Examination of Current and Future Permafrost Dynamics Across the North American Taiga-Tundra Ecotone

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Abstract

In the Arctic, the spatial distribution of boreal forest cover and soil profile transition characterizing the taiga-tundra ecological transition zone (TTE) is experiencing an alarming transformation. The SIBBORK-TTE model provides a unique opportunity to predict the spatiotemporal distribution patterns of vegetation heterogeneity, forest structure change, arctic-boreal forest interactions, and ecosystem transitions with high resolution scaling across broad domains. Within the TTE, evolving climatological and biogeochemical dynamics facilitate moisture signaling and nutrient cycle disruption, i.e. permafrost thaw and nutrient decomposition, thereby catalyzing land cover change and ecosystem instability. To demonstrate these trends, in situ ground measurements for active layer depth were collected to cross-validate below-ground-enhanced modeled simulations from 1980-2017. Shifting trends in permafrost variability (i.e. active layer depth) and seasonality were derived from model results and compared statistically to the in situ data. The SIBBORK-TTE model was then run to project future below-ground conditions utilizing CMIP6 scenarios. Upon visualization and curve-integrated analysis of the simulated freeze-thaw dynamics, the calculated performance metric associated with annual active layer depth rate of change yielded 76.19%. Future climatic conditions indicate an increase in active layer depth and shifting seasonality across the TTE. With this novel approach, spatiotemporal variation of active layer depth provides an opportunity for identifying climate and topographic drivers and forecasting permafrost variability and earth system feedback mechanisms.

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EXAMINATION OF CURRENT AND FUTURE PERMAFROST DYNAMICS IN THE NORTH AMERICAN TAIGA-TUNDRA ECOTONE

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ABoVE ARCTIC – BOREAL VULNERABILITY EXPERIMENT

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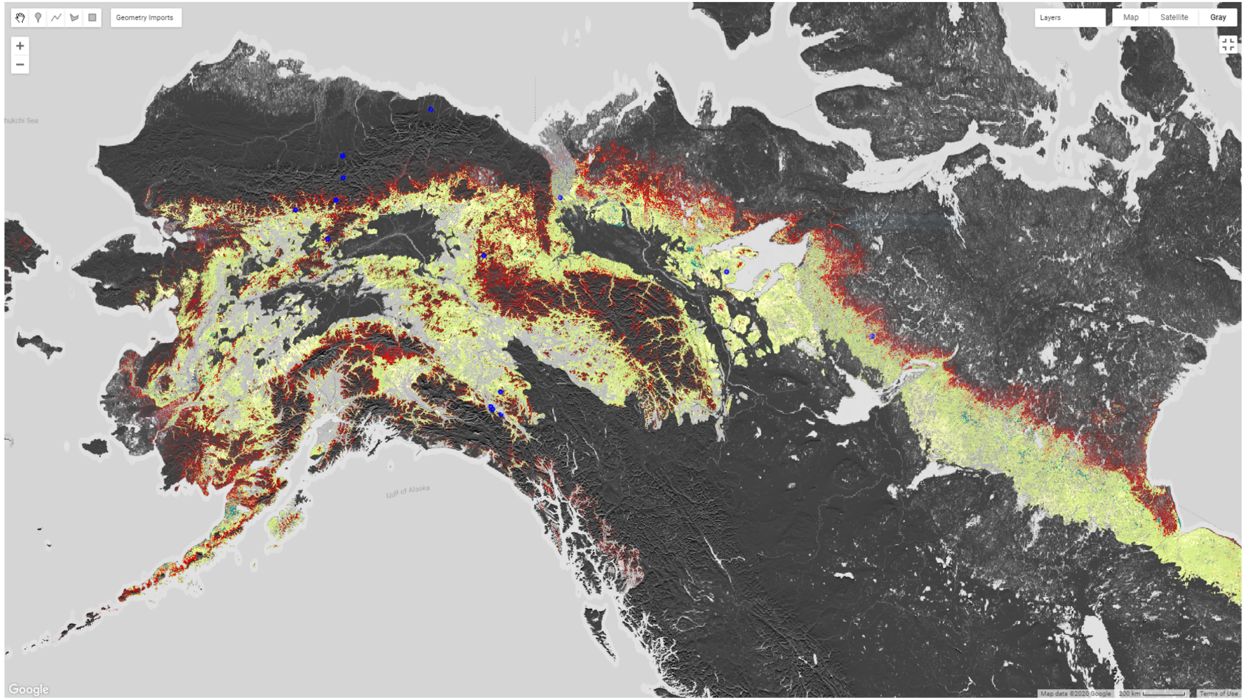
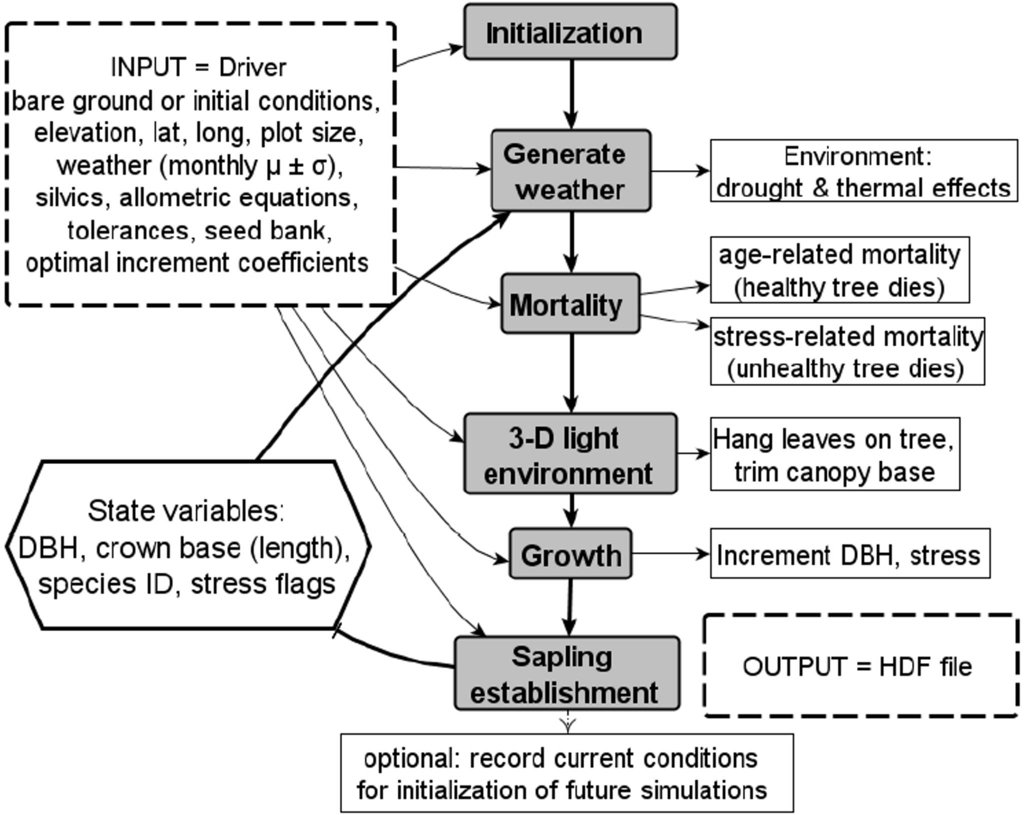
In the Arctic, the spatial distribution of boreal forest cover and soil profile transition characterizing the Taiga-Tundra Ecological Transition Zone (Taiga-Tundra Ecotone: TTE) is experiencing an alarming transformation.

Permafrost thaw and feedback mechanisms remain critical of climate change in this region.





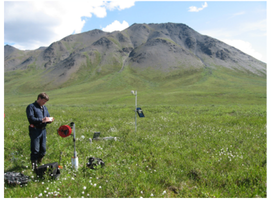
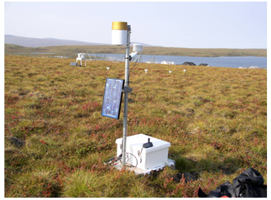
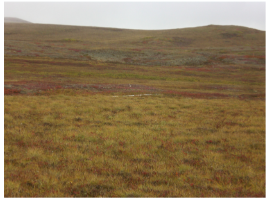
A modular application of the *ABoVE SIBBORK-TTE* modeling framework and *CALM* site validation practices jointly support the monitoring and forecasting precision of *permafrost thaw/active layer depth* dynamics and forest canopy/vegetation distribution spatiotemporality among the Tundra and Taiga ecosystems.

SIBBORK-TTE MODEL FRAMEWORK | TESTING PERMAFROST MODULAR UPGRADES (SUBROUTINES) WITH CALM SITE IN-SITU DATA COLLECTION

- To evaluate the performance of the SIBBORK-TTE model and continue monitoring permafrost thaw and vegetation distribution in the TTE, four CALM validation sites were selected based on geographic proximity to a pre-existing TTE site in the Brooks Range (Brooks02; 67.476ºN, 150.059ºW); the low temporal resolution is a function of site institution/accessibility and terrain constraints accompanying in-situ data sampling collection (1996-2017).
- Prior to validation, Brooks02 model simulation performance metrics were first analyzed relative to CALM model simulations with cross-model output comparisons/residuals (RMSE) based on annual maximum permafrost thaw depth and rate of change (August). After cross-model simulation analyses, CALM site model-in situ data validation processing began. DEM-upscaled simulations of annual maximum permafrost thaw depths and rates of change were compared to the in situ measurements.

Sites: Brooks02 (Mountainous Trees/Shrubs Site, TTE), Old Man (Flat Trees/Shrubs Site, CALM), Chandalar Shelf (Mountainous Shrubs Site, CALM), Toolik1km (Flat Shrubs Site, CALM), and ToolikMAT (Flat Shrubs Site, CALM)



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We validated site-specific model simulations with CALM in-situ field observations.

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

GTN-P
Global Terrestrial Network for Permafrost

US Permafrost Association

IPA

ARCTIC PORTAL

CALM

Circumpolar Active Layer Monitoring

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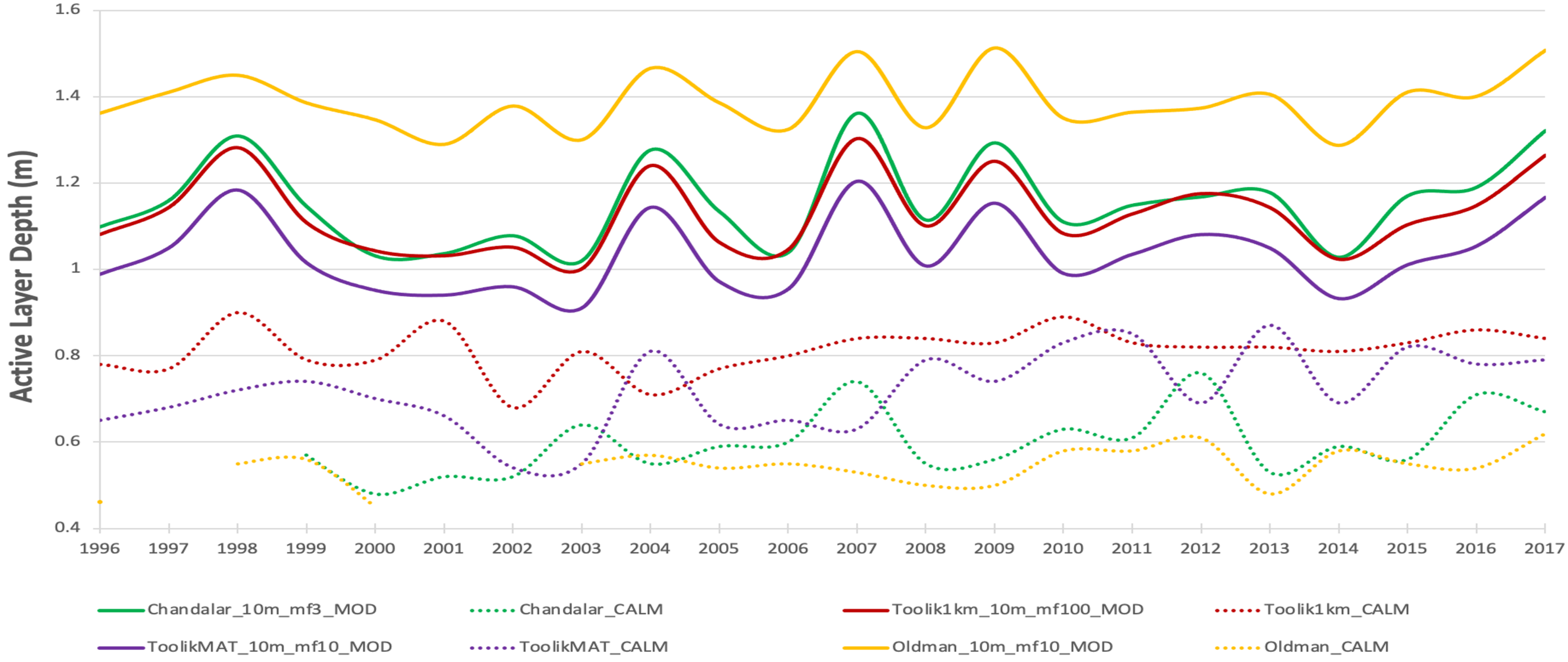
CALM Site SIBBORK-TTE Model v. In-Situ Validation: Annual Maximum Permafrost Thaw Depth (RMSE:0.3280)



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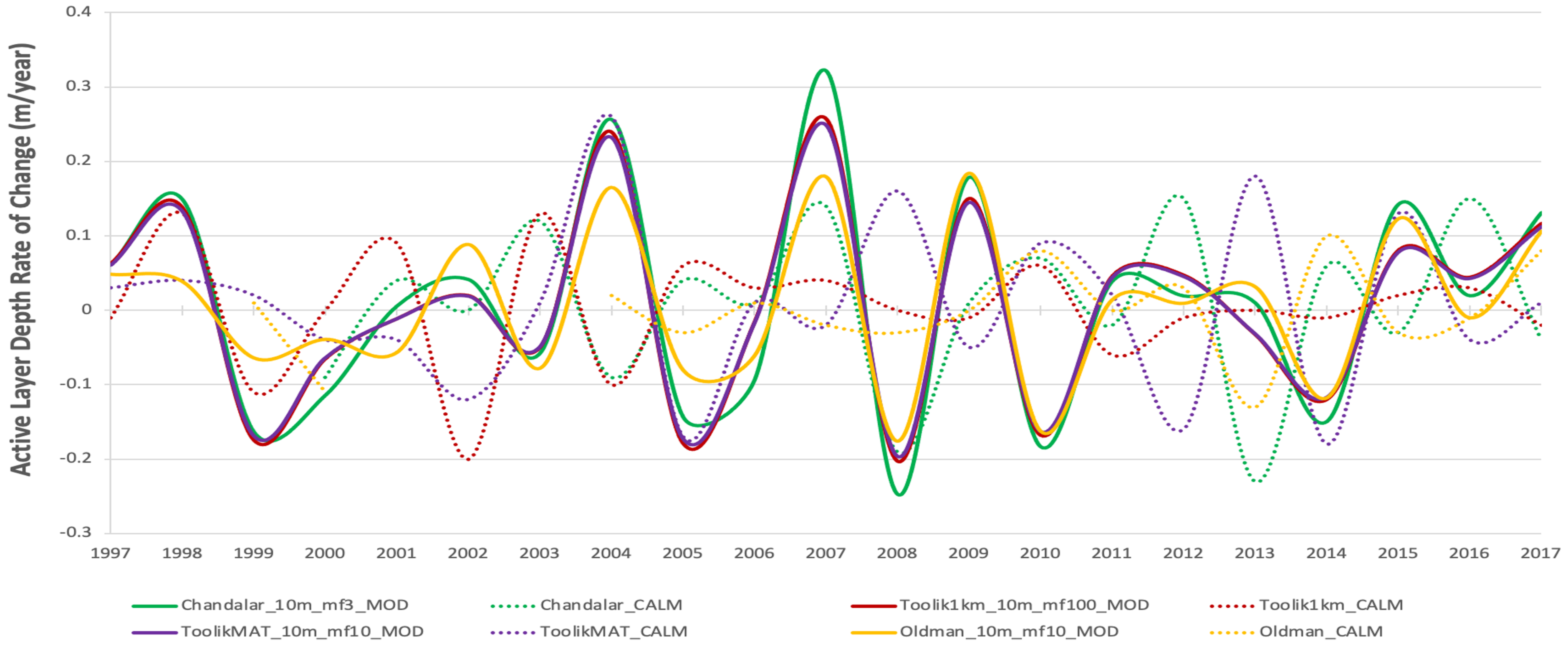
CALM Site SIBBORK-TTE Model v. In-Situ Validation: Annual Maximum Permafrost Thaw Depth Rate of Change (RMSE:0.1380)



SIBBORK-TTE MODEL CMIP6 PROJECTIONS (1980-2100)

- SIBBORK-TTE Model Driver: Instantiation of a warming climate function with mean monthly temperature and precipitation (with standard deviations) and average seasonal rate of change (slope) alongside real climate collection arrays, i.e. MERRA2 (1980-2017) + CMIP6 (2018-2100) datasets.
  - CMIP6.ScenarioMIP.CAS.FGOALS-f3-L.ssp585.r1i1p1f1.Amon.tas.gr, Version: 20191013
  - CMIP6.ScenarioMIP.CAS.FGOALS-f3-L.ssp585.r1i1p1f1.Amon.pr.gr, Version: 20191013

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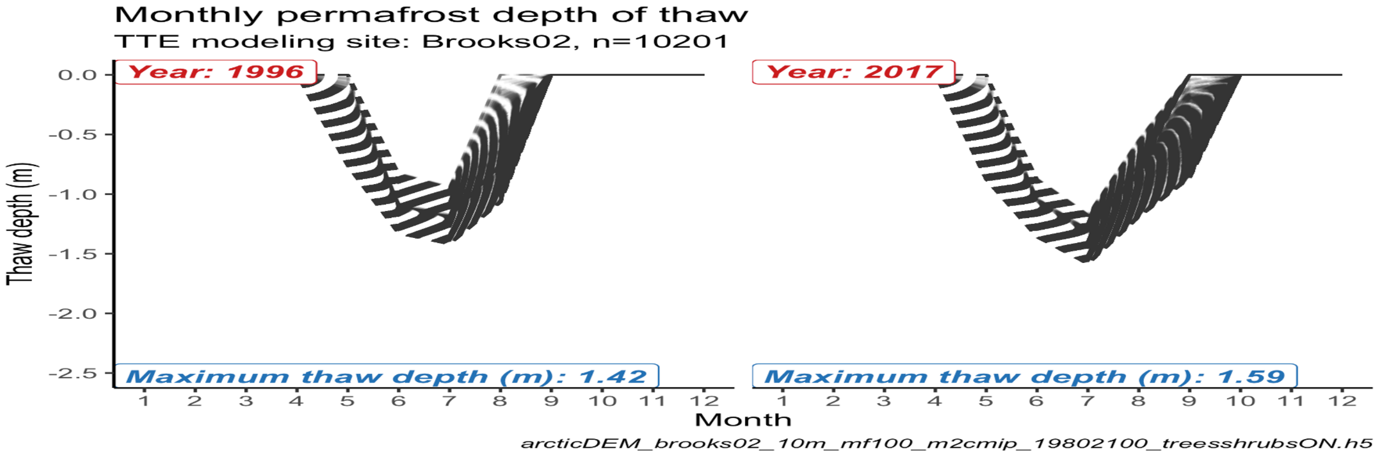

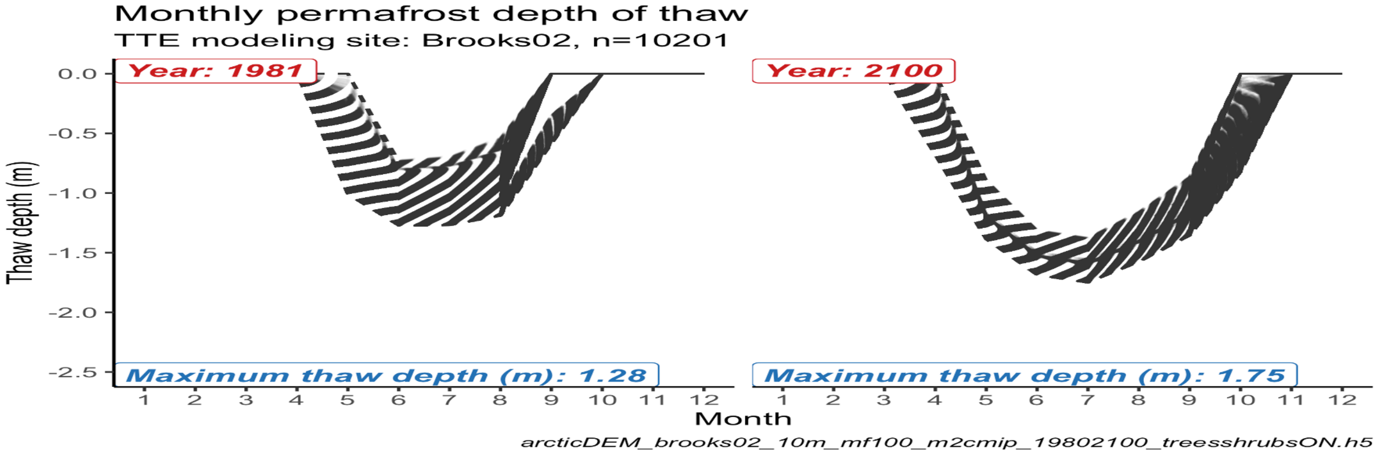

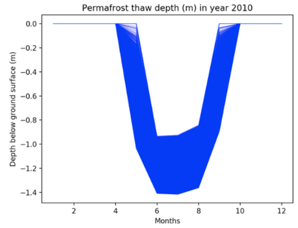

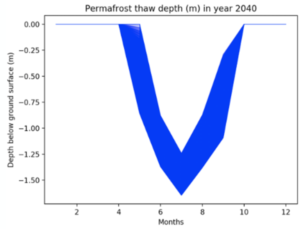

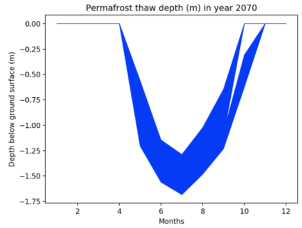

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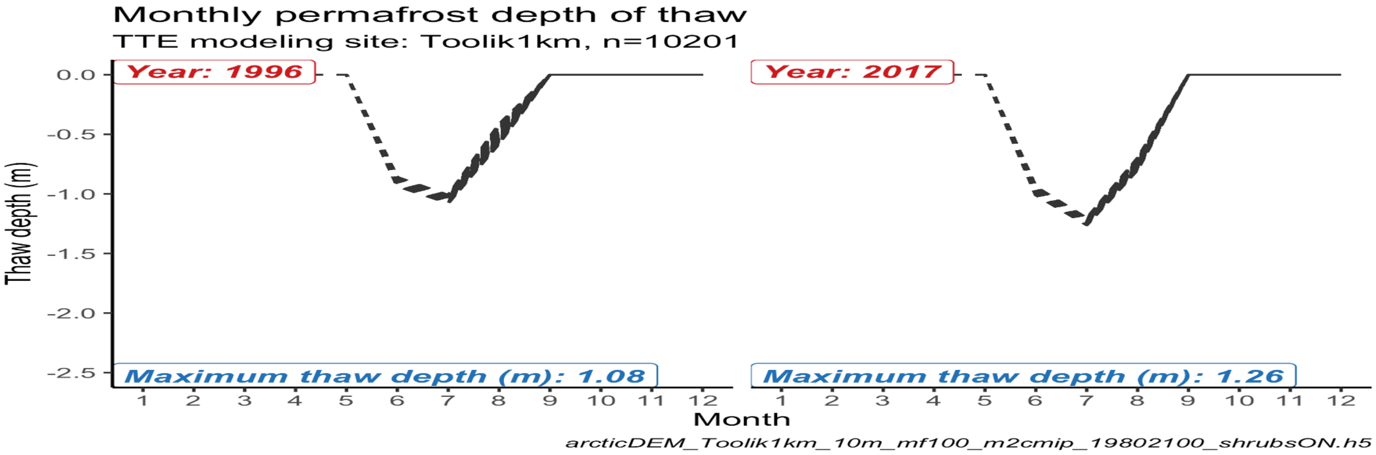

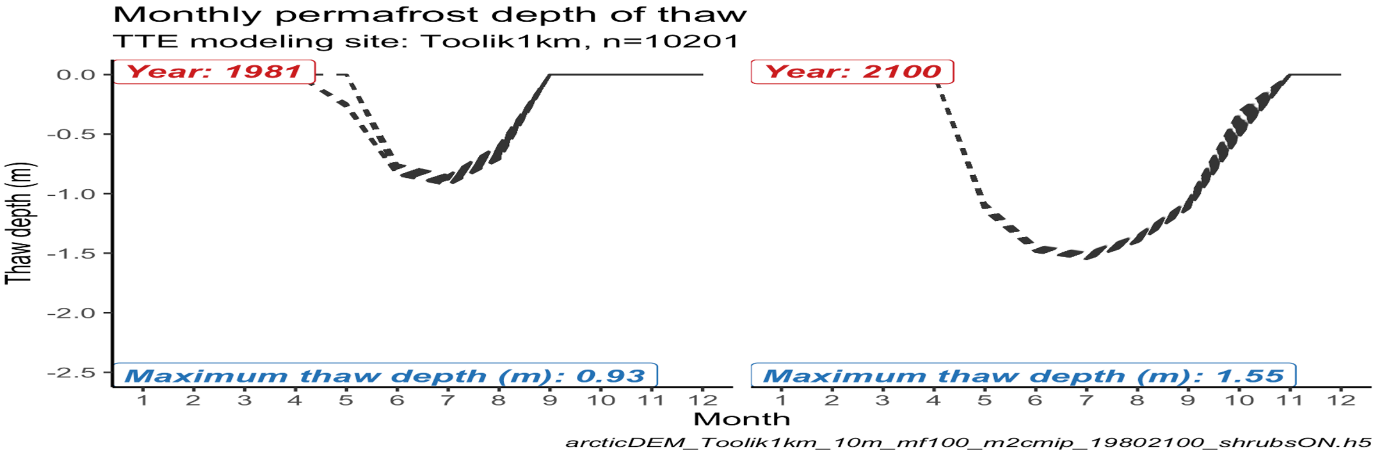

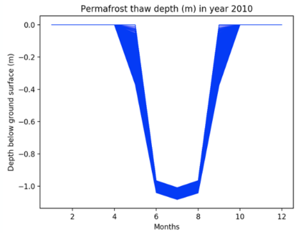

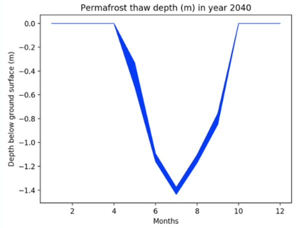

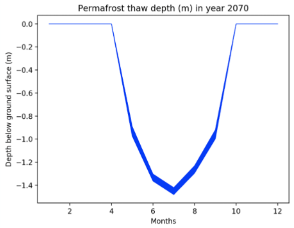

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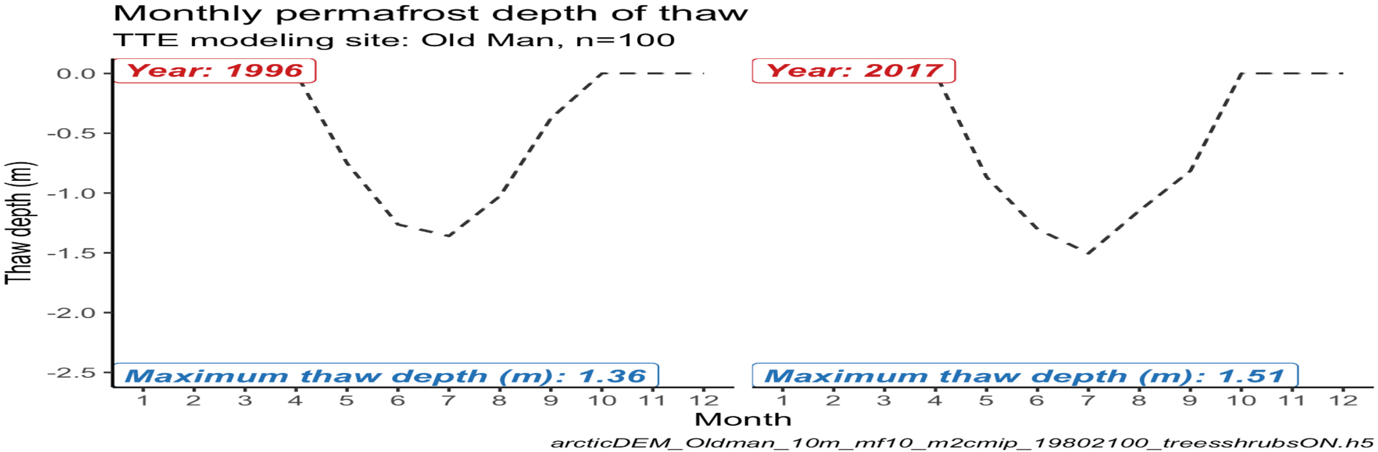

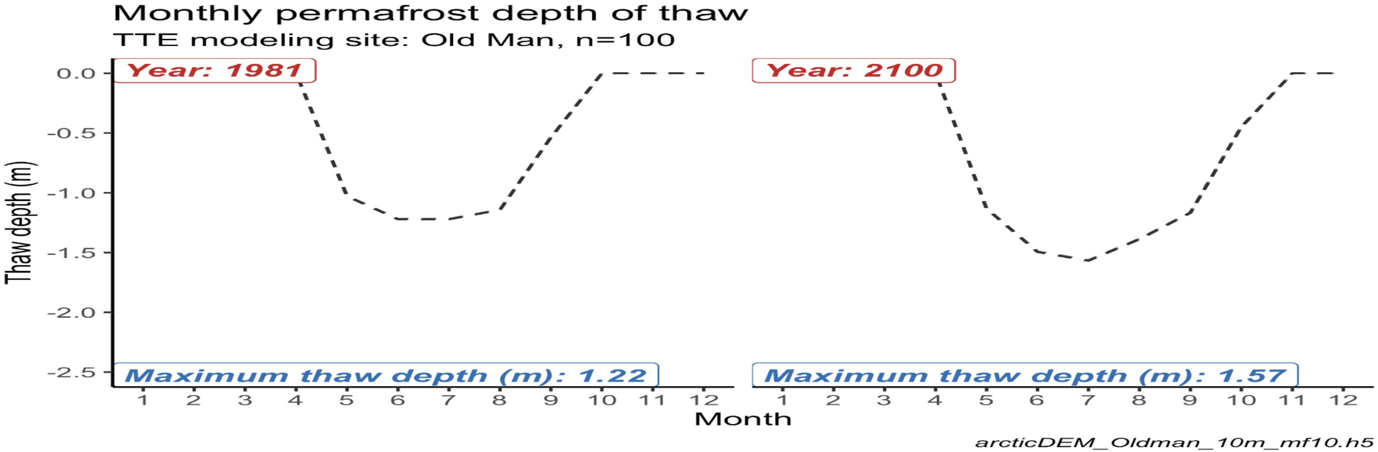

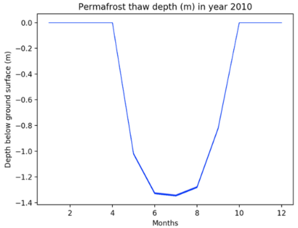

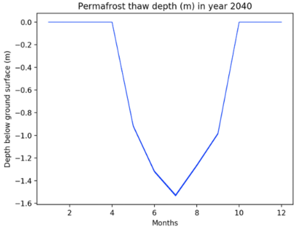

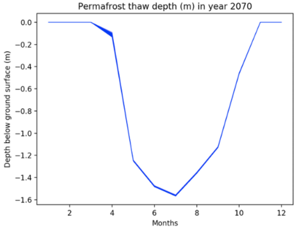

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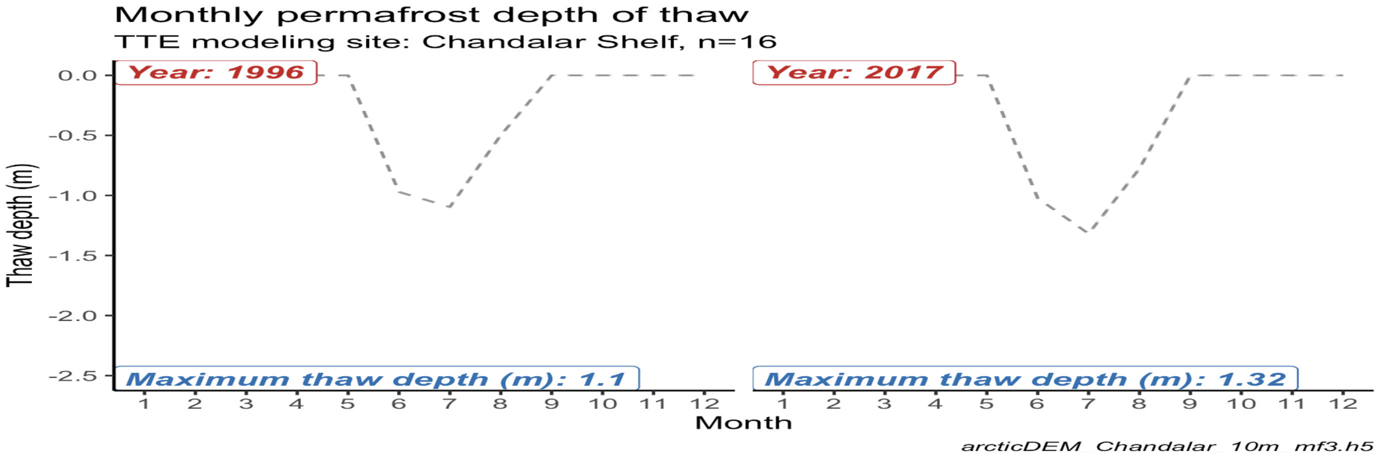

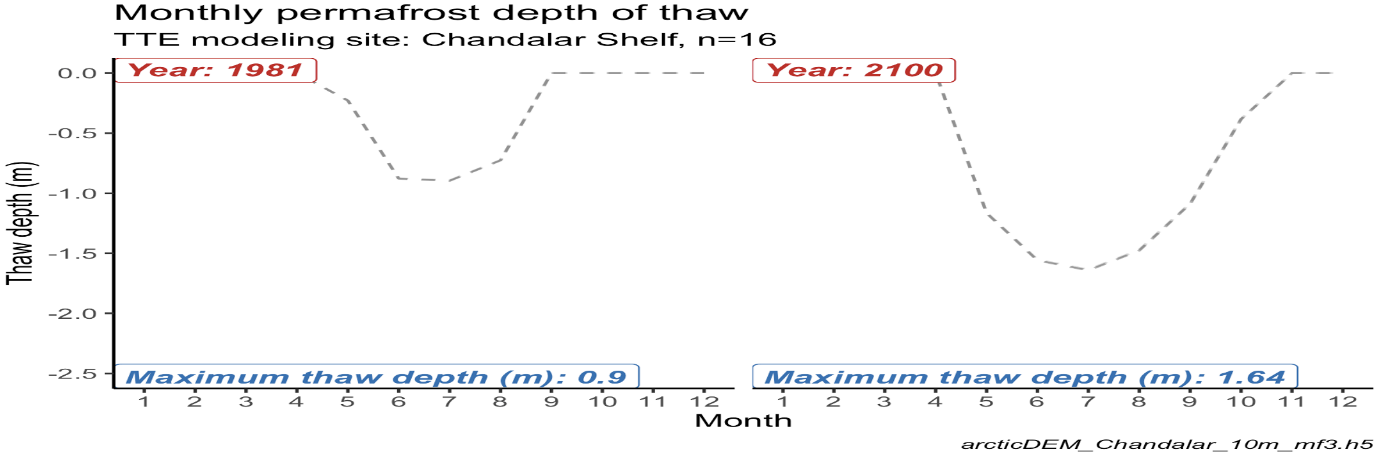

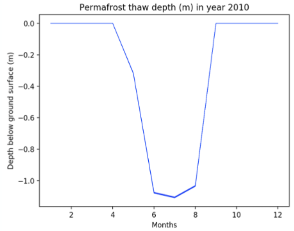

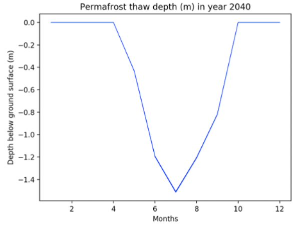

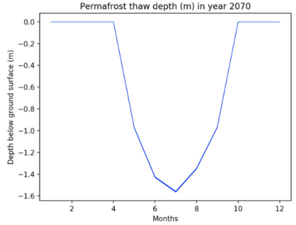

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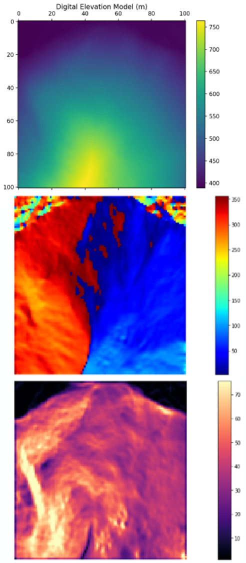
Model Results and Analyses

- As indicated by the bi-decadal CALM-validated annual plots (1996-2017) and 120-year CMIP6-integrated projections (1980-2100), seasonal disturbance is evident. The broadening of the growing season facilitates more opportunity for rapid +thaw/-freeze kinetics and increased permafrost thaw, as illustrated via plot widening and deepening (i.e. annual thaw curve integration).
- In addition to climate forcing (i.e. increasing surface temperature and precipitation) and localized spatial scaling corrections, microtopography and vegetation classification appear to play a critical role in annual active layer depth variability and seasonal pattern disruption.
- Topographic disparities and hydrogeochemical factors between sites may help identify specific drivers of permafrost dynamics and support the development of topographic hyperparameters strongly contributing to the spatiotemporal distribution of soil water content and associated vegetation patterns. As a result, these causal feedbacks instigate wide active layer depth variability and thaw subsistence, advance water infiltration and mineral dislocation, disrupt carbon and nutrient cycling, and exacerbate localized warming and global climate change.

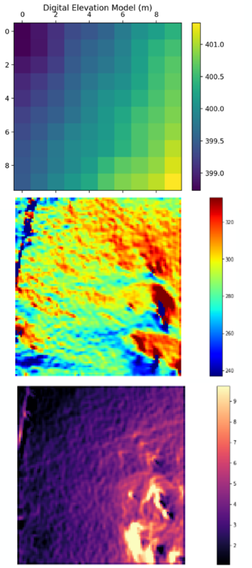
Potential Drivers of Thaw Depth Variability

Topography | Elevation, Aspect, Slope

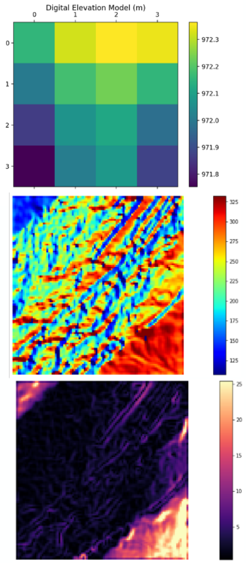
Brooks02 TTE Site



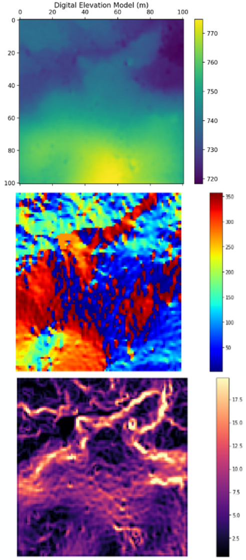
Old Man CALM Site



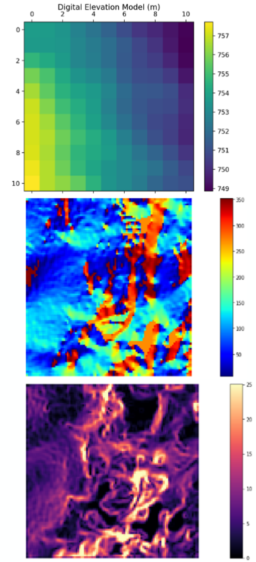
Chandalar CALM Site



Toolik1km CALM Site



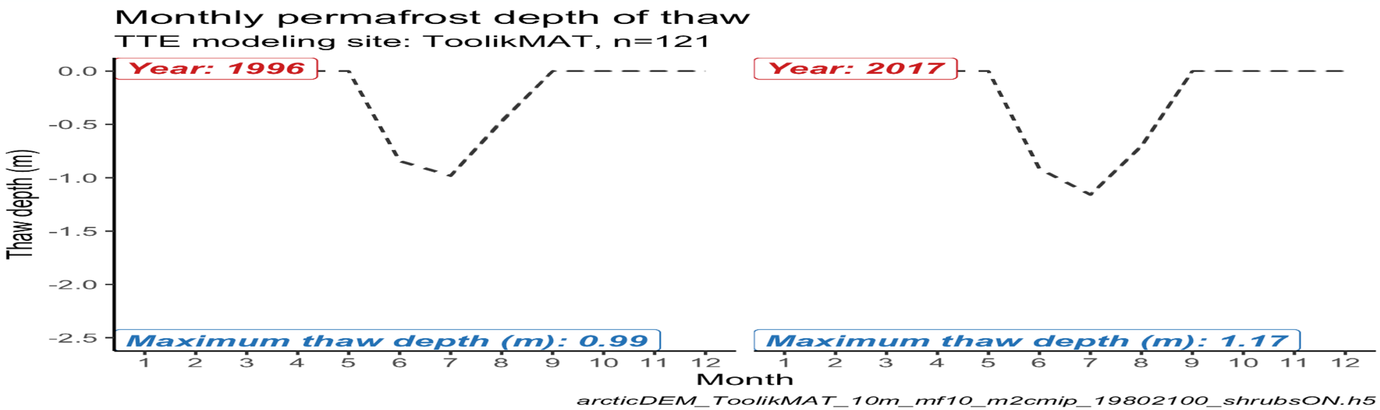
ToolikMAT CALM Site

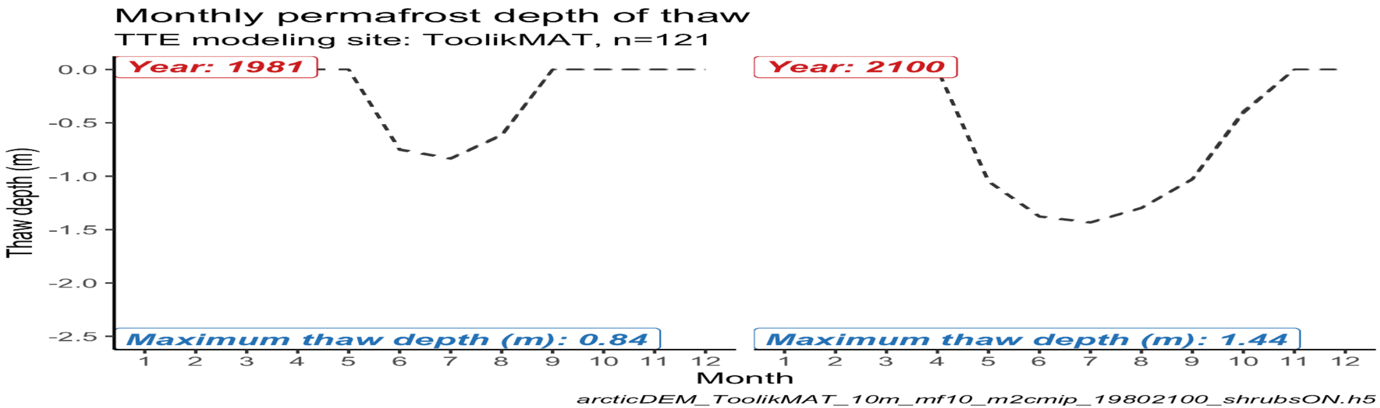


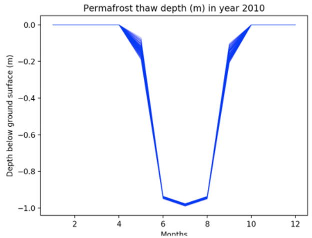
Future Directions for Improving Permafrost Thaw Projections

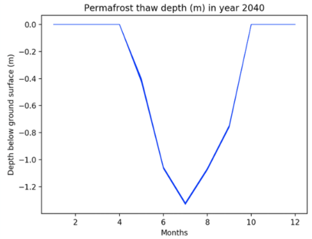
- Model enhancement
  - MERRA2 replacement with a more robust, dynamic, higher spatially-resolved precipitation dataset; continued integration of shrub allometry and plant functional types with belowground processes via Bonan-ArcVeg code translation/integration (nutrient cycling, moss/lichen distribution, and decomposition/mortality.
- Utilization of additional CALM and other model-in situ validation results and subsequent model hyperparameterization updates in order to further simulate, monitor, and project permafrost dynamics, vegetation dynamics, and forest distribution within the TTE
- Dissertation: Incorporate soil-ecosystem-carbon-climate nexus (SECCN) database and pattern recognition via machine/transfer learning/AI technology (soil carbon, ecosystem response) to further validate and enhance modeling framework for future projections

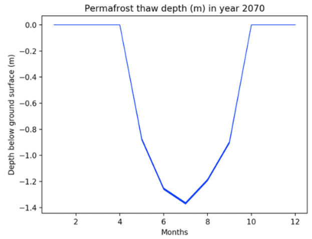
Appendix











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THANK YOU

Contact me with any questions:

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Special thanks to Dr. Amanda H. Armstrong and the NASA ABoVE team and my ESGS PhD advisor at George Mason University, Dr. John Qu.

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