What avalanche research can do for ice cream

Bernd R. Pinzer

Tools developed to visualize snow microstructure and investigate processes leading to snowslides reveal the microscopic coarsening mechanisms that degrade the quality of frozen desserts.

Have you ever bitten into a piece of ice cream that had been lying in the freezer for several weeks? Obviously, the quality of ice cream can degrade over time as the individual components become coarser. The transition from fresh and soft to old and crunchy ice cream depends on physical coarsening processes that, for example, are responsible for the growth of ice crystals to a level where one can feel individual crystals on the tongue. As with ice cream, the fact that the microscopic structure determines the macroscopic properties is true for any class of material which is microscopically heterogeneous, in particular for snow. Although these subjects seem to be fairly unrelated on first sight, snow and ice cream share some important characteristics: they are heterogeneous on a similar length scale, their structure evolves dynamically on similar time scales, and their ‘natural environment’ is below 0°C. In the past, classical microscopy methods for both snow and ice cream suffered from the same problem: imaging the spatial distribution of phases was destructive, which possibly introduced artifacts and prevented the measurement of structural changes over time.

The 3D distribution of ice in snow can be measured in a non-destructive manner using x-rays, and this has recently enabled big progress in investigating microstructural evolution in snow.\(^1,2\) We used a desktop computed tomography (CT) scanner that was embedded in a cold laboratory and supplemented with a sample environment that allowed detailed control of the thermal boundary conditions. This approach allowed the undisturbed observation of water recrystallization over time inside the snow under both steady and periodically changing temperature gradients,\(^3,4\) conditions that can be regularly found in alpine snow packs. The ability to observe repeatedly the same subvolume of metamorphosing snow gives completely new insight into the microscopic evolution. For example, insight is gained into the time that water molecules typically remain in the solid ice network before that part of the structure gets dissolved again (see Figure 1).

While snow consists only of the two phases ice and air, ice cream can contain many different ingredients, including sugars, fat droplets, colorants, and flavors. However, the three most prominent phases (by volume), which determine most of the basic material properties, are air bubbles, liquid freeze-concentrated sugar solution, and water ice crystals. To distinguish these three phases in ice cream with our desktop CT we added iodine—which is also used in medical imaging—as a contrast agent to the recipe.

Figure 1. One slice of the 3D ice crystal residence time, within metamorphosing snow subjected to a temperature gradient of 50Km\(^{-1}\) (pointing downward). The residence time can be derived by observing the changes in the ice structure while doing precise bookkeeping of the appearance time of an ice voxel.\(^4\) The image reflects a later stage of snow metamorphism (after 608 hours), and it clearly shows that the crystals are growing at the bottom (‘youngest’ voxels) and sublimating at the top, where the oldest voxels can be found. It is striking that most of the ice structures are actually younger than 100 hours.

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Temperature variations are well known to have a detrimental effect on ice cream quality, so we cycled the temperature of the cold laboratory between $-16$ and $-4^\circ C$ to investigate the structural changes induced by temperature changes. An additional complication—compared to snow—was the segmentation of the three-phase system because some interfaces produce artifacts with simple thresholding. We developed an iterative algorithm that discards the erroneous volume elements and approaches a target ice fraction derived from the measured temperature. To obtain quantitative insight, the size distributions of both ice crystals and air bubbles were analyzed and correlated with the temperature boundary conditions. As expected, at cold temperatures the system was very stable, indicating relaxation times way beyond the observed time period of a few days. For higher temperatures, the bubble sizes increased linearly with time, while the size distributions broadened significantly. This typically indicates coarsening by coalescence and not coarsening driven by differences in interfacial energy (Ostwald ripening). We even observed single coalescence events inside the undisturbed ice cream, which has never been reported before (see Figure 2). However, the disagreement with the typical $t^{1/3}$ growth law for Ostwald ripening can also be attributed to the length of the observation time, which could have been too short to reach the scaling regime.

The ice crystal size distributions showed pronounced oscillations between cold and warm periods, in fact more pronounced than the oscillations in ice fraction would imply, even if anisotropic growth was assumed. This can only be accomplished by the ice crystal network breaking up into several unconnected parts when the temperature rises, followed by a reconnection when the temperature drops again. Coarsening by this melt-refreeze cycling provides a much more effective mechanism than Ostwald ripening.

In summary, the direct observation of structural changes that becomes feasible with x-rays provides the potential to challenge and improve our current understanding of coarsening mechanisms in ice cream. This, in turn, is key to influencing the microstructure to obtain a better product. We now plan to use synchrotron light to further improve the spatial resolution to measure even the smallest air bubbles and ice crystals. With the latest developments in phase contrast imaging, we do not even need a contrast agent any more. Interesting and yummy results are ahead!

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**References**

doi:10.5194/tcd-6-1673-2012

**Figure 2. Coalescence event of two air bubbles.** The overview image (right) shows a visualization of air bubbles within a small thin slab of the investigated ice cream volume. The close-up (left) depicts the coalescence of two air bubbles within a time period of 4 hours.