Estimate of the global distribution of stratiform supercooled liquid water clouds using the LITE lidar

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[1] Supercooled liquid water clouds can occur in the form of thin layers that have a much larger radiative impact than ice clouds of the same water content because of their smaller particle size, yet they are poorly represented in climate models. Such clouds may be easily distinguished from ice by their high lidar backscatter coefficient and sharp backscatter gradient at cloud top. In this paper, data from the Lidar In-space Technology Experiment (LITE), which flew on the space shuttle in 1994, are used to estimate the fraction of clouds that contain supercooled liquid water over the latitude range ±60°. Around 20% of clouds between −10°C and −15°C were found to contain liquid water, falling with temperature to essentially zero below −35°C. Even from this limited dataset some clear latitudinal clear trends were evident, with a distinctly more frequent occurrence of supercooled water in clouds associated with mid-latitude weather systems in the southern hemisphere, as well as in tropical clouds warmer than around −15°C. The results between 40 and 60°N agree well with the distribution previously found at Chilbolton in Southern England (51°N), implying that the forthcoming long-term lidar observations from space will be able to infer the global distribution of mixed-phase clouds with much greater accuracy and vertical resolution than has been possible until now. *INDEX TERMS:* 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 3359 Meteorology and Atmospheric Dynamics: Radiative processes; 3360 Meteorology and Atmospheric Dynamics: Remote sensing; 3394 Meteorology and Atmospheric Dynamics: Instruments and techniques. **Citation:** Hogan, R. J., M. D. Behera, E. J. O'Connor, and A. J. Illingworth (2004), Estimate of the global distribution of stratiform supercooled liquid water clouds using the LITE lidar, *Geophys. Res. Lett.*, *31*, L05106, doi:10.1029/2003GL018977.

1. Introduction

[2] Mixed-phase clouds have the potential to play an important role in the climate system [*Li and Le Treut*, 1992; *Sun and Shine*, 1995], but their representation in climate models has remained rather crude because of the lack of reliable observations that can be used for validation on a global scale. Depolarization lidar is the most established way to infer cloud phase with high vertical resolution [*Sassen*, 1991], and has been used to demonstrate that supercooled liquid clouds tend to occur in the form of thin layers even to temperatures approaching −40°C [*Sassen*, 1984]. However, it is possible to infer phase with reasonable confidence from lidar without depolarization capability. Due to the very different concentrations of cloud condensation nuclei and ice nuclei in the atmosphere, the concentration of droplets in supercooled liquid water clouds tends to be several orders of magnitude greater than the particle concentrations in ice clouds at the same temperature. This makes a given mass of cloud condensate much more optically thick (at visible wavelengths) when in the liquid phase, which in turn causes it to be much more reflective to lidar. *Hogan et al.* [2003a, 2003b] used this property to estimate the occurrence of supercooled layer clouds in over a year of unpolarized ground-based lidar data from Chilbolton in Southern England. The phase of the layers was confirmed by aircraft measurements, and radiative transfer calculations suggested that, when present, their high optical depth caused them to generally have a greater effect on the net radiative fluxes than any ice clouds in the profile.

[3] For such measurements to be of maximum use for models they need to be made around the whole globe. The potential of spaceborne cloud lidar was demonstrated by the LITE instrument, which operated for 53 hours from the space shuttle Discovery in September 1994 [*Winker et al.*, 1996]. It has been used to evaluate the clouds in the model of the European Centre for Medium-range Weather Forecasts [*Miller et al.*, 1999]. As supercooled water tends to occur at the top of cold clouds [*Rauber and Tokay*, 1991], there is an advantage in viewing the scene from above as there is much less obscuration by intervening cloud. In this paper we use LITE data to show how the global distribution of stratiform supercooled liquid water clouds can be estimated from spaceborne lidar. Although the sampling period was very short, the coverage was sufficient to build up reasonable statistics as a function of latitude and temperature, and thereby demonstrate what will be possible from long-term satellite lidar missions, such as IceSat launched in January 2003 [*Zwally et al.*, 2002] and Calipso, due for launch in spring 2005 [*Winker et al.*, 2002].

2. Method

[4] Figure 1 shows two examples of LITE data in which both ice and supercooled liquid water clouds were observed. There is a distinct difference in appearance between the purely ice clouds (such as the one centered at −142° longitude in Figure 1b) and the thin but highly reflective layers which are believed to be composed of liquid water (e.g., centered at −139.5° longitude in Figure 1b). This difference in the backscatter profiles provides a basis by which an algorithm may distinguish between the two.

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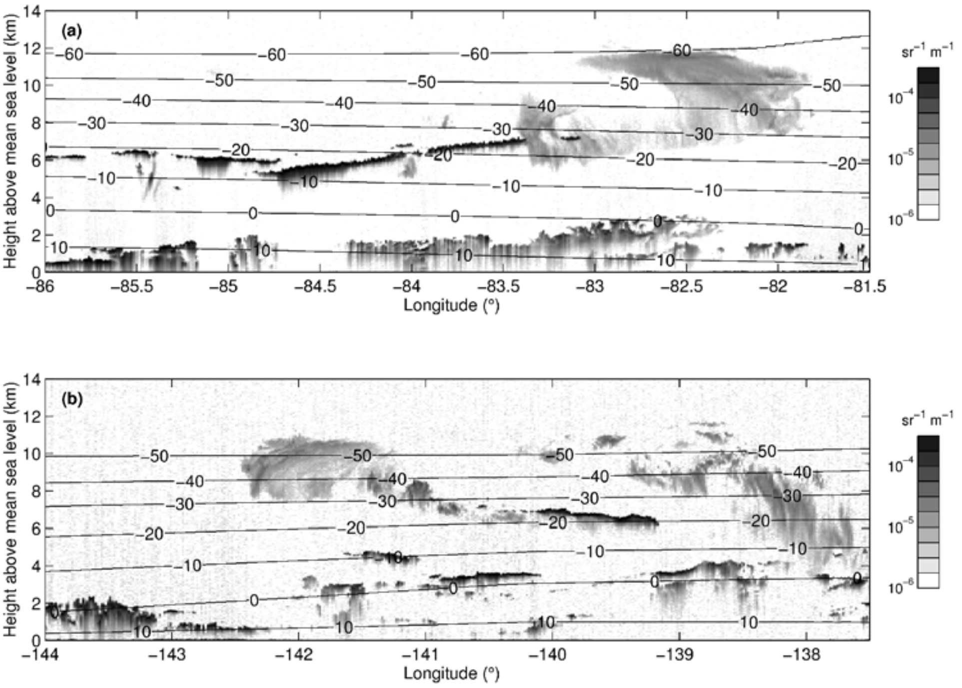

Figure 1. Lidar backscatter at 532 nm from LITE during two 90-s periods containing supercooled liquid water layers, with temperature from the NCEP analysis superimposed: (a) from orbit 72 on 14 September 1994, between the latitudes of 31.5°S and 36.2°S; (b) from orbit 135 on 18 September 1994, between latitudes of 49.6°N and 46.4°N.

[5] The analysis method is similar to that used by *Hogan et al.* [2003b]. Lidar profiles are examined in turn and in each 5°C temperature interval we determine both whether a cloud was observed and whether a liquid layer was present. In thick clouds the lidar signal can be completely extinguished, which causes the total cloud fraction to be underestimated, but since neither a cloud nor a liquid water layer are identified below the region of full extinction, the statistics are unaffected. The temperature was taken from the NCEP analyses, provided as part of the standard LITE product. It should be noted that we are concerned primarily with stratiform clouds; supercooled water in the cores of cumulonimbus clouds is much less radiatively important due to the much lower areal coverage and the fact that convective cores would still be very optically thick even if supercooled water were not present.

[6] Wavelengths of 1064 nm, 532 nm and 355 nm were present, but the 532-nm channel was used as it was found to have the best cloud detection. The data were available with 15-m vertical resolution and 700-m along-track averaging. Cloud was distinguished from instrument noise by using the top 32 pixels (480 m) of each profile to characterize the noise; pixels that had a backscatter less than four standard deviations above the median noise level were rejected. To reduce the probability of contamination by speckle noise, each 5°C temperature interval was deemed to contain cloud only if 4 or more pixels (not necessarily adjacent) within it lay above the threshold. To minimize contamination by aerosols, data in the lowest 2 km above the surface were not used, although as the 0°C isotherm was usually above this height, the effect on the statistics was small.

[7] By integrating the backscatter coefficient through the 300 m around the highest backscatter value in a profile, and utilizing the fact that the extinction-to-backscatter ratio of liquid cloud droplets is approximately constant [*Pinnick et al.*, 1983], *Hogan et al.* [2003b] were able to design an algorithm to identify specifically those liquid water layers with an optical depth greater than 0.7. A correction for the effects of multiple scattering was necessary. Unfortunately, due to the limited dynamic range of the LITE instrument, when the receiver gain was set high enough for reasonable detection of optically thin ice clouds, the reflective nature of liquid water layers meant that they tended to cause receiver saturation and this approach could not be used. We therefore use a much simpler algorithm: a liquid water layer is diagnosed if the maximum attenuated lidar backscatter coefficient in the profile exceeds a trigger level of 2.5×10^{-4} sr^{-1} m^{-1} and the backscatter falls by more than a factor of 20 in the 200 m above the peak value. When a similar simple approach was applied to some Chilbolton lidar data [*Hogan and Illingworth*, 1999], the results were broadly comparable to those from the more complex algorithm of *Hogan et al.* [2003b], but indicated that an accuracy to no better than 20% should be expected.

[8] Profiles are analysed only if the gain setting permits attenuated backscatter measurements of at least 3×10^{-4} sr^{-1} m^{-1} without saturation, thus providing a 20% "headroom" above the trigger level. In fact, only 10.5 hours of LITE data satisfied this criterion, although it should be pointed out that this corresponds to a total distance of 2.8×10^5 km, equivalent to nearly 6 months of observations from a ground-based lidar assuming a mean cloud-level wind speed of 20 m s^{-1}. This gain setting meant that aerosols were generally not detected which helped to minimize the chance of them biasing the estimate of cloud occurrence.

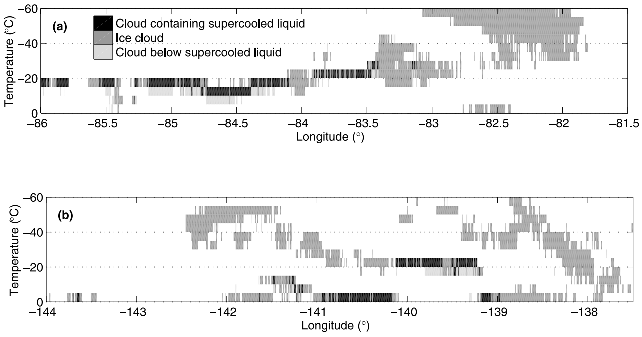

Figure 2. Diagnosis of purely ice cloud and cloud containing supercooled water in each 5°C temperature interval, for the two cases shown in Figure 1. The light gray areas are clouds detected by the lidar but rejected from the analysis because they lie beneath a higher supercooled liquid layer and the algorithm is unable to determine their phase with confidence.

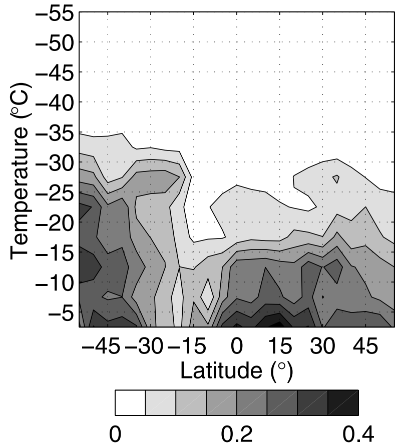

Figure 4. Fraction of clouds in each 5°C temperature interval containing a supercooled liquid layer.

[9] It is unfortunately only possible to identify one liquid layer with confidence in each profile using this algorithm, invariably the highest layer. As the phase of clouds detected beneath the highest liquid layer cannot be determined, such clouds are removed from the analysis. It should be noted that the highest layer in a profile often attenuates the signal to such an extent that the lower clouds of any phase are not detected, although the highest layer is usually the one that influences the radiative fluxes the most [*Hogan et al.*, 2003a].

[10] The values of the parameters used in the algorithm are justified by the agreement with liquid water layers identified subjectively from LITE imagery, and in section 3 by the agreement with ground-based lidar using a more sophisticated algorithm based on integrated backscatter. Nonetheless, it is appreciated that more robust results should be possible from IceSat provided that the low-gain 1064-nm channel does not saturate in liquid clouds.

[11] Figure 2 demonstrates the diagnosis of supercooled water versus temperature for the two cases shown in Figure 1. Note that no attempt is made to diagnose layers lower than 2 km above the surface. The algorithm shows considerable skill in identifying the reflective layers in Figure 1, although some layers are missed because extinction by ice clouds higher in the profile reduces the backscatter of the layer to an extent that it does not trigger the algorithm. This will result in a slight underestimate of the frequency of occurrence of supercooled water.

3. Results

[12] Figure 3 depicts the frequency that cloud of any phase was observed by LITE as a function of latitude, height and temperature. The clouds associated with tropical anvil cirrus and mid-latitude weather systems are clearly apparent, as well as the depleted cloud amount beneath the descending branch of the southern hemisphere Hadley Cell.

[13] The fraction of these clouds that contained a supercooled liquid water layer in each 5°C temperature interval is shown in Figure 4. A clear tendency for the occurrence of supercooled water to decrease with falling temperature is observed, with no significant liquid water detected below around −35°C (indicating that optically thick anvil cirrus do not trigger the algorithm). The existence of enhanced supercooled water between 10°S and 30°N at temperatures down to −10°C could be explained by the previously reported occurrence of shallow convective clouds in the tropics that tend to reach a level of neutral buoyancy a short way above the melting level [*Johnson et al.*, 1999], and possibly detrain into layers at that level. The abundance of super-

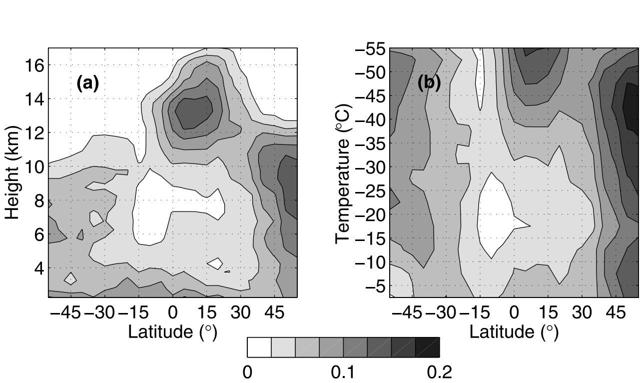

Figure 3. Fraction of pixels in which cloud was observed versus (a) height and latitude; (b) temperature and latitude.

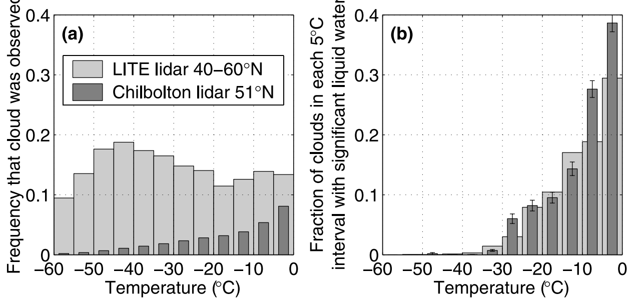

Figure 5. Comparison of lidar observations from LITE between 40°N and 60°N and from Chilbolton at 51°N: (a) fraction of pixels above 2 km observed to be cloudy; (b) fraction of clouds in each 5°C temperature interval containing a supercooled layer.

cooled water between 30°S and 60°S at temperatures down to −30°C is presumably associated with the southern hemisphere storm track, although it is intriguing that so much more supercooled water is observed than at the same latitude band in the northern hemisphere. Much more reliable statistics on supercooled cloud occurrence will be possible from IceSat and Calipso, enabling the latitudinal and seasonal differences to be fully explored.

[14] Lastly we compare spaceborne observations of cloud and supercooled water occurrence with values obtained from the ground. Figure 5 shows the LITE lidar retrievals between 40°N and 60°N (a total distance of 6.2×10^4 km) together with the same parameters estimated from one year of lidar data at Chilbolton in Southern England (51°N). The Chilbolton data were reported by *Hogan et al.* [2003b], and calculated using a more sophisticated algorithm that utilized the integrated backscatter. Figure 5a demonstrates the much better sampling of cold clouds from space; from the ground higher clouds are frequently obscured by the presence of optically thick boundary-layer clouds. The results from space are also much closer to the mean cloud fraction values in the range 0.15–0.2 found by *Hogan et al.* [2001] for heights between 2 and 9 km using ground-based cloud radar at Chilbolton.

[15] Figure 5b shows good agreement between the occurrence of supercooled water from space and the ground, particularly at temperatures colder than −10°C. This is encouraging as one might have expected a single site to be atypical and ground-based lidar observations to be somewhat biased as they exclude the mixed-phase regions of frontal systems due to extinction by low-level cloud.

4. Conclusions

[16] We have shown that spaceborne lidar has the potential to provide very valuable information on the distribution of stratiform supercooled liquid water clouds around the globe, which could play an important role in the global radiation balance, and are also of concern as a potential aircraft icing hazard. Despite the limitations of the LITE instrument, the statistics produced agree very well with those obtained by ground-based lidar, and give us confidence that the tendencies exhibited in Figure 4 are robust. Furthermore, lidar has the ability to detect supercooled water beneath overriding cirrus (e.g., at around −139° longitude in Figure 1b), an improvement over current passive techniques [e.g., *Baum et al.*, 2000].

[17] A much more complete study will soon be possible with data from long-term satellite missions IceSat and Calipso. Both are in a polar orbit, allowing statistics on the phase of polar clouds to be studied. The long term coverage will also allow more subtle aspects of supercooled clouds to be characterized, such as their dependence on orographic forcing and cloud type. It will also be possible to evaluate the representation of mixed-phase clouds in forecast and climate models. Calipso will carry the first spaceborne cloud lidar with depolarization capability, allowing cloud phase to be determined with much greater confidence. The vicinity of the CloudSat radar and the other instruments on the "A-train" of satellites [*Stephens et al.*, 2002] will enable the observations of supercooled clouds to be put in the context of the full cloud profile.

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