Editor comments

Comment 1

1) Your Response 1.1 to Comment 1.1 is not considered as sufficient by the editor. Please add a better description of the novelty and advancement of the submitted manuscript compared to earlier studies would be beneficial. This should be placed into the Discussion.

Response 1

We appreciate the editor's careful review and comments. The paper was further revised accordingly. All changes were highlighted in blue in the revised manuscript and the responses below.

Thanks for the comment. Compared with the recent studies with a similar focus on resolving multi-resolution ALT patterns and their environmental linkages (Brodylo et al., 2024; Hantson et al., 2025), our study differs in three respects, which include (a) advancing from transect-based (1-dimensional) sampling to intensive 2-dimensional grid-cell sampling, which provided a more comprehensive representation of spatial variability to support multi-resolution analysis; (b) characterizing ALT patterns in the unique Arctic-foothills tundra environment, thereby complementing existing studies for Interior Alaska (Brodylo et al. 2024) and the Seward Peninsula (Hantson et al. 2025); and (c) quantifying resolution-dependent uncertainties in ALT retrievals, offering additional support for improved interpretation of multi-resolution ALT products derived from remote sensing and process-based simulations for the changing Arctic.

In the revision, we added the following in the Discussion section.

"Recent studies have focused on resolving multi-resolution ALT patterns and their environmental linkages using multi-sensor remote sensing (Brodylo et al., 2024; Hantson et al., 2025). Compared with the existing studies, our study differs in three respects, which include (a) advancing from transect-based (1-dimensional) sampling to intensive 2-dimensional grid-cell sampling, which provided a more comprehensive representation of spatial variability to support multi-resolution analysis; (b) characterizing ALT patterns in the unique Arctic-foothills tundra environment, thereby complementing existing studies for Interior Alaska (Brodylo et al. 2024) and the Seward Peninsula (Hantson et al. 2025); and (c) quantifying resolution-dependent uncertainties in ALT retrievals, offering additional support for improved interpretation of multi-resolution ALT products derived from remote sensing and process-based simulations for the changing Arctic".

Comment 2

2) Your Response 1.3 to Comment 1.3 is not considered as sufficient by the editor. Unless you refer to changes pointed out in later responses. If not, please add improvements directly addressing the comment by Reviewer #1, i.e.:
a. It is difficult for example, for the reader to compare the measured values to the ML outputs in figure 4 as the study plot area isn't clear.
b. The text refers to ALT variability near water bodies, but the results presented (i.e. maps) do not allow the reader to see this.
c. Consideration of the accuracy of the models in terms of the entire area covered is fine but it is useful to

consider which areas of the study area and under what conditions the accuracy is better.

Response 2

Thanks for pointing out the issue. As suggested, we directly addressed the reviewer comments as follows:

To address the comment “It is difficult for example, for the reader to compare the measured values to the ML outputs in figure 4 as the study plot area isn’t clear”, Figure 4 was re-plotted to improve presentation and comparison, and ensure ALT measurements and ML predictions were mapped over the same overlapping areas for each study plot. The updated Figure 4 is also presented below.

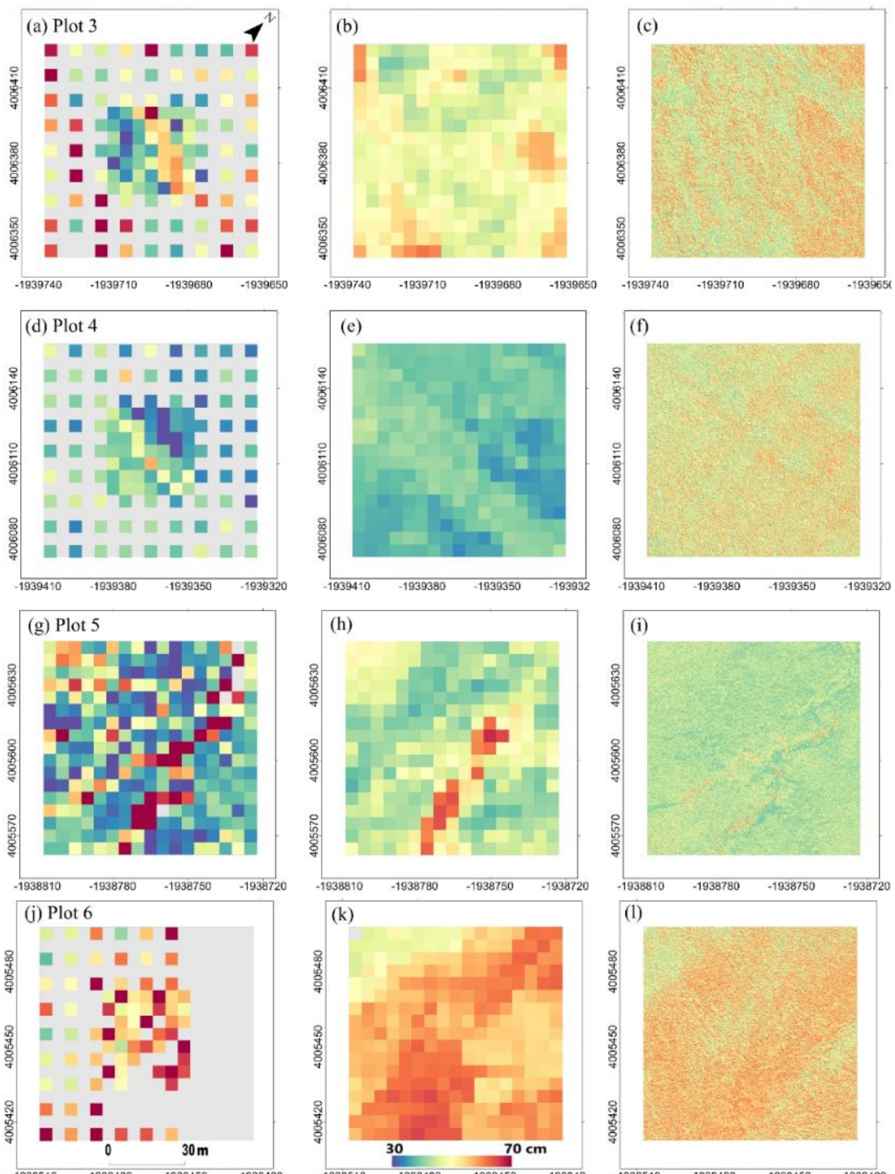

Figure 4: Comparisons of ALT spatial patterns derived from field measurements (a, d, g, j), 5-m machine learning outputs (b, e, h, k), and 0.1-m machine learning estimates (c, f, i, l) for the intensively sampled plots (grey shading indicates areas without sampling). The map was plotted using Canada Albers Equal Area Conic projection.

To address the comment "The text refers to ALT variability near water bodies, but the results presented (i.e. maps) do not allow the reader to see this", we re-plotted Figure 4 (please refer to the figure above) for improved presentation and added the following in Section 4.1.1 to specify (a) the areas with substantial ALT variations near water bodies and (b) the differences of the ML-results in different resolutions:

"Specifically, higher ALT values are visible along Imnavait Creek within Plot 5, as shown by the red pixels in the field measurements (Fig. 4g), 5-m ML predictions (Fig. 4h), and 0.1-m ML results (Fig. 4i). However, field sampling revealed substantial ALT variation within individual 5-m grid cells, with a standard deviation of up to 32 cm as distance from the watercourse increases. These meter- to sub-meter variations are only resolved in the 0.1-m results (Fig. 4i), which distinguish the high ALT values along the creek (red pixels) from the lower values in adjacent areas (blue pixels). Similarly, the stripe patterns of ALT in Plot 4 associated with alternating bands of dwarf willow, grasses, and tussocks (Fig. 1; Section 2) are clearly defined in the 0.1-m predictions (Fig. 4c) but are not discernible in the 5-m results (Fig. 4b). For Plot 6 where overall high ALT is observed (Fig.4 j, 4k, and 4i), heterogeneity is only captured by the 0.1-m results (Fig. 4l). The pattern of interspersed lower-ALT (non-red) pixels within high ALT areas (Fig. 4l) is likely associated with widespread clusters of underlying rocks and complex vegetation cover observed in the field (Fig. 1; Section 2)".

To address the comment "Consideration of the accuracy of the models in terms of the entire area covered is fine but it is useful to consider which areas of the study area and under what conditions the accuracy is better", we added the following in Section 4.1.1 for clarifying the model performance and uncertainties.

"Considering the larger ALT variability and more diversified surface conditions at 0.1-m resolution relative to the 5-m resolution, the RF model trained using limited 5-m data set may not be able to fully capture the 0.1-m ALT variations, leading to inconsistency of the overall ALT patterns between the 5-m and 0.1-m results (e.g., Plot 4; Fig. 4d, 4e, 4f) and additional uncertainties in the multi-resolution analysis. In addition, the RF predictions tended to be centralized, which may underestimate larger ALT values (e.g., fewer dark red pixels with ALT higher than 65 cm in Fig. 4h and 4i than the measurements in Fig. 4g) and overestimate smaller ones relative to the measurements (e.g., dark blue pixels with measured ALT smaller than 35 cm in Fig. 4g but not in the ML predictions in Fig. 4h and 4i)".

Comment 3

3) Your response addresses the difference of the ML-results in different resolutions, but not actually in which areas of the actual study area and under what conditions the accuracy is better. This has to be amended.

Response 3

Thanks for the comment. We first specified the differences of the ML-results in different resolutions in Section 4.1.1 as follows:

"The resulting 5-m and 0.1-m ALT maps were compared with the field measurements (Fig. 4). The 5-m ALT maps (Fig.4b, 4e, 4h, 4k) captured the primary ALT patterns observed from the field measurements (Fig. 4a, 4d, 4g, 4j) including elevated ALT along the perimeter of Plot 3, consistently low ALT throughout Plot 4, high ALT values following the water tracks in Plot 5, and generally deep ALT in Plot 6. The 0.1-m results revealed significantly finer variations (Fig. 4c, 4f, 4i, and 4l) …. Specifically, higher ALT values are visible along Imnavait Creek within Plot 5, as shown by the red pixels in the field measurements (Fig. 4g), 5-m ML predictions (Fig. 4h), and 0.1-m ML results (Fig. 4i). However, field sampling revealed substantial ALT variation within individual 5-m grid cells, with a standard deviation of up to 32 cm as distance from the watercourse increases. These meter- to sub-meter variations are only resolved in the 0.1-m results (Fig. 4i), which distinguish the high ALT values along the creek (red pixels) from the lower values in adjacent areas (blue pixels). Similarly, the stripe patterns of ALT in Plot 4 associated with alternating bands of dwarf willow, grasses, and tussocks (Fig. 1; Section 2) are clearly defined in the 0.1-m predictions (Fig. 4c) but are not discernible in the 5-m results (Fig. 4b). For Plot 6 where overall high ALT is observed (Fig.4 j, 4k, and 4i), heterogeneity is only captured by the 0.1-m results (Fig. 4l). The pattern of interspersed lower-ALT (non-red) pixels within high ALT areas (Fig. 4l) is likely associated with widespread clusters of underlying rocks and complex vegetation cover observed in the field (Fig. 1; Section 2)".

We then added the following in section 4.1.1 for clarifying the model performance and uncertainties.

"Considering the larger ALT variability and more diversified surface conditions at 0.1-m resolution relative to the 5-m resolution, the RF model trained using limited 5-m data set may not be able to fully capture the 0.1-m ALT variations, leading to inconsistency of the overall ALT patterns between the 5-m and 0.1-m results (e.g., Plot 4; Fig. 4d, 4e, 4f) and additional uncertainties in the multi-resolution analysis. In addition, the RF predictions tended to be centralized, which may underestimate larger ALT values (e.g., fewer dark red pixels with ALT higher than 65 cm in Fig. 4h and 4i than the measurements in Fig. 4g) and overestimate smaller ones relative to the measurements (e.g., dark blue pixels with measured ALT smaller than 35 cm in Fig. 4g but not in the ML predictions in Fig. 4h and 4i)".

Comment 4

4) Your Response 1.5 does not include an updated version of Section 2, so your improvements are not visible to the editor yet.

Response 4

As suggested, the updated version of Section 2 was added in the Response 1.5 and is presented below.

"Our study focused on the Imnavait Creek (68.6167° N, 149.3167° W) area within the Alaskan North Slope tundra foothills region (Fig. 1). The study region experiences a cold climate with a mean annual temperature of -7.4°C, ranging from an average of -17°C in January to 9.4°C in July (Schramm et al., 2007). Annual precipitation averages 340 mm, two-thirds of which falls as light rainfall during the summer (Schramm et al., 2007). The dominant vegetation consists of water-tolerant plants like tussock sedges and mosses, grasses and low shrubs (Schramm et al., 2007). Vegetation and soil patterns vary with slope, aspect, and drainage conditions, exhibiting a patchy distribution across the study domain (Hinkel and Nelson, 2003). The region is also characterized by diverse glacial landforms, including deposits, stream networks, and bedrock outcrops (Hinkel and Nelson, 2003). The region has gently rolling terrain, with elevations ranging from ~750 m to 980 m. Vegetation and soil patterns vary with slope, aspect, and drainage conditions, exhibiting a patchy distribution across the study domain (Hinkel and Nelson, 2003). The region is also characterized by diverse glacial landforms, including deposits, stream networks, and bedrock outcrops (Hinkel and Nelson, 2003). Increasing ALT was observed from both in-situ measurements at the Circumpolar Active Layer Monitoring (CALM) sites (https://www2.gwu.edu/~calm/data/north.htm) and regional ALT records at 1-km resolution, which were generated using machine learning by combining in situ ALT observations with a suite of observational biophysical variables (Liu et al., 2024).

The local study area consisted of four intensively sampled field plots (Plot 3, Plot 4, Plot 5, and Plot 6 in Fig. 1; 90m ×90m each) distributed across an elevation gradient along west facing hill slopes, and surrounded by a larger (5 km by 5 km) landscape domain used for analyzing ALT across different resolutions (Fig.1; Table 1). The field plots are dominated by tussock-forming sedges and moss-lichen mats, along with scattered dwarf birch shrubs, and riparian grasses (Fig. 1-2). The common species identified near the ALT sampling points include dwarf birch (*Betula nana*), alpine blueberry (*Vaccinium uliginosum*), black bearberry (*Arctous* spp.), crowberry (*Empetrum nigrum*), and *Arctostaphylos uva-ursi*, among other less-recognizable species. Our soil coring samples indicated high organic matter content of the topsoil (0-10 cm depth) for Plots 3, 4 and 5, with the respective values of 77.3%, 75.1%, and 71.8%, contrasting with a relatively low value of 45.5% for Plot 6.

Plot 3 and Plot 4 are located on west-facing downhill slopes characterized by gradual elevation changes (10-15 m across the plot), small water tracks, and scattered glacial erratics. Plot 3 is crossed by multiple drainage features that are transverse to the Kuparuk River (Fig. 1). These features are evident in the topography as well as the vegetation, with alternating bands of dwarf willow, grasses, and tussocks. Standing water is present in many places, as are glacial erratics, particularly along the drainage channels. Plot 4 is more homogeneous in vegetation character and height, consisting mostly of grass tussocks and moss, with some larger glacial erratics present.

Plots 5 and 6 are on the east side of the access road and are more level than Plots 3 and 4. Plot 5 is located at a valley bottom and is partitioned by Imnavait Creek, which winds directly through the middle of the plot. Shallow drainage channels transverse to Imnavait Creek are found on the west side of the plot, while the east side is upland and drier. Vegetation cover in Plot 5 follows the typical mix of grasses, mosses, and sedges, with some moss forming humps about 20 cm tall, while shrub density and height increase close to the creek. Along Imnavait Creek there are taller (0.5-1.0 m) birch shrubs and more grasses. Plot 6 is characterized by widespread subsurface rocks (Fig. 1) and overall short-statured grass-sedge tussocks and mosses, lichens, small bunchgrasses, *Arctous spp*., and alpine blueberry, interrupted by areas of bare rock and gravel. Bare areas are common in the center of the plot.

As part of the NASA Arctic Boreal Vulnerability (ABoVE) field campaign, our study used ABoVE standard projection, which is Canada Albers Equal Area projection (https://above.nasa.gov/implementation_plan/standard_projection.html), for data visualization and analysis.

Table 1. Summary of surface and soil conditions for the sampling plots

Name	Plot 3	Plot 4	Plot 5	Plot 6
Elevation	810 m	846 m	855 m	875 m
vegetation	dwarf willow, grasses, and tussocks	grass tussocks and moss	mix of grasses, mosses, and sedges	grass tussocks and mosses
Organic matter content	77.3%	75.1%	71.8%	45.5%
Unique characteristics	ephemeral, drainage features	homogeneous in vegetation character and height	located in a valley bottom and partitioned by Imnavait Creek	widespread subsurface rocks
ALT	49 cm	39 cm	44 cm	58 cm

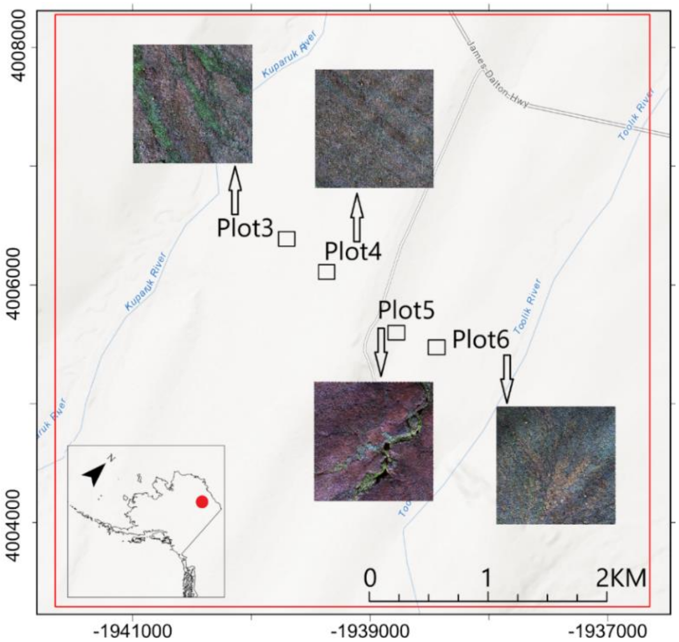

Figure 1: The study region encompasses an Arctic tundra area (68.6167°, -149.3167°; red dot in the inset) in the northern foothills of the Brooks Range, Alaska. The region consists of four intensively sampled plots (Plot 3, Plot 4, Plot 5, and Plot 6; 90 m x 90 m each) with their corresponding true-color RGB (red-green-blue) drone images displayed alongside alongside for visual inspection only, and surrounded by a larger 5km by 5km study region (red rectangle) used for analyzing ALT scaling effects. The map was plotted using Canada Albers Equal Area Conic projection.

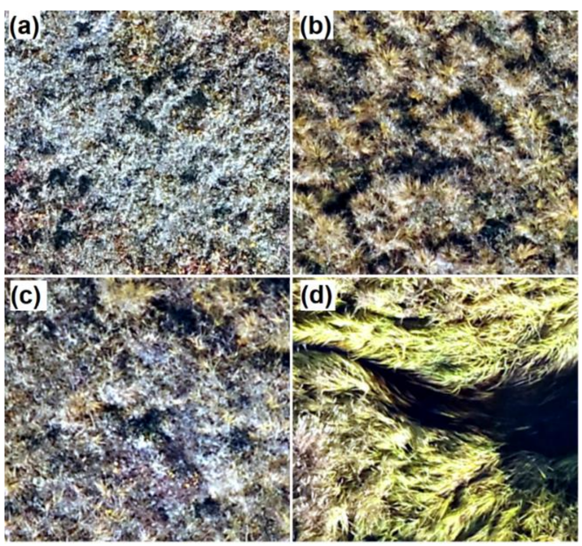

Figure 2: The study region contains characteristic tundra vegetation types, including dwarf shrubs (a), tussock-forming sedges (b), moss-lichen mats (c), and riparian grasses along watercourses (d). The images (0.7cm resolution) were acquired from a drone-based RGB camera.

”

Comment 5

5) Your Response 1.21: What is “an informal survey”? Please explain or use a better expression.

Response 5

We used “an informal survey” to reflect that species identification was limited to the areas near the ALT sampling points. To be clearer, we deleted “an informal survey” and revised the sentence as "The common species identified near the ALT sampling points..."

Comment 6

6) Your Response to Comment 2.3: cf. point 3) above. The same applies to this reply. You only comment on the difference of the ML-results in different resolutions, but not actually in which areas of the actual study area and under what conditions the accuracy is better. This has to be amended.

Response 6

Thanks for the comment. We first specified the differences of the ML-results in different resolutions in Section 4.1.1 as follows:

“The resulting 5-m and 0.1-m ALT maps were compared with the field measurements (Fig. 4). The 5-m ALT maps (Fig.4b, 4e, 4h, 4k) captured the primary ALT patterns observed from the field measurements (Fig. 4a, 4d, 4g, 4j) including elevated ALT along the perimeter of Plot 3, consistently low ALT throughout Plot 4, high ALT values following the water tracks in Plot 5, and generally deep ALT in Plot 6. The 0.1-m results revealed significantly finer variations (Fig. 4c, 4f, 4i, and 4l) …. Specifically, higher ALT values are visible along Imnavait Creek within Plot 5, as shown by the red pixels in the field measurements (Fig. 4g), 5-m ML predictions (Fig. 4h), and 0.1-m ML results (Fig. 4i). However, field sampling revealed substantial ALT variation within individual 5-m grid cells, with a standard deviation of up to 32 cm as distance from the watercourse increases. These meter- to sub-meter variations are only resolved in the 0.1-m results (Fig. 4i), which distinguish the high ALT values along the creek (red pixels) from the lower values in adjacent areas (blue pixels). Similarly, the stripe patterns of ALT in Plot 4 associated with alternating bands of dwarf willow, grasses, and tussocks (Fig. 1; Section 2) are clearly defined in the 0.1-m predictions (Fig. 4c) but are not discernible in the 5-m results (Fig. 4b). For Plot 6 where overall high ALT is observed (Fig.4 j, 4k, and 4i), heterogeneity is only captured by the 0.1-m results (Fig. 4l). The pattern of interspersed lower-ALT (non-red) pixels within high ALT areas (Fig. 4l) is likely associated with widespread clusters of underlying rocks and complex vegetation cover observed in the field (Fig. 1; Section 2)”.

We then added the following in section 4.1.1 for clarifying the model performance and uncertainties.

“Considering the larger ALT variability and more diversified surface conditions at 0.1-m resolution relative to the 5-m resolution, the RF model trained using limited 5-m data set may not be able to fully capture the 0.1-m ALT variations, leading to inconsistency of the overall ALT patterns between the 5-m and 0.1-m results (e.g., Plot 4; Fig. 4d, 4e, 4f) and additional uncertainties in the multi-resolution analysis. In addition, the RF predictions tended to be centralized, which may underestimate larger ALT values (e.g., fewer dark red pixels with ALT higher than 65 cm in Fig. 4h and 4i than the measurements in Fig. 4g) and overestimate smaller ones relative to the measurements (e.g., dark blue pixels with measured ALT smaller than 35 cm in Fig. 4g but not in the ML predictions in Fig. 4h and 4i)”.

Comment 7

7) Your Response 2.5: it does not become clear if you actually changed something in the updated manuscript version.

Response 7

Please check below the updated Response 2.5 with the associated revisions in the manuscript included.

As suggested, we compared the two DEM data sets at the same 5-m resolution. The two DEMs were highly correlated (R = 0.99) across the four plots, though ArcticDEM is consistently higher in elevation for approximately 5.1 m than the drone-based DEM. After removing the bias, the RMSE between the two DEMs is 0.47m. The associated 5-m ALT predictions using ArcticDEM performed nearly as well as those from the drone-based DEM, with RMSE increasing from 6.53 cm to 7.24 cm and correlation declining slightly from 0.78 to 0.72.

Accordingly, we added the following discussion in Section 5.1

"To assess the impact of DEM choice on 5-m ALT predictions, we compared drone-based DEM and ArcticDEM across the four plots. The two DEMs were highly correlated (R = 0.99), though ArcticDEM showed a positive bias of approximately 5.1 m. Nevertheless, ALT predictions derived from ArcticDEM performed nearly as well as the drone-based benchmark, with RMSE increasing slightly from 6.53 cm to 7.24 cm, and correlation decreasing from 0.78 to 0.72".

Comment 8

8) Your Responses 2.6 and 2.7: The responses are better than the text actually added to the discussion. Please update.

Response 8

As suggested, we updated Section 5.1 based on the Responses 2.6 and 2.7 as below.

"Based on the Circumpolar Arctic Vegetation Map (CAVM) (Raynolds et al., 2019), plot 3 and 4 belong to vegetation type G3 (Non-tussock sedge, dwarf-shrub, moss tundra) while plot 5 and 6 belong to vegetation type S1 (Erect dwarf-shrub, moss tundra), where G3 and S1 together represent 29.8% area of the Arctic (excluding glacier and water bodies). The Arctic here was defined as the "area of the Earth with tundra vegetation, an arctic climate and arctic flora, with the tree line defining the southern limit" (Raynolds et al., 2019). Accordingly, the model, parameter importance and scaling effects are more suitable for representing the Arctic G3 and S1 areas relative to other regions. However, the study area is also unique in its abundance of glacier deposits and low rolling terrain. For a more rigorous assessment of the applicability or transferability of the data-driven model for other regions, in-situ measurements over a few spatially-distributed regions within the Arctic would be necessary.

In addition, the ALT inter-annual variations are affected by many dynamic factors (e.g., air temperature, snow cover properties, and disturbances), which are not explicitly accounted for by the current model. Multi-season ALT measurements and inclusion of temporally variant predictors in the data-driven model would help extend the current approach and better capture the ALT inter-annual dynamics"

Comment 9

9) Your Response 2.15: Please make sure to add this justification into the paper as well.

Response 9

As suggested, we updated Response 2.15 and added the following in Section 2 of the revised manuscript.

"As part of the NASA Arctic Boreal Vulnerability (ABoVE) field campaign, our study used ABoVE standard projection, which is Canada Albers Equal Area projection, for data visualization and analysis (https://above.nasa.gov/implementation_plan/standard_projection.html)".