or the magnitude of climatic changes during the study period.

The results highlight large cumulative changes in European invertebrate communities, with an increase of individuals and diversity (both taxa and ecological traits) at rates sometimes greater than 1% per year across the decades. The abundance results correspond closely to those of a global insect-focused meta-analysis study[3], whereas the diversity increases are consistent with changes seen from studies undertaken on smaller scales[6]. The increases are interpreted as biological recovery from poor water quality in particular, driven mainly by improvements to wastewater treatment (for example, following the European Union's 1991 Urban Waste Water Treatment Directive), and the decline or offshoring of polluting industries, as well as the outcome of habitat-restoration efforts. Haase *et al.* report that some of the largest increases in abundance were observed in pollution-sensitive taxa such as mayflies (Ephemeroptera) and stoneflies (*Dinocras cephalotes*; Fig. 1), supporting this general conclusion, although future analyses looking in more detail at changes in the constituent taxa could strengthen the case.

This picture of Europe is a more optimistic finding than a similarly large-scale assessment across the United States[7], which showed declining invertebrate abundance while richness increased. Beyond rivers, such analysis also enriches the wider narrative around global insect and invertebrate declines, although the devil might be in the detail. For instance, in the United States, insects fared worse than other invertebrates, with a loss of richness and steeper declines in abundance[7], whereas in Europe, Haase and colleagues report that insects showed larger abundance gains but smaller increases in diversity than did the invertebrate community as a whole. There is unquestionably more work to do.

Although Haase *et al.* carefully filtered and analysed the data, adjusting for a range of environmental variables, the precise magnitudes of estimated changes need to be treated with caution because of the uneven spatial and temporal coverage, and the variability of invertebrate data from many sources. Fortunately, the authors' sensitivity analyses suggest that the broad picture is robust in relation to several of these possible issues. Change estimated at the continental-scale will inevitably disguise underlying geographic variation. The authors found that richness declined at approximately 30% of locations and abundance at 40%, and it would be interesting to understand more about whether these declines were concentrated in particular river types or regions.

The overall percentage changes presented by Haase and colleagues are important results, confirming and extending earlier work[3]. However, the really striking finding is in how biodiversity gains have slowed in the past 20 years, with little or no net change among many measures in the last 5–10 years. Smaller-scale studies have hinted at these results[6,8], but Haase *et al.* present a compelling picture of a slowdown across Europe. Attributing a cause is a formidable challenge in this context, with rivers exposed to a complex and ever-changing mix of stressors that probably vary across the continent.

One possible explanation for the slowdown is simply that biological recovery is near-complete, but this is quickly undermined by the extent to which rivers across Europe still fail to reach 'good ecological status' as defined by the EU's 2000 Water Framework Directive. A more plausible explanation is that recovery is running out of steam because the benefits derived from past interventions have been exhausted, or because new stressors are emerging or existing ones are intensifying (for example, new types of pollutant or the effect of a changing climate). Such factors might slow and potentially reverse biodiversity gains. Consistent with this hypothesis, Haase *et al.* demonstrate that increases in abundance and diversity were often smaller and less frequent in rivers with a more rapidly warming climate, in those that drain urban and agricultural areas and in those downstream of dams. However further work will be needed to determine the causes.

Assuming that the biological recovery of Europe's rivers is stalling, the obvious question is how to revive and extend recovery. The challenges facing freshwater ecosystems are manifold and the required interventions are similarly multifaceted, involving some blend of legislation, technological development (for example, in wastewater treatment), changes to land-use practice and reduced exploitation, among others[9]. Further work to understand the causes of the deceleration would help to guide these actions.

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Atmospheric science

Clues to rain formation found in droplet images

Thomas Leisner

X-ray and optical imaging have revealed the intricate process through which droplets freeze during the formation of rain. The results could help to explain how clouds are able to produce enough ice particles to make rain. **See p.557**

The first few drips of a rain shower are usually a sign that 'supercooled' droplets in the cloud above have started to freeze. Supercooled water exists as a liquid below the normal freezing point of water, and the freezing of these droplets has a key role in the process of rain formation. Writing on page 557, Kalita *et al.*[1] have imaged this process with exquisite time resolution, enabling them to analyse the evolving crystalline structure of the ice in real time. Their observations provide a way of calibrating and improving models that help to explain the physics of clouds.

At temperatures below freezing, but above −36 °C, liquid water freezes only in the presence of tiny 'ice-nucleating' particles, which initiate the formation of ice in the supercooled cloud droplets. Ice has a lower vapour pressure than does supercooled liquid water, so it grows rapidly by sucking up water vapour from the surroundings at the expense of the liquid droplets. As the ice particles grow, they start to fall and collide with the cloud droplets to form larger particles called graupels. These graupels then melt as they fall to lower altitudes, contributing to the eventual formation of rain.

Each ice-nucleating particle can freeze only a single cloud droplet, so the number of ice

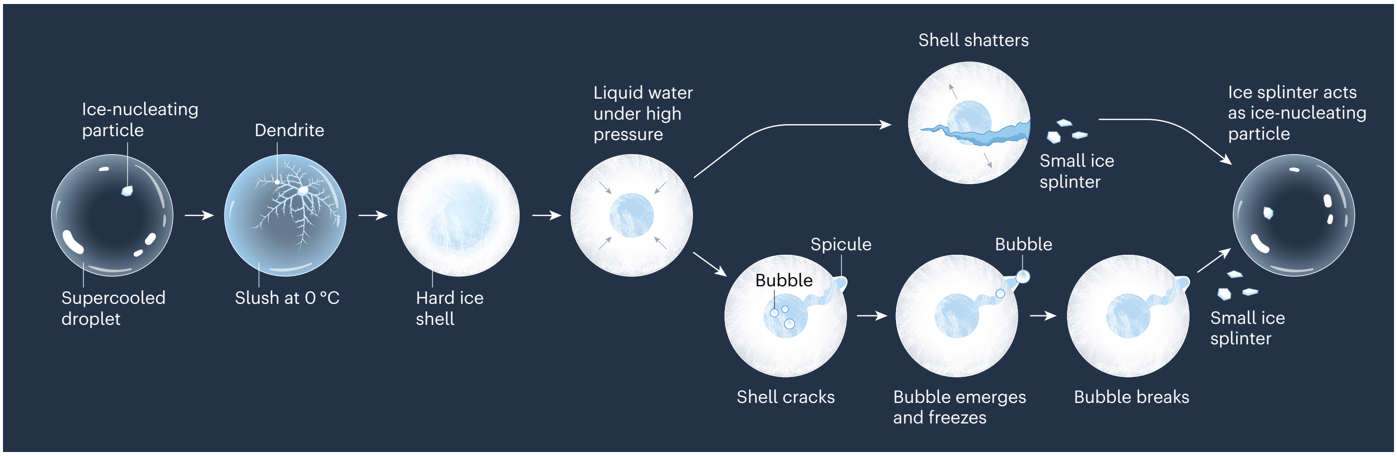

Figure 1 | How water droplets in clouds freeze. Rain formation involves the freezing of 'supercooled' water droplets. These are liquid below 0 °C and freeze only in the presence of 'ice-nucleating' particles, which are often scarcer than ice particles in real clouds. Kalita *et al.*[1] imaged this process, showing the formation of ice splinters that can act as ice-nucleating particles. When freezing begins, ice dendrites spread out through the droplet, transforming it into a slushy ice structure at 0 °C. It then freezes slowly from the outside in, creating a hard exterior shell that is put under strain as the interior pressure increases until it is high enough to melt the slush. This shell can either shatter to form ice splinters, or crack to form chimney-like structures called spicules, through which gases from the interior can bubble to the surface. These bubbles also make ice splinters by freezing and breaking. Splinters formed by either route can nucleate freezing[7].

particles in the cloud should be lower than the number of available ice-nucleating particles. However, field observations conducted since the late 1960s have revealed that clouds often have several thousand times more ice particles than ice-nucleating particles[2]. The most widely accepted explanation for this disparity is known as the Hallet–Mossop process[3], which involves the ejection of small ice splinters during the formation of graupels. These splinters act as ideal ice-nucleating particles, freezing cloud droplets as they collide with them and possibly triggering an avalanche of these ice particles inside a cloud.

The Hallet–Mossop process has been observed in the laboratory, albeit only in a narrow temperature range around −5 °C (ref. 3). However, at temperatures between −13 °C and −7 °C, clouds containing supercooled 'drizzle' droplets (which are larger than the droplets in clouds but smaller than raindrops) can generate a substantial number of small ice particles[4]. This suggests that the freezing of drizzle droplets could serve as another source of ice particles. But understanding this process is complicated by the fact that it is extremely intricate, and occurs in several stages[5] (Fig. 1).

After freezing has been initiated, ice dendrites extend quickly through the entire droplet, turning it into a slushy ice structure. The release of heat warms the droplet to 0 °C, causing the rapid freezing to cease. The droplet then freezes gradually from the outside in, as heat is dissipated to the surroundings. During this part of the process, the pressure inside the droplet can increase considerably — up to around 240 bar (ref. 6) — because ice is less dense than supercooled water. This pressure strains the ice shell and can eventually melt the slushy interior.

When the strain exceeds the shell's tensile strength, the shell will either shatter or crack. Shattering results in the formation of ice splinters, but cracking can have a similar effect. When cracks form, water from the interior is expelled and freezes on the outside, creating chimney-like structures called spicules. Dissolved gases from the liquid interior can then be released through the spicules, forming bubbles that freeze and break up, resulting in the release of ice splinters.

These processes have been observed in laboratory settings[7], but the specific temperature range and the quantity of ice splinters had yet to be quantified. Kalita *et al.* uncovered hitherto unknown details of this process by imaging supercooled water droplets, and analysing the data using a model that incorporates the many stages of freezing and the random nature of the process.

The imaging experiments were conducted at the SLAC National Accelerator Laboratory in Menlo Park, California. The authors injected a beam of liquid droplets into a vacuum chamber, where they were cooled rapidly, resulting in the nucleation of ice and the subsequent freezing of the droplets. They then fired ultrashort X-ray pulses and two longer light pulses at the beam and used the resulting scattering pattern and optical images to determine the structure of the droplets at multiple times during the freezing process, which took about one millisecond to complete.

> **"The authors uncovered hitherto unknown details of the process by imaging supercooled water droplets."**

Each droplet was probed only once, and freezing times varied considerably, but by analysing around 1,000 droplets at each time point, Kalita *et al.* were able to map the evolution of the freezing process. They then simulated freezing as a random process, averaging over large groups of droplets to determine that approximately 60% of the droplets split on freezing. At least one of the splitting events that the authors observed resulted in the formation of seven ice fragments. The authors were also able to detect and quantify the amount of strain in the ice as it formed.

It should be noted that the experimental conditions in a vacuum chamber differ markedly from those in the natural environment in which clouds form. Therefore, direct application of these results to cloud models is not possible. However, Kalita and colleagues' study serves as a crucial step in the process of developing and calibrating numerical models of droplet freezing, which will ultimately contribute to solving one of the longest-standing puzzles in cloud physics.

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