Response to RC2 comment on "Sublimation Measurements of Tundra and Taiga Snowpack in Alaska" by Kelsey Spehlmann, Eugénie Euskirchen, and Svetlana Stuefer.

RC2: 'Comment on tc-2023-153', Anonymous Referee #2, 21 Jan 2024

Dear Reviewer,

We thank you for your constructive and insightful comments. The following pages contain comments that appear exactly as they were received. Our responses are inserted next to each comment in blue text. Thank you again for taking time to review our manuscript.

Sincerely,
Kelsey Spehlmann, Eugenie Euskirchen, and Svetlana Stuefer

General Comments:

The manuscript presents an interesting study on snow sublimation quantification in tundra and boreal forest sites in Northern Alaska. Snow sublimation was calculated using latent heat data from eddy covariance measurements over ~12 years at six sites differing by snow classes, vegetation communities, and permafrost. As stated in the manuscript, few studies have quantified sublimation in such environments by direct measurements. However, the knowledge gaps this study aims to address compared to previous studies, which are only briefly mentioned, need to be better highlighted in the Introduction.

Response 1: Thank you for your review and suggestions. We expanded our introduction by including references to the previous studies: "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, in the Arctic, using field observations to make this moisture budget calculation produces sublimation estimates that are wide-ranging and unreliable due to errors associated with solid precipitation measurements (Goodison et al., 1998; Nitu et al., 2018). Systematic biases in solid precipitation measurements include wind undercatch, wetting loss, and evaporation loss (Fassnacht 2004; Goodison et al. 1998; Nitu et al. 2018). Sublimation can also be estimated by solving energy balance equations; including the Penman Monteith, bulk aerodynamic, and aerodynamic profile methods (Marks et al., 2008; Sexstone et al., 2016; Stigter et al., 2018) or direct measurements.

Next to quantifying the magnitude of snow sublimation, the study aimed to assess the sublimation spatial and temporal variability. This assessment can benefit significantly from the availability of the time series length at different sites. However, this variability is not enough described and discussed, for example among sites within the same snow class as shown by the mean monthly sublimation analysis. The relation between sublimation rates and snow cover length shows that the strength of the connection between the two variables can be quite different among sites for the same snow class, too. Differences in the interannual variability of cumulative annual sublimation between snow classes are also not described and further explored. Additional investigations and links to the effect of meteorological variables and, or site characteristics will be beneficial to improve this assessment.

Response 2: Thank you for this feedback. We have extended the discussion section to include these points. Specifically, we further assess the two snow classes presented (between and within) with regard to

(1) mean monthly sublimation rate variability, (2) cumulative annual sublimation rate interannual variability, (3) snow cover duration, (4) meteorological variables, and (5) site characteristics.

Similar considerations apply to the analysis between sublimation rates and meteorological drivers. No figures with the spatial and temporal variability of the meteorological data are shown, nor figures with correlations between variables. These figures need to be included to support the study results and discussion.

Response 3: The focus of this study is on sublimation rates; we therefore limited the bulk of the analysis to those rates. As a result, both the spatial and temporal variability as well as the correlations between variables of the meteorological data are not analyzed. To address this comment, we added monthly summaries of wind speed, air temperature, and precipitation to provide comparison of meteorological settings between the Tundra and Boreal Forest sites.

Table 1: Monthly meteorological summaries for tundra and lowland boreal regions.

	Mean Daily Air Temperature (°C)		Mean Daily Wind Speed ($m\ s^{-1}$)		Max Daily Wind Speed ($m\ s^{-1}$)		Total Precipitation Normal[1] (mm)	
	Tundra	Lowland Boreal	Tundra	Lowland Boreal	Tundra	Lowland Boreal	Tundra	Lowland Boreal
January	-18	-20	2.6	0.9	22.7	12.6	9	15
February	-17	-16	2.9	1.1	20.1	8.3	13	13
March	-16	-10	2.6	1.3	15.9	8.8	9	10
April	-9	1	2.5	1.5	12.7	8.5	10	9
May	0	11	2.4	1.5	14.5	7.6	18	14
June	8	16	2.5	1.4	12.2	6.2	46	38
July	10	17	2.4	1.3	26.9	21.4	80	57
August	6	13	2.3	1.2	11.2	6.3	72	53
September	0	7	2.3	1.1	14.4	8.8	33	34
October	-7	-1	2.3	1.0	12.9	13.0	23	19
November	-15	-12	2.6	1.0	19.5	18.4	14	19
December	-18	-16	2.4	0.9	15.9	10.8	12	14
Annual	-6.3	-0.8	2.5	1.2	16.6	10.9	339	295

Some variables, e.g. vapour pressure deficit and temperature gradient, need to be introduced, and the information they provide regarding processes at the different sites needs to be explained.

Response 4: We introduced VPD and temperature gradient in Section 3.2 and expanded on process-related explanations in the results and discussion.

The reasons why some correlations are more robust than others depending on the site and why correlation strength increases with the time scale should be adequately discussed.

Response 5: We added the explanation of correlation strength with time to the discussion. “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.”

The discussion of the study's results compared to other studies is valuable. However, more clarity is necessary on how this study stands compared to the other studies, for example, in the vegetation and meteorological controls paragraphs.

Response 6: We clarified comparison with our study to other studies in the discussion. "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 high latitude areas experience lower rates of daily sublimation than areas at lower latitudes in Table 7. 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."

Consider addressing all the points mentioned above and in the following detailed comments to enhance the presented work's clarity, readability, and strength.

Detailed Comments:

Line 12: What does it mean "with differing permafrost conditions"? Please clarify.

Response 7: Replaced that phrase with "discontinuous permafrost and differing ecosystems" to distinguish the boreal forest sites from the continuous permafrost at the tundra sites.

Line 17-18: What is the key finding of this analysis? Please add.

Response 8: Added that "sublimation is a substantial component of the winter hydrologic cycle" into the abstract.

Line 25: Only one reference?

Response 9: The Stigter et al. (2018) reference provided that particular estimate of sublimation importance. Other papers have varying estimates.

Line 26: Please elaborate more on the challenges of measuring snow sublimation.

Response 10: The challenges of measuring snow sublimation is elaborated in the Introduction: "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."

Line 30: Please elaborate more on the error associated with precipitation measurements.

Response 11: Added that "Systematic biases in solid precipitation measurements include wind induced undercatch, wetting loss, and evaporation loss (Fassnacht 2004; Goodison et al., 1998, Nitu et al., 2018)."

Line 34-35: Please add references.

Response 12: Added Guo et al. 2018; Herrero & Polo, 2016

Line 54: This could be moved in the study area section.

Response 13: We believe that the Introduction section benefits from noting the EC locations and associated snow classes in the study.

Line 69: Please mention what is Ameriflux.

Response 14: Clarification that "AmeriFlux is a network of EC research sites across the Americas" was added to Section 2.1.

Line 116: The function of this section here needs to be clarified. Types of sublimation can be mentioned in the Introduction, and details on the sublimation estimated by EC in section 3.1.

Response 15: This section is important part of study characteristics. It points out sublimation processes typical for our study locations: "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."

Line 127: If the instrument measures latent heat fluxes at 2.5-3m, is it below or above the vegetation canopy? In line 121, it is stated that the canopy sublimation term does not apply for five out of six EC sites; what about the site with tall vegetation? What is the effect of canopy sublimation there? Please clarify.

Response 16: This is a good point. The instruments are all above the canopy, as necessitated by the requirements of the eddy covariance methodology. We have added information specifying that the black spruce instrumentation is mounted higher – at 5 m. "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) 2.5–5 m above the ground (and above the canopy)." The effect of canopy sublimation is summarized in results, Section 4.3 Differences between Sites, Tree Presence, and Regions.

Line 129-130: This sentence needs to be clarified. What are filtered latent heat measurements and gap-filled data? How are gaps filled? It is not enough to mention that information is described in the references as this is the primary measuring method used. Please provide essential information.

Response 17: More detailed, essential information has been added to Section 3.1 regarding filtered and gap-filled data processing, such as "Filtering primarily refers to removing data when there is optical impedance by precipitation or aerial contaminants. This is denoted by the automatic gain control values measured by the infrared gas analyzers. These values are used as a quality assurance/quality control variable for both flux and radiation data, with 60% as the maximum threshold AGC value."

Line 163: This variable has yet to be introduced; please specify what it is and which measure it provides.

Response 18: We added the vapor pressure deficit definition to Section 3.2.

Line 164-165: Please add references, explain the purpose of using a post hoc Tukey test and add the significance level.

Response 19: Included the Gottelli and Ellison (2004) reference, explained the Tukey test, and added the significance level for all statistical methods in Section 3.3: "Standard statistical methods were applied to the dataset for the following analyses (Gottelli & Ellison, 2004): 1) Ordinary least squares (OLS) regressions were used to evaluate sublimation rates with other water fluxes, with meteorological and environmental variables, and over time; 2) Analysis of variance (ANOVA) calculated whether there are differences in sublimation rates between the six sites, between regions, and between sites with a canopy. For tests with more than two groups, the ANOVA is followed by post hoc Tukey test s for pairwise comparisons to identify which means among a set of groups are significantly different from each other; 3) and Pearson's correlation coefficient (r) and single (OLS) and multiple linear regressions (MLR) evaluated the relationship between sublimation rates and meteorological and environmental variables: Pearson's correlation coefficient (r) and single and multiple linear regression (MLR). The three methods use a significance level of 0.05."

Line 177: Please clarify what is meant for "an average winter".

Response 20: Modified the sentence to read "over the snow season".

Line 180-181: What do these sublimation rates represent? The mean of the three sites? Please clarify.

Response 21: "*a range of* 1.5-2.4 mm/month…" added to the sentence to clarify.

Line 181-182: See previous comment.

Response 22: See Response 21.

Line 189-190: The relative change among a region's sites is quite variable over the years. Additional analyses are needed to support this statement.

Response 23: We removed those lines in the revised manuscript.

Line 220: Please specify whether significant differences refer to the mean of the annual sublimation rates at the different sites.

Response 24: We talk about cumulative annual rates (not mean of the annual sublimation rates). That line has been rephrased for clarity.

Line 231: Please state the two variables of the correlation. Please specify the type of correlation coefficient.

Response 25: Added the two variables (hourly and daily sublimation rates) as well as the type of correlation coefficient. Methods Section 3.3 also states that Pearson's correlation coefficient are used.

Line 251: Are the same explanatory variables providing the highest r^2 for the lowland boreal forest and tundra sites? It would be informative to show how the r^2 increases by including stepwise the explanatory variables.

Response 26: Yes, this is noted in Section 4.4 and further discussed in Section 5.2.

Line 235: This sentence needs to be clarified. Please refer to where information about "higher wind speed" and "lower relative humidity" can be found in the manuscript.

Response 27: We clarified this sentence and added reference to Table 4 in that sentence, where the reader can compare the r^2 values between sites for a given explanatory variable.

Line 272: Please elaborate more about the findings from the literature and this study.

Response 28: The intent of this line is to state how the scientific community does not have resolution on the matter and likely varies by site, as supported with numerous references (Lackner et al., 2022; Marks et al., 2008; Reba et al., 2012; Sexstone et al., 2016; Stigter et al., 2018; Wang et al. 2019).

Line 285-286: This sentence needs to be clarified. How is it possible to deduce this statement from Tables 4 and 5?

Response 29: Thank you for pointing this out. We restated the sentence to state that sublimation rates were positively correlated with air temperatures, VPD, and net radiation and negatively correlated with temperature gradient, wind speeds, and relative humidity.

Line 301: Which lower latitudes? Please clarify. This terminology is used in line 312, too, making the context unclear.

Response 30: Latitude is in Table 6: Comparison of sublimation rates from all known studies that use the eddy covariance method (please see fourth column).

Line 309-310: This sentence needs to be clarified.

Response 31: The sentence has been rephrased to clarify what high-quality measurements are.

Line 319-320: Is it not possible to advance any explanation about these results?

Response 32: This sentence has been removed.

Figure 4: Legend is missing; please add it.

Response 33: Thank you, the legend was added.

Figure 5: Please add some explanation in the caption about significant differences.

Response 34: The explanation was added: "Cumulative annual sublimation by site. Red dots represent the mean, boxes enclose the 1st and 3rd quartiles, horizontal line within the box is the median, whiskers denote the minimum value below the closest quartile ± 1.5 x interquartile range, and points outside the whisker are outliers. US-BZB sublimation is significantly different from US-BZS and US-ICt."

Figure 6: In the manuscript, the range reported for r^2 is 0.4-0.8. Please check consistency. Please add which r^2 belongs to which relation and define what r^2 is in the caption.

Response 35: We fixed this inconsistency and appreciate you noting the mistake.

Table 5: Please define r^2 in the caption.

Response 36: Added to the caption "coefficient of determination (r^2)"

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Response 37: Thank you again for taking time and providing comments on this sublimation manuscript.