

A Warming Arctic Will Not Affect Supercooling Levels of Cloud Water Droplets

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Abstract

It is now well understood that Arctic regions are warming more rapidly than other areas of Earth. Cloud formation and levels of supercooling of water droplets in clouds might be thought vulnerable to such change. We discuss here the lack of affect the highest temperature reached by the droplets has on the supercooling ability and so show that the warming Arctic is unable to affect the actual freezing temperature of clouds, at a given level of supercooling and so with a given level of nucleation site(s).

Keywords

Arctic, Supercooling, Water, Droplets, Freezing

1. Introduction

Over the past decades, the Arctic has been seen to be warming much faster than the global average [1]. Several factors contribute to this Arctic amplification; convection currents, albedo effect, water vapor transport, oceanic currents and lapse rate feedback are all involved. Global temperatures from 2005-2009 were, on average, 0.6°C higher than the averages from 1951-1980, and in the same time the Arctic has warmed about 2°C [2]. Polar amplification has impacted the Arctic more than Antarctica due to geological position, landscape, sea ice and convection currents in both the atmosphere and the ocean. These factors together make the

Arctic more vulnerable to warming.

Cloud cover is becoming greater in the Arctic and so it is possible that the cloud makeup is also changing, *i.e.* mixed phase clouds, frozen (nacreous) clouds, water vapour and the various altitudes, all may be changing along with this temperature increase. The temperature at which supercooled water droplets freeze, the nucleation temperature, will however not be changing. This temperature is that at which the liquid water actually turns to ice, known as the supercooling point, or nucleation temperature. This temperature would normally be a factor of altitude, latitude, levels of mineral dust and even biological factors. We show here, however, that the so-called supercooling point is potentially unchanged, regardless of the warmest temperature that the water droplets had reached at any different altitude. That is, the liquid cloud droplets will spend some time, and sit at some temperatures, prior to cooling into the supercooled region and freezing. We are arguing here that the highest temperature these droplets reach (climate change related) will not actually affect the lowest temperature they reach before freezing.

In a recent study by Stratta *et al.* [3], it was suggested that the melting temperature, or, in fact, the warmest temperature reached by a given volume of water could affect the level of supercooling available to that water. If this was the case, then a warming Arctic could cause a change in the freezing temperature of supercooled clouds and in turn affect the ice content at a given altitude and so the albedo effect of clouds. Stratta used a differential scanning calorimeter (DSC) and aluminum pans to supercool about 5 μl of water and used the DSC to detect the exotherm when that water froze, on multiple runs, at various highest temperatures the water had been held at. They then argued, because the warm runs had a less well-defined survival curve (fraction of runs unfrozen as a function of temperature), that the warm temperatures reached had altered the diffusion ability of the water in the pans.

Our own studies are in contradiction to the conclusions of Stratta and show that, for any volume of water, the supercooling ability is completely unrelated to how warm the water has been above its melting temperature [4]. We argue therefore that our laboratory results on bulk samples demonstrate that, even in the small volumes of cloud droplets, water cannot supercool to a different temperature based on the warmest temperature reached. Rather, the supercooling ability is determined solely by the best nucleation site within that water droplet.

2. The Arctic

The Albedo Effect, as darker ocean surfaces absorb more solar radiation, rather than reflecting it, creates further melting of the Arctic, thus creating a positive feedback loop. Sea ice in the Arctic shrinks by 13% per decade [5]. In cold biomes, the Arctic and the Antarctic, the atmospheric convection currents allow air near the ground to warm much faster than the air higher in the atmosphere. Warm air rising to let cooler air sink down creates what is known as the lid effect and the

atmosphere is mixed and therefore stable. These vertical currents allow heat to be distributed evenly and so control global temperatures. However, as the polar regions receive less solar radiation, there is less convection. This heat is trapped in the lower regions of the ecosystem, *i.e.* near the surface. More greenhouse gases have less freedom to mix vertically as the solar radiation is very low. This means the gases stay closer to the surface, resulting in the surface temperature rising, increasing warming faster than in other regions.

Cloud cover in polar regions impacts the overall process, affecting the feedback loop. Ocean circulation and heat transport, in some cases also convection currents, essentially transport water in the same way that air is transported. By moving the warm water from the tropics towards the polar regions, convection currents are critical in regulating heat, and so in moderation of global climate. However, the amplification effect has impacted these currents. This effect is named the Heat Blob inflow, and the so-called Atlantic Meridional Overturning Circulation (AMOC) plays a role in these ocean currents [6]. AMOC has weakened in the past decades.

The Polar biome also has a halocline, a cold, fresh layer of water. This cold water acts as a freezer for the ocean and also like a barrier preventing the warm water from the tropics (Atlantic) from coming in contact with polar ice. However, just like the added greenhouse gases, the increased freshwater input from melting glaciers and sea ice, such as from Greenland, is resulting in disrupting the vertical mixing in the convection currents. The mixing with freshwater dilutes the salt content of the saltwater, resulting in less dense water and stopping the sinking process that essentially controls the AMOC, and so deep water circulation [7]. As there is reduced dense-water circulation to sink, the heat is mixed upward, penetrating the halocline and melting the sea ice from below. This can still occur during the winter seasons in the polar region. Furthermore, this adds to the already high freshwater content, making the Arctic system more vulnerable to changing oceanic patterns. This prevents new ice-formation and further increases the feedback loop.

The Gulf Stream plays a very critical role in these processes. It is essentially a giant energy conveyor belt for Europe, providing warmth. Not only does this system establish the currents and transport warm water from the tropics to Europe, but it also delivers most of the water to the Arctic. The gulf stream has been said to be under threat because of the thermocline of the water.

Satellite data shows that between 2002 and 2020, 149 billion metric tons of ice has been lost on average per year from Antarctica. Glaciers in Arctic Scandinavia and Svalbard have had the largest net loss per year of ice on record, largely happening between 2023 and 2024 [8]. This shows that it is not just the ocean that is warming in the sense that Scandinavia and Svalbard are less affected by the warming oceans. Surface air temperatures are also warming in the Arctic area. October 2024 through to September of 2025 were the warmest since 1900. Warming is not just confined to the water, but is also affecting the temperature of the air and the land (**Figure 1**).

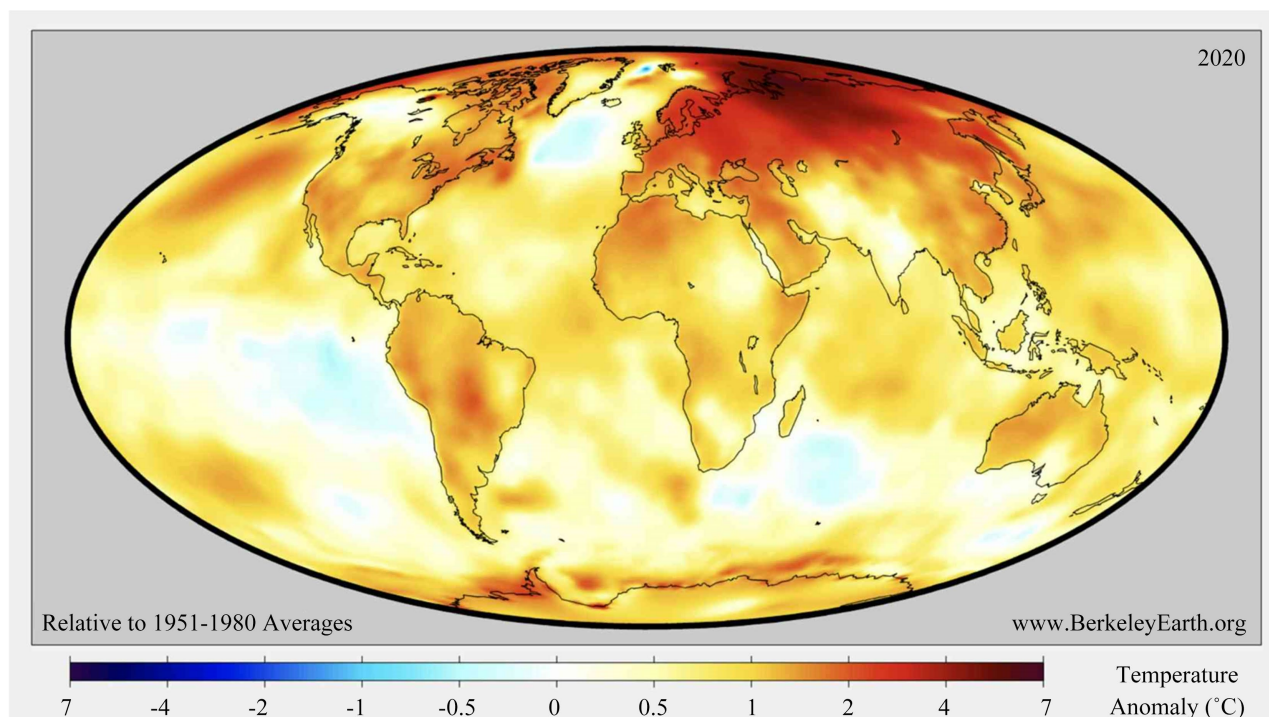


Figure 1. Geographical distribution of temperature anomalies globally in 2020 [from <https://www.berkeleyearth.org/march-2026-temperature-update/>].

3. Clouds

At mid-latitudes, the occurrence of liquid phase clouds at temperatures between -40°C and 0°C depends jointly on both cloud height and cloud temperature. At high latitudes, more than 95% of low-level clouds with temperatures between -40°C and 0°C , are water clouds. Supercooled water clouds are mostly observed over ocean near what are called storm-track regions and at high-latitude regions [9] [10]. Supercooled water clouds over land are observed in the Northern Hemisphere over Europe, East Asia, and North America, and these are the supercooled water clouds with highest liquid water contents. Furthermore, this adds to the already high freshwater content, it makes the Arctic system more vulnerable to changing oceanic patterns. This prevents new ice-formation and further increases the feedback loop.

Even in summer, the Arctic rarely gets above freezing, capping at 0°C except in extreme heat waves, and so the freezing level of clouds is sea level. It is important to note that even at below 0°C , clouds can still have supercooled water in them, thanks to the low level of aerosol particles in the atmosphere in the Arctic [11]. The low level of aerosol particles not explaining cloud freezing has recently been discussed and the concept of nucleation by cosmogenic neutrons at high latitudes introduced as a possibility [12] [13]. However, that discussion is beyond the scope of this report. So, while theoretically Arctic clouds should always be frozen, supercooled water means that they aren't always frozen, especially as the temperatures climb close to 0°C in summer. Only at higher altitudes, or in winter, do the

clouds become fully frozen. The typical freezing level at the equator is around 4500 - 5000 m above sea level, with high-altitude cirrus clouds starting to form above 5500 m above sea level [14].

There has been an almost linear increase in the amount of cloud cover in central Arctic region in the past two decades (see Figure 2) [15]. Clouds are thought to amplify the temperature increase rather than offset it. Cloud cover has recently been introduced as the main role in increasing global warming. Indeed, clouds are both absorbing and reflecting the radiation from the sun to various degrees. The levels of ice (or water) in mixed phase clouds is therefore a significant factor.

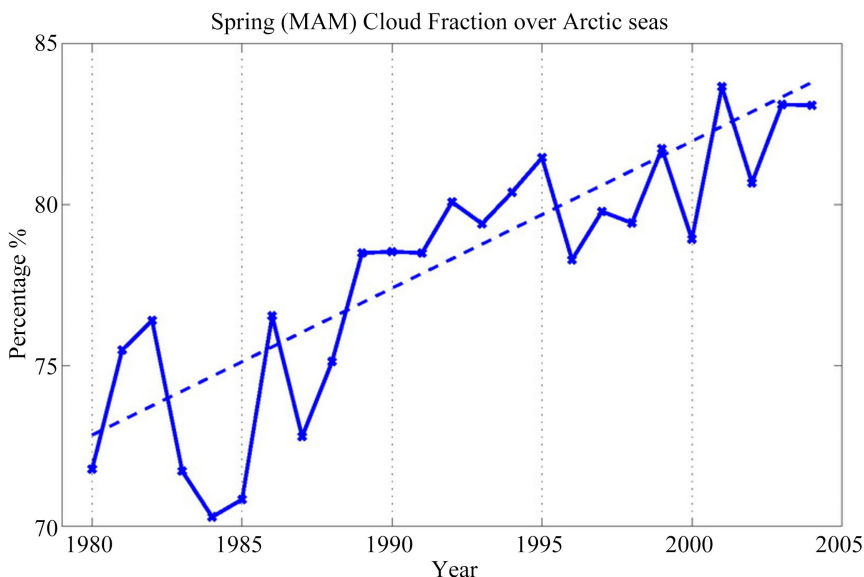


Figure 2. Increase in cloud cover from 1980 to 2005 over the Arctic shows a 15% increase [Adapted from <https://www.pmel.noaa.gov/arctic-zone/detect/climate-clouds.shtml?>].

4. Cloud Freezing and Supercooling of Water

Table 1, below, summarizes briefly freezing heights at some latitudes, demonstrating that at high latitudes freezing can occur as low as 500 m above sea level.

Table 1. Freezing heights at some latitudes, demonstrating that at high latitudes freezing can occur as low as 500 m above sea level.

| Latitude | Height | Type | References |
|------------------|--------------------|---------------------------------------|------------|
| ~66.5°N, ~66.5°S | 500 - 2500 m | Stratiform clouds with a single layer | [1] |
| 75°S, 123°E | ~1000 - 3500 m | Stratus | [2] [5] |
| ~33.25°N, 3.25°S | ~800 - 1000 m | Stratus | [1] [5] |
| 0°N, 0°S | ~10,000 - 15,000 m | Alto cumulus | [3] [6] |

The height at which water vapor in clouds freezes varies largely from season to season and with latitude, typically decreasing from the equator to the North and South poles. However, for tropical regions freezing occurs at very high altitudes, often around 4500 - 5000 m. For 30 - 60 degrees North and South (approx.) the

freezing level is much lower on average, around 3000 m. At the Poles, the freezing level is often very low, even on occasion 0 m. However, because water vapor in clouds can be liquid (supercooled) even at -35°C , to pinpoint water levels in mixed phase clouds is often inexact [16].

5. Supercooling Is Not Affected by the Warmest Temperature

5.1. Materials

In our previous work on supercooled water [4], we used commercially available plastic bottles of spring water (such as Fiji, Nu and so on) and measured supercooling ability as a function of the warmest temperature reached by that water. The experiments were conducted in nine different countries and over many repeat runs. Cooling rates of a few $^{\circ}\text{C}$ per minute and warmest temperatures of 20°C , 40°C and 60°C were all used. Results were analysed against volume, cooling rate, latitude, longitude and no correlation could be found between supercooling ability of a given volume of water, in a given container, and warmest temperature that water had reached prior. The effect has long been known as the Mpemba Effect and has been examined many times over the past decades, with conflicting results and conclusions.

5.2. Argument

Figure 3, below, demonstrates our results from recent sets of experiments [4]. Set volumes of water were cooled into the supercooled region and the freezing temperature recorded over multiple runs, with the warmest temperature reached above melting altered between 20°C , 40°C and 60°C . These sets of experiments were carried out at multiple latitudes and longitudes globally and show conclusively that the highest temperature reached by the water has no effect whatsoever on the levels of supercooling reached by any given volume of water.

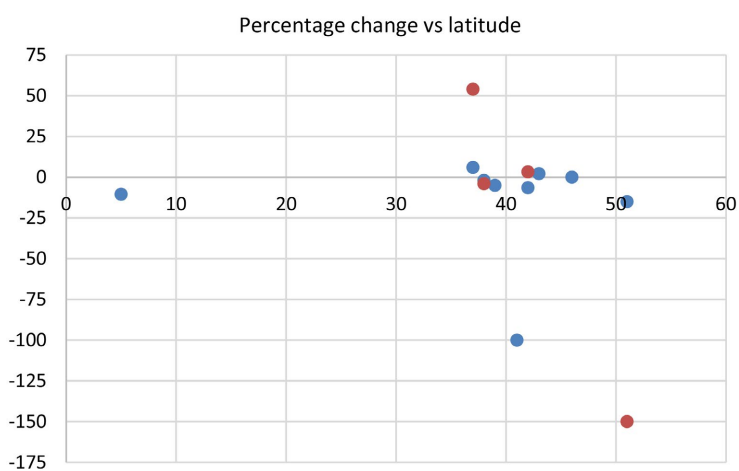


Figure 3. Percentage difference in freezing times between starting temperatures of 20°C , 40°C and 60°C , as a function of latitude. Note that freezing times was directly proportional to supercooling temperature reached by a given sample of water (adapted from [4]).

6. Conclusions

What is often known as the “best nucleation site” within a given volume of water will cause the freezing event at some (the highest) temperature below the melting point. Such a site is often a defect in the container wall, but could be dirt or other particles within the water. In the case of clouds, it is often mineral dust in the atmosphere. Our results [4] show no trend towards any effect, as analysed by many experiments, at various volumes of water, at various water qualities, at various cooling rates and many locations globally. Once into the supercooled regime, we might expect a given volume of water to freeze at roughly the same temperature on each run. Indeed, with multiple runs the spread of freezing temperatures is measured to be less than 1 °C, all other factors being held constant.

Limitations on our results and conclusions revolve around the fact that cloud-relevant factors were not tested by us. These would include droplet size, dissolved solutes, aerosol composition, biological ice-nucleating particles, and atmospheric cooling histories. Our assumptions are that makeup and density of the various types of ice nucleation particles available in the Arctic air, at various heights, is not changing. Of course, this may not be the case, but we are simply arguing that if all those held constant, then a warmer atmosphere will not cause a change in the lowest temperature reached by a given droplet.

There exists a causal chain linking Arctic warming, cloud phase partitioning, and freezing temperature. The cloud microphysics connecting all these factors is well beyond the scope of this article, but we do acknowledge a distinction between intrinsic freezing temperature of the droplets and changes in cloud phase caused by humidity, aerosol loading, and vertical motion.

In summary, if the air temperatures of the Arctic are warming, even seasonally, water droplets may be warmer during some part of their life as a cloud, but this will not affect the level of supercooling they achieve once cooled to below 0 °C.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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