

PHYSICS AND STRUCTURE OF SNOW AND ICE, FORMATION PROCESSES AND PROPERTIES

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Keywords: Snow and Ice Physics, Hydrogen bonding, Hexagonal structure, Sea Ice, Glaciers, Ice sheets

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Summary

Snow and ice, as the naturally occurring solid phases of water substance, are critical elements of Earth's environment, whether appearing as: ice in the atmosphere, seasonal snow cover on the ground, glaciers and ice sheets, floating freshwater ice covers on rivers and lakes, or sea ice on the seas and oceans. Properties of ice such as its unusually high melting point and its high strength at high temperatures relative to its melting point result from the hydrogen bonds between water molecules in the ice-crystal lattice. Violations of hydrogen bonding, as naturally occurring imperfections in the lattice of ice, are responsible for many of its other properties, such as the electrical and mechanical properties. The growth of ice, as snow crystals in the atmosphere, frazil crystals in rivers, lakes and the ocean and their subsequent structural changes as snow on the ground, ice covers on rivers, lakes and the ocean, and of ice masses as glaciers and ice sheets all relate back to its fundamental structure which dictate the forms and behavior for these large-scale structures.

1. Introduction—Importance of Ice and Snow Fundamental Properties, Physics and Structures

The presence and properties of water define the natural environment, and life itself on the surface of the earth. Snow and ice, as the naturally occurring solid phases of water substance, are critical elements of this environment, whether appearing as: ice in the atmosphere, seasonal snow cover on the ground, glaciers and ice sheets, floating freshwater ice covers on rivers and lakes, or sea ice on the seas and oceans. Each element has its own characteristics, depending on and influencing diverse processes such as the hydrological cycle (snow in the atmosphere and snow on the ground); the radiative balance of the earth's surface and short-term climate (snow and sea ice

reflectivity or albedo); the ocean thermohaline circulation (salt flux from freezing of sea ice); glacial and interglacial climate cycles (growth and decay of large ice sheets); mountain landscapes (movement of glaciers). As a “force of nature”, changes in snow and ice cover are among the greatest, if we consider alone that the melting or development of large ice sheets can simultaneously change the volume of water in the global ocean, change the area occupied by continents or make islands appear and disappear. Among the shorter-term influences directly on mankind are the adverse effects on ocean navigation by sea ice, land transportation effects from sudden snowstorms, mountain disasters from avalanches, water resources from snowpack and glaciers, frost damage on agriculture, ice jam floods on rivers, and atmospheric icing hazards on aircraft and power lines. Recreational uses of snow and ice include alpine and Nordic skiing, snowmobiling, ice skating as well as a host of Winter Olympic competitive sports from ski jumping and bobsled racing to ice dancing.

Remarkably, all these diverse effects and activities, in their own way, rely on fundamental properties of water in the solid state and the development of particular properties and structures as these various forms grow and develop.

2. Ice Physics

2.1. Molecular Structure of Ice

A well-known attribute of water, unusual to most substances, is that its solid phase is less dense than its liquid phase, i.e. ice floats. If ice sank into its melt, as do most solids, natural water bodies might freeze completely to their beds, hardly conducive to the development of aquatic life in either temperate or polar regions. Other properties, compared to hydrogen compounds of similar molecular weight (Hydrogen Fluoride(HF), Hydrogen Sulfide(H₂S), Methane(CH₄)), are its unusually high melting point (e.g. 0 C compared to -182 C for Methane) and its high strength at high temperatures relative to its melting point (the homologous temperature). All these properties result from the hydrogen bonds between water molecules in the ice-crystal lattice. Water is a polar molecule, with a positive and negative side, consisting of two relatively mobile protons (hydrogen atoms) located at the two positively charged sites on the molecule and two negative charge clouds associated with the single oxygen atom. These charge clouds are distributed, at roughly equal angles to each other, around the oxygen atom at the center (Figure 1) an arrangement identified as tetrahedral coordination (Hobbs, 1974). Four bonds, corresponding to these charge clouds point to the vertices of the tetrahedron with the oxygen atom at the center. In the ice lattice, the protons, because of their small size and mobility, can arrange to point to the two negative ends (oxygen charge clouds) of adjacent water molecules, forming hydrogen bonds. Hydrogen bonds in strength fall between a covalent bond (high strength, where electrons instead of protons are shared between atoms) and a weak ionic bond (where electrons are given up to the other atom rather than shared). Each of the four bonds in ice that connect it to other water molecules has one hydrogen atom only. Of the four hydrogen atoms around an oxygen atom, only two are close, so each lattice site also looks like an individual water molecule. Since the hydrogen bond is linear, ice has an open crystal lattice structure and gives its lower density relative to water, as the hydrogen bonds are broken down in the liquid state and the molecules can pack more closely. The tetrahedral coordination gives

ice a crystal structure with hexagonal symmetry, which further affects many of the large-scale characteristics.

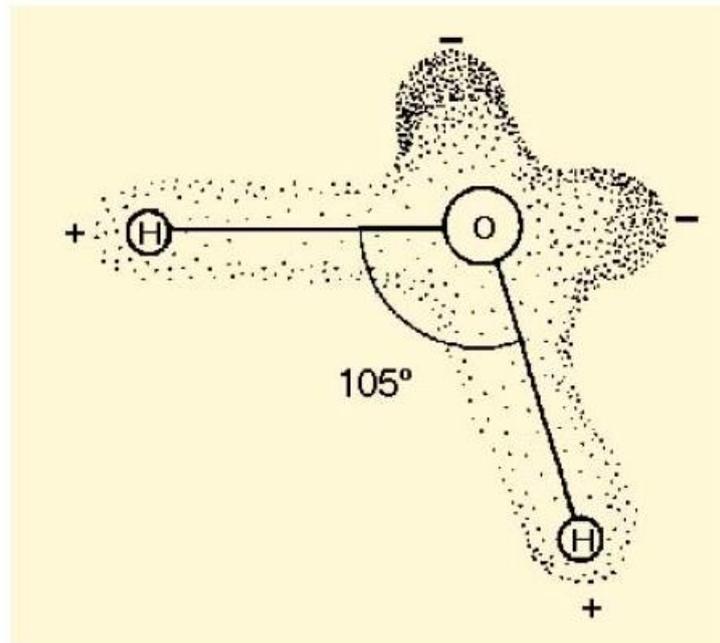


Figure 1. Water Molecule showing the dipolar nature and the roughly tetrahedral or four-fold coordination of the bonding orbitals.

The relative insolubility of impurities in ice also results from hydrogen bonding. Hydrogen bonding applies to the sharing of a proton between pairs of electronegative atoms. These atoms are limited to oxygen, nitrogen or fluorine (Hobbs, 1974). Electronegative impurities, such as the principal one found in sea water, the chloride ion, do not hydrogen bond, so chloride ion cannot substitute for oxygen in the ice lattice. These types of impurities are therefore rejected during the phase transition, so sea ice consists of a matrix of pure ice, with concentrated brine and salt crystals between the pure ice in alternating layers.

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Biographical Sketch

Stephen Ackley was a sea ice geophysicist and branch chief, when he was at the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) for approximately 30 years. He joined the research group at the Laboratory for Remote Sensing and Geoinformatics (LRSG) in the Department of Geological Sciences at UTSA in 2006. Professor Ackley has been the co-chairman of the Scientific Committee on Antarctic Research (SCAR) program on Antarctic Sea Ice Processes and Climate (ASPeCt) and chaired the Science Steering Group for the Autosub-Under-Ice program which developed and used an Autonomous Underwater Vehicle to make the first AUV trips under sea ice in the Arctic and the Fimbul Ice Shelf in the Antarctic. He was the Arctic Chair recipient at the Naval Postgraduate School in 1985-6. He has been the recipient of peer-reviewed research grants from the US National Science Foundation since 1976 for research on Antarctic sea ice. This research has been conducted during twelve research cruises on several nations' icebreakers into the sea ice zone surrounding Antarctica and on the first Antarctic sea ice drifting station, Ice Station Weddell (1992). He was awarded the National Science Foundation's Antarctic Service Medal for service in Antarctica. Ackley Point was named in Antarctica in honor of his outstanding sea ice research in Antarctica by the U.S. Board on Geographic Names.