Estimating Potential Damping of Cryoturbation on Permafrost Carbon Emissions Using a Perturbed Parameters Approach in a Land Surface Model

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Introduction

Permafrost soils in the northern high latitudes (NHLs) contain about half of the world's total soil organic carbon (SOC), which has a potential to be a large carbon source as a consequence of anticipated climate changes. Few studies addressed the role of cryoturbation on future soil organic carbon storage in NHLs. Here we coupled a land surface model, Integrated Science and Assessment Model, with one dimensional soil biogeochemistry (ISAM-1DSB) to examine how the changes in cryoturbation due to changes in the thermal and hydrological regime will affect the NHL permafrost carbon storage under the IPCC RCP8.5 climate scenario.

Rationale

- Deepening of the active layer under climate warming in permafrost regions exposes a substantial amount of deep soil carbon to the open air, enhancing microbial decomposition of soil organic carbon hence cause a positive permafrost carbon climate feedback to accelerate the warming trend.
- Cryoturbation process, that is the displacement of soil during seasonal and/or diurnal freezing and thawing, may damping this feedback (Pinget al., 2015) since:
  - The elongated duration of freezing/thawing under warming may strengthen the frost heave activities, bringing more soil organic carbon (SOC) downward to be stabilized.
  - The increased active layer thickness (ALT) cause more SOC being cryoturbated.

Model Description

ISAM-1DSOC

- ISAM land surface model contains fully coupled biogeophysical and biogeochemical cycles. Recent advancements of the model on representing permafrost hydrology and carbon cycle include:
  - Snow compaction, depth hoar formation and SOC thermal insulation processes to accurately account the soil thermal status and permafrost table depth. (Barman and Jain, 2016)
  - Vertically resolved soil biogeochemistry to account for the vertical movement of SOC and the SOC profile under different long-timescale forces (bioturbation, cryoturbation and sediment deposition) (Shu et al., 2015)
  - Hydraulic impedance of ice and the perched water table to refine the model performance on arctic hydrology and the seasonal wet soil and wetland. (Swenson et al., 2012)
  - Aqueous and gaseous CH_4 and O_2 diffusion, CH_4 production, oxidation and ebullition in the wet soil to consider the preservation of SOC through preventing the aerobic decomposition under the prevailing seasonal anoxic environment in permafrost region. (Shu et al., 2017, in prep)

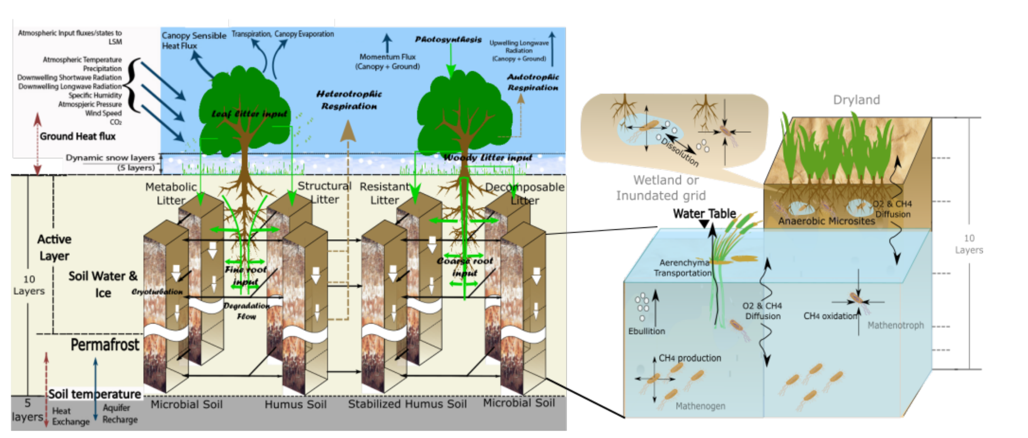

Figure 1: *Schematic diagram of the ISAM model with the extended schemes.*

Representation of Cryoturbation

- Cryoturbation is parameterized as the advective rate in the advection-diffusion equation describing vertical movement of SOC.
- The driver of cryoturbation is the growth of ice lens heaving nearby soil particles, which can be described by Miller's rigid ice lens growth model (O'Neill and Miller, 1985) derived from mass balance equation:

$$V_I = -k\frac{(\frac{\partial\psi_w}{\partial z} - \rho_w g)}{\rho_I g(1 - I_{pore})} \quad (1)$$

  - V_I is the ice growth rate and also the ice lens growth velocity (mm/s)
  - k is the hydraulic conductivity of the soil layer (mm/s)
  - ψ_w is the soil water potential of the corresponding layer (mm)
  - ρ_w and ρ_I are constant water and ice density, respectively
  - g is the gravitational acceleration (kg/m^2) and
  - I_{pore} is the fraction of pore ice in total soil ice
- Ice lens is separated from soil ice and initialized at the same time when start freezing and reset once the soil is completely thawed. We assume 50% of the total soil ice to be initialized as ice lens.

- The linkage between frost heave rate and vertical cryoturbation rate is complicated by the soil structure and the plastic deformation modulus of soil particles. We simply generalize such a linkage through a decay parameter and the cryoturbation can be described as:

$$v = \frac{V_I}{\tau} \quad (2)$$

  - v is the net vertical cryoturbation rate being coupled as the advective rate in the vertical soil movement model (mm/s)
  - τ is the decay parameter and need to be calibrated

Data and Experimental Design

Data

- As shown in Figure 2, five Gelisol radiocarbon profiles (He et al., 2016) are selected to evaluate the modeled SOC storage and soil $\delta^{14}C$ and determine the uncertain range of the decay parameter of cryoturbation rate τ.

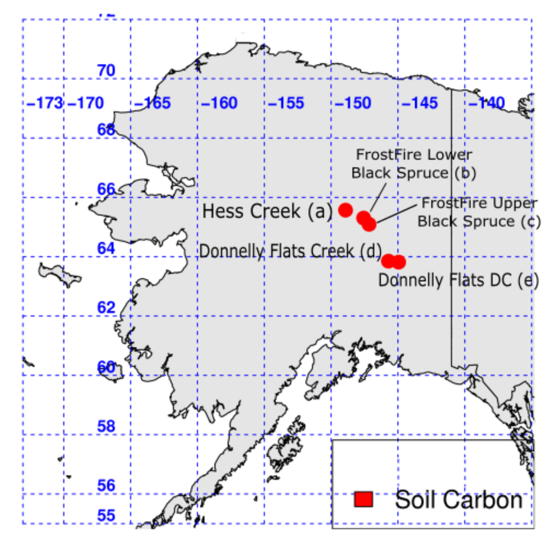

Figure 2: *Location of the sites being used in this study.*

Experimental Design

- ISAM-1DSCOC is set to perform single site spinup for the 5 radiocarbon sites (Figure 2) with all components (biogeophysics, gas diffusion, biogeochemistry and soil vertical movement) with fixed site specific land cover distribution. Soil texture, plant functional type and topographic factor for constraining lateral drainage were used to force the model. The spinup simulation cycled 1500 times with 1901 - 1920 CRU NCEP climate forcing due to the slow turnover of arctic SOC to reach the quasi-equilibrium of SOC storage.
- The historical simulation starts from 1801 till 2013 through forcing model with historical CO_2 concentration, N decomposition and atmospheric $\Delta^{14}C$. In the first hundred years (1800-1899) we randomly pick climate forcing from 1901 to 1920. Starting year 1900 the historical climate forcing data is used.
- The decay parameter for determining cryoturbation rate is evaluated by matching the results of the historical run with observation sampled in the corresponding years.
- For each 14C site four cases of simulations under RCP8.5 scenario were performed from 2006 to 2100: (1) no cryoturbation, (2) using smallest decay parameter (i.e., highest sensitivity of cryoturbation to ice lens dynamics), (3) using calibrated decay parameter for each site, and (4) using largest decay parameter (i.e., lowest sensitivity of cryoturbation to ice lens dynamics). The projected SOC storage will be presented in the result section. The model is forced by the climate forcing data generated from the CESM1.2 RCP8.5 run.

Preliminary Results

SOC Storage of Historical Run

- Comparison shows the model is able to capture the trends of the SOC storage profiles collected at various NHL sites
- Soil samples sites for shrub lands (Figures b and c) have accumulated soil carbon of 7.75 and 7.76 kgC/m^2 that are relatively lower than other sites (20.35, 25.89 and 28.66 kgC/m^2, respectively) due to a strong CO2 fertilization effect and higher turnover of aboveground shrub comparing to boreal forest.

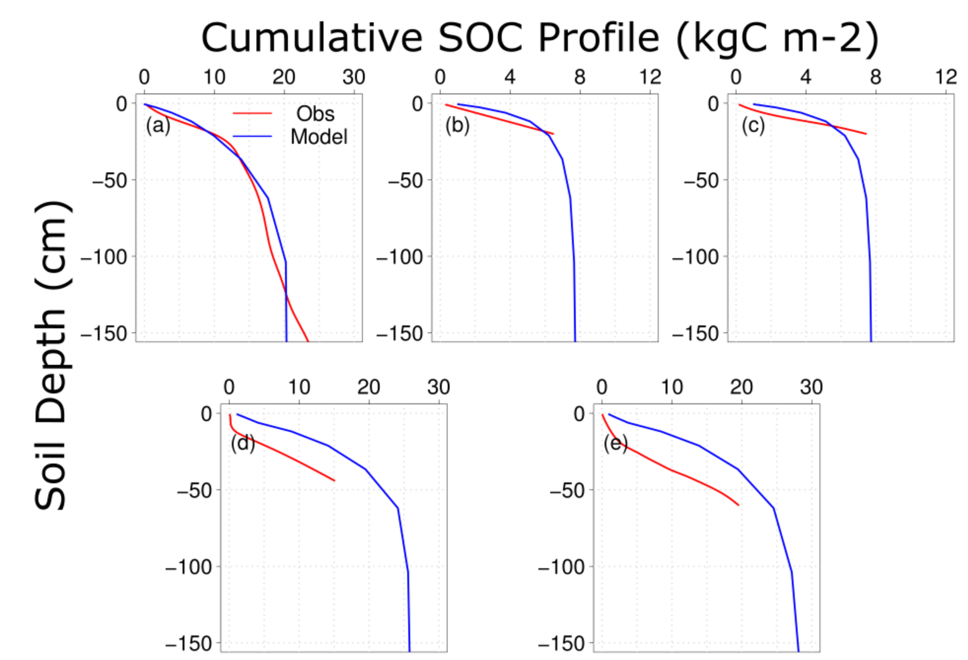

Figure 3: *Comparison of the model estimated cumulative depth distribution of SOC storage with soil sample data for (a) Hess Creek, (b) Frost-Fire Lower Black Spruce, (c) Frost-Fire Upper Balck Spruce, (d) Donnelly Flats Creek and (e) Donnelly Flat DC.*

Radiocarbon Profile

- We implemented an isotopic carbon tracer into ISAM-1DSOC and forced the tracer by the atmospheric $\Delta^{14}C$ compiled from several published studies (Levin and Kromer, 2004; Quan et al., 2013) and calibrated the decay parameter τ (shown for each site).
- The simulated soil $\Delta^{14}C$ from model displays a good match to the general shape of the observed profiles while model tends to estimate a smaller or shallower peak $\Delta^{14}C$ comparing to observation.
- Figure 4(f) shows a set of sensitivity test for site (c) and indicated an overestimation of SOC turnover at the top soil that cannot be adjusted by tuning τ .

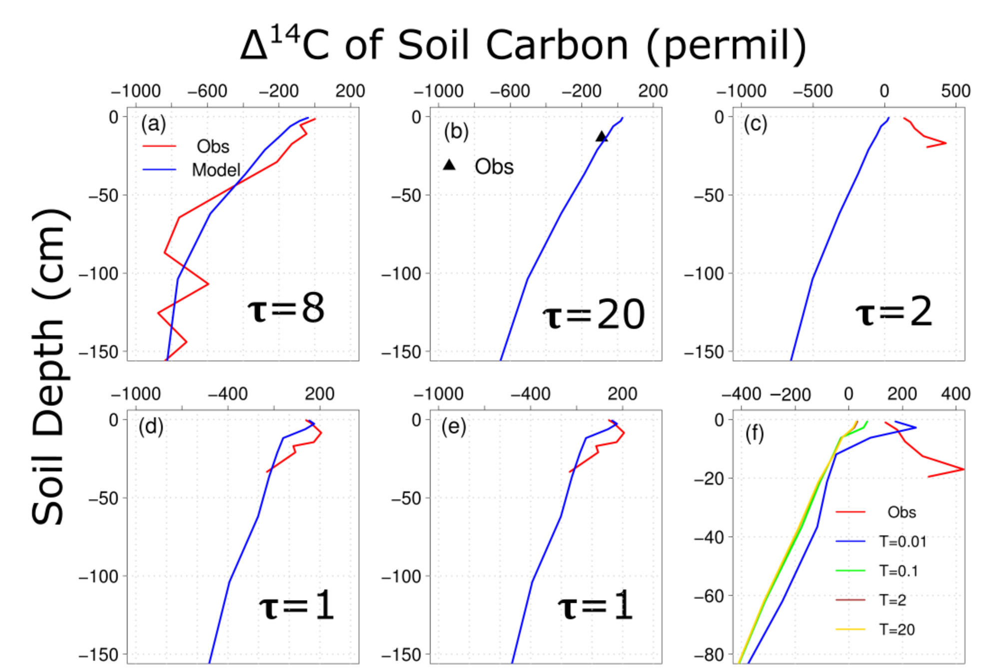

Figure 4: *Comparison of modeled and measured Soil $\Delta^{14}C$ profiles. Subplot (f) shows the model outputs from a series of sensitivity experiments for site (c) by varying the decay parameter.*

Projected SOC storage under RCP8.5 Scenario

- We use τ = 1 as the low decay parameter and τ = 20 as the high decay parameter.
- The change of SOC storage appears to be inconsistent between different sites, with three sites losing soil carbon but sites (b) and (c) gaining a total amount of 2 kgC/m^2 from 2006 to 2100 which mostly due to the strong CO_2 fertilizer effect and the fast turnover speed of shrub.
- The no cryoturbation case (black line) estimates less multi-site mean SOC storgae comparing to the calibrated (red line, 0.15 kgC/m^2) and high (blue line, 0.09 kgC/m^2) cryoturbation cases and approximately the same SOC storage comapring to the low cryoturbation case.
- The effect of cryoturbation on preserving carbon is strongly depend on speciic site, with site (a) shows 0.4 kgC/m^2 difference but only 0.12 kgC/m^2 for site (e). For site (a) the magnitude of the preservation effect is even higher than the total amount of the change of SOC storage (0.27 kgC/m^2 under no cryoturbation case).

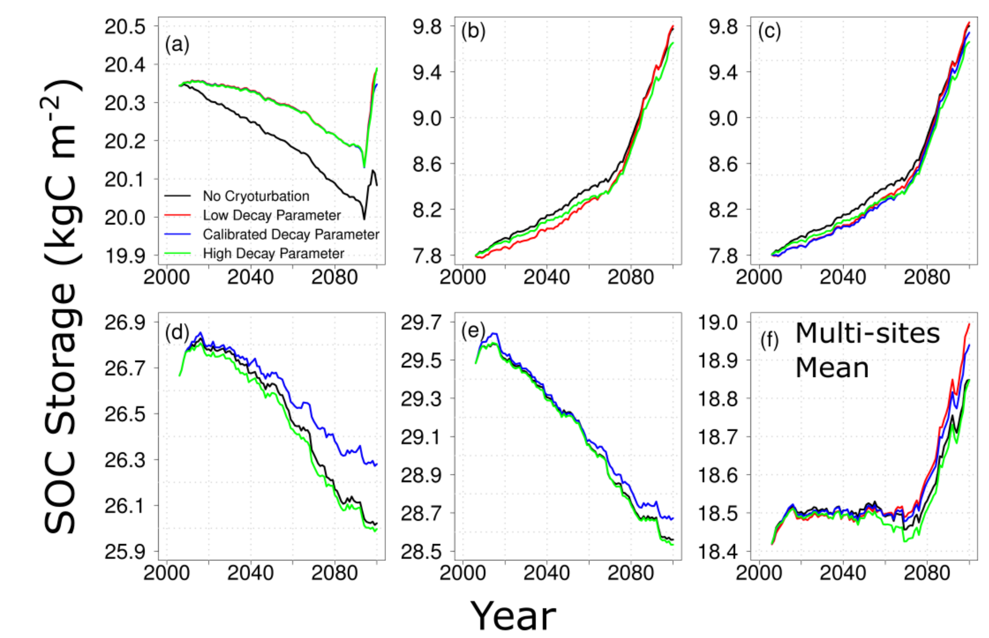

Figure 5: *The projection of SOC storage at each site from 2006 - 2100.*

Summary and Next Steps

- Evaluation of the historical simulation indicates that ISAM-1DSOC is able to reproduce the water table, SOC content profile and its vertical movement after the decay parameters being tuned to capture the site level condition
- Results of the soil $Delta^{14}C$ profile indicate that the decay parameter could vary from 1.0 to 20.0, suggesting a wide range of the cryoturbation rate across the arctic region.
- Sites with peak $\Delta^{14}C$ residing in subsoil can be caused by either the misrepresentation of SOC decomposition or missing processes other than cryoturbation (i.e. the vertical movement caused by freezing and thawing), possible mechanisms including strong bioturbation, the vertical deposition and the lateral transport of dissolved organic carbon.
- The projected SOC storage shows the importance of accounting for the potential damping of cryoturbation to soil carbon loss under RCP 8.5 projection. These results suggests that for global scale the decay parameter could vary with different soil groups.
- A full understanding on the implication of cryoturbation to the climate - carbon cycle feedback is needed for the next step.

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Acknowledgments

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