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Characterizing permafrost active layer dynamics and sensitivity to landscape spatial heterogeneity in Alaska

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Table S1: Characteristics of the Alaska tower sites used for site-level model simulations and validation. Three tundra community types are represented by the tower measurements at Imnavait Creek, characterized by different surface organic layer thickness (OLT) and ALT conditions.

	AK-Imn	US-Atq	AK-PFR
Site	Imnavait Creek	Atqasuk	Poker Flat Research Range
Biome	Tundra	Tundra	Black spruce
Location	68°37′N, 149°18′W	70°28′N, 157°24′W	65°07′N, 147°29′W
OLT (cm)	2 - 34[*]	~ 18[†]	~ 25[‡]
ALT mean (cm)	40 - 70[*]	~ 40[†]	~ 43[‡]
Observation period	2008 - 2011	2003 - 2007	2011 - 2013
Soil temperature measurement depth (cm)	0, 5	0, 5	5, 20, 30, 40, 100
Soil moisture measurement depths (cm)	5	N/A	5, 10, 20, 30, 40

[*]Euskirchen et al., 2012; [†]Oechel et al., 2014; [‡]Nakai et al., 2013

Table S2: Prescribed vertical decaying rate (k, m^{-1}) of the SOC density [Eq. (1)] for boreal forest and other Alaskan biome types used in the soil model sensitivity analyses for different SOC vertical allocation schemes.

	"Surface" C allocation	Baseline C allocation	"Even" C allocation
Boreal forest	0.05	0.04	0.03
Other biome type	0.03	0.02	0.01

Table S3: Statistics of comparisons of model simulated and in situ observed soil temperatures at the three tower validation sites.

	AK-Imn	US-Atq	AK-PFR
R	0.97 (5 cm)	0.97 (5 cm)	> 0.92 (5-100 cm)
RMSE (°C)	2.06 (5 cm)	2.38 (5 cm)	< 1.20 (5-100 cm)

Table S4: MODIS LST statistics for different seasons and correlations with model simulated ALT from 2001 to 2015. The LST trends were only calculated for areas where the model estimated mean ALT was within 300 cm depth during the study period.

	Spring	summer	LST degree days (snow free season)
LST trends (°C yr^{-1})	0.095 ± 0.090	0.006 ± 0.066	0.415 ± 0.982
R vs. ALT	0.37 ± 0.30	0.53 ± 0.32	0.60 ± 0.32

Table S5: Temporal trends (% yr^{-1}, 2001-2015) of model simulated areas with ALT < 300 cm in proportion to model simulations in 2000 in the permafrost zone with permafrost probability (PP) < 70%. Here, the ALT < 300 cm threshold defines the boundary of estimated regional permafrost extent. There were negligible changes in the model simulated areas with ALT < 300 cm in permafrost zone where PP ≥ 70%. All trends are significant at the 0.01 level.

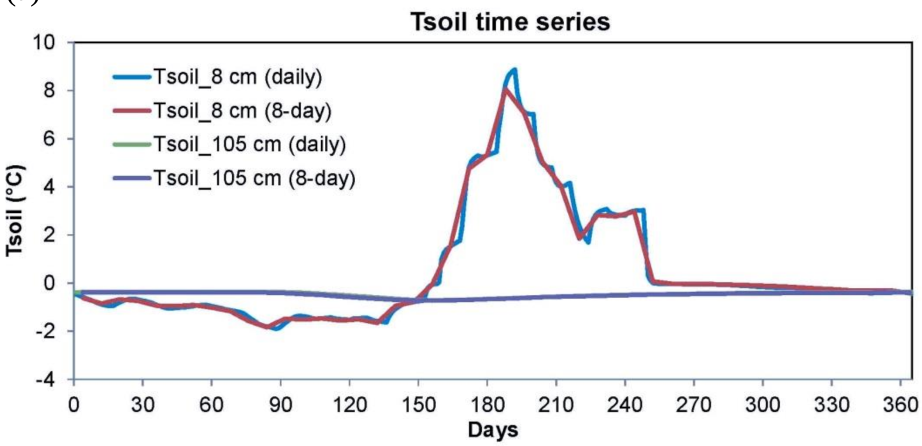
	SOC allocation			SM	
	"surface"	"baseline"	"even"	"high SM"	"low SM"
High SOC	-0.76	-0.94	-1.14	-1.13	-0.68
Baseline	-1.02	-1.19	-1.62	-1.54	-0.99
Low SOC	-1.45	-1.82	-2.26	-2.12	-1.44

Table S6: The sensitivity of simulated ALT to snow density in different permafrost zones. Model results presented include mean ALT, and temporal trends (2001-2015) in model simulated area with ALT < 300 cm (used as a proxy for near surface permafrost spatial extent) in proportion to model simulations in 2000.

Snow cover density	Mean ALT (cm) PP < 70%	Mean ALT (cm) PP ≥ 70%	Trends of areas with ALT < 300 cm (% yr^{-1}) PP < 70%	Trends of areas with ALT < 300 cm (% yr^{-1}) PP ≥ 70%
High	129.51 ± 15.51	50.92 ± 6.18	-0.77*	0.06
Baseline	146.17 ± 16.69	60.73 ± 8.99	-1.19*	-0.09
Low	217.63 ± 27.38	94.82 ± 15.38	-2.65*	-0.92*

* indicates $p < 0.01$

(a)



(b)

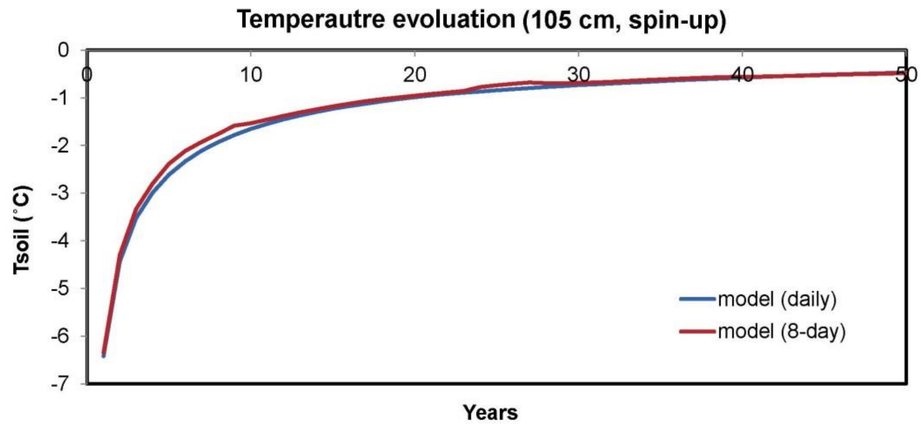


Figure S1: Comparisons of model test runs at 8-day and daily time steps for pixel 149.3°W, 68.6°N: (a) the model simulated annual time series of soil temperature at 8 cm and 105 cm; (b) the model simulated annual mean soil temperatures at 105 cm during the 50-year spin-up process. The daily model simulations were derived using daily LST inputs interpolated from the coarser 8-day MODIS data, with daily snow depth and density inputs from MERRA2 reanalysis.

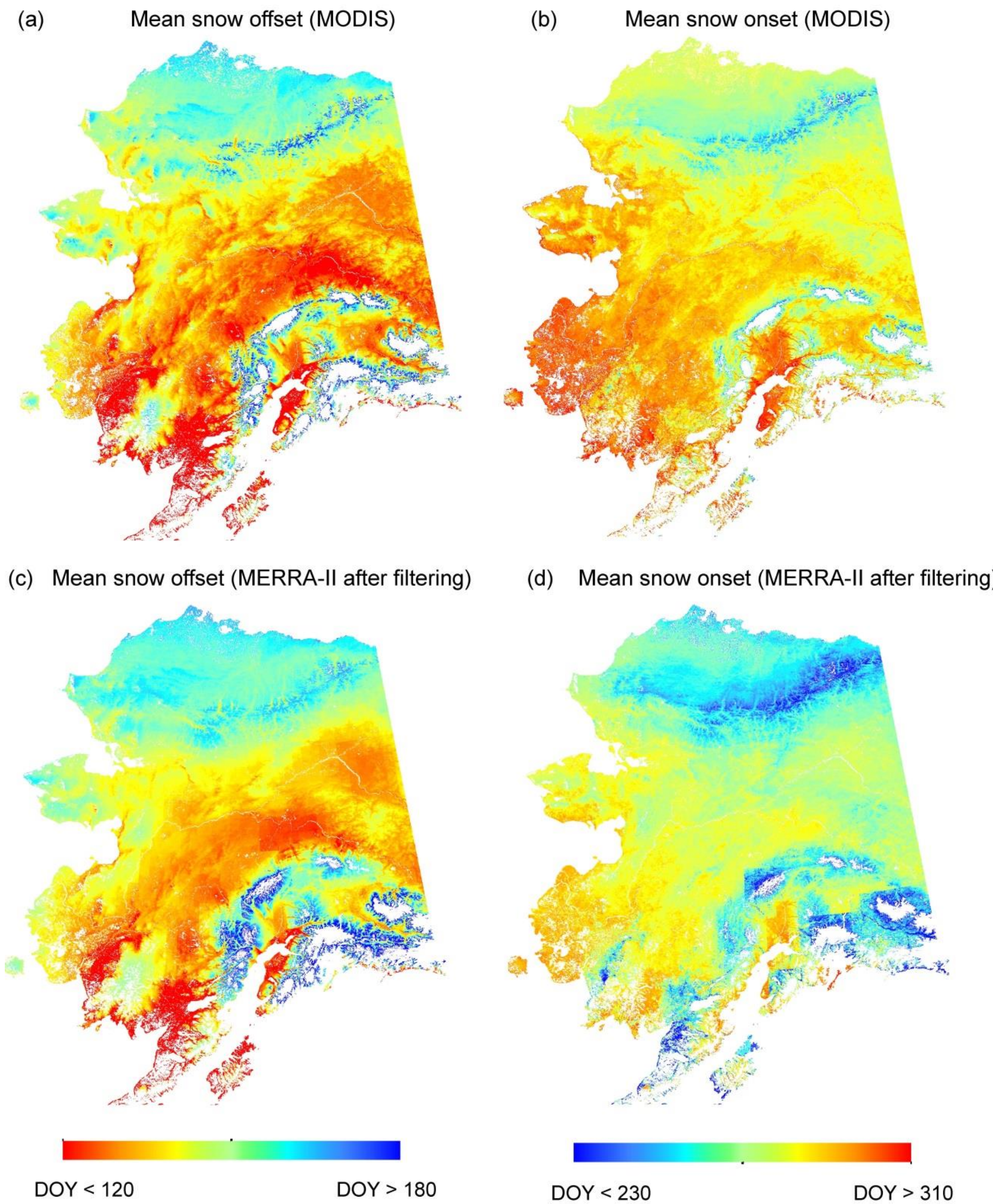


Figure S2: Spatial pattern of the timing of mean snow offset and onset derived from the MOD10A2 8-day snow cover extent (SCE) product (a-b) and MERRA-2 daily snow depth data (after filtering using the MOD10A2 product, c-d) during the 2001-2015 study period. The timing of snow offset in spring was defined as the 8-day composite period with two continuous snow-free periods. The timing of snow onset in autumn was chosen as the composite period with more than 3 adjacent snow-covered periods within a 40-day moving window period; this long window period was used to account for more variable snow cover conditions during autumn.

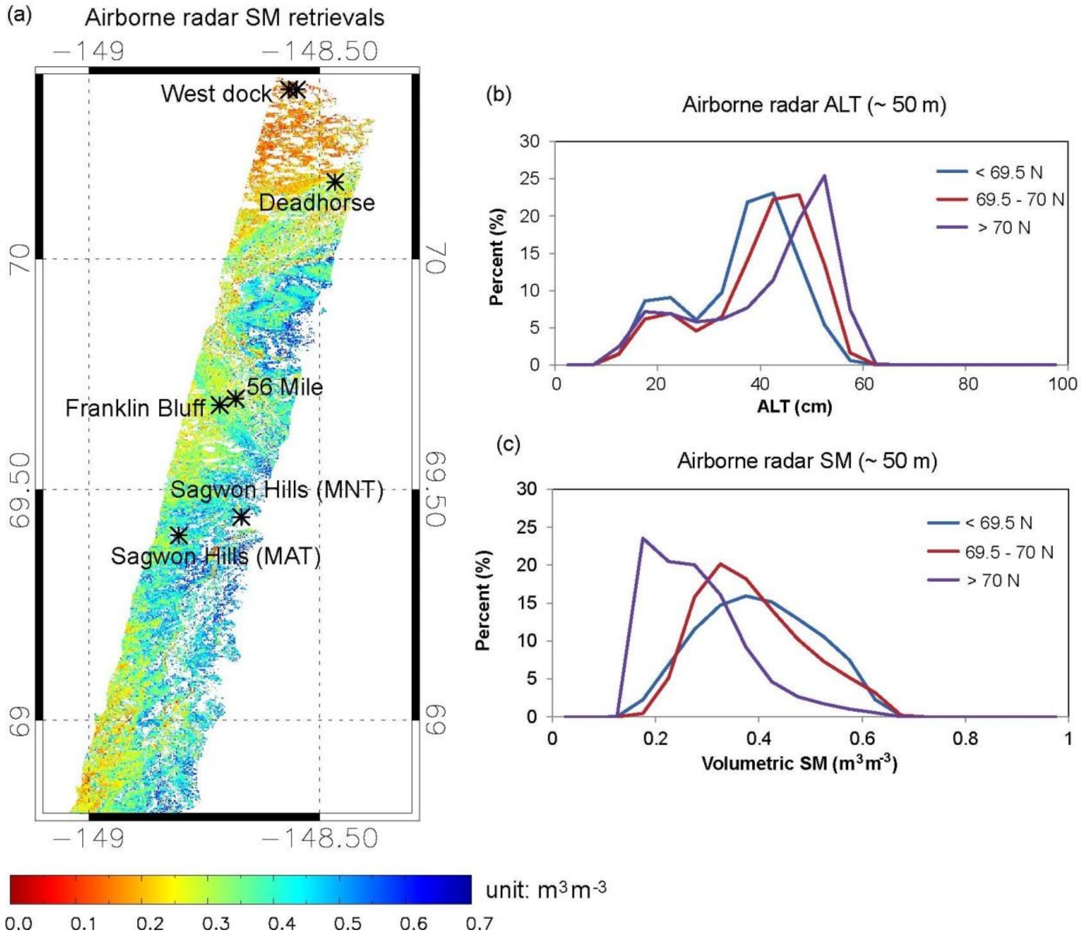


Figure S3: Regional ALT and soil moisture (SM) spatial distributions derived from AirMOSS P-band and UAVSAR L-band radar backscatter retrievals within the Alaska Dalton Highway (DH) sub-region acquired in October 2015: (a) the radar retrieved volumetric SM (m^3 m^{-3}) of the soil active layer; the locations of in situ CALM site are denoted by black stars. (b-c): the frequency distribution of the local scale (50-m resolution) ariborne radar based ALT (c) and active layer SM (c) estimates for different latitudinal bands within the DH sub-region.

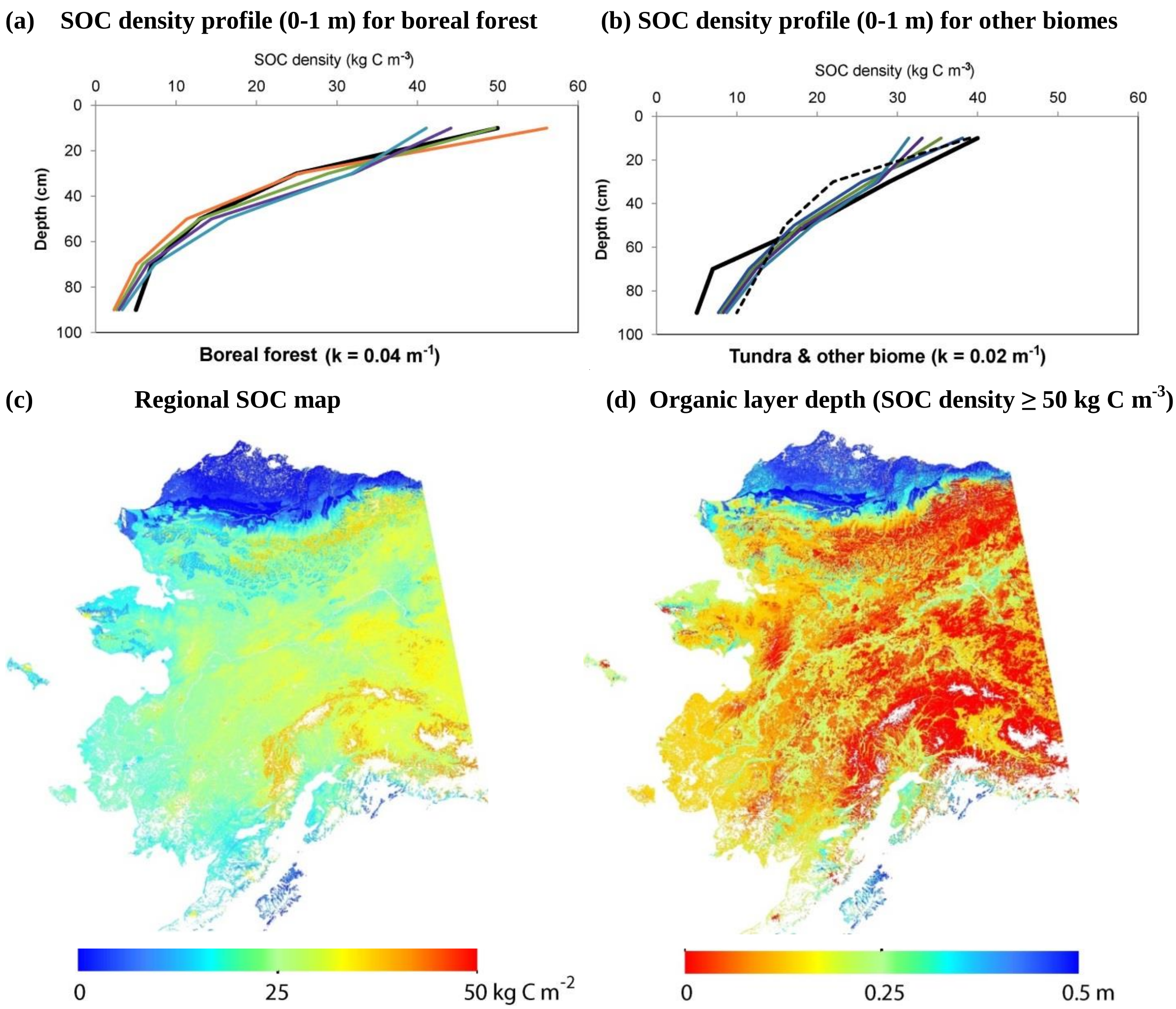


Figure S4: (a-b) SOC vertical distributions within the top 0-1m soil depth for boreal forest (a), tundra and other biome types (b). The black line is drawn based on available in situ observations (Jobbagy and Kackson, 2000); the color lines represented the estimated SOC vertical distribution profiles determined using Eq. (1) and prescribed total SOC content. (c): the regional 50-m Alaskan SOC map (Mishra et al., 2016) used for the model simulations; (d) estimated soil orgaic layer depth with SOC density ≥ 50 kg C m^{-3} derived from the regional SOC map and prescribed SOC vertical distribution in (a) and (b).

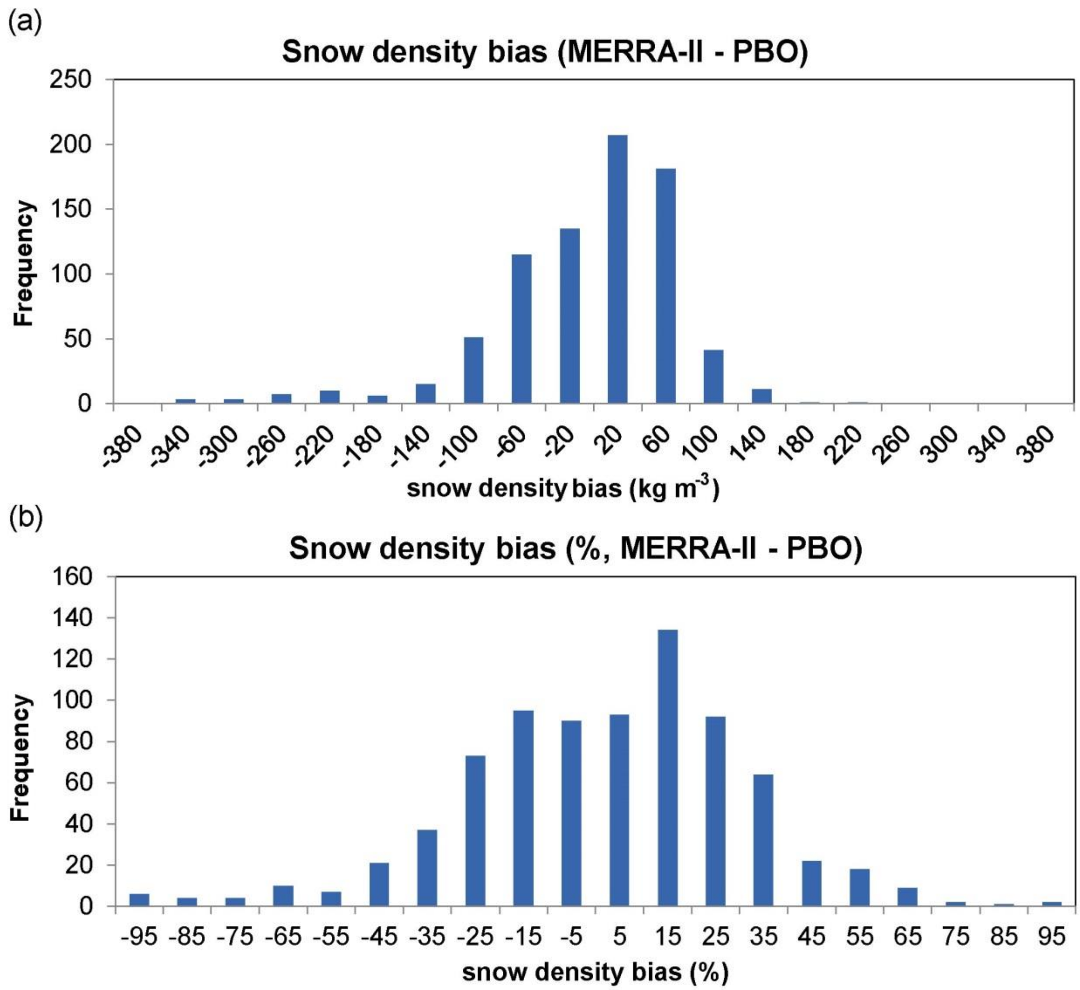
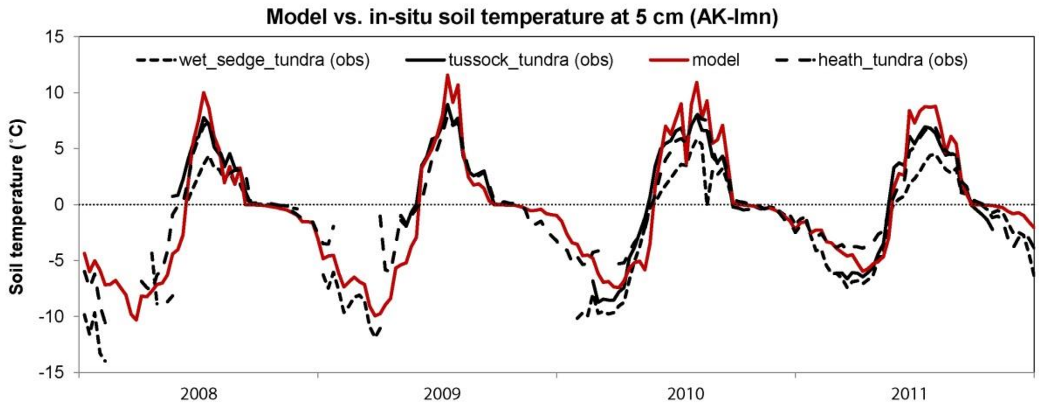


Figure S5: Comparisons of MERRA-2 data with snow density estimates derived from Global Positioning System (GPS) L-band signals (Larson and Nievinski, 2013) from six Plate Boundary Observatory (PBO) sites across Alaska, including three evergreen needleleaf forest sites, two grassland sites and one additional site (biome type unknown).

(a)



(b)

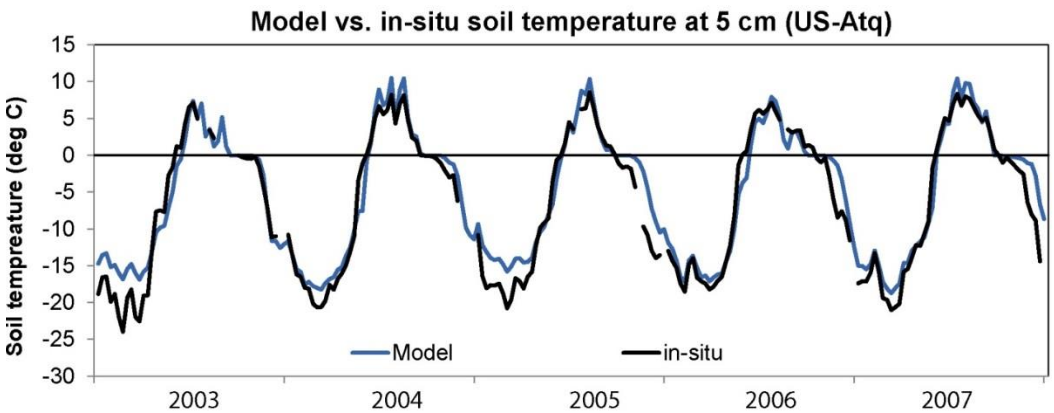


Figure S6: Comparisons of model simulated and in situ observed 8-day soil temperatures at 5 cm depth at two tundra tower sites (a: AK-Imn; b: US-Atq).

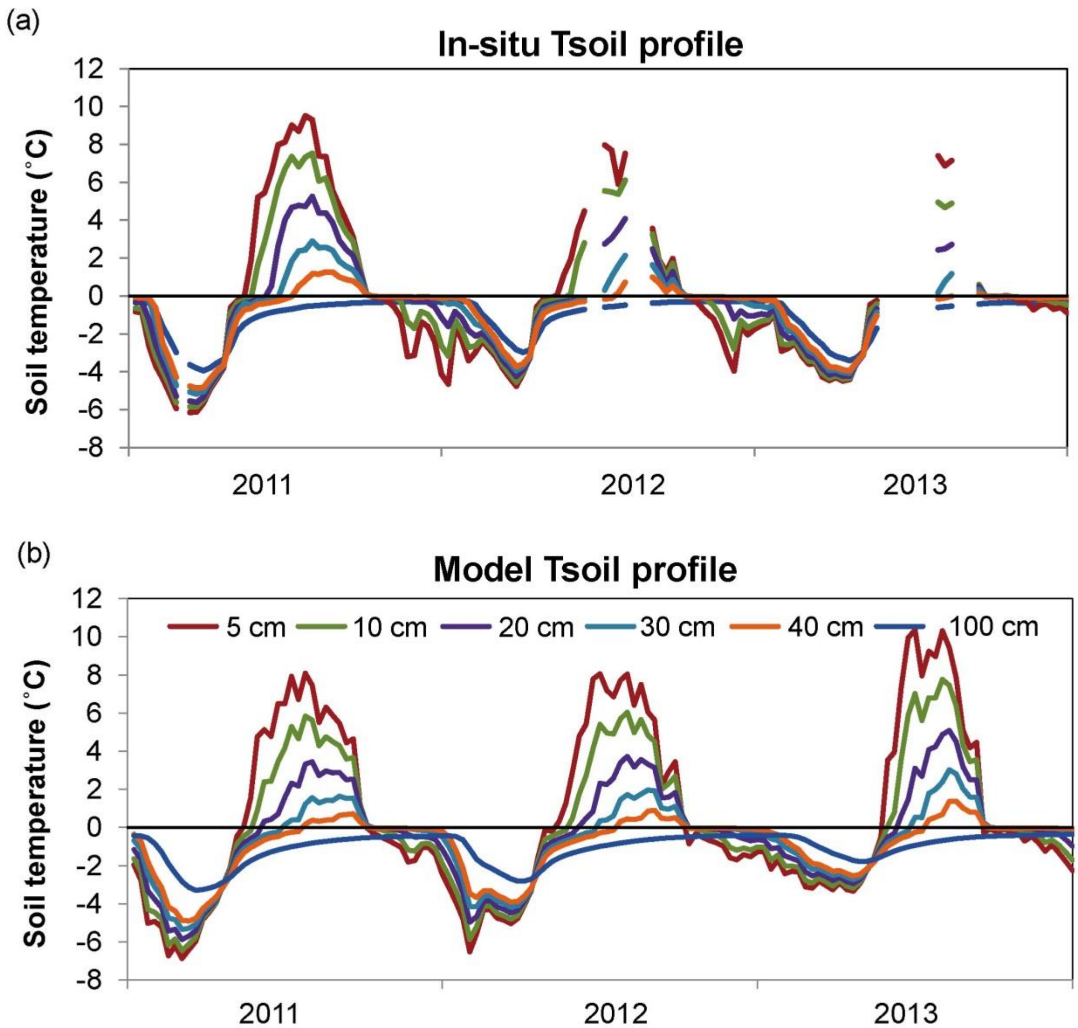


Figure S7: Comparisons of in situ observed (a) and model simulated (b) 8-day soil temperature profile at different depths (5 cm – 100 cm) at the boreal forest site (AK-PFR).

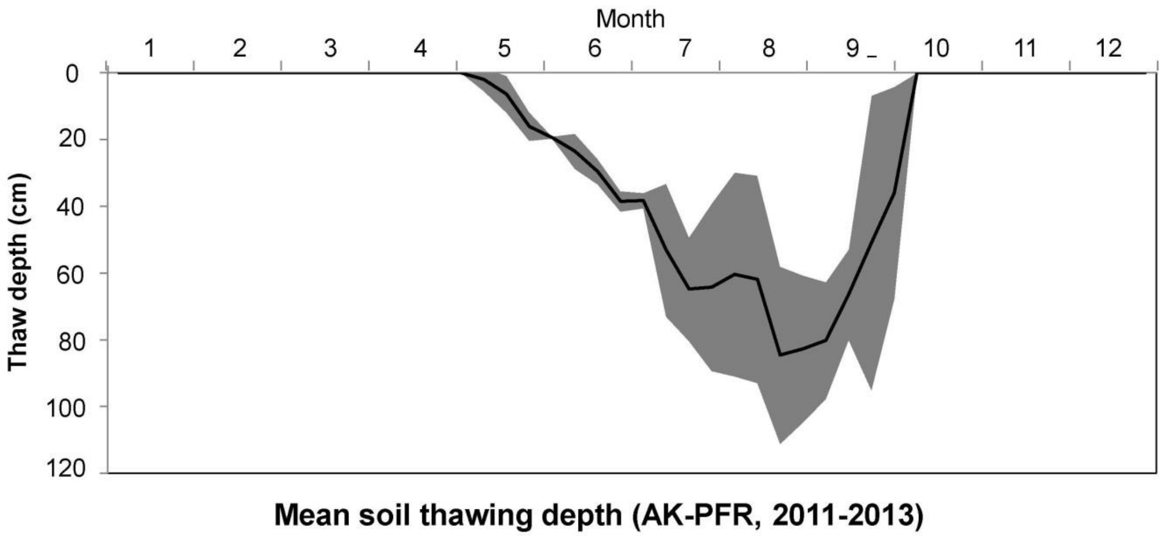


Figure S8: The mean soil thawing depth at the boreal forest site (AK-PFR), calculated from in situ soil temperature measurements (Figure S7a). Dark gray shade indicates 1 standard deviation for the calculated soil thawing depth during the observation period.

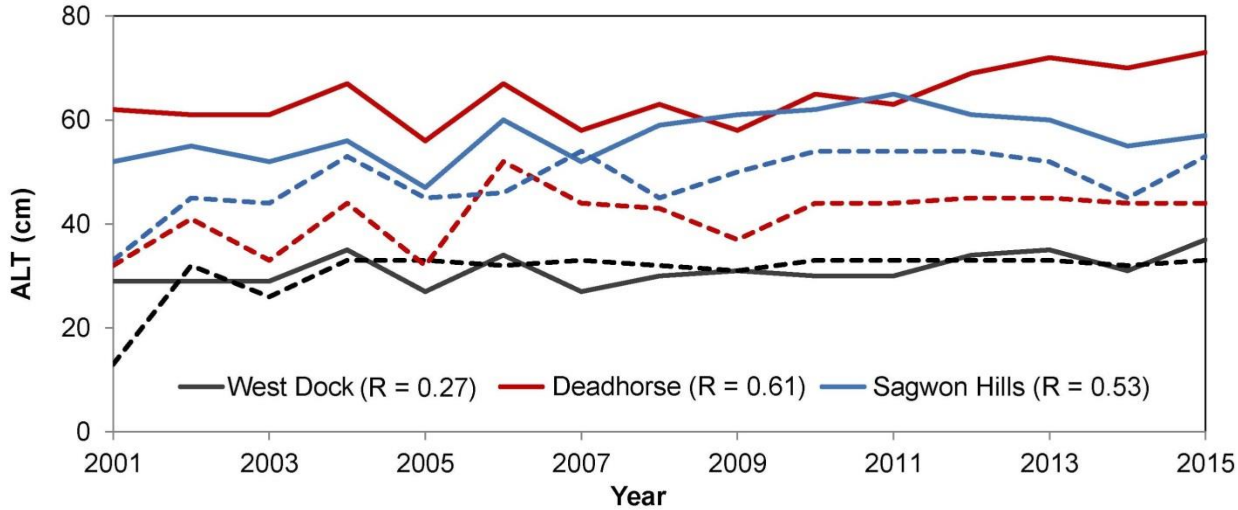


Figure S9: Comparisons of model simulated (dashed lines) and in situ observed (solid lines) ALT time series at the three in situ CALM sites located within the DH sub-region (Figure 4). Both the model simulations and in situ observations at the Franklin Bluff site show similar inter-annual variability as the Deadhorse site, and are thus not shown. The R values are the correlations between the in situ observed and model ALT estimates from 2001 to 2015.

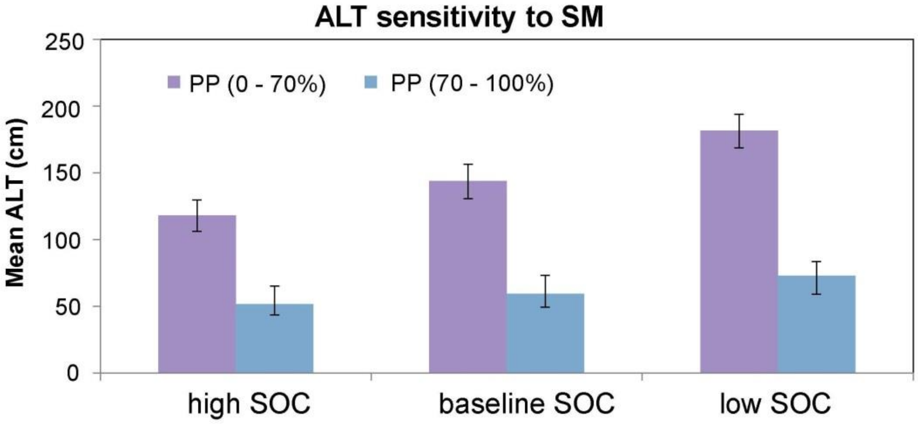


Figure S10: The sensitivity of model simulated ALT to soil moisture for two different permafrost probability zones (PP < 70% vs PP ≥ 70%) and different SOC scenarios. The error bars represent the standard deviation of the model ALT simulations using high/low soil moisture wetness (baseline soil wetness ± 10%) from the baseline simulations.

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