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A Modeling Toolbox for Permafrost Landscapes

A new resource makes it easier for researchers to explore predictions of how melting permafrost might affect carbon release, wetlands, and river deltas as they evolve and other interacting effects.



This aerial photo taken over Alaska shows one of the ways that thawing permafrost reshapes the landscape. A user-friendly modeling toolbox from the University of helps novice and expert modelers alike study the causes and effects of permafrost thawing. Credit: iStock.com/GeorgeBurba

By [Irina Overeem](#), Elchin Jafarov, Kang Wang, Kevin Schaefer, Scott Stewart, Gary Clow, Mark Piper, and Yasin Elshorbany © 28 September 2018

Climate change is currently causing vast expanses of permafrost to thaw. Currently, scientists are busy quantifying how future thawing could expose massive, previously frozen pools of carbon and trace elements, releasing them to the global biogeochemical cycles [Schuur *et al.*, 2015; Schuster *et al.*, 2018]. But the ways that permafrost is interwoven with hydrological and geomorphological processes and how carbon and [toxic](https://eos.org/scientific-press/scientists-find-massive-reserves-of-mercury-hidden-in-permafrost) (https://eos.org/scientific-press/scientists-find-massive-reserves-of-mercury-hidden-in-permafrost) heavy metals spread throughout the thawing Arctic are sweeping, yet unanswered, research questions.

Permafrost—ground that stays at or below 0°C for 2 or more years—can be found under 24% of the Northern Hemisphere's land surface [Zhang *et al.*, 1999]. The fr

subsurface profoundly influences the hydrological cycle of the Arctic region.

For example, the thawing ground below creates unique geomorphic patterns: drooling solifluction lobes (<http://www.landforms.eu/cairngorms/solifluction.htm>) that form w/ soil oozes downhill, giraffe skin polygons (<https://frontierscientists.com/2016/07/lines-polygons-permafrost-thaw-ecosystem-changes/>) formed by ice wedges filling the cracks in fre shrunken soil, thaw lakes and seasonal wetlands, and melting coastal bluffs.

Permafrost thaw contributes to the global hydrological and carbon cycles (<https://eos.org/editors-vox/thawing-permafrost-monitored-quantified-predicted>), but it also has a signii impact on roads, housing, and coastal infrastructure. This impact is predicted to create a multibillion-dollar infrastructure maintenance (<https://eos.org/articles/engineer-foundations-for-a-thawing-arctic>) problem for Alaska over the span of the 21st century [Melvin *et al.*, 2017].



Repeated freezing and thawing of subsurface permafrost has buckled this road in Canada's Northwest Territories. Thawing permafrost is expected to do significant damage to roads and other infrastructure in the coming decades. Credit: iStock.com/RyersonClark

Evaluating current and future permafrost conditions requires numerical modeling, but the time and effort required to develop or run such models remain a barrier to use. To address this issue, we have developed online, easily accessible permafrost process models for use by scientists and educators through the Community Surface Dynamics Modeling System (CSDMS (https://csdms.colorado.edu/wiki/About_CSDMS)) at the University of Colorado. We call this product the Permafrost Modeling Toolbox

An Easy-to-Use Interface

CSDMS provides a Web-based modeling environment consisting of selected open-source numerical models of permafrost dynamics and other surface processes. Our efforts, which use the CSDMS cyberinfrastructure specifically for permafrost research, are funded by the National Science Foundation Office of Polar Programs, NASA, and the Department of Energy.

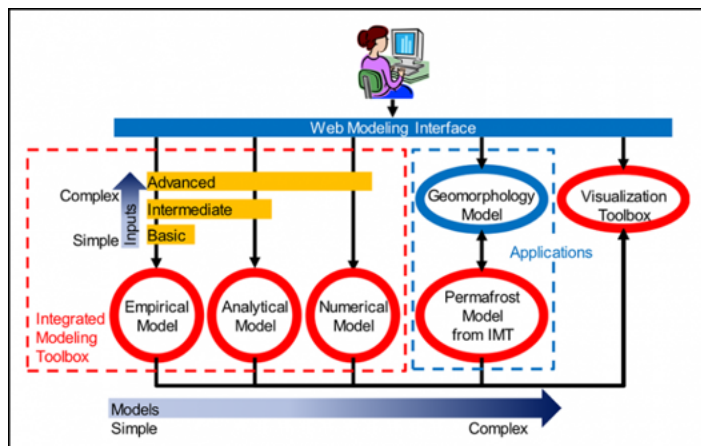


Fig. 1. The Permafrost Modeling Toolbox contains models with varying degrees of complexity that can be coupled to preprocessed data sets. The

models can also be coupled with hydrological, geomorphological, or other types of models.

Our toolbox of coupled permafrost and Earth surface models is designed to be modular to meet the needs of a variety of users: students learning about thermal processes, industry scientists who need to make an initial environmental assessment, and members of the academic community interested in system feedbacks (Figure 1).

We use a Web-based modeling tool (WMT) that allows users to quickly select a model and configure its inputs and then run it remotely. Leveraging CSDMS [standard software infrastructure](https://arxiv.org/abs/1407.4106) (<https://arxiv.org/abs/1407.4106>) allows users to quickly document metadata with the models, share code through a version-controlled repository online hosting service [GitHub](https://github.com/) (<https://github.com/>), and distribute educational material through hands-on modeling labs.

A Flexible Design

The toolbox currently includes three permafrost models of increasing complexity, all driven by local climate forcing, to meet a variety of needs:

An empirical model, the Air Frost Number model [*Nelson and Outcalt*, 1987] predicts the likelihood of permafrost occurring at a given location.

An analytical-empirical model, the Kudryavtsev model [*Anisimov et al.*, 1997] provides an exact solution to thermodynamic equations accounting for snow, vegetation, and soil to calculate [active layer](https://eos.org/research-spotlights/a-deeper-understanding-of-carbon-decomposition-in-arctic-soils) (<https://eos.org/research-spotlights/a-deeper-understanding-of-carbon-decomposition-in-arctic-soils>) thickness, the average annual thaw depth.

A numerical heat flow model, the Geophysical Institute Permafrost Lab (GIPL) model [*Jafarov et al.*, 2012] includes the latent heat effects in the active layer zone. It divides a vertical profile into multiple layers of soil and substrate with different thermal properties, and it calculates temperature profiles with depth.

The first two models are developed as “components” that can be coupled to other CSDMS models. The GIPL model functions as a stand-alone code, and it will be fully embedded into the CSDMS model coupling framework at a later date. All three models are inherently one-dimensional; that is, they calculate the thermal state over a single vertical column, but they do not calculate heat exchange among columns. However, each model can run regional simulations or even be implemented for the entire Arctic region.



The waterlogged permafrost landscape of the North Slope of Alaska demonstrates the importance of feedback linkages between permafrost thaw, the hydrological system, and river transport, but these feedbacks have not yet been quantified in predictive models of permafrost. Credit: Irina Overeem

Straightforward Data-Model Coupling

Our project pairs these models with preassembled data sets of input parameters. Casual model users can then quickly run experiments for selected time series and regions.

Our project pairs these models with preassembled data sets of input parameters. Casual model users can then quickly run experiments for selected time series and regions. Data sets include long-term climatological and permafrost observations in coastal and interior Alaska (Barrow and Fairbanks, respectively), as measured at Circumpolar Active Layer Monitoring Network (CALM) and U.S. Geological Survey stations [*Urban and Clow*, 2017].

Access to data and models together allows users to compare model output with in situ observations directly. Additionally, a regional climatological data set comprising observed monthly temperature and precipitation data for the 20th century is available to drive the models for Alaska. To explore future trends in permafrost, another data set comprises parameters of the Coupled Model Intercomparison Project Phase 5 (CMIP5) (<https://cmip.llnl.gov/cmip5/>) modeled climate data until 2100 [*Taylor et al.*, 2012].

specifically applied to the known permafrost zone.

We realize that additional data sets will need to be brought in to facilitate new discoveries, but we offer the preprocessed data sets so that users can test a hypothesis before embarking on a more detailed coupling of models with data. Moreover, the data sets and models are set up with common interfaces, so that puzzle pieces can together in different combinations with relative ease.

Applications of the permafrost toolbox include calculating permafrost for real-world sites in the Arctic region, looking at warming trends over the past century, making of future permafrost, and comparing models with different complexities.

Figure 2 shows one such example: Calculations of the current and future active layer thickness over the entire Arctic region demonstrate a considerable deepening of critical seasonal layer. This experiment is relatively straightforward to perform using the Web-based modeling tool.

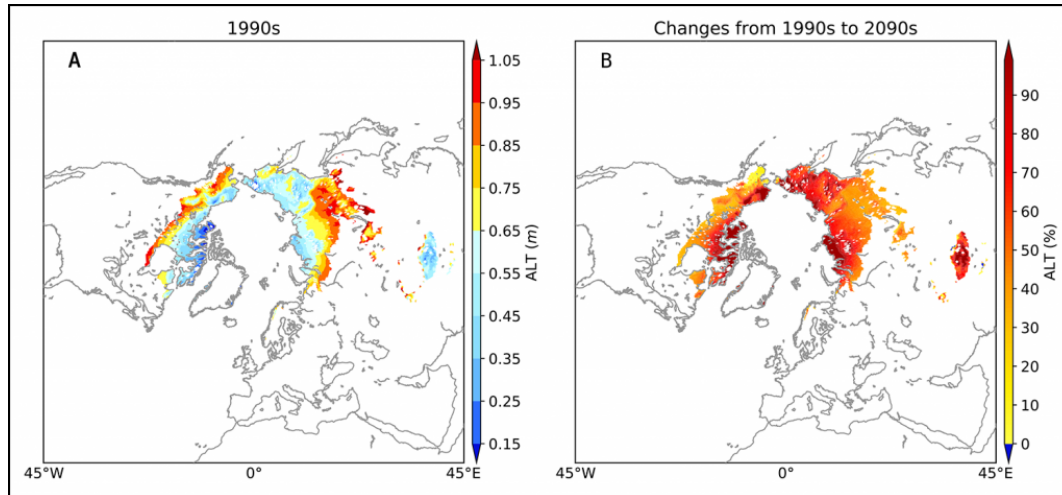


Fig. 2. Calculation of the recent state of permafrost and a projection of changes by the end of the 21st century. (a)

This map of the permafrost active layer thickness—the average annual thaw depth—over the entire Northern Hemisphere was calculated with climate data from the 1990s. (b) This map of the relative deepening in permafrost active layer thickness was calculated with CMIP5 climate model output for the 2090s.

We have developed educational material to help users learn about these tools or, more generally, to learn about the physical processes of permafrost dynamics. Four [modeling labs](https://csdms.colorado.edu/wiki/Labs_portal) (https://csdms.colorado.edu/wiki/Labs_portal) are available for new users. This material is accessible for teaching use, and the online labs include instructor classroom use and undergraduate lesson plans.

Coupled Permafrost and Earth Surface Process Modeling

More challenging problems involve assembling models that couple the new components with other Earth surface process models. The design of models in our toolbox includes a basic model interface that allows information to be passed easily between different models. This capability could be applied, for example, to feedbacks between geomorphic processes and [sequestering of carbon](https://eos.org/research-spotlights/carbon-release-from-permafrost-erosion-along-the-yukon-coast) (<https://eos.org/research-spotlights/carbon-release-from-permafrost-erosion-along-the-yukon-coast>). These coupled processes are unexplored, but they have been shown to be potentially significant in topographically complex terrain [Sheleff *et al.*, 2017].

Currently, we are using this capability to investigate the unique evolution of river deltas in permafrost terrain.

Currently, we are using this capability to investigate the unique evolution of [river deltas](https://eos.org/project-updates/small-rivers-could-have-big-impact-on-arctic-ocean) (<https://eos.org/project-updates/small-rivers-could-have-big-impact-on-arctic-ocean>) in permafrost terrain. Modeling of the intrinsic controls of permafrost on Arctic deltas highlights the role of the cohesiveness of frozen sediment and shows less dense, more stable distributary deltaic networks than in typical lower-latitude settings. Such effects on deposition in delta networks may importantly affect the role of these deltas as [carbon storage](https://eos.org/articles/map-reveals-hot-spots-for-arctic-greenhouse-gas-emissions) (<https://eos.org/articles/map-reveals-hot-spots-for-arctic-greenhouse-gas-emissions>).

Other possible couplings are between landscape evolution models, hydrological models, and the new permafrost models. Such entirely new integrated models require a high level of programming expertise and scientific creativity to generate hypotheses and identify the physical processes to be coupled in each of the process domains. The framework of CSDMS can expedite such modeling endeavors.

More advanced modelers interested in permafrost and Earth surface processes will find detailed information on our online [collaborative platform](https://github.com/) (<https://github.com/>) on GitHub. This platform also provides a means for advanced modelers to comment, suggest improvements, download code, or contribute new codes.

We anticipate that this resource will bring together researchers with various levels of modeling and field expertise to find answers to long-standing questions about permafrost and its link to surface processes and to formulate predictions about how these processes will evolve.



These abandoned buildings once housed the Distant Early Warning radar station at Point Lonely, along Alaska's Beaufort Sea coast. Rapid coastal erosion of the permafrost threatened to wash some nearby sections of land into the ocean, triggering mitigation efforts in 2009. Credit: Irina Overeem

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