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Changes in precipitation and air temperature contribute comparably to permafrost degradation in a warmer climate

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Abstract
Surface energy budgets of high-latitude permafrost systems are poorly represented in Earth system models (ESMs), yet permafrost is rapidly degrading and these dynamics are critical to future carbon-climate feedback predictions. A potentially important factor in permafrost degradation neglected so far by ESMs is heat transfer from precipitation, although increases in soil temperature and thaw depth have been observed following increases in precipitation. Using observations and a mechanistic ecosystem model, we show here that increases in precipitation hasten active layer development beyond that caused by surface air warming across the North Slope of Alaska (NSA) under recent and 21st century climate (RCP8.5). Modeled active layer depth (ALD) in simulations that allow precipitation heat transfer agreed very well with observations from 28 Circumpolar Active Layer Monitoring sites ($R^2 = 0.63; \text{RMSE} = 10 \text{ cm}$). Simulations that ignored precipitation heat transfer resulted in lower spatially-averaged soil temperatures and a 39 cm shallower ALD by 2100 across the NSA. The results from our sensitivity analysis show that projected increases in 21st century precipitation deepen the active layer by enhancing precipitation heat transfer and ground thermal conductivity, suggesting that precipitation is as important an environmental control on permafrost degradation as surface air temperature. We conclude that ESMs that do not account for precipitation heat transfer likely underestimate ALD rates of change, and thus likely predict biased ecosystem responses.

1. Introduction
The permafrost region stores more than twice as much carbon as currently in the atmosphere (Zimov et al 2006, Ping et al 2008, Schuur et al 2008). Over the past few decades, rapid thawing of the permafrost and increases in the active layer depth (ALD; maximum annual thaw depth) have been reported in response to near-surface air warming and increases in precipitation across the high-latitudes of the northern hemisphere (Brown and Romanovsky 2008, IPCC 2013). These rapid permafrost changes could affect the atmosphere and climate system through effects on the carbon cycle (Davidson and Janssens 2006, Schuur et al 2008, Nowinski et al 2010, Commane et al 2017, Turetsky et al 2020), surface water, and energy balances (Schuur et al, 2015, Stiegler et al 2016). Permafrost thaw is also projected to increase under projected warmer climate (Zhang et al 2008, Koven et al 2015).

The magnitude and direction of permafrost carbon-climate feedbacks are major sources of uncertainty in Earth system models (ESMs) (Burke et al 2013, Koven et al 2015), at least partially because many interacting factors affect active layer development. The surface energy balance, which is affected by surface air temperature and precipitation (Grant et al 2017b), drives freezing and thawing in snow, surface organic residue, and soil layers. Near-surface air warming can warm the soil and thereby increase thaw depth (Smith et al 2005, Natali et al, 2011). Increases in snow accumulation during winter may insulate the
soil, thus increasing soil temperatures (Schimel et al 2004, Lafrenière et al 2013).

Increases in soil temperature and thaw depth have been observed following higher precipitation events (Wright et al. 2009, Guan et al. 2010, Iijima et al. 2010, Kokelj et al. 2015, Douglas et al. 2020) from heat advection and wetter soils that increased thermal conductivity (Hinzman et al. 1991). This mechanism is particularly important since most climate models are projecting overall increases in precipitation across the Arctic (IPCC 2013) and increases in the rain vs. snow ratio under warmer climate (Bintanja and Andry, 2017, Räisänen 2008). Projected changes in Arctic tundra precipitation may alter surface and subsurface energy and water exchanges and thus affect the soil temperature and ALD in permafrost regions (Iijima et al. 2010). With observed increases in permafrost degradation (Brown and Romanovsky 2008, IPCC 2013) under warmer climate, the relative importance of changes in precipitation vs. air temperature in controlling permafrost thaw has not been systematically explored. A potentially important factor in permafrost degradation neglected so far by ESMs is heat transfer from precipitation (Kollet et al. 2009).

Here, we applied a mechanistic ecosystem model, ecosys (Grant et al. 2017b), to examine (1) how changes in precipitation affect the ALD modeled under recent and future climate and (2) the relative importance of changes in surface air temperature and precipitation on permafrost degradation in the continuous permafrost zone (Brown et al. 2002) (>90% of the area underlain by permafrost) of the North Slope of Alaska (NSA). Ecosys has been rigorously tested against observations from many high-latitude sites and large-scale remote sensing (supplementary I methods (stacks.iop.org/ERL/16/024008/mmedia)). Recently, the model was tested against observations to study temperature and precipitation effects on active layer development (Grant et al. 2017b, 2019) in polygonal tundra at Utkiagvik, Alaska; ALD and CO2 exchange as affected by hydrology in Arctic mixed tundra and fen (Grant et al. 2015, Grant 2015) at Daring Lake, Canada; and in permafrost peatlands in a subarctic site in Sweden (Chang et al. 2019). The model represents fully coupled biological and hydrological processes with vertical and lateral transfers of water, heat, solutes, and gases. Coupled surface energy and water exchanges drive soil heat and water transfers.

2. Methods

Ecosys is an hourly time step model with multiple canopy and soil layers. The model represents fully coupled transformations of soil carbon, nitrogen, and phosphorus through microbially driven processes. A detailed description of inputs, parameters, and algorithms used in ecosys can be found in Grant (2001), and supplementary information II. Below we present a brief model description most relevant to modeling the effects of surface air temperature and precipitation on ALD and net ecosystem energy exchange.

2.1. Energy balance

Surface energy exchange is calculated from first-order closure of surface energy balances for net radiation, latent heat, sensible heat, and soil heat. Surface and subsurface energy and water exchanges drive soil heat and water transfers to determine soil temperatures and soil water content in multiple soil layers (Grant 2004). These transfers drive soil freezing, thawing, and temperature in the snowpack, surface litter, and soil layers (Grant et al. 2019). Changes in ground ice content are used to calculate ALD, modeled from the general heat flux equation (Grant et al. 2017b). Atmospheric warming increases precipitation heat, soil heat transfers, and hence ALD. Net radiation is calculated from boundary inputs for shortwave and longwave radiation using set values for albedo and emissivity of the different surfaces. Latent heat and sensible heat are modeled from surface atmosphere vapor density and temperature gradients and driven by boundary inputs for shortwave radiation, air temperature, wind speed, and humidity and from canopy stomatal and ground surface resistances driven by canopy water potential and soil water potential maintained from precipitation versus evapotranspiration and lateral flows. Surface energy exchange drives conductive heat transfers from temperature gradients and from snow and soil thermal conductivities. These combined transfers drive latent heats of freezing and thawing using the general heat flux equation and hence drive active layer development.

2.2. Phenology

The model represents basic plant functional type-specific traits that are known to differ among plants (Mekonnen et al. 2018b). These traits drive modeled differences in carbon and nutrient investment and retention strategies in leaves, stems, and roots and control high-latitude vegetation competition under a changing climate. Phenological changes (leafout and leafoff (deciduous plants) or dehardening and hardening (evergreen plants)) are determined by accumulated exposure to temperatures above set values while day length is increasing or below set values while day length is decreasing. Senescence is driven by excess maintenance respiration and by phenology in deciduous plant functional types.

Carbon uptake is controlled by plant water status calculated from convergence solutions that equilibrate total root water uptake with transpiration. Canopy temperatures affect CO2 fixation rates due to their effects on carboxylation and oxygenation modeled with Arrhenius functions for light and dark reactions. Soil temperatures affect heterotrophic
respiration through the same Arrhenius function as for dark reactions. Carbon uptake is also affected by plant nitrogen uptake. Soil warming enhances carbon uptake by hastening microbial mineralization and root nitrogen uptake.

### 2.3. Simulation design

We conducted modeling experiments to test the effect of precipitation heat transfer on ALD development under recent and future climates across the NSA. The reasons we chose the NSA spatial domain for this modeling experiment are (1) the region is a continuous permafrost zone with >90% of the area underlain by permafrost (Brown et al 2002); (2) the region has the highest density of Circumpolar Active Layer Monitoring (CALM) sites; and (3) a data-constrained regional active layer dataset is available (Nicolsky et al 2017), allowing a rigorous testing of the model.

The model was initialized with (1) prescribed seed densities of five plant functional types (deciduous shrubs, evergreen shrubs, sedge, moss, lichen) across the simulation spatial domain and (2) soil attributes obtained from the Unified North America Soil Map (clay and sand fraction, pH, cation exchange capacity, bulk density) and the Northern Circumpolar Soil Carbon Database (soil organic carbon) across vertical soil profiles. The model was forced with temporally dynamic climate, atmospheric CO2 concentrations, and nitrogen deposition from 1800 to 2100. Climate forcing (surface air temperature, precipitation, incoming shortwave radiation, relative humidity, and wind speed) from 1979–1988 was taken from the North American Regional Reanalysis (NARR) (Wei et al, 2014) and cycled through 1800–1978. The full NARR time series was used to force the model from 1979 to 2010. Field measurements of precipitation temperature are rare (Kollet et al 2009), but have been reported to be close to the ambient near surface air temperature (Byers et al 1949). In this study we assumed the temperature of NARR precipitation to be the same as ambient near surface air temperature.

All model inputs were gridded to 0.25° × 0.25° spatial resolution. Twenty-first century climate forcing was derived from the RCP8.5 scenario ensemble projections downscaled and averaged across 15 CMIP5 models (Wang et al 2016). We chose the RCP8.5 climate scenario because the current trend of global carbon emissions from 2006 to 2017 is increasing at a rate that is broadly consistent with this high emissions scenario.

We conducted seven 25 km resolution simulations from 1800 to 2100 to partition the impacts of heat transport from precipitation and surface air warming on modeled ALD (supplementary I table 1). First, we conducted simulations which (S1) allow (baseline) and (S2) ignore precipitation heat transfer, while keeping all other model inputs (i.e., soil properties, plant and microbial traits, and other climate variables (incoming shortwave radiation, wind speed and humidity)) the same. These sets of simulations were used to examine the effects of precipitation heat transfer on modeled thaw depth. Four sensitivity simulations were conducted to test the relative effects of changes in 21st century surface air temperature and precipitation on modeled thaw depth: (S3) maintaining the historical temperature time series but using 21st century precipitation with precipitation heat transfer; (S4) maintaining the historical temperature time series but using 21st century precipitation without precipitation heat transfer; (S5) maintaining the historical precipitation time series but using 21st century temperature with precipitation heat transfer; and (S6) maintaining the historical precipitation time series but using 21st century temperature without precipitation heat transfer (supplementary I table 1). Finally, we conducted one more simulation (S7) using the highest trend precipitation scenario from the 15 CMIP5 models to assess the sensitivity of our results to uncertainty in 21st century precipitation projections.

The extent to which the ALD is changing in the permafrost regions in response to recent changes in temperature and precipitation has been monitored across several Circumpolar Active Layer Monitoring (CALM, www2.gwu.edu/~calm/data/north.html) observational sites. Thus, we tested the model against 28 CALM sites across the NSA. Where more than one CALM site exists within the model grid cell boundary, average values within the grid cell were used to compare with the model output. We used the gradient boosting machine (GBM; (Friedman 2001)) approach to test the non-linear relationships and relative importance of precipitation and surface air temperature from NARR grids on modeled and measured ALD at the 28 CALM sites.

### 3. Results and discussion

#### 3.1. Model testing

In addition to the extensive high-latitude ecosys evaluations described in supplementary I, we further tested model performance here against ALD measurements from 28 CALM sites across the NSA. At site scale the modeled ALD agreed very well with the CALM observations (figure 1(b); R² = 0.63; RMSE = 10 cm). Further, the spatial distribution of the modeled ALD across the NSA compared very well against regional scale data-derived ALD values (Nicolsky et al 2017) (Geographically weight regression, GWR, R² = 0.68) aggregated to 25 km resolution for consistency with model simulations (figure 1(a), (b)).

#### 3.2. Effects of precipitation heat transfer on ALD

In our regional scale NSA baseline simulation (S1), climate warming and changes in precipitation over the 21st century increased modeled spatially averaged daily maximum 0–100 cm soil temperature by 4.2 °C between years 2010 and 2100 (figure 2(a)). Warmer
Figure 1. Modeled ALDs agreed very well with measurements at site and regional scales. The baseline simulation (with precipitation heat transfer) was used to test the model. Modeled spatially distributed (a) and NSA average (b) ALD agreed very well with data-derived (Nicolsky et al 2017) (2006–2010) average values aggregated to 25 km spatial resolution (Geographically weight regression, GWR, R² = 0.68) and to measurements from 28 CALM sites from 1990 to 2018 (c; R² = 0.63; RMSE = 10 cm). Pink asterisks in panel (a) indicate the locations of CALM sites and the corresponding model grid cells for the comparisons. The error bars in panels (b) and (c) represent one standard deviation and the boxes in panel (b) represent 25th and 75th percentile bounds.

Figure 2. Precipitation heat transfer resulted in warmer soils and deeper active layers. Modeled NSA spatially averaged daily maximum 0–100 cm soil temperature (a) and ALD (b) in simulations with and without precipitation heat transfer. Lower soil temperature simulated without precipitation heat transfer led to ALD reductions of ~39 cm in year 2100. Spatially averaged 0–100 cm depth soil temperatures were modeled to be 1.1 °C and 2.0 °C colder in years 2010 and 2100, respectively, when ignoring precipitation heat transfer compared to the baseline (figure 3(a)).

Although the lack of heat transfer from precipitation led to an ALD reduction of 11 cm in year 2010 compared to baseline (figure 2(b)), we modeled an increase of 52 cm between years 2010 and 2100 (41–93 cm). This increase in ALD in the absence of heat from precipitation was mainly attributed to increases in surface air temperature that elevated soil temperature, and from greater thermal conductivity of wetter soils and thus greater heat conduction. Melting ground ice during thawing of permafrost further increases soil wetness and thus soil thermal heat conductivity, although melting ice requires energy. Ignoring heat transfer resulted in a reduction in spatially averaged ALD both under current and 21st century precipitation (figure 2(b)). However, the overall reductions in modeled ALD in the simulation without vs. with precipitation heat content increased with increasingly warmer climate (11 cm in year 2010 vs. 39 cm shallower ALD by year 2100).

Relevant to this study, rapid increases in soil temperature following precipitation were observed in our recent high temporal resolution measurements at the Bonanza Creek site in Alaska (supplementary I figure 1). The measurements show variations in soil moisture and temperature before and after precipitation events at 0.19 m, 0.36 m, and 0.54 m soil depths. Unlike the soil in the top 0.19 m that showed rapid increase in soil moisture during the precipitation events, there were only slight changes in soil moisture at 0.36 m and 0.54 m soil depth, thus maintaining the initial soil thermal conductivity (supplementary I figure 1). However, rapid increases in soil temperature were shown in all three soil
Table 1. Spatially averaged modeled ALD (cm) in the sensitivity simulations with changes in surface air temperature ($T_a$) and precipitation ($P$) in years 2010 vs. 2100 across the North Slope of Alaska.

| Year  | With precipitation heat transfer | Without precipitation heat transfer |
|-------|----------------------------------|------------------------------------|
|       | Increase in $T_a$ and $P$ (S1)    | Increase in $P$ and constant $T_a$ (S3) | Increase $T_a$ and constant $P$ (S5) | Increase $T_a$ and $P$ (S7) |
|       | Increase $T_a$ and constant $P$ (S2) | Increase $T_a$ and constant $P$ (S6) |
| 2010  | 52                               | 52                                 | 52                                 | 40 |
| 2100  | 132                              | 70                                 | 99                                 | 140 |
| Change in ALD (2100–2010) | 80                               | 18                                 | 47                                 | 88 |

$^a$21st century (2010–2100) $T_a$ (surface air temperature) and $P$ (precipitation) from mean of 15 CMIP models (Wang et al. 2016).

Figure 3. Increases in modeled ALD caused by increases in surface air temperature and precipitation across the North Slope of Alaska. Spatially-averaged modeled ALD in simulations (a) with and (b) without precipitation heat transfers and increased precipitation while keeping 21st century (years 2010–2100) surface air temperature constant (S3 and S4), increased surface air temperature while keeping the precipitation constant (S5 and S6), and the combined effects of increased precipitation and surface air temperature (S1 and S2), which hasten permafrost degradation beyond that caused by each forcing alone.

layers, suggesting downward advective heat flux from increased soil moisture in the surface soil layer. These measurements indicate that soil wetting from precipitation abruptly increased soil temperature as a result of enhanced downward heat fluxes through heat conduction and advection. The measurements are consistent with recent conclusions that transfer of heat from precipitation further hastens permafrost degradation (Grant et al. 2017b) beyond that caused by surface air warming (Wright et al. 2009, Guan et al. 2010, Grant 2013), thus leading to greater changes in subsurface thermal and biogeochemical dynamics in permafrost regions. Overall, precipitation affects soil moisture, which has been shown in several studies to have strong relationships with thaw depth, although the effects may vary with site conditions (Nelson et al. 1997, Miller et al. 1998, Hinkel and Nelson 2003, Wollschläger et al. 2010, Grant et al. 2017b).

3.3. Relative importance to ALD of air temperature and precipitation

Permafrost degradation rates under future climate depend on changes in both surface air temperature and precipitation. A simulation (S5) with increases in surface air temperature while maintaining historical precipitation resulted in a 47 cm increase in ALD from years 2010 to 2100 (figure 3; table 1). In contrast, the simulation with increased precipitation and historical surface air temperature (S3) resulted in an 18 cm increase in ALD by year 2100. This result shows that projected changes in the magnitude of high-latitude precipitation, which vary with climate models (IPCC 2013), may be an important control on active layer development. To test the uncertainties in projected trends in 21st century precipitation on the extent of active layer deepening, we modeled that the highest vs. the mean 21st century precipitation trend of the 15 CMIP5 models (S7) resulted in an 8 cm deeper spatially-averaged ALD by year 2100 (supplementary figure 2). Warmer climate increased the precipitation heat content which contributed to further deepening of the active layer. The separate effects on ALD of relative increases in air warming, precipitation heat content, and heat conduction from wetter soil under 21st century climate are partitioned in the sensitivity simulations described below.

The sensitivity simulation forced with 21st century warming and historical precipitation in the absence of precipitation heat content (S6) increased the ALD by 37 cm, which we attribute to the effect
of air warming on soil temperature (table 1). In contrast, the simulation with increasing 21st century precipitation in the absence of warming and precipitation heat content (S4) increased the ALD by only 2 cm. This slight increase in ALD with precipitation in the absence of future warming is mainly attributed to more thermally conductive soils because of wetting (Hinzman et al. 1991) that enhance downward soil heat fluxes. The combined effects of 21st century surface air warming and precipitation, but ignoring precipitation heat content, enhanced heat conduction from wetter soils and increased the ALD by 53 cm (S2; table 1). An increase in surface air temperature deepens the active layer by warming the soil surface and increasing precipitation heat content. Overall, the combined effects of increased thermal conductivity and heat transfer from precipitation substantially increases permafrost degradation beyond that caused solely by surface air warming across the North Slope of Alaska.

The results from our model sensitivity analysis show that projected increases in 21st century precipitation deepen the active layer by enhancing precipitation heat transfer and soil thermal conductivity. Precipitation heat content will be greater from warmer surface air temperatures, further enhancing active layer depths across the 21st century. Modeled ALDs were generally shallower in simulations with constant surface air temperature vs. constant precipitation through 2100 (figure 4(a)). These model results show that increases in precipitation alone (in the absence of air warming) have smaller effects on permafrost degradation compared to the simulation with increased precipitation in a warmer 21st century climate. Increases in surface air warming and precipitation were shown to cause greater downward advective heat transfer and soil thermal conductivity, both of which intensify permafrost degradation.

These results confirm that both air temperature and precipitation are important drivers for permafrost degradation in the Arctic (figure 4(a)). This pattern was further corroborated by our GBM analysis that shows that precipitation is as important as surface air temperature for both modeled and measured ALD across the 28 NSA CALM sites (figure 4(b)). Although increases in air temperature and precipitation dominated effects on ALD, other localized factors such as landscape heterogeneity in soil physical and thermal properties, changes in vegetation composition and density, and drainage may also affect downward heat fluxes (Nelson et al. 1997, Hinkel and Nelson 2003, Grant et al. 2019).

In a recent site-level study using ecosys at the Barrow Experimental Observatory (BEO) polygonal tundra site in Utqiâgayk, Alaska, the relative changes in soil moisture as affected by microtopography, drainage, and vegetation were shown to control rates of permafrost thaw (Grant et al. 2017b, 2019).

Increases in vegetation leaf area may alter the soil water and surface energy balance under future climate. Changes in vegetation may increase transpiration, reducing soil warming. Greater vegetation canopy also decreases surface albedo (Pomeroy et al. 2006), and thus increases absorbed net radiation (Pearson et al. 2013), downward long wave radiation, advances in spring snow-free days (Livensperger et al. 2016), and thereby soil warming. Increases in atmospheric CO₂ concentration may also reduce transpiration through effects on stomatal conductance, leading to greater water use efficiency (Grant et al. 2019). Overall, these interacting and contrasting modeled processes were shown to result in greater ALD in simulations with (S1) vs. without (S2) precipitation heat transfer, suggesting that precipitation heat is an important control on active layer development that should not be ignored by ESMs.

Modeled ALD in the simulation without precipitation heat transfer (S2) was generally shallower in much of the NSA both under current and 21st century climate (figure 5). The spatial distributions of modeled ALD under 21st century climate are heterogeneous (figure 5). Although localized differences exist throughout the study spatial domain, much of the NSA was modeled to have deeper active layers by year 2100 even in the absence of precipitation heat transfer (figure 5(d)). Uncertainties in the magnitude and sign of predictions by ESMs are attributed to complex ecosystem interactions, which are directly and indirectly affected by

![Figure 4.](image-url)
the extent to which permafrost changes in response to climate (Mcguire et al. 2009, Koven et al. 2011). We show here that accounting for precipitation heat transfer led to deeper active layers under 21st century climate. The relatively coarse spatial resolution (~25 km) of our simulations, although finer than ESMs participating in CMIP6 (Eyring et al. 2016), precludes simulation of potentially important three-dimensional changes in landscape-scale hydrological dynamics; landscape level hydrological process that can result in abrupt increases in permafrost degradation and landslides (Turetsky et al. 2020); thermokarst and subsidence (Nelson et al. 2001, Turetsky et al. 2019); and the effects of sub-gridcell scale soil and topographic heterogeneity (Grant et al. 2017a, 2019) and thus should be addressed in future analyses.

Projected permafrost degradation may result in several ecological and climatic feedbacks that affect the carbon cycle. Permafrost regions store huge amounts of carbon (Schuur et al. 2008), which may be available for microbial decomposition and release to the atmosphere (Schuur et al. 2009, Deconto et al. 2012), thereby affecting the climate system (Macdougall et al. 2012). Changes in nutrient regimes with increases in ALD may affect plant growth, competition, and community composition (Lloyd et al. 2003, Mekonnen et al. 2018a), with subsequent effects on ecosystem leaf area, albedo, and surface energy balances (Hinzman et al. 2005, Mekonnen et al. 2019). Permafrost thaw may also have socioeconomic implications, including damage to buildings and infrastructure (Nelson et al. 2001, AMAP 2017). Warmer future climate will increase precipitation with a higher rain to snow ratio (Bintanja and Andry 2017) that can further hasten permafrost degradation.

4. Conclusions

We examined the extent of permafrost degradation in response to changes in air temperature and precipitation under current and future climates in a continuous permafrost region on the NSA. Using a thoroughly tested ecosystem model, we performed sensitivity simulations to partition the relative effects of air temperature and precipitation on active layer development. We showed, from current observations and historical and future simulations, that precipitation and surface air temperature have comparable impacts on permafrost dynamics. We conclude that increases in precipitation under 21st century warmer climate will hasten permafrost degradation through increases in heat transfer from warmer precipitation, soil thermal conductivity, and thus rapid downward soil heat fluxes. Further, uncertainties in projected 21st century precipitation trends strongly affect simulated permafrost degradation. Earth system models, which do not account for changes in soil thermal regime driven by precipitation heat transfer, likely underestimate predicted increases in thaw depth and therefore their effects on high-latitude carbon interactions with the atmosphere.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: http://ngee-arctic.ornl.gov/ and https://doi.org/10.5440/1692382.

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