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Sublimation Measurements of Tundra and Taiga Snowpack in Alaska

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Abstract. Snow sublimation plays a fundamental role in the winter water balance. To date, few studies have quantified sublimation in tundra and boreal forest snow by direct measurements. Continuous latent heat data collected with eddy covariance (EC) measurements from 2010 to 2021 were used to calculate snow sublimation at six locations in northern Alaska: three Arctic tundra sites at distinct topographical and vegetation communities in the Imnavait Creek watershed on the North Slope underlain by continuous permafrost and three lowland boreal forest/taiga sites of differing permafrost conditions and ecosystems in interior Alaska near Fairbanks. Mean surface sublimation rates range from 0.08–0.15 mm day^{-1} and 15–27 mm year^{-1} at the six sites, representing on average 21% of the measured solid precipitation and 8–16% of the cumulative annual water vapor flux to the atmosphere (evaporation plus sublimation). The mean daily sublimation rates of the lowland boreal forest sites are higher than those of the tundra sites, but the longer snow cover period of the tundra sites leads to greater mean annual sublimation rates. We examined the potential controls, drivers, and trends of the sublimation rates by using meteorological data collected in conjunction with EC measurements. This research offers results to better understand how site conditions affect sublimation rates and the winter hydrologic cycle. Our study contributes to the sparse literature on tundra and boreal sublimation measurements and finds comparable rates to sublimation estimates in other northern climates.

1 Introduction

Sublimation is the phase change from ice crystals in the snowpack to water vapor in the atmosphere. It is a fundamental process in the winter water balance that affects the amount of snow on the ground at the end of winter (Bowling et al., 2004; Molotch et al., 2007; Pomeroy & Essery, 1999; Reba et al., 2012). Studies estimate that sublimation is responsible for between 0.1% and 90% of snow mass loss to the atmosphere (Stigter et al., 2018). Liston and Sturm (2004) estimate that 10–50% of annual snowfall in the Arctic sublimates. These large ranges are due to the difficulties in measuring sublimation.

Because of a lack of direct measurements, sublimation is often calculated by solving the water and energy balance equations. The winter water balance (in the absence of wind transport) is simple: snow water equivalent (SWE) equals precipitation minus sublimation (Liston & Sturm, 2004; Stuefer et al., 2020), but the resulting estimates are wide-ranging and unreliable due to errors associated with solid precipitation measurements in the Arctic (Goodison et al., 1998). Modeling is another approach commonly used to estimate sublimation, including the Penman Monteith, bulk aerodynamic, and aerodynamic profile methods (Marks et al., 2008; Sexstone et al., 2016; Stigter et al., 2018). There are only two conventional options for direct measurements: a sublimation pan and the eddy covariance (EC) method, which continuously measure latent heat fluxes. Sublimation pans are not feasible in remote, windy locations because overestimates of sublimation occur when snow is blown from the pan and redistributed nearby. EC measurements are the most direct means available to measure vertical turbulent fluxes (Marks et al., 2008; Molotch et al., 2007; Reba et al., 2009, 2012; Sexstone et al., 2016; Stigter et al., 2018). However, EC towers that operate year-round are rare in much of Alaska due to challenges associated with the complexity and expense of maintenance during the harsh winter.

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Sublimation is important because it affects the amount of seasonal snow that accumulates on the ground during winter periods. In northern Alaska, snow can be present on the earth's surface for most of the year. Snow affects permafrost, thermal properties, and freezing rates of lakes and sea ice, soil microbiology, soil chemistry, the animals that spend winter under the snow, humans, and infrastructure (Gray & Male, 1981). Snow affects how much solar radiation is absorbed by the earth and how much is reflected, a fundamental process in the global climate and a key component of global warming (Loaiciga et al., 1996). Snow also affects water supply and how much water is available for human activities and resources. A recent example from 2021 highlights the importance of understanding the relationship between snow, sublimation, groundwater, and streamflow: the Colorado River snowpack was estimated at 90% of average, but streamflows were only 36% of average. It is currently speculated that the discrepancy may in part be explained by sublimation (SOS Project, 2023).

EC measurements in different climatic and snow regions improve our understanding of how site conditions affect sublimation rates. Global seasonal snow classes (tundra, boreal forest, montane forest, maritime, prairie, and ephemeral) are used to put local Alaska study sites into a global seasonal snow perspective (Sturm & Liston, 2021). Globally, almost half of Earth's terrestrial area is covered by tundra and boreal forest snow classes, at 31.8% and 28.3%, respectively (Sturm & Liston, 2021). Both blowing snow and static sublimation are common winter processes in tundra environments (Liston & Sturm, 2004), while canopy snow sublimation is a characteristic feature of boreal forest environments (Pomeroy et al., 1998). The EC towers used in this study are established in locations representative of the tundra and boreal forest snow classes (Figure 1).

To the authors' knowledge, there are no published studies in the literature that have calculated sublimation using the EC method for durations greater than 3 years anywhere in the world. In this study, twelve years of EC measurements from six sites in northern Alaska distinguished by snow classes, vegetation communities, and permafrost (Figure 1) were analysed to 1) quantify the magnitude of snow sublimation, 2) assess spatial and temporal variability, 3) compare sublimation rates with other water fluxes, and 4) investigate drivers of sublimation using available meteorological and environmental data.

Figure 1: Location of study sites within tundra and boreal forest snow classes (Sturm & Liston, 2021) in northern Alaska (a); Arctic tundra EC tower at Imnavait Creek (b); SNOTEL and UAF weather stations at Imnavait Creek (c); snow cover at a boreal fen EC tower in the Alaska Peatland Experiment (APEX), which is associated with the Bonanza Creek Long Term Ecological Research program (d); boreal forest black spruce site at APEX (e); boreal forest thermokarst bog site at APEX (f).

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2 Background

2.1 Study Area

This study occurred at six sites in two northern Alaska environments: three tundra sites on the North Slope in the northern foothills of the Brooks Range and three lowland boreal forest sites in the subarctic Interior (Figure 2). The sites are referenced in this paper by their Ameriflux site ID (https://ameriflux.lbl.gov/).

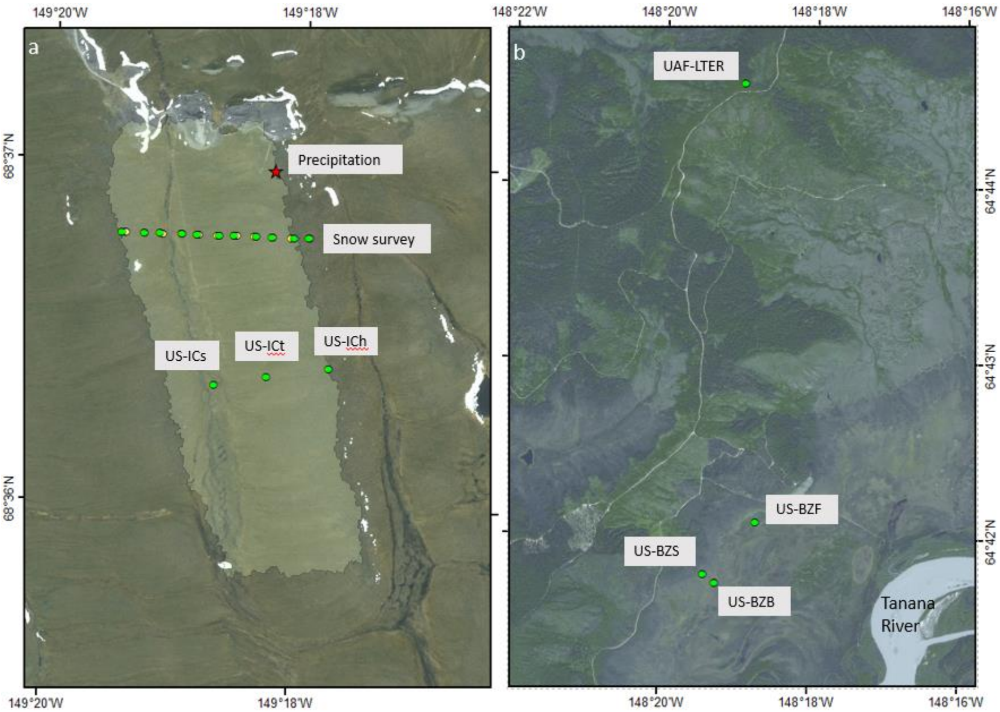

Figure 2: Location of study sites: tundra sites at Imnavait Creek watershed (a); lowland boreal forest sites at the Alaska Peatland Experiment, part of the Bonanza Creek Long Term Ecological Research program (b). Basemaps credited SPOT 5 Image Corporation.

2.1.1 Tundra Sites at Imnavait Creek Watershed

The tundra sites are within the Imnavait Creek watershed, a small arctic watershed (2.2 km^2) located on the North Slope in the foothills of the Brooks Range at 68°37′N, 149°18′W, and 770–980 m above sea level (Figure 2a) (Euskirchen et al., 2017; Walker et al., 1994). Within the watershed, the towers are located less than 0.5 km from each other along a topographic sequence from valley bottom to ridge and within distinct vegetative communities: wet sedge (Us-ICs), tussock (US-ICt), and dry heath (US-ICh), respectively.

The landscape is treeless with rolling hills, broad valleys, and continuous permafrost. Imnavait Creek is a small, beaded tributary of the Kuparuk River. The mean annual air temperature (MAAT) is –7.4°C and mean annual precipitation (MAP) is 140–270 mm, with 60% of that occurring as snow (Euskirchen et al., 2017). Mean monthly air temperatures are below freezing from October to May, and generally, snowpack is present during those same months (Stuefer et al., 2020).

Snow cover in the Imnavait Creek area is representative of tundra snow class; that is, windblown with drifts, hard packed, cold, dry, and thin (Sturm & Liston, 2021; Brown et al., 2021). The snow covers low stature vegetation in the treeless, exposed, windy environment. Large spatial variability in snow depth is a common feature of the tundra snow class (Benson & Sturm, 1993).

Predominant winds in the Imnavait Creek watershed are from the south and west and can top 20 m s^{-1} (Sturm & Stuefer, 2013), creating deep, dense drifts in depressions on the lee side of landscape features (Parr et al., 2020). The snowpack structure often consists of low-density depth hoar at the base, covered by a hard wind slab layer on top (Benson & Sturm, 1993). At the end of winter in late April from 1985–2017, mean snow depth at the Imnavait Creek watershed was 50 cm and average SWE was 125 mm (Stuefer et al., 2020). Snow and wind conditions at this watershed are similar to those throughout the gently rolling foothills of the northern Brooks Range. In the mountain valleys, snow and wind conditions differ, affected by katabatic winds. The Arctic Coastal Plain to the north is prone to prolonged winds.

2.1.2 Lowland Boreal Forest Sites at the Alaska Peatland Experiment

The lowland boreal forest sites are in the Tanana Flats of interior Alaska, approximately 30 km southeast of Fairbanks at 64°42′N, 148°19′W (Figure 2b). These sites are associated with the Bonanza Creek Long Term Ecological Research Program (lter.uaf.edu) and are part of the Alaska Peatland Experiment (APEX), which began in 2005 as an effort to understand water and carbon cycling in a rich fen (Turetsky et al., 2008) and has expanded to include thermokarst bogs and black spruce peat plateau areas (Euskirchen et al., 2014). As with the tundra sites, the boreal forest sites are in close proximity at 0.5 km apart, in distinct ecosystems and permafrost regimes.

With trees ~100 years old, the US-BZS site (Figure 2b) is in a mature black spruce forest (*Picea mariana*) that overlays an intact peat plateau of cold soils that rises ~130 cm from the surrounding landscape. US-BZF is a rich fen composed of grasses, sedges, and forbs but lacks trees and permafrost. The US-BZB site is in a collapsed scar bog within a circular depression that formed through thermokarst (subsidence resulting from the thaw of ground ice). The site contains active thaw margins with significant dieback of the *Picea mariana*.

Interior Alaska has a subarctic continental climate. Typically, snowpack is present from mid–late October through mid–late April. From 1991–2020, the 30-year MAAT was –2.1°C and the MAP was 296 mm, as measured at the Fairbanks International Airport (Geophysical Institute - University of Alaska Fairbanks, 2023), with 36% of the precipitation occurring as snow from October through April (Euskirchen et al., 2020).

These sites are representative of the boreal forest snow class. Sometimes called taiga snow, the snow here is characterized as thin, dry, and low density, consisting mainly of depth hoar by the end of winter (Sturm & Benson, 1997). This snow class is found in forested environments, where there is less wind action than on the tundra snow (Sturm & Liston, 2021). Wind is typically low in the Tanana Flats, with strong inversions present. Fairbanks International Airport mean winter (October–April) wind speeds are 1.7 m s^{-1} (Geophysical Institute - University of Alaska Fairbanks, 2023).

2.2 Types of Sublimation

Total sublimation equals surface sublimation plus blowing snow sublimation plus canopy sublimation (Molotch et al., 2007). During wind transport, blowing snow particles sublimate, but EC primarily measures only the turbulent fluxes of surface sublimation and does not directly measure blowing snow sublimation (Lackner et al., 2022; Reba et al., 2012; Stigter et al., 2018). This possible underestimate will be examined further in the Discussion section. Canopy sublimation takes place where snow is captured in tree canopies, but five of the six EC sites in this study are in low-growing vegetation environments where plants are completely covered by snow during the winter season so that the canopy sublimation term does not apply.

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3 Data and Methods

3.1 Eddy Covariance Sublimation Processing and Calculations

The EC technique measures turbulent fluxes between the land and atmosphere to calculate fluxes of gases, water, and heat per unit time (Burba & Anderson, 2008). EC towers at each of the six sites are equipped with a 3-D sonic anemometer and an infrared gas analyzer (IRGA) that measure the latent heat fluxes 10 times per second (10 Hz) 2.5–3 m above the ground. The instrument configurations, set-up, and data processing at the tundra and boreal forest sites have been fully described in Euskirchen et al. (2012, 2014, 2017, 2020). When making sublimation calculations, both filtered latent heat measurements (70%) and gap-filled data (30%) are used. When compared for all years, mean daily sublimation rates with only the filtered data were identical to within one hundredth of a millimetre to the gap-filled data. Due to prolonged power outages and equipment malfunction, some water years (defined as October 1–September 30) have missing data that were unable to be gap filled. Water years with missing data were not included in our analysis. Complete water years are listed in Table 1 in the Results. This is a unique dataset, as there are few long-term EC systems operating year-round in northern regions, particularly in the Arctic tundra.

Measured latent heat flux can be converted to half-hour averages of water vapor flux (mm) by dividing latent heat by either the latent heat of sublimation to derive sublimation and deposition (2.838×10^6 J kg^{-1}) or the latent heat of vaporization for evapotranspiration (ET) and condensation (2.454×10^6 J kg^{-1}). Sublimation and ET are calculated when the flux is positive (meaning direction of flux is to the atmosphere), while condensation and deposition are calculated when the flux is negative. Sublimation and deposition are calculated when snowpack is present; snowpack presence is determined from the albedometer installed on the EC towers and from webcam images at the sites. Total annual sublimation for each year is calculated based on the total number of days with snow cover present each snow season.

3.2 Meteorological and Snow Data

Meteorological data are collected at each EC tower at 15-second intervals and averaged over 30-minute periods. This includes air temperature, relative humidity, snow depth, net radiation, albedo, soil heat flux, and wind speed and direction.

At Imnavait Creek (Figure 2a), the University of Alaska Fairbanks (UAF) measures the end-of-winter SWE accumulation, and the U.S. Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS), measures solid precipitation at SNOTEL site 968 (Stuefer et al., 2020). The 900 snow depths and 50 snow density measurements are collected across Imnavait Creek, the same course every year, to calculate watershed average SWE (Figure 2a). Snow depth, snow density, and SWE data are available at the Arctic Data Center (Stuefer et al., 2019). The NRCS operates a storage gauge with a Wyoming wind shield (Figure 1c) and reports automated daily precipitation measurements (https://wcc.sc.egov.usda.gov/nwcc/site?sitenum=968). The NRCS Imnaviat [sic] SNOTEL site is collocated with the UAF 10 m weather station and has provided meteorological data collection since 1976 (Figure 2a). The weather station collects air temperature, relative humidity, and wind speed at 1 m, 3 m, and 10 m heights (https://ine.uaf.edu/werc/imnavait).

At the APEX sites (Figure 2b), SWE is measured with an automated snow pillow managed by the UAF Long Term Ecological Research (LTER) program (https://www.lter.uaf.edu/data/site-detail/id/52). Solid precipitation is not measured at boreal forest sites; therefore, we used precipitation measurements from the NOAA, NWS (National Oceanic and Atmospheric Administration, National Weather Service) weather station at Fairbanks International Airport (https://www.ncdc.noaa.gov/cdo-web/datasets/GHCND/stations/GHCND:USW00026411/detail).

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3.3 Statistical Methods and GIS

Standard statistical methods were applied to evaluate the relationship between sublimation rates and meteorological and environmental variables: Pearson's correlation coefficient (r) and single and multiple linear regression (MLR). Meteorological data used in statistical analysis included air temperature, net radiation, wind speed, vapor pressure deficit, and relative humidity. Analysis of variance (ANOVA) followed by a post hoc Tukey test was used to assess differences in sublimation rates between sites and study areas. GIS software ArcMap 10.8 was used for producing maps in Figure 1 and Figure 2.

4 Results

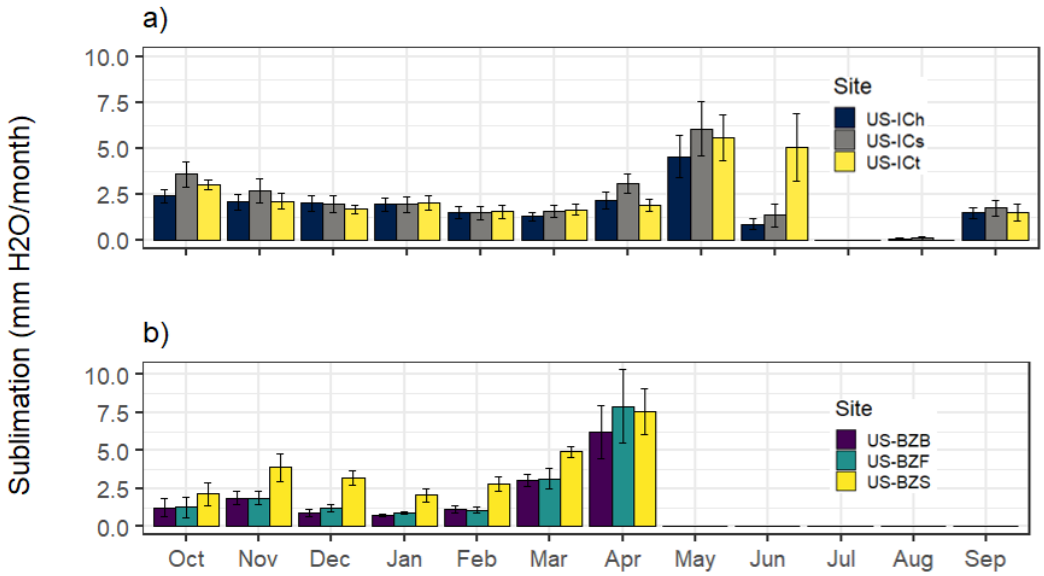
4.1 Daily, Monthly, and Annual Sublimation Rates

The summary statistics in Table 1 show daily and annual snow sublimation values. For the twelve-year period, mean daily sublimation rates are 0.08–0.10 mm per day in tundra and 0.08–0.15 mm per day in lowland boreal forest. The daily sublimation variability is high: standard deviation values are greater than the mean, and mean rates are 5–7% of the maximum daily rate. Mean annual rates are 20–26 mm per year in tundra and 15–27 mm per year in boreal forest. Annual standard deviation is nearly 50% of the mean. Across the six sites, daily and annual rates are highest at the black spruce site (US-BZS) and lowest at the thermokarst bog site (US-BZB) in the boreal forest snow class (Table 1). Snow cover duration at the tundra sites is two months (69 days) longer, on average, than at the lowland boreal forest sites. In Section 4.2.1, we further evaluate these sublimation rates in the context of the study area snow regime.

Table 1: Daily and annual sublimation rates in boreal forest and tundra snow.

Snow Sublimation Rates							
				Daily (mm day^{-1})		Annual (mm year^{-1})	
Ameriflux Site Name	Description	Water Years with Complete Record	# Days with Sublimation Data	Mean ± SD	Max	Mean ± SD	Max
US-ICt	Tussock Tundra	2013-2014, 2016-2021	1,761	0.10 ± 0.18	1.78	26 ± 7	38
US-ICh	Dry Heath Tundra	2010-2021	3,040	0.08 ± 0.13	2.25	20 ± 9	39
US-ICs	Wet Sedge Tundra	2010-2012, 2015-2021	2,518	0.10 ± 0.16	2.44	25 ± 12	49
US-BZF	Rich Fen	2015, 2017-2021	1,042	0.10 ± 0.16	1.92	17 ± 5	22
US-BZB	Thermokarst Bog	2014-2021	1,385	0.08 ± 0.13	1.52	15 ± 5	21
US-BZS	Mature Black Spruce	2011-2012, 2014-2021	1,106	0.15 ± 0.18	2.08	27 ± 6	35

Mean monthly (Figure 3) and cumulative annual (Figure 4) sublimation rates illustrate the variability over the course of an average winter, over the duration of the study period, and between sites within tundra and boreal forest snow classes. There is a steady loss of water vapor to the atmosphere over the course of the winter until spring. During the snow season, 1.5–2.4 mm month^{-1} of SWE sublimates at the tundra sites (Figure 3a) and 1.2–3.7 mm month^{-1} of SWE sublimates at the lowland boreal sites (Figure 3b). In the spring, prior to snowmelt, mean monthly sublimation increases to 5.4 mm month^{-1} in May at tundra sites (Figure 3a) and to 7.2 mm month^{-1} in April at lowland boreal sites (Figure 3b).



185 **Figure 3: Mean monthly sublimation throughout the water year at tundra sites (a) and lowland boreal forest sites (b). Error bars represent the standard error of the mean.**

Annually, relative rates between sites within tundra and lowland boreal forest snow classes are consistent (Figure 4). Specifically, in order of magnitude, tundra site sublimation rates increase from US-ICh (site on the ridge) to US-ICs (site at the valley bottom) to US-ICt (site at mid-slope). At the lowland boreal sites, sublimation rates are greatest at US-BZS (black spruce) and lowest at US-BZB (bog). In this way, sublimation rates during the years with incomplete data can be inferred
190 relative to the site(s) with available data.

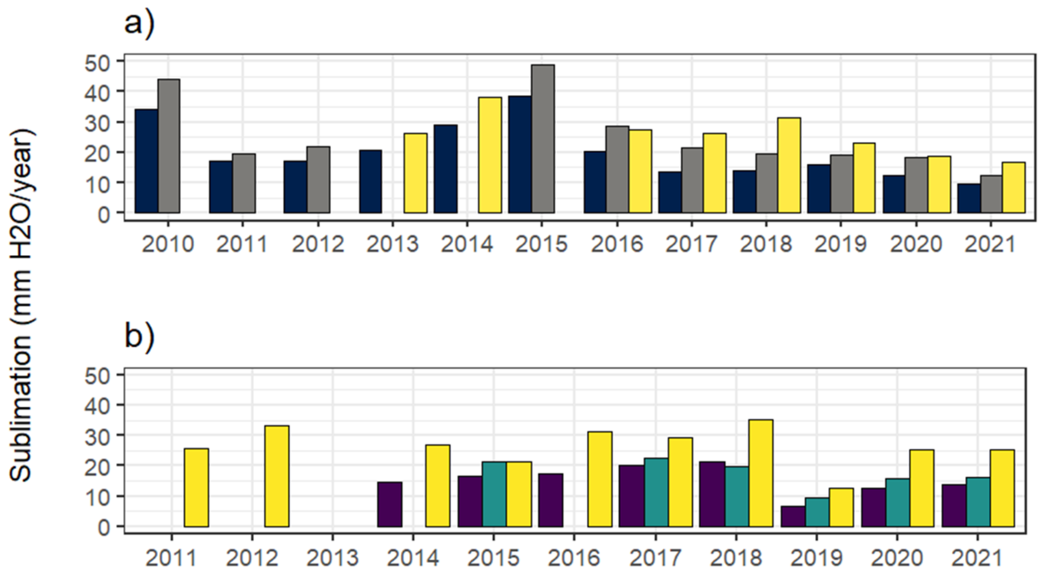


Figure 4: Cumulative annual sublimation by water year at tundra sites (a) and lowland boreal forest sites (b).

4.2 Comparison of Sublimation Rates with Other Water Fluxes

Snowpack, solid precipitation, snow cover duration, and other water vapor fluxes were compared with cumulative annual sublimation rates.

4.2.1 Snow Cover Duration, Snow Water Equivalent, and Solid Precipitation

On average, snow cover duration is 254 days at tundra sites (mean date of snow onset is September 19 and snow melt is June 1) and 185 days at boreal sites (mean date of snow onset is October 19 and snow melt is April 22; Table 2). Snow cover duration affects the magnitude of annual sublimation rates between snow classes: the lowland boreal sites have higher mean daily sublimation rates than the tundra sites, but the longer snow cover period on the tundra results in greater cumulative annual sublimation rates. Overall, there is nearly 2 cm of SWE that sublimates throughout the winter in both tundra and boreal forest snow classes.

Average end-of-winter SWE and winter precipitation were slightly higher at tundra sites (157 mm and 123 mm, respectively) than at boreal forest sites (145 mm and 114 mm, respectively). Between 2010 and 2021, winter solid precipitation increased at the lowland boreal sites (p value = 0.02 and r^2 = 0.39). There were no significant trends in the sublimation rates or in snow cover duration at the lowland boreal sites during the same time, nor were there any significant trends at the tundra sites. Snow sublimation flux equates to approximately 21% of the measured cumulative solid winter precipitation and 16% of end-of-winter SWE accumulated on the ground (Table 2).

Table 2: Mean annual sublimation rates compared with snow cover duration, solid precipitation measurements, and snow water equivalent (SWE) measurements.

	Mean Sublimation ± SD (mm yr^{-1})	Snow Cover Duration (days)	SWE (mm)	Percent of SWE that Sublimates (%)	Solid Precipitation (mm)	Percent of Solid Precipitation that Sublimates (%)
Tundra	24 ± 10	254 ± 13	157 ± 29	16% ± 7%	123 ± 31	20% ± 8%
Lowland Boreal	21 ± 7	185 ± 20	145 ± 37	16% ± 7%	114 ± 35	21% ± 10%

4.2.2 Water Vapor Fluxes

Table 3 details sublimation in conjunction with other seasonal vapor fluxes (ET, condensation, and deposition) to show the relative magnitude of moisture transfer in two northern climatic and snow regions throughout the year. Mean ET is 124 mm per year at tundra sites and 258 mm per year at boreal sites (Table 3). While mean ET is the largest vertical vapor flux during the warm season, sublimation is a substantial component of the winter water balance. Mean annual sublimation accounts for 8% of cumulative annual water vapor flux to the atmosphere (ET plus sublimation) at lowland boreal sites and 16% at tundra sites.

Table 3: Sublimation rates and other mean annual water vapor fluxes measured by the eddy covariance sensors.

	Mean Sublimation ± SD (mm yr^{-1})	Mean ET ± SD (mm yr^{-1})	Mean Condensation ± SD (mm yr^{-1})	Mean Deposition ± SD (mm yr^{-1})
Tundra	24 ± 10	124 ± 37	2.5 ± 1.2	6.0 ± 3.3
Lowland Boreal	21 ± 7	258 ± 39	5.1 ± 2.5	3.0 ± 1.0

4.3 Differences between Sites, Tree Presence, and Regions

Annual sublimation rates are grouped in box plots in Figure 5 by site. ANOVA and post hoc Tukey tests reveal that on an annual scale, the lowland boreal bog (US-BZB) measures significantly lower cumulative annual sublimation rates than the

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lowland boreal black spruce (US-BZS, p value = 0.01), the wet sedge tundra (US-ICs, p value = 0.03), and the tussock tundra (US-ICt, p value = 0.01). At no other site are cumulative annual sublimation rates significantly different.

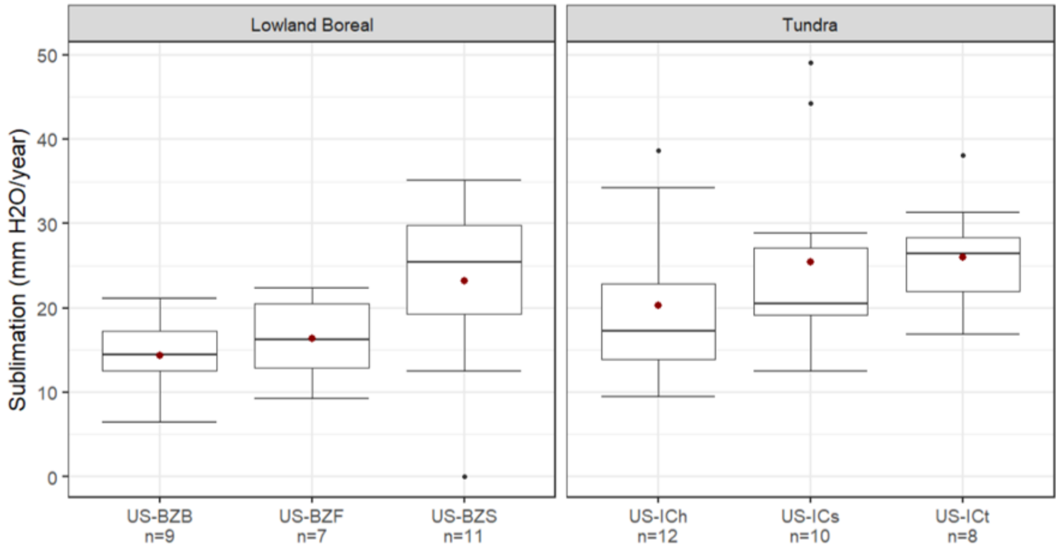

Figure 5: Cumulative annual sublimation by site. Red dot represents the mean.

When sites are grouped as containing trees or being treeless, to assess whether the canopy sublimation term differentiates a site's sublimation rates, an ANOVA test indicates that these rates are insignificantly different (p value = 0.08). Sites grouped by region, to assess whether tundra site cumulative annual sublimation rates are different from the rates of lowland boreal sites, show an insignificant difference (p value = 0.07).

4.4 Meteorologic Drivers of Sublimation Rates

Table 4 contains the mean correlation coefficients and standard deviations at lowland boreal forest and tundra sites. The magnitude of the coefficients varied between sites, and correlations generally improved when the time scale was increased to daily summaries (mean value for all variables, except as the sum of net radiation). Across all variables, the lowland boreal sites have stronger correlations with meteorological variables than the tundra sites. The greatest disparities in the strength of relationship between regions are higher wind speed and lower relative humidity; these variables have a stronger effect on sublimation rates at the lowland boreal sites than at the tundra sites. Vapor pressure deficit (VPD) has the strongest relationship with daily sublimation at both lowland boreal (r = 0.69) and tundra (r = 0.40) sites. Other factors that promote greater sublimation rates include warmer air temperature, elevated net radiation, and a low temperature gradient between the soil and the air. The low temperature gradient may be proxy for air temperature and indicate that extreme cold hinders sublimation.

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Table 4: Mean correlation coefficients (r) with standard deviations at the lowland boreal forest and tundra sites.

		Hourly	Daily[1]
Air Temperature (°C)	Lowland Boreal	0.40 ± 0.06	0.53 ± 0.05
	Tundra	0.30 ± 0.04	0.40 ± 0.05
Net Radiation (W m^{-2})	Lowland Boreal	0.43 ± 0.09	0.38 ± 0.16
	Tundra	0.36 ± 0.14	0.37 ± 0.12
Wind Speed (m sec^{-1})	Lowland Boreal	0.48 ± 0.06	0.56 ± 0.05
	Tundra	0.20 ± 0.05	0.25 ± 0.03
Vapor Pressure Deficit (hPa)	Lowland Boreal	0.56 ± 0.10	0.69 ± 0.05
	Tundra	0.33 ± 0.07	0.40 ± 0.08
Temperature Gradient[2] (°C)	Lowland Boreal	-0.40 ± 0.05	-0.47 ± 0.07
	Tundra	-0.28 ± 0.03	-0.32 ± 0.03
Relative Humidity (%)	Lowland Boreal	-0.44 ± 0.09	-0.48 ± 0.07
	Tundra	-0.08 ± 0.02	-0.05 ± 0.04

[1]Daily data are summarized as the mean value of all variables except for the sum of net radiation.

[2]Temperature gradient equals soil temperature minus air temperature.

Single and multiple linear regression (r^2) results between daily sublimation rates and meteorological variables are in Table 5. Three patterns consistent with the correlation coefficients hold:

1. wind speed and relative humidity at the lowland boreal sites have substantially stronger relationships with sublimation rates than at the tundra sites,
2. the lowland boreal sites have stronger trends with all meteorological variables than the tundra sites, and
3. the strength of the relationship of meteorological variables generally improved when the time scale was increased to daily summaries (mean value for all variables, except as the sum of net radiation).

The highest quality fully-crossed MLR at all sites was between air temperature, VPD, net radiation, temperature gradient (soil temperature minus air temperature), and wind speed, which explains 54–81% of the variance in daily sublimation and 43–62% of the variance in hourly sublimation rates depending on the site.

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Table 5: Single and multiple linear regression mean r^2 results with standard deviation values between sublimation rates and meteorological variables at the lowland boreal forest and tundra sites. All p-values < 0.05.

		Hourly	Daily[1]
Air Temperature (°C)	Lowland Boreal	0.17 ± 0.05	0.28 ± 0.05
	Tundra	0.09 ± 0.002	0.16 ± 0.04
Net Radiation (W m^{-2})	Lowland Boreal	0.19 ± 0.08	0.17 ± 0.11
	Tundra	0.17 ± 0.08	0.16 ± 0.09
Wind Speed (m sec^{-1})	Lowland Boreal	0.23 ± 0.06	0.32 ± 0.05
	Tundra	0.03 ± 0.01	0.06 ± 0.01
Vapor Pressure Deficit (hPa)	Lowland Boreal	0.32 ± 0.10	0.48 ± 0.07
	Tundra	0.11 ± 0.05	0.17 ± 0.07
Temperature Gradient[2] (°C)	Lowland Boreal	0.16 ± 0.04	0.22 ± 0.07
	Tundra	0.08 ± 0.02	0.11 ± 0.02
Relative Humidity (%)	Lowland Boreal	0.20 ± 0.07	0.23 ± 0.06
	Tundra	0.00 ± 0.00	0.00 ± 0.00
MLR: Air Temperature * VPD * Net Radiation * Temperature Gradient * Wind Speed	Lowland Boreal	0.62 ± 0.17	0.81 ± 0.05
	Tundra	0.43 ± 0.13	0.54 ± 0.09

[1]Daily data are summarized as the mean value of all variables except for the sum of net radiation.

[2]Temperature gradient equals soil temperature minus air temperature.

Cumulative annual sublimation rates are proportional to the length of the snow cover season at the lowland boreal sites (Figure 6; all p-values < 0.05 and r^2 is 0.4–0.8). There were no significant relationships between the sublimation rates and amount of solid precipitation or SWE at the lowland boreal sites. There were also no significant trends between sublimation rates and the same variables at the tundra sites.

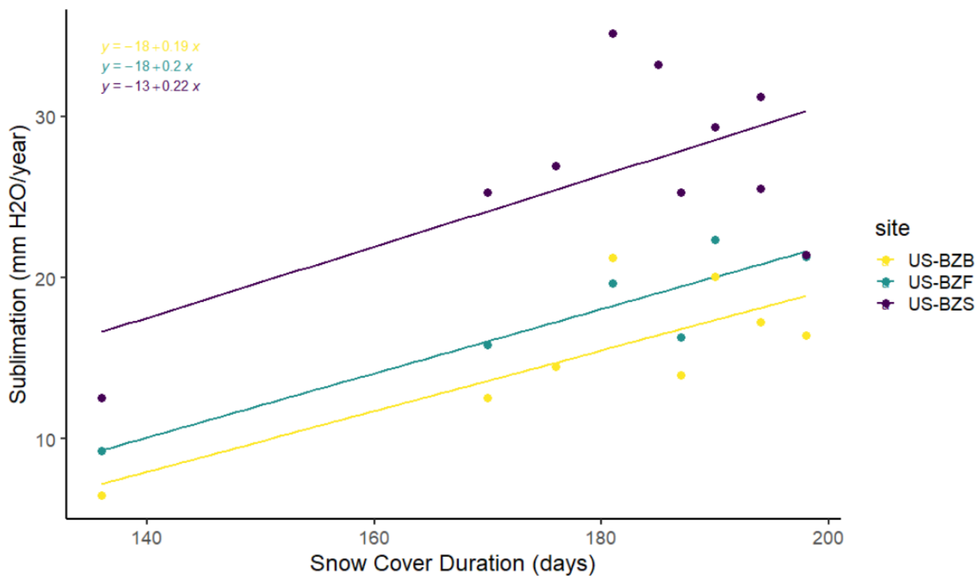

Figure 6: Significant linear model between sublimation rates and snow cover duration at the lowland boreal sites (p-values = 0.009–0.05 and r^2 = 0.3–0.8).

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5 Discussion

5.1 Uncertainty of Sublimation Measurements

EC measurements of sublimation contain a level of uncertainty. First, the EC method primarily measures surface sublimation (Lackner et al., 2022; Marks et al., 2008; Reba et al., 2012; Sexstone et al., 2016; Stigter et al., 2018) and substantially lacks the blowing snow term due to 1) sublimation of snow crystals that occurs above the sensors in the suspension layer and 2) affected / lost measurements due to the obstruction of the optical path of the IRGA by suspended snow (Lackner et al., 2022). The literature is inconclusive as to the percentage of total sublimation measured by EC, which is related to site-specific conditions of the snowpack and wind regime (Reba et al., 2012). Recent results from a numerical model of drifting snow sublimation indicate that the dominant contributor of total sublimation occurs in the saltation layer (Wang et al., 2019), which is the near-surface layer where blowing snow particles move in a bounding motion over the snow surface (Kobayashi, 1972). These findings suggest that the EC method should be capable of quantifying most of the latent heat loss since the saltation layer is well below EC sensors at the study sites. Nevertheless, it is necessary for drawing appropriate conclusions that these findings be viewed as underestimates of total sublimation in environments prone to snow transport by wind (e.g., tundra snow).

Data processing poses another uncertainty. This study chose to calculate sublimation when snowpack is present, from snow cover onset in the fall to complete melt in the spring. During the melt season in the spring, it is possible that liquid water is present in the snowpack and, therefore, that the measurement period was in fact evaporation of water, not sublimation of snow or ice crystals. This uncertainty when defining the measurement period results in a possible overestimate of sublimation rates in May.

5.2 Assessing Sublimation Rates with Meteorologic and Environmental Data

Hourly and daily sublimation rates exhibit moderate-quality significant relationships (Table 4 and Table 5): sublimation rates increase from warmer air temperatures, higher VPD, increased net radiation, low temperature gradient between the soil and air (which may be another way to evaluate that very cold winter temperatures hinder sublimation), elevated winds, and low relative humidity. The VPD has the strongest correlation with sublimination, which on average accounts for 48% of the variance in daily sublimation at the lowland boreal sites and 17% at the tundra sites. Across all meteorological variables, correlations with sublimation rates are substantially stronger at the lowland boreal sites than at the tundra sites.

Cumulative annual sublimation has a positive significant relationship with snow cover duration at the lowland boreal sites. The snow cover duration relationship is logical: more days with snow present are more days that sublimation is possible. This relationship may be an important environmental driver of sublimation rates as climate changes, since it is predicted that as Arctic and subarctic air temperatures continue to rise in the coming decades, the snow cover duration will decrease, though the amount of snow will increase (Brown et al., 2021).

5.3 Comparison of Sublimation Results with Other Studies

The daily sublimation rates (0.08–0.15 mm day^{-1}) reported in this study are on the low end when compared with all reported rates found in the literature by the same method (see Table 6 for studies), though similar to those in northern climates. Nakai et al. (2013) measured 0.09 mm day^{-1} and 18.2 mm year^{-1} in a 1-year study at a site within a lowland black spruce forest in Interior Alaska. Another study in the subarctic tundra of Hudson Bay (Lackner et al., 2022) measured 0.12 mm day^{-1}. These findings suggest that areas at high latitudes experience lower rates of daily sublimation than areas at lower latitudes. Longer snow cover seasons in Arctic tundra and boreal regions may lead to annual sublimation rates more comparable to those of lower latitudes; however, annual rates of sublimation in high latitudes are either not available or not included in the published research.

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There are noteworthy differences between this study and some of those included in Table 6. Some studies took place for less than a snow season (Molotch et al., 2007; Pomeroy & Essery, 1999; Stigter et al., 2018). Sublimation rates from Pomeroy and Essery (1999) were measured during blowing snow events only and are thus different from this study. Stigter et al. (2018) took measurements for 32 days in early winter months, rather than an entire snow season. Similarly, the study by Molotch et al. (2007) was confined to 40 days in the spring. Reba et al. (2012) only analysed sublimation for high-quality measurements and did not include gap-filled data, which left one site with as little as 16 days for the entire snow season from which to average. Furthermore, most of the studies (Knowles et al., 2012; Marks et al., 2008; Molotch et al., 2007; Reba et al., 2012; Sexstone et al., 2016; Stigter et al., 2018) took place at significantly lower latitudes, where energy inputs are greater than in northern Alaska and the Arctic.

Vegetation is a factor that contributes to the comparatively low sublimation rates at treeless sites. The tundra and fen vegetation communities (US-ICh, US-ICs, US-ICt, US-BZF) had similar sublimation rates since vegetation is completely buried under snow. Vegetation that remains above the snowpack, such as trees and tall shrubs, increases total sublimation rates due to the addition of the canopy sublimation term (Molotch et al., 2007) or increases snow availability in sufficiently tall, exposed shrubs where blowing snow collects (Mahrt & Vickers, 2005). While the results of the present study, which compared sites with trees (US-BZS) with sites without trees (all others), showed no significant difference (p value = 0.08), additional years of data and additional sites could provide more insight into the relationship.

Table 6: Comparison of sublimation rates from all known studies that use the eddy covariance method.

Study	Site Type	Location	Latitude, Longitude	Sublimation (mm day $^{-1}$)
This study	Arctic tundra	North Slope, Alaska	68°N,149°W	0.08–0.10
This study	Lowland boreal	Interior Alaska	64°N, 148°W	0.08–0.15
Knowles et al., 2012	Alpine tundra	Niwot Ridge, Colorado	40°N, 105°W	0.55
Lackner et al., 2022	Low-Arctic tundra	Hudson Bay, Canada	56°N, 76°W	0.12
Marks et al., 2008	Lodgepole pine forest	Fraser Forest, Colorado	40°N, 106°W	0.21
Molotch et al., 2007	Sub-alpine forest, below canopy	Niwot Ridge Forest, Colorado	40°N, 105°W	0.41
Molotch et al., 2007	Sub-alpine forest, above canopy	Niwot Ridge Forest, Colorado	40°N, 105°W	0.71
Nakai et al., 1999	Boreal forest, above canopy	Northern Japan	42°N, 141°E	0.6
Nakai et al., 2013	Lowland boreal	Interior Alaska	65°N, 147°W	0.09
Pomeroy & Essery, 1999	Prairie (blowing snow)	Western Canada	52°N, 107°W	1.8
Reba et al., 2012	Forest opening	Idaho	43°N, 116°W	0.39
Reba et al., 2012	Aspen forest	Idaho	43°N, 116°W	0.15
Sexstone et al., 2016	Forest opening	Colorado Rocky Mountains	40°N, 105°W	0.33–0.36
Stigter et al., 2018	Glacier	Himalaya	28°N, 86°E	0.99
Stössel et al., 2010	Alpine	Swiss Alps	46°N, 9°E	0.1

A few studies reported snow sublimation as the percentage of SWE lost to the atmosphere. Marks et al. (2008) measured 6.5% of total SWE sublimated over one snow season in Colorado. The study by Reba et al. (2012) occurred over two seasons and at two sites: a sheltered and an exposed site. Sublimation accounted for 4–8% and 16–41% of winter SWE, respectively. While Stigter et al. (2018) at the Yala Glacier in Nepal measured sublimation rates up to 30 times higher than in this study, the

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fraction of snowfall returned to the atmosphere was comparable, equalling 21% for the year investigated. Sublimation was only 5% of winter solid precipitation in a study conducted over three winters by Lackner et al. (2022) in the Canadian subarctic, though the authors noted that solid precipitation is high at the study site which thereby lowered the percentage.

Some studies assessed the environmental controls on sublimation rates. Reba et al. (2012) determined that a strong vapor pressure difference, moderate wind speeds, and cold temperatures resulted in the highest sublimation rates. Molotch et al. (2007) concluded that snowpack temperature gradients, diurnal temperature fluctuations, and unstable atmospheric conditions (measured by the Monin-Obukhov-length ratio) led to high vapor fluxes. Stigter et al. (2018) found a good-quality relationship between sublimation rates and vapor pressure difference, wind speed, and air temperature using multiple regression analysis (r^2 = 0.8) for a site in Nepal.

A study on ET from numerous EC measurements in Alaska found that ET at forest sites shows a stronger relationship with relative humidity and wind speed than ET at tundra sites (Thungberg et al., 2021). This result is congruent with findings from the present study regarding sublimation, where both correlation coefficients (Table 4) and linear regression (Table 5) show that the lowland boreal sites have a substantially higher dependence on relative humidity and wind speed relative to other factors compared with the tundra sites.

6 Conclusion

Sublimation rates were computed for 12 water years at three tundra sites and three lowland boreal sites in northern Alaska. Mean surface sublimation rates range from 0.08–0.15 mm day^{-1} and 15–27 mm year^{-1}, which is comparable to mean daily sublimation rates in northern regions reported by others using the same method (Lackner et al., 2022; Nakai et al., 2013). There is substantial variability in annual sublimation rates between water years at all sites, with the standard deviation equal to nearly 50% of the mean. The lowland boreal sites have higher mean daily sublimation rates than the tundra sites, though the longer snow cover period on the tundra produces greater mean annual sublimation rates. Water vapor loss to the atmosphere is relatively steady throughout the winter months and highest during spring months.

Annual sublimation rates significantly increase during years with longer snow cover seasons at the boreal forest sites. Sublimation rates are most strongly driven by high VPD, warm air temperature, high net radiation, and low temperature gradient at all sites. The lowland boreal sites exhibit strong dependence on wind speed and relative humidity, which is not seen at the tundra sites. This difference was also noted in a similar study on summer ET at Alaska EC sites (Thungberg et al., 2021).

On average, approximately 21% of solid precipitation and 16% of SWE sublimate each year. Mean annual sublimation accounts for 8% of the cumulative mean annual water vapor flux to the atmosphere (ET plus sublimation) at lowland boreal sites and 16% in tundra. Our measurements confirm that sublimation is a substantial component of the annual water balance and that sublimation measurements contribute to an improved understanding of the regional winter hydrologic cycle.

Six northern Alaska EC towers present a unique dataset, with measurements capable of computing surface sublimation at better certainty than estimates made to date at these research sites. Measurements are put in global perspective, as the sites are representative of boreal forest and tundra seasonal snow classes as defined by Sturm and Liston (2021). These data can be used for diagnosing problems, improving, and validating turbulent fluxes in energy and mass balance models (Marks et al., 2008), which is particularly important under changing climate conditions that include modifications in snow cover.

Data and code availability

Eddy covariance data from 2010 to 2021 are available through the Ameriflux website (https://ameriflux.lbl.gov/sites/site-search/?availability) using Ameriflux site ID listed in study area section.

Imnavait Creek SNOTEL daily precipitation data were downloaded from NRCS website (https://wcc.sc.egov.usda.gov/nwcc/site?sitenum=968) from 1981 to 2022.

The Imnavait Creek SWE data are available at the Arctic Data Center (https://arcticdata.io/catalog/view/doi%3A10.18739%2FA29G5GD77) from 1985 to 2017.

The UAF Imnavait Creek weather station data are available on the Water and Environmental Research Center website (https://ine.uaf.edu/werc/werc-projects/imnavait/current-data/meteorological-stations/imnavait-met/).

The SWE automated snow pillow is available at the Bonanza Creek LTER website (https://www.lter.uaf.edu/data/data-detail/id/177).

Scripts used for analysis and plots are written in RStudio version 4.2.2. The code and datasets are available on GitHub (https://github.com/kstockert4/sublimation.git).

Author contribution

Kelsey Spehlmann performed the formal analyses and prepared the manuscript. Svetlana Stuefer and Eugénie Euskirchen supervised the project and reviewed and edited the manuscript. Svetlana Stuefer and Kelsey Spehlmann conceptualized this project and acquired the funding. Eugénie Euskirchen curated the eddy covariance data and provided technical expertise with that dataset.

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