Ice Crystal Growth: The Bergeron-Findeisen Process

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This article serves to introduce readers to a process that is partly responsible for the growth of ice crystals in clouds. Nearly every precipitation type starts out as an ice crystal except for warm rain clouds whose droplets form in a much different way. Ice crystals that grow by this process may become large enough to precipitate out of a cloud. In order for atmospheric scientists to begin to understand the microphysics of clouds and precipitation, it is important to understand how ice crystals grow to form complex precipitation types that are observed in nature. It is expected that readers have some familiarity with meteorology, as this article draws upon concepts that are presented in introductory level meteorology courses. The introductory material will serve as a review and orient readers to the background knowledge associated with the process.

The Wegener-Bergeron-Findeisen[ǂ] process is a cloud microphysical process in which ice crystals grow in an environment whose ambient vapor pressure is between the saturation vapor pressures over ice and over water. This process occurs in mixed phase clouds – clouds that contain both ice crystals and supercooled liquid water droplets. Supercooled liquid water droplets are water droplets that exist in the liquid form at temperatures less than 0°C. In this environment, water molecules from numerous liquid water droplets will deposit onto a single ice crystal. Vapor deposition onto the ice crystal results in a shrinking of the liquid water droplets and a growing of the ice crystal. This process is shown in Figure 1.

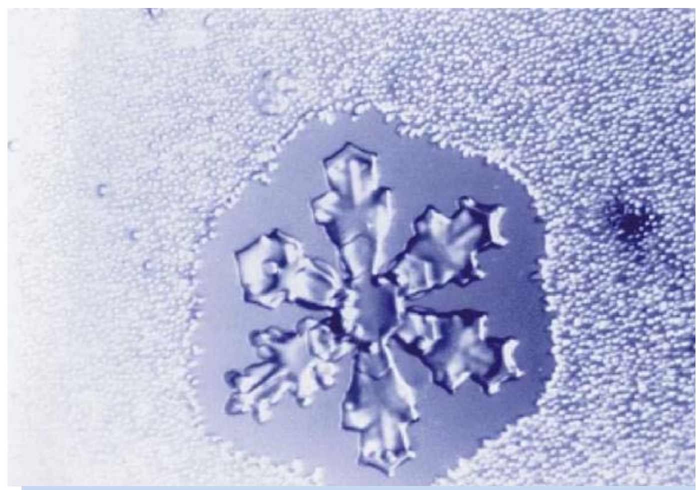

Figure 1: The Bergeron-Findeisen Process

Photograph by R. Pitter.

Introductory Concepts and Terminology

In order to begin to understand this process, which we will herein after refer to as the Bergeron-Findeisen process, we must first introduce the key concepts and terminology involved. The most important concepts that will be addressed are vapor pressure, saturation vapor pressure, and vapor deposition.

Vapor Pressure and Saturation Vapor Pressure

Vapor pressure is the partial pressure of a vapor that contributes to the total atmospheric pressure. In this case we refer specifically to atmospheric water vapor. Saturation vapor pressure is the equilibrium vapor pressure in which the rate of evaporation of the liquid water is equal to the rate of condensation of the water vapor. While vapor pressure is a measure of the actual water vapor content of the atmosphere and is independent of temperature, the saturation vapor pressure is a function of temperature. The Clausius-Clapeyron equation relates saturation vapor pressure to the inverse

[ǂ] Alfred Wegener, Tor Bergeron, and Walter Findeisen are all credited for their work related to the process. In 1911, Wegener theorized that the process which creates hoarfrost, if it also occurs in clouds, could be a mechanism for precipitation if the crystals grow sufficiently large to fall out. Bergeron, who is most closely associated with the process, presented his theory in 1933 in support of Wegener. He states that ice crystals will grow large enough to precipitate if the ice crystal population is much smaller than that of the liquid water droplets in mixed-phase clouds. Findeisen continued and refined the work of Bergeron in the late 1930s.

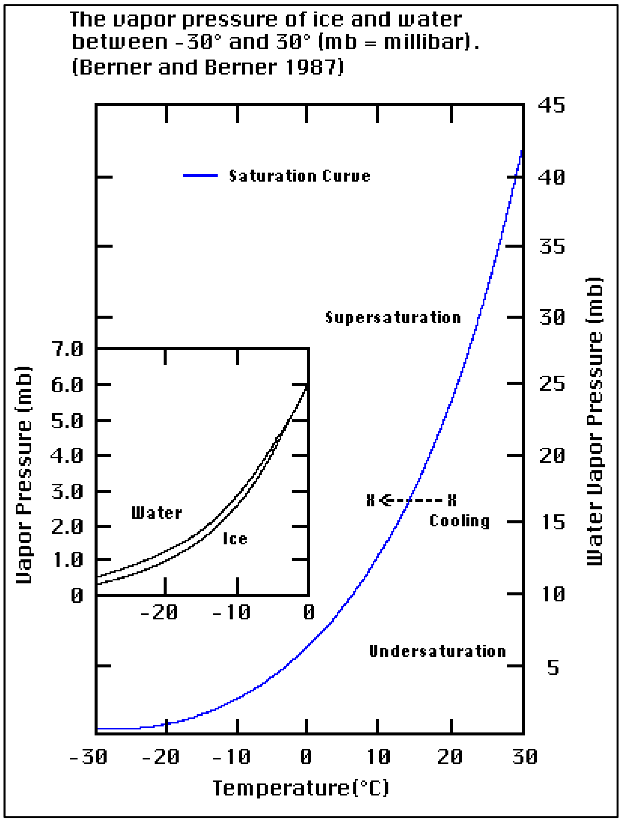

Figure 2: Vapor Pressure over Water and Ice
http://www.ldeo.columbia.edu/~martins/climate_water/lectures/evap_precip.ht

exponential of inverse temperature, as shown in Figure 2.

The Clausius-Clapeyron equation, however, only applies to the saturation vapor pressure over a liquid water surface. As shown in Figure 2, the saturation vapor pressure over an ice surface is less than the saturation vapor pressure represented by the Clausius-Clapeyron equation. It is within this region of Figure 2 that we would expect to find the Bergeron-Findeisen process. The process occurs more specifically in the range of temperatures between -10°C and -20°C where the difference between the saturation vapor pressure and the saturation vapor pressure over ice is the greatest.

Vapor Deposition

Vapor deposition is a physical process in which water changes from its gaseous phase to its solid phase without first condensing to its liquid phase. Although it is the primary mechanism for ice crystal growth and is responsible for the Bergeron-Findeisen process, it is among a few other mechanisms for ice nucleation. One other such mechanism is contact nucleation. This occurs when an ice nucleus – a particle on which an ice crystal forms – collides with a supercooled water droplet and the droplet subsequently freezes. While this process can also occur when an ice crystal comes into contact with a supercooled water droplet, the Bergeron-Findeisen process is more important and takes place much more rapidly.

Steps of the Bergeron-Findeisen Process

Now that we have explained the underlying concepts, we may now detail all the step of the Bergeron-Findeisen process. We will begin with presenting the environmental setup and conditions that may initiate the process, and follow the process until the ice crystals grow large enough to precipitate out. The process is shown schematically in Figure 3.

- ***Equilibrium of Liquid Water Droplets:*** Initially, supercooled liquid water droplets are in equilibrium with the ambient air. At this point, there is no further growth of the liquid water droplets.
- ***Introduction of Ice Crystal:*** Within a given domain, a single ice crystal is introduced into this environment of supercooled liquid water droplets. While the ambient vapor pressure is initially saturated with respect to the droplets, it is supersaturated with respect to the ice crystal.
- ***Vapor Deposition onto Ice Crystal:*** Atmospheric water vapor molecules immediately surrounding the ice crystal begin to deposit onto the ice crystal surface through vapor deposition. This occurs because the water vapor is not in

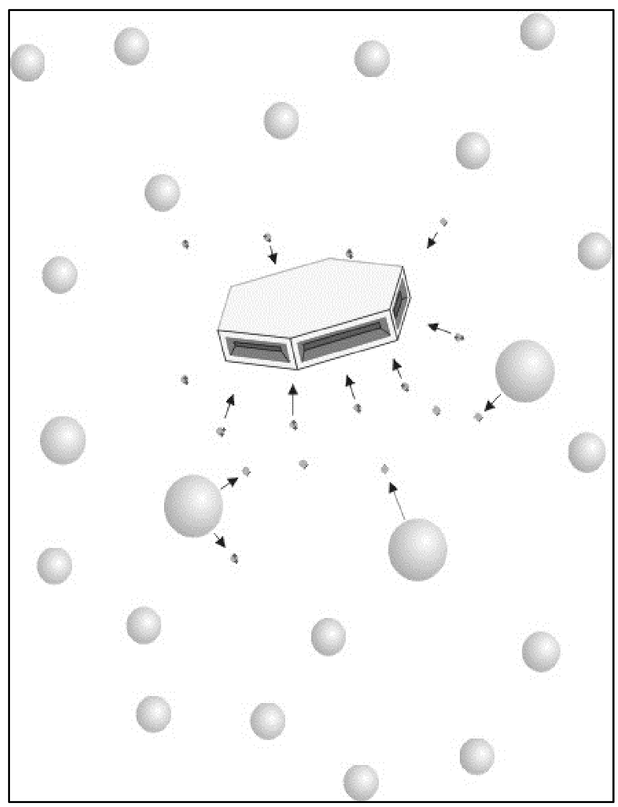

Figure 3: Schematic Diagram of the Bergeron-Findeisen Process
http://www.ems.psu.edu/~lno/Meteo437/Bergeron.jpg

equilibrium over the ice crystal surface. In order to attain equilibrium, the water vapor molecules deposit onto the ice crystal to reduce the vapor pressure of the ambient air.

- ***Evaporation of Liquid Water Droplets:*** As water vapor molecules deposit onto the ice crystal to achieve equilibrium over the ice crystal surface, the liquid water droplets surrounding the ice crystal are no longer in equilibrium with the ambient air. In order for the liquid water droplets to maintain equilibrium, water molecules must evaporate from the liquid surface to increase the vapor pressure of the ambient air.
- ***Growth of Ice Crystal:*** The additional vapor pressure surrounding the ice crystal from the evaporation of the liquid water droplets support further vapor deposition onto the ice crystal surface. This vapor deposition causes the ice crystal to grow in this environment which is supersaturated with respect to its surface.
- ***Shrinking of Liquid Water Droplets:*** As atmospheric water vapor continues to deposit onto the ice crystal, surrounding water droplets continue to evaporate to maintain equilibrium. Evaporation of these droplets causes the droplets to shrink and ultimately disappear as all the water molecules migrate to the ice crystal.
- ***Precipitation of Ice Crystal:*** If the ice crystal grows sufficiently large, its mass will no longer allow it to remain suspended in the air and will precipitate out of the cloud.

Figure 4: Picture of the Effect of the Bergeron-Findeisen Process

Photograph by D. Tobin

Summary and Application

In an environment where the vapor pressure is greater than the saturation vapor pressure with respect to ice but less than the saturation vapor pressure with respect to water, an ice crystal will grow through vapor deposition. This situation may occur when an ice condensation nuclei comes into contact with a supercooled liquid water droplet. Upon contact, the liquid water freezes instantaneously and forms an ice nucleus. Water vapor in this environment deposits onto the ice crystal surface to maintain equilibrium. Water molecules on the surface of the water droplets evaporate to maintain equilibrium over the liquid surface. The processes of liquid water evaporation and water vapor deposition result in the net growth of the ice crystal and the net shrinking and disappearance of the water droplets. This effect can be seen in Figure 1 where there are no water droplets immediately surrounding the ice crystal. This process continues until the ice crystal becomes large enough to precipitate out of the cloud. Figure 4 shows the effect of the process on a fair weather day where cumulus cloud droplets are depositing onto the cirrus or ice clouds. The result is an area surrounding the cirrus clouds that is free of cloud droplets.

The Bergeron-Findeisen process is a primary mechanism for precipitation. Although there are many other cloud processes that are also responsible for precipitation, this process plays an important part in the growth of ice crystals. These crystals may form a variety of different types of precipitation which include, but is certainly not limited to: Rain, ice pellets, snow, freezing rain, sleet, and virga – precipitation that evaporates before it is able to reach the ground.