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The Wegener-Bergeron-Findeisen process – Its discovery and vital importance for weather and climate

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Abstract

The *Wegener-Bergeron-Findeisen process* refers to the rapid growth of ice crystals at the expense of surrounding cloud droplets, which frequently occurs in atmospheric mixed-phase clouds. The process is a result of the difference in saturation vapor pressures with respect to liquid and ice, and may in some circumstances lead to abrupt and complete cloud glaciation at temperatures between −40 °C and 0 °C in the Earth's atmosphere. The process is named after three eminent scientists who were active in the first half of the 20th century, among them being German meteorologist WALTER FINDEISEN (1909–1945). In his classical paper published in 1938, FINDEISEN described the contemporary understanding of the Wegener-Bergeron-Findeisen process and other key cloud microphysical processes. Here, we compare the understanding of aforementioned processes at the time with that of the present, and find that they are remarkably similar. We also discuss how the Wegener-Bergeron-Findeisen process is implemented in state-of-the-art numerical models of the atmosphere, and highlight its importance for both weather and climate.

Keywords: Wegener-Bergeron-Findeisen process, mixed-phase clouds, weather and climate

1 Introduction

The importance of the Wegener-Bergeron-Findeisen (WBF) process, or simply the Bergeron-Findeisen process, is well known to meteorologists and climatologists alike. By abruptly transforming non-precipitating liquid clouds to heavily precipitating ice clouds and dramatically changing cloud radiative properties, it can have a profound impact on both weather and climate. Its discovery, which dates back almost a century ago, should be equally accredited to three eminent scientists of the time: ALFRED WEGENER, TOR BERGERON and WALTER FINDEISEN.

The German scientist ALFRED WEGENER (1880–1930), well-known for his then-controversial theory on continental drift, first laid the theoretical foundation for the WBF process (WEGENER, 1911), by showing that the co-existence of liquid and ice is a thermodynamically unstable state. This revelation allegedly came to WEGENER while studying the formation of hoarfrost. A decade later, in the winter of 1922, the Swede TOR BERGERON (1891–1977) found himself pondering the theory put forth in WEGENER's book during a stay at a health resort in Voksenkollen (430 m above sea level) outside of Oslo in Norway. Observant as he was, BERGERON had noticed that when the temperature was below freezing, nearby forest roads were clear of fog while trees were covered in frost. Fog, however, would typically be present and extend all the way to the ground when temperatures were above 0 °C. As an active member of the prestigious Bergen School of Meteorology, BERGERON became immersed in his duties in Bergen in the years following his discovery in Voksenkollen, so much to the extent that he did not further pursue his ideas on the matter until 1928, when the topic became one of the chapters in his PhD thesis (BERGERON, 1928).

It wasn't until 1938 that WALTER FINDEISEN entered the scene, contributing to the previous work of WEGENER and BERGERON by providing additional theoretical calculations, as well as cloud chamber experiments to further develop their theories. FINDEISEN's PhD thesis (1931) focused on cloud droplet size distributions, and included cloud chamber experiments, a novel approach at the time. FINDEISEN's cloud chamber was approximately 2 m^3 in volume, and was connected to a vacuum pump, allowing the process of adiabatic expansion and atmospheric cloud formation to be mimicked in the chamber. After World War II, FINDEISEN's cloud chamber was recovered from the ruins of Prague, where FINDEISEN had his last appointment as director of the Prague branch of the German Meteorological Office. Fig. 1 shows the rebuilt cloud chamber, as it appeared in PODZIMEK (1957).

FINDEISEN frequently cites the work of WEGENER and BERGERON in his seminal paper from 1938 (FINDEISEN, 1938, hereafter F38), whose work allowed him to present a coherent and comprehensive overview of the most recent understanding of atmospheric cloud and precipitation formation at the time. As such, the paper goes beyond the WBF process that FINDEISEN later became known for, and can in many ways be considered the first complete description of cloud microphysics as we understand it today.

Atmospheric scientists today are privileged to conduct research in an age as data-rich as the present, with

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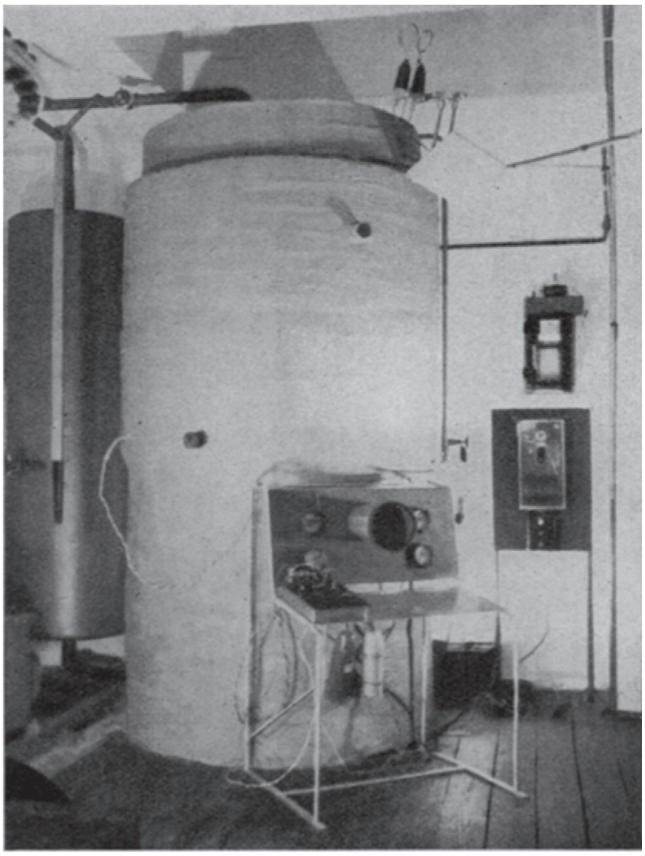

Figure 1: Walter Findeisen's cloud chamber, as it appeared in the publication that reported the first successful measurements with the chamber after it was recovered and rebuilt after World War II (Podzimek, 1957). Published with permission from ©Springer.

in situ measurements, remote sensing observations, laboratory work and numerical modeling all contributing to this wealth of data. By contrast, the earliest works on cloud microphysics by Wegener, Bergeron and Findeisen had very little *in situ* observations and of course no satellite data available to them. It is a testimony to their brilliance that they nevertheless came to many of the same valid conclusions we find today. In fact, the understanding of the microphysical processes involved in liquid and ice cloud formation and subsequent cloud evolution has changed relatively little relative to that presented by F38. To give an example, in F38 Findeisen claimed that *every precipitation event of at least medium intensity, and in particular every event with larger raindrops, is caused by ice crystals*. A more recent study based on satellite data has confirmed the truth of this statement, and found that the majority (~ 70 %) of tropical precipitation events indeed originate from the ice phase (Lau and Wu, 2003).

The remainder of this paper is dedicated to comparing the microphysical processes as they were described in F38 with our understanding of them today. Section 2 describes the theoretical foundation for the WBF process, Section 3 discusses the co-existence of supercooled liquid (i.e. liquid water existing at temperatures below 0 °C) and ice crystals required for the WBF process to occur, and Section 4 describes how the WBF process is implemented in state-of-the-art numerical models of weather and climate. Finally, Section 5 offers a brief conclusion.

2 The Wegener-Bergeron-Findeisen process

The WBF process refers to the rapid conversion of liquid to ice that may occur when supercooled droplets and ice crystals co-exist (Pruppacher and Klett 2010). The conversion occurs due to the difference in saturation vapor pressures over liquid and ice surfaces at temperatures below 273 K (e_l and e_i, respectively, with $e_\mathrm{l} > e_\mathrm{i}$), which can be approximated from the *Clausius-Clapeyron relation*. In other words, an environment that is saturated with respect to liquid water will be highly supersaturated with respect to ice, and the relative difference in supersaturation is exacerbated with decreasing temperature (Fig. 2). A common misconception is that the WBF process is automatically activated when liquid and ice co-exist, i.e. ice crystals are guaranteed to grow at the expense of cloud droplets without exception. However, as pointed out for example by Korolev (2007) and Korolev and Mazin (2003), the WBF process is only one of three possible cases that may occur when a cloud consists of liquid and ice. The WBF process (i) will occur when the vapor pressure (e) lies between e_i and e_l. The other two possible cases involve either (ii) simultaneous growth of liquid droplets and ice crystals ($e > e_\mathrm{l} > e_\mathrm{i}$) or (iii) simultaneous evaporation/sublimation of cloud droplets ($e < e_\mathrm{i} < e_\mathrm{l}$). Cloud dynamics in the form of small-scale updrafts and downdrafts exert an important control over which case plays out for a given mixture of droplets and crystals. Findeisen understood this, and described case (ii) in Section 4 of his 1938 paper: sufficient updrafts and hence adiabatic cooling can result in the counter-intuitive process of droplet formation and growth in a glaciated cloud. The reason why sufficiently high supersaturations for droplet formation can occur in ice clouds was also addressed in F38: the nuclei on which ice crystals form in the atmosphere are very rare relative to the nuclei that cloud droplets nucleate on. Hence, even though ice crystals are present in a cloud, they may not be present in high enough number concentrations for their growth to deplete supersaturation faster than the rate at which high supersaturation is produced via adiabatic cooling.

3 Liquid in the supercooled state and the scarcity of ice nuclei

The distinction between the two classes of nuclei, cloud condensation nuclei (CCN) and ice nuclei (IN), was offered by F38 as an explanation for the frequent observations of supercooled liquid water in the atmosphere that had been reported at the time. While the reported

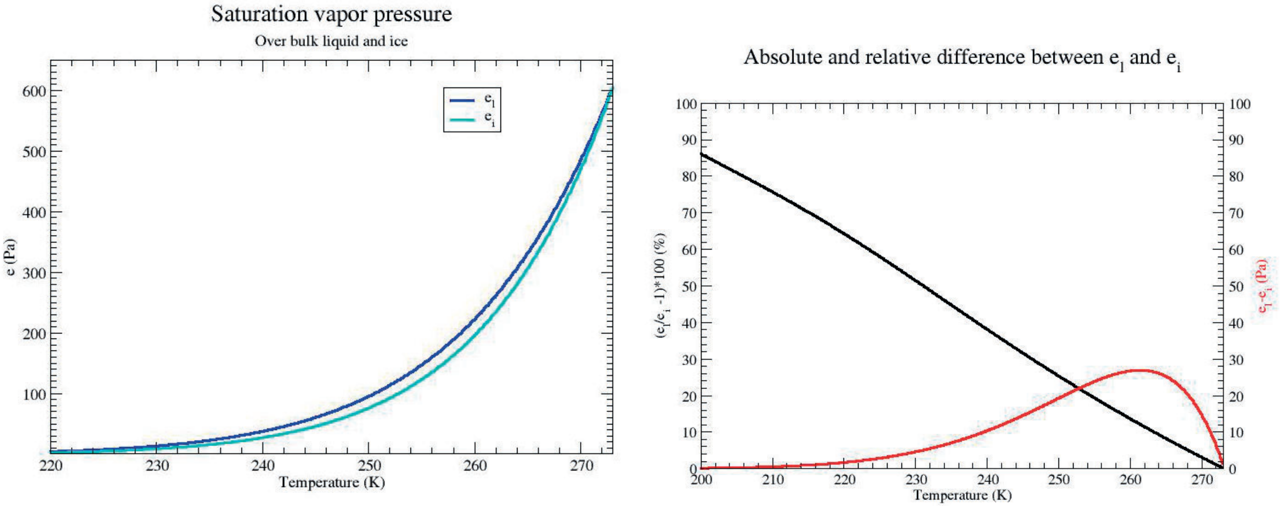

Figure 2: Left: Saturation vapor pressure over bulk liquid (e_l) and over bulk ice (e_i) as a function of temperature, calculated using the *Magnus formula* (Magnus, 1844). Right: Absolute (red line) and relative difference (black line) between e_l and e_i, the latter given as $(e_\mathrm{l}/e_\mathrm{i} - 1) \cdot 100\,\%$, all as functions of temperature. The black line corresponds to the supersaturation that would be experienced by an ice crystal forming in a supercooled liquid cloud under the assumption that the water phase is in equilibrium with the liquid phase at the time of crystal formation.

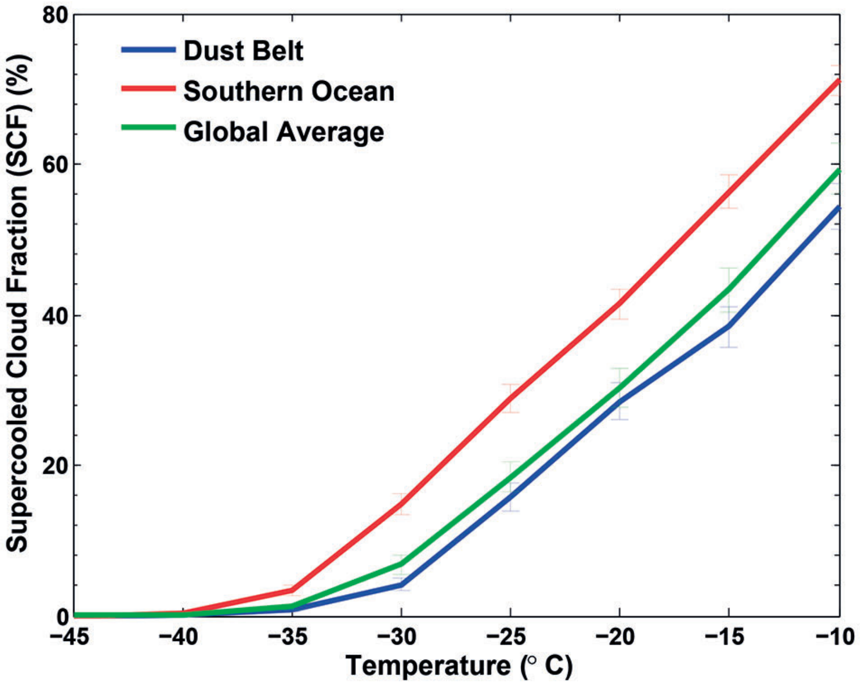

Figure 3: Supercooled cloud fraction (SCF, %) based on CALIOP retrievals; global mean (green), the dust belt (blue, average over the region 0–120 ° W and 30–50 ° N) and the Southern Ocean (red, average over the region 0–360 ° W and 60–70 ° S). For further details on how SCFs were calculated based on the CALIOP retrievals, and associated uncertainties, see Tan et al. (2014a).

observations were naturally sporadic and few, they supported the existence of liquid at temperatures even below −20 °C. Now, several decades into the satellite era, we are able to take advantage of global datasets that provide information on cloud thermodynamic phase with relatively high temporal coverage. An example is shown in Fig. 3, displaying the observed supercooled cloud fraction (SCF, in %) as a function of temperature, as retrieved by the Cloud and Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument onboard NASA's Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite (Hu et al. 2009, Tan, Storelvmo and Choi 2014b, Winker et al. 2009). These CALIOP retrievals are representative of cloud tops only, and the SCF was calculated by taking the ratio of liquid cloud top pixels to total cloud top pixels within 2.0 ° longitude by 2.5 ° latitude grid boxes. The cloud top temperatures were determined using the

NCEP-DOE Reanalysis 2 dataset (Kanamitsu et al., 2002). The satellite observations support a global average liquid cloud fraction of ~ 30 % at −20 °C, in agreement with the findings from a century ago. Furthermore, a comparison of the SCF in the Southern Ocean region (0–360 ° W, 60–70 ° S) with those found in the so-called *Dust belt* (0–120 ° W, 30–50 ° N), suggests that SCF is spatially heterogeneous and that although certainly important, temperature is not the sole factor influencing cloud phase.

Substantial amounts of liquid exist over the Southern Ocean, even at temperatures as low as ~ −30 °C, presumably owing to the scarcity of IN that are required to initiate freezing at temperatures above approximately −40 °C in the atmosphere. Findeisen was aware of this and had documented it in Section 1 of F38. He estimated that the ratio of CCN to IN number concentrations was on the order of 10^4, a number that matches current observations using so-called CCN and IN-counters (Hudson and Squires, 1974; Roberts and Nenes, 2005; Rogers 1988; Stetzer et al., 2008), instrumentation that was not available during Findeisen's time. However, Findeisen did state that it would be possible to design such instruments and remarked that they had the potential to "clarify the controversial questions" presented in his paper.

Given the lack of instrumentation at the time, Findeisen's description of the properties of CCN versus those of IN is remarkably similar to that of any contemporary paper on the subject. In a recent review of atmospherically relevant IN, Murray et al. (2012) reaffirmed Findeisen's description of IN (referred to as *sublimation nuclei* by Findeisen) in F38 as insoluble particles of terrestrial origin, mainly in the form of mineral dust (quartz, according to Findeisen). Beyond this, Findeisen also stated that the chemical composition and origin of IN are largely unknown, a statement that to some degree still holds today. Notwithstanding Findeisen's pioneering discoveries, atmospheric ice nucleation is currently a very active field of research, and our understanding of what particles are able to act as IN under what conditions is rapidly evolving. We now know that certain mineral dust types are better at nucleating ice than others, and that quartz is not a particularly good IN (Atkinson et al., 2013). We also know that biological particles and potentially anthropogenic particles such as soot, ash and metallic particles (Cziczo et al., 2009; Hoose and Mohler, 2012) may also be acting as IN in the atmosphere.

In addition to his work on the WBF process, Findeisen had also performed laboratory work on cloud droplet formation (F38) at approximately the same time that Hilding Köhler was developing the relatively straightforward theory of cloud droplet formation by the so-called process of "CCN activation" in 1936, now sometimes referred to as Köhler Theory. Findeisen's untimely death towards the end of World War II in 1945 at the tender age of 36 in Prague, meant that Köhler, outliving him, was able to influence the field for decades thereafter, perhaps resulting in the different legacies of the two scientists.

4 Representations of the WBF process in numerical weather and climate models

Returning to the WBF process that brought Findeisen fame, its importance for weather and climate has increasingly attracted attention in recent years. A realistic representation of the WBF process in numerical weather prediction (NWP) and global climate models (GCMs) is critical for more accurate simulations of atmospheric dynamical and radiative processes, and hence the climate system as a whole. The typical horizontal resolution of such models is on the order of 10 to 100 km, while the WBF process occurs on scales orders of magnitude smaller. Such unresolved processes pose a challenge for numerical models of weather and climate. The impact of these small-scale processes on resolved large-scale processes can be accounted for by including *parameterizations* of the small-scale processes that are otherwise unresolved. In recent years, new parameterizations with various levels of sophistication have been developed. The simplest parameterizations impose a critical threshold of in-cloud ice mixing ratio, above which the WBF process is assumed to become efficient enough to deplete all remaining liquid in the model grid box within a single model time step (typically ~ 30 min) (Storelvmo, Kristjansson and Lohmann 2008a, Lohmann and Hoose 2009). However, more recent studies have attempted to treat the WBF process in a more rigorous fashion. In a parameterization frequently used in both GCMs and NWP models (Morrison et al. 2005), the WBF process is diagnosed based on the rate of depositional growth of ice crystals, A, and the rate of condensation of liquid, Q. If $A > Q$ the WBF process is assumed to deplete liquid water within the model's time step. While this approach is consistent with the understanding of how the WBF process operates in the atmosphere, it is oversimplified in the sense that it assumes that all cloud properties are uniform within the cloudy portion of each model grid-box, which, in a GCM, typically spans ~ 100 km in both longitudinal and latitudinal directions.

A few studies have sought remedy for the aforementioned oversimplified parameterizations of the WBF process by introducing sub-gridscale variability in cloud properties that are key to accurately representing the WBF process (Rotstayn, Ryan and Katzfey 2000, Storelvmo et al. 2008b, Storelvmo et al. 2010, Rotstayn 1997). In attempt to account for this sub-gridscale variability, Rotstayn (1997) introduced a triangular probability density function (PDF) for the total-water mixing ratio, q, within each model grid box, following Smith (1990). The PDF was centered at the grid box mean total-water mixing ratio. Instead of considering differences in vapor pressure, e, between the two phases

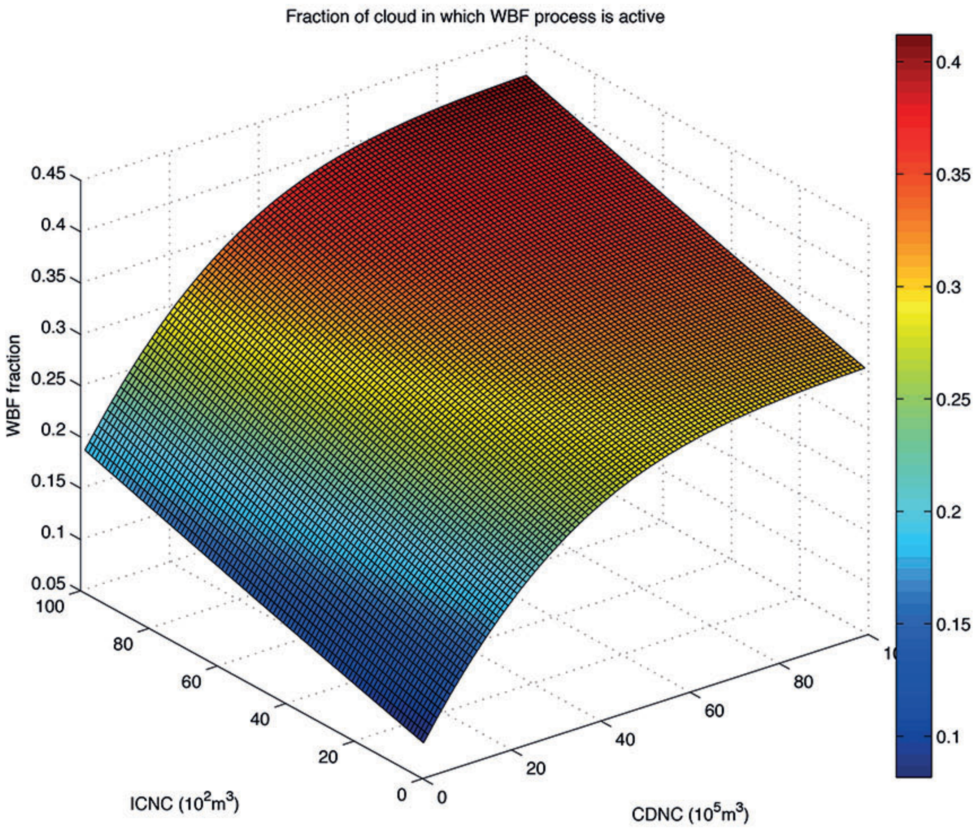

Figure 4: The fraction of cloud in which the WBF process is active, as a function of cloud droplet number concentration (CDNC, 10^5 m^3) and ice crystal number concentration (ICNC, 10^2m^{-3}), assuming a Gaussian PDF of w centered at 0.1 m/s with a standard deviation of 0.2 m/s. Ice crystal and cloud

(as in Section 1), the corresponding difference in saturation vapor mixing ratio ($q_{\mathrm{s,l}}$ and $q_{\mathrm{s,i}}$ for liquid and ice, respectively) was used to determine the portion of the cloud that consists of co-existing ice and liquid. In a grid box containing both liquid and ice, coexistence would be possible for the portion of the grid box with $q > q_{\mathrm{s,l}}$, while the portion with $q_{\mathrm{s,i}} < q < q_{\mathrm{s,l}}$ would have ice clouds only, and $q < q_{\mathrm{s,i}}$ would correspond to cloud-free conditions. Note that this framework assumes that the cloud droplet and ice crystal response to sub-saturation is fast, and that complete evaporation occurs within one model time step (~ 30 min) Following up on the work of Rotstayn (1997) and Smith (1990), Storelvmo et al. (2008b) implemented a normal distribution for the vertical velocity, w, in place of the triangular PDF for q used in Rotstayn (1997). Previously, Korolev (2007), Korolev and Mazin (2003) had derived parameterizations for the critical updraft above which liquid and ice could co-exist ($w_{\mathrm{c,u}}$), and the critical downdraft below which both liquid and ice crystals are bound to evaporate ($w_{\mathrm{c,d}}$). By combining this with the PDF of w, the evolution of the thermodynamic phase of clouds can be divided into three distinct regimes: i) simultaneous growth of droplets and ice crystals, ii) growth of ice crystals at the expense of cloud droplets (the WBF process), and iii) simultaneous evaporation of droplets and ice crystals. $w_{\mathrm{c,u}}$ (always positive) and $w_{\mathrm{c,d}}$ (always negative) are functions of ice crystal number concentration (ICNC) and cloud droplet number concentration (CDNC), among other variables. Fig. 4 displays the fraction of a cloud that will be dominated by the WBF process (regime ii above) as a function of CDNC and ICNC, calculated according to the formulae in Korolev (2007) (for other assumptions made for the calculation, see the caption of Fig. 4). At high CDNCs, saturation can still be maintained in strong downdrafts by evaporating the many cloud droplets present. The parameterization accounts for this by allowing $w_{\mathrm{c,d}}$ to become increasingly negative, thereby causing the fraction of the cloud in which ice crystals can grow at the expense of cloud droplets to increase. At high ICNC, ice crystal growth on the many ice crystals present rapidly depletes water vapor and brings the vapor pressure below that of saturation with respect to liquid water. In this case, very strong updrafts are required for simultaneous growth of droplets and ice crystals (i.e. $w_{\mathrm{c,u}}$ is large). As a result, the fraction of the cloud dominated by the WBF process increases with increasing ICNCs.

Independently of how the WBF process is treated in GCMs and/or NWP, the extent to which ice crystals

Table 1: Net Cloud Radiative Effect (CRE) evaluated at the top of the atmosphere, Total Water Path (TWP), total precipitation and the ratio of stratiform to convective precipitation for simulations in which i) cloud phase is prescribed according to temperature (i.e. no representation of the WBF process, NO_WBF), ii) a crude critical ice mixing ratio threshold treatment (see above, SIMPLE_WBF) is applied and iii) a WBF treatment which accounts for subgrid scale variability (see above, SUBGRID_WBF) is implemented. Observations are from satellite retrievals (Loeb et al., 2009; Komurcu et al. 2014).

Simulations	**NO_WBF**	**SIMPLE_WBF**	**SUBGRID_WBF**	**OBSERVATIONS**
Net CRE (Wm^{-2})	−15.7	−24.9	−21.4	−24.5–17.9
TWP (gm^{-2})	148.3	112.2	132.1	47–109
Total precipitation (mm/day)	2.84	2.80	2.78	2.74
Stratiform/convective precipitation ratio	0.37	0.54	0.51	N/A

and cloud droplets are assumed to be well-mixed with each other in the cloud volume, or whether they are assumed to exist in separate pockets of ice and liquid, is of critical importance (Korolev and Isaac, 2006). This statement can be illustrated with two sensitivity simulations[1] using the CAM5 GCM (http://www.cesm.ucar.edu/models/cesm1.2/cam/) that attempt to mimick pure homogeneous (i.e. well-mixed) and pure heterogeneous mixing between the two phases (simulations HOM and HET, respectively). Between the two simulations, HOM yielded three times the amount of vertically integrated amount of ice in the atmosphere (Ice Water Path, IWP) relative to HET. The contrast between homogeneous and heterogeneous mixing was mimicked by reducing the efficiency of the WBF process by a factor of 10^{-6}, physically corresponding to a situation in which there is only contact between the pockets of liquid and ice in relatively narrow mixing zones. High-frequency *in situ* measurements of cloud phase may aid in developing parameterizations that realistically represent the degree of mixing that occurs within mixed-phase clouds, but such measurements are presently scarce.

To illustrate how sensitive model-simulated cloud, radiation and precipitation fields can be to the representation of the WBF process, Table 4 shows global mean output from three 5-year simulations with the same atmospheric GCM (Storelvmo et al., 2008b). The simulations only differ in their treatment of the WBF treatment. Drastic changes in the net radiative effect of clouds, as well as in the column-integrated amount of liquid and ice in the atmosphere, are evident. Since the design of atmospheric GCM simulations is such that surface evaporation remains relatively constant (because of prescribed climatological sea surface temperatures), total precipitation does not change much between the simulations. However, the partitioning of the precipitation between the stratiform and convective type can, and does, change drastically.

5 Conclusion

The WBF process is an extremely powerful microphysical mechanism that can cause rapid transformation of cloud macrophysical and radiative properties. It can play a tremendously important role in both climate forcing and feedback mechanisms by amplifying the effect that anthropogenic perturbations in IN have on climate. It may also affect the cloud-climate feedback mechanism sometimes referred to as the *cloud optical depth feedback* (Zelinka, Klein and Hartmann, 2012) by amplifying the effect that warming temperatures has on cloud phase (McCoy, Hartmann and Grosvenor, 2014). As such, the significance of the WBF process is gaining attention, as it becomes increasingly clear that realistic representations of aerosol-cloud interactions and cloud feedbacks in climate models rely on the accuracy of the representation of the WBF process in these models. In retrospect, Findeisen's paper from 1938 is thus more relevant now than ever before, but ironically for reasons that Findeisen could not have predicted when he wrote his seminal paper. Global warming was not yet detectable at the time, and the early warnings by Arrhenius (1896) had largely been forgotten.

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[1] The simulations were run for one year after a three-month spin-up, at a relatively coarse horizontal resolution of 4 ° × 5 °.

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