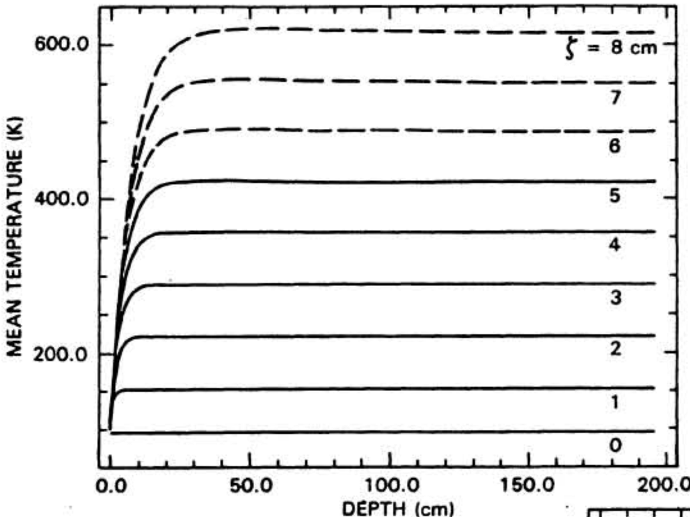
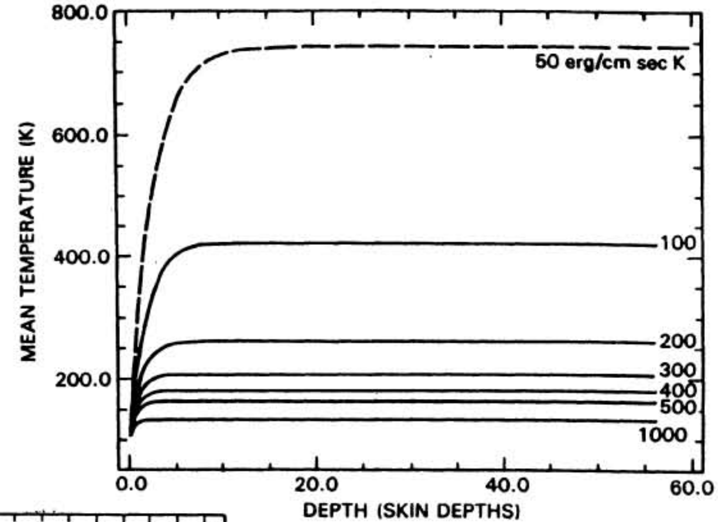
SOLID-STATE GREENHOUSES AND THEIR ROLE ON ICY SATELLITES; Robert Hamilton Brown and Dennis L. Matson, Jet Propulsion Laboratory, California Institute of Technology

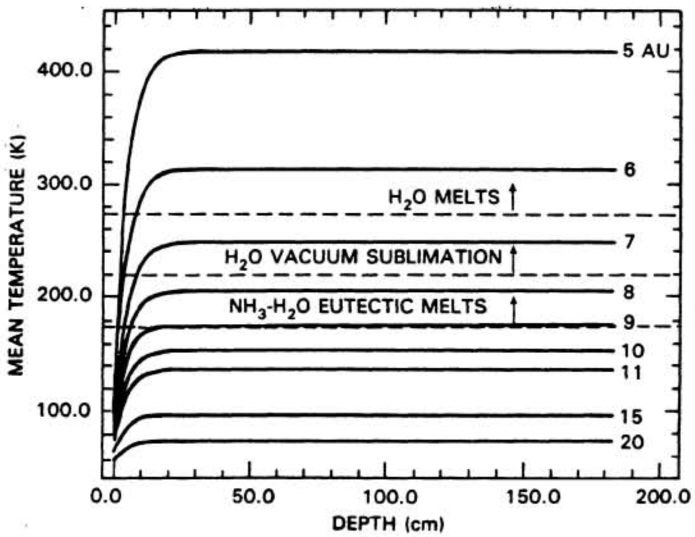
We have constructed thermal models for planetary surfaces composed of particles that are bright and optically thin in the visual, and dark and opaque in the thermal infrared [Brown and Matson (1987), *Icarus* 72, 84-94]. Our models incorporate the assumption that insolation is absorbed over a finite distance in the regolith, rather than at the surface as is assumed by most classical thermophysical models used for thermal modeling of airless solar-system surfaces. Besides predicting significant effects on the surface temperature distribution relative to models that don't account for insolation penetration, if insolation penetrates deeply enough into a surface, and the thermal-infrared opacity of its constituent particles is very high (e.g., in a regolith composed of particles of water ice), a solid-state greenhouse can result! This has important implications for geophysical models of high-albedo, icy bodies because actual boundary-layer temperatures may in fact be significantly higher than those assumed in previous studies, making it easier to melt the interiors of such bodies [Matson and Brown (1988), *Icarus*, submitted].

That sunlight can penetrate to considerable depths in terrestrial snow and ice has been recognized in the literature for over 50 years [Niederdorfer, E. (1933), Meteor. A., **50**, 84-94]. Several studies have shown via models and actual measurements that mean daily subsurface temperatures in dry, fresh Antarctic snowpacks can be several degrees higher than the maximum mean daily surface temperatures. In fact, it has been observed in terrestrial snowpacks that melting is initiated several centimeters below the surface rather than at the surface, mostly because a mild solid-state greenhouse exists within the snowpack. Similarly, we have applied our solid-state greenhouse models to the question of the surface and subsurface temperatures of icy satellites in the outer solar system, and have found that under a wide range of conditions, solid-state greenhouses can be formed on these satellites. Some of the parameters we have used (such as the penetration depth scale and absorption profile for sunlight) are derived from the literature on terrestrial snowpacks of the same average grain size and albedo as the bodies we have chosen to model. Other parameters such as the density and thermal conductivity have been adopted from eclipse observations of the Galilean satellites and laboratory measurements of the thermal conductity of various types of particulates in a vacuum.

The subsurface temperature enhancements seen in our models can range from a few °K to well over 100 °K depending upon the penetration scale depth and the thermal conductivity of the icy regolith (see figures). One of the most striking implications of our work so far is that a solid-state greenhouse on an icy satellite acts as a thermal barrier to heat attempting to escape from the deep interior of such a body; that is, the relevant upper boundary condition for geophysical thermal history calculations in such a scenario is the maximum diurnal mean greenhouse temperature. In very simple terms, the greenhouse behaves as a thermal barrier because for heat to escape from the interior, the geophysical gradient must be such that the average temperature in the deep interior is greater than that of the diurnal mean maximum greenhouse temperature. This has implications for icy satellites in general and in particular for high albedo icy satellites such as Europa and Enceladus, especially regarding explanations for the geologically recent resurfacing evident in Voyager images of these two satellites.







Please note that in all these figures, neither sublimation nor phase changes have been taken into account. Thus, these calculations are literally applicable only to materials like a bed of fine glass beads in a vacuum. Below about 220 °K, however, these calculations are also relevant to particulate water ice in a vacuum. The major point of these plots is to show that there is ample energy available to drive subsurface temperatures to the point where sublimation and phase changes will begin to prevent further temperature rise. Upper left: A plot of diurnal mean temperature versus depth for different values of ζ, the propagation scale depth; other parameters assumed are hemispherical albedo A = 0.6, heliocentric distance R = 5 AU, thermal conductivity κ = 100 erg (cm sec K)$^{-1}$, density ρ = 0.15 g/cm^3 and heat capacity c = 1 x 10^7 erg/g. Upper right: A plot of diurnal mean temperature versus thermal conductivity assuming ζ = 5 cm. All other parameters are the same as in the upper left figure. Lower center: A plot of diurnal mean temperature versus depth for various heliocentric distances and ζ = 5 cm. All other parameters are the same as in the figure on the upper left.