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Learning Soil Freeze Characteristic Curves with Universal Differential Equations

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Permafrost thaw is considered one of the major climate feedback processes and is currently a significant source of uncertainty in predicting future climate states. Coverage of in-situ meteorological and land-surface observations is sparse throughout the Arctic, making it difficult to track the large-scale evolution of the Arctic surface and subsurface energy balance. Furthermore, permafrost thaw is a highly non-linear process with its own feedback mechanisms such as thermokarst and thermo-erosion. Land surface models, therefore, play an important role in our ability to understand how permafrost responds to the changing climate. There is also a need to quantify freeze-thaw cycling and the incomplete freezing of soil at depth (talik formation). One of the key difficulties in modeling the Arctic subsurface is the complexity of the thermal regime during phase change under freezing or thawing conditions. Modeling heat conduction with phase change accurately requires estimation of the soil freeze characteristic curve (SFCC) which governs the change in soil liquid water content with respect to temperature and depends on the soil physical characteristics (texture). In this work, we propose a method for replacing existing brute-force approximations of the SFCC in the CryoGrid 3 permafrost model with universal differential equations, i.e. differential equations that include one or more terms represented by a universal approximator (e.g. a neural network). The approximator is thus tasked with inferring a suitable SFCC from available soil temperature, moisture, and texture data. We also explore how remote sensing data might be used with universal approximators to extrapolate soil freezing characteristics where in-situ observations are not available.