FORUM: Atmospheric science

The seeds of ice in clouds

An investigation of droplet freezing in clouds suggests that a minor component of mineral dust in the atmosphere is the main catalyst for this process. Two experts discuss the ramifications of this finding for those investigating cloud–droplet freezing, and for scientists studying atmospheric aerosols. [SEE LETTER P.355](#)

THE PAPER IN BRIEF

- Mixed-phase clouds contain both liquid water droplets that have been ‘supercooled’ to temperatures below the freezing point of water and ice particles.
- The amount of ice affects many of these clouds’ properties, such as their extent and lifetime.
- Aerosol particles of minerals in the

atmosphere, known as ice nuclei, catalyse the freezing of cloud droplets.

- Atkinson *et al.*¹, as they report on page 355 of this issue, have studied ice nucleation in conditions found in mixed-phase clouds*.
- They find that ice nucleation is dominated by feldspar minerals rather than clay minerals, as had been generally thought.

Rare but active

THOMAS KOOP

Earth’s weather and climate are governed by clouds whose properties are largely determined by aerosol particles and by physical processes that occur at the micrometre to metre scale². Although the basics of cloud formation are well understood, quantitatively predicting cloud properties remains challenging, partly because of the chemical diversity and varying abundance of aerosol particles. Atkinson and co-workers have helped to address this problem by considering the effects of different kinds of mineral particles on ice nucleation in clouds.

In many clouds, tiny water droplets super-cool significantly before heterogeneous ice nucleation is triggered by ice nuclei, a process known as ice activation. The resulting frozen cloud droplets grow into larger ice particles, which may then initiate precipitation (Fig. 1). This cascade of processes depends crucially on local concentrations of ice nuclei and on the temperature at which these nuclei activate ice.

There are two approaches for establishing a global representation of ice-nuclei concentrations and ice-activation temperatures. The first is to use *in situ* measurements to construct an empirical relationship of how the concentration of active ice nuclei varies with temperature³. The second approach, and that adopted by Atkinson *et al.*, is to perform laboratory studies with aerosol particles for which

the atmospheric abundance is known^{4,5}. The authors froze micrometre- and millimetre-sized water droplets containing ice nuclei at temperatures typical of mixed-phase clouds (about 250–265 kelvin). Surprisingly, they found that potassium-rich feldspar seems to be the most active mineral for ice nucleation, even when its low abundance of just a few per cent by mass in soil-mineral dusts — the main source of mineral dust in the atmosphere — is taken into account.

However, when the authors combined a global model of atmospheric feldspar-dust concentration with their laboratory results, the predicted concentrations of feldspar ice nuclei did not fully agree with those derived from field studies, indicating the need for improved dust modelling, or for alternative ice nuclei to be identified in certain regions. Moreover, the authors argue that ice-nucleation activities reported in earlier studies of more-abundant clay-mineral dusts could have been elevated by traces of feldspar — a proposition that will spark controversy, as well as more attentive characterization of ice nuclei in future experiments.

The results of field and laboratory studies should eventually converge towards a consistent representation of atmospheric ice nuclei that is sufficient for cloud modelling. But for now, it is disappointing to acknowledge how little fundamental understanding we have about heterogeneous ice nucleation. For example, what makes a good ice nucleus? Initial proposals suggested that the lattice of an ice nucleus must match that of ice, as in the ‘classical’ case of silver iodide. But such lattice matching does not seem to be a reliable

predictor of ice-nucleation activity⁶. Moreover, a wide variety of non-crystalline ice nuclei have been identified, for example amorphous solids, pollen and bacteria, surfactant monolayers, and even dissolved polymer molecules and proteins.

Resolving the unknowns will surely require the efforts of collaborative multidisciplinary consortia to combine the results obtained from elaborate experimental tools with those of theoretical simulations. Even then, it could be decades before a clear picture of heterogeneous ice nucleation emerges. The results will not only benefit the atmospheric sciences, but will also have applications in engineering, for example the cryostorage of biological tissues and food, and in the development of methods for preventing aircraft icing up or pipes freezing. In the meantime, further surprising discoveries such as that of Atkinson *et al.* are likely to be made.

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Not all dust is equal

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Atkinson *et al.*¹ suggest not only that the effects of mineral aerosols dominate those of other ice nuclei, as has been reported elsewhere⁷, but also that feldspar is the most effective ice nucleus of all. The importance of aerosol–cloud interactions to climate⁸ means that the authors’ work is a call to arms for scientists who study atmospheric aerosols, and in particular for those who study dust.

Atmospheric aerosols are highly heterogeneous in space and time, and so measurements and models of these aerosols tend to simplify their complexity. Researchers feel lucky if they can obtain sufficiently long time series at enough locations to characterize the variability; even fewer measurements include

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Figure 1 | Ice formation and precipitation. **a, b,** Aerosol particles known as ice nuclei catalyse the formation of a few frozen cloud droplets (typically several micrometres in diameter) from supercooled droplets of liquid water. These ice crystals grow at the expense of the remaining majority of liquid droplets,

through transfer of water vapour (blue arrows). **c,** The resulting large ice particles (often several tens to more than 100 micrometres in diameter) have higher fall velocities than the small liquid droplets, and may initiate precipitation. Atkinson *et al.*¹ report that feldspar particles are the most effective mineral ice nuclei.

details of aerosol composition. Rarer still are studies that, as well as estimating the fraction of aerosols that is composed of minerals, also analyse what the different minerals are. Similarly, because of the expense of simulating the effects of many types of minerals and the lack of comprehensive data, the incredible variability of mineral aerosol composition is ignored in climate models. Instead, mineral aerosols are usually modelled together, as a bulk dust. Any atmospheric processing of mineral aerosols that would modify their chemical and physical properties is also commonly ignored in models.

Atkinson and co-workers' findings demonstrate the need for more observations of the mineralogical composition of mineral aerosols; currently, such observations are few and far between (see the Supplementary Information of the paper¹). More information about the effects of acids on mineral aerosols is also required to gauge the role of these reactions in the atmospheric processing of minerals. For example, do acids convert feldspar into less-effective ice nuclei, such as clays? We also need a better understanding of the distribution of minerals in areas of soil that act as sources of dust. In addition, we must learn more about how humans and climate have changed, and will change, desert dust (and feldspar dust in particular) over time. The limited evidence available suggests that the mass of dust world-wide doubled over the twentieth century⁹.

Finally, Atkinson and colleagues' work requires us to rethink how aerosols and aerosol–cloud interactions are modelled: multiple types of minerals, as well as their chemical reactions with compounds such as sulphates or organic acids in the atmosphere, must be considered. This means that substantial increases in the complexity and computational expense of models are needed. Scientists should consider whether we can use a proxy for the potential of different mineral compositions to nucleate ice — instead of the effects of specific minerals — to reduce the complexity of the problem such that mineral aerosols can be included in computationally expensive climate models more correctly.

In retrospect, the finding that a specific mineral is responsible for most ice-nucleation

events in mixed-phase clouds is perhaps not that surprising, because the chemical and physical properties of different mineral aerosols are so disparate. For instance, earlier studies have highlighted the importance of aerosol mineralogy in the interactions of atmospheric dust with light¹⁰ and in ocean biogeochemistry¹¹. Nevertheless, Atkinson and colleagues' discovery is extremely important: when it comes to ice nucleation, not all dust is created equal. ■

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BEHAVIOURAL BIOLOGY

Archaeology meets primate technology

A study of wild capuchin monkeys that crack nuts using stone hammers reveals temporal and spatial patterning of the relics of their technological efforts, confirming that such behaviours can be studied from an archaeological perspective.

ANDREW WHITEN

Our ancestors have been fashioning and using stone tools for at least 2.5 million years¹. Bronze blades began to replace lithic axes a mere few thousand years ago, so percussive stone tools — hammers and axes that function through targeted force — have characterized more than 99.9% of human technological evolution². The discovery of stone-tool use in other primates has offered exciting opportunities to examine such behaviour in living species. West African chimpanzees have provided the focus for this research for 30 years, but it was revealed a decade ago³ that bearded capuchin monkeys (*Sapajus libidinosus*) also use hammer stones to crack nuts

(Fig. 1a). Writing in the *Journal of Archaeological Science*, Visalberghi *et al.*⁴ present the fruits of an interdisciplinary project⁵ that emerged from this discovery. Their study goes beyond behavioural observations to log the archaeological signatures of percussive tool use by capuchins.

This research represents one of the first comprehensive empirical examples of the new discipline of primate archaeology^{6–8}. Working in the monkeys' open, savannah-like woodland habitat in Brazil, the authors located 58 active nut-cracking anvil sites, which they identified by the presence of hammer stones, pits on the stone or wooden-log anvils, and nut remains. Each month for three years, the scene at each anvil was inspected and photographed,