High Resolution Characterization of Heterogeneous Arctic Tundra Subsurface Properties using a Multiscale Bayesian Fusion Approach with Geophysical Datasets

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Recent findings suggest that climate change has a significant impact on the arctic landscape, which could in turn cause feedback to the climate system due to the large amount of carbon stored in permafrost. A new Department of Energy, Office of Science project–called the Next-Generation Ecosystem Experiment (NGEE Arctic)–will develop a process-rich predictive model for understanding how permafrost thaw and degradation changes landscape, hydrology, biogeochemical processes and vegetation, and predicting how these changes affect the feedbacks to the climate system. The subsurface properties–such as active layer thickness (ALT), soil moisture, snow depth and geochemical parameters–are key parameters for such modeling; especially for simulation of the hydrological and geochemical processes that control microbial carbon decomposition. Although models require a large-scale domain to represent a system, these subsurface properties are known to be highly heterogeneous over small spatial scales due to the influence of factors such as microtopography and drainage network distribution.

This work presents a data fusion method based on a hierarchical Bayesian model for integrating multiscale, multi-type datasets and prior knowledge to provide estimates of heterogeneous subsurface properties and their associated uncertainty. The surface geophysical data are non-invasive and spatially extensive, which increases the spatial coverage in subsurface and reveals the fine-scale variability. Remote sensing data can further increase the spatial coverage through the subsurface-surface property correlation. The model consists of two sub-models: data model and process model. First, the process model describes the heterogeneous field of each subsurface property mathematically; it can be a mechanistic model (e.g., land evolution model, hydrological model) or data-driven model. The data-driven process model – developed based on the prior knowledge and exploratory data analysis – is particularly powerful to constrain the estimation of heterogeneous fields in the arctic tundra system, where the mechanistic process models are highly complex. Second, the data model connects the heterogeneous field to multiscale datasets. Once we establish the data and process models, we estimate the heterogeneous fields using the Markov Chain Monte-Carlo method.

We demonstrate our approach using co-located datasets collected at the Barrow Environmental Observatory, Alaska, including thaw depth, soil temperature, snow depth, aqueous geochemistry, ground penetrating radar data, electrical resistivity tomography, and airborne LIDAR. We obtain high-resolution estimates of ALT, soil water content, snow depth and other subsurface properties over a several hundred meter-scale domain, which allows us to closely examine the controls of, for example, microtopography on snow accumulation and resulting thaw depth and thermal profiles. We discuss the value and utility of the method and each dataset for parameterizing NGEE Arctic process-resolving reactive transport simulators and understanding linkages between land surface and subsurface variability.