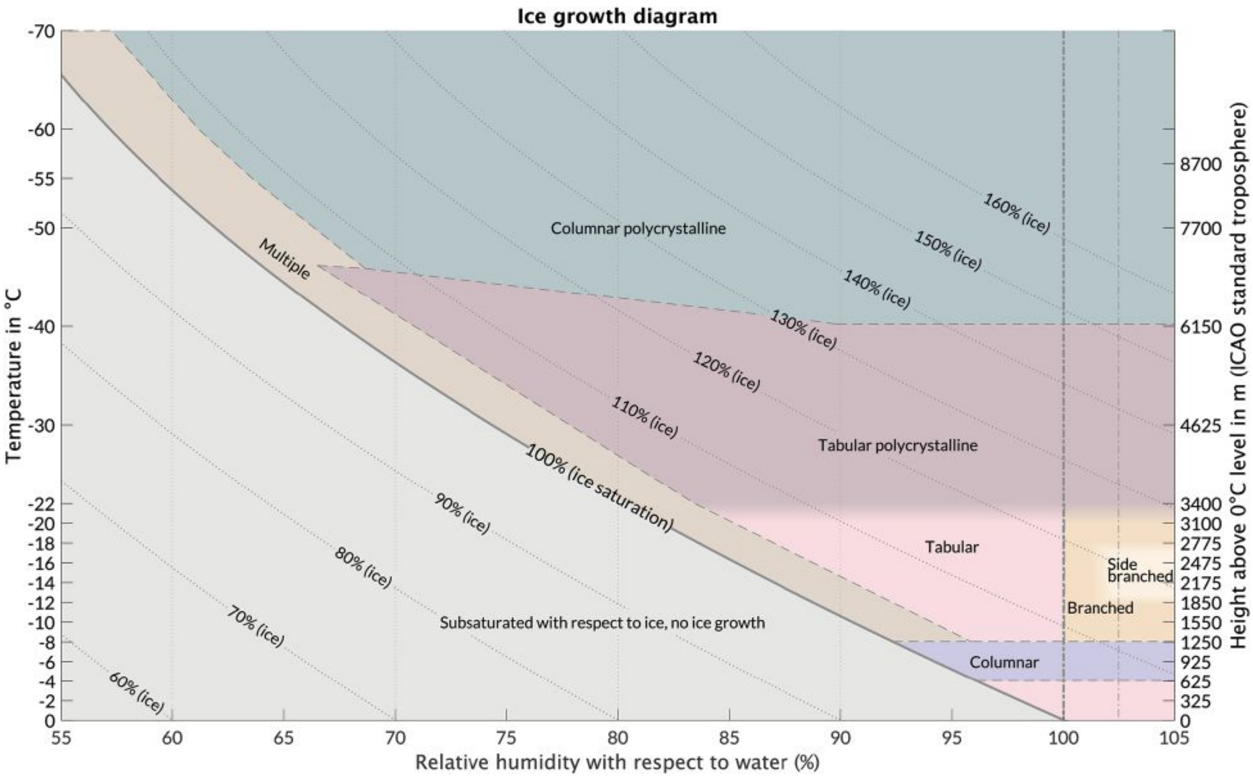
Revisualizing Instructional Ice Growth Diagrams

Key messages from
"Revisiting Diagrams of Ice Growth Environments," by **Daniel M. Hueholt** (Colorado State University), **Sandra E. Yuter**, and **Matthew A. Miller**. Published online in *BAMS*, November 2022. For the full, citable article, see **https://doi.org/10.1175/BAMS-D-21-0271.1**.

Many ice habit diagrams in published literature, textbooks, and online educational materials exhibit substantive differences, which largely arise from a combination of inconsistent terminology and errors propagated from older source materials. State-of-the-science diagrams designed for use by ice microphysics specialists may not clearly communicate key concepts to nonexperts, especially students. To fill this need, we have designed simplified ice diagrams adapted from specialist materials. Our diagrams are intended to be accessible by students and popular science sources while facilitating meteorological data visualization.

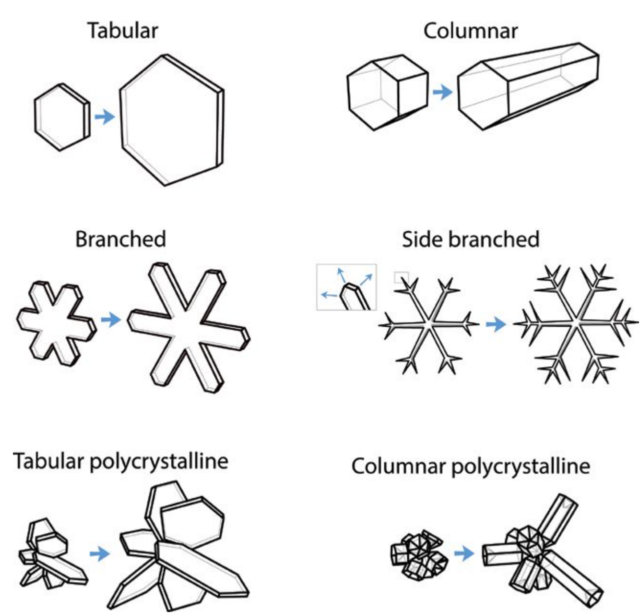
The shapes (crystal habits) of atmospheric ice particles resulting from growth by vapor deposition as a function of temperature and moisture between 0°C and –70°C are well established. In the early 2000s, three papers by Bailey and



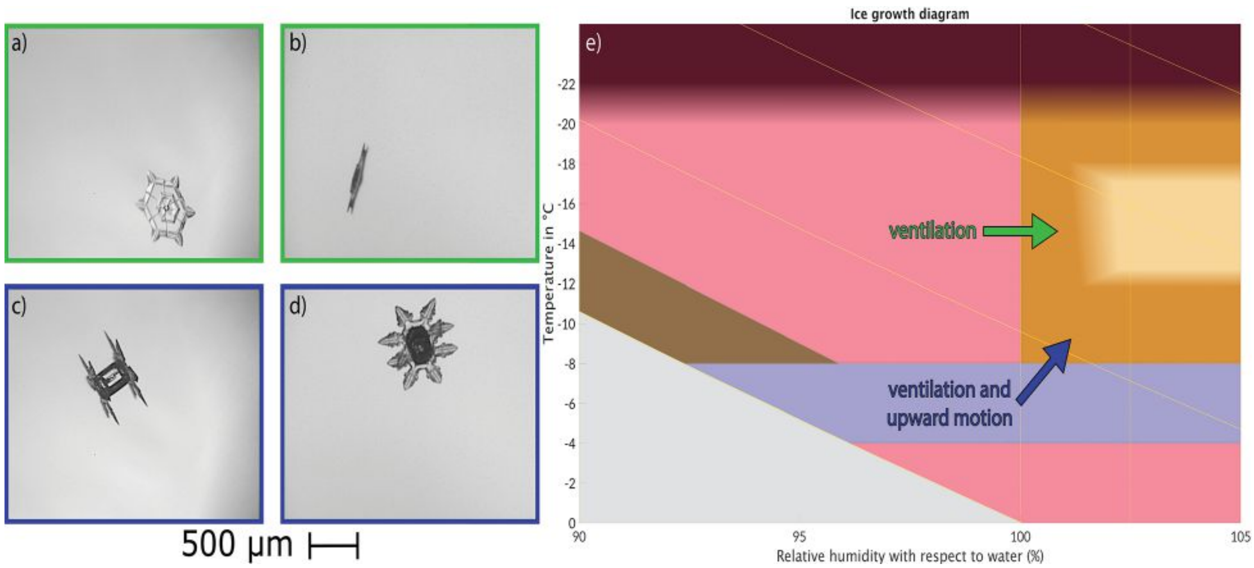
Ice growth forms diagram in terms of relative humidity with respect to water, with contours of relative humidity with respect to ice overlaid. The International Civil Aviation Organization standard reference atmosphere is used to map temperature (left *y*-axis) to height above the 0°C level (right *y*-axis). Dashed lines indicate uncertainty in the exact bounding conditions between different ice growth forms. Blurred regions indicate transition zones between ice growth forms.

Hallett (two of which were published in AMS journals) made major revisions to previous ice habit research in order to fully represent the breadth of particles observed in extensive fieldwork and laboratory experiments. Their results have since been supported by numerous subsequent field observations and independent analyses. However, Bailey and Hallett's ice habit diagrams have not been widely disseminated into educational materials, likely because their figures are complex and intended for an expert audience.

We present revisualized atmospheric ice growth diagrams based on the science of Bailey and Hallett, designed for students at the sophomore undergraduate level and above. The physical intuition provided by these diagrams is useful in many meteorological research applications, although we do not propose that these simplified diagrams replace specialized materials used in ice microphysics and crystallography. In



Illustrations of the main ice growth forms in the troposphere. Each pair shows a sequence of a single growth form with a particular archetypal shape.



Examples of sequential growth with possible physical pathways annotated on (e) a portion of the ice growth form diagram. Colors of annotations on (e) correspond to colors bordering the PHIPS image pairs. Image pairs are different views of the same particle; all are from the 25 Jan 2020 IMPACTS flight. (a)–(b) Images obtained at 2257 UTC at 4.8-km altitude of a crystal formed by a sequence of tabular growth followed by branched growth. (c)–(d) Images obtained at 2225 UTC at 4.9-km altitude of a crystal formed by a sequence of columnar growth followed by branched and then side-branched growth.

revisualizing the diagram, we make four key changes designed to lower the cognitive load: using a *y*-axis with decreasing temperature, casting the diagram in terms of relative humidity with respect to water (RH_{water}), focusing on ice growth form (the main direction or pattern of growth of an ice crystal) rather than ice habit, and restricting the phase space to common tropospheric conditions. We provide open source software to tailor the diagrams to user preferences and to produce alternate versions of the diagram with an *x*-axis as a function of relative humidity with respect to ice (RH_{ice}) or vapor density excess.

The revisualized diagrams emphasize the relatively small number of ice growth forms by vapor deposition and where these growth forms occur as a function of air temperature and RH_{water}. The six ice growth forms–tabular, columnar, branched, side branched, tabular polycrystalline, and columnar polycrystalline–emerge directly from the underlying surface processes by which mass is added to a crystal. In conditions with RH_{ice} just above 100%, multiple growth forms can co-occur. In contrast to categorization of observed ice habits, the concept of ice growth form uniquely connects regions of the diagram to the physical pathways by which an ice crystal grows.

At air temperatures below −20°C, ice crystal growth is mainly polycrystalline, consisting of either tabular or columnar growth occurring simultaneously on multiple elements at different orientations. The growth of polycrystalline forms through vapor deposition is distinct from aggregation. Aggregation involves multiple crystals that grow separately and jumble together after a collision, which rearranges preexisting ice mass with no latent heat change. In the presence of favorable ambient conditions, an aggregate may subsequently grow by vapor deposition corresponding to the appropriate growth form.

The temperature range from −12°C to −18°C encompasses multiple, tabular, branched, and side-branched growth forms. Branched and side-branched growth responsible for dendrites only occur at these temperatures in environments with $RH_{water} \geq 100\%$. Persistent ambient environments with $RH_{water} \geq 100\%$ are relatively rare in winter storms where updraft speeds are slower compared to deep convection. Ventilation acts to increase the local relative humidity at the crystal over the ambient value by enhancing the vapor density immediately adjacent to a crystal's outer edges. Ventilation occurs when there is nonzero airflow around a crystal, such as when it is falling and/or advected by horizontal wind, updrafts, or downdrafts. For a given temperature, one can infer the effects of ventilation by shifting ambient relative humidity values to the right on the diagram.

The myriad shapes of observed ice particles are often the result of a sequence of growth forms that occur as a particle traverses different temperature and humidity environments as it falls. It is likely that many, if not all, of the more than 100 documented pristine ice shapes are reducible to their component growth form sequences. Joint analysis of high-resolution ice particle images and thermodynamic profiles in the context of the ice growth diagram may yield a classification system for ice crystals based on their sequence of growth forms. Plotting atmospheric profiles from observed radiosonde data and weather and climate model output on the ice growth diagram can provide insight on where and why differences between model physics and the real atmosphere occur.

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BAMS: What would you like readers to learn from this article?

Daniel Hueholt (North Carolina State University; current affiliation: Colorado State University), Sandra Yuter (North Carolina State University), and Matthew Miller (North Carolina State University): *Revisualizing ice growth diagrams and simplifying terminology makes it more straightforward for both students and researchers to understand relationships among ice particle shapes and the sequence of temperature and moisture conditions in which they form.*

BAMS: How did you become interested in the topic of this article?

DH, SY, and MM: *We became aware of substantive disagreements among published ice diagrams when we searched the web and the literature for a "definitive" ice diagram as a function of temperature and moisture. Detective work tracing back the origins of different ice diagrams through several decades of journal articles suggested a combination of misinterpretations, and some problematic methods in older laboratory work explained many of the discrepancies among published ice diagrams. We also realized that diagrams designed for use by ice microphysics specialists were not clearly communicating key concepts to nonexperts, especially students.*

BAMS: What surprised you the most about the work you document in this article?

DH, SY, and MM: *One key surprise was the depth of information we could obtain from the Particle Habit Imaging and Scattering Probe (PHIPS) imagery. This was vital to identify the sequences of growth, which could then be connected to the temperature and moisture conditions an ice crystal traversed from initial formation in cloud to the surface. We are very grateful to our colleagues with the NASA Investigation of Microphysics and Precipitation for Atlantic Coast-Threatening Snowstorm (IMPACTS) field campaign for their perspectives and datasets.*

BAMS: What was the biggest challenge you encountered while doing this work?

DH, SY, and MM: *A key challenge was understanding the differences in nomenclature among authors of previous works on ice habits and growth. Several distinct fields overlap in this domain, including observational meteorology, laboratory ice microphysics, and crystallography. Each field has its own terminology, and sometimes different terms would be used for the same concept. Iterative feedback from the paper's reviewers resulted in a nomenclature that captured the full range of phenomena seen in ice microphysics, was consistent with a modern understanding of ice crystal surface processes, and was straightforward to use in classroom environments.*