A multiscale strategy for process-rich, microtopography-aware simulations of thermal hydrology in polygonal tundra

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The use of simulations to advance environmental systems science is most effective when insights about the system behavior can be exploited to design computationally effective modeling strategies. However, limitations of current tools often make it difficult to express those thoughtful approximations in simulation software. The Interoperable Design of Extreme-scale Application Software (IDEAS) project is addressing this barrier to productivity using a novel strategy for simulating the thermal hydrology of thawing polygonal tundra as a use case. Simulating the soil thermal hydrology system in degrading carbon-rich permafrost regions is challenging because of strong coupling among thermal and hydrologic processes, the important role of organized microtopography in controlling water flows, strong coupling between the surface and subsurface, and the potential for topographic changes as ground ice melts (e.g. Painter et al. 2013). Motivated by results of fine-scale simulations and in collaboration with the Next Generation Ecosystem Experiments-Arctic (NGEE-Arctic) project, we have designed a computationally tractable strategy that uses individual ice-wedge polygons as the horizontal discretization of the landscape. The independent subsurface columns resulting from that discretization are then coupled indirectly through an overland flow system using a subgrid model to represent the effects of subgrid microtopography on surface flow. Simulations that include thaw-induced subsidence become tractable in this framework because the subsurface thermal hydrology and deformation processes are represented on independent one-dimensional columns, which avoids issues of poor mesh quality that can result from representing dynamic topography in a three-dimensional model. The capability is being implemented in the ATS simulator and will be used by the NGEE-Arctic project to simulate the evolution of polygonal tundra in a changing climate. In addition, the mixed-dimensional spatial structure has broader applicability in watershed modeling. Managing the multiple meshes and multiple process representations in these intuitively appealing mixed-dimensional simulations is a significant software challenge. As part of the IDEAS project's broader goal of enabling a "virtual ecosystem" of composable software components, this Use Case explores how a configurable model coupling system (Coon et al. 2016) can enable this class of mixed-dimensional model.

Painter SL, Moulton JD, Wilson CJ. 2013. Modeling challenges for predicting hydrologic response to degrading permafrost. Hydrogeology Journal. 21(1):221-224.

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