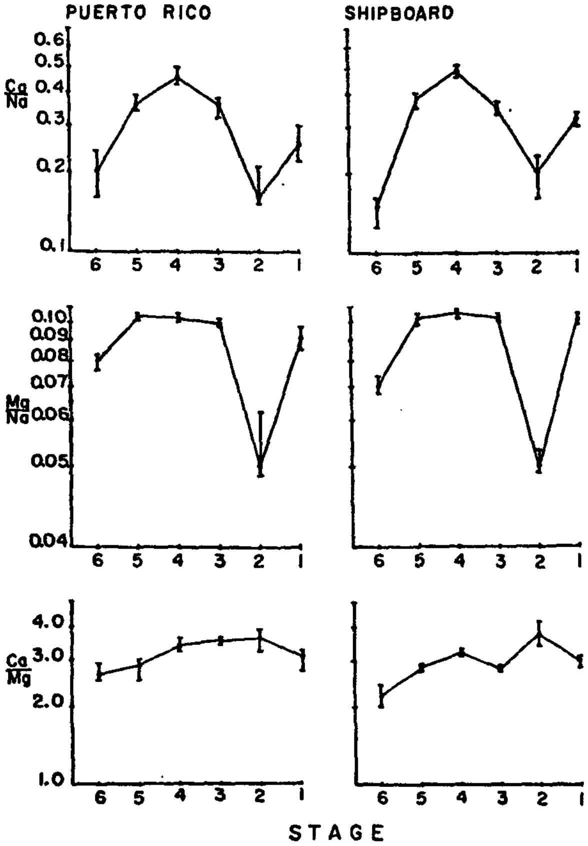

FIG. 1. Ion ratios for Puerto Rico and *R/V Eastward*. Each graph is a composite of three collections.

variation with particle size which possibly indicates continental influence.

The data are highly consistent over the separate marine aerosol samples taken. They are difficult to interpret in terms of mixing of particles that are derived from different sources, and fractionation effects at the sea surface seem to be the most likely origin of the Ca/Mg ratios in marine aerosols.

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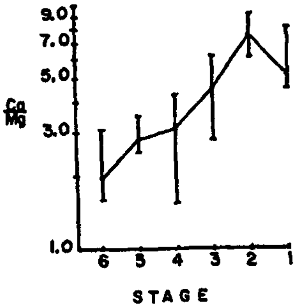

FIG. 2. Average and extreme Ca/Mg ratios for six collections from the coast of Florida.

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Freezing of Supercooled Clouds Induced by Shock Waves

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The formation of ice particles in a supercooled cloud by the action of shock waves has been experimentally studied under laboratory conditions. It was found that the overpressure in the shock front has to exceed a definite threshold value to produce such an effect and that there are indications that the threshold value decreases for increased supercooling.

The shock wave was produced by blasting the plastic window of a shock chamber. To blast the window, nitrogen under pressure was injected in the chamber.

Shocks of different intensities were obtained by employing windows of different thickness. The nitrogen was electrically heated, inside the chamber, in order that its temperature after the expansion, never was below the temperature of the cloud. The initial temperature of the nitrogen ranged between 100 and 145C according to the expected blasting pressure and, in a typical experiment, the minimum temperature of the nitrogen, calculated by assuming an adiabatic expansion, was 30C above the temperature of the cloud.

The cloud was produced by injecting low pressure steam in a 15 m^3 cold room. The walls were painted with diethylene glycol to avoid the formation of ice.

Formvar replicas of the cloud particles were taken 1 min before and 1 min after the shock. The median diameter of the cloud droplets was 7.5 μm and 99% of the droplets were in the range 5–35 μm. The largest drop found had a diameter of 70 μm.

The results of 16 separate experiments are plotted in Fig. 1. These data show the existence of a threshold for ice production in the shock pressure (1.5 atm) for a temperature range of −2.8 to −7.2C. Also, there is some evidence that this threshold is lowered when the supercooling is increased.

The concentrations of ice particles was estimated to be in the order of thousands per liter.

In the replicas of ice particles two broad classes can be distinguished: 1) frozen droplets, which includes the ice crystals grown on frozen droplets, and 2) regular ice crystals (hexagonal plates, columns and some needles). Approximately two-thirds of the ice particles were in the regular ice crystal class.

When a shock wave passes through a cloud it produces transient changes in pressure and temperature, turbulent motions, and mechanical disturbances in the droplets. The transient changes in temperature are larger in the air than in the droplets, while the mechanical disturbances can be sufficient to shatter the droplets into myriads of smaller droplets (Engels, 1958; Edwards *et al.*, 1969).

Regular ice crystals and frozen droplets could be produced by the action of the shock wave in different ways.

Regular ice crystals can grow on sublimation nuclei. These nuclei could be activated in the expansion that follows the shock front. In this expansion, the air cools faster than the cloud droplets. Thus, only a limited amount of water vapor can condense and a high supersaturation develops which can activate the nuclei. Experiments with the transient expansion of a supercooled cloud will help to determine whether sublimation nuclei can be activated.

Frozen droplets can be produced either by the action of shock waves or by the contact of supercooled droplets with ice particles formed by another mechanism. The following will briefly summarize the ways in which a shock wave can produce primarily frozen droplets:

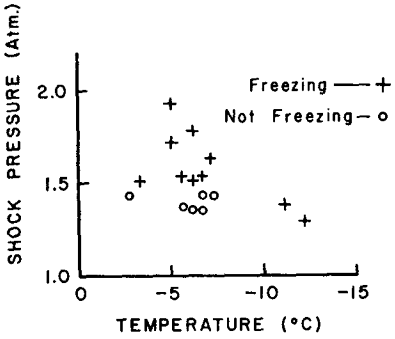

FIG. 1. Results of 16 separate experiments. Crosses indicate that the concentration of ice particles has substantially increased after the shock, while open circles represent cases of little or no change.

1) Edwards *et al.* (1969) have reported that shock pressures of 1.13 atm can shatter supercooled droplets of 2 mm diameter. They have also reported that the fragments of the shattered droplets are frozen if the original drop was in contact with a hydrophobic surface. This result suggests that some kind of nuclei are needed, inside the droplets, to assist the freezing.

This mechanism will produce frozen droplets in clouds only when the droplets are big enough to be shattered by the shock wave and they contain nuclei with some hydrophobic surface. This was not the case in our experiment.

2) Gitlin and Lin (1969) have observed that only a mechanical disturbance capable of inducing the growth and collapse of cavitating bubbles can trigger freezing in bulk supercooled water. These cavities, more easily produced when water is in contact with hydrophobic surfaces, would be formed when the water is accelerated away from the surface at points of weak adhesion.

This mechanism, to be effective in a cloud droplet, needs the presence inside the droplet of an insoluble particle with some patches of hydrophobic surface, and a shock-wave-induced mechanical disturbance that can trigger the formation of a cavity by pulling the water away from the surface of the particle.

3) Alkezweeny (1969) has found that when supercooled droplets collide freezing may result. The turbulent motion behind the shock front, by promoting droplet collisions, could be a mechanism to produce frozen droplets.

4) Abbas and Latham (1969) have observed an increase in the frequency of freezing of supercooled droplets when the surface of the droplets is pierced by a nylon thread or a thin wire. Bubbles of gas bursting through the surface of the droplets may have a similar effect to that observed by Abbas and Latham. These bubbles of gas could be formed in the expansion following the shock, and the presence of gases with solubilities higher than the air would help this effect.

The freezing of droplets by this mechanism would be accompanied by the ejection of ice splinters.

Regular ice crystals and frozen droplets can also be formed by secondary processes. Regular ice crystals can grow on small ice splinters and droplets can be frozen by the contact of supercooled droplets with ice crystals or ice splinters.

From the above review it can be seen that several mechanisms are likely to be active and perhaps more than one could be responsible for the observed ice particles. Our experiments do not indicate a mechanism, but do indicate a phenomenon which may be of meteorological significance.

Shock waves produced by a lightning stroke can induce freezing in a column, the diameter of which depends on the energy released by the stroke.

Freezing could also be triggered by supersonic flight through supercooled clouds, and in cloud-seeding procedures which employ explosive devices.

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Fall Velocity of Snowflakes[1]

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1. Introduction

While the fall velocity of individual type crystals of symmetric form is reasonably well known (Magono, 1954; Bashkirova and Pershina, 1964; Holroyd, 1971), that of snowflakes is somewhat less certain. Most snowflakes fall at about 1–1.5 m sec^{-1}, as anyone with a stop watch and some patience can readily verify. However, one would like to understand better the governing variables and to have a reliable analytical expression for snowflake fall velocities.

Owing to the random collision process involved in snowflake aggregation, and the variety of shapes and densities that can result, it would be naive to expect too much from any fall velocity equation. One customarily assumes a spherical cluster, which appears adequate, although it will be observed that many flakes become aerodynamically flattened or are sometimes tapered to a bottom conical shape during fall. Nevertheless, the narrow range of average fall velocities mentioned suggests that shape, drag and density variables are not overly critical. Snowflakes that have accreted substantial supercooled cloud droplets will fall considerably faster and possess greater variability.

An attempt was made to develop simple but adequate fall velocity expressions for dry snowflakes as a function of diameter, the most readily measured parameter in the field; to test these expressions with measured data; and to resolve some seeming inconsistencies in prior reported work.

2. Analytical expressions

Magono and Nakamura (1965) have done extensive work in this area, arriving at the empirical fall velocity equation

$$v_f = 377(\rho_f - \rho_a)^{\frac{1}{4}}, \qquad (1)$$

where v_f is fall velocity, ρ_f the density of the flake, and ρ_a the density of the air (cgs units). They also experimentally determined a relationship between flake size (radius r_f) and density of the form

$$(\rho_f - \rho_a) r_f^2 = 0.005. \qquad (2)$$

Their data in both cases included dry and wet (melting) snowflakes. Combining the above equations, the fall velocity can be expressed in terms of snowflake size as

$$v_f = 100/(r_f^{\frac{1}{2}}). \qquad (3)$$

The obvious implication that small snowflakes fall faster than large ones is attributed by the authors to a significant flake density decrease with increasing size. Such an inverse velocity-size trend is in contrast to measurements of Langleben (1954). O'Brien (1970) also has arrived at empirical velocity expressions that indicate a directly proportional dependence on size, i.e.,

$$v_f = AD^n[\log_e(v_f D) - B], \qquad (4)$$

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