The Electrical Nucleation of Ice In Supercooled Clouds

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ABSTRACT

An electrified wire suspended in a supercooled cloud generates a jet of ice crystals only when there is ice on the wire. On a clean platinum wire no ice forms on the wire down to −20°C, but if the wire is coated with a hydrophobic material, ice nucleates on the wire at temperatures as high as −5°C. The electrical field of the wire is found to be insufficient to promote ice nucleation by enhancing the free energy difference for the transformation of bulk supercooled water to ice.

A mechanism is proposed to explain how the electric field induces an otherwise inert substrate to generate the jet of ice crystals.

1. Introduction

Several authors have reported that the nucleation of ice in supercooled water kept on inert hydrophobic substrates is facilitated by the application of a strong electric field (Rau, 1951; Salt, 1961; Pruppacher, 1963). Pruppacher experimentally identified that the effect was accompanied by movement of the drop along the hydrophobic solid surface. However, since the solid surface necessary for the nucleation is not to be expected in atmospheric clouds, he concluded that freezing of droplets by electric fields there is unlikely.

Rouleau (1964) and Rouleau and Poc (1967) reported a large number of ice crystals formed in a supercooled cloud in a cold chamber when a strong electric field was applied via two metal grids located in the cloud, but the relevance of this work to natural clouds has been challenged by Garraud (1969) who claimed that the ice crystals were generated from the frost on the metal grids. Schaefer (1968) photographically presented evidence of the formation of an ice crystal stream from a very fine electrically conducting wire or fiber when charged to ∼3000 V dc in a cold chamber, and suggested that fibers of vegetable origin might be responsible for an ice crystal stream in the natural electric field of the atmosphere.

Abbas and Latham (1969) investigated the mechanism of drop freezing under an electric field and presented some evidence that nucleation takes place at the point where the water droplet is stretched and disrupted under the influence of the applied field.

The purpose of the present work was to study, under well-defined conditions, the mechanism by which a large number of ice crystals are generated in a supercooled cloud under the influence of an electrified wire, and the relation, if any, between the formation of ice crystals in the surrounding cloud and frosting of the wire.

In previous work by one of the authors (M. R.) it was established, for ice crystal formation, that the diameter of the electrode must not exceed a critical value for a given magnitude and duration of the applied voltage. Furthermore, the number of ice crystals formed under any one set of conditions was extremely erratic. There-

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FIG. 1. Schematic section of cold chamber showing electrode position.

1 On leave from the University of Paris, France.
2 On leave from CSIRO, Australia.
3 As used here voltage is in an MKS unit.
4 Studies carried out at the State University of New York at Albany, 1968.
justable direct current supplied by a battery. The wire
temperature was calibrated to an accuracy of ±1°C by
determining the current necessary to melt small crystals
placed on the wire. To be sure that no part of the elec-
trode was colder than the chosen wire temperature, the
copper rods were heated by conduction from a heater
attached to the upper end of each rod. The tempera-
ture of the lower end of each rod, checked with a
thermocouple, was 4°C when the temperature of the
chamber was −20°C.

The usual experimental procedure was as follows.
The chamber walls were coated with a mixture of
glycerol and detergent, the Plexiglas cover was placed
in position and the chamber was purged with filtered
air. After generating a suitable number of NaCl par-
ticles, the electrode was brought to its chosen tempera-
ture and a fog was formed by heating the humidifier.
The field was applied for 10 sec and the ice crystals generated
fell into the sugar solution where they were counted.

Because the ice crystals in the sugar solution were
concentrated in a narrow band, many crystals over-
lapped; thus exact counts were not always possible.

3. Results

a. Dependence of ice crystal formation on the nature of the
wire surface

In a series of experiments conducted with the chamber
walls at −20°C, it was established that the platinum
wire, cleaned by heating to red heat in the clean atmo-
sphere of the chamber, generated no ice crystals when
charged to 8000 V in a supercooled cloud. On the other
hand when the wire was smeared with a thin coating of
certain hydrophobic organic substances, thousands
of ice crystals were generated by the application of
8000 V dc to the wire. Large numbers of ice crystals
formed only in the presence of a dense cloud, none
forming in air which was merely saturated with respect
to water. The ice crystals appeared in the sugar solution
along a line perpendicular to the direction of the wire
and directly underneath the point on the wire on which
the organic substance was smeared (see Fig. 3). We use

<table>
<thead>
<tr>
<th>Coating</th>
<th>Wire temperature (°C)</th>
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<tbody>
<tr>
<td></td>
<td>−20</td>
</tr>
<tr>
<td>Vaseline</td>
<td>~2000</td>
</tr>
<tr>
<td>Silicone oil</td>
<td>~1000</td>
</tr>
<tr>
<td>(Dow Corning, DC-330)</td>
<td>~2000</td>
</tr>
<tr>
<td>Paraffin oil</td>
<td>200</td>
</tr>
<tr>
<td>Paraffin wax</td>
<td>300</td>
</tr>
<tr>
<td>Naphthalene</td>
<td>500</td>
</tr>
<tr>
<td>Dodecane</td>
<td>500</td>
</tr>
<tr>
<td>Phloroglucinol</td>
<td>200</td>
</tr>
</tbody>
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* Chamber temperature, −20°C; applied voltage, 8000 V dc.
the term "jet" to denote this stream of ice crystals which is ejected by the wire.

As Table 1 shows, a number of hydrophobic substances produced a jet of ice crystals at -20°C, the most effective substances tested being paraffin oil, vaseline and silicone oil.

In each case the number of ice crystals generated decreased as the chamber temperature was raised. For example, with the wire coated with paraffin oil, the number of ice crystals diminished from a few thousand at -20°C to a few hundred at -10°C. No ice crystals were observed above a threshold wire temperature of -5°C. The less effective coatings exhibited somewhat lower threshold temperatures. In every case, after a jet of ice crystals had been generated, needles of frost were seen to grow on the coated wire after a few minutes exposure to supercooled fog. Once visible needles had grown on the wire it was not possible to generate a jet of ice crystals by a subsequent application of the field.

If a clean wire was coated with a thin layer of ice, its behavior with 8000 V dc applied was identical to that of the paraffin-coated wire, the threshold temperature for jet formation being -5°C.

b. Dependence of ice crystal concentration on wire temperature

For these tests, the wire was held at a predetermined temperature during the 10-sec application of the field. The jet of ice crystals was counted as before. To test for the formation of frost on the wire, the wire warming current and the field were turned off simultaneously, leaving the wire suspended in the supercooled fog at the temperature of the chamber (~20°C). After 5 min, visible needles of ice on the wire indicated that frost had been present on the wire during the experimental period where the wire was heated. In all cases, it was established that if the field was not applied, no frost formation took place.

Rather unexpectedly, it was found that warming the wire to a temperature which would prevent its frosting in the absence of a field did not prevent either ice crystal formation or frosting when the electric field was applied. Apparently the electrostatic precipitation of cloud drops on the wire maintained the humidity in the immediate vicinity of the wire at a level greater than ice saturation, allowing the formation and survival of a coating of frost. Although the coating was unable to grow to visible size while the wire was heated, visible needles formed when the heating was discontinued.

Table 1 shows the results for a number of surface treatments. It is noteworthy that for paraffin oil and silicone oil (Dow Corning DC-330) the highest wire temperature for jet formation was the same as the threshold temperature for jet formation obtained by varying the chamber temperature (Table 2). Similarly, the threshold wire temperature for frost formation corresponded to the threshold temperature for jet formation.

4. Discussion

The main feature of the present experiments is the close correlation between the presence of ice on the electrode and the formation of a jet of ice crystals in the surrounding cloud, a conclusion which agrees with Garraud's finding. There are reports (Bartlett et al., 1963; Maybank and Barthakur, 1967) that an ice crystal growing in a strong electric field tends to generate a few ice splinters. However, as mentioned above, one of the necessary conditions for the present jet formation is the existence of supercooled droplets; therefore, simple fragmentation of ice without consideration of the role played by droplets is not sufficient explanation.

A possible explanation may be the electric atomization of precipitated droplets on the electrode, the
droplets leaving a pointed surface (the place of the highest field divergence) from which germs of ice are subsequently torn off. The difficulty with this hypothesis is the migration of precipitated liquid water along the equi-potential surface of the electrode, because one of the requirements of the ice jet is that the generating surface must be either hydrophobic or ice. Since an ice crystal without fog droplets does not generate the jet, the liquid-like layer on ice proposed by Fletcher (1962, 1963) cannot be responsible for the jet.

The ice jet formation mechanism must therefore involve a direct supply of supercooled droplets from which either rapid ice nucleation or ice crystal growth takes place. Considering all these factors, only the following mechanism appears possible. Once ice nucleates on the wire the ice needle serves as a center of droplet attraction because of strong field convergence. Droplets moving toward the needle develop enough momentum to make momentary contact with it. Simultaneously, a like charge is transferred to the drop, causing the droplets to be repelled with torn-off ice germs in them. The distribution of ice crystals in the sugar solution (Fig. 3) confirms that the crystals are charged, and have thus been compelled to follow the electric field gradient from their point of origin on the wire into the sugar solution. The failure to generate a jet from long (1 mm) ice needles on the electrode is probably due to the fact that the growing tip of the needle is out of the region of high field divergence.

It has been found for a given voltage that jet formation is favored by a reduction in the wire diameter, suggesting that the potential gradient at the curved wire surface is the important factor. A high potential gradient would increase both the velocity of droplets toward the wire and the velocity of ice crystals away from the wire. Which of these phenomena is important cannot be ascertained from the present evidence.

We have thus far discussed the dynamic process of ice jet formation only. Possible mechanisms by which an electric field induces ice nucleation on an otherwise inert substrate also need to be considered. The first possibility is the effect of the field on the free energy change for the transformation of supercooled water to ice. However, the estimated bulk free energy change involved in the freezing of water, under the dc or ac field used, was not only several orders of magnitude smaller than that of normal water-ice phase change but the sign of the change also reversed depending on the frequency of the applied field and the temperature. Therefore, this effect cannot be responsible for ice nucleation under the electric field. The second possibility is the effect of the electric field on the surface free energies involved in ice nucleation. This presents a delicate problem of surface free energy balance under the electric field which may result in a favorable condition for ice nucleation, and further discussion is premature at this time.

Another possible explanation is that under the applied electric field some of the supercooled fog droplets impinge and spread on the hydrophobic electrode, thus creating the moving front of supercooled water on the solid which Pruppacher has associated with ice nucleation under the electric field. It may be significant that high-speed spreading of water over a hydrophobic surface induces ice nucleation even without an electric field (Edwards et al., 1969). Particularly strange is the ability of the field to promote ice nucleation on a liquid surface such as paraffin oil, there being no previous reports of ice nucleation by a liquid. Further study is necessary regarding this subject.

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