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ENVIRONMENTAL RESEARCH  
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## LETTER

## Are vegetation influences on Arctic–boreal snow melt rates detectable across the Northern Hemisphere?

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E-mail: [hkropp@hamilton.edu](mailto:hkropp@hamilton.edu)**Keywords:** snowmelt, snow water equivalent, vegetation, borealSupplementary material for this article is available [online](#)**Abstract**

The timing and rate of northern high latitude spring snowmelt plays a critical role in surface albedo, hydrology, and soil carbon cycling. Ongoing changes in the abundance and distribution of trees and shrubs in tundra and boreal ecosystems can alter snowmelt via canopy impacts on surface energy partitioning. It is unclear whether vegetation-related processes observed at the ecosystem scale influence snowmelt patterns at regional or continental scales. We examined the influence of vegetation cover on snowmelt across the boreal and Arctic region across a ten-year reference period (2000–2009) using a blended snow water equivalent (SWE) data product and gridded estimates of surface temperature, tree cover, and land cover characterized by the dominant plant functional type. Snow melt rates were highest in locations with a late onset of melt, higher temperatures during the melt period, and higher maximum SWE before the onset of melt. After controlling for temperature, melt onset, and the maximum SWE, we found snow melt rates were highest in evergreen needleleaf forest, mixed boreal forest, and herbaceous tundra compared to deciduous needleleaf forest and deciduous shrub tundra. Tree canopy cover had little effect on snowmelt rate within each land cover type. While accounting for the influence of vegetative land cover type is necessary for predictive understanding of snowmelt rate variability across the Arctic–Boreal region. The relationships differed from observations at the ecosystem and catchment scales in other studies. Thus highlighting the importance of spatial scale in identifying snow-vegetation relationships.

**1. Introduction**

Northern hemisphere snow cover is an important component of the global energy budget and hydrologic cycle (Hall 2004, Rawlins *et al* 2010). Snow cover increases land surface albedo, thereby reducing surface net radiation and cooling climate (Betts and Ball 1997, Chapin 2005). Consequently, decreases in the spatial extent and/or duration of snow cover associated with climate change act as a positive climate feedback (Thackeray *et al* 2019). This is especially

important in Arctic and Boreal regions where snow cover can persist upwards of eight months per year (Donat-Magnin *et al* 2021). Precipitation is relatively low in these regions, and snow represents an appreciable fraction of annual totals, meaning that snowmelt has important implications for surface hydrology and soil moisture dynamics (Callaghan *et al* 2011). Spring snowmelt exerts strong control on ecosystem carbon and water cycling via impacts on the timing and magnitude of water availability for transpiration and photosynthesis (Pulliainen *et al* 2017,

Young-Robertson *et al* 2017). In addition, the insulative properties of snow exert a strong influence on winter soil temperatures, which are particularly important in regions underlain by permafrost (Stieglitz *et al* 2003). Consequently, changes in snow cover duration and extent also impact soil moisture and thermal regimes (Yi *et al* 2020), which have implications for carbon cycling.

Snow cover extent and associated climatic radiative cooling effects have declined significantly in recent decades (Flanner *et al* 2011, Derksen and Brown 2012), and observational estimates of the magnitude of both these changes exceed climate model estimates of snow cover change (Mudryk *et al* 2017). Snow cover declines are largely associated with earlier spring snowmelt, driven primarily by rising temperatures (Choi *et al* 2010, Thackeray *et al* 2019). Musselman *et al* 2017 provide evidence that earlier spring snow melt onset and decreases in snowpack depth result in slower melt rates based on observations in the western United States, and this finding has been supported by observations across the northern hemisphere (Wu *et al* 2018). While it is understood that future snow cover dynamics will largely be driven by temperature and precipitation changes, snow impurities and vegetation dynamics are important sources of heterogeneity (Thackeray *et al* 2019). Vegetation change is occurring in Arctic and Boreal regions with trees and shrubs advancing northward as temperatures increase (Tape *et al* 2006, Frost *et al* 2018, Berner and Goetz 2022). Disturbances such as fire and permafrost thaw are driving changes in forest composition (Goetz *et al* 2007, Lara *et al* 2020) or loss of forest cover altogether (Helbig *et al* 2016). These vegetation changes could affect snowmelt dynamics directly through impacts on surface energy partitioning, and indirectly through impacts on snow redistribution (Link and Marks 1999, Pomeroy *et al* 2006, Rutter *et al* 2009).

Forest canopies block incoming solar radiation, which reduces the amount of energy available for snowmelt (Ellis *et al* 2011). However, shortwave radiation absorbed by canopies is reemitted as longwave radiation below the canopy, and this longwave enhancement increases the amount of energy available for snowmelt (Webster *et al* 2016, Todt *et al* 2018). Tree and shrub canopies can act as windbreaks that enhance snow accumulation (Pomeroy *et al* 2006), or conversely, can intercept snow and enhance sublimation losses that reduce accumulation (Hedstrom and Pomeroy 1998, Gelfan *et al* 2004). The net effects of forest canopies on snow accumulation and melt dynamics are difficult to generalize because they depend on complex interactions between topography, vegetation patch dynamics, prevailing weather patterns, and climate (Essery and Pomeroy 2004, Jost *et al* 2007, Marsh *et al* 2010). Higher forest cover is associated with shorter snow duration in boreal regions with higher winter

temperatures (Lundquist *et al* 2013), due in part to the enhancement of longwave energy by trees (Pomeroy *et al* 2009). Simulations of forest driven longwave energy enhancement in climate models find that evergreen forests are subject to greater longwave enhancement than deciduous forests, particularly in areas with high canopy density (Todt *et al* 2018). Despite the importance of canopy impacts on snowmelt dynamics, the degree to which forest type and canopy cover affect changes in snow cover extent across northern high latitude regions remains unclear.

To date, interactions between spring snowmelt and vegetation have primarily been examined with observational or modeling studies carried out at ecosystem or catchment scales (approximately 10–100 km<sup>2</sup>; (Lundquist and Dettinger 2005, Broxton *et al* 2015, Roth and Nolin 2017, Mazzotti *et al* 2021). Consequently, it is unclear whether continental-scale snowmelt dynamics, which by necessity need to be estimated from coarse resolution datasets, are sensitive to canopy cover variation, and in turn whether canopy processes may explain discrepancies between observed and modeled declines in snow cover extent in recent decades. Here we examine the link between forest canopy cover and snowmelt across boreal regions of the northern hemisphere. Using gridded datasets that quantify snow water equivalent (SWE), climatic conditions, and vegetation cover we answer the following research questions: (a) do snowmelt rates vary between different Arctic and boreal vegetation types at the continental-scale after controlling for climate-related drivers of snowmelt? (b) Is earlier snowmelt onset associated with slower melt rates in all vegetation types? And (c) do snowmelt rates vary with canopy cover across Northern Hemisphere boreal forests in gridded continental scale datasets?

## 2. Methods

### 2.1. Datasets

Our study area focused on non-mountainous areas of the Arctic and Boreal regions poleward of 50° N latitude. We examined snowmelt in three types of boreal forest types: deciduous needleleaf (central and northeastern Eurasia), evergreen boreal forest (North America), and mixed deciduous broadleaf and evergreen boreal forest (North America and western and central Eurasia). We also examined snowmelt in two types of tundra (herbaceous and deciduous shrub) located in high latitudes of North America and Eurasia. Our study focused on regions across which snowmelt occurs between March and June. We examined snowmelt rates during the years 2000–2009.

To characterize snowmelt, we used daily maps of SWE calculated as a mean of four existing datasets; the European Space Agency GlobSnow v2.0 (Takala *et al* 2011), the NASA Modern-Era Retrospective Analysis for Research and Applications

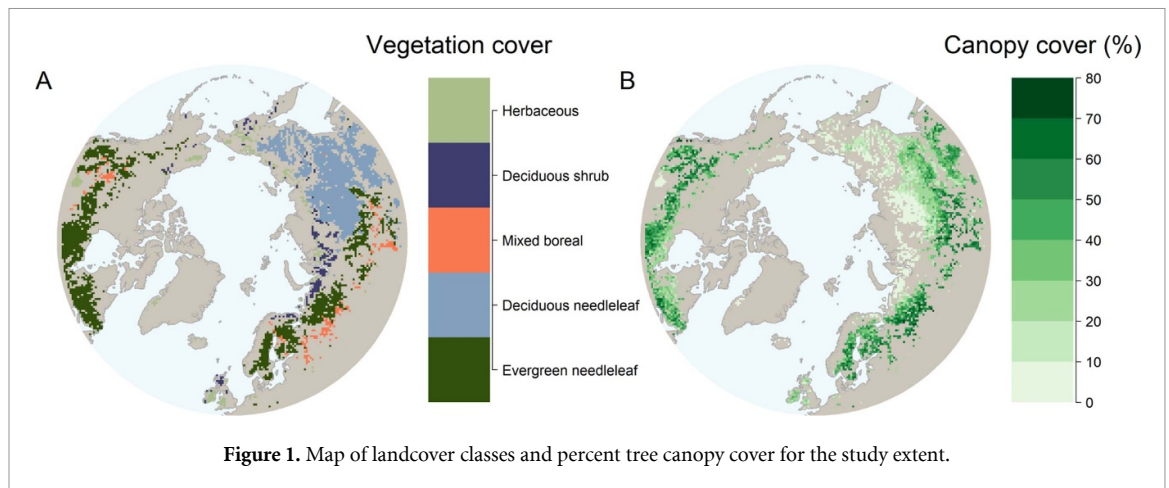


Figure 1. Map of landcover classes and percent tree canopy cover for the study extent.

version 2 (Gelaro *et al* 2017), the Crocus snow model driven by ERA-Interim meteorology (Brun *et al* 2013), and a temperature-index model also driven by ERA-interim (Brown *et al* 2003). Assessments of the blended SWE estimates are described by Mortimer *et al* (2020). SWE products with coarse grid spacing are difficult to validate and subject to greater error in complex terrain (Mortimer *et al* 2020), so we used the ETOPO1 elevation dataset ( $\sim 1.8$  km native spatial resolution) to identify and mask mountainous areas (Amante and Eakins 2009). We examined the relationship between SWE, land cover, and climatological drivers using gridded data derived from remote sensing or reanalysis. Surface air temperature was characterized using ERA-Interim 2 m daily surface air temperature data (Dee *et al* 2011). The MODIS Vegetation Continuous Fields data product (500 m native spatial resolution MOD44B) was used to quantify variation in forest cover across the study domain (Hansen *et al* 2003). We used the GLC2000 global land cover data (1 km native spatial resolution) set to characterize ecosystem types (Bartholome and Belward 2005).

All data were re-projected to a common EASE 2.0 equal area projection with 50 km spatial resolution. For the elevation data we calculated the standard deviation after reprojection, and used the threshold of 200 m to identify areas of complex terrain to exclude from analysis. We used the modal GLC2000 land cover type to determine the land cover class for resampled 50 km pixels, for all other variables mean values were calculated during resampling. Our analysis focused on the following boreal forest land classes: deciduous needleleaf, evergreen needleleaf, and mixed boreal. We also included two tundra land classes that can contain trees in transitional tundra–boreal regions for comparison: herbaceous and deciduous shrub tundra. We excluded all mixed pixels where no single class comprised more than 50% of the area within a pixel (figure 1). In addition, pixels were also excluded where (a) maximum SWE did not exceed 40 mm because low levels of SWE

can be difficult to accurately measure and characterize melt (Gascoin *et al* 2015), and (b) sites had less than 30 d of SWE observations above the minimum threshold of 40 mm during the spring (February–June). This eliminated locations that do not have persistent snow cover and melt timing may not follow our assumptions related to the timing and duration of melt.

Snowmelt rate was calculated from the central period of snowmelt defined as the period starting once SWE dropped below 80% of the annual maximum SWE value and ending at 20% of maximum SWE ( $>5$  d in duration). This central period of snowmelt can be approximated as a linear decline (Essery and Pomeroy 2004).

## 2.2. Modeling drivers of snowmelt

We investigated the relationship between the snowmelt rate and forest cover using a multiple linear regression in a hierarchical Bayesian framework to account for other climatic variables, vegetation, and the annual variation in snow melt in each grid cell and year of observation. The snowmelt rate was log-transformed to linearize the relationships with the following explanatory variables: forest cover, the average melt period temperature, day of year of melt onset, and log-transformed maximum SWE prior to the melt period in the regression. We used covariate centering to transform the data where each explanatory value is shifted to avoid extrapolation at a non-meaningful value of zero in the regression intercept. For example, a value of zero forest canopy cover in mixed, evergreen needleleaf, and deciduous needleleaf forests would represent a pixel classified as a forest landcover type with no tree cover. Given these pixels could arise from disturbance, large gaps, or inaccurate characterization, we did not think it would be appropriate to closely interpret intercepts at a value of zero. We transformed the explanatory variables by subtracting the average or an interpretable value from each observation. We used the average value for maximum SWE ( $\log(150$  mm)) and for the onset day of

year (107th day) for covariate centering. We subtracted a value of 20% from canopy cover since this is a value that occurs in both forested and tundra vegetation types with sparse tree cover.

Regression parameters were treated as fixed effects for each land cover class and year ( $n = 10 \text{ years} \times 5 \text{ classes}$ ) to account for variability in the melt rate relationships that occur annually within each vegetative land cover class. This annual variability likely arises from conditions that could not be captured by our existing datasets. The model was fit in a hierarchical framework that considered the fixed effect parameters for each year within a land cover class to be nested within a global parameter for each land cover class. A hierarchical Bayesian approach can increase statistical power and reduce issues associated with overfitting and family-wise error from multiple comparisons (Gelman *et al* 2004).

The analysis was run in R 4.1.0 (R Core Team 2021) and the model was implemented in JAGS (v4.3.0) using the rjags, coda, and mcmcplots packages (Plummer *et al* 2006, McKay Curtis 2018, Plummer 2019). Spatial analysis used raster, sf, and sp packages (Pebesma and Bivand 2005, Pebesma 2018, Hijmans 2021). Under our hierarchical model, all regression parameters were assigned distributions using global hyper-priors. We assigned diffuse, non-informative distributions to parameters. Mean parameters were assigned distributions of normal(0.316) and standard deviation parameters were assigned uniform distributions between uniform(0.1000). All code for analysis is archived (Kropp 2022).

## 3. Results

### 3.1. Patterns of snowmelt across boreal and tundra regions

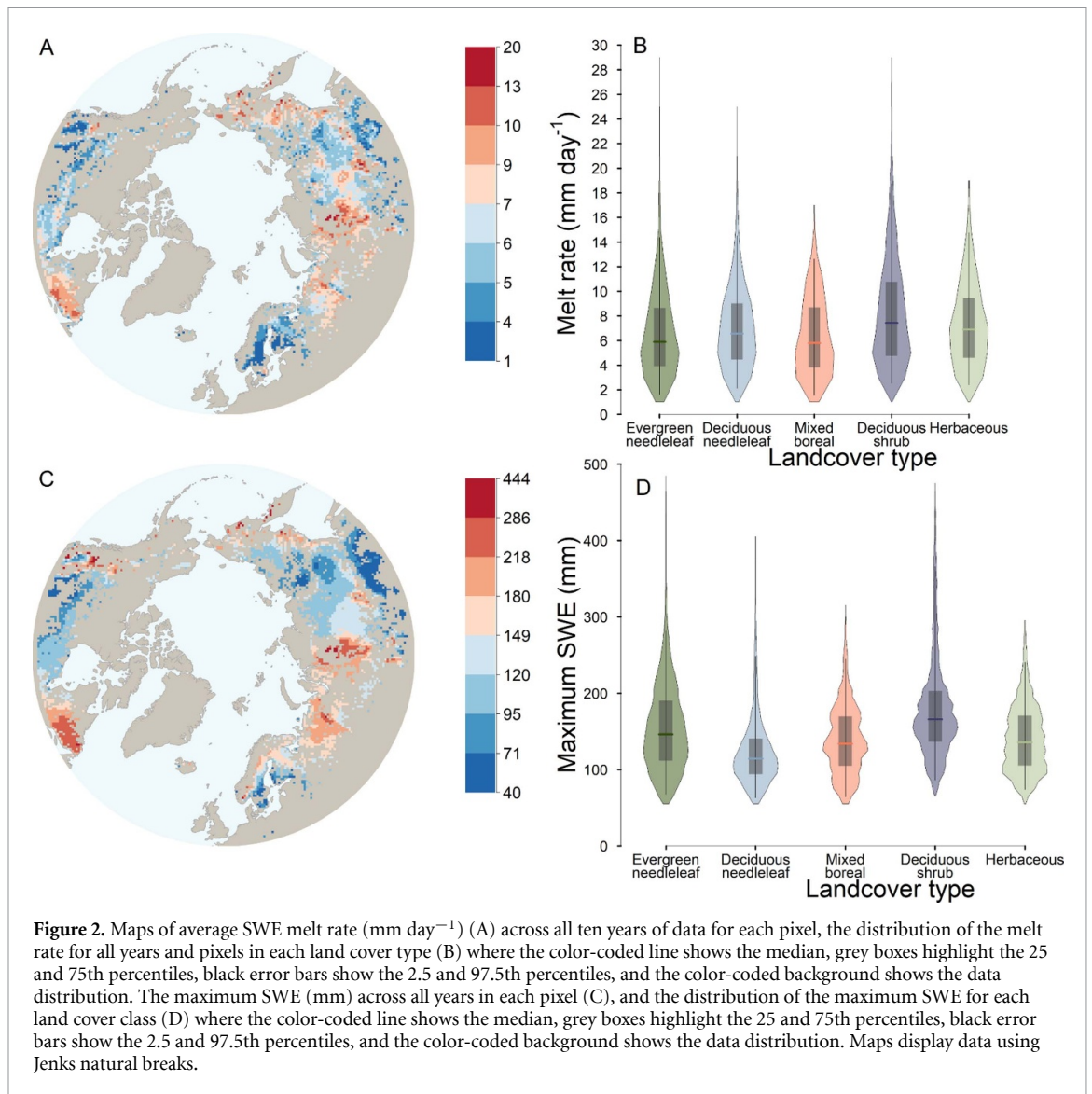
Average snowmelt rates in the ten years of data across our study domain ranged from 0.9 to 19.6 mm day<sup>-1</sup> with a median of 6.5 mm day<sup>-1</sup> (figure 2(a)). Observed snowmelt rates exhibited a high degree of variability within land cover classes (figure 2(b)). Median snowmelt rates were similar between forest classes with values of 5.8 mm day<sup>-1</sup>, 5.8 mm day<sup>-1</sup>, and 6.6 mm day<sup>-1</sup> in evergreen needleleaf, mixed-leaf, and deciduous needleleaf forests, respectively. In tundra, median snowmelt rates were slightly higher at 6.9 mm day<sup>-1</sup> for herbaceous and 7.4 mm day<sup>-1</sup> for deciduous shrub classes, but the range of values largely overlapped with forest land cover classes (figure 2(b)). Maximum SWE was similar between landcover types with median values ranging from 114 mm in deciduous needleleaf to 166 mm in deciduous shrub tundra (figures 2(c) and (d)). The median values of the average temperature during the melt period ranged from 2.9 °C in deciduous needleleaf and 2.5 °C in mixed boreal to 1.6 °C in herbaceous tundra (figures 3(a) and (b)). The first day of melt onset during the central melt period

varied mostly with latitude (figures 3(c) and S1). Herbaceous and deciduous shrub tundra had the latest onset of the melt period with the median day of year of 135 and 134 respectively (figure 3(d)). Mixed boreal forest had the earliest day of onset with the median day occurring on the 96th day of year. The median day of melt onset was day of year 122 for deciduous needleleaf and 103 for evergreen needleleaf.

### 3.2. Drivers of snowmelt variability

The model had an  $R^2$  of 0.65 and a root mean square error of 0.26 log(mm day<sup>-1</sup>). The model over-predicted lower values of melt and under-predicted the highest values of melt (figure S11). For most years and land cover classes, snowmelt rate was positively related to average surface temperature during the melt period, and the mean rates in all were similar between land cover classes (figures 4(a), (b), S2(a), (b), S10(a), (b) and 5(a)). There was no significant relationship between the snowmelt rate and tree canopy cover (95% credible interval overlaps with zero) in all years for mixed boreal forest and most years for evergreen needleleaf forests (figures 4(c), S2(c)–S10(c), and 5(b)). The relationship between canopy cover slope and snowmelt did significantly differ from zero in deciduous needleleaf forest and deciduous shrub tundra for most years (figures 4(c), (d), S2(c), (d)–S10(c) and (d)). However, snowmelt rate was highly variable across all ranges of tree canopy cover and the slope coefficients are small with the log-scale melt rate changing by as little as 0.006–0.5 log(mm day<sup>-1</sup>) under a 60% increase in tree cover. This indicates that the statistical significance should not be overinterpreted as a meaningful relationship between snowmelt rate and canopy cover in deciduous needleleaf forests and deciduous shrub tundra. The snowmelt rate increased with later melt onset periods, and the mean slope coefficients for all years did not significantly differ between land cover classes (figures 4(e) and (f)). In deciduous needleleaf forests, mixed boreal forests, and deciduous shrub tundra, a few years did not show significant relationships suggesting that the day of melt onset does not always explain variability in melt rate. Higher maximum SWE was associated with a higher melt rate for all land cover classes (figures 4(g) and (h)).

The intercept values for the regression model indicate that the snowmelt rate differs between land surface classes when normalized to the same melt period surface temperature, tree cover, melt onset day of year, and maximum SWE (figure 6). The mean values for all years in Evergreen needleleaf forests and mixed boreal forests had the highest melt rates of 1.7 log(mm day<sup>-1</sup>) [95% credible interval (CI): 1.6, 1.9] and 1.6 log(mm day<sup>-1</sup>) [CI: 1.5, 1.8], respectively. Herbaceous tundra had a mean melt rate of 1.6 log(mm day<sup>-1</sup>) [CI: 1.5, 1.7], similar to evergreen and mixed boreal forests. Deciduous needleleaf



forests melt rate was lower than other forests with a mean value of  $1.4 \log(\text{mm day}^{-1})$  [CI: 1.3, 1.5]. Deciduous shrub tundra had the lowest melt rate of  $1.3 \log(\text{mm day}^{-1})$  [CI: 1.2, 1.4]. With similar SWE and temperature conditions, deciduous leaf tundra and deciduous needleleaf boreal forests were expected to have lower melt rates than herbaceous tundra or forests that include evergreen needleleaf trees.

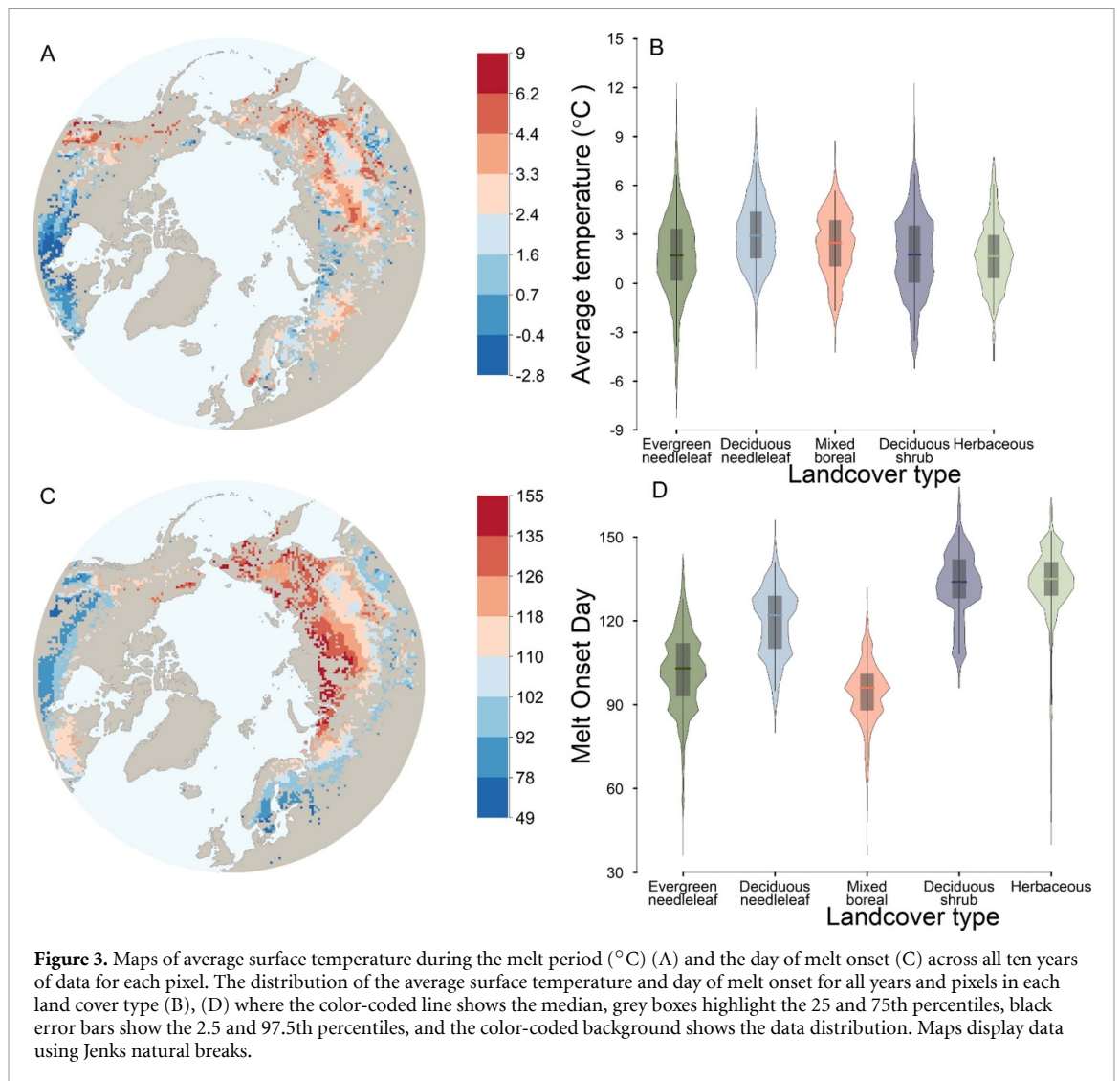
#### 4. Discussion

Snowmelt rates were largely driven by meteorological conditions related to the atmosphere-snowpack energy cycling such as air temperature and day of year of melt onset (figures 2–4). Higher average air temperatures during the melt period, higher maximum pre-melt SWE, and a later day of onset during the melt period were associated with increased melt rate (figure 4). Snowmelt depends on the accumulation and exchange of energy in the snowpack (Price and Dunne 1976, Tarboton *et al* 1994, Callaghan *et al* 2011). Prior studies also found a tight coupling

between air temperature and the melt rate and suggested that sensible heat may dominate the snow pack energy balance, although longwave radiation is important as well (Ohmura 2001, Bewley *et al* 2010, Mahat *et al* 2013, Schlögl *et al* 2018).

In most years, higher snowmelt rates are associated with a later day of melt onset for all landcover classes in the Boreal–Arctic region. This supports the hypothesis described by Musselman *et al* (2017) that snowmelt will be slower with an earlier onset of melt and shallower snowpack based on observations in Western North America. An analysis of long term trends of SWE across the northern hemisphere found a similar relationship: earlier melt onset and slow melt rates are occurring alongside a multi-decadal trend towards lower peak SWE (Wu *et al* 2018). Our results lend further support to the hypothesis that a warmer world with lower SWE and earlier melt timing can lead to slower snow melt.

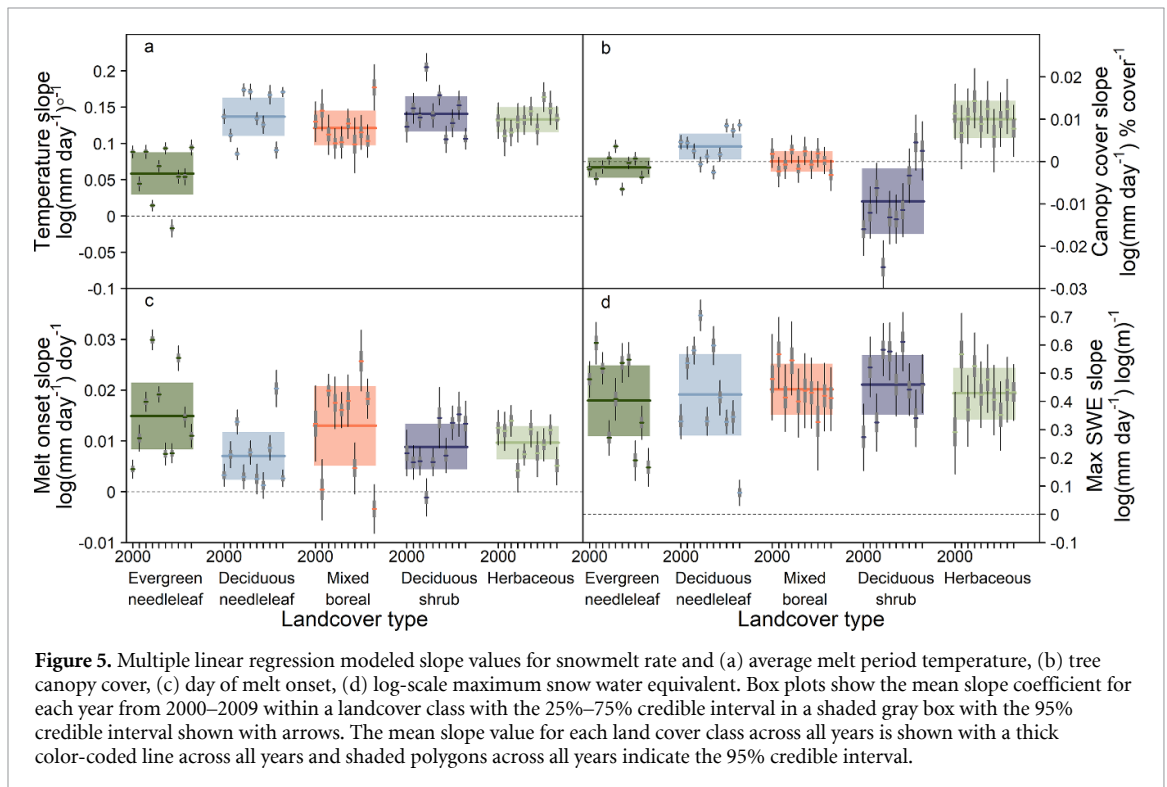
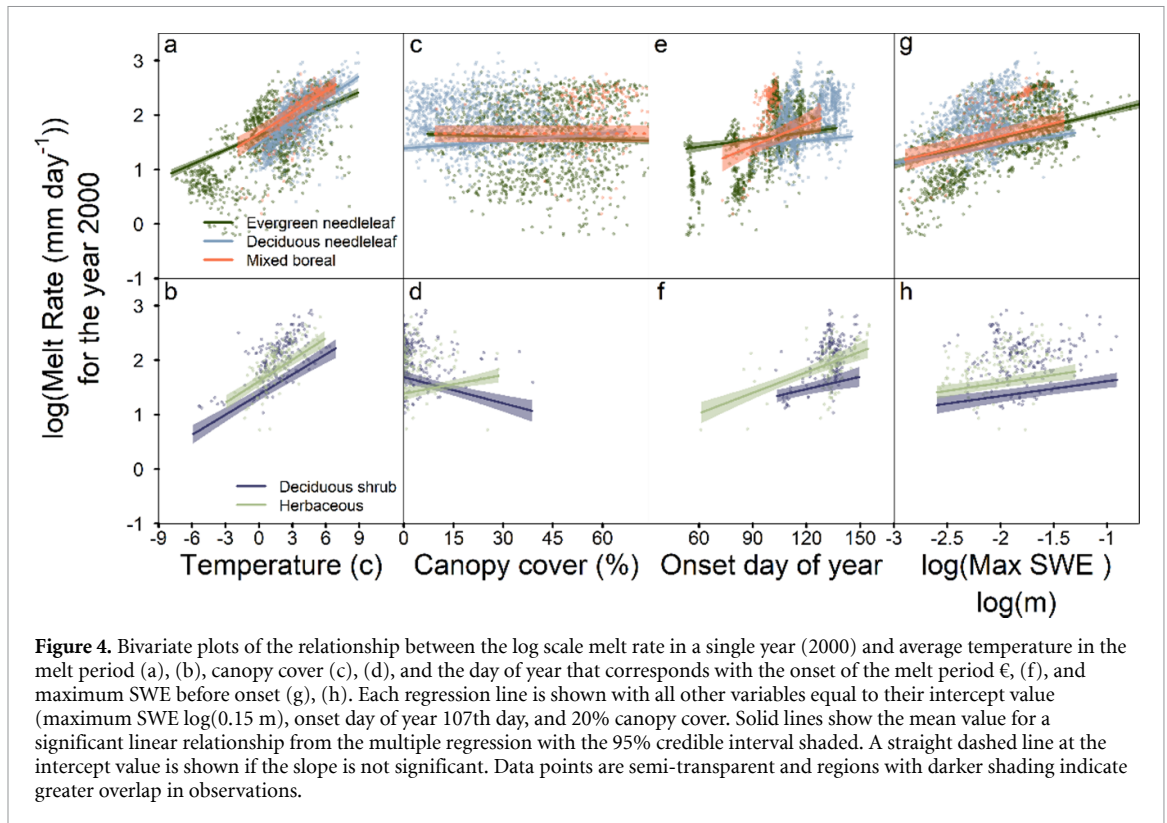
We found similar relationships between the day of melt onset and the melt rate for all vegetation types, although these relationships had greater interannual



variability within boreal forests and deciduous shrub tundra. In these landcover types, some years had a non-significant relationship between day of onset and snow melt (figures 4(b) and (c)). This interannual variation in the relationship between melt onset and melt rate suggests that additional meteorological factors that vary interannually may influence the coupling between melt onset timing and snowmelt rate. Further studies that investigate drivers of melt timing are needed to help understand year-to-year variability in the coupling between melt timing and snowmelt rates. However, when averaged over multiple years, our data suggest that the relationships between snowmelt rate and melt onset timing and maximum SWE are not largely influenced by vegetative landcover.

When comparing snowmelt rates at the same average air temperature, maximum SWE and day of melt onset, we found the highest melt rates in evergreen needleleaf forests, mixed leaf forests, and herbaceous tundra with lower melt rates in deciduous shrub tundra and deciduous needleleaf forests (figure 5). Observations and models indicate that

increased longwave radiation from tree canopies can be higher in high density evergreen forests compared to lower density deciduous needleleaf forests (Todt *et al* 2018), potentially explaining the highest melt rates in evergreen needleleaf forests. However, our observations conflict with stand scale observations of a higher melt rate in a mixed leaf forest compared to evergreen needleleaf forests (Faria *et al* 2000). Several studies suggest that shrub-induced heating slightly enhances snowmelt relative to non-shrub tundra (Pomeroy *et al* 2006, Bewley *et al* 2010, Marsh *et al* 2010). While this suggests that the effects of shrub-canopy shading are negligible, impacts of shrub canopies on albedo, shading, and longwave dynamics depend on both the protrusion of stems above the snowpack and the incoming shortwave radiative conditions (Marsh *et al* 2010). We found that the snowmelt rate was lower in deciduous shrub tundra compared to herbaceous tundra after controlling for the starting day of melt, the maximum SWE, and the air temperature during melt (figure 6). This result directly contradicts well documented impacts of shrubs on snowmelt from observational studies conducted at

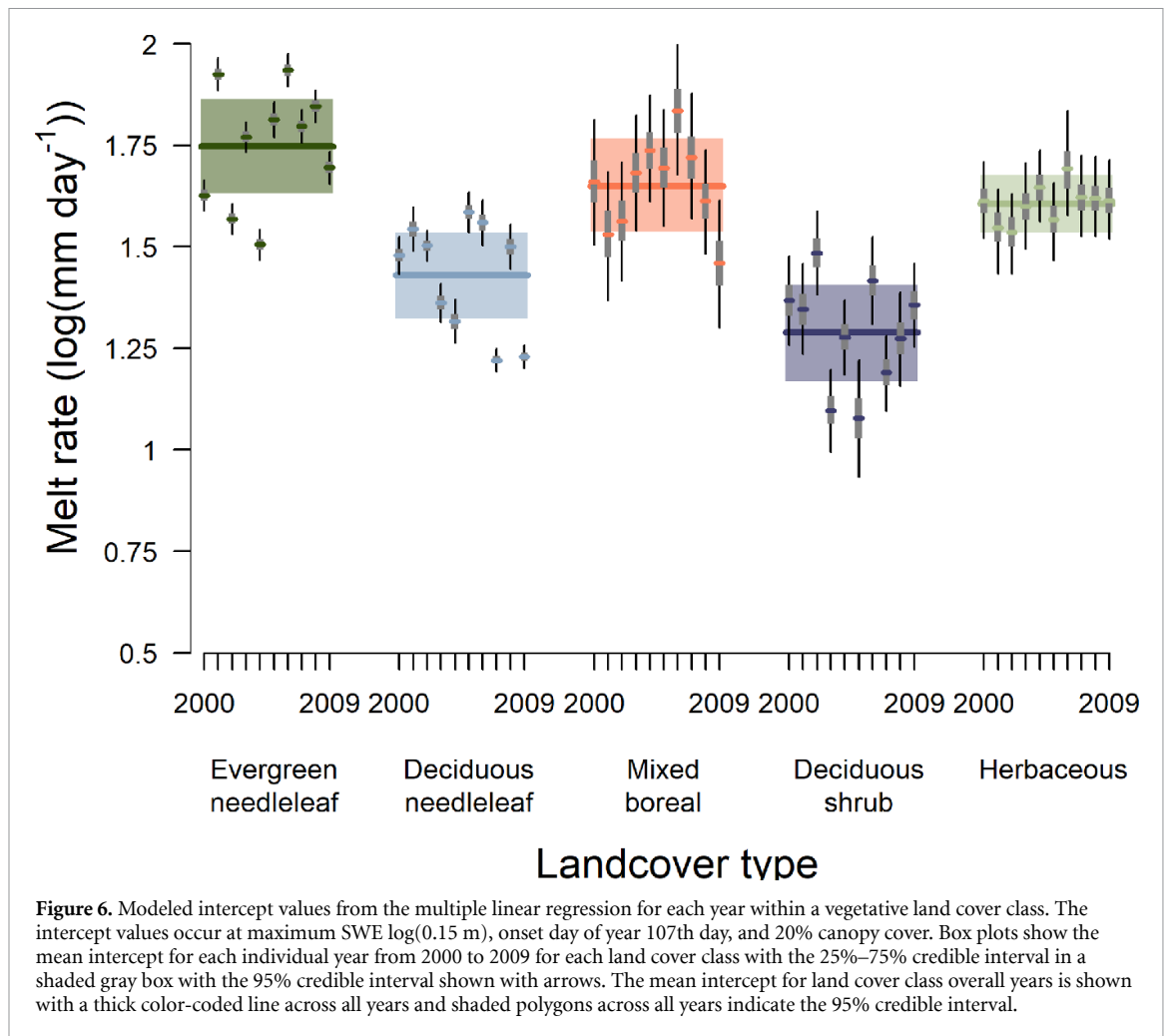


the stand/ecosystem scale (Pomeroy *et al* 2006, Marsh *et al* 2010, Lafleur and Humphreys 2018).

The two most plausible explanations for the apparent disagreement between landscape-scale observational studies and our continental-scale analysis are related to either spatial limitations and/or uncertainties related to the known limitations and

coarse native grid spacing of the SWE datasets. The first possible explanation is that the vegetative canopy influences on snowmelt are scale-dependent, and the contributions of climatic controls on snow accumulation and melt along with topographic controls on snow accumulation predominate at broader spatial scales (i.e. the 50 km grid cells required for





continental scale analysis). While we controlled for heterogeneity in topography and vegetation, it is still possible that spatial averaging within 50 km grid cells dampened the relationship between vegetation cover and snow melt. Until intermediate and higher resolution SWE data are available, it will be difficult to determine what influence, if any, the grid spacing of our data has on the analysis. A second possible explanation is that uncertainties in the SWE data cause the apparent discrepancy between our analysis and previous local-scale studies. In this case, uncertainty in the data (noise) could be larger than the magnitude of vegetation influences on snowmelt (signal). Alternatively, uncertainties in how vegetation is incorporated in the land surface models and remotely sensed algorithms used to derive the temperature and SWE data products could lead to systematic bias related to vegetation distribution in those data sets, which could also dampen vegetation-snowmelt relationships. Our data do not support resolving the veracity or magnitude of these potential explanations with statistical analysis alone.

Despite the uncertainties outlined above, our results highlight that vegetative landcover accounts for some variability in snowmelt rate under similar climatic conditions. This suggests that the type of

vegetative land cover is relevant for continental-scale predictions of snowmelt, but the mechanisms by which land cover influences snowmelt at these scales cannot be resolved from our analysis. Global land surface prediction systems and earth system models represent vegetation types on coarse resolution grids similar to that used in this study, so further quantifying these uncertainties remains highly relevant.

Increasing snowmelt rates are commonly considered to be one of the main impacts of the ‘shrubification’ of Arctic tundra ecosystems (Myers-Smith *et al* 2011, Loranty *et al* 2018), but our results caution against applying these assumptions to large-scale analysis based on coarse measures of vegetative land cover alone. Our analysis highlights the need for additional data products and research on snowmelt dynamics that bridge ecosystem, regional, and continental scales.

Contrary to expectations based on local scale studies, we found that snowmelt rates were not related to canopy cover within individual land cover classes (figures 4(c) and (d)). This result contradicts ecosystem and catchment scale studies that clearly identify forest canopy related influences on snowmelt dynamics via impacts on shortwave and longwave

radiation partitioning (Davis *et al* 1997, Link and Marks 1999, Pomeroy *et al* 2009, Webster *et al* 2016). It is possible that forest canopy influences on snowmelt are important in the context of regional snowmelt dynamics, but cannot be resolved due to the scaling artifacts of using coarse-scale data sets that are limited by the available resolution of global blended snow products (Mortimer *et al* 2020). In this case, understanding the hemispheric-scale climatic drivers of snowmelt and land cover are sufficient to predict future Arctic–Boreal snow cover dynamics for continental-scale analyses or models. Further research with finer resolution SWE and vegetation data is necessary to determine whether this is indeed true. If it is, models that incorporate sub-grid heterogeneity and covariation in vegetation and snow cover should offer more accurate regional representation of snowmelt dynamics. Without finer spatial resolution data for both SWE and vegetation cover, our data cannot confirm whether the lack of forest cover–snowmelt relationship is an accurate representation of forest–snow–energy interactions or arises from scaling artifacts.

## 5. Conclusions

Changing snow cover dynamics will have important implications for a host of regional and global processes. Snow cover duration exerts important controls on albedo, while SWE is closely linked to seasonal hydrology (Callaghan *et al* 2011) and snow depth impacts winter soil CO<sub>2</sub> emissions (Natali *et al* 2019) and permafrost vulnerability to thaw (Jorgenson *et al* 2010). In coarse resolution products (50 km) required for circumboreal analysis and modeling, snowmelt rates were highest in evergreen needleleaf, mixed evergreen and broadleaf forests after controlling for meteorological conditions. In contrast with observational studies at the stand/ecosystem scale, snowmelt rates were higher in herbaceous tundra compared to deciduous shrub tundra after controlling for meteorological conditions. Our results highlight the inconsistencies in snowmelt rates between ecosystem scale observation and coarse resolution gridded data across the Arctic–boreal region, and caution against applying assumptions based on ecosystem-level observations to large-scale analysis with only coarse measures of vegetative land cover. Coupled changes in snow and shrub and forest expansion with warming temperatures across the Arctic–Boreal region have the potential to amplify ongoing climatic change (Foley 2005). Therefore, better understanding of interactions between vegetation and snow cover are necessary to reduce predictive uncertainty for key climate feedbacks.

## Data availability statement

No new data were created or analyzed in this study.

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