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Optical properties of ice and snow

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Radiative properties of ice, and of ice-containing media such as snow and clouds, are determined by ice's refractive index and absorption coefficient ("optical constants"). The dominant absorption mechanisms are electronic in the ultraviolet and visible, molecular vibration in the near-infrared, (hindered) rotation in the thermal IR, and lattice translations in the far-IR.

The molecular vibrations of water vapor are seen also in liquid water and ice; they are shifted somewhat in frequency by formation of the hydrogen bond. Cubic and hexagonal ice have nearly identical absorption spectra. The spectrum of liquid water is close to that of ice from the UV to the near-IR, but they diverge in the thermal-IR and become very different in the far-IR, microwave, and radiowave regions.

The absorption coefficient of ice depends slightly on temperature ($\sim 1\%/K$) in all weakly-absorbing regions from the UV to the microwave. The temperature dependence increases rapidly with wavelength beyond 1 cm.

The absorption coefficient varies by ten orders of magnitude from the near-UV (300 nm wavelength) to the near-IR (3 micrometers). The blue and near-UV absorption is so weak, with photon mean-free-path ~ 1000 m in pure ice, that it is essentially zero for many purposes, but its exact value does matter for computation of photochemical fluxes in snow and of ice thickness on the tropical ocean of "Snowball Earth".

Proceeding across the visible spectrum from blue to red, the absorption length decreases from ~ 1000 m to 2 m, explaining the blue color of crevasses and icebergs. But snow is white. The reflection of sunlight by snow is the result of successive refraction through small snow grains (~ 100 micrometers); the short total path length through ice experienced by a solar photon means that nearly all UV and visible photons survive to re-emerge from the snowpack. Indeed, the snow surface of Antarctica has been used as a calibration target for visible channels on satellites.

Because the absorption of visible and UV radiation by ice is so weak, the absorption of sunlight at these wavelengths in natural snow is dominated by trace amounts of absorptive impurities such as black carbon (soot) and mineral dust.

Although neither clouds nor snow absorb significantly at visible wavelengths, clouds can be detected over snow in reflected sunlight by satellite remote-sensing because they alter the angular reflectance pattern.

Half the solar energy is in the near-IR, where ice is sufficiently absorptive that the near-IR flux-reflectance (albedo) becomes sensitive to the area-to-mass ratio (specific surface area, SSA). As snow ages the SSA decreases, darkening the snow.

Beyond the solar spectrum, at thermal infrared wavelengths, ice is moderately absorptive, so snow is nearly a blackbody, with emissivity $\sim 99\%$. But continuing on to longer wavelengths we come to the second region of weak absorption, the microwave and radiowave region (centimeters to meters), so that radiowaves can penetrate several kilometers of ice-sheet depth for sounding of ice thickness.

Significance statement

Optical constants of ice are needed for understanding radiative properties of ice and ice-containing media such as snow, sea ice, and clouds, with applications to energy budgets, satellite-remote sensing, and radio-echo sounding of glaciers and ice sheets.

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