ATMOSPHERIC SCIENCE

Ocean algae and atmospheric ice

Mineral dust and biological particles of terrestrial origin initiate ice formation in the atmosphere. Laboratory experiments suggest that ocean diatoms are another potential source of ice nuclei in clouds.

Ottmar Möhler and Corinna Hoose

Clouds that lie in the troposphere, the 8- to 16-km-thick atmospheric layer above the Earth's surface, influence the water cycle and global climate. For example, clouds cool the surface by reflecting solar radiation back to space, and warm the surface by trapping heat. The environmental impact of clouds depends on numerous factors, including the nature of the small particles they consist of[1]. In the lower troposphere, clouds are mainly composed of small water droplets, which form when water condenses on atmospheric aerosol particles. In the middle and upper troposphere, where temperatures are cooler, clouds contain ice. The formation of ice in mid–upper tropospheric clouds is triggered by small amounts of atmospheric aerosols, known as ice nuclei[2]. Writing in *Nature Geoscience*, Knopf and co-workers[3] report that ocean diatoms can initiate ice formation under typical tropospheric conditions.

In clouds, water droplets remain in a supercooled liquid state down to temperatures of about −37 °C (ref. 2), at least within the typical lifetime of clouds of minutes to hours. Water droplets containing dissolved substances such as sulphate can remain in liquid form down to even lower temperatures, depending on the concentration of the solute[4]. The spontaneous freezing of water and solution at or below −37 °C — homogenous freezing — can occur with equal probability throughout the water droplet. Above −37 °C, ice can form in supercooled water and solution droplets in the presence of insoluble aerosol particles — ice nuclei. Structures on the surface of the nuclei — potentially similar to those in crystalline ice[2] — facilitate the transition from supercooled water to ice. Aerosol particles can also trigger the formation of ice from water vapour. This mechanism takes place in cold conditions where the air holds more water vapour than it would in equilibrium with an ice surface — ice-supersaturated regions. Ice-supersaturated regions are common in the upper troposphere. Depending on temperature, relative humidities with respect to ice of 150% or more can be reached before homogeneous freezing sets in. Ice nuclei lower the relative humidity required for ice-cloud formation, thereby influencing ice-cloud properties. The latter two mechanisms of ice formation, known as heterogeneous freezing, occur only when the appropriate ice nuclei are present.

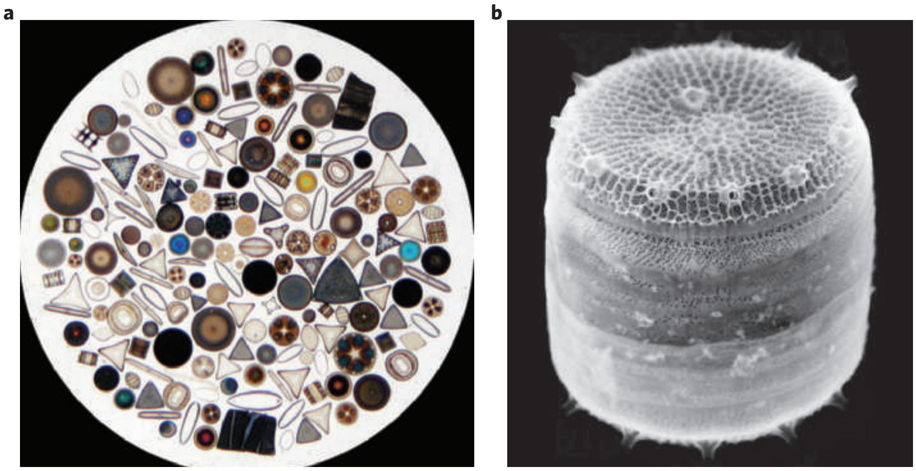

Figure 1 | A collection of diatoms (**a**) and the diatom species *Thalassiosira pseudonana* (**b**). Knopf and colleagues[3] examined the ability of the diatom *Thalassiosira pseudonana* to initiate ice formation in a series of laboratory experiments, carried out under typical tropospheric conditions. The diatoms stimulated ice formation both in supercooled liquids and water vapour. The results suggest that diatoms lofted from the ocean to the atmosphere could constitute a source of atmospheric ice nuclei. Images from: **a**, Wikimedia Commons © Wipeter; **b**, © Nils Kröger, Georgia Tech, USA.

Only a small fraction of the complex mixture of aerosols in the troposphere induces ice nucleation, and the nature and identity of ice nuclei is poorly understood[2]. Mineral particles and biological particles of terrestrial origin, including bacteria and spores, are good candidates for inducing ice formation in tropospheric clouds[5–7]. Their relative importance is actively debated among microbiologists and atmospheric scientists[8]. Whether biological particles of marine origin also initiate ice formation remains uncertain. However, diatoms — miniature algae with silicon-based cell walls — are distributed throughout the surface waters of the world ocean, and can be lofted into the atmosphere through bubble breaking and wave activity (Fig. 1).

Knopf and colleagues[3] examined the ability of the diatom species *Thalassiosira pseudonana* to initiate ice formation in a series of laboratory experiments, carried out under typical tropospheric conditions conducive to the formation of ice-containing clouds. Diatoms and diatom fragments initiated ice formation from supercooled water droplets at temperatures of up to −23 °C, thereby raising the temperature for ice nucleation by 14 °C. The diatoms also initiated ice formation from water vapour, at relative humidities with respect to ice as low as 132%. Knopf and colleagues suggest that the structure of the siliceous cell wall and the organic matrix of the diatoms are responsible for the formation of the ice. If true, other diatom species, with a similar structural make-up, could also facilitate ice formation.

Once in the atmosphere, diatoms will compete with other ice nuclei that are active under the same conditions, for instance mineral dust particles from desert regions[9,10]. Therefore, the importance of diatoms as atmospheric ice nuclei will ultimately depend on their abundance relative to other, competing ice nuclei. Quantitative data on the source, distribution and abundance of diatoms in the atmosphere are rare. Without such data, one can only speculate about the atmospheric residence time and transport of such particles, and thus their environmental impact, for example on the radiative properties of clouds. However, diatoms may well prove to be important in clouds in that part of the atmosphere directly influenced by the ocean at high latitudes, where diatom sources are close and the influence of dust is limited.

Knopf and co-workers[3] introduce the possibility that siliceous marine diatoms are lifted to cloud level, where they initiate nucleation. However, a solid conclusion about the importance of diatoms for clouds, weather and climate awaits further observational and modelling efforts. In particular, diatom species in atmospheric aerosols need to be identified, and their ice-forming potential assessed. The ability of ancient diatom fragments to initiate ice formation should also be considered, as fragments of fossilized diatoms from the Bodélé depression in Chad, situated at the edge of the Sahara Desert, constitute one of the largest dust sources in the world[11]. Only then will we be in a position to determine the atmospheric impact of one of the most abundant groups of ocean algae. ❐

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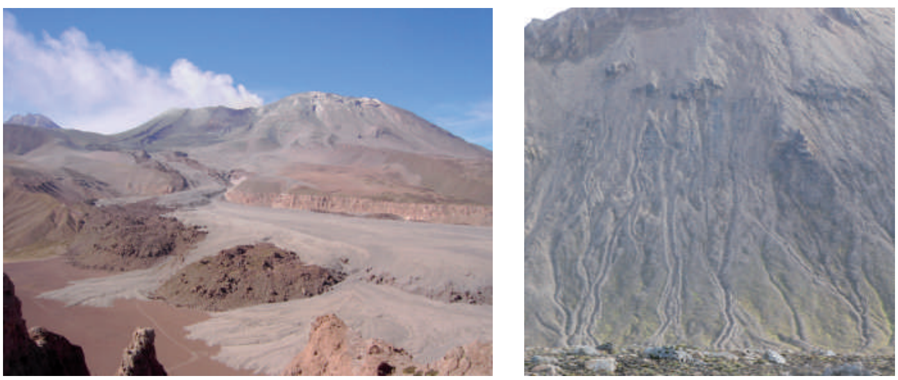
GEOMORPHOLOGY

Landslide boost from entrainment

The mechanisms that govern the growth of debris flows are largely unclear, hampering efforts to assess natural hazards in landslide-prone areas. Experiments suggest that high bed-water content increases flow velocity and mass entrainment in landslides.

Anne Mangeney

Landslides, debris flows and avalanches are natural hazards that threaten life and property in mountainous, volcanic, coastal and seismically active areas. Collectively known as gravitational flows, they begin when debris on a slope is destabilized. The mass of debris tends to accelerate as gravity pulls it down the slope, and will slow on more gentle slopes, when dissipation overcomes the driving forces. The entrainment of material along the slope has long been suspected to play a key role in flow dynamics, possibly driving landslides over unusually long distances. Writing in *Nature Geoscience*, Iverson and co-authors[1] suggest, based on large-scale flume experiments, that relatively high amounts of water in the pores of the slope bed help to drive both the acceleration of landslides and the entrainment of additional slope material.



ANNE MANGENEY

Figure 1 | The remains of debris flows. Pyroclastic flows from the 1993 eruption of the Lascar Volcano, Chile (left) and debris flows in Iceland[9] (right) both cover previous deposits from gravitational flows in these areas, hindering our understanding of the mechanisms that govern such events. Iverson and co-authors[1] use large-scale experiments to assess the role of wet bed sediments in landslide growth, and find that high pore pressures facilitate the scouring of the bed and the growth of mass and momentum in the flows.

The entrainment of sediments or debris into gravity flows is suspected to be critical to the dynamics of the flows, but measurement of material entrainment in natural flows is very difficult. Erosion tracks are often hidden by subsequent flows (Fig. 1), and it is generally hard to distinguish the flow deposit from the underlying erodible layer because they are both usually composed of the same material. Nevertheless, qualitative and quantitative field observations[2–6] suggest that material entrainment can either increase or decrease flow velocity and deposit extent, depending on the geological setting and the type of gravitational flow. In landslides involving significant amounts of water, the pore water pressure is generally considered crucial to the efficiency of the erosion of material from the bed[2,8].

Using a 95-m-long flume lined with a mixture of sand, gravel and mud, Iverson and co-authors[1] assessed the mechanics of granular flows over wet, erodible beds. They measured both the pore water pressure and the total normal stress at the base of the sediment layer during flow. Based on these measurements and on mechanical reasoning, they suggest that the loading of the overflowing material produces high pore pressures in the wet bed sediment. The high pore pressure in turn reduces friction at the base of the flow and promotes the scouring of the bed surface. Iverson and co-authors also found that the entrainment of wet material resulted in the acceleration