholds. The threshold methods have been developed mainly in the USA, where a data base of pilot reports of icing (PIREPS) has been gathered. The PIREP data base has facilitated the training and evaluation of the algorithms. The performance of the threshold-based algorithms has been evaluated by Thompson et al. (1997), Brown et al. (1997) and Carriere et al. (1997). The consistent feature to emerge was that the algorithms which correctly forecast the location of a high proportion of the PIREPS did so by forecasting icing over a larger area. When the number of PIREPS correctly forecast was normalised by the area over which icing was forecast there was much less difference between the skill of the various threshold algorithms. Brown et al. (1997) concluded that further tuning of the thresholds is unlikely to yield much improvement. It would clearly be of benefit to both military and civil aircraft operations to be able to reduce the area over which icing is forecast whilst retaining a high probability of detection.

The logical way forward is to consider the use of explicit SLWC forecasts which are starting to be provided by the most recent NWP cloud and precipitation schemes. However, there are several factors which can lead inaccuracies in such forecasts, as will become apparent during the report, so a thorough evaluation is required. Brown et al. (1997) also evaluated explicit SLWC forecasts from the ETA model run at the USA National Center for Environmental Prediction. These were more skilful than threshold methods, when normalised by the area where icing was forecast. However, the explicit forecasts of SLWC only captured 30% of PIREPS on average and this may not be acceptable to customers.

Recently, a new cloud and precipitation scheme has been developed for the Met. Office's Unified Model (UM), Wilson and Ballard (1999), which predicts ice and cloud liquid water contents explicitly. The new scheme has been made operational in the mesoscale version of the UM. The availability of operational forecasts of SLWC provided an excellent opportunity to evaluate their usefulness as the basis of icing forecasts. The SLWC forecasts have been evaluated by comparison with in-situ aircraft measurements made by the C-130 of the UK Meteorological Research Flight. The scheme has also been evaluated by forming a one-month climatology of SLWC values for comparison with existing icing forecast algorithms and the icing atmosphere used for civil aircraft design as presented in FAA/JAA Appendix C. The results are described in a companion report, Steadman (1999). The results of the comparison with aircraft data are the subject of this report.

2. The New UM Cloud and Precipitation Scheme

The new UM cloud and precipitation scheme is based on that of Rutledge and Hobbs (1983) but with a few simplifications. In particular, cloud ice and precipitation-sized ice are treated as one variable (called snow). Rain is diagnosed and falls out in one timestep rather than being a prognostic variable which is advected like snow. Cloud forms initially as liquid water. The growth of droplets on CCN is not considered, sufficient cloud water condenses to remove supersaturation. Where knowledge of the cloud droplet concentration or size is needed this is specified explicitly or implicitly. All cloud water freezes at -40°C. Ice crystals are nucleated where cloud water exists somewhere within a model grid box. The concentration of ice nuclei is given by the Fletcher (1962) equation, which states that the concentration increases exponentially with temperature depression below zero. Because initial tests showed that the scheme produced too high a degree of glaciation when the cloud-top temperature was warmer than -10°C, no nucleation of ice is allowed until the cloud-top temperature is below this. However, such clouds can still become glaciated if ice fall into them from a separate cloud layer above.

Once ice has formed it can grow by vapour diffusion and by riming. The water vapour for the diffusional growth comes straight from the cloud droplets, so that both ice growth mechanisms deplete the supercooled liquid water. Raindrops also freeze if they capture an ice crystal. Raindrops form from the melting of snow and by coalescence of cloud droplets (autoconversion) and they can grow further by collecting cloud droplets. A minimum cloud-droplet size (implying a minimum water content) is required for autoconversion to occur. If the supercooled liquid water content exceeds this then the scheme can produce supercooled drizzle or raindrops.

Full details of the new scheme are given in Wilson and Ballard (1999), including how it is implemented in the context of that part of the cloud scheme which diagnoses fractional cloud cover within a model grid box. Separate partial cloud covers are diagnosed for liquid and ice cloud. This complexity has been neglected so far during the evaluation; only the grid-box mean values of ice and liquid water mixing ratios have been considered.

3. MRF Instrumentation and Flight Plan

The key MRF instruments for the evaluation were those that measured cloud liquid water content, precipitation ice (or water) content and temperature. Cloud liquid water content (in droplets up to about 40 μm diameter was measured with the Johnson-Williams (J-W) Probe. This measures the cooling as the droplets impinge on a heated wire normal to the airflow and evaporate. The size distribution and phase of hydrometeors (diameter above about 25 - 50μm was obtained from two Particle Measuring Systems (PMS) 2-Dimesional Optical Array probes. The 2-D Cloud Probe covers the range 25 - 800 μm in 25 μm width classes and the 2-D Precipitation Probe the range 200 - 6400 μm in 200 μm width. Both probes produce 2-dimensional shadow images of the hydrometers allowing classification into drops, aggregates, needles etc. However, they have to larger than about 150 μm for the 2D-C probe and 1.2 mm for the 2D-P probe before they can be classified. Particle mass is derived from the image size and form using empirical relationships.

Combining this information with the measured concentration in each size range, the ice or liquid water content can be obtained. The initial analyses used ice water contents obtained by assuming a mass-diameter relationship for aggregates.

During the experimental period, MRF were also flying a Nevzerov Probe in order to evaluate its performance. This instrument actually comprises two probes. One measures cloud liquid water content using a hot wire techniques similar to the J-W Probe. The other measure total water content ie cloud water, cloud ice, precipitation water and precipitation ice, again using an evaporative technique. The evaporative technique requires no assumptions to be made about particle density in order to estimate IWC, as do the 2-D Probes. Promising results have been obtained from an initial evaluation performed by Atmospheric Environment Services, Canada as described by Korolev et al. (1998). They believe the Nevzerov Probe represents a significant advance in measuring the ratio of liquid water to ice water content, although cautioning that further test are desirable. During the evaluation reported here it was used to help substantiate the values from the other probes. In general, the correlation between the data from the Nevzerov and other probes has been high and the magnitudes have been similar. The J-W and Nevzerov Probes can suffer from baseline drift ie a non-zero signal in clear air and corrections have been applied during the analysis.

The size distribution of cloud droplets to 45 μm diameter and hence mean droplet size was obtained from a PMS Forward Scattering Spectrometer Probe (FSSP). Integrations of the FSSP size distribution give another estimate of cloud liquid water content. For the cases presented here the FSSP LWC has generally been a factor of 2 - 3 lower than from the J-W and Nevzerov probes, although the correlation was often high. The advantage of the FSSP is that it has no baseline drift problem. One disadvantage is that it can produce spuriously-wide size distributions when a high concentration of ice crystals are present.

Aircraft height was taken to be the pressure altitude. Temperature was converted to true air temperature. Latitude and longitude were obtained from the GPS system. The ice and water contents were obtained in gm^{-3} but were converted to mixing ratios in gKg^{-1} using air density derived from the measured temperature and pressure. This was because the model forecasts mixing ratios. (The acronyms SLWC, IWC will still be used). All aircraft data were obtained at 1 Hz representing a sample length around 100 m.

The icing flight plan comprised a mixture of saw-tooth runs interspersed with an occasional deep profile. Saw-tooth runs were performed between 0 and -5°C, -5 and -10°C etc. until no more liquid water was observed. Data were also obtained from level runs on some flights not specifically aimed at icing, but saw-tooth runs were preferred because there was more chance of sampling supercooled liquid water occurring over a shallow layer, especially near 0°C. The model often produced supercooled liquid water just above 0°C but not extending to -5°C. It was hoped to determine whether this behaviour was realistic. The profiles were performed to determine the cloud-top temperature and especially whether multiple cloud layers were present.

4. Basic Analysis Strategy

The analysis faced two complicating factors, the difference in resolution between aircraft data and the model grid and the possibility of model timing or development errors. Whilst software was developed to plot model cross sections along the tracks of the MRF runs, sole reliance on these would be naïve eg if the model had a positional error or if there was significant supercooled liquid water a couple of grid boxes away but not along the aircraft track.

The analysis used satellite and radar data, plus surface observations to determine the general level of realism of the model cloud and precipitation features. In the cases examined the model positioning of frontal cloud bands was quite realistic but detailed cloud features and the location of precipitation sometimes less so. Whilst it was straightforward to produce images of the LWC and IWC field for every model level, examination of these was time consuming, so composite fields were produced. These showed the maximum IWC at any level, the maximum LWC and maximum SLWC at any level, stratified into four mixing ratio bands. Cross sections were also produced along any desired latitude or longitude, as well as along the aircraft track. All handling and display of the model fields used the UKMO PV Wave PP package routines and a few limitations were found. A way was not found to exclude LWC above $0^{o}C$ on a cross section. Sometimes it was not clear if liquid water extended below $0^{o}C$ or whether the contouring had spread it. Note that the 06z model was used in all cases run.

5. Results of the Analyses

5.1 22 March 1999

Synoptic Situation

During the 22nd March an open wave moved rapidly southeastwards from NE Scotland, the triple point being over the Wash by midnight on the 23rd. The experimental area for the MRF comparisons was mainly NE of the Humber, with some runs SSE of this over land. During the main experimental period, 16 – 18z, the Humber was at the southern end of the warm front. This may have rendered the comparison more sensitive to forecast errors, because the cloud here was a little more variable than further north where the front was more active.

The Meteosat infrared image shows that at 15z the coldest cloud was north and west of the Humber and this moved into the experimental area between 15 and 18z. In the model, the frontal cloud just extended south to the Humber at 15z and moved southeastwards to cover most of southern England by 18z. The Nimrod rainfall analyses show rain spreading southeastwards from southern Scotland to reach the experimental area by 17z. The model rainfall field behaved similarly.

Aircraft Data

The first flight used horizontal runs. The flight commenced around 15z and the first few runs, flying NNE from Boscombe Down were cloud physics runs. SLWC of up to 0.15 gKg^{-1} was encountered at 1518z, T = $-7^{o}C$. The model had no cloud in this region but farther southeast it did have small areas of supercooled cloud (probably Sc) at a temperature around $-3^{o}C$, composed entirely of water with LWC values up to 0.2 gKg^{-1}.

The main runs of interest are 4, 5, 10, 11 which were north of $52.5^{o}N$ and partly northeast of the Humber. Two deep profiles were obtained over the North Sea as well. The other runs were either at temperatures above $0^{o}C$ or around $-50^{o}C$. Model freezing levels in the experimental area varied from 600 - 1200 m but were mainly around 800 - 1000 m. The few values observed were around 800 m.

Details of the runs are summarised in Table 1, while Table 2 gives the average and peak values of the mixing ratios from the microphysical probes. The average values quoted in this study exclude values < 0.02 gKg^{-1} to avoid holes in the cloud and very tenuous cloud. The 2D-C mixing ratios are referred to as IWC on the assumption most of the particles sampled within its size range will be ice at temperatures below zero. This is probably a reasonable assumption for frontal cloud, apart from the possibility of supercooled drizzle drops. Figure 1 shows the aircraft data plotted as a function of distance along run 4 and run 5 which was a continuation of run 4. The fair degree of correlation between LWC, IWC and TWC can be seen. Figure 1 shows that the observed SLWC was very variable. Other runs were similar. To get an idea of it's significance for aircraft icing, ice accretions for each entire run have been calculated. These are the maximum possible values because a unit collection efficiency was assumed and latent heat release was ignored. The density of the deposited ice was taken to be 8×10^5 Kgm^{-3}.

Table 1 Horizontal Run Details for 22March 1999

Run No.	Time	Temperature (^{o}C)	Run Length (Km)
4	1546-1552	-2 to –5.3	35
5	1552-1558	-4.1 to –5.2	31
10	1747-1807	-3.5 to –5.5	108
11	1809-1811	-5.5 to –6.0	11

Table 2 Average and Peak Mixing Ratios, Plus Maximum Ice Accretion on 22 March 1999

Run No.	J-W LWC (g/Kg)	Max Ice Accretion (mm)	2D-C IWC (g/Kg)	Nev. TWC (g/Kg)
4	0.19 (0.38)	4.7	0.13 (0.27)	0.30 (0.40)
5	0.10 (0.20)	2.6	0.14 (0.35)	0.17 (0.33)
10	0.047 (0.09)	4.4	0.18 (0.37)	0.18 (0.39)
11	0.056 (0.11)	0.5	0.13 (0.22)	0.10 (0.18)

Tables 1 and 2 show that on runs 4 and 5 supercooled liquid water comprised a substantial fraction of the total cloud and precipitation mixing ratio. This is consistent with the relatively warm infrared cloud-top temperature on both runs, Table 3. On run 4 the LWC/TWC ratio from the J-W and 2D-C decreased along the run which is consistent with a decrease in cloud-top temperature from -10 to –18^{o}C, but ratio from the Nevzerov Probe increased. On run 5 the cloud appeared to become more glaciated as the cloud-top temperature increased but at the same time LWC , IWC and TWC decreased, as did the liquid water fraction. This might indicate a dissipating cloud, with no recent ascent.

Model Forecasts

Table 3 Summary of Model Forecasts for 22 March 1999

MRF Run	IR Cloud-Top Temp. (°C)	Model Cloud-top temp. (°C)	LWC Flight Level (g/Kg)	Max SLWC Any Level (g/Kg)	IWC Flight Level (g/Kg)	Max IWC Any Level (g/Kg)
4	-10 to -18	-7 to -25	0	0	0.02 - 0.05	0.02 - 0.05
5	-10 to -18	-30 to -40	0	0	0.02 - 0.2	0.1 - 0.2
10	-18 to -25	-45	0	0.02 - 0.1	0.1 - 0.4	0.3 - 0.4
11	-20 to -25	-40	0	0.02 - 0.1	0.02 - 0.1	0.1 - 0.2

The properties of the model forecasts are summarised in Table 3. The 16z forecast was used for runs 4 and 5 and the 18z forecast for runs 10 and 11. The liquid water and ice water contents are taken from the model cross sections so the range given corresponds to the class widths used for plotting. The model cross section along run 4 shows a completely glaciated cloud with base at 1.9 km and top increasing northwards from 3 km to around 6.5 km. The cloud-top temperature is similar to that from Meteosat. Model IWC values are significantly less than observed. Looking at horizontal IWC fields it is clear that model IWC increases northwards and exceeds 0.25 gKg^{-1} north of the Humber, more in accord with the aircraft data. The 16z model LWC forecast had no supercooled water near the aircraft run at any height. It appears that near the start of the aircraft run, where the model cloud-top temperature is warm enough for supercooled water to occur, there is little ascent leading to a tenuous glaciated cloud. Since the microphysical scheme does not allow any glaciation until the cloud-top temperature is below –10°C, the occurrence of glaciated cloud with a warmer cloud-top temperature suggests that the cloud must have been deeper earlier and is decaying. North of the run, where the model has higher IWC, the cloud tops are cold enough for complete glaciation.

The model IWC along run 5 was up to 0.2 gKg^{-1}, so comparable with the aircraft data, but the model has no supercooled liquid water anywhere near the flight track. The model cloud-top temperature is much colder than the infrared temperature and the cloud is solid up to 6 – 10 km. This is in reasonable agreement with profiles observed an hour later, but given the infrared temperature was as high as -10°C at 16z, the model cloud was probably too deep at this time. The complete glaciation of the cloud is therefore no condemnation of the microphysics scheme but a reflection of the deeper cloud forecast than observed.

Between runs 4 & 5 and runs 10 & 11 two profiles (P1 from 1652 - 1718z and P2 from 1735 1747z) were performed. Unfortunately, the cloud was becoming rather tenuous by this time, although deep. The 2DC IWC and Neverov TWC profiles for P1 show cloud or precipitation from 1 - 8.5 km, 0 to -50°C. Maximum values were around 0.12 gKg^{-1}. The Nevzerov TWC decreased below 0.03 gKg^{-1} above 4 km, but the 2DC IWC did not. The Meteosat temperature varied from -25 to -35°C along the profile track, which is much warmer than from the aircraft profiles but ties in with the upper cloud having a very low IWC. A small LWC signal, up to 0.04 gKg^{-1} was obtained from the J-W, Nevzerov and FSSP probes through the entire profile. Since the signal extended to -50°C and since there was little correlation between the data from the three instruments, it is likely to be spurious eg baseline drift, instrument noise and the effect of ice crystals.

The model profile for P1 is in quite good agreement with the observed profile, except the IWC values are about four time those observed. Ice cloud extends to -50°C and the IWC values (peaking at 0.3 - 0.4 gKg^{-1}) fall off rapidly below -30°C. The model profile shows no supercooled liquid water.

Profile 2 was a descent from 6 to 2.6 km (-28 to -4°C). It shows similar features to profile 1 although it is more spiky and the Nevzerov TWC is zero above 4km. The low signal from the liquid water probes is evident again but now with 3 spikes to 0.06 gKg^{-1} which are correlated so may be real. The model cross section has a few grid boxes with an SLWC of 0.02 - 0.1 gKg^{-1} between 0 and -2°C, co-located with an IWC of 0.3 - 0.4 gKg^{-1}.

Run 10 was from just south of the Humber to inland of the Wash. The liquid water probes and FSSP all have low LWC signals, averaging < 0.05 gm^{-3}. These were not well correlated and so may be spurious. A few peak values reached 0.1 gKg^{-1} and may indicate patches of supercooled liquid water. The Meteosat infrared temperature was mainly around –20 to –25°C. Assuming the cloud deck was solid, one would expect a fairly glaciated frontal cloud from these temperatures at typical widespread ascent rates.

Cross sections of model temperature, IWC and LWC for run 10 are shown in Figure 2. Comparison with Table 3 shows the model had a lower cloud-top temperature than observed. However model IWC values are < 0.1 gKg^{-1} at temperatures below -35°C, so the infrared temperature would be warmer than the model cloud-top temperature. The model IWCvalues are up to 0.3 - 0.4 gKg^{-1}, twice the observed mean values. This suggests more rigorous ascent than in reality. There are a few grid boxes with SLWC < 0.1 gKg^{-1} down to -2°C but none at lower temperatures.

The ice contents on run 11 were lower than on run 10, Tables 1. Data from the LWC probes was similar to run 10, again suggesting mainly glaciated cloud with patches of supercooled liquid water. The model cross sections for run 11 shows agreement with the observations in having lower IWCs. There is a thin liquid cloud at the freezing level but it is not clear if this extends below 0°C. The rest of the cloud is entirely glaciated. There is some model supercooled liquid water (< 0.1 gKg^{-1}) down to -2°C near the flight path.

General Features of Model SLWC Field

During the period 15 - 18z, the model forecast large areas of supercooled liquid water, especially over France, Holland, Belgium and Germany where values exceeded 0.4 gKg^{-1}. Here the supercooled liquid water extended down to -12°C, with values 0.3 - 0.4 gKg^{-1} down to -5°C and 0.2 - 0.3 gKg^{-1} down to -10°C. Most of this occurred where there was no ice cloud or where IWC < 0.1 gKg^{-1}. There were also a large area over the southern North Sea, < 0.2 gKg^{-1} and all above -2°C. A large area over eastern Scotland extending into the North Sea was also mainly < 0.2 gKg^{-1} and mainly above -2°C. This was associated with the more active portion of the front lying through the experimental area. Higher SLWCs extended to lower temperatures over the Western Highlands, despite the presence of IWC values of 0.2 - 0.3 gKg^{-1}.

Conclusions from 22 March 99 Case

This case illustrates the difficulty of making local comparisons where details of the model cloud can differ from reality. Where the cloud-top temperature was < -20 to -25°C, both observations and model had low or zero SLWC values. However, the model failed to predict the moderate SLWC values observed on the runs 4 and 5, either because it had no recent ascent or the model cloud-top temperature was too low. Around the UK in general the model had very little supercooled liquid water at T < -2°C but on runs 4 and 5 it was observed between -2 and -5°C.

5.2 30 June 1999

Synoptic Situation

The experimental area was south of Ireland, 50°N, 8 - 10°W and the experimental period 0930 - 1400z. The NMC analyses for 00 and 12z both show two warm fronts. The leading one is analysed as a short trough-like feature which is shown reaching the SW tip of Ireland at 12z, so must have passed through the experimental area around 11z. The main warm front reached the western edge of the experimental area around 13z.

The Meteosat infrared imagery shows an expanding area of cold cloud moving eastwards, minimum temperature around -45 to -50°C. At 0930z the coldest cloud was mainly west of Ireland with fingers of cold cloud extending into the experimental area. The coldest cloud entered the experimental area around 1030z. Comparison of the 12z infrared picture with the NMC analysis shows that the cold cloud was all ahead of the surface front. The experimental area was beyond radar range but rain had reached the SW tip of Ireland by 10z, which was three hours earlier than forecast by the model. Possibly this is because the model failed to capture the double frontal structure. The radar field was banded and looked rather convective, whilst the model had a solid area of rain.

Comparison of the composite model IWC field with the area of sub-zero cloud inferred from Meteosat infrared imagery show basically good agreement, with two exceptions. The observed sub-zero cloud extended further south than in the model from 10 - 14z and after 12z it extended further north eastwards over the Irish Sea. The back edges of the model and observed cloud sheet were in good agreement at all times. At 10z the model cloud-top temperature was warmer than observed, around -15 to -20°C. The cloud deepened so that by 12z the model cloud-top temperature was in the range -40 to -50°C. Comparison of the model rain and cloud field shows that part of the rain area is associated with cloud which is entirely liquid.

Aircraft Data

This was the most successful and comprehensive icing flight, with the entire flight devoted to the icing flight plan. The experimental area remained fixed as the warm front passed through. Supercooled liquid water was ubiquitous but the model forecast very little. The instruments performed well except the FSSP LWC data does not look believable.

Four profile descents were made during the experimental period on the western or eastern boundary of the area, generally between 6.3 and 2.5 km. Basic details are shown in Table 4, together with model cloud-top temperatures and freezing levels and Meteosat infrared temperatures. Profiles 3 and 4 are shown plotted in Figures 3 and 4. It can be seen from Table 4 that the model freezing level agrees closely with the observations. Table 4 shows that the model and observed infrared cloud-top temperatures tend to decrease with time, the model to a much greater extent. This ties in with the impression gained from comparing the cloud fields that the development of the model cloud feature lagged reality. Although the observed IWC and TWC values were close to zero at the top of the descent, the temperature there was higher than the Meteosat infrared temperature on profiles 3 and 4, Table 4. This suggests the existence of another (third) cloud layer above.

Table 4 Observed and Model Profile Details for 30 June 1999

Profile	Relevant Model Field	Model Freezing Level (Km)	Observed Freezing Level (Km)	Model T_{ct} (°C)	MRF Profile T_{ct} (°C)	Meteosat IR T_{ct} (°C)
1	10z	2.8	3.0	-15 to -20	-	-30 to -35
2	11z	3.1	3.1	-15 to -20	-20	-20
3	12&13z	3.4	3.4	-40	-18	-35 to -40
4	14z	2.8	3.2	-45 to -50	-25	-35 to -40

The most important feature of the profiles is that they all suggest the existence of two cloud layers below 6 km and this was also noted in the aircraft scientist's log. On P1 only the lower cloud layer was sampled as the aircraft was north of the experimental area at the start of the descent. The aircraft must have flown under the upper cloud layer during the descent because at 4200 m the aircraft scientist noted "8/8 thick Ci above, 5/8 Ac/Sc layer below". On P1 the lower cloud top was at -2°C and on P2, P4 at -4°C with the base of the upper cloud at -12°C. The gap can be seen clearly on Figure 4, especially in the IWC and TWC profiles. On P3, Figure 3, there was only a hint of a gap around -13°C, 5.3 km, but the existence of a gap there was noted by the aircraft scientist. However, it is not clear if this is a gap in the horizontal or vertical. The existence of a gap can be important in promoting the persistence of supercooled liquid water in the lower cloud layer, if it is not subject to seeding by ice crystals from the upper cloud layer. Supercooled liquid water was observed on all profiles in both cloud layers, although with low LWC values in the upper cloud until P4. The model had only one ice cloud layer in the vicinity of the profiles except for P3 which was located at the edge of the model ice cloud on both 12z and 13z forecast fields. Model cross sections along the track of the profiles only show supercooled liquid water for P3.

Table 5 Basic Details of the Saw-Tooth Runs on 30 June 1999

Run No.	Time	Temp. Range °C	Run Length (Km)	Aircraft Scientist's Comments
1 W-E	0959 - 1015	0.2 to -7.5	147	Columns/needles to 800 μm
2 E-W	1024 - 1040	-4 to -12	134	Snow to 800 μm. Embedded convection, riming
3 W-E	1044 - 1058	-10 to -16	75	Snowflakes to 600 μm. Cloud thins at eastern end.
4 E-W	1119 - 1139	1.7 to -4.7	110	Snowflakes to 600 μm
5 W-E	1142 - 1156	-4 to -11	81	Lots of snow
6 E-W	1159 - 1217	-10 to -16	100	Snowflakes towards end of run
7 W-E	1241 - 1257	1.8 to -6	87	Snowy blobs to 800 μm. Bumpy ride, convective cells
8 E-W	1300 - 1320	-4.5 to -12.5	108	Big blobs on 2D-C > 800 μm at 13Z. Cloud clearance visible to the west at 1314z.
9 W-E	1322 - 1338	-10 to -15	84	In and out of cloud at 1325, 5200m, -13°C. Main cloud layer below, thick Ci/Cs above.

Nine saw-tooth runs were made comprising three sets covering three temperature ranges to -15°C. Because many of the features found were the same, the runs will not be described individually. Basic details of each run are given in Table 5, with the average and peak mixing ratios given in Table 6. The averages apply to sample distance around 50 – 100 km which is around 4 - 8 model grid lengths. Only J-W LWCs are shown because the Nevzerov LWCs are very similar on most runs. Cloud-top infrared temperatures can be inferred from Table 4.

The J-W LWC, 2D-C IWC and Nevzerov TWC for runs 3 and 9 are shown plotted as a function of distance in Figures 5 and 6. Both runs were at the lowest temperature range sampled yet supercooled liquid water is still found. The correlation between LWC, IWC and TWC is apparent again.

Table 6 Average and Peak Mixing ratios, Plus Maximum Ice Accretion on 30 June 1999

Run No.	J-W LWC (g/Kg)	Maximum Ice Accretion (mm)	2D-C IWC (g/Kg)	Nevzerov TWC (g/Kg)
1	0.067 (0.3)	2.4	0.125 (0.8)	0.16 (0.4)
2	0.069 (0.13)	2.6	0.17 (0.4)	0.18 (0.42)
3	0.053 (0.12)	2.1	0.18 (0.6)	0.14 (0.62)
4	0.079 (0.6)	5.0	0.135 (0.95)	0.16 (1.1)
5	0.075 (0.25)	4.2	0.19 (1.6)	0.20 (1.6)
6	0.20 (0.5)	12.1	0.65 (2.5)	0.53 (1.4)
7	0.13 (0.28)	5.0	0.27 (0.75)	0.40 (0.75)
8	0.15 (0.4)	7.8	0.41 (1.9)	0.45 (1.3)
9	0.13 (0.4)	5.9	0.45 (1.4)	0.37 (1.2)

The following conclusions have been drawn from examination of the detailed plots and the average and peak values -

(i) Supercooled liquid water was found within all three temperature ranges, and the amounts became more significant after run 5. There was no obvious trend to lower SLWC values at lower temperatures, in fact run 6 had the highest SLWCs of all runs, yet covered the temperature range -10 to -16°C. However, the ratio of average LWC to average (IWC + LWC) does decrease from around 0.35 from 0 to -5°C to 0.22 from -10 to -15°C.

(ii) Both average and peak LWC, IWC and TWC values increase with time, e.g. Figures 5 and 6. The larger peak values may be associated with the embedded convection noted by the aircraft scientist.

(iii) The increase in mean and peaks SLWCs after run 5 is accompanied by an increase in 2D-C IWC (assuming the 2D-C size range mainly comprises ice, see Aircraft Scientists notes in Table 6). The IWC inferred from Nevzerov TWC - LWC also shows this increase. This suggests the larger values are associated with higher ascent rates which would generate more total condensate, whilst maintaining SLWC values. The ratio LWC/TWC at 1 Hz is mainly around 0.15 to 0.4 when the cloud is solid and is relatively insensitive to temperature and mixing ratio. This is found using both the Nevzerov data and from combining 2D-C and J-W data. Thus ice and water often coexist down to the 100 m scale. Where the cloud is broken, the LWC/IWC ratio varies from 0 to 1, the latter being more common.

(iv) There is further evidence for the existence of two cloud layers below 6 km. Runs 1 and 4 contain evidence of a cloud top at -1 to -4°C and of a cloud base between -7 and -10°C, consistent with P1, P2 and P4. The middle saw-tooth runs show cloud at all levels sampled, more consistent with P3. The aircraft scientist's log for run 9 indicates a cloud base at 5.2 km, -13°C, with the main cloud layer beneath this.

Model Forecasts

Hourly composite SLWC and IWC model fields have been examined as well as cross sections along the flight track at 50°N. The composite fields for 13z are shown in Figure 7. Because the flight track was nearer the southern edge of the model ice cloud than in reality, cross sections along 51.5°N have also been examined. Table 7 shows peak mixing ratios from the model for the same temperature ranges as the saw-tooth runs.

Table 7 Sample Peak values from the Model Forecasts for 30 June 1999

Temp Range °C	10z		12z		14z	
Expt. area	LWC g/Kg	IWC g/Kg	LWC g/Kg	IWC g/Kg	LWC g/Kg	IWC g/Kg
0 to -5	0	0.02 - 0.1	0	0.1 - 0.2	0.02 - 0.1	0.1 - 0.2
-5 to -10	0	0.02 - 0.1	0	0.02 - 0.1	0	0.1 - 0.2
-10 to -15	0	0	0	0.02 - 0.1	0	0.02 - 0.1
51.25°N						
0 to -5	0	0.1 - 0.2	0.01 - 0.1	0.2 - 0.3	0.1 - 0.2	0.2 - 0.3
-5 to -10	0	0.02 - 0.1	0	0.1 - 0.2	0	0.2 - 0.3
-10 to -15	0	0.02 - 0.1	0	0.1 - 0.2	0	0.1 - 0.2

The key features of the forecasts are -

(i) From 09 - 11z inclusive there was no supercooled liquid water forecast anywhere near the experimental area, except for a narrow band between 0 and -0.1°C. There is an area of supercooled liquid water where the front intersects the model boundary, with SLWC up to 0.4 gKg^{-1}. This is a spurious feature related to the model boundary. Such boundary-related features were often observed and are due to the fact the global version of the UM does not contain the new cloud and precipitation scheme yet. When it is introduced they should disappear.

(ii) A band of supercooled liquid water approaches the experimental area at 12z and encroaches upon it at 13z, Figure 7a. This band is located towards the rear of the model's ice cloud, Figure 7b and so is near the surface front. Figure 7a shows that the band extends from the area of high SLWC on the model boundary and it is not clear how far the influence of the boundary extends along the band. Figure 8 shows the model west to east cross sections at 13z. The ice cloud is more tenuous in the west and two layers are evident near the western edge. The supercooled liquid water extends to lower temperatures in the west but still only to –4°C.

(iii) Table 7 shows that an SLWC up to around 0.1 gKg^{-1} appears at 51.25°N at 12z and this appeared in the experimental area at 13z. The largest discrepancy with the observations is that the model supercooled liquid water was always confined to temperatures above -5°C when it was actually observed down to -16°C. The maximum model SLWCs are less than the average values observed at the same time, except for 14z at 51.25°N. Those from the later times are comparable with the observed average values before run 6. In going from no supercooled liquid water before 12z, to having some, the model could be seen as giving an indication of the observed increase in SLWC values with time.

(iv) The model IWC cross sections show an increase in cloud depth with time and increasing peak IWC values in agreement with the observed trends. However, the maximum model IWC values along the flight track (0.1 - 0.2 gKg^{-1}) are less than the average observed values, especially at 12z and after. The maximum values from 51.25°N (0.2 - 0.3 gKg^{-1}) are in better agreement but are still an underestimate after 12z. This is especially true for the lower temperature runs because the observed IWCs peak in the -10 to -15°C range

Conclusions for 30 June 1999 Case

It is clear that the warm front cloud feature contained much more supercooled liquid water than forecast. However, the frontal system may have contained an unusual amount, at least this is the impression of the aircraft scientist. While the model underestimation is worrying, there is at least the possibility that the discrepancy may not normally be so large. Also the maximum ice accretion values for the first three runs are not very significant.

One major reason for the discrepancy appears to be the failure of the model to produce the two-layered (or multi-layered) cloud system suggested by the observations. The cloud system had at least two layers in the east initially although these may have merged in the west.

A second reason for the discrepancy may be that much of the supercooled water was generated by embedded convection which is not dealt with by the new cloud scheme. While the rain over southern Ireland looked quite convective on the radar, examination of the separate dynamic and convective model rainfall rate fields shows that most of the rain was dynamic in origin, except towards the rear edge of the system. It is unlikely that this is the entire explanation because on many runs the supercooled liquid water is continuous over a distance of up to 50 km.

A much more speculative possibility is that the vertical velocity profile was wrong in the model, with the ascent being too low down. This would help explain the too rapid fall off of IWC values in the model forecasts. The model produces rain, without an obvious discontinuity in the rainfall rate, even when the cloud is all below the freezing level. This may be evidence of significant ascent beneath the freezing level, which would be required to maintain the cloud liquid water content against autoconversion and accretion.

5.3 27 May 1999

Synoptic Situation

This was a flight to test the Nevzerov probe with the second half devoted to an icing flight in a band of cloud and rain moving northwards. The location was west of the Bristol Channel.

A frontal system was moving northwards towards or through the experimental area. However, there were differences between the London Weather Centre and NMC analyses. The London Weather Centre chart has an occlusion stretching from the southern coast of Ireland to Cornwall at 12z, which links back to a very open triple point south of Cornwall. The model temperature cross sections are consistent with this.

The 12 - 14z Meteosat infrared images show a band of cold cloud stretching from southern Ireland to the NW tip of France. This moved northwards and the coldest cloud reached the experimental area around 13z. The minimum cloud-top temperature within the band was -40 to -50°C. The combined model IWC field shows a similar feature but with the northern edge further north, just reaching Wales at 12z The model had a band of rain with holes moving northwards and becoming more fragmented. The model rain occupied the southern half of the flight track at 12z and was leaving it at 14z. Model rain rates were 1 - 2 mmh^{-1} in the experimental area where the rain was entirely of dynamic origin, except at 12z when it was partly convective.

Aircraft Data

The Nevzerov LWC probe had a large baseline error which was corrected up to run 5 by subtracting 0.58 gKg^{-1} to give values in excellent agreement with the J-W. The baseline drifted rapidly after this and the Nevzerov LWC data were ignored. There were 5 horizontal runs (1 saw-tooth, the rest horizontal) along a N - S line at 5.9°W, extending from 51.8°N to 50.5°N, followed by a profile from 0 to -40°C. Basic details are given in Table 8. Table 9 shows the mean and peak values of SLWC, IWC, TWC, together with maximum possible ice accretion for each run. Apart from 14z, the warmest IR temperatures listed in Table 8 were located in the northern part of the experimental area

Table 8 Basic Information on Aircraft Runs for 27 May 1999

Run	Time	Temperature (°C)	Run Length (km)	IR T_{ct} (°C)	Aircraft Scientist's Comments
3	1210 - 1226	0 to -6.5	82	-20 to -40	Freezing level 3.2 km
4	1228 - 1240	-2 to -5	62	-20 to -40	Peaks in LWC but not obviously correlated with updraughts
5	1241 - 1304	-2.7 to -4.9	123	-25 to –40	Some Cu tops, not related to LWC features
6	1307 - 1324	-8.7 to -10.5	91	-25 to –40	Clear air at start.
7	1326 - 1337	-8.6 to -10	59	-30 to –40	
Profile	1340 - 1407	0 to -40	-	-30 to -40	Cloud top believed to be just above top of ascent.

It can be seen from Table 9 that some supercooled liquid water was found on every run. This was predominantly in the northern part of each run, in accord with higher infrared temperatures in the northern half of the area up to 13z. This is illustrated by the aircraft data from run 3 shown in Figure 9. Run 3 was from north to south. By 14z the infrared temperature was -30 to -40°C over the entire experimental area, in agreement with the Aircraft Scientist's comment at the end of the ascent, Table 8. The mean SLWC values found between -8 and -10°C (runs 7 - 8), were about a third of those from 0 to -5°C (runs 3 - 5) and the peak values decreased even more. This is more in agreement with the rapid fall off of SLWC with decreasing temperature generally characteristic of the model than the observations from the 30th June case, but much less abrupt.

Table 9 Average and Peak Mixing Ratios plus Maximum Ice Accretion on 27 May 1999

Run No.	J-W LWC (gKg^{-1})	Max. Ice Accretion (mm)	2D-C IWC (gKg^{-1})	Nev. TWC (gKg^{-1})
3	0.15 (0.48)	6.3	0.063 (0.30)	0.18 (0.65)
4	0.19 (0.77)	4.5	0.085 (0.32)	0.185 (0.67)
5	0.14 (0.48)	5.7	0.085 (0.27)	0.18 (0.52)
6	0.048 (0.14)	1.5	0.14 (0.26)	0.12 (0.26)
7	0.048 (0.10)	1.6	0.14 (0.26)	0.12 (0.31)

Maximum possible ice accretion values on runs 3 - 5 are similar to those on 30 June runs 4 - 9. However, on this day the largest values are all found where T> -5°C, whereas on 30 June large values were found at lower temperatures.

The cloud comprised a substantial fraction of supercooled liquid water on runs 3 -5, more than on 30 June. This can be seen from the peak in Nevzerov TWC between 20 and 40 km on Figure 9c which corresponds to a peak in LWC, Figure 9a, but not a peak in IWC, Figure 9b. The fraction was lower on runs 6, 7, similar to the runs at lower temperatures on 30 June. The plots of the LWC/TWC ratio at 1 Hz show about half the values are above about 0.4 on runs 3 - 5 in the region with significant cloud. The ratio is very variable and reaches unity several times. On runs 6/7 it is much less variable with most values in the range 0.2 - 0.4.

The only profile was an ascent near 14z from 3 km (0°C) to 8.8 km (-41°C). The model freezing level at 14 z was at 3.5 km. According to the 2D-C data unbroken cloud extended from 5 km upwards with IWC 0.05 - 0.4 gKg^{-1} and only a thin layer of cloud beneath. The Nevzerov TWC data and J-W data show unbroken cloud from 3 to 8.8 km. The signal from below 5 km could be due to baseline drift, LWC values were only around 0.03 - 0.08 gKg^{-1}. However, the FSSP gave a signal above 5 km which correlates well with the LWC and IWC data. The question arises again as to whether there were regions of supercooled liquid water content down to -40°C or whether the J-W and FSSP are responding to ice crystals. The main message from the profile is that there appeared to be only one cloud layer and LWC values were very low by 14z.

Model Results

Figure 10a shows the combined model SLWC field for 12z. A band of supercooled liquid water stretches from south of Devon to south of the west coast of Ireland. This again joins up with a spurious area of high SLWC produced at the model boundary. There is only a narrow band with SLWC < 0.1 gKg^{-1} over the experimental area. The band widens south of Ireland with peak SLWC of 0.1 – 0.2 gKg^{-1}. Over the sea virtually all the supercooled liquid water is at a temperature > -4°C and nearly all SLWC values > 0.1 gKg^{-1} occur between 0 and –1°C. The band widens over Devon and extends to -5°C with peak values 0.2 - 0.3 gKg^{-1} down to -3°C. Comparison with Figure 10b shows that supercooled liquid water only occupies a small fraction of the frontal cloud band.

At 13 and 14z the forecast SLW band moves northwards decaying in the east but remaining a significant feature south of Ireland, where the SLWC is up to 0.2 – 0.3 gKg^{-1} at 14z. There is always a minimum in SLWC near the experimental area. At both times all SLWC > 0.1 gKg^{-1} is found between 0 and –1°C and over the sea most of the supercooled liquid water is also within this temperature range. A few grid boxes with SLWC < 0.1 gKg^{-1} persist to –5°C at 13z but only to –2°C at 14z.

Cross sections have been produced for aircraft runs 3, 5, 7 using the 12, 13 and 14z forecasts respectively. These show a dense ice cloud moving northwards with IWC values up to 0.6 gKg^{-1} at 12 and 13z but by 14z the densest cloud had moved north and IWC values are < 0.2 gKg^{-1} and mainly < 0.1 gKg^{-1}. The cross sections for run 5 are shown in Figure 11. At the height of the aircraft runs, IWC values are up to 0.5 gKg^{-1} on the 12 and 13z cross sections but only up to 0.1 gKg^{-1} on the 14z cross section. Thus on the first two cross sections the model IWCs are much larger than observed, even larger than the observed peak values in places. The model thins the cloud more quickly than observed. The model cloud-top temperature is around -55°C, rather colder than observed.

At 12 and 13z the supercooled liquid water in the experimental area tends to be found under the densest ice cloud where the melting of the ice has depressed the freezing level, stretching back into a region of less dense ice cloud at 13z, Figure 11. A similar feature is found at 8°W where the most extensive supercooled liquid water is forecast. The higher SLWC values over Devon occur where IWCs are lower, < 0.2 gKg^{-1} or where the supercooled cloud is detached from an upper ice cloud. Wave motion, presumably triggered by the topography, is suggested by a wave pattern in the isotherms.

Conclusions for 27 May 1999

This was the best model performance of the cases so far, in that a band of supercooled liquid water was forecast in a frontal cloud band where it was observed. Unfortunately, the model forecast a minimum in SLWC around the aircraft flight track. It is difficult to know whether this is real. If it is, then it is fair to compare the aircraft data with the model fields locally and assume the aircraft would have measured larger SLWC values elsewhere. It is probably more realistic to compare the aircraft data with the general levels of SLWC produced by the model in the frontal band over the sea.

Peak model SLWCs over the sea were comparable with the run average values for runs 3 - 5. However, the model values occur where T > -1°C while the observations show supercooled liquid water between -2 and -5°C, with the largest values equally likely at the lower temperature, e.g. Figure 9. Although the observed SLWC values fall off by about a factor of three in the -6 to -10°C range, the model has no supercooled liquid water at these temperatures.

5.4 <u>9 June 1999</u>

Synoptic Situation

A low was centred south of Norway and a bent-back occlusion stretched around this from SW Norway passed the NE coast of Scotland to the central North Sea. The aircraft flight track from 54.7°N, 1.8°E to 55.3°N, 3°E was normal to the occlusion.

The Meteosat infrared imagery for 1130 and 12z shows a band of cold cloud stretching along the occlusion with temperatures down to –40 to –50°C. The model has a band of ice cloud which was accurately positioned with respect to the observed cold cloud, although the Meteosat image shows cloud at –15 to –30°C stretching farther east than the model ice cloud. The model has a band of rain along the front with rainfall rates in the experimental area up to 2 – 4 mmh^{-1}. This cannot be verified by radar but the nearest synoptic observations, which are north of the experimental area, show drizzle just west of the front and light rain at the low centre. The model has 4 - 8 mmh^{-1} where drizzle was reported and no rain near the low centre. Further north of the experimental area moderate continuous rain was reported.

Aircraft Data

This was mainly a test of the Nevzerov Probe so horizontal runs were made. No profile data is available. Details of the runs are given in Table 10 and average and peak mixing ratios in Table 11, together with the maximum ice accretion along a run. The aircraft data for run 3 are shown in Figure 12.

Table 10 Basic Information on Aircraft Runs for 9 June 1999

Run No.	Time	Temperature (°C)	Run Length (Km)	IR T_{ct} (°C)
3	1133 – 1143	-0.7 to –2.3	54	-30 to -40
4	1145 – 1155	-4.5 to –6.9	54	-30 to -40
5	1157 – 1207	-8.8 to -10.2	51	-30 to -40
6	1209 - 1220	-11.5 to -12.3	68	-30 to -40

Table 11 Average and Peak Mixing Ratios, plus Maximum Ice Accretion on 9 June 1999

Run No.	J-W LWC	Max. Ice Accretion (mm)	2D-C IWC (gKg^{-1})	Nev. TWC (gKg^{-1})
3	0.17 (0.97)	6.5	0.11 (0.47)	0.15 (0.50)
4	0.052 (0.16)	0.6	0.081 (0.29)	0.066 (0.33)
5	0.041 (0.08)	0.2	0.043 (0.17)	0.052 (0.24)
6	0.0 (0.02)	-	0.057 (0.15)	0.050 (0.15)

Table 10 shows that most of the significant supercooled liquid water was found on run 3 between –0.7 and –2.3°C. Figure 13 shows three regions with high SLWC and IWC values which may be associated with embedded convection. Both SLWC and IWC decreased at lower temperatures but SLWC values decreased slightly more. The 2D-C and Nevzerov TWC data show mainly unbroken cloud/precipitation along the runs, e.g. Figure 12. There were only a few gaps in the SLWC data on run 3 but a lot of run 4 to run 6 had no supercooled liquid water, hence ice accretion values in Table 11 were insignificant. For the previous cases it was found that even when the mean SLWC was low, the maximum ice accretion tended to be a few mm because supercooled liquid water extended along much of the flight track. On run 6 the Aircraft Scientist mentions a gap in the cloud layer at -12°C, 3.8 km. If this was the cloud top, one would expect enhanced SLWC values and increased ratio of SLWC to TWC, but the data do not suggest this. The low IWC, TWC values, apart from run 3, suggest a low ascent rate which could explain the lack of supercooled liquid water.

Model Forecasts

The model forecast a broken band of supercooled liquid water along the frontal cloud at 12z, a lot of which is coincident with large maximum IWC values, although it also extends beyond the eastern edge of the ice cloud to Denmark. The peak SLWC is 0.3 - 0.4 gKg^{-1} in a few scattered grid boxes but the band mainly comprises SLWC < 0.1 gKg^{-1}. Most of the band occurs at T > -3°C. The band was also forecast at 11z and 13z but is more broken in the experimental area at 11z. Model cross sections along the flight track for the 11 and 12z forecasts show a single ice cloud, Figure 13. The model cloud-top temperature is –40 to –45°C at 11z and –35 to –40°C at 12z, in reasonable agreement with the infrared values. Both cross sections show an SLWC of 0.02 – 0.1 gKg^{-1} down to –3°C, about a half to a third of that observed on run 3 in the same temperature range. The absence of supercooled liquid water below –3°C is not a problem because the amount observed was insignificant for aircraft icing.

The largest discrepancy between model and observations is that the model forecast much larger IWC values. At run 3 level, model IWC values are 0.4 – 0.5 gKg^{-1} at 11z. At run 6 level in the 12z forecast they are still around 0.3 – 0.4 gKg^{-1}, reflecting the fact that the forecast IWC values peak in the experimental area. The high model rainfall rates there indicate that the model had a large vertical velocity which managed to maintain some supercooled liquid water despite the high ice contents. However, the ratio of mean LWC to mean LWC+IWC for run 3 is around 0.6 from the observations but only 0.13 in the model. The melting of the unrealistically high model ice content may have caused the model freezing level at 1.4 km to be lower than observed, 1.9 km on run 3.

The model forecast large areas of supercooled liquid water away from the frontal influence, in particular a large band stretching from the northern model boundary to southern Ireland. There was an area around 100 by 70 km over Ireland with SLWC > 0.4 gKg^{-1}. The cloud band was on the eastern side of an anticyclone and was presumably stratocumulus. There was no ice cloud because cloud-top temperature was -2°C so glaciation was switched off.

In conclusion, the model made a reasonably good job of forecasting the supercooled liquid water observed within the frontal cloud band, despite the likelihood that the forecast ascent rate was too large in the experimental area.

5.5 30 March 1999

Synoptic Situation

The icing part of this flight was from 1411 – 1555z and the experimental area extended southeastwards from north of the Wash as far south as central East Anglia. At 12 z a warm front was oriented WSW to ENE from the Isle of Wight to the Thames estuary and then into the southern North sea. A wave was developing on the front SW of Cornwall. The Meteosat infrared images show a band of cold cloud, minimum cloud-top temperature –40 to – 50°C aligned with the front. The developing wave was signaled by a bulge in the northern edge of the cloud extending to the Bristol Channel and the Midlands.

The model combined IWC field shows a band of cloud in excellent agreement with the satellite imagery, although the bulge in the cloud associated with the wave extends further north east than observed. Near the developing wave, the model IWCs exceed 0.4 gKg^{-1} but there is a minimum over the experimental area where IWC < 0.1 gKg^{-1}. Presumably this is a region of descent ahead of the wave. The model rainfall rate field closely follows the maximum IWC field, with peak rates 4 – 8 mmh^{-1} associated with the wave and minimum rates < 0.5 mmh^{-1} over the experimental area. There are no observations near the experimental area but the nearest synoptic observations show no rain , drizzle or light rain.

Aircraft Data

There were two profiles and three horizontal runs during the period 1411 - 1555z. Negligible cloud was encountered during P1. Table 12 gives details of the horizontal runs and mean mixing ratios.

Table 12 Details of Horizontal Runs and Mean Mixing Ratios for 30 March 1999

Run No.	Time	Temperature (°C)	Run Length (Km)	LWC (gKg^{-1})	2D-C IWC (gKg^{-1})	Nev. TWC (gKg^{-1})
36	1437 - 1507	-3.5 to -5.5	162	0.051	0.067	0.070
37	1508 - 1519	0 to -8	59	0.090	0.10	0.12
38	1543 - 1555	0 to -9	62	0.046	0.068	0.057

The essential feature of Table 12 is the low SLWC, IWC and TWC values, although LWC/(LWC + IWC) is still around 0.4. Although the SLWC values are quite low, the high degree of correlation between the FSSP, J-W and Nevzerov data suggests a genuine signal.The low values are compatible with this being an inactive part of the front. Profile 2 shows a cloud which is virtually continuous from 1.5 to 4.7 Km (-16°C) but with LWC and IWC values < 0.1 gKg^{-1} apart from a few large peaks. The infrared cloud-top temperature was -40 to -50°C so the cloud extended well above the top of the profile. Only the maximum ice accretion for run 3 (2.5 mm) was not entirely negligible.

Model forecasts

The main features of the forecasts are -

(i) The model has no supercooled liquid water anywhere near the experimental area

(ii) The model IWC values are all < 0.1 gKg^{-1} along the flight track and in the majority of the North sea, although values 0.1 - 0.2 gKg^{-1} approach from the east at 15 and 16z.

(iii) The model had a single ice cloud layer with cloud-top temperature -35°C for run 36 and -20 to -30°C for run 38. Although this is significantly warmer than reality, it is not warm enough to inhibit glaciation in the model.

(iv) The model freezing level was 1.5 - 1.9 km compared to 1.6 to 2 km observed.

(v) The model again forecasts some large areas of supercooled liquid water, with maximum SLWC in excess of 0.4 kKg^{-1}. One area coincides with the developing wave and this only extends to -3°C. The others areas appear to be layer cloud and have no or little ice cloud associated with them as they only extend down to -5 to -8°C.

It can be seen the model has produced a basically realistic solution, except for a degree of overglaciation again. This would at most lead to a failure to forecast a trace icing.

5.6 3 December 1998

It has been noted that on several of the days studied the model forecast large areas of supercooled liquid water away from frontal zones, with SLWC values occasionally exceeding 0.4 gKg^{-1}. This appeared to be Sc/St cloud with cloud-top temperature above -10^oC and so not glaciated by the new scheme. The flight of 3 December was made prior to the icing campaign but significant icing was encountered in an extensive sheet of stratocumulus off the coast of East Anglia. This case has been examined briefly to see if the model predicted this.

The experimental period was 11 – 16z and during this time the properties of the stratocumulus sheet varied little. Profiles of average values and standard deviations are shown in Figure 14. Cloud base was at 400 m (0^oC) and cloud top around 1200 m (-5^oC). The maximum average LWC was 0.8 gm^{-3}, cloud-droplet concentration was 250 – 300 cm^{-3} and r_e around 5 – 8 μm. The Aircraft Scientist's log noted the wind vanes freezing solid at one stage.

The model forecast a band of supercooled cloud stretching along the English Channel and then through the southern North Sea to Denmark, Figure 15. SLWC values exceeded 0.4 gKg^{-1} in places and were generally above 0.2 gKg^{-1}. Values in the experimental area were generally 0.2 – 0.4 gKg^{-1}. Part of the model cloud band also comprised some ice cloud, with IWC values < 0.1 gKg^{-1}. North – South model cross sections through the experimental at 2.3^oE from 11 – 14z show a supercooled liquid water cloud topped by a weak inversion, with cloud base around 600 m and maximum cloud-top height 1300 – 1500 m. Maximum SLWC values were 0.3 – 0.4 gKg^{-1}. A patch of ice cloud is found after 12z, at cloud base. There is no ice cloud at any other level and it is not clear how it was generated.

This case clearly illustrates the benefit of switching off glaciation when $T > -10^oC$ and also the advantage of the new scheme over the previous scheme. The SLWC values are still underestimated even though the new scheme produces an almost entirely liquid cloud. The scheme based purely on temperature would have diagnosed up to 50% ice in the upper part of the cloud which would have settled out, leaving much lower SLWC values. Although this is only one case it helps to give confidence in the forecasts of similar cloud areas in the previous cases.

6. Discussion and Conclusions

Although the SLWC forecasts have been found to be deficient for the frontal cases studied in detail, the forecast SLWC fields are not without merit overall and have some advantages over what would have been diagnosed from the previous scheme. During winter the new scheme produced large areas of supercooled Sc/St, albeit by switching off the initiation of ice when $T > -10^oC$. The previous scheme would have eventually glaciated such cloud, causing it to settle out. The new scheme also forecasts higher SLWC values in association with forced ascent over topographic features. It also forecasts high SLWC values to extend to lower temperatures over high ground. Although not verified by this study, this is believed to be realistic behaviour. The previous scheme was only affected by high ground through the TWC being increased. It would not have diagnosed higher SLWC values appearing at lower temperatures over high ground.

The results for frontal cases strongly suggest that the new scheme produces too great a degree of glaciation. This manifests itself in the forecast supercooled liquid water being confined to a higher temperature range than in reality, generally where $T > -5^oC$. The previous scheme would have always forecast some supercooled liquid water down to -9^oC. A second symptom is the lower ratio of LWC to TWC in the model compared to reality. The fact that initiation of ice has to be switched off in the new scheme if the cloud-top temperature is warmer than -10°C shows the scheme glaciates too much. Reisner et al. (1998) compared aircraft data with SLWC predictions from the NCAR/Penn State MM5 model for two cyclonic winter storms. The model was run with explicit microphysics schemes of increasing complexity. The simpler schemes produced too little supercooled liquid water. Realistic estimates were produced with the most complex scheme which predicted separate mixing ratios for cloud ice, cloud liquid water, snow and graupel. The most important feature for obtaining the realistic SLWC predictions appeared to be the explicit prediction of ice and snow concentrations rather than use of a parameterization. The successful scheme is of a complexity generally associated with cloud-resolving models and appears too costly to implement in the mesoscale model at present.

A second reason for the model to fail to forecast sufficient supercooled liquid water was an incorrect forecast of cloud-top temperature in the range 0 to -20°C. There was no obvious effect of an error in cloud-top temperature when both model and observed values were well below -20°C. An important reason for the model to forecast too cold a cloud-top temperature was the failure of the model to predict multiple cloud layers, as on 30 June 1999. The lower cloud layer had a cloud-top temperature around -4 to -13°C. The model was not helped on this occasion by the high freezing level. This meant the gap occurred at a height where the model has a low vertical resolution. The model may have more chance of resolving gaps within this critical temperature range in the winter when the freezing level is lower.

The model vertical velocity may be another source of error. If this is too small there will be insufficient supercooled liquid water. On 9 June 1999 it appeared to be too large. This generated about the right mean SLWC value but the ratio LWC/IWC was too low. The persistence of supercooled liquid water to -16°C on 30 June 1999 suggests the model vertical velocity may have peaked too low down. Therefore, the model probably has to do better than get the peak vertical velocity correct, it has to get it correct in the layer around 0 to -20°C . Reisner et al. (1998) also concluded that a model had to forecast accurately the kinematic and thermodynamic properties of a cyclonic system in order to make realistic SLWC forecasts.

Another reason for more supercooled liquid water in reality is that it can be produced by convection embedded in a frontal system, while the new scheme is only applied to dynamic cloud and precipitation. This appears to have been a feature of the 9th and 30th June cases. This is likely to be a more serious problem when the scheme is introduced into the global version of the UM.

It is difficult to relate the observed and forecast SLWC values to icing intensity because there is no agreed definition. The Forecaster's Handbook, Table 2.18, suggests only moderate icing is to be found in altostratus, associated with an LWC range 0.1 - 0.3 gm^{-3}. The lower half of this range is comparable with the larger average LWC values observed on the flights reported here. Lewis (1947) produced a more specific definition, based upon the rate of ice accretion on a 3" diameter rod travelling at 200 mph (89 ms^{-1}). This approach emphasises the important role of drop size, which the model could, in principle, attempt to forecast using the model aerosol concentration. According to the Lewis (1947), light icing is associated with accretion rates 1 - 6 gcm^{-2}h^{-1}, moderate icing with 6 - 12.9 gcm^{-2}h^{-1} with severe icing above this. Anything less than 1 gcm^{-2}h^{-1} represents just a trace of icing. These accretion rates are shown plotted in terms of LWC and MVD in Lewis (1947) and sample values are shown in Table 13. (The limit for severe icing at 10 μm is off the graph). The median volume diameter for the flights reported here would mainly be 20 - 30 μm so that most pf the SLWC values encountered should represent light icing or a trace.

Table 13 Ice accretion rates from Lewis (1947) converted to mixing ratios

Median Vol. Diam. (μm)	Light Icing	Moderate Icing	Severe Icing
10	0.23 - 1.3	1.3 -	-
30	0.066 - 0.43	0.43 - 0.82	> 0.82
40	0.033 - 0.3	0.3 - 0.6	> 0.6

The glossary of the FAA Aircraft Icing Handbook (1991) defines icing severity qualitatively as follows -

Moderate icing - The rate of accumulation is such that even short encounters become potentially hazardous and use of de-icing/anti-icing equipment or diversion from the area or altitude is necessary.

Severe icing - The rate of accumulation is such that de-icing/anti-icing fails to reduce or control the hazard requiring immediate diversion from the area and/or altitude.

These descriptions suggest severe icing is associated with intense convection and so it is probably unrealistic to expect the model to forecast it explicitly. Although the description of moderate icing does not restrict it to short distances, it suggests it can occur over short distances, in which case it may not be resolved by the model or be associated with convection. Since the model can only properly resolve features of several grid lengths, it will tend to spread out small scale SLWC features into larger features of lower LWC and fill in holes. It is suggested that rather than just compare LWC values with aircraft data, the maximum accretion over a path length around 50 km should also be used. The fact that only light to possibly moderate icing was found in the frontal flights ties in with the fact that no flights were made into frontal systems where the model had forecast a large area of supercooled liquid water, including some high SLWC values. Such forecasts do occur sometimes, especially in winter.

7. Implications for Forecasting and Future Work

The comparison with in-situ observations shows that the model SLWC forecasts could not be used alone to indicate all the areas where icing was possible. It is likely they would give good guidance for Sc/St cloud with cloud-top temperature warmer than -10°C. In frontal cloud, the horizontal extent of icing would be underestimated, even if the temperature at which the supercooled liquid water was forecast to occur was disregarded. Considering the general underestimation of the occurrence of supercooled liquid water at temperatures more than a few degrees below zero, the forecasts should definitely not be used to indicate the temperature at which the supercooled liquid water will occur. Instead the fields showing the maximum SLWC at any level should be used as an indicator of icing down to -16 to -20°C.

The model forecast could be used in conjunction with the threshold based algorithms to delineate where icing is most likely, because there did appear to be a good correspondence the model forecasting supercooled liquid water and higher SLWC values being observed. It was very rare for the model to forecast supercooled liquid water where none was observed. The model forecasts of convection should also be taken into account, especially to delineate likely areas of severe icing.

The forecasts should not be used within about 10 grid points of the model boundary to avoid spurious areas of supercooled liquid water, until the new scheme is introduced into the global version of the UM.

It is likely that the overglaciation will be accentuated in the global version of the UM because the larger rid box size will lead to lower mean ascent rates.

For the supercooled liquid water fields to form the major component of the forecast and especially to use the forecast temperature range for supercooled liquid water, it is necessary to investigate ways of reducing the glaciation rate.

APPENDIX 1. Microphysical Aspects of the Data

Some of the microphysical aspects of the data are recorded here which might be of relevance to the treatment of cloud and precipitation in the model.

Table A1 Typical Range of Effective Radii (μm)

Date	22 March	30 March	27 May	9 June	30 June
r_e (μm)	12 - 15	8 - 11	4 - 6	8 - 15	10 - 14

In general, r_e settled down to a fairly narrow range once LWC exceeded 0.05 – 0.1 gKg^{-1}. This means that r_e did not generally appear to be correlated with LWC as generally assumed in model parameterisations. This behaviour is well known in stratocumulus where inhomogeneous mixing means that LWC variations are mainly correlated with variations in droplet concentration. It is perhaps surprising to find it in frontal cloud.

A feature of relevance to the cloud fraction parameterisation is the length of unbroken liquid and ice water data. The maximum unbroken length on a run varied from case to case. On 30th June many runs had unbroken liquid water for 30 – 55 km and 2D-C IWC for 40 – 70 km. Assuming the sample along a line is representative of a volume, this suggests several connected model grid boxes would have unit cloud fraction. A completely filled global UM grid box would be much rarer. At the other extreme, on 27 May the maximum unbroken LWC or IWC sample length varied from 3.5 to 16 km so many mesoscale model grid boxes would contain holes.

The longest unbroken length of LWC along a run was generally less than the unbroken length of IWC. However, finite IWCs were generally accompanied by supercooled liquid water, except on 30 March. This has been shown by plotting the 1 Hz data as the ratio LWC/TWC, either from the Nevzerov Probe of from the J-W and 2D-C probes. Although there are excursions from zero to unity the ratio is generally around 0,2 –0.6. Thus liquid and ice generally were found together, at least down to the 100 m scale.

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Figure Legend

Figure 1. Plot of aircraft data against time from runs 4 & 5 on 22 March 1999. (a) J-W LWC (gKg^{-1}), (b) 2D-C IWC (gKg^{-1}), (c) Nevzerov TWC (gKg^{-1}), (d) temperature (^oC)

Figure 2. Model cross sections along run 10 on 22 March 1999, data time 06z, forecast time18z.

Figure 3. Profiles of J-W LWC, 2D-C IWC and Nevzerov TWC from profile 3 on 30 June 1999.

Figure 4. As Figure 3 but for profile 4.

Figure 5. As Figure 1 for run 3 on 30 June 1999.

Figure 6. As Figure 1 for run 9 on 30 June 1999

Figure 7. (a) Maximum SLWC (gKg^{-1}) at any model level from the model forecast for 13z on 30 June 1999, data time 06z. (b) As (a) but maximum IWC (gKg^{-1}).

Figure 8. As Figure 2 but along run 7 on 30 June , forecast time 13z, data time 06z.

Figure 9. As Figure 1 for run 3 on 27 May 1999.

Figure 10. As Figure 7 but from the forecast for 12z on 27 May 1999

Figure 11. Model cross section along run 5 on 27 May 1999, data time 06z, forecast time13z.

Figure 12. As Figure 1 for run 3 on 9 June 1999.

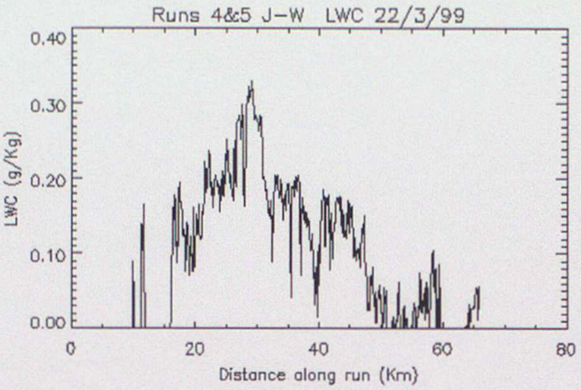
Figure 13. Model cross section along run 3 on 9 June 1999, data time 06z, forecast time12z.

Figure 14. Profiles of average values of liquid water content (gm^{-3}), cloud-droplet concentration (cm^{-3}), effective radius (μm) and total water concentration (gm^{-3}) from the stratocumulus flight of 3 December 1998. The bars indicate standard deviation about the mean.

Figure 15. Maximum SLWC (gKg^{-1}) at any model level from the model forecast for 12z on 3 December 1999, data time 06z

Figure 1 Runs 4&5 on 22 March 1999

(a)



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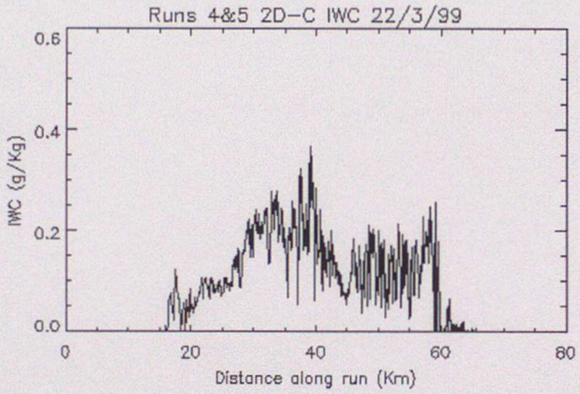

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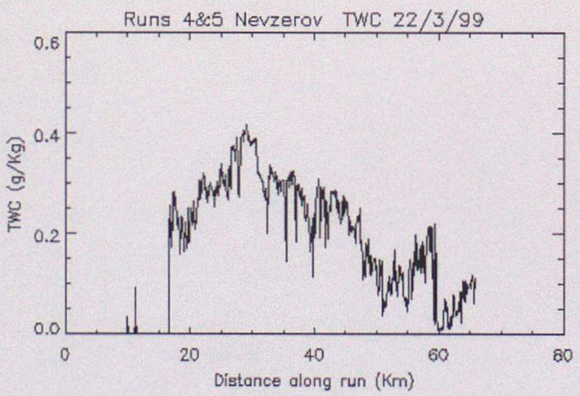

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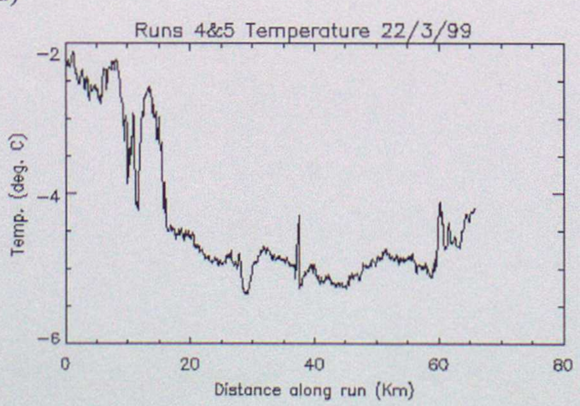


Figure 2. Model cross sections along run 10 on 22 March 19999 based on the 18z forecast

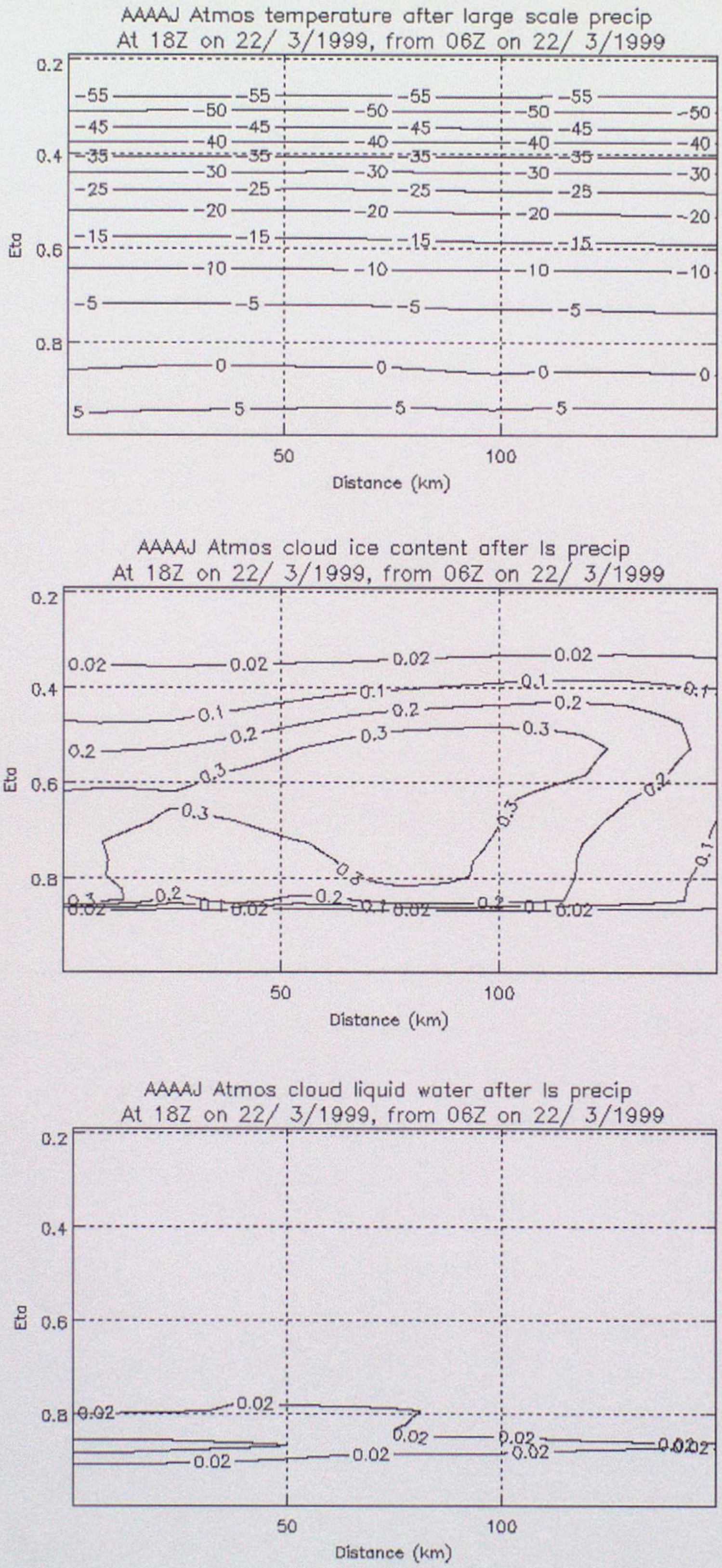


Figure 3 Profile 3 LWC, IWC and TWC on 30 June 1999

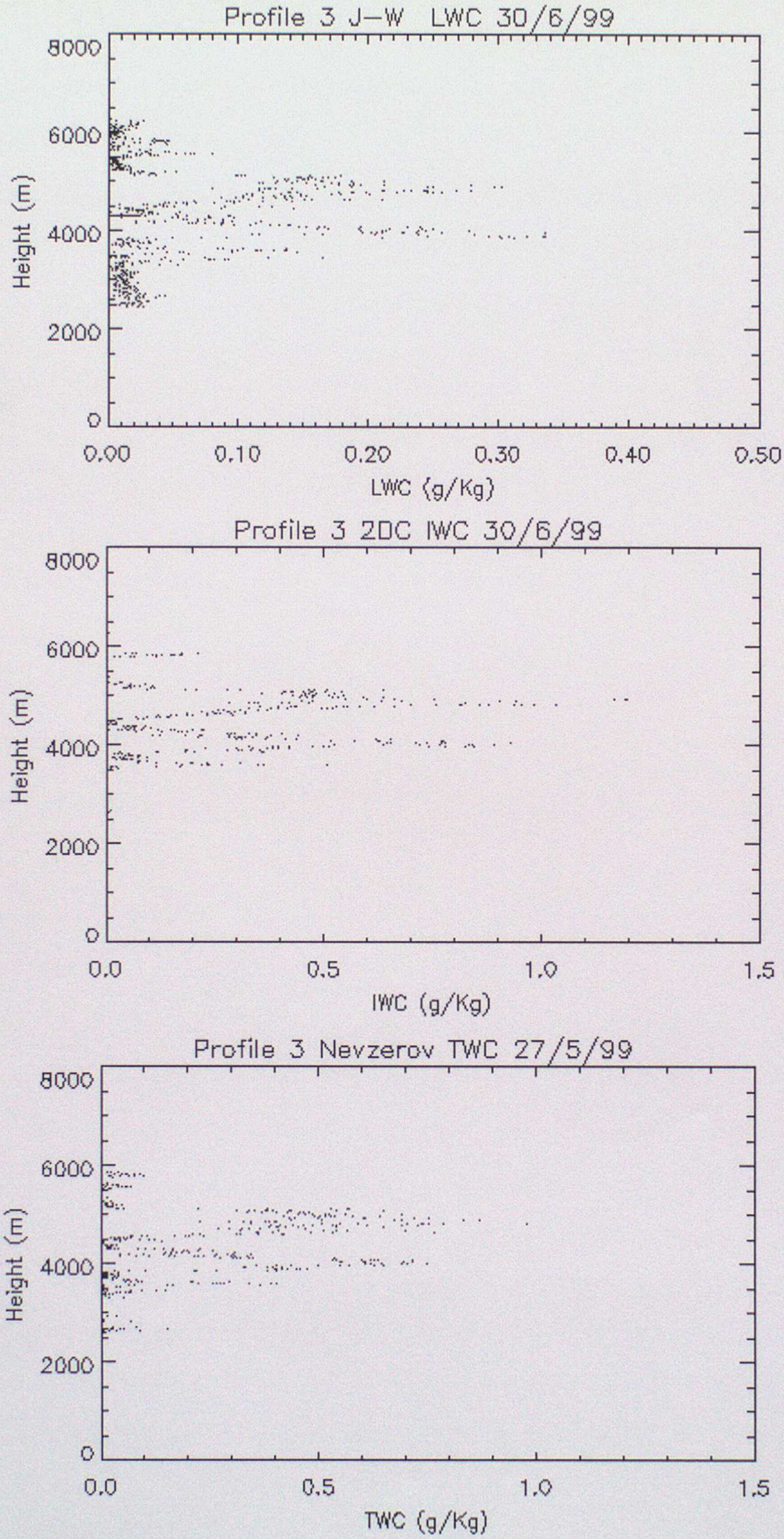


Figure 4 Profile 4 LWC, IWC and TWC on 30 June 1999

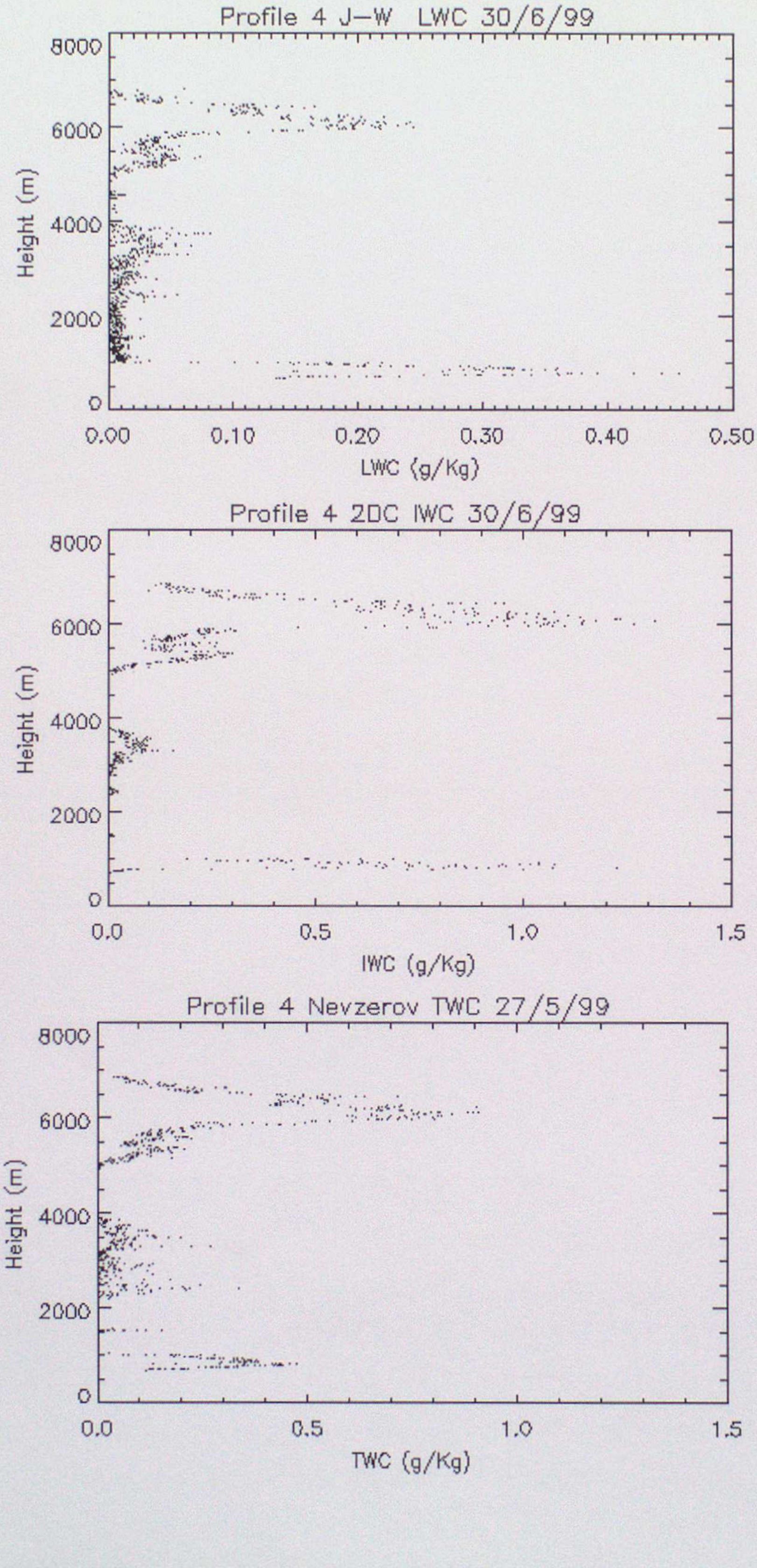
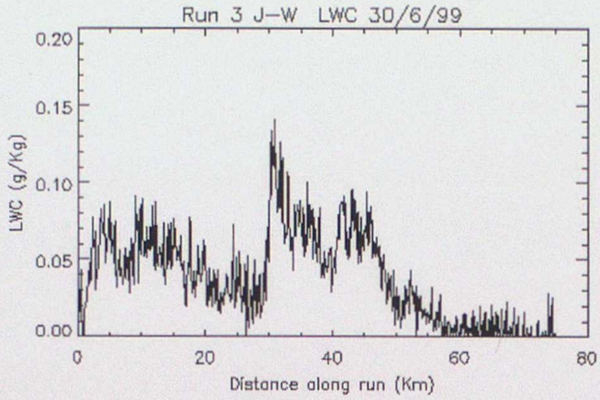
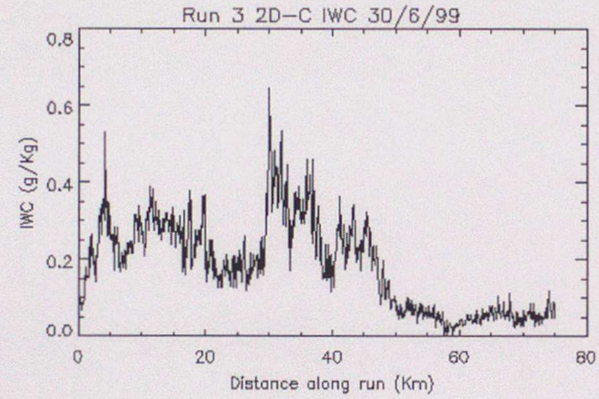


Figure 5 Run 3 on 30th June 1999

(a)



(b)



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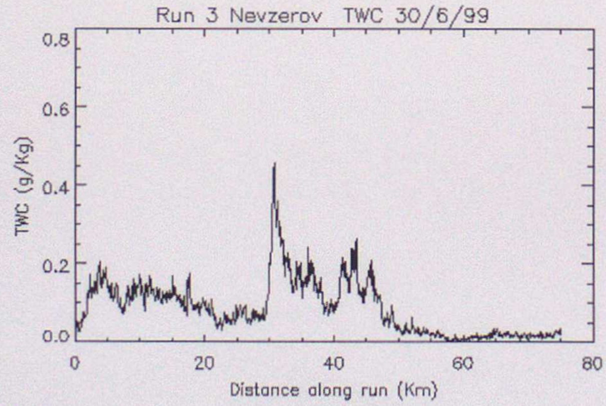

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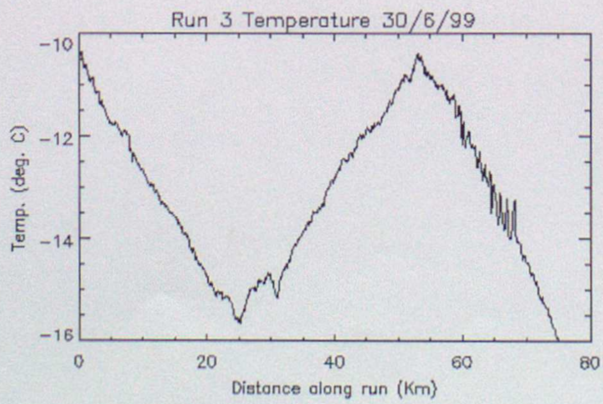
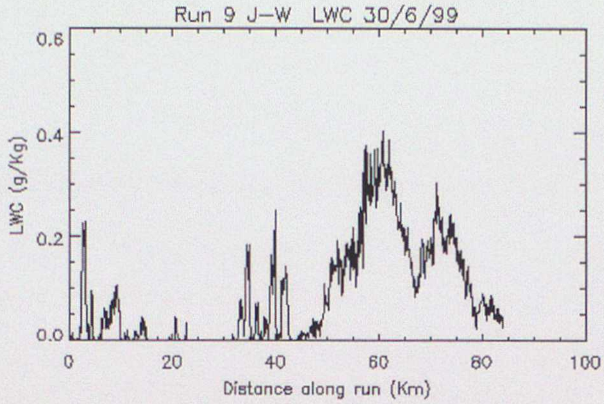
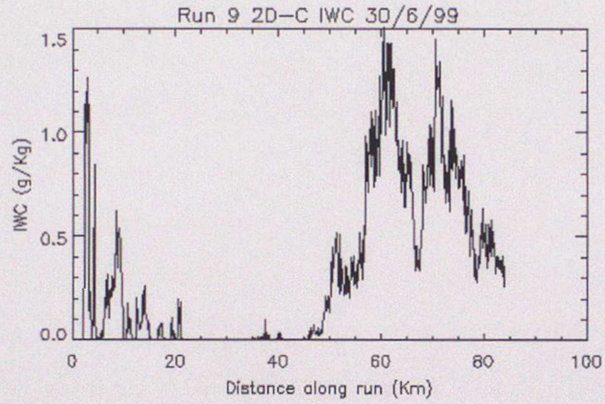


Figure 6 Run 9 on 30th June 1999

(a)



(b)



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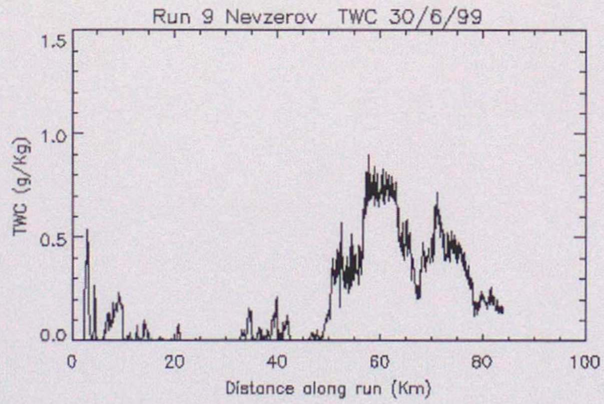


(d)

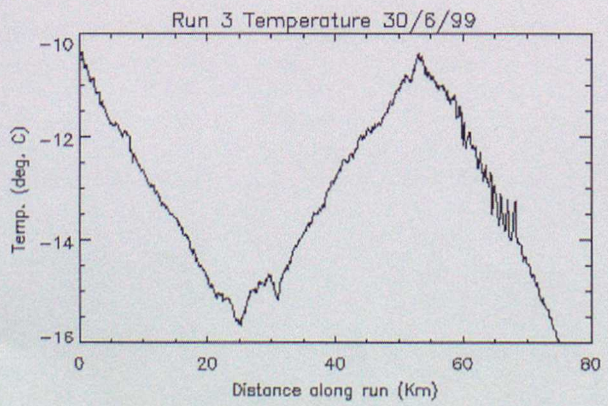


Figure 7 Maximum supercooled LWC and IWC at any model level, 13z forecast for 30 June 1999

(a)

(b)

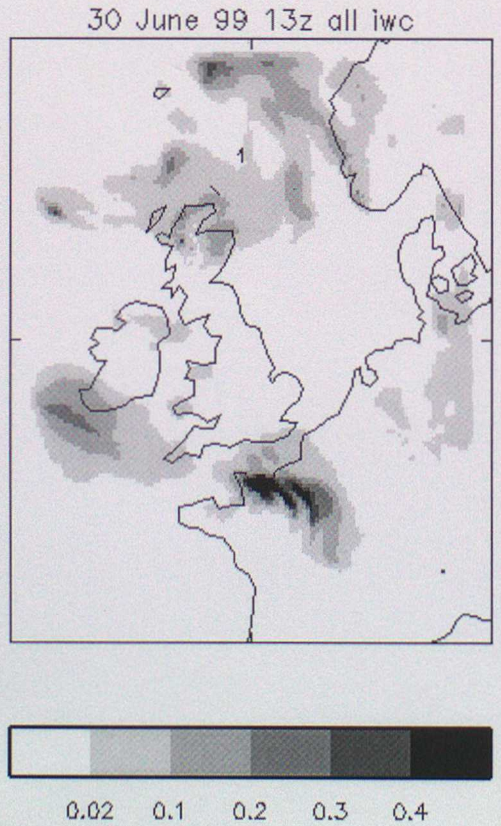
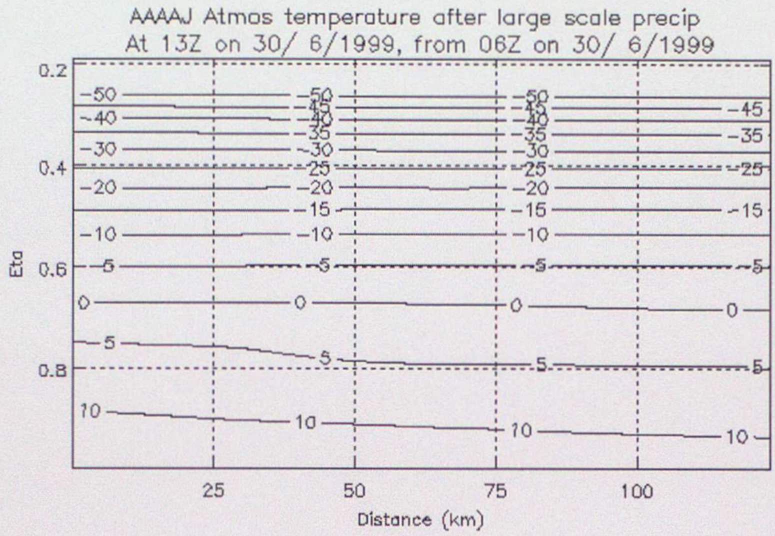
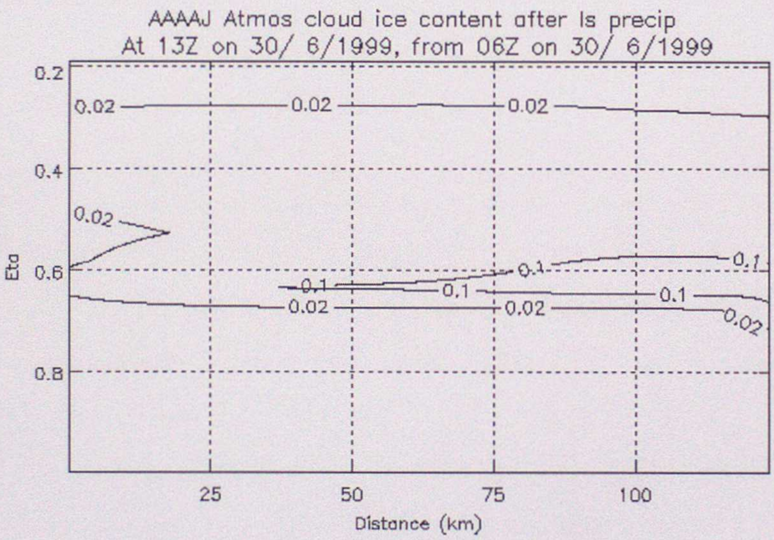


Figure 8. Model cross section along run 7 on 30 June 1999 based on the 13z forecast





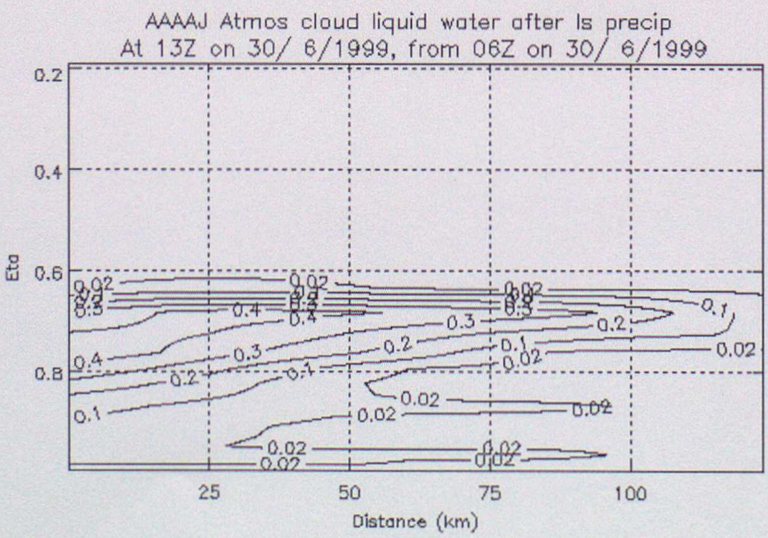
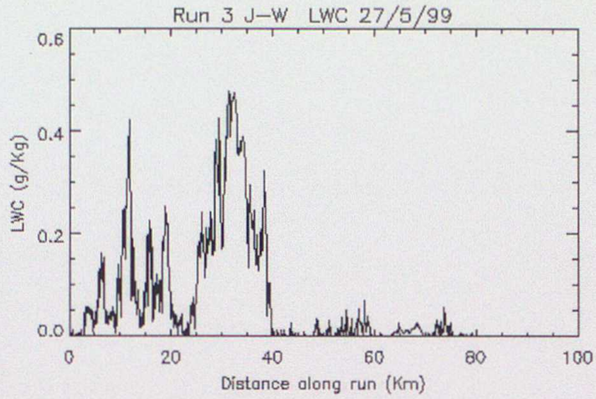


Figure 9 Run 3 on 27th May 1999

(a)



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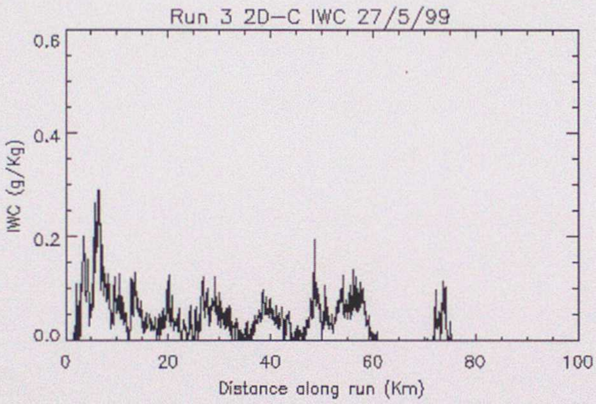

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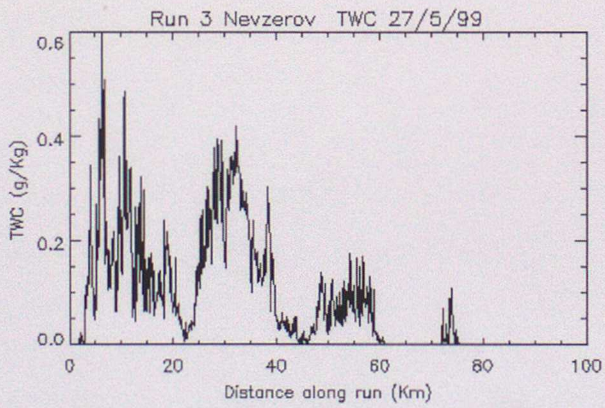

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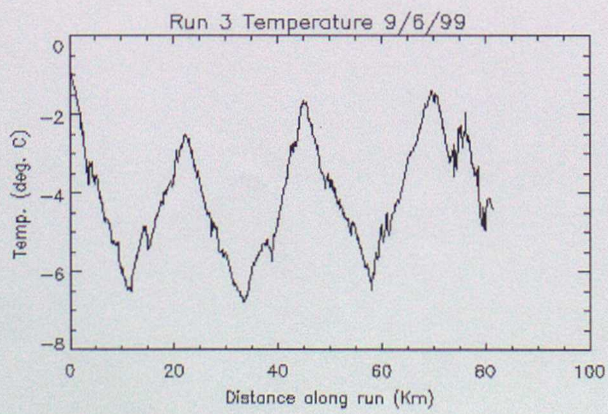


Figure 10 Maximum model supercooled LWC and IWC at any model level, 12z forecast for 27 May 1999

(a)

(b)

Figure 11. Model cross section along run 5 on 27 May 1999 based on the 13z forecast

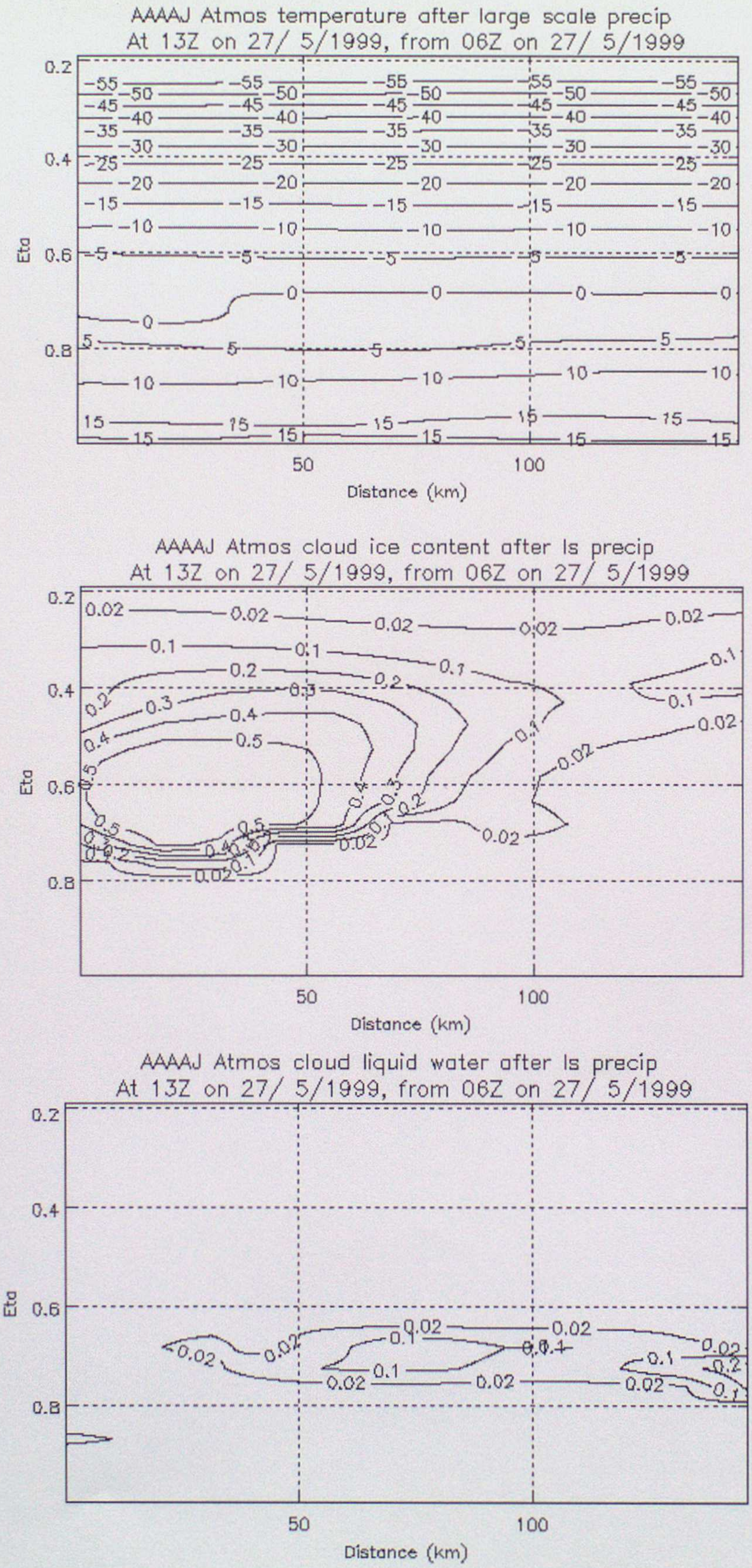
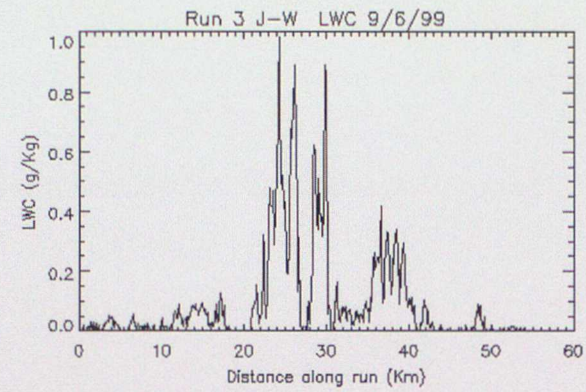


Figure 12 Run 3 on 9 June 1999

(a)



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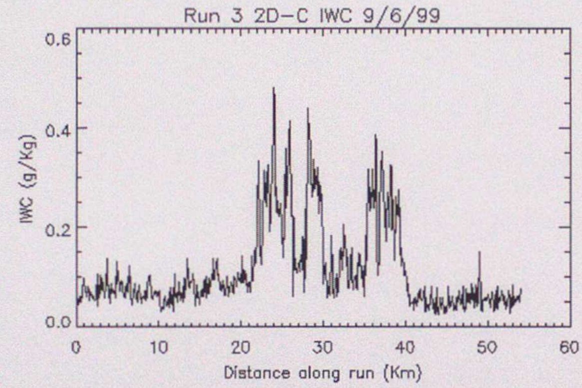

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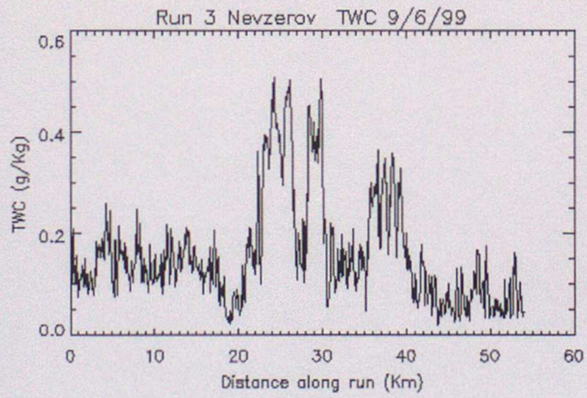

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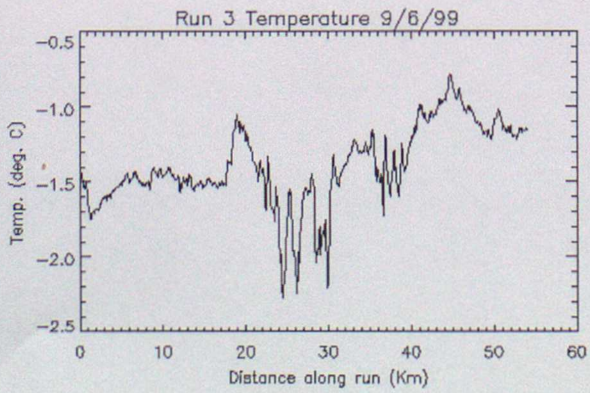

Figure 13 Model cross sections along run 3 on 9 June 1999 based on the 12z forecast

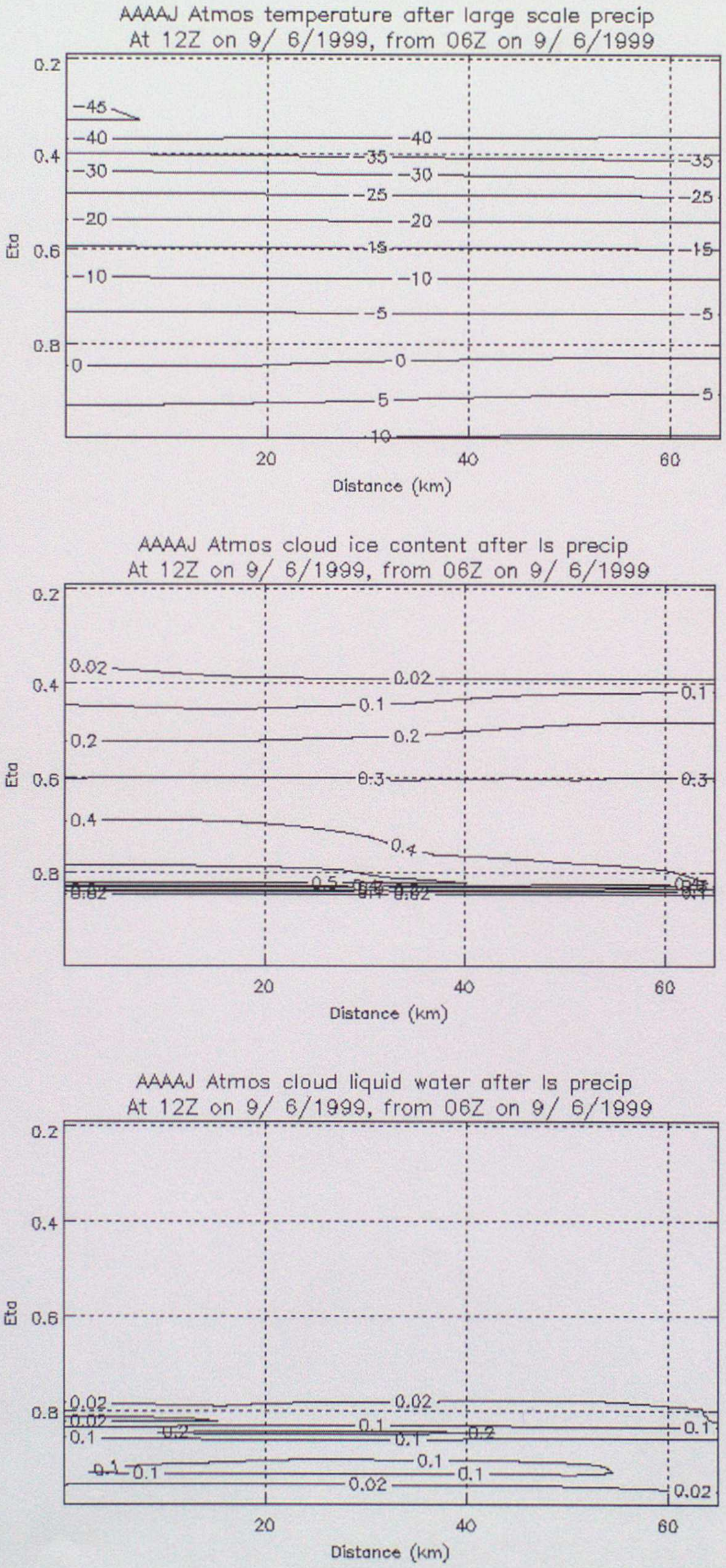

Figure 14 Mean profiles through the stratocumulus cloud on 3 December 1998

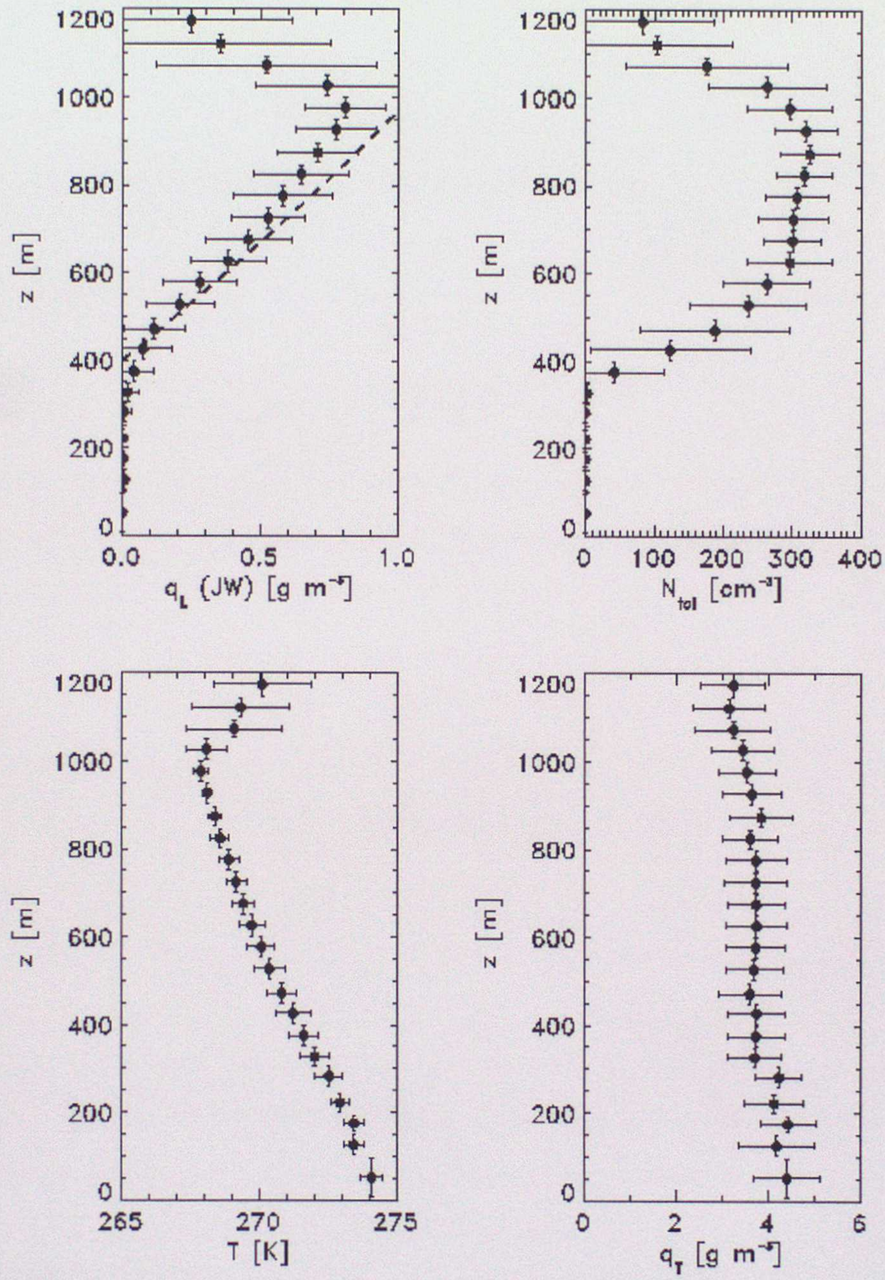

Figure 15 Maximum supercooled LWC at any mode level, 12z forecast for 3 December 1998