Evidence that ice forms primarily in supercooled liquid clouds at temperatures > -27°C

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Abstract:

Using 4 years of radar and lidar observations of layer clouds from the Chilbolton Observatory in the UK, we show that almost all (95%) ice particles formed at temperatures >-20°C appear to originate from supercooled liquid clouds. At colder temperatures, there is a monotonic decline in the fraction of liquid-topped ice clouds: 50% at -27°C, falling to zero at -37°C (where homogeneous freezing of water droplets occurs). This strongly suggests that deposition nucleation plays a relatively minor role in the initiation of ice in mid-level clouds. It also means that the initial growth of the ice particles occurs predominantly within a liquid cloud, a situation which promotes rapid production of precipitation via the Bergeron-Findeison mechanism.

1. Introduction

The formation of ice in the troposphere is fundamental to the production of precipitation and the maintenance of the global water cycle. Yet this process remains one of the most poorly understood topics in cloud physics, and a major uncertainty in climate models (DeMott et al 2010). Two key factors contributing to this uncertainty are: (i) we do not have a robust characterisation of the way ice is initially nucleated within clouds, and (ii) we do not know the environmental conditions in which the newly-formed ice particles grow, and therefore the rate at which precipitation-sized particles are produced. Clearly problems (i) and (ii) are intimately linked.

The relatively frequent occurrence of a thin layer of supercooled liquid water droplets at the top of ice-phase clouds has been observed in several cases (Rauber and Tokay 1991), but the fraction of ice clouds which have liquid water at the top has not yet been quantified. Recently, Ansmann et al (2009) analysed 4 weeks of observations of short-lived tropical altocumulus clouds and found that liquid droplets were always observed first, before the appearance of ice falling beneath: hence they inferred that deposition nucleation was unimportant in such clouds. Similarly, de Boer et al (2011) analysed low- and mid-level arctic clouds (<4km altitude) using coincident radar, lidar and radiosonde profiles. They show 6 case studies of vertically-pointing radar and lidar observations where liquid was observed overhead before the appearance of ice virga below, although one could argue that this might be due to wind shear near cloud top. They also highlighted one case where the air was supersaturated with respect to ice but below liquid water saturation: ice particles were absent, suggesting liquid droplets were needed for ice to form. Finally, they applied the classification scheme of Shupe (2007) to remote sensing observations over a longer period, from 3 arctic sites, to conclude that liquid-topped ice clouds are the most common cloud type at temperatures between ≈ -25 and -10°C.

The aim of this letter is to use long term radar and lidar observations from the Chilbolton Observatory in the UK to explicitly estimate the fraction of ice clouds (at all heights) which have liquid water at the top, and what this implies for ice nucleation and growth of precipitation-sized particles.

2. Method

Observations were made using the 8.6 and 3.2mm cloud radars (30s integration time, 60m gate length oversampled to 30m), and 905nm lidar (30s x 30m) at the Chilbolton Observatory in the UK. See Illingworth et al (2010) for more details of the instrument specifications. The lidar points 4° off zenith to avoid specular reflection from ice crystals. All data is interpolated on to a universal 30s x 30m grid and smoothed over 1.5 minutes.

The combination of millimetre radar and infrared lidar is a powerful one: it is well established (e.g. Hogan et al 2004) that lidar measurements are extremely sensitive to the presence of supercooled liquid water droplets, because although only ~10μm in diameter, they are present in large numbers (~100cm^{-3}). In contrast, at radar wavelengths backscatter from clouds containing only droplets is extremely weak (<-20dBZ: Khain et al 2008). The strong size dependence of Rayleigh scattering means that although the concentration of ice particles is typically 3-5 orders of magnitude lower than that of droplets, ice crystals are much more reflective, and dominate the radar signal when present (Westbrook et al 2010). An example 5 hour period from 25 June 2009 is shown in figure 1a,b, where ice particles are clearly observed falling from a thin supercooled layer cloud at 5000m altitude (-13°C) between 1920 and 2040UTC. The lidar imagery shows a thin, highly reflective stripe at the top (the supercooled droplets, backscatter > 10^{-4}m^{-1}sr^{-1}), whilst the radar shows the ice particles within the supercooled layer, and falling below with characteristic fallstreak structure. Also shown in this time series are ice-only cirrus clouds (a tenuous layer at 2130-2200 UTC, top -37°C; and a deeper layer near midnight, top -45°C) – radar reflectivities *Z* are within a similar range, but lidar backscatters are much lower, and there are no sharp gradients in the lidar signal.

Rather than analysing the radar and lidar observations profile-by-profile (ie. treating each profile as an independent cloud), discrete ‘layers’ of cloud are identified from the time series. This is done by looking for contiguous regions of radar reflectivity, and labelling each as a separate cloud. To determine if the layer contains ice, we look for clouds where $Z>-20$dBZ for at least 15 rays (7.5 minutes). This *Z* threshold was chosen based on figure 1 of Khain et al (2008) which shows that cloud layers containing only droplets always have reflectivities less than this value.

To avoid misdiagnosis of drizzle drops as ice, only clouds with tops <-10°C are included. Sensitivity tests (see section 4) confirm that our statistics are not affected by drizzle.

Following this segregation, each ice-containing cloud layer is searched for profiles where there is a lidar return ($>10^{-6}$m^{-1}sr^{-1}) within 90m of the radar echo top. This condition is an important one – if the lidar cannot penetrate to the top of the cloud layer, we cannot be sure whether liquid droplets are present or not, and we therefore throw away cloud layers for which this is not satisfied. This methodology distinguishes our statistical analysis from the classification of de Boer et al (2011), who applied Shupe’s (2007) classification scheme. Their scheme infers the presence of mixed-phase layers even when the lidar is extinguished, provided an elevated value (>0.4m/s) of radar Doppler spectral width is present. Spectral width is primarily an indicator of turbulence, and while it is certainly our experience that the top few hundred metres of mixed-phase clouds often have elevated levels of spectral width, this is not always the case: for example no part of the mixed-phase cloud in figure 1 had spectral width values exceeding 0.4m/s. In addition, there are other situations (eg cirrus generating cells) where this turbulent threshold is exceeded. A more robust approach to quantifying the fraction of liquid-topped ice clouds therefore is to only consider cloud layers where the supercooled liquid (or lack of it) can be directly observed by lidar, and this is the approach we have taken in this work.

To determine whether a supercooled layer is present at the top of an ice cloud layer, we look for the sharp increase in backscatter produced at the base of a liquid cloud. Each lidar backscatter profile is searched for a gradient exceeding $5x10^{-7}m^{-2}sr^{-1}$ in the top 500m of the cloud layer, and the lowest range gate in which this occurs is identified as liquid cloud base. If liquid is observed at the top of the ice layer for at least 7.5 minutes, we diagnose it as 'liquid-topped'. If liquid is not observed, but a detectable lidar signal (backscatter > $10^{-6}m^{-1}sr^{-1}$) is obtained from cloud top for at least 7.5 minutes we diagnose it as 'ice-topped'. These thresholds of 7.5 minutes mean that the minimum width of cloud layer included in the analysis is dependent on wind speed, but since most of our cloud layers persist for much longer than 7.5 minutes (see section 3) this is not expected to affect our statistics.

For the purpose of accumulating statistics as a function of cloud-top temperature, clouds where the top is highly variable in temperature (standard deviation for the complete cloud layer >5°C) are discarded. The 5°C value was a compromise between restricting the analysis to well-defined layer clouds with flat-tops, whilst not rejecting upper-level cirrus clouds which are often less homogeneous. The temperature field for each day was obtained from the Met Office operational forecast model with 6-11 hour lead time. Errors in model temperature at a given level are expected to be small (≈1°C: Mittermaier and Illingworth 2002) because of the regular assimilation of radiosonde profiles.

Figure 1c shows how the classification works in practice. The analysis was repeated for 1496 days (4 years) of coincident radar and lidar observations made between 2003-2010 where radar and lidar were available. A total of 917 hours (110,000 30-s profiles) of ice-containing cloud layers which the lidar could penetrate to the cloud top were identified and analysed. The median depth of the liquid layers was 210m (derived from lidar-detected base and radar detected top).

3. Results

Figure 2 (square markers) shows the fraction of ice cloud layers which have supercooled liquid water at the top, as a function of cloud top temperature T. Each temperature bin contains approximately 40 separate cloud layers, persisting for an average of 1.5 hours each. Strikingly, when T>-20°C we observe that almost every single ice cloud has supercooled liquid at the top. This is strong evidence that ice is produced via freezing of droplets in this temperature range, and that either deposition nucleation plays little role in the formation of ice at these temperatures, or that for some reason such nuclei can only become active in liquid clouds.

In colder clouds the fraction of liquid-topped cases falls off steadily. At -27°C half of the ice cloud layers are liquid-topped; at -37°C no liquid-topped clouds are detected. This is consistent with the onset of homogeneous freezing of cloud droplets at this temperature (Mason 1971). Note that the fractions in figure 2 are necessarily underestimates of the fraction of clouds which have had liquid water at the top at some point in their lifetime, because some clouds will have glaciated by the time they are observed, particularly at colder temperatures. This suggests then that ice nucleation *via* the liquid phase is extremely important for a wide range of temperatures: even in clouds as cold as -33C, liquid droplets are detected at the top in ≈15% of cases.

In addition to the implications for ice nucleation, there is also an important ramification for the initial growth and evolution of the ice crystals produced. Ice crystals growing in supercooled clouds do so at the maximum possible rate by vapour deposition, hence producing precipitation-sized particles more rapidly than would occur if nucleation were to occur at lower supersaturations. This should therefore focus our attention on characterising the vapour deposition growth rates in these highly supersaturated conditions.

4. Sensitivity tests

We now test the use of the threshold Z>-20dBZ to diagnose the presence of ice. The first sensitivity test is to simply increase the threshold to -10dBZ to be completely sure that no liquid droplet clouds are being diagnosed as containing ice. The statistics obtained in this case are shown by the diamonds in figure 2. The data is slightly noisier because of the smaller sample (average of 15 layers per temperature bin, as few as 8 in high, cold clouds), but the result is essentially the same, suggesting that our diagnosis is robust.

A second test was carried out to determine whether supercooled drizzle might be mistaken for ice. Large drizzle drops, like ice crystals, have a significant radar cross section. To be sure that drizzle is not affecting our statistics in the warmer clouds, we have analysed a subset (861 days between 2006-2010) of the data where a second lidar pointing directly at zenith was also operating at Chilbolton. Using this data we can easily identify regions of cloud affected by specular reflection from oriented plate-like ice crystals (Westbrook et al 2010). Since we can be sure that clouds with this signature must contain ice, statistics were recomputed for layers where Z>-20dBZ and a layer of specular reflection at least 100m deep was also present. We focus on the temperature range between -10 and -20°C which are the warmest clouds in our analysis, and hence where drizzle would be most likely to form. Conveniently, this also the temperature range where the growth of plate-like crystals occurs

(Mason 1971). The results obtained when this more stringent condition is applied are shown by the triangles in figure 2: again the data are noisier because of the more limited sample, but we observe no significant change from the previous results.

We therefore conclude that our analysis is not sensitive to the thresholds used to diagnose the presence of ice.

5. Conclusions and discussion

The fraction of ice clouds which have a layer of supercooled liquid water at the top has been estimated from an extensive data set of collocated radar and lidar observations. The results strongly suggest that:

1. Supercooled liquid water occurs at the top of the majority of ice cloud layers warmer than -27°C, and is almost always present when the cloud top temperature is greater than -20°C.

2. From the lack of ice-only clouds we infer that deposition nucleation is weak in mid-level clouds, and that ice nucleation proceeds *via* the liquid phase at temperatures > -20°C. This extends the inference made by Ansmann et al (2009) from 4 weeks of lidar observations, to a conclusion based on four years of continuous radar and lidar data.

3. The initial growth of ice crystals takes place in the presence of liquid droplets at temperatures >-27°C, maximising the rate at which the ice particles grow and form precipitation.

Finally, we discuss the limitations of our analysis. First, it was necessary to remove clouds where the top temperature varied significantly. This is a frequent occurrence: many clouds associated with frontal systems are sloped, and multilayered clouds are also common - our analysis rejects these clouds. Second, the radar reflectivity threshold may well filter out cold cirrus layers, simply because the particles are too small to pass the -20dBZ threshold (eg the layer at 2130-2200 UTC in figure 1). In future work we hope to investigate the sensitivity of our results to this using polarisation lidar, which is more sensitive to the presence of small crystals.

The influence of aerosols on the formation of ice has not been considered in this paper: segregating the data according to the origin of the air masses following Seifert et al (2010) may provide a means of assessing this.

The requirement that the lidar has to detect the top of the cloud layer inevitably means that the majority of clouds in our analysis have an optical depth through the ice-phase part of the cloud less than ~ 3; likewise we cannot sample cold clouds which lie above low-level liquid clouds, or during rain. While we see no obvious argument that the nucleation characteristics of clouds obscured in this way would be different to the layers which we can see, it would be desirable to test this. Future work will focus on using space-borne radar and lidar to perform the same analysis, since any liquid at the top of the uppermost cloud layer is then easily detectable.

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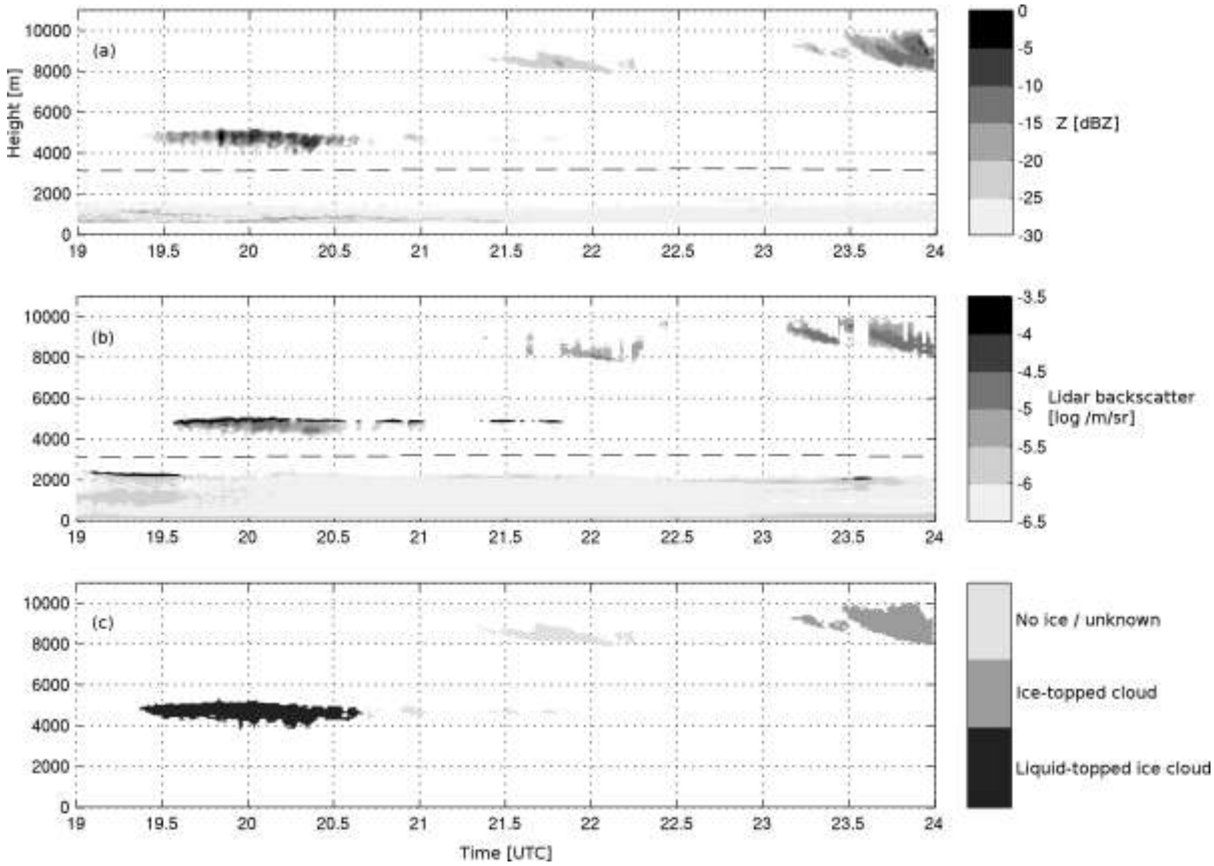

Figure 1: example of cloud observations from 25 June 2009: (a) radar reflectivity, (b) lidar backscatter, (c) classification of cloud layers into liquid-topped ice clouds, ice-topped clouds, and clouds which do not contain ice, whose phase is uncertain, or whose top varies by undulates by more than 5°C. Dashed line in panels (a,b) indicates 0°C isotherm: below this level weak radar returns from insects and lidar returns from boundary layer aerosol/cloud are visible - these features are not included in our analysis.

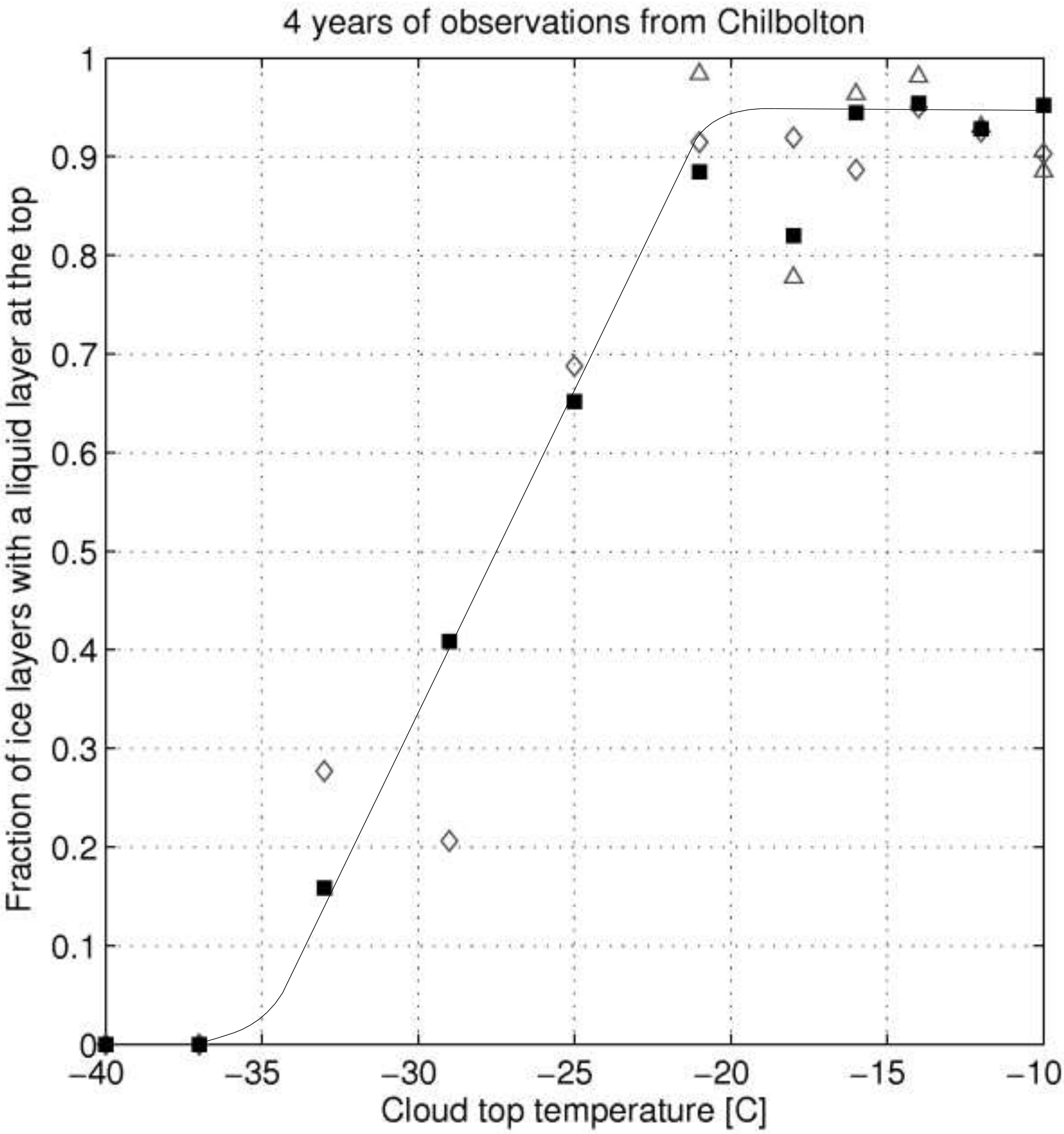

Figure 2: Fraction of ice-phase cloud layers which also have supercooled liquid water droplets at the top, as a function of cloud top temperature (filled black squares). The solid line is intended to guide the eye. Gray symbols are results of sensitivity tests where: threshold for diagnosis of ice particles is increased to -10dBZ (diamonds); specular reflection from oriented ice crystals is needed for diagnosis of ice (triangles). See text for more details.