Limitations of the Wegener–Bergeron–Findeisen Mechanism in the Evolution of Mixed-Phase Clouds

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ABSTRACT

Phase transformation and precipitation formation in mixed-phase clouds are usually associated with the Wegener–Bergeron–Findeisen (WBF) process in which ice crystals grow at the expense of liquid droplets. The evolution of mixed-phase clouds, however, is closely related to local thermodynamical conditions, and the WBF process is just one of three possible scenarios. The other two scenarios involve simultaneous growth or evaporation of liquid droplets and ice particles. Particle evolution in the other two scenarios differs significantly from that associated with the WBF process. Thus, during simultaneous growth, liquid droplets compete for the water vapor with the ice particle, which slows down the depositional growth of ice particles instead of promoting their growth at the expense of the liquid as in the WBF process. It is shown that the WBF process is expected to occur under a limited range of conditions and that ice particles and liquid droplets in mixed-phase clouds are not always processed in accordance with the WBF mechanism.

Mixed-phase clouds play an important role in the formation of precipitation, radiative transfer for cloudy atmospheres, Earth's radiation budget, and climate. Mixed-phase clouds are thermodynamically unstable and the process of phase transformation in them is often referred to as the "ice crystal theory," which originated in the works of Wegener (1911), Bergeron (1935), and Findeisen (1938).

In 1911, Alfred Wegener proposed a theory of ice crystal growth based on the difference in saturated water vapor pressure between ice crystals and supercooled liquid water droplets. According to Wegener (1911, p. 81), "The vapour tension will adjust itself to a value in between the saturation values over ice and over water. The effect of this must then be, that condensation continuously will take place on the ice, whereas at the same time liquid water evaporates, and this process must go on until the liquid phase is entirely consumed." Furthermore, he suggested that this effect might lead to the formation of ice crystals large enough to fall through cloud, melt at lower (warmer) levels, and finally turn into raindrops.

In the 1930s, Swedish meteorologist Tor Bergeron and German meteorologist Walter Findeisen contributed further to the ice crystal theory, which became known as the Wegener–Bergeron–Findeisen[1] (WBF) theory. The important point, which apparently Bergeron (1935) was the first to recognize, is the condition that the number density of ice particles must be much smaller than that of the liquid droplets. Findeisen (1938) provided experimental confirmation of enhanced growth of ice crystals in clouds containing both ice crystals and supercooled liquid droplets.

Glickman (2000) gives the following explanation for the "Bergeron–Findeisen process":

> The basis of this theory is in fact that the equilibrium water vapor pressure with respect to ice is less than that with respect to liquid at the same subfreezing temperature. Thus within an admixture of these (ice and liquid) particles, and provided that the total water

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[1] Ice crystal theory (or the ice process of precipitation) has also been referred to as "Bergeron," "Bergeron–Findeisen," and "Bergeron–Findeisen–Wegener" process or theory.

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content were sufficiently high, the ice crystals would gain mass by vapor deposition at the expense of the liquid drops that would lose their mass by evaporation.

In many publications that discuss precipitation mechanisms, it is assumed a priori that the WBF process can be applied to any mixed-phase cloud, regardless of local thermodynamical conditions. The purpose of this paper is to show that in mixed-phase clouds the WBF process can occur only under a limited range of conditions, and that ice particles and liquid droplets in mixed-phase clouds do not always evolve via the WBF process.

In this current study, the term "mixed-phase cloud" is applied to a three-phase admixture consisting of water vapor, liquid droplets, and ice particles. The rate of condensational growth (or evaporation) of the droplets and ice particles in mixed-phase clouds is proportional to the difference between in-cloud vapor pressure (e) and equilibrium vapor pressure over liquid water (e_s) and ice (e_i), respectively. Since at subfreezing temperatures $e_s > e_i$, there are three possible inequalities for e, e_s, and e_i thereby resulting in three scenarios for the evolution of mixed-phase clouds:

$$e > e_s > e_i \tag{1}$$

$$e_s > e > e_i \tag{2}$$

$$e_s > e_i > e. \tag{3}$$

Figure 1 shows a schematic illustration of the conditions in (1), (2), and (3) in which ice crystals and liquid droplets are embedded in the water vapor of pressure e. Consider now, in turn, the thermodynamical conditions that result in (1)–(3) for mixed-phase clouds.

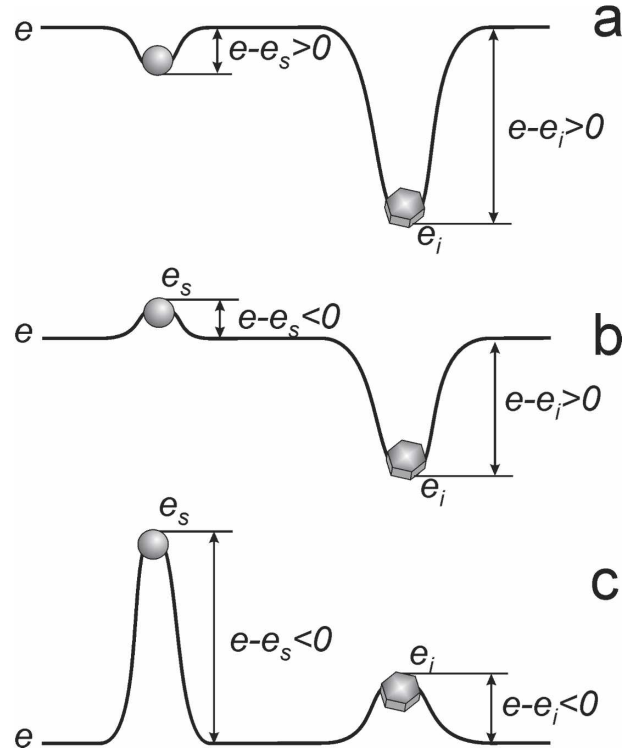

FIG. 1. Schematic diagram of possible proportions between e, e_s, and e_i in a mixed-phase cloud: (a) $e > e_s$ and $e > e_i$ in which both liquid droplets and ice particle grow; (b) $e < e_s$ and $e > e_i$ in which liquid droplets evaporate and ice particles grow—the WBF mechanism; and (c) $e < e_s$ and $e < e_i$ in which both liquid droplets and ice particles evaporate. The solid lines trace the profile of ambient vapor pressure in the vicinity of liquid droplets and ice crystals.

1) When (1) is true, both droplets and ice particles grow simultaneously (Fig. 1a). Korolev and Mazin (2003) have shown that this condition may occur in ascending mixed-phase clouds when updraft velocity u_z exceeds u_z^*:

$$u_z^* = \frac{e_s - e_i}{e_i} \eta N_i \bar{r}_i, \tag{4}$$

whereη is a coefficient dependent on temperature T and pressure P, and N_i and $\bar{r}_i$ are the number concentration and mean radius of ice particles, respectively.

Figure 2a shows that for typical values of $N_i\bar{r}_i$ in clouds (10^{-2}–10^{2} μm cm^{-3}), the vertical velocity required to provide simultaneous growth of ice crystals and liquid droplets ranges from a few cm s^{-1} to a few m s^{-1}. Such velocities can be generated easily in clouds by regular (convection, waves) or turbulent motions. Therefore, one can expect that it is not uncommon to find simultaneous growth of ice particles and liquid droplets in mixed-phase clouds.

Besides updrafts, simultaneous growth of ice and liquid may occur in zones of isobaric mixing. At vertical velocities close to zero, air in mixed-phase clouds is subsaturated with respect to water (Korolev and Mazin 2003). Isobaric mixing of two subsaturated parcels having different temperatures may result in higher relative humidity than in either of the parcels (e.g., Rogers 1976). Under certain conditions, the resulting relative humidity may exceed saturation over liquid, providing simultaneous growth of droplets and ice particles.

In contrast to the WBF process, which results in the glaciation of mixed-phase clouds, the condition described in (1) will maintain the mixed-phase for an indefinite period for as long as (1) holds.

The fundamental difference between the WBF process in (2) and the one under discussion is that liquid droplets play opposite roles. During the WBF process, liquid droplets serve to feed ice particles by

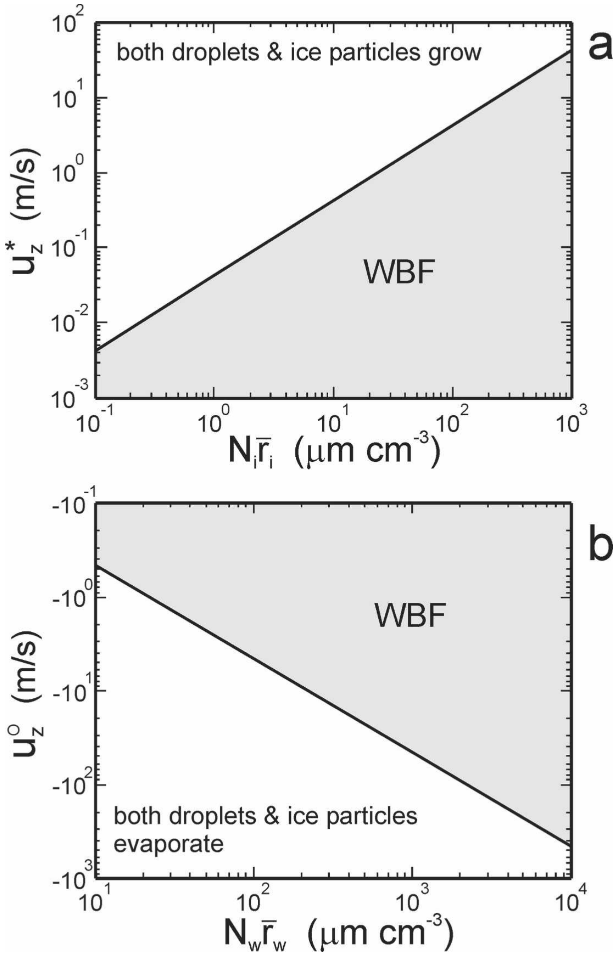

FIG. 2. Threshold vertical velocities (a) u_z^* and (b) u_z^o vs the integral radii of ice particles and droplets, respectively, calculated for $T = -10°C$ and $P = 800$ mb. The gray color indicates areas with conditions for the WBF process.

providing water vapor, via their evaporation, thereby enhancing depositional growth of ice particles. However, when (1) is satisfied, liquid droplets and ice particles compete for water vapor.

2) When (2) is true, droplets evaporate, whereas ice particles grow (Fig. 1b). The evolution of the mixed phase under the conditions in (2) defines the WBF process. In mixed-phase clouds the WBF process may occur in both updrafts and downdrafts when $u_z^o < u_z < u_z^*$, where u_z^o is the vertical velocity separating growth and sublimation of ice particles in presence of liquid droplets. The shaded area in Fig. 2 indicates the conditions for the WBF process.
3) When (3) is true, both droplets and ice particles evaporate (Fig. 1c). As shown by Korolev and Mazin (2003), simultaneous evaporation of ice particles and liquid droplets may occur in downdrafts when $u_z < u_z^o$ and

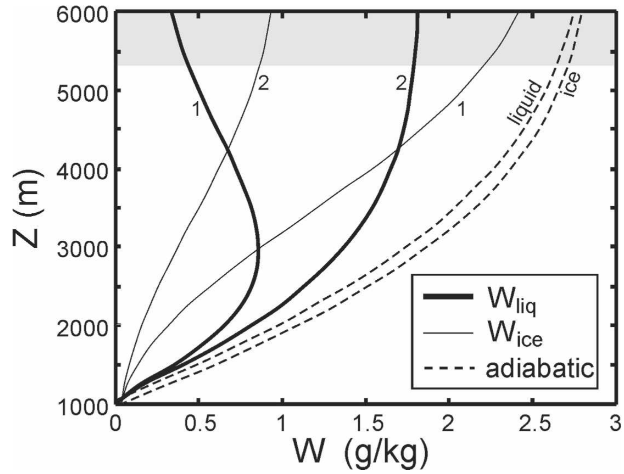

FIG. 3. Numerical modeling of ice and liquid water content changes in an adiabatic parcel uniformly ascending at $u_z = 1$ m s^{-1} (labeled 1) and $u_z = 2$ m s^{-1} (labeled 2) with concentration of ice particles $N_i = 100$ L^{-1}, and initial ice radii $r_{i0} = 50$ μm, supersaturation $S_{i0} = 0$; and temperature $T_0 = -5°C$. The gray color indicates an area with $T < -40°C$ where liquid droplets will homogeneously freeze.

$$u_z^o = \frac{e_i - e_s}{e_s}\chi N_w \bar{r}_w, \tag{5}$$

where χ is a coefficient dependent on T and P; N_w and $\bar{r}_w$ are the number concentration and mean radius of liquid droplets, respectively. Figure 2b indicates that for typical values of $N_w\bar{r}_w$ (10^2–10^3 μm cm^{-3}), downdraft velocity needed to satisfy (3) should exceed a few m s^{-1}. Such velocities can be generated by compensating downdrafts in convective clouds.

Simultaneous evaporation of droplets and ice particles may occur due to entrainment and mixing with out-of-cloud dry air near cloud boundaries. This is the most likely process for the simultaneous evaporation of ice particles and droplets.

In a mixed-phase cloud condition, (3) results in a process distinctly different from the WBF process, since ice particles will ultimately evaporate. The evolution of a mixed-phase cloud obeying (3) terminates in complete evaporation of the whole cloud. Depending on N_w, N_i, $\bar{r}_{w0}$, and $\bar{r}_{i0}$, ice particles may sublimate prior to complete evaporation of liquid droplets. If so, the mixed-phase cloud becomes a liquid cloud before its evaporation is complete. Otherwise, the evaporating mixed-phase cloud will go though the stage of glaciation.

The next example demonstrates the effect of thermodynamical characteristics on the evolution of mixed-phase clouds. Figure 3 shows the modeled changes in the liquid and ice water contents for two adiabatic parcels ascending with different velocities $u_z = 1$ m s^{-1} and 2 m s^{-1}. The gray area at the top of the diagram indicates the region where the air temperature drops below −40°C and spontaneous droplet freezing takes place. As seen from Fig. 3 for $u_z = 1$ m s^{-1} (lines 1) liquid and ice particles both grow at altitudes below $Z < 2900$ m. For the altitudes above $Z > 2900$ m the droplets evaporate, whereas the ice particles keep growing. Therefore, the WBF process is enabled only in the part of cloud where $Z > 2900$ m, whereas for $Z < 2900$ m it is turned off.

For the vertical ascent $u_z = 2$ m s^{-1} (lines 2) both droplets and ice particles always grow, and therefore the WBF mechanism is turned off throughout the whole cloud. Hence, even relatively weak updrafts may disable the WBF mechanism in convective clouds.

The above consideration suggests that in convective clouds the role of the WBF mechanism may have a limited significance. As seen from Fig. 3 at $Z = 5000$ m for the case $u_z = 1$ m s^{-1} (when the WBF process is enabled) the ice water content is approximately 2.5 times greater than for $u_z = 2$ m s^{-1} (when the WBF process is declined).

In conclusion, it should be emphasized that the evolution of the mixed phase is closely related to local thermodynamical characteristics of the cloud, resulting in three distinctly different scenarios of phase transformation of mixed-phase clouds. In future publications researchers should take extra care to properly describe the process of precipitation formation in mixed-phase clouds, and be careful not to confuse three separate processes of phase transformation by categorizing them all under the label of "WBF mechanism."

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