A parametrization of the ice water content observed in frontal and convective clouds

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SUMMARY

The properties of the ice phase in a number of cloud types are investigated to improve the ice phase parametrization in atmospheric global-climate models. Frontal clouds over southern England and the sea areas around the British Isles, maritime convective clouds over the North Atlantic, and continental convective clouds over New Mexico and Montana in the USA are studied.

Ice concentrations are seen to be several orders of magnitude higher than those which could be attributed to primary nucleation of ice nuclei at cloud-top temperatures. Thus secondary ice multiplication processes must be operating in each cloud type. Evidence suggests that the process of ice splinter production during riming, the Hallett–Mossop process which operates at temperatures around \(-6\,^\circ\text{C}\), is the dominant mechanism operating.

The data analysed are parametrized as phase ratios, the fraction of cloud condensed water found in the liquid phase, and the variation of this phase ratio with temperature is examined. The greatest differences are observed between frontal and convective clouds, although smaller differences between continental and maritime clouds of the same type are also seen. In general, frontal clouds possess very high fractions of ice across a wide range of temperature. In contrast, convective clouds exhibit a wide range of phase ratio across the whole temperature range observed. These differences are attributed to the greater vertical wind velocities present in convective clouds. These parametrizations have been used in the UK Meteorological Office Global Climate Model. They are valid for clouds which span the Hallett–Mossop splinter-production temperature range.

KEYWORDS: Ice–water mass ratio Parametrization Frontal cloud Convective cloud Secondary ice multiplication

1. INTRODUCTION

Mitchell \textit{et al.} (1989) have shown that the way clouds are treated in atmospheric global-climate models (AGCMs) is very important in determining the climate sensitivity to changes in greenhouse-gas concentrations. The accurate parametrization of the ice phase in AGCMs is important for the following reasons. Firstly, the presence of ice has a major effect on the precipitation efficiency of clouds. In mixed-phase clouds, precipitation grows very efficiently by the Bergeron process or by riming. This can have an important effect on the cloud water budget and microphysics. Secondly, the release of the latent heat in the development of the ice phase can have a marked effect on cloud dynamics and consequently the vertical depth and cloud microphysics (Raymond and Blyth 1992). Thirdly, as clouds become glaciated their optical properties will be determined by the size and shape of the ice crystals rather than the size distribution of water droplets. These will significantly alter the optical depth and particle effective radii of the clouds, which in turn will modify their radiative properties.

The parametrization of mixed-phase clouds in the UK Meteorological Office AGCM relates the proportion of liquid and ice in cloud throughout a grid box to the mean ambient air temperature, \(T\), in the grid box. It is assumed that at temperatures above \(0\,^\circ\text{C}\) all the cloud water is liquid, and at temperatures below \(-15\,^\circ\text{C}\) all ice. The proportion of water in

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the liquid phase, \( F_1 \), between these temperatures is given by the following (Smith 1990).

\[
F_1 = \frac{1}{6} \left( \frac{T + 15}{5} \right)^2 \quad \text{for} \quad -15 \, ^\circ\text{C} < T < -5 \, ^\circ\text{C}
\]

\[
F_1 = 1 - \frac{1}{3} \left( \frac{T}{5} \right)^2 \quad \text{for} \quad -5 \, ^\circ\text{C} \leq T < 0 \, ^\circ\text{C}.
\]

The aim of the work presented in this paper is to examine data from a range of cloud types with a view to refining the parametrization of mixed-phase clouds in AGCMs. These parametrizations need to be simple enough to be used within existing AGCM microphysical schemes but should be based upon a better understanding of processes involved in the development of the ice phase. Cloud types studied include frontal clouds in the vicinity of the British Isles, maritime convective clouds over the North Atlantic, and continental convective clouds from the USA. Published data from other cloud types and regions are also considered. The origins of the ice phase in each cloud type are examined.

2. Data sets, instrumentation and analysis procedures

(a) Data sets

(i) Frontal clouds (UK). In this paper the measurements associated with frontal clouds were all obtained in flights undertaken by the C-130 aircraft of the UK Meteorological Research Flight (MRF), (Nicholls 1978). The flights were carried out in a variety of frontal situations either over the Chilbolton area (Hampshire, southern England), or over the sea areas around the British Isles. In all, eleven flights have been analysed and these are summarized in Table 1.

(ii) Maritime convective clouds (UK). During the middle 1980s a number of flights through maritime cumulus clouds forming in the airstreams off the north and west coasts

<table>
<thead>
<tr>
<th>Flight number</th>
<th>Date</th>
<th>Frontal type</th>
<th>Location</th>
<th>Airmass</th>
<th>Cloud top</th>
<th>Cloud base</th>
</tr>
</thead>
<tbody>
<tr>
<td>H933</td>
<td>18 Sept. 1989</td>
<td>Warm</td>
<td>E North Sea</td>
<td>C</td>
<td>7163</td>
<td>6096</td>
</tr>
<tr>
<td>H963</td>
<td>14 Dec. 1989</td>
<td>Occluded</td>
<td>North Sea</td>
<td>C</td>
<td>3353</td>
<td>610</td>
</tr>
<tr>
<td>H994</td>
<td>2 Apr. 1990</td>
<td>Cold</td>
<td>Chilbolton</td>
<td>M</td>
<td>3048</td>
<td>1829</td>
</tr>
<tr>
<td>H999</td>
<td>10 Apr. 1990</td>
<td>Cold</td>
<td>North Sea</td>
<td>M</td>
<td>5334</td>
<td>1067</td>
</tr>
<tr>
<td>A071</td>
<td>28 Feb. 1991</td>
<td>Cold</td>
<td>North Sea</td>
<td>C</td>
<td>6431</td>
<td>1585</td>
</tr>
<tr>
<td>A162</td>
<td>8 Jan. 1992</td>
<td>Cold with waves</td>
<td>Chilbolton</td>
<td>M</td>
<td>3962</td>
<td>1524</td>
</tr>
<tr>
<td>A163</td>
<td>9 Jan. 1992</td>
<td>Occluded</td>
<td>Chilbolton</td>
<td>C</td>
<td>2499</td>
<td>1433</td>
</tr>
<tr>
<td>A192</td>
<td>28 Apr. 1992</td>
<td>Warm</td>
<td>SW of Cornwall</td>
<td>M</td>
<td>4572</td>
<td>2438</td>
</tr>
<tr>
<td>A201</td>
<td>15 May 1992</td>
<td>Cold</td>
<td>North Sea</td>
<td>M</td>
<td>5364</td>
<td>2316</td>
</tr>
<tr>
<td>A275</td>
<td>8 Sept. 1993</td>
<td>Occluded</td>
<td>W of Scotland</td>
<td>C</td>
<td>4328</td>
<td>1829</td>
</tr>
<tr>
<td>A277</td>
<td>10 Sept. 1993</td>
<td>Occluded</td>
<td>W of Scotland</td>
<td>C</td>
<td>7925</td>
<td>671</td>
</tr>
</tbody>
</table>

Under airmass heading: C = continental and M = maritime.
Under cloud top and cloud base headings: more than one set of numbers refer to measurements made in different regions of the same cloud.
of the British Isles were undertaken by the MRF C-130 aircraft. Penetrations were initially made at around the $-5 \, ^\circ C$ isotherm, usually a mid-cloud level. If the cloud was suitable, additional penetrations were made near to cloud top and cloud base. Particular attention was given to clouds which were seen to be isolated from other clouds of similar depth, were still in their growth phase, and had cloud tops in the vicinity of the $-11 \, ^\circ C$ level.

The results from a preliminary analysis of data from these flights were first reported by Brown and Choularton (1988). In this paper we concentrate on an analysis of results obtained from multiple-level penetrations through two cumulus clouds which were measured in the sea areas off the west coast of Cornwall and north-east coast of Scotland on 1 March and 18 September 1985, respectively. Table 2 summarizes the exact positions and main properties of these clouds.

### Table 2. Summary of UK marine cumulus case-study clouds

<table>
<thead>
<tr>
<th>Property of cloud</th>
<th>Cloud 1 (Flight H708)</th>
<th>Cloud 3 (Flight H750)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date of flight</td>
<td>1 March 1985</td>
<td>18 September 1985</td>
</tr>
<tr>
<td>Approximate position (°N, °W)</td>
<td>50.3°N, 7.5°W</td>
<td>60.2°N, 3.8°W</td>
</tr>
<tr>
<td>Cloud-base temperature (°C)</td>
<td>1.3 ± 0.3</td>
<td>5.1 ± 0.3</td>
</tr>
<tr>
<td>Cloud-top temperature (°C)</td>
<td>−10.0 ± 0.5</td>
<td>−11.0 ± 0.5</td>
</tr>
<tr>
<td>Wind speed and direction</td>
<td>16.5 m s$^{-1}$, 260°</td>
<td>8.5 m s$^{-1}$, 270°</td>
</tr>
</tbody>
</table>

(iii) **Continental convective clouds (USA)**

(a) **New Mexico.** The King Air aircraft of the National Center for Atmospheric Research (NCAR) was used during August 1987 to investigate the clouds that grow over the Magdalena mountains near Socorro, New Mexico. Many of the clouds produce precipitation and lightning, and develop into vigorous thunderstorms. For safety reasons, the King Air aircraft usually discontinued its investigations before the onset of these more severe conditions. Details and results from an analysis of the data from this project have been discussed by Blyth and Latham (1993). The examination of the origins of the ice phase in these clouds is continued in this paper, and a method of parametrizing the concentrations of ice observed considered.

(b) **Montana.** As part of the Cooperative Convective Precipitation Experiment (CCOPE) conducted over the plains of Montana during the summer of 1981, the University of Wyoming King Air research aircraft penetrated many cumulus clouds, chiefly near to cloud top. Many of the clouds investigated were seen to contain significant concentrations of ice. Although a detailed investigation into the origins of the ice phase in these clouds has not been undertaken in this paper, use has been made of the King Air measurements in consideration of the parametrization of the ice phase in convective clouds.

**Instrumentation**

The instrumentation packages aboard the different aircraft were essentially similar for the parameters analysed in this work. The main measurements of the size, shape and number concentration of large water and ice particles in the size range 25–800 μm and 200–6400 μm were made by the Particle Measuring Systems (PMS) two-dimensional cloud (2DC) and precipitation (2DP) probes, respectively. The optical and electronic principles of these devices are fully described by Knollenberg (1970, 1981).
Temperatures were measured by a reverse flow platinum resistance thermometer as well as by other instruments (e.g. aboard the MRF C-130 a remote sensing in-cloud temperature probe (Atkinson et al. 1984) was also used).

In each experiment, cloud liquid-water contents (LWCs) were measured by Johnson–Williams (JW) hot-wire probes. LWC was also derived from or measured by other instruments. In the New Mexican experiment, a King probe was used but this was seen to saturate at around 1.5 g m⁻³. In the absence of significant concentrations of ice (in the CCOPe and New Mexican experiment) Forward Scattering Spectrometer Probe (FSSP) derived values of LWC showed good agreement with JW values (to better than 20% after allowing for the time-lag response of the JW) and were used in the analyses. PMS FSSPs were used primarily to measure cloud droplet size distributions (in the size range 2–47 μm). However, in the presence of significant ice concentrations, the FSSP data can become unreliable (Gardiner and Hallett 1985). Under these conditions, the FSSP LWC is seen to be in excess of JW values by more than 20%, and when this occurred in the continental convective cloud data sets, JW values of LWC were used in the analysis. Ice concentrations were too high in all UK frontal cloud flights to enable use of the FSSP.

Larger cloud drops were measured by a PMS 1D 200X probe (20–280 μm) in the New Mexican experiment, and in Montana by a PMS 1DC probe (19–90 μm). In the UK maritime convective cloud flights presented, a 1D probe was not used, and the FSSP was found to be unserviceable. The C-130 aircraft was, however, fitted with a holographic imaging system on this occasion. These images can be used to derive the number concentration and sizes of water droplets and ice crystals in the size range 10 μm to 1 mm (Adams 1975; Brown 1985, 1989). The drawback is that the analysis of holographic images recorded every second is very labour intensive and lengthy, and so only a few images have been processed. The glaciated regions expected to be of most interest were chosen using the 2D data record.

Details of the full instrumentation package aboard the MRF C-130 aircraft are given by Rogers et al. (1994). Blyth and Latham (1993) discuss in detail the instrumentation aboard the NCAR King Air aircraft during the New Mexico experiment, and also the corrections applied to the data. A detailed account of the instrumentation aboard the University of Wyoming King Air during the CCOPe is given by Cooper et al. (1984). Additional information about the project and some of the issues concerning the instruments may be found in Hill and Choularton (1985), Blyth and Latham (1985) and Bower and Choularton (1988).

(c) Analysis procedures

In each of the data sets examined, information on the size, shape and concentration of large cloud particles has been derived from PMS 2D probe data sets. There are many well documented problems associated with the operation of these probes, such as free running and image truncation (Baumgardner 1987). Also spurious images such as zero area images, hollow images, streakers and splashers need to be removed from data sets before classifying image shapes (Baumgardner 1989). Corrections for these problems were carried out on all data sets, although the method by which subsequent analysis and image classification were carried out varied between data sets.

MRF 2D image-characterization software, based on a method of determining the rotational symmetry of an image by taking a Fourier series representation of its outline (Duroe 1982), was used in the analysis of 2D data recorded aboard the C-130 aircraft. This software and its limitations were described in detail by Moss and Johnson (1994).

For the New Mexican data set, 2D image analysis was mainly carried out by visual recognition, with the aid of simple routines for distinguishing between spherical and non-
spherical particles. For compatibility, MRF characterization software was also used for some of the continental convective cloud data presented. As expected, absolute concentrations of ice differed considerably between the two methods, primarily because of the high fraction of particles rejected by the automatic technique. However, trends in concentrations were consistent, enabling calculated ratios of the concentrations of particles in each phase (the parameters considered in the subsequent sections of this paper) to be compared across data sets.

Images from the holographic system used during the maritime cumulus flights can be consistently characterized if larger than 60 μm. This, together with uncertainties in 2D probe-sample volumes (and the large fraction of crystals rejected by the automatic classification technique), caused concentrations of characterized ice crystals to be consistently larger (by up to a factor of five) when measured by the holographic system in these flights. Known problems associated with the holographic technique (discussed in detail by Brown (1985, 1989)) were reduced by a careful determination of the sample volume, and by restricting the region of sample volume subsequently analysed.

3. ORIGINS OF THE ICE IN THE CLOUDS INVESTIGATED

Analysis and interpretation of the data presented in this and subsequent sections of this paper make consistent reference to the secondary process of ice splinter production during riming, first investigated in laboratory experiments by Hallett and Mossop (1974). In this process (referred to hereafter as the H–M process), ice particles are generated when large ice particles (usually graupel) collide with and accrete supercooled water droplets within the temperature range from −2.5 to −8 °C, leading to the production of ice splinters. The rate at which this process operates (number of ice crystals produced per freezing event) is known to depend upon such factors as the temperature, the concentration of graupel (or riming ice particles), the riming rate (i.e. the rate of sweeping out of supercooled droplets and to a lesser extent the graupel-droplet impact velocity) and the size distribution of supercooled drops (Mossop 1976, 1978a, b, 1985c; Choularton et al. 1980; Foster and Hallett 1982; Heymsfield and Mossop 1984). It is believed that the process is favoured by the presence of cloud droplets larger than about 25 μm in diameter (Mossop and Hallett 1974), and so the mechanism is likely to be more effective in maritime than in continental clouds (where increased droplet numbers generally lead to a smaller mean cloud droplet size).

The presence of smaller droplets (diameter < 12 μm) is also believed to be an essential requirement (Goldsmith et al. 1976; Mossop 1978a); the ratio of smaller to larger drops playing an important role in determining the efficiency of the mechanism. Some studies (e.g. Mossop and Wishart 1978; Mossop 1980; Griggs and Choularton 1983) have suggested that ice splinters are produced when the larger droplets (> 25 μm) impinge upon an already rimed surface of accreted small drops (< 12 μm). Because of their poor thermal contact with the main graupel body, it is suggested that these larger droplets begin to freeze from the outside in rather than from their point of contact. Continued freezing leads to an increase in stress within this shell of ice, and eventually the pressure build-up causes the ice shell to fracture, ejecting several ice splinters. Each splinter may in time grow by vapour diffusion to form further rimers capable of continuing the multiplication process, but new ice particles may be generated instantaneously following collision between splinters and other large supercooled drops.

Under favourable conditions, the H–M process is considered capable of enhancing ice crystal concentrations (at ~ −6 °C) by up to four or five orders of magnitude over concentrations expected to occur as a result of primary nucleation of ice nuclei at the same
Figure 1. (a)–(d) The concentration of (a) bullet rosettes, (b) graupel particles and (c) unclassified small ice particles (see text for definition) seen by the 2DC probe during the descending profile through the cold front cloud layer of 10 April 1990 over the North Sea. (d) The total concentration of all classified ice particles observed (i.e. greater than 125 μm in size and excluding all particles in (c)).
Figure 1. (c)–(h) The concentration of (c) water drops, (f) dendrites, (g) columns and (h) aggregates larger than 125 μm seen by the 2DC probe during the descending profile through the cold front cloud layer of 10 April 1990 over the North Sea.
temperature (e.g. Harris-Hobbs and Cooper 1987), over a time-scale of around 20 minutes in convective clouds (e.g. Chisnell and Latham 1976). As a guide to the degree of ice multiplication occurring within the observed clouds, ice concentrations have been consistently compared in this paper with concentrations of ice nuclei (IN) predicted by Fletcher’s (1962) curve. This parametrizes the number of active IN as a function of temperature, and is based upon a compilation of IN concentration measurements carried out using a variety of techniques. The curve predicts a nearly exponential increase in average IN concentrations with decreasing temperature (in the range from \(-10\) °C to about \(-30\) °C). Meyers et al. (1992) produced an alternative parametrization of the ice crystal concentrations predicted to result from deposition and condensation freezing nucleation (based upon more recent continuous-flow chamber studies). They suggest (1 ice) concentrations are virtually independent of \(T\) above \(-20\) °C and are more strongly related to ice supersaturations, \(S_i\). At higher values of \(S_i\) (above \(-20\) °C) the Fletcher curve is considered to underpredict IN by up to an order of magnitude (although at \(T < -25\) °C the curve is generally considered to overpredict IN). Observed ice concentrations presented in this study still consistently exceed (by several orders of magnitude) the higher values predicted by Meyers et al. (even at the higher \(S_i\) values which may accompany processes such as coalescence). Since the latter parametrization also requires knowledge of ice supersaturations (in the absence of in situ IN measurements) we have continued to compare ice crystal concentrations with the simple temperature relationship of Fletcher, which (limitations accepted) still serves as a useful and consistent tool for this purpose.

Other mechanisms of ice multiplication, which may have been operating in the clouds investigated, are discussed in section 5.

(a) Frontal cloud

Many of the microphysical aspects of the frontal clouds analysed were similar. A typical case was a cold front over the North Sea that was flown through on 10 April 1990. The front was associated with a low-pressure system, centred to the north of Scotland, which was moving quickly eastward into Scandinavia. Although the cold front weakened as it moved south-eastward across the British Isles, in the east it remained quite active with some associated moderate to heavy precipitation. Extensive sheets of altocumulus and thick nimbostratus clouds were encountered during the flight, and cirrus and cirrostratus clouds were observed above the aircraft throughout the study.

A descent was made through the thickest part of the cloud layer associated with the front. The top of the nimbostratus was found to be at around 5.6 km and at a temperature of \(-21.5\) °C. The freezing level (0 °C) was at around 1.8 km. Figure 1 shows how the ice particle habit sampled by the 2DC probe varied with temperature during the descent. The 2DC small-ice category (Fig. 1(c)) includes all ice particles with area less than 50 2DC pixels, and all particles less than 6 pixels wide. The automatic technique is not able to classify these images accurately and so it is not possible to determine the phase or habit of these smaller cloud particles (\(\leq 125 \mu m\)) which can be quite numerous in these clouds. The 2DC ice-concentration category (Fig. 1(d)) includes all ice particles except for those included in the 2DC small-ice category.

During the continuous descent through cloud, three areas were encountered where ice particle concentrations were significantly higher than in adjacent regions. These occurred at temperatures of \(-15\) °C, \(-6\) °C, and near to the freezing level (\(-3.0\) to 0 °C) and can be clearly seen in Fig. 1(d). The enhancement between the temperatures of \(-5\) and \(-7\) °C was observed in nearly all of the frontal cases examined, but the peak at \(-15\) °C was less common. It can be seen that at \(-6\) °C the dominant particle habits are small ice, columns
and aggregates. All the other ice habits have concentrations at least an order of magnitude less than these.

Images recorded by the 2DC probe showed that particles were relatively small (100 to 300 \( \mu m \)) when the aircraft first entered the \(-6^\circ C\) region from above. They appeared to consist of a mixture of small graupel and rimed columns. In the middle of the region columns were more pristine in appearance and quite large, sometimes exceeding 1000 \( \mu m \). Figure 2 shows a typical selection of 2D images from this region. As the aircraft descended towards the freezing level large aggregates were observed together with columns. These were interspersed with smaller particles which could have been either droplets or small graupel.

The temperature, dew-point and total water content all increased relatively smoothly through this region. Although both the vertical velocity and LWC were close to zero, there appeared to be some degree of correlation between them. In the middle of the \(-6^\circ C\) region, LWC peaked at around 0.09 g kg\(^{-1}\), corresponding to a maximum in the vertical wind of about 0.7 m s\(^{-1}\).

The ice particle concentrations recorded at the \(-6^\circ C\) temperature level are much higher than would be expected through primary nucleation processes (by at least four orders of magnitude). This implies that secondary ice-particle production must have been occurring. The concentrations and particle habits observed are consistent with the operation of the H–M splinter production process described earlier.

In frontal clouds, localized areas of convection occur which can produce vertical velocities of the order of 0.6 m s\(^{-1}\) or higher. To enable the H–M process to operate, these updraughts would, firstly, have to occur within the specified temperature regime and, secondly, their velocities would have to be high enough to produce air parcels which

Figure 2. Typical images seen by the 2DC probe as the aircraft moved through the cloud region containing pristine columns at a temperature of around \(-6^\circ C\), on 10 April 1990.
Figure 3. (a)–(h) As Fig. 1, but for a descent through the occluded front cloud layer of 10 September 1993 over the ocean to the west of Scotland.
were supersaturated with respect to water. This would enable cloud condensation nuclei (CCN) to activate and grow into supercooled water droplets. These droplets would have to grow to a large enough size for accretion by ice particles to occur. The lifetime of these droplets would be relatively short, as ice particles would either fall into or be entrained into this parcel of air, causing the water droplets to be either swept out by collision or to evaporate through the Bergeron–Findeisen process. Should collisions occur, then it is likely that a large number of ice splinters would be produced. These would grow initially into ice columns—the preferred ice habit in this temperature and humidity regime. These increased ice concentrations would then be transported away from their generation region either by advection and turbulent diffusion processes or by gravitational settling.

This hypothesized scenario fits well with the observations. Large numbers of ice columns and small ice particles are seen (Figs. 1 and 2) and there is evidence in the 2D probe image data of the presence of graupel and other rimed particles. Because the convective cells and water droplets are relatively short lived it is not surprising that large positive velocities or large numbers of supercooled water droplets are not observed. It is possible that what is being observed in this case is the effect of an active updraught once it has decayed, but before the large ice–particle concentrations can be dispersed to other parts of the cloud. In some frontal flights there is evidence that this advection process is occurring, because the peak in ice concentrations at $-5$ °C becomes very broad. Figure 3 shows an example of this in a profile through an occluded front to the west of Scotland on 10 September 1993. Here the concentrations of ice particles, small ice and to a certain extent columns, peak at $-4$ to $-5$ °C. This is similar to the previous example, but the enhanced concentrations extend to beyond $-10$ °C. This implies that secondary ice production is occurring in the H–M zone and that these particles are then growing and being advected up to higher altitudes in the cloud.

Another area in the profile through the cloud of 10 April (Fig. 1) where secondary ice-particle production appears to be occurring is near the $-15$ °C temperature level. The observed concentrations of ice ($\sim 2$ cm$^{-3}$) are much larger than can be attributed to primary nucleation even at these colder temperatures. In this case, relatively large numbers of pristine stellar and hexagonal plate type particles were observed, together with large aggregate particles (Fig. 4). Laboratory experiments indicate that these ice habits only occur under a fairly limited range of conditions. The temperature has to be close to $-15$ °C in each case. For stellar shaped particles the air has to be supersaturated with respect to water, while hexagonal plates are generally seen to grow only when the air is subsaturated with respect to water but supersaturated with respect to ice. The presence and large size of these crystal habits implies that secondary ice splinters are growing and developing crystal habits characteristic of the ambient environmental temperature and humidity regime at the level of observation. Although seeding from the cirrus or cirrostratus layers above may be occurring, this would tend to increase ice crystal concentrations throughout the cloud especially near to cloud top (which in this case is around the $-21.5$ °C level). This is not what has been found in most of the data, where highest ice crystal concentrations generally occur in narrow bands well within the depth of the cloud. The lack of dispersion in the band of enhanced ice concentrations around $-15$ °C suggests that an ice multiplication process is operating within this localized region. In this case, secondary ice splinters may be the result of water droplets shattering during freezing or the collisional fragmentation of dendritic crystals (Vardiman 1978).

Secondary ice production via the H–M process is not expected to play an important role in cloud layers which do not fall at least partially within the temperature range from $-3$ to $-8$ °C. In the absence of any other significant ice multiplication processes, much lower ice particle concentrations are expected to result. This was apparently the case in a
mixed-phase stratocumulus layer flown through over East Anglia on 18 December 1990. This cloud layer persisted for several days in a south-easterly flow which originated over the European continent. The layer formed under a strong subsidence inversion and had a cloud-top temperature of between $-12$ and $-13 \, ^\circ\text{C}$ (at around 1830 m), and a cloud-base temperature of $-10 \, ^\circ\text{C}$ (at around 1500 m). Figure 5 shows how concentrations of each ice particle habit varied with temperature in a profile through this stratocumulus layer. Dendrites and aggregates are the most frequently observed habits, and visual inspection of the 2D images showed that pristine stellar particles and hexagonal plates were abundant in the cloud. However, the concentrations of ice particles were at least an order of magnitude less than the ice particle concentrations seen in the clouds that had part of their depth in the temperature range from $-3$ to $-8 \, ^\circ\text{C}$.

(b) Maritime convective clouds

Of the clouds investigated, two (Table 2) were chosen for more detailed analysis on the basis of having good quality holographic data available at two levels or more. To aid interpretation of data, measurements made at each level in both clouds were divided up into averaging intervals of 3 to 10 seconds, within which similar values of updraught, LWC and ice crystal concentration were observed. Tables 3(a) and (b) show the main microphysical properties of clouds 1 and 3 (of 1 March and 18 September 1985, respectively) from a selection of these short averaging intervals (denoted by the letters A to M and A to N). Variations in the concentrations and sizes of particular image categories were seen to occur within these intervals on time-scales of 1 second or less. These were generally associated with particular features in the dynamical structure of the cloud, and were also observed within the holographic data record.
Figure 5. (a)-(h) As Fig. 1, but for the descent through the stratus/cloud layer of 18 December 1991 over East Anglia.
Figure 5. Continued.
<table>
<thead>
<tr>
<th>Run No.</th>
<th>Temperature (°C)</th>
<th>Vertical velocity (m s(^{-1}))</th>
<th>Liquid-water content (g m(^{-3}))</th>
<th>2DC probe data</th>
<th>Holography data</th>
<th>Number of drops (cm(^{-3}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Ice particle concentration (l(^{-1}))</td>
<td>Ice particle concentration (l(^{-1}))</td>
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<td></td>
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<td>Column Diameter &gt; 140 (\mu m)</td>
<td>Column Diameter &lt; 140 (\mu m)</td>
<td>Column Diameter &gt; 140 (\mu m)</td>
</tr>
<tr>
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<td>-0.71</td>
<td>0.33</td>
<td>1.3</td>
<td>15.1</td>
<td></td>
</tr>
<tr>
<td>B</td>
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<td>0.41</td>
<td>0.06</td>
<td>58.3</td>
<td>166.4</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>-9.0</td>
<td>1.03</td>
<td>0.06</td>
<td>2.9</td>
<td>24.9</td>
<td></td>
</tr>
<tr>
<td>R1.1D</td>
<td>-5.9</td>
<td>-1.58</td>
<td>0.05</td>
<td>1.6</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>-6.9</td>
<td>1.52</td>
<td>0.57</td>
<td>23.9</td>
<td>8.8</td>
<td></td>
</tr>
<tr>
<td>F</td>
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<td>0.12</td>
<td>97.2</td>
<td>37.5</td>
<td></td>
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<tr>
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<td>0.34</td>
<td>0.70</td>
<td>5.9</td>
<td>4.8</td>
<td></td>
</tr>
<tr>
<td>R1.3H</td>
<td>-2.6</td>
<td>0.99</td>
<td>0.31</td>
<td>0.3</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>I</td>
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<td>0.19</td>
<td>18.3</td>
<td>25.7</td>
<td></td>
</tr>
<tr>
<td>J</td>
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<td>-0.21</td>
<td>0.06</td>
<td>37.8</td>
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</tr>
<tr>
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<td>0.07</td>
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<td>0.11</td>
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</tr>
<tr>
<td>Run No.</td>
<td>Temperature (°C)</td>
<td>Vertical velocity (m s⁻¹)</td>
<td>Liquid-water content (g m⁻³)</td>
<td>2DC probe data</td>
<td>Holography data</td>
<td>Number of drops (cm⁻³)</td>
</tr>
<tr>
<td>---------</td>
<td>------------------</td>
<td>---------------------------</td>
<td>-------------------------------</td>
<td>----------------</td>
<td>----------------</td>
<td>------------------------</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Ice particle concentration (1⁻²)</td>
<td>Ice particle concentration (1⁻¹)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Column Diameter &gt; 140 μm</td>
<td>Irregular Diameter &lt; 140 μm</td>
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<td>0.00</td>
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<tr>
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<td>0.05</td>
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<td>0.03</td>
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<td></td>
</tr>
<tr>
<td>D</td>
<td>-10.4</td>
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<td>12.9</td>
<td>26.2</td>
<td></td>
</tr>
<tr>
<td>R3.2E</td>
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<td>0.02</td>
<td>14.6</td>
<td>24.9</td>
<td>24.3</td>
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<tr>
<td>F</td>
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<td>0.27</td>
<td>41.7</td>
<td>17.7</td>
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</tr>
<tr>
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<td>39.3</td>
<td>18.4</td>
<td></td>
</tr>
<tr>
<td>H</td>
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<td>58.7</td>
<td>22.1</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>-8.9</td>
<td>-0.13</td>
<td>0.00</td>
<td>5.4</td>
<td>21.3</td>
<td></td>
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<tr>
<td>R3.1J</td>
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<td>-0.05</td>
<td>0.20</td>
<td>25.7</td>
<td>19.4</td>
<td>34.1</td>
</tr>
<tr>
<td>K</td>
<td>-4.6</td>
<td>3.37</td>
<td>0.52</td>
<td>9.8</td>
<td>11.0</td>
<td>19.3</td>
</tr>
<tr>
<td>L</td>
<td>-5.2</td>
<td>0.44</td>
<td>0.18</td>
<td>31.6</td>
<td>13.9</td>
<td>63.8</td>
</tr>
<tr>
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<td>-0.19</td>
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<td></td>
</tr>
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<td>N</td>
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<td>0.46</td>
<td>0.12</td>
<td>32.2</td>
<td>19.0</td>
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</table>

The periods correspond to regions of approximately constant values of liquid-water content, vertical wind speed and ice concentrations (as measured by 2D probes).
In both clouds, larger particles consisted of a mixture of drops, irregular ice crystals and columns, the latter being the habit expected to dominate in the observed temperature range. On average, total ice concentrations (particles of all habits) exceeded concentrations of IN predicted by Fletcher’s (1962) curve for clouds with tops at around the $-11 \degree C$ level by at least three orders of magnitude. It is likely, therefore, that a secondary ice-production mechanism was operating in these clouds. To determine the nature of this mechanism, cloud passes were divided up into regions according to updraught strength. The characteristics of these strong updraught regions ($W > 0.8 \text{ m s}^{-1}$), regions of weak updraught ($0 < W \leq 0.8 \text{ m s}^{-1}$) and regions where downdraughts were predominant have been considered separately.

Cloud 3, investigated during flight H750 (discussed by Brown and Choularton (1988)) was seen to have relatively strong updraught regions ($> 0.8 \text{ m s}^{-1}$) present at all three penetration levels (passes R3.1, R3.2 and R3.3 made at $-4.5 \degree C$, $-8.5 \degree C$ and $-10.0 \degree C$, respectively). R3.3 was made in the vicinity of cloud top and so this observation suggests the cloud was still actively growing. The 2DC data showed that the majority of the ice particles consisted of columns and irregularly shaped crystals. A significant increase in the average concentration of columns was observed in the holographic record between levels R3.1 and R3.2. Allowing for the possibility that some particles may have resulted from fragmentation of larger ice particles striking the camera pod (Brown 1989), the number of pristine columns present at level 1 may have been less than $10^4$. This is still in excess of both the predicted Fletcher IN concentration ($< 0.01 \text{ L}^{-1}$) or the Meyers et al. primary ice concentrations (of $< 1 \text{ L}^{-1}$ assuming water saturation) at this temperature. Brown and Choularton estimated (from manual categorization of 2DC data images with appropriate corrections; the 2DP probe was non-operational) that the concentration of graupel particles ($> 500 \mu m$) was about $1-2 \text{ L}^{-1}$ at this level. Together with a sufficiently high value of LWC (up to $0.5 \text{ g m}^{-3}$), these observations suggest strongly that the H–M process was operating in these clouds.

Using a splinter production rate which was proportional to a function of temperature (based on the laboratory studies of Mossop (1976, 1978a)), and assuming a constant rate of accretion of droplets in the $-3$ to $-8 \degree C$ temperature range, Brown and Choularton estimated the total (cumulative) number of secondary ice particles expected to be present at each of the observation levels. The calculations suggested that for pass R3.1, a column concentration of around $200 \text{ L}^{-1}$ (about half that observed in the mid-level pass R3.2) should have been seen. This is considerably larger than the concentrations actually observed in pass R3.1, but the calculation includes crystals which would have been too small to be positively identified from 2DC or holographic records.

The maximum column length observed in pass R3.2 was $\sim 650 \mu m$. Such crystals have a fall speed of about $0.8 \text{ m s}^{-1}$ (Heymsfield 1972). In the regions identified as strong updraught regions, these (and smaller) particles will have been advected up to the level of each pass from warmer regions below. An estimate was made of the level at which splinter production would need to occur in order to enable growth to the smallest identifiable crystal size at the level of observation. This was achieved by calculating the time taken for splinters (a few micrometres in size) to grow to $60 \mu m$ (effectively the smallest consistently identifiable crystal size using the holographic technique) in a mean updraught of $2.5 \text{ m s}^{-1}$ (a value near to the upper limit of observed updraughts), assuming a crystal growth rate which was a linear function of temperature (Ryan et al. 1976). The temperature profile used followed a moist adiabat to the level of observation. The results of these calculations suggest that columns observed at the lowest level, R3.1, would need to have been formed at or below the $-2.5 \degree C$ level. This is outside the main H–M zone, and so high concentrations of ice would not be expected in such updraughts. Columns observed at the mid R3.2 level,
however, would have grown from splinters produced at or below the $-6.8 \, ^\circ C$ level. This is in the region of maximum secondary ice-particle production by the H–M process. A further large increase in ice crystal concentration between the mid and upper levels (R3.2 and R3.3) would not be expected; only the growth of those crystals ($< 60 \, \mu m$) too small to be identified in pass R3.2 might add to the upper-level concentration. These predictions are in good agreement with the observations.

In cloud 1, updraughts stronger than $0.8 \, m \, s^{-1}$ were observed in the uppermost penetration (pass R1.2 at the $-9 \, ^\circ C$ level), but only in regions horizontally separated from those containing the highest values of droplet and ice crystal concentrations. These latter regions were the only ones which contained significant column concentrations and were thought to correspond to the remains of the updraught regions observed in the middle and lower-level penetrations (passes R1.1 and R1.3 made at the $-6.5 \, ^\circ C$ and $-2.7 \, ^\circ C$ level respectively). The largest column observed in the updraughts of pass R1.1 was about $550 \, \mu m$, and so is likely to have been transported up from lower levels in the cloud. The size spectrum of columns averaged over all updraught regions in this mid-level pass peaked at around $130 \, \mu m$. This is consistent with the growth of splinters formed at the $-4.5 \, ^\circ C$ level by the H–M process. The largest column observed near to cloud top in pass R1.2 was $750 \, \mu m$ long, again consistent with the continued growth of crystals from the mid-cloud level. Although the maximum concentration of columns observed in pass R1.2 was around 270 $l^{-1}$, about 50% larger than the average concentration observed in pass R1.1, individual holograms showed the column concentration to vary between 50 and 265 $l^{-1}$ across pass R1.1 (the mid-cloud level).

In both clouds there were regions of weak updraught ($W < 0.8 \, m \, s^{-1}$) close to the $-5 \, ^\circ C$ level in which there were non-zero values of LWC, and where concentrations of column crystals were larger than those found in neighbouring stronger updraught regions. Because large rimed particles were present across the whole width of these clouds, it is believed likely that the H–M process was also operating in these weak updraught regions.

It is not clear as to whether we should expect the H–M process to operate efficiently in regions of weak updraught. Weak updraughts are unable to sustain riming or graupel particles in the main region of splinter production for as long as strong updraughts. The supply of liquid water to the region would also be diminished, making it less easy to maintain the droplet distributions required in the riming process. Conversely, in weak updraughts, air parcels could remain in the region of maximum splinter production (around the $-5 \, ^\circ C$) level for much longer. If an adequate supply of riming or graupel particles from the upper levels of cloud above could be maintained, and a sufficient supply of droplets was available to continue the riming process, the splinter production mechanism might operate very effectively in these regions.

Calculations suggest that columns grown from splinters formed in an updraught of $0.5 \, m \, s^{-1}$ could remain within 100 m of the zone of maximum production for up to 5 minutes. The concentrations of columns in the weak updraught regions of the mid-level pass of cloud 1 (R1.1) were twice as large as any measured near cloud top in the strong updraught regions (cf. R1.1F or G and R1.2C). In addition, the holographic record showed large concentrations of columns smaller than $140 \, \mu m$ existing in these regions. Assuming the regions remained close to water saturation, then these columns would have been growing at a rate of about $1 \, \mu m \, s^{-1}$ and so must have been observed close to the level at which they were formed. This evidence tends to suggest that the H–M process was operating particularly efficiently in these weak updraught regions.

In the lowest penetration of cloud 1 (pass R1.3 at $-2.5 \, ^\circ C$), the largest concentrations of columns were observed in weak downdraught regions. 2DC data showed these columns to be around $150 \, \mu m$ long, consistent with the idea that they were formed in the region
of maximum splinter production and carried away by sedimentation or downdraughts to the levels of observation. Columns were also detected in neighbouring regions of weak updraught, but holographic records suggest that these were generally larger than 140 μm. This observation level is on the warm temperature limit for the H–M process, suggesting that these more mature crystals were not produced locally but were mixed into the updraughts from neighbouring downdraught regions. This recycling of ice crystals may in part help to maintain the presence of graupel particles in the concentrations required in the H–M zone.

(c) **New Mexican continental convective clouds**

The maximum ice particle concentrations observed in these clouds (as high as 10001−1) showed little dependence on temperature (Blyth and Latham 1993), and were generally several orders of magnitude greater than the concentrations expected to be produced by primary nucleation of IN (at cloud-top temperatures). This is similar to other observations of very high ice particle concentrations in convective clouds (e.g. Keller and Sax 1981; Durosere 1982; Hobbs and Rangno 1985; Mossop 1985a, b; Harris-Hobbs and Cooper 1987; Rangno and Hobbs 1991, 1994), and implies that a secondary ice-multiplication mechanism must have been operating in these clouds. Blyth and Latham presented evidence that the H–M process was the most likely mechanism.

The rate of splinter production via the H–M process has been estimated for the New Mexican clouds, using the equation derived by Harris-Hobbs and Cooper (1987). The pass-averaged rates obtained are summarized in Table 4. They are comparable with those obtained by Harris-Hobbs and Cooper for cumulus clouds over Montana and Florida, and for cloud bands over the Sierra Nevada mountains in California. Calculations were not possible for some New Mexican clouds because they were not penetrated in the relevant temperature zone. In some of the other clouds that were, zero splinter production rates were calculated when no particles classified as graupel were observed in the H–M zone, although graupel was often observed in the regions above and just below. A potential source of riming centres for future splinter production was, therefore, available in many of these cases.

For non pass-averaged (1 Hz) data, splinter production rates of up to several hundreds per cubic metre per second were not uncommon and, in a few cases, rates of a thousand per cubic metre per second were predicted. Figure 6 shows how the unaveraged splinter production rates vary with updraught for the New Mexican data set. The highest rates are

<table>
<thead>
<tr>
<th>Cloud number (as in Blyth and Latham (1993))</th>
<th>Splinter production rate (m⁻³s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.1</td>
</tr>
<tr>
<td>4</td>
<td>16</td>
</tr>
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<td>5</td>
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<td>17</td>
<td>3</td>
</tr>
<tr>
<td>20</td>
<td>16</td>
</tr>
</tbody>
</table>
predicted to occur in the less vigorous regions of cloud, although measurements from within the most vigorous regions (such as strong updraughts containing large concentrations of graupel) are limited. The pass-averaged rates presented in Table 4 may be an underestimate for this reason.

The average splinter production rate for the whole New Mexican data set, limited to updraught regions in the valid temperature range, was found to be about 10 m\(^{-3}\)s\(^{-1}\), again a possible underestimation. The average updraught observed in the H–M zone was then used to estimate the time spent by a typical air parcel in this active region, from which a conservative estimate of the cumulative number of ice particles expected to result from the H–M process was calculated. This figure, around 12 l\(^{-1}\), compares favourably with the average concentration of ice observed at the \(-11\) to \(-12\) °C temperature level, which was around 16 l\(^{-1}\). At this level the majority of splinters (generated by the most recent excursion through the H–M zone) are expected to have had sufficient time to grow to a detectable size. However, larger concentrations of ice of up to 200 l\(^{-1}\) were also observed in moderate updraughts (0.5 < W < 2.5 m s\(^{-1}\)). If generated via the H–M process, some of the higher splinter production rates shown in Fig. 6 (often over an order of magnitude greater than the mean value) must play an important role. If this is so, then the H–M process is capable of generating the very high ice particle concentrations (> 100 l\(^{-1}\)) observed in these clouds.

Figure 7 shows a plot of ice crystal concentration against vertical wind for the complete New Mexican data set (1 Hz data). The majority of ice particles are observed in the less vigorous regions of cloud (|W| < 5 m s\(^{-1}\)), but the highest concentrations seem to occur in weak updraught regions. This is consistent with the H–M process. More cloud passes were undertaken at levels above (rather than below) the H–M zone, so we would expect the largest ice concentrations to be observed in updraughts (if the H–M process is the dominant secondary process operating). Evidence presented earlier suggests that the H–M process is most efficient in weak updraughts, so it is not surprising that the majority of ice particles are observed in the more quiescent regions of cloud. Ice water contents also appear largest.
in quiescent regions, but as expected the largest concentrations of supercooled liquid water are generally found in updraughts.

4. Parametrization of the ice phase

In this section we present parametrizations of the ice phase in frontal and convective clouds. The results, which will be discussed in detail in the next section, suggest that the two cloud types should be treated separately. The parametrizations are only applicable to clouds which span the H–M splinter production zone around \(-6{^\circ}C\).

(a) Frontal clouds

The 2DC image data from the eleven flights in frontal and layer clouds have been analysed to determine the ratio of the mass of water to ice in these clouds with a view to producing a parametrization for numerical models. The analysis is very similar to that described and discussed in detail by Moss and Johnson (1994) for a variety of different cloud types. The frontal flights used by them have been included in this new analysis and data from more recent flights have been added. As in Moss and Johnson, a parametrization of the ratio of the mass of water in the liquid phase to that in the combined ice and liquid phases in frontal clouds, based on the ambient air temperature (as suggested by Smith (1990)), has been derived.

Figure 8 shows how the measured proportion of water varies with ambient air temperature. Each data point represents the mass of liquid water to the mass of liquid water plus ice (the ratio henceforth known as the phase ratio, \(F_1\)), averaged over 2-minute horizontal runs in frontal cloud. This kilometre-scale average removes the variability in phase ratio that occurs across individual cloud passes. However, the large scatter in pass-averaged phase ratios that is seen at temperatures above \(-10{^\circ}C\) (Fig. 8), indicates the large variation in the degree of development of the ice phase that occurs from one cloud to another at these temperatures. In order to generate a grid-box style average phase ratio for use in AGCMs
Figure 8. The phase ratio (the proportion of water to ice and water by mass) in cloud against temperature from the 11 frontal flights in Table 1. Each point represents the average value over a 2-minute horizontal leg in cloud. Crosses indicate clouds in continental airmasses and squares clouds in maritime airmasses. The dotted line is the best-fit line to the data for continental clouds and the dashed line for maritime clouds. The solid line is the current parametrization in the UK Meteorological Office atmospheric global-climate model.

that encompasses these different developmental histories, further averaging is required by fitting best-fit curves to the data presented in Fig. 8. The solid line is the parametrization currently being used in the UK Meteorological Office AGCM. The agreement between the pass-averaged data and this line is relatively good, with the line of best fit through the aircraft results having a similar gradient to the AGCM curve. Although there is a large spread in the data points, the best-fit line indicates that the AGCM curve is approximately 3 degC too cold for frontal clouds. The equation of the best-fit line to all of the data is:

\[ F_1 = 0.0664T + 0.621 \]

where \( T({}^\circ C) \) is the ambient air temperature.

In Fig. 8 the data have been plotted to indicate the difference between maritime and continental airmass clouds, and linear best-fit lines to the data have been calculated and plotted. The equations of these lines are:

\[ F_1 = 0.0631T + 0.857 \quad \text{for continental air} \]

and

\[ F_1 = 0.0686T + 0.616 \quad \text{for maritime air}. \]

This suggests that continental frontal clouds have a slightly smaller proportion of ice in them for a given temperature than maritime clouds. The parametrizations also imply that ice is present at temperatures above 0 °C. This is physically realistic in a cloud with a base temperature above 0 °C as large ice particles would have to fall several hundreds of metres below the freezing level before completely melting. Only phase-ratio values of
between 0 and 1 inclusive are allowed, and so at very low temperatures $F_1 = 0$ and at warm temperatures $F_1 = 1$.

(b) Convective clouds

Phase-ratio values have been calculated for each of the convective cloud data sets. Figure 9 shows a combined plot of the pass-averaged values of this ratio versus temperature. Although averaging across cloud passes removes many of the more extreme values of phase ratio, a wide range of pass-averaged ratios are still observed over a wide range of temperatures. This scatter may be the result, in part, of carrying out penetrations at various levels through clouds of differing age with different basic microphysical properties such as cloud base and cloud-top temperatures, cloud width, and cloud droplet spectrum width (e.g. as suggested by Rangno and Hobbs (1994)), and which may thus be in different stages of development of the ice phase. However, a large spread in phase-ratio values (ranging from regions with virtually no ice to regions of almost complete glaciation) is also observed across individual cloud passes. Figure 10 shows a plot of phase ratio versus temperature for the complete non pass-averaged (1 Hz) New Mexican data set. On this scale, a substantial fraction of cloud water exists in the liquid phase across the whole observed temperature range. Some regions are completely unglaciated at temperatures as low as $-30^\circ$C, and above $-15^\circ$C many regions are still composed of over 90% supercooled water. In contrast, above $-10^\circ$C there are considerably fewer regions where near total glaciation is observed (although highly glaciated regions may have been avoided during aircraft flights). Reasons for this variation will be discussed in section 5.

To obtain a parametrization of the ice fraction based on temperature, the data have been averaged using a ten-point running mean across the temperature range. The solid symbols in Fig. 9 show the result of this averaging process. Again no simple relationship between ice fraction and temperature is obtained, although a trend of decreasing phase
ratio with decreasing temperature is now more evident. Some of the scatter in phase ratio brought about by sampling clouds of different age and ice-phase development has now been removed. As in the frontal cloud case, the aim is to obtain a grid-box style phase-ratio value which in some way averages out the observed variability between clouds and across cloud passes (whatever the source of this variability). Straight-line fits to both the ten-point running mean data (curve 1) and to the simple combined pass-averaged data set without running mean (curve 2) are presented in Fig. 9. Both lines predict similar phase ratios at all temperatures within the observed range. The equation of the best-fit straight line to the ten-point running mean data (curve 1, Fig. 9) is:

\[ F_1 = 0.0151T + 0.885 \]

and the equation of the best-fit line through the pass-averaged data set (without running mean; curve 2, Fig. 9) is:

\[ F_1 = 0.0161T + 0.890 \]

Clearly with no data from regions colder than \(-30 \, ^\circ C\), the parametrizations are valid only at temperatures above \(-30 \, ^\circ C\) and until the phase ratio attains a value of unity above \(0 \, ^\circ C\). Ice is predicted to be present at temperatures above \(0 \, ^\circ C\) for the reasons described in the frontal cloud section above.

Reasons why the phase-ratio values differ so markedly between frontal and convective clouds while the process believed to be responsible for generating ice multiplication in both cloud types (H–M) is the same, will be considered in the next section.

5. Discussion

The properties of the ice phase in frontal clouds over the sea areas around the British Isles, of maritime convective clouds over the North Atlantic, and of continental convective
clouds over the USA have been examined. In all cloud types, ice particle concentrations were several orders of magnitude higher than could be attributed to primary nucleation of ice nuclei at cloud-top temperatures. Therefore, a secondary process of ice multiplication must have operated in each cloud type. Much evidence points to the H–M process of ice splinter production during riming being the dominant mechanism. For example, in frontal clouds graupel particles were present, there were occasional patches of supercooled water, and large concentrations of small columns were found particularly at around the −6 °C isotherm. Major contributions from processes such as seeding from higher cloud layers above have been ruled out on the grounds that such contributions would tend to increase ice-crystal concentrations throughout the clouds, especially near cloud top. This is not what has been found in most of the data, where the highest ice-crystal concentrations have generally occurred in narrow bands well within the depth of the clouds observed.

To use the results of this study in large-scale numerical models the data have been presented as fractions of cloud condensed water present in the ice or liquid phase. The variation of this phase ratio (defined as the fraction of cloud water in the liquid phase) with temperature has been found. The largest differences were seen to exist between frontal and convective cloud types, although smaller differences between maritime and continental clouds of the same type were also evident (particularly in the frontal data set). Thus, separate parametrizations of this phase ratio for frontal and convective clouds have been presented.

Frontal clouds are seen to have very low values of phase ratio over a wide range of temperature, indicating the presence of high ice fractions even at temperatures just below 0 °C. A wide range of ice fractions is observed only in the zone close to the freezing level (0 °C). In contrast, in convective clouds the range of phase ratios is large across the whole temperature range (0 to −30 °C). This difference is attributed to the greater efficiency of the H–M process in frontal clouds.

In convective clouds, the evidence for the H–M process is also strong. Calculations of splinter production rates suggest the mechanism can account for the high ice concentrations observed. However, the larger vertical velocities in convective clouds are believed to limit the efficiency of the mechanism, causing the wide spread in phase ratios observed even at low temperatures, an effect which is even more pronounced on the smaller scale as illustrated in Fig. 10 for the non pass-averaged (1 Hz) data.

It is suggested that the differences in the pattern of glaciation in convective and frontal clouds arise as a result of differences in the characteristic time-scales which operate in each cloud type, and are not due to major differences in the dominant ice multiplication mechanism. These time-scales are governed by the internal dynamics of the clouds. In convective clouds, where updraughts are generally considerably stronger, the time spent in the H–M zone is insufficient to remove all the available supercooled water. Hence, significant proportions of liquid water remain within strong updraughts after passing through the H–M zone. This accounts for the substantial values of supercooled water observed within these clouds at much colder temperatures. In addition, evidence suggests that the H–M process is more efficient in regions of cloud not contained within the strongest updraughts. In weaker updraughts, parcels of air remain resident in the H–M zone for periods long enough to generate high ice multiplication factors. Therefore, the process is believed to have been more efficient in the frontal clouds examined, where average vertical velocities were at least an order of magnitude lower than those in the convective clouds. This would explain the very high phase ratios observed in the convective clouds at temperatures as low as −30 °C.

There is evidence suggesting that in both the frontal and convective clouds examined, another ice multiplication process was operating at temperatures colder than those in the
H–M zone. In frontal clouds, the peak in ice particle concentration at \(-15\ \degree C\) (Fig. 1) is one such example. In the Montana clouds, large concentrations of small ice crystals were also observed high up in clouds where cloud-top temperatures were below \(-20\ \degree C\) (Heapy 1985). Candidate mechanisms for increasing ice concentrations in these regions include ice-crystal seeding from higher cloud layers above, droplet shattering during freezing, and ice-crystal fracture due to collision (Vardiman 1978) and/or due to rapid changes in ambient conditions e.g. during evaporation (Orallay and Hallett 1988). Similarly, at lower levels repeated cycling of ice crystals through the freezing level (Telford et al. 1987) may be the cause of some multiplication. Other processes may cause an enhancement in primary nucleation. Phoretic forces in the vicinity of evaporating cloud droplets, once considered to enhance contact nucleation (Young 1974; Hobbs and Rango 1985), are now considered too short range to have a significant effect (Baker 1991). Increased nucleation may occur in the vicinity of freezing drops (Finnegan and Pitter 1988; Pitter and Finnegan 1990a, b) or in regions of high supersaturation associated with evaporating cloud drops (Rosinski and Morgan 1991) or coalescence (Hobbs and Rango 1990; Rango and Hobbs 1991, 1994). Some of these mechanisms may be capable of generating more ice per event (or per localized region) than the H–M process, but it is considered that these will occur too infrequently in the ambient conditions to generate the ice concentrations observed in the data presented, particularly around the \(-6\ \degree C\) level. However, the parametrized phase-ratio relationships derived should remain valid irrespective of the mechanisms responsible for generating the ice, since they are based on the resultant observed cloud properties.

Rango and Hobbs (1991, 1994) have also analysed large quantities of data from cumulus clouds measured over continental and oceanic regions. Their calculations suggest that in many cases glaciation occurs far too rapidly in these clouds for H–M processes to explain the large concentrations of ice observed. They observe that maximum ice-crystal concentrations are better correlated to the breadth of the droplet spectrum near cloud top than to cloud-top temperatures, and that concentrations in clouds with similar drop size spectra and cloud-top temperatures are higher the wider the cloud (until a critical cloud width is reached, which needs to be larger in the case of continental clouds). They propose that another ice formation mechanism operates in these clouds, producing large concentrations of vapour-grown crystals in regions of enhanced supersaturation near to cloud top. They link this process to the observation of broad droplet spectra, and in particular to the presence of droplets larger than about 30 \(\mu m\) in diameter. We have not included these measurements in our phase-ratio plots because we have not been able to compute ice water contents from their published data. Generally, however, the behaviour of their clouds must be similar to the other convective clouds we have studied and they are probably little different when considering how they should be parametrized in an AGCM. The origin of the high concentrations of ice in these clouds remains an open question.

Clouds which have been analysed in this study and which have not satisfied the conditions required for efficient operation of the H–M process have been found generally to contain significantly lower concentrations of ice. Of particular note is a New Mexican cloud observed on 19 August 1987 (cloud 9 of Blyth and Latham 1993), which persisted for over an hour without collapse, but contained very little ice even though a succession of turrets ascended to around the \(-16\ \degree C\) level before descending back down again to around the \(-13\ \degree C\) level. In this case, the cloud droplet spectrum was much narrower than that measured within other clouds in the same area on the 9th, and few droplets larger than 20 \(\mu m\) diameter were present. The stratocumulus cloud of 18 December 1990 (discussed in section 3(a)) is another example. This cloud layer, which persisted for several days, did not span the H–M region and was found to contain significantly lower levels of ice than other examples which did. Heymsfield et al. (1991) also found the proportion of liquid
water to be very high in altocumulus clouds at temperatures as low as $-30^\circ$C. These clouds did not span the ice splinter production zone and were not subject to seeding from cirrus layers above. In the absence of identified processes for generating ice in substantial quantities in such shallow layer clouds it may be appropriate to consider a parametrization based on primary nucleation processes only.

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