Thermal and hydrological limitations on modeling carbon dynamics at wetland sites of discontinuous and continuous permafrost extent

Benjamin C. Maglio[1], Ruth Rutter[1], Tobey Carman[1], Colin Edgar[1], Eugénie Euskirchen[1], Hélène Genet[1], Andrew Mullen[2], Valeria Briones[2], Elchin Jafarov[2] & Kristen Manies[3]

[1]*Institute of Arctic Biology, University of Alaska Fairbanks, Fairbanks, Alaska, United States*

[2]*Woodwell Climate Research Center, Falmouth, Massachusetts, United States*

[3]*US Geological Survey, Menlo Park, California, United States*

Abstract

Accurate representation of cryohydrological processes is fundamental for biosphere models, particularly at high-latitudes, given their influence on carbon and permafrost dynamics in carbon-rich peatlands and wetlands. This study analyzes site-level simulations in moist and wet drainage conditions in continuous or discontinuous permafrost regions, using a terrestrial ecosystem model DVM-DOS-TEM. Functional benchmarking was conducted against eddy covariance flux alongside soil temperature, moisture, and thaw depth observations. Thermal and hydrological analysis reveals parameter sensitivity and uncertainty concerning carbon cycling and permafrost dynamics. Flux representation is markedly consistent at sites characterized by continuous permafrost with less seasonal variation, owing to longer soil freezing duration. Sites in discontinuous permafrost, exhibiting active permafrost degradation and talik formation, pose considerable challenges in accurately depicting thaw depth. Underprediction of soil moisture across all sites has more pronounced effects on boreal wetlands characterized by thick organic layers up to 1 m. These results illustrate the limitations of terrestrial ecosystem models to represent environmental and ecological dynamics in wetlands. Attempts to adjust model hydrology have yielded marginal improvements in thaw depth prediction, but revealed large effects of abrupt phase changes for poorly drained sites on discontinuous permafrost. Our analysis suggests the importance of gradual phase change representation, particularly in ice-rich wetlands with thick organic layers, which will be crucial when evaluating the permafrost carbon-climate feedback in model projections.

1 Introduction

Boreal and arctic biomes are climate-sensitive systems whose response to climate warming is dependent on local characteristics, such as drainage conditions and permafrost status (Schuur et al. 2009). Rising soil temperature increases soil carbon loss directly through the response of soil respiration to temperature (Wang et al. 2014) and indirectly through the thawing of permafrost, providing a larger pool of soil organic matter for decomposition (Trucco et al. 2012). However, hydrological regimes can slow respiration rates with increasing saturation levels, particularly in ice-rich permafrost regions, where thaw can increase thermokarst-induced wetland features on the landscape.

The northern permafrost zone may be susceptible to substantial increases in active layer through abrupt thaw of ice-rich permafrost (Hayes et al. 2014). Yet, decomposition temperature dependencies in the boreal region, occurring predominantly over discontinuous permafrost in Alaska, have been shown to be among the most variable (Chen and Tian 2005) which can inhibit the reliability of terrestrial biosphere models. Temperature and decomposition are influenced by soil moisture, thus simultaneous representation of thermal and hydrological processes is required to assess the permafrost carbon-climate feedback, though biosphere models remain uncertain when representing this linkage (McGuire et al. 2018).

In wetlands, higher saturation levels can reduce respiration rates by creating anaerobic environments (Chivers et al. 2009). This effect might be partially offset by relatively higher soil temperatures during the growing season due to modulated surface thermal conductivity and albedo related to subsurface seasonal or permanent inundation (Chapin III et al. 2000). Boreal wetlands in particular contain thick soil organic layers (OLs)—sometimes in excess of 1 m (Jorgenson et al. 1999)—insulating the ground. OL thickness (OLT) is highly coupled to permafrost occurrence and persistence (Johnson et al. 2013). Yet, areas with thick soil OLs and poor drainage conditions (such as peatlands) may experience higher thermal conductivity in thawing permafrost.

To examine linkages between soil cyrohydrology and carbon cycling, we used DVM-DOS-TEM, a terrestrial biosphere model specifically developed for the high latitudes (Raich et al. 1991; McGuire et al. 1992; Tian et al. 1999; Yi et al. 2010; Euskirchen et al. 2009). We estimated soil and vegetation carbon fluxes in a pair of poorly and moderately drained sites in both discontinuous and continuous permafrost regions. We compared simulations of a thermokarst bog and a black spruce permafrost plateau site in boreal interior Alaska (discontinuous), to a wet sedge and an acidic tussock site in the Alaskan arctic tundra (continuous). Through functional benchmarking, this study identified thermal and hydrological processes and parameters that are sources of uncertainty and evaluated model representation of drainage conditions on the linkage

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between permafrost dynamics and ecosystem carbon cycling. With boreal wetland extent predicted to increase under climate warming scenarios (Zhang et al. 2017), interpretation of these processes is required to produce meaningful model predictions.

2 METHODOLOGY

2.1 Field Sites

Field sites selected for model applications were chosen to represent combinations of contrasted drainage conditions (moist versus wet), and permafrost extent (continuous versus discontinuous). To inform model-data comparisons, the sites were also characterized by long-term ecological monitoring, including eddy covariance flux measurement data, and active layer depth (ALD), across similar study periods. Sites in Alaska, fitting these criteria, were found through the ABCFlux database (Virkkala et al. 2021) shown in Figure 1. The pair of moist and wet sites in discontinuous permafrost belong to the Alaskan Peatland EXperiment (Turetsky et al. 2023; Euskirchen et al. 2024) within the Bonanza Creek Long Term Ecological Research (LTER) Experimental Forest in boreal Alaska. The pair of sites included an intermediate to old aged thermokarst collapse-scar bog (BZB) wetland site, and a nearby mature black spruce stand on a permafrost peat plateau (BZS). Detailed descriptions of the boreal sites are provided by (Manies et al. 2017). The pair of sites located in continuous permafrost belong to the Imnavait Creek watershed in Arctic Alaska. The pair is composed of a fen on permanently wet sedge tundra (ICs), and a moist acidic tussock tundra (ICt). BZB and BZS had thick OLs up to 1 m (Manies et al. 2017). ICs and ICt had OLs in the range of 15–35 cm, as described by the Circumpolar Active Layer Monitoring (CALM; Brown et al. 2003) program. Detailed descriptions of the arctic sites are provided by Euskirchen et al. (2012).

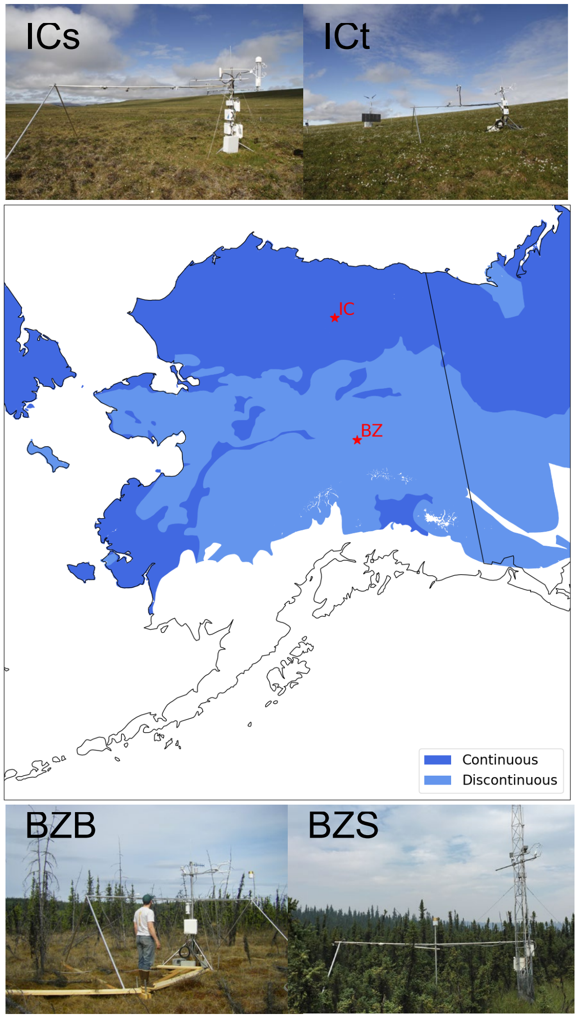

Figure 1. Continuous and discontinuous permafrost extent map (Brown and Melnikov 2002) with Imnavait Creek (IC) and Bonanza Creek (BZ) locations. Photo credits: Sebastien Biraud, Eugenie Euskirchen, Benjamin Maglio.

2.2 Data sources

Monthly flux tower data from 2011–2015 were used at all sites, though some years had missing data at BZS. ALD measurements for ICs and ICt were available through CALM. Observations of ALD at BZB and BZS were synthesized from soil temperature measurements (Turetsky et al. 2014; Manies et al. 2017; Pastick et al. 2018; Neumann et al. 2019; James et al. 2021). Subsequently, ancillary data including soil temperature and moisture at 2 cm depth, was synthesized from the AmeriFlux network (Euskirchen 2022a, b; Euskirchen et al. 2022a, b).

2.3 Model description

We used the Terrestrial Ecosystem Model with Dynamic Vegetation and Dynamic Organic Soil, DVM-DOS-TEM, (Raich et al. 1991; Tian et al. 1999; Yi et al. 2010; Euskirchen et al. 2009) to explore soil physical and biogeochemical dynamics and interactions. DVM-DOS-TEM is a process-based terrestrial biosphere model, specifically developed for high latitude ecosystems. It couples a dynamic organic soil (DOS) module, which relates moss and OL (fibric, humic) carbon stocks and thickness (Yi et al. 2010), with a dynamic vegetation model (DVM) simulating various plant functional types (PFTs) dynamics and competition for light, water and nutrients (Euskirchen et al. 2009). Soil thermal processes are resolved through numerical integration of the 1D heat equation with thaw depth derived from the Stefan algorithm (Yi et al. 2009). Hydrological dynamics are derived using the Richards equation (Zhuang et al. 2002, 2003). Biogeochemical cycling is represented by a monthly nitrogen-constrained carbon-balance representing seasonal and interannual variation, capable of simulating disturbance (e.g., wildfire, logging) and climate warming scenarios (Genet et al. 2013, 2018). Climatic Research Unit (CRU) V4.0 high resolution gridded input forcing data (University Of East Anglia CRU et al. 2019) was used to drive the model at Bonanza and Imnavait creeks respectively.

2.4 Model parameterization

Site-level parameterizations are represented by community types (CMTs)—grouped soil and vegetation-related parameters characteristic of that CMT. Parameter values were determined from observational data, literature review or model calibration. Here, we used existing parameterizations for boreal bog and black spruce peatland for BZB and BZS respectively, and for arctic wet-sedge and tussock tundra for ICs and ICt respectively. Drainage conditions for the boreal bog and arctic wet sedge sites were set to poorly drained conditions. Drainage conditions for the boreal peatland black spruce forest and the arctic tussock tundra were set to moderately-drained conditions. Although appropriate fibric and amorphous OLTs were represented across all simulations, there were distinct differences between the thermal and hydraulic conductivity ranges which could be present between sites due to different saturation levels and peat composition. Both boreal sites were composed of thick sphagnum peat, whereas the Arctic sites were primarily composed of *Carex*-dominated peat soils, both with differing combinations of live and dead, sphagnum and feather moss, providing different thermal and hydraulic conductivity (Letts et al. 2000; O'Donnell et al. 2009). *Carex* dominated peat soils have shown higher bulk density and lower porosity compared to sphagnum dominated soils (Szajdak et al. 2016; Liu and Lennartz 2019). Thus, we defined different thermal and hydraulic conductivity values at Bonanza and Imnavait creek sites respectively, as shown in Table 1, which fell within the large observed ranges.

Table 1. Solid thermal conductivity (λ_{soild}), hydraulic conductivity at saturation (k_{sat}), and OLT for modeled Bonanza Creek (BZB, BZS) and Imnavait Creek (ICs, ICt) sites.

Organic horizon	λ_{soild} [W/m/K]	k_{sat} [mm/s]	OLT (cm)	
Bonanza Creek			BZB	BZS
Moss	0.35	0.0010	2.6	2.3
Fibric	0.37	0.0020	47.1	17.7
Humic	1.90	0.0001	81.4	33.3
Imnavait Creek			ICs	ICt
Moss	0.25	0.0100	~1.0	~1.0
Fibric	0.26	0.0200	11.2	10.3
Humic	0.31	0.0010	14.7	5.4

(Manies et al. 2001) suggested that the thickness of the insulating OL is then an important control on the thermal exchange across sites of different drainage conditions in interior Alaska.

Uncertainty was greater in the hydraulic conductivity (Yi et al. 2009), which was originally parameterized using the saturated hydraulic conductivity based on (Berkowitz and Balberg 1992; Stauffer and Aharony 2017). New values were determined by considering variation in observed von Post humification index from soil cores at BZB and BZS reported by (Manies et al. 2017) compared to synthesized hydraulic conductivity values in sphagnum peat reported by (Letts et al. 2000). From these data a hydraulic conductivity depth profile was constructed in Figure 2. Not only was uncertainty high for these parameters, but due to cryoturbation processes and varying annual soil saturation levels, organic matter was not distributed linearly (increasing decomposition with increasing depth). By comparing these data, we formulated approximate hydraulic conductivity depth profiles at Bonanza Creek and used this to inform the parameters in Table 1. Data were not available at Imnavait Creek, and was estimated from *Carex*-peat literature ranges (Szajdak et al. 2016; Liu and Lennartz 2019).

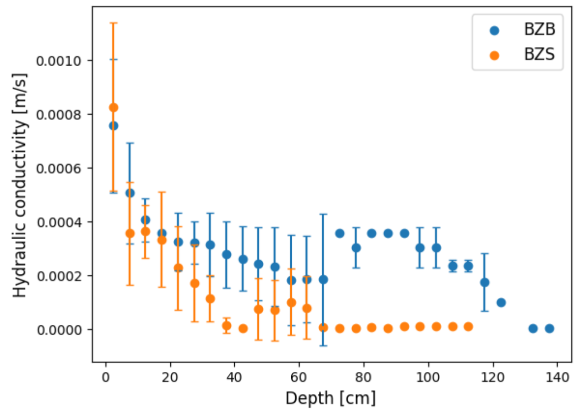

Figure 2. Conversion of observed von Post humification index at BZB and BZS (Manies et al. 2017) with synthesized hydraulic conductivity values from (Letts et al. 2000).

2.5 Model development

Adjustments to the DVM-DOS-TEM hydrology model were also considered at wetland sites (ICt and BZB), as site-level simulations have been shown to demonstrate high variability (Ekici et al. 2015) requiring more precise information on spatially explicit processes local to particular sites. BZB, the collapse-scar bog site, is hydrologically isolated and sits lower than surrounding black spruce permafrost plateaus (BZS; Wickland et al. 2006). Runoff losses were thus removed and additional input, representing surface drainage from raised forested plateau, was added. Runoff input for the bog was set to equal to the runoff simulated for the permafrost plateau black spruce forest site. Although ICs has poor drainage, it is not hydrologically isolated, instead fed by gradual subsurface flow (Connon et al. 2014), hence only surface runoff losses were removed.

2.6 Model simulation and benchmarking

To study model representation of thermal and hydrological regimes, we conducted simulations of a 100-year pre-run using constant climate based on computed monthly averages between 1901–1930 to determine biophysical state variables. Secondly, a 1000-year equilibrium stage initiated with the results of the pre-run, and using the same average climate forcing as the pre-run was conducted to determine biogeochemical state variables. This was followed by a 250-year spinup using a cyclical but varying climate forcing from the 1901–1930 period. Finally, a transient simulation initiated with information from the spinup run, of historical data up to the end of our study period (2015).

At monthly intervals gross primary production (GPP), autotrophic respiration (RA; i.e., summed maintenance respiration (RM) and growth respiration (RG)), and heterotrophic respiration (RH) were computed (Tian et al. 1999; Euskirchen et al. 2009). GPP was computed based on air temperature from climate forcing, though can be indirectly related to soil temperature through sensible heat exchange. It is indirectly affected by soil moisture through evapotranspiration functions. RM is directly related to soil temperature based on an empirical exponential relationship scaled by a calibrated per-gram-biomass respiration rate at 0°C, and indirectly to soil moisture based on modulation of thermal conductivities. RG equated to a 20% difference between GPP and RM. RH is affected by soil temperature through an empirical exponential relationship and proportional to a nonlinear function of soil moisture based on observed minimum, maximum, and optimum values. Ecosystem respiration (RECO = RH + RA) was calculated and used to find net ecosystem exchange (NEE = RECO - GPP). Thus, functional relationships (Luo et al. 2012) were created between GPP, RECO and soil temperature and moisture to assess model representation of carbon dynamics. Both modeled and measured data were analyzed to benchmark these behaviors. At wetland sites, simulations were run a second time with altered hydrology previously described.

3 Results

GPP, RECO, and NEE more closely matched observations, particularly in shoulder seasons, for continuous permafrost sites in Figure 3 with consistently lower root mean squared error (RMSE). The moist site (ICt) outperformed the wet site (ICs) in each instance.

GPP and RECO were underestimated at BZS and overestimated at BZB. The underestimation of fluxes at BZS offset one another and provided reasonable prediction of NEE at BZS with RMSE against observations closely following ICt for years with data. Variations to model runoff showed little effect for GPP at ICs and BZB (Figure 3). There were small increases for ICs and small decreases for BZB in RECO with decreased runoff respectively. This led to only minor variation in the magnitude and seasonal patterns of NEE at BZB and ICs. There was good representation of soil temperature in Figure 4, particularly during the winter at continuous permafrost sites, though maximum summer temperatures were overpredicted at all sites.

BZS demonstrated fairly good consistency with observed thermal regimes. BZB represented summer maximum temperatures well, but significantly underpredicted winter temperatures. Model hydrology changes increased winter temperatures at ICs, more closely matching observations for some years, but had little effect on summer temperatures. At BZB the increased hydrological input modulated both summer and winter temperatures with better representation to observations, though winter temperatures were still underpredicted.

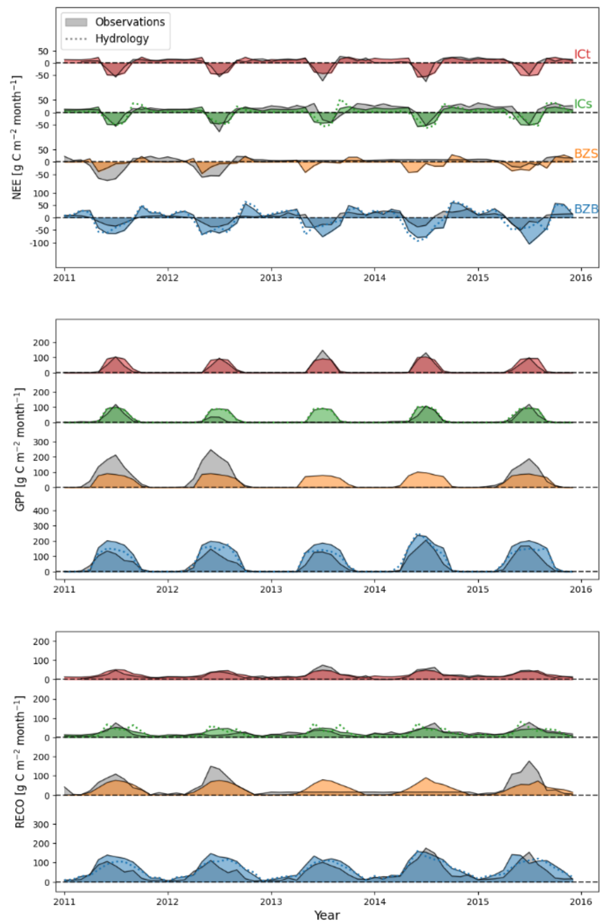

Figure 3. Observed and simulated monthly NEE, GPP and RECO.

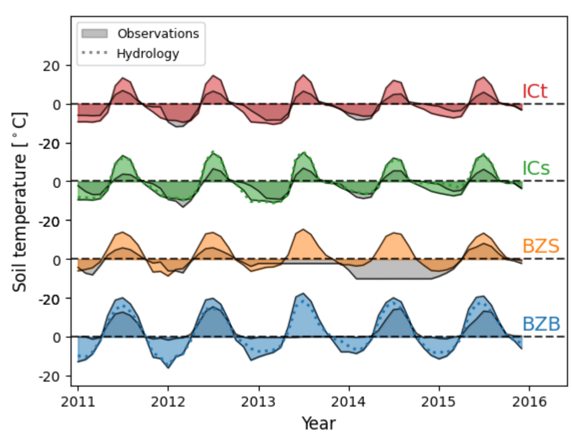

Figure 4. Observed and simulated monthly soil temperature at 2 cm depth.

Figure 5 showed soil moisture at 2 cm depth. Soil moisture was underpredicted compared to observations at every site, though BZB showed the closest representation to observations prior to variations in the hydrological model. Nevertheless, the higher soil moisture recorded at the end of 2015 was only matched when these changes were made. There was also a zeroing of soil moisture at all sites during the winter with and without hydrological changes. The effects described in Figures 4 and 5 were further conveyed by the ALD in Figure 6. Observations at BZB were not shown as this site was thermokarst and ALD was > 1.5 m showing the greatest underprediction. Observations from 2011–2015 showed BZS undergoing active permafrost degradation. The amount of permafrost was overpredicted at each site with the exception of ICt and ICs for the first two years, with ICs showing a slight increase of mean ALD compared to ICt. Hydrological model changes showed improvements at BZB and ICs, though BZB remained significantly lower than 1.5 m.

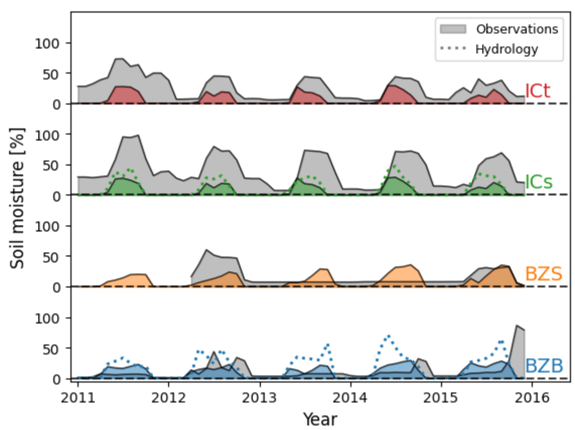

Figure 5. Observed and simulated monthly soil moisture content at 2 cm depth.

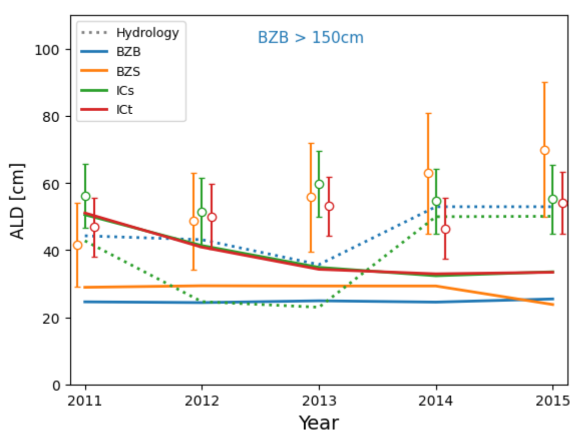

Figure 6. Observed and simulated ALD. Mean and standard deviation of ALD measurements are shown as points and error bars respectively.

Figures 7 and 8 show the functional relationship between soil temperature at 2 cm depth for GPP and RECO respectively. This relationship is best captured at continuous permafrost sites, though higher temperatures were reached in the simulation. GPP and RECO were underpredicted at BZS and overpredicted at BZB, during the summer with the highest temperatures reached at BZB. Hydrological changes had little effect at ICs, but increased maximum GPP, and RECO, while marginally reducing maximum temperatures at BZB. Figures 9 and 10 show the functional relationship between soil moisture at 2 cm depth with GPP and RECO respectively. Hydrological model changes extended simulated deeper soil moisture closer to the observed range at BZB but still underestimated all sites, with the zeroing effect shown by a clustering of points in Figures 9 and 10.

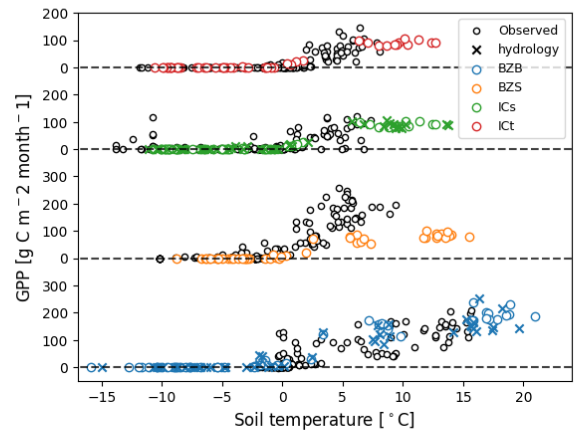

Figure 7. Observed and simulated monthly soil temperature at 2 cm depth versus GPP.

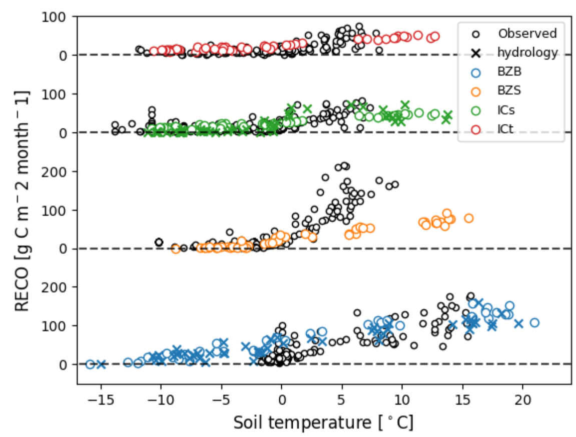

Figure 8. Observed and simulated monthly soil temperature at 2 cm depth versus RECO.

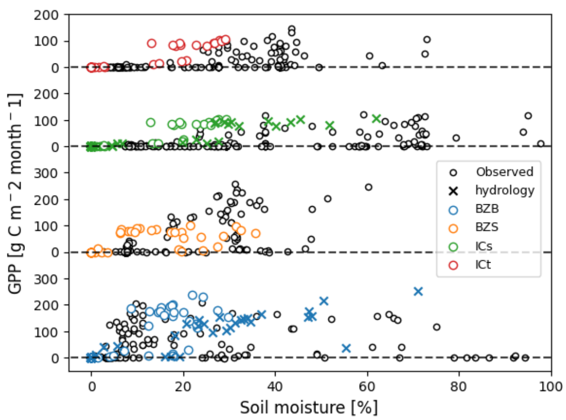

Figure 9. Observed and simulated monthly soil moisture at 2 cm depth versus GPP.

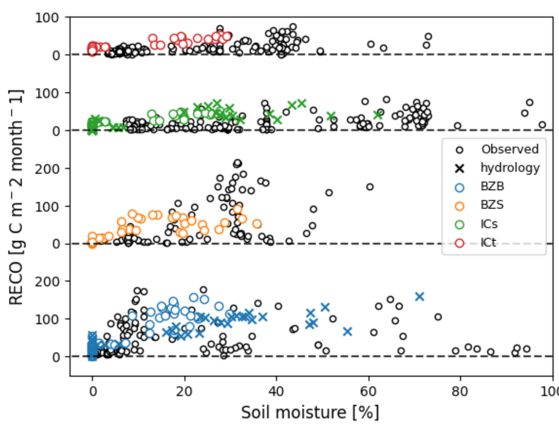

Figure 10. Observed and simulated monthly soil moisture at 2 cm depth versus RECO.

There was an increase in the range for ICs but did not surpass ~60%. The variation in predicted NEE was highest at BZB, with BZS marginally underpredicted in the summer and ICs in the winter, but with ICt showing reasonable representation across all seasons. While changes to model hydrology provided benefits in matching the observed range of soil moisture, particularly in the bog, the zeroing of winter soil moisture strongly impacted ALD prediction.

4 Discussion

We performed four site-level simulations using DVM-DOS-TEM, with paired moist and wet drainage conditions in continuous and discontinuous permafrost regions. Site-level simulations using biosphere models typically encounter large variation (Ekici et al. 2015) yet remain an integral part of benchmarking to evaluate limitations, sensitivity, and uncertainty (Mahecha et al. 2010; Ekici et al. 2014). Understanding these limitations is important when expanding simulation models to regional scales, as uncertainties may be amplified leading to misclassification of carbon sources and sinks.

Our study revealed reductions in model performance as thermal and hydrological complexity increased. Sites on continuous permafrost performed best, which was attributed to longer soil freezing duration. Soil temperatures were overpredicted at both sites of continuous permafrost for seasonal peaks with higher calculated rates of change, suggesting abrupt model phase changes. Soil moisture was significantly underpredicted for both sites, with changes to the hydrological model at ICs yielding only marginal improvements to carbon fluxes with a more variable, yet not significantly improved ALD. Depth profiles of soil moisture at continuous permafrost sites were unavailable, though may help determine hydrology influencing ALD in deeper soil layers. Modeled fluxes at sites underlain by discontinuous permafrost had greater deviation from observations, with GPP and RECO underpredicted at BZS and overpredicted at BZB. Seasonal temperature variation was captured well at BZS with soil moisture more closely matched (for years with data) than other sites. Fluxes were overpredicted at BZB, with changes to the hydrological model but showing some benefits across the study period. Summer soil temperatures were predicted well for BZB though winter temperatures were up to 18°C colder than observed suggesting the largest impact of this abrupt phase change.

Soil moisture at BZB appeared to be significantly overpredicted at 2 cm depth, particularly after changes to the hydrological model, though this improved the mean soil moisture content at deeper layers. This suggests total hydrologic inputs may not be correctly represented without our changes. ALD was underpredicted at both discontinuous sites, while the hydrological model changes did improve outputs for BZB this came at the expense of worsening flux estimates prior to calibration of carbon cycle associated parameters. These sites present complex but important dynamics for modeling, including active permafrost degradation shown in Figure 9 at BZS and indication of a deepening talik at BZB from soil temperature profiles down to 240 cm taken during and after our study period (Turetsky et al. 2014; Manies et al. 2017; Pastick et al. 2018; Neumann et al. 2019; James et al. 2021). Additionally, both sites contained thick sphagnum peat, which can insulate permafrost, but with recent soil moisture measurements up to 80% at 30 cm depth, the thermal regime will be strongly modulated. There was zeroing of soil moisture shown in the time series in Figure 5 and clustering of points in Figure 10. This indicates that latent heat processes are occurring too fast, with abrupt transition from liquid water to ice. Hence thermal moderation from water in the soil during freeze-up is lost and significantly lower temperatures are predicted. Ultimately, this causes underprediction of the ALD and appears most prominent at BZB with larger water inputs and OLT.

The thermal and hydrological regimes, particularly at BZB, offer some insight into where model predictions can be enhanced. It is evident that thermal and hydraulic parameterization plays a role in permafrost carbon dynamics though changes to these and the underlying hydrological model may not necessarily have effects on both in the same direction nor by a high enough magnitude. Carbon fluxes are highly sensitive to parameters which are difficult to measure, so highly uncertain, therefore requiring preliminary calibration. If soil thermal and more importantly hydrological conditions are not representative prior to or as part of this calibration it is unlikely that both permafrost and carbon dynamics will be appropriately captured simultaneously. This elucidates the importance of a stringent model calibration process alongside initial thermal and hydrological parameterization. Due to a dearth of hydraulic data, it is of utmost importance to develop parameterizations informed by soil profile measurements where available and drawing relationships between observed soil properties. However, once evaluated, additional thermal and hydrological processes may be needed to provide a more realistic representation of particular ecosystems. For example, the need to capture unfrozen water to accurately represent winter temperatures either through pore water content (Romanovsky and Osterkamp 2000) or through latent heat consideration (Hinzman et al. 1998). It may also be useful to extend the soil column depth to capture sufficient thermal inertia (Lawrence et al. 2008). Interannual variability is expected to be higher in the discontinuous permafrost with greater influence on subsurface water pathways (Walvoord and Kurylyk 2016) and advective heat transport (Neumann et al. 2019) which remain difficult to capture in biosphere models. The calibration approach present in many of these models focuses on the carbon cycle but does not effectively couple thermal and hydrological processes to provide accurate representation of the full system, which is necessary for more robust and reliable ecosystem models.

5 Conclusions

Site-level simulations were performed for areas with continuous and discontinuous permafrost extent and with differing soil saturation levels. Carbon fluxes, active layer depth, soil thermal and hydrological estimates best matched observations at areas of continuous permafrost extent due to a reduction in system complexity. Sites with higher soil moisture content performed worse, with changes to the hydrological model marginally improving active layer calculations. However, soil moisture zeroing at the beginning of winter revealed the rapidity of simulated freeze up suggesting losses in latent heat. This appears to be particularly important in boreal wetlands for capturing deeper permafrost tables and talik development.

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