Nucleation of Ice Formation in Supercooled Clouds as the Result of Lightning

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1. Introduction

In a recent note, Goyer, Bhadra and Gitlin (1965) interpret their laboratory experiments with a shock tube as indicating that nucleation of supercooled water was being caused by cavitation, and they suggest that in a similar fashion the acoustic wave resulting from lightning might produce cavitation that could nucleate supercooled clouds.

While cavitation may cause nucleation, it appears unlikely to us that cavitation will occur in the liquid water droplets of atmospheric clouds. In order for this phenomenon to take place it is necessary that the pressure within some portion of the liquid become sufficiently low that a bubble of vapor can form and the mechanism proposed by Goyer *et al.* therefore requires that the shock wave reduce the pressure in supercooled cloud droplets to some value below the vapor pressure of the liquid water. Water at a temperature of 0C has a vapor pressure of the order of 7 mb absolute and it is improbable that the shock wave either in the laboratory experiment or in the thundercloud could produce pressures this low.

2. Nucleation by adiabatic expansion

We agree that lightning may be able to cause nucleation in supercooled clouds but suggest an alternative explanation that involves pressure decreases smaller than those required for cavitation: the temperatures produced during adiabatic expansion in the low pressure portion of a sound wave may sometimes be low enough to cause nucleation.

Cwilong (1945) has demonstrated that the homogeneous nucleation of ice crystals can be initiated by an adiabatic expansion in a cloud chamber and Vonnegut (1948) has shown that a supercooled cloud in a Schaefer (1946) cold box can be seeded by the very large number of ice crystals produced by firing a toy pop gun or by bursting a small rubber balloon about 1 mm in diameter. Photographs of large explosions clearly show that the adiabatic expansion of the atmosphere following the initial pressure wave can produce sufficient cooling to cause the formation of a cloud of water droplets (Glasstone, 1962, p. 48). We believe that, when the temperature is low, the adiabatic cooling in intense sound waves such as are produced by lightning, an explosion, or a high speed airplane may be capable of causing the formation of ice crystals in a supercooled cloud.

The expansion that would be required at various temperatures to reduce the temperature to −40C, which Schaefer (1946) has shown to be the threshold for spontaneous nucleation, is given by

$$\frac{P}{P_0}=\left(\frac{233}{T_0}\right)^{c_p/c_p-c_v},$$

where P_0 is the initial pressure, P is the minimum pressure and T_0 the initial absolute temperature. And we find that:

T_0		P/P_0
238K	(−35C)	0.93
243	(−30C)	0.86
248	(−25C)	0.80
253	(−20C)	0.75
258	(−15C)	0.70
263	(−10C)	0.65

Thus air at −25C will be cooled briefly to −40C if the air pressure drops to 80% of the ambient value in a sound wave. Measurements made on the acoustical waves produced by explosions (Glasstone, 1962, p. 104) indicate pressures as low as 73% of the undisturbed ambient value in the rarefaction, and this, according to the table, could cause nucleation in a cloud with supercooled droplets at −18C.

We have carried out laboratory experiments to see if nucleation occurs in a supercooled cloud at −20C after the passage of a pressure wave produced by the discharge of a 1 mf capacitor charged to 20 kilovolts. The noisy spark created many ice crystals and seeded the cloud; however, it is possible that the cloud was seeded by aerosols caused by the sputtering of the electrodes instead of by the acoustic wave.

3. Observations of thunderstorms

There are observations of thunderstorms indicating that lightning may initiate the formation of ice crystals. We have examined a number of time lapse films of thunderstorms in New Mexico and note that the first visible sign of glaciation sometimes appears at the top of a new convective thundercloud shortly after the first indication of lightning.

We have observed what we think may be radar evidence for the nucleation of ice formation as the result of lightning during our studies of thunderstorms from the summit of Mt. Withington, New Mexico, in 1962. Then, on several occasions we observed thunderclouds with a sensitive, vertically scanning, 3 cm radar (Moore *et al.*, 1964) and noted that there sometimes was a sudden decrease of the radar reflectivity of a portion of the cloud just after a lightning discharge. We think that this effect may be due to the sudden transformation of part of the cloud from supercooled water droplets into ice and may have been caused by thunder.

A good example of this phenomenon occurred on the afternoon of 2 September 1962. A strongly convective cloud grew just west of the mountain and at 1527:10 MST, when it reached an altitude of 8 km, one of the first nearby lightning discharges occurred in the region above the radar. An intense echo then formed 2 km above and just to the west of the radar; this echo was recorded in photographs of the radar indicators. Rain and hail arrived at the radar about 2 minutes later.

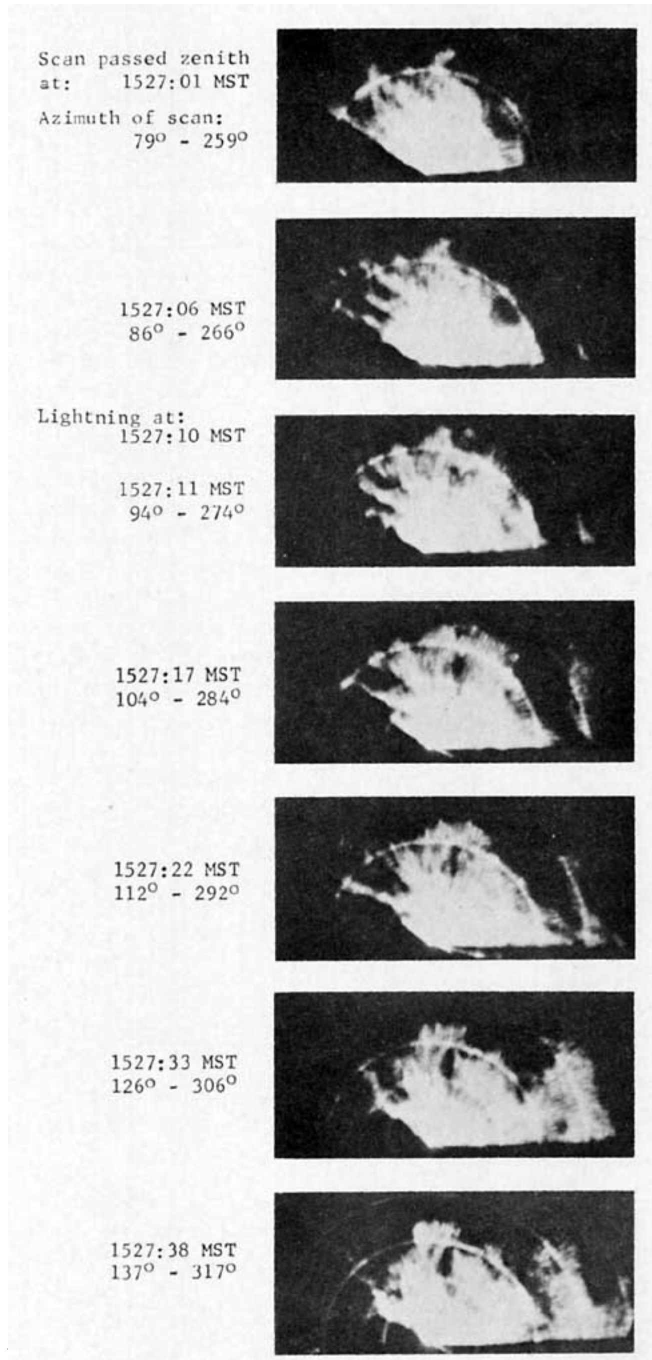
On examining the films of this sequence, we found that, 2 km higher in the cloud above the intense echo, a 'hole' developed in the cloud return where the reflectivity Z factor had been about 150 mm^6m^{-3}. This 'hole' first appeared in the sweep through the volume overhead at 1527:11 MST, one second after the time recorded for the discharge. The cloud reflectivity in the 'hole' decreased by a factor of about 10 or 20 in the next 10 seconds although the cloud reflectivity on the far side of the 'hole' remained about the same as it had been before the discharge.

A series of radar indicator photographs showing the development of this 'hole' is given in Fig. 1. All of the arcs except the second one out from the center are range marks with a 2 km interval; the second arc shows the position of a range gate for a pulse integrator. Zenith is the direction toward the top of the page. The azimuth of the vertical plane of scan and the time when the beam passed zenith are indicated to the left of each photograph.

We estimate that the temperature in the cloud 4 km above the radar (7.1 km above sea level) was about −16C. The radar bright band indicating the presence of melting ice crystals could first be seen on the radar films taken about 6 minutes after this discharge; the bright band appeared at an altitude of about 1.5 km above the radar (4.6 km above sea level).

4. Possible explanations for the sudden development of 'holes' in radar echoes

Attenuation of the radar signal by the formation of intense rain is often observed during these thunder-



thunderstorm on 2 September 1962 illustrating the development of a 'hole' in the echo immediately after lightning occurred over the radar.

storms and gives rise to 'notches' in the cloud echo. On passing through a shaft of intense rain, the radar signal at 3 cm wavelength is attenuated so greatly that little can be detected behind the rain shaft and therefore the apparent boundary of any echo there is moved in toward the radar. We doubt that this effect is the dominant one in creating the 'holes', for in Fig. 1 we can see an echo from the cloud on the other side of the 'hole.'

In this case we further doubt that the sudden decrease in the reflectivity of a portion of the cloud after the lightning can be explained on the basis that the radar beam scans into a pre-existing 'hole' as the result of radar beam movement or winds aloft. The effect occurs too rapidly to be accounted for in terms of wind and the effect is observed almost directly overhead where there is little or no change in the volume scanned as the radar rotates about its vertical axis.

We suggest that the development of an echo 'hole' is the result of the formation of a large number of ice crystals in this part of the cloud. The 'holes' observed always formed immediately after lightning and in the region of a cloud that was colder than 0C. The lightning preceding the detection of a 'hole' usually took place early in the development of a cloud which probably contained large numbers of supercooled water droplets.

Nucleation by an adiabatic expansion can produce up to 10^{10} nuclei per cm^3 (Vonnegut, 1948). The creation of ice crystals with even a fraction of this concentration should overseed small portions of the cloud; many of the supercooled water droplets will be converted into a much larger number of ice crystals which will reduce the average size of the scattering particles. When corrected for the change in concentration, this effect should decrease the reflectivity of spherical scatterers by about the cube of the ratio of the original particle sizes to the final sizes.

We may further expect that, when the water drops are transformed into ice crystals, the decrease in the dielectric constant will result in a reduction in radar reflectivity. This change in state should reduce the power of the radar backscatter by a factor of about five. It is possible that an additional reduction in reflectivity could result when the particles, upon freezing, change from spheres to some other shape.

5. Conclusion

These observations lend support to the idea that when ice forming nuclei are deficient, a thundercloud may be seeded by the effects of a lightning discharge. It will be interesting to determine the extent to which ice nucleation in supercooled clouds can be initiated by sound waves from lightning and from explosives.

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