CLOUDS: WHAT ARE THE SOURCES OF ICE CRYSTALS?

ETH Zurich's Professor Ulrike Lohmann discusses clouds and asks: what are the sources of ice crystals?

Clouds are not only fascinating to observe for their myriad shapes and shades, but are also scientifically challenging because their formation requires both knowledge about the large-scale meteorological environment as well as about the details of cloud droplet and ice crystal formation on the micro-scale.

Clouds and precipitation – why does ice matter?

The majority of precipitation in mid-latitudes originates in clouds containing ice. Precipitation, in particular orographic precipitation, plays a central role in land-climate interactions and natural ecosystems. Orographic precipitation is important for human water resources around the world as it determines the discharge in many rivers. The Alps are therefore also referred to as the 'water towers of Europe'. The Alps are the most important topographic feature in Europe modifying high and low pressure systems. Air is forced around a mountain, blocked by it or lifted over it depending on the synoptic conditions and the mountain characteristics such as the height, length, width, orientation and slope of the mountains. Orographic precipitation results from the interaction of the prominent weather pattern and processes within the cloud. It can fall as rain or snow and can cause extreme events such as avalanches, landslides and flash floods. The intensity of extreme precipitation events is expected to increase with future warming, at a rate that well exceeds the increase in mean precipitation. If the occurrence of extreme precipitation events can be well predicted, some of these increases can be partly mitigated by adaptive measures.

The ice phase in clouds

While every water puddle on the road freezes as soon as the temperature drops below 0°C, cloud droplets can remain liquid until temperatures of -38°C. Below these temperatures, cloud droplets freeze spontaneously. At higher sub-zero temperatures, cloud droplets must contain an aerosol particle that acts as a centre for the formation of ice crystals (so-called 'ice nucleating particle', INP). Our observations at the high altitude research station Jungfraujoch in the Swiss Alps have shown that the ice crystal number concentrations at a given temperature can exceed the number concentrations of INP by orders of magnitude (Fig. 1). While we observe around 1,000 ice crystals per litre of air at -25°C, less than one INP per litre is found at this temperature.

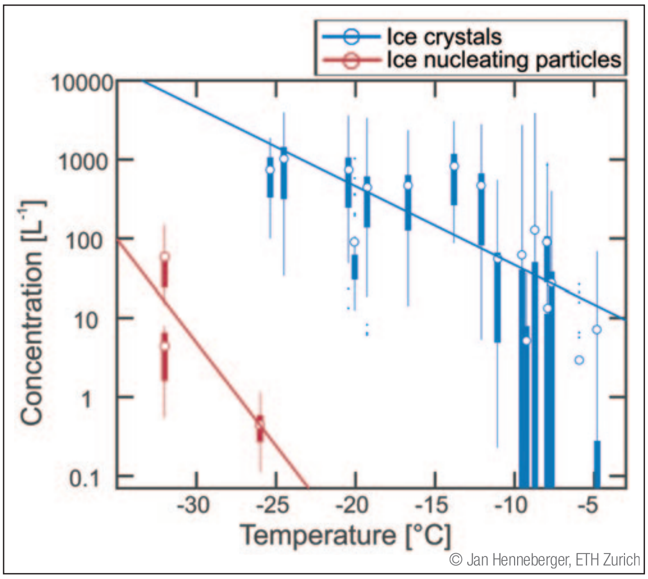

Fig. 1 Measurements of the concentration of ice crystals (blue) and INP (red) in L^{-1} obtained at high-altitude research station Jungfraujoch in the Swiss Alps

The ice phase in clouds remains enigmatic

The discrepancy between the concentration of ice crystals and INP is not new, but points to other sources of ice crystals. Among them are the so-called 'ice multiplication' or 'secondary ice processes', where ice crystals either break up into fragments or ice splinters are ejected during the freezing process (Fig. 2). At a mountain top station, where a cloud can be in contact with the surface, ice crystals could also have a surface based source, such as blowing snow or hoar frost that is entrained into the cloud. Lastly, the ice crystals may fall into the cloud from an above-lying cloud that is at a colder temperature. This so-called 'seeder-feeder' process (Fig. 2) can efficiently lead to or enhance precipitation. The relative importance of the different ice sources varies for different cloud types and will depend on the temperature of the cloud being investigated.

Ice nucleating particles

The most abundant INPs are mineral dust particles that originate from the major deserts as well as from agricultural and road dust. In addition, biological particles such as pollen, fungal spores, bacteria and leaf litters are very active INPs; however, they are found in much smaller concentrations in the atmosphere than

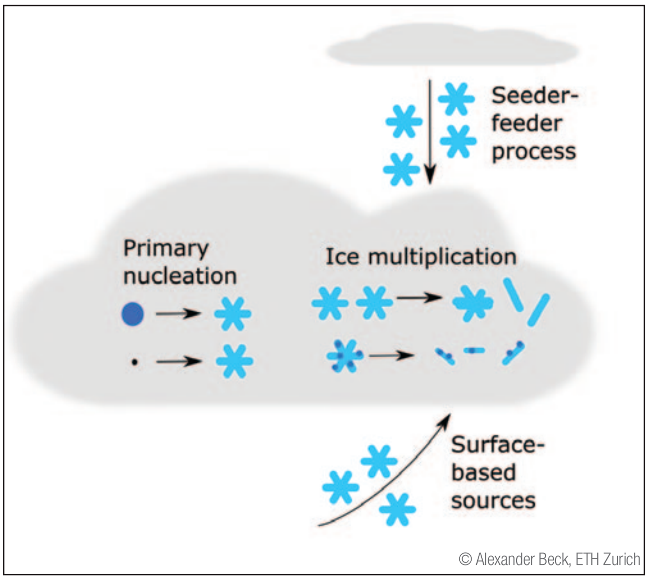

Fig. 2 Schematic of sources of ice crystals

mineral dust. The suitability of soot aerosols from fossil fuel combustion and biomass burning as INPs is still a question of ongoing research. The INP measurements at Jungfraujoch shown in Fig. 1 were taken in winter, where the contribution from biological particles is negligible. Episodically Sahara dust is observed at the Jungfraujoch and can be visible as a brown sand layer on the snow and ice in the Swiss Alps. During these Sahara dust events, the average INP concentrations at Jungfraujoch can be enhanced by a factor of ten or more. Yet, even during Sahara dust events, the ice crystal concentration remains orders of magnitude higher than the INP concentration, further confirming the role of secondary ice sources.

The BACCHUS project

The current EU PF7 project BACCHUS (Impact of Biogenic versus Anthropogenic emissions on Clouds and Climate: towards a Holistic UnderStanding) has placed major emphasis on the primary source of ice formation by better understanding the sources and chemical and mineralogical composition of INPs. To that effect BACCHUS has conducted field projects at Mace Head at the west coast of Ireland and in Cyprus amongst participation in other field campaigns. In addition BACCHUS collects as many INP measurements as possible in a single database. This will help to better understand the contribution of primary ice nucleation to the ice phase in clouds. During the Cyprus field campaign, INPs were not only sampled at the ground, but also unmanned aerial systems were employed to obtain their concentration within the atmosphere.

Clouds and climate change

Clouds have different effects on climate. For low-lying dense water clouds such as stratus and stratocumulus the reflection of sunlight back to space dominates. Hence, they cool the climate. Thin high-level cirrus clouds, on the contrary, act like greenhouse gases and predominantly warm the climate. They allow the majority of the sunlight to reach Earth's surface and therefore have a negligible cooling effect. Instead they absorb the radiation emitted from Earth and re-emit some of it back to the Earth surface, warming it. Because of the counteracting effects of different cloud types together with uncertainties related to their representation in global climate models, it remains uncertain how clouds will change in a warmer climate.

The collection of the INP data in the BACCHUS project will be used to improve global climate models, in which all the different sources of ice crystals are included. In a first step, the simulated INPs will be compared against the observed ones from all BACCHUS sites. Thereafter the description of INP in these models can be improved to better match the observations. This should lead to better simulations of ice clouds in global climate models.

The phase of the clouds in the present-day climate is also important for the impact of clouds in a changing climate. When the climate warms, more clouds will consist of liquid water instead of ice and reflect more sunlight back to space, referred to as cloud-phase feedback. This negative feedback will counteract some of the warming resulting from anthropogenic greenhouse gases. A recent study suggests that climate models may have too much ice in present-day clouds. Therefore they overestimate the negative cloud-phase feedback and underestimate global warming. Whether this finding is generally true or was particular to this one climate model remains to be seen.

Further reading:

- EU FP7 BACCHUS project: www.bacchus-env.eu; and
- IPCC AR5, especially chapter seven on clouds and aerosols (Boucher *et al.*, 2013).

Research literature on mixed-phase clouds and INP:

- Kanji *et al.* (2017), *Meteorological Monographs,* AMS;
- Lohmann *et al.* (2016), *GRL;*
- Tan *et al.* (2016), *Science; and*
- *Lohmann* (2017), Current Climate Change Report.

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