

Author comment RC1

Review: Rapid mass loss and climate-driven dynamics of the Juvfonne ice patch, Norway (2010–2025), Andreassen et al, 2026

General comments The authors present an overview of ~15 years of monitoring activity at the Juvfonne ice patch, describing glaciological changes as well as atmospheric conditions, with an interesting and nice to-read discussion of how wind influences accumulation at the site and what this means for the potential future evolution of the ice patch. The manuscript presents clear results and is generally well written and structured. I would mainly ask the authors to include some more detail regarding certain parts of the methods. Other than that I have various comments on technicalities and phrasing. These are fairly numerous but mostly very small. This will make a nice contribution to TC after some (I think) relatively minor adjustments.

Response: We thank the reviewer for the kind and constructive comments to our paper. In the following we give a point-by-point response in blue italic.

Other changes: *In addition to addressing the reviewers' comments as detailed below, we conducted a new UAV survey on 13 August 2026. This allowed us to incorporate the latest 2026 field observations into the revised manuscript. Consequently, we have updated the following figures and associated text:*

- *Figure 4: Updated with the 2026 orthophoto (replacing 2025).*
- *Figure 5: Updated with the 2026 ice patch extent and area calculation.*
- *Figure 6: Updated elevation change maps for the periods 2023–2026 and 2011–2026 (replacing 2023–2025 and 2011–2025).*
- *Figure 7b: Added the 2025 orthophoto as a background layer for improved visual context.*

The original figures can be viewed for comparison in the published preprint (egusphere-2026-3152.pdf).

Methods:

Getis-Ord Gi method: Please provide a bit more context, specifically on the concept of the hotspots (Fig 8). I know this is an established method and we don't need a huge level of detail, but it would be good to give enough explanation to follow your reasoning for applying this method and to allow a general interpretation of the hotspot figure for readers not familiar with the method.

Response: Some more details are given explaining the methods in more detail defining hotspots in chapter 3.1. See our response to the specific comments for further response.

Albedo/webcam analysis: I struggled to follow the explanation of this (Section 3.6) and did not fully understand what was done or what, specifically, the purpose of this was. I think this is mainly a matter of expanding and perhaps restructuring the description in the methods section.

Response: We have restructured the text, to make the goal of the albedo and webcam comparison clear early on and expanded the description of the methods, by adding details on why we chose certain thresholds that affect the resulting snow cover threshold. We also

added a sentence to describe uncertainty from not having the webcam and radiometers at the same location.

We added: “Because of the large contrast between the albedo of bare ground and snow, the albedo measurements at the Juvasshøe weather station are ideal for describing the snow cover duration around Juvfonne and for identifying summer snowfall. To find a representative ground albedo value and a threshold for snow cover we manually compared the albedo measurements with the webcam of the summer ski centre. We identify a bare ground albedo of approximately 0.10. The albedo threshold for snow cover is based on measurements when more than 50% of the rocky and uneven ground that is not covered by perennial snow in the images was covered by snow. At an albedo of 0.15 or higher we define it as covered by snow. The 50% criterium is a result of the field of view of the camera which exposes the sides of many large rocks, which would require much more snow to fully cover them. The 30m elevation difference between the webcam and Juvvasshøe only marginally affects the method, but the higher wind exposure of Juvvasshøe is an unquantifiable source of uncertainty. “ to replace the following part: “We compared the imagery with albedo at the Juvvasshøe weather station, defined as the ratio of incoming to outgoing shortwave radiation, to distinguish between bare ground and snow-covered conditions around the glacier. Based on this comparison, we used an albedo of 0.10 as an approximate threshold for bare ground and 0.15 as a threshold for snow cover exceeding 50% of the surface. The higher threshold was used because albedo is highly sensitive to small amounts of snow on bare rock.”

Uncertainties: Various uncertainty estimates are provided but it is not always explained how these were obtained (e.g., glacier area, point mass balance). Can uncertainty of surface elevation change be estimated and added to the results? See also specific comments on the above issues in the list below.

Response: Agreed, more details are given on uncertainties in the revised manuscript..

Specific comments

L87 Two tunnels have been excavated by hand with specially designed ice axes in the Juvfonne ice patch —> a short explanation on why this was done would be helpful to readers unfamiliar with the location.

Response: We have added a sentence to help the readers. ‘The current tunnel is used for guided tours for the public and serves as an educational tourist attraction.’

L121-124 Spatial patterns in snow accumulation pattern were analysed using the “Getis-Ord Gi*” method (Getis and Ord, 1992; Ord and Getis 1995). Snow depth values were normalised as deviation from annual mean, and the analysis was conducted using a fixed bandwidth of 300 m. False discovery rate corrections were not applied. Can some additional context be provided here? Are deviations of single measurement dates computed as deviations from the annual mean of that year, or does this refer to a multiyear mean or some other approach? Does “fixed bandwidth of 300m” refer to elevation bands? What are false discovery rates in this context? Briefly explain the concept of the Getis Ord method and what the output of this is.

Response: We have updated the text in 3.1. with more details on the method. The first section in 4.5 has been rewritten explaining the results using the Getis Ord method.

L128 Measurements represent the outermost continuous boundary of snow or ice. How do you exclude seasonal snow? (Or is it included?)

Response: it is included, as it is written 'Measurements represent the outermost continuous boundary of snow or ice.'

L139 accuracy assessment showed that the vertical accuracy of the surface elevations was generally better than ± 0.1 m How was accuracy assessed? *Response: See response below.*

L151 *The accuracy of the 2023 and 2025 surveys is estimated to be within 0.1 m, with the 2016 survey suffering from some doming and have lower accuracy* As above, how was accuracy assessed? Check grammar in the second part of this sentence

Response: This part has been rewritten in the revised manuscript. The accuracy of the 2023 and 2025 surveys are estimated using the distribution of difference in elevation over non-glaciated terrain from the 2019 reference. Ground sampling differences and actual ground movement create a layer of uncertainty to that estimate, but the magnitude of the signal over the glacier is much higher,

Section 3. 4 Ice thickness Can you clarify if the two independent surveys were conducted to cross-check the two sensors and the airborne vs walking approach, or if both were combined to improve coverage? This is not clear to me from the text. Similarly, are the “overlapping measurements” used to assess uncertainty always from the two separate campaigns, or was there overlap within the individual campaigns? Consider referring to Fig 7 in this section to indicate the profile lines. Was the airborne survey intentionally conducted in the shape of a star? If so, why?

Response: The two surveys were conducted independently and combined to improve coverage. Added “which were then combined to improve coverage” in the first sentence of the section (L163). We considered all overlaps/crossings of survey lines both within the individual campaigns and between the two campaigns. Clarified this in the text by changing the sentence (L181-183) to: “To assess uncertainty, we compared all crossing points between survey lines from both measurement campaigns and obtained a mean crossover error of 0.72 ± 0.41 m, with a maximum discrepancy of 2.13 m at crossing points.” We added a reference to Fig 7 to refer to the profile lines. It is the ground-based campaign that was conducted in the shape of a star, clarified this in the figure text of Fig 7 by revising the description of map (b) to: “...point data from 24-09 ground-based campaign (star pattern in grey) and 03-09 drone-borne campaign (regular lines in purple)...”. The fact that it was collected in the shape of a star was not intentional.

L224-228 *We compared the imagery with albedo at the Juvvasshøe weather station, defined as the ratio of incoming to outgoing shortwave radiation, to distinguish between bare ground and snow-covered conditions around the glacier. Based on this comparison, we used an albedo of 0.10 as an approximate threshold for bare ground and 0.15 as a threshold for snow cover exceeding 50% of the surface. The higher threshold was used because albedo is highly sensitive to small amounts of snow on bare rock.* Not sure I understand what was done here. Was this a visual comparison of webcam imagery with albedo at the weather station? Is the station included in the webcam images? If not, how was it compared? When you say “50% of the surface”, which surface are you referring to?

Response: Thank you for highlighting the need for a clearer description of this methodology. To address your specific questions:

- Comparison method: Yes, this was a visual comparison between snow cover visible in webcam imagery (from the Galdhøpiggen summer ski centre) and the recorded albedo at the Juvvasshøe AWS.*
- Station location: The AWS is not directly within the camera's field of view (it is located ~1 km away and ~30 m higher in elevation), but both sites experience the same synoptic summer snowfall events.*
- Surface definition: "50% of the surface" refers to the rocky, unglaciated ground surrounding the ice patch visible in the webcam images. Due to the camera's oblique viewing angle, rocks are photographed from the side, requiring a moderate snow layer before 50% of the visible surface appears covered.*

To ensure this methodology is completely clear to the reader, we have thoroughly rewritten Section 3.6 in the manuscript as follows:

"Because of the large contrast between the albedo of bare ground and snow, the albedo measurements at the Juvvasshøe weather station are ideal for describing the snow cover duration around Juvfonne and for identifying summer snowfall events. To find a representative ground albedo value and a threshold for snow cover, we manually compared the albedo time series with webcam imagery from the nearby summer ski centre. We identified a bare-ground albedo of approximately 0.10. An albedo threshold of 0.15 or higher was defined as snow-covered, corresponding to times when more than 50% of the rocky, unglaciated terrain in the webcam field of view was covered by snow. This 50% criterion accounts for the oblique field of view of the camera, where the vertical sides of large boulders remain exposed during initial light snowfalls. The 30 m elevation difference and ~1 km distance between the webcam field of view and the Juvvasshøe AWS marginally affect the comparison, though the higher wind exposure at Juvvasshøe introduces a minor, unquantifiable source of uncertainty."

Section 4.1 Mass balance data. How were the uncertainty values determined? Consider also providing them for cumulative values. *Response: This is based on our best estimate, but uncertainties in mass balance measurements are not straightforward to calculate. We have added uncertainty for cumulative values as well.*

Fig. 4, Table S1: How was the uncertainty of the extent determined? I don't think this is explained anywhere. *Response: The area uncertainty was estimated to be within $\pm 3\%$ of the area for all surveys by foot and from orthophotos. We will add this to the manuscript.*

L278 indicating the effect of the geotextile installed in 2016 Would this be better in the discussion? I think this should be either omitted or explained in a bit more more detail (how does the textile cause reduced melt/mass gain?)

Response: We agree that artificial influence can be further discussed in the discussion with reference to other studies. We reworded and shortened here to 'The elevation change is smaller at the ice tunnel location than in the surrounding areas, and the area around the tunnel appears to have thickened during 2023-2026.'

In the discussion, end of chapter 5.1. we suggest to include 'It should also be noted that the recent evolution of Juvfonne has likely been influenced not only by climatic forcing but also by local interventions. The geotextile covering the tunnel during the summer season, since 2016, was intended to protect the tunnel by reducing the ice melt. Studies have shown that such covers can substantially reduce melt rates relative to adjacent uncovered ice (e.g. Huss et al., 2021). In addition, snow redistribution since 2024 above the tunnel has altered the spatial distribution of winter accumulation. These interventions have likely contributed to the smaller elevation changes observed near the tunnel compared with the surrounding parts. The apparent thickening around the tunnel during 2023-2026 is consistent with enhanced local accumulation and reduced melt and is therefore not fully representative of the natural evolution of Juvfonne. Consequently, the area influenced by geotextile protection and artificial snow redistribution should be interpreted with caution when assessing recent geometric changes and climate-driven mass loss.'

288 This artificial effect locally reduces the observed thinning relative to the surrounding areas Similar to above comment. Maybe better as part of the discussion? Arguably it is not an “artificial effect” since the effect on surface elevation is real. Consider rephrasing.
Response: it is the artificial influence, corrected.

Fig. 8. Getis-Ord Gi method: please provide at least enough background on this method so that readers unfamiliar with it can understand the general message of this figure. What are “hot spots” in this context? Hot implies temperature but is related to snow accumulation here. Briefly explain the general concept in the methods. *Response: Hot spots are now explained in more details in chapter 3.1. (methods) and in results section (4.5) to help the reader.*

L342 The warm front also brings a small decrease in snow depth. Technically, it is not really the warm front as such that brings this but, presumably, settling due to temperatures, wind, etc. Consider rephrasing. *Response: That is absolutely correct, thank you; these processes only show after it stopped snowing. We have replaced that sentence with: “The small decrease of snow depth after the warm front is due to settling of the snow pack.”*

L367 Additionally, the erosion or deposition of blowing snow can have influenced this result, because blowing snow only takes place during strong wind and often during precipitation. Most likely, erosion due to blowing snow is the key reason why the overall snowfall values are low. Consider moving to discussion. *Response: Based on a comment by the second reviewer we replaced: “Most likely, erosion due to blowing snow is the key reason why the overall snowfall values are low.” with: “Most likely, wind erosion of blowing snow at the nearby off-patch snow depth sensor is the key reason why the recorded snow accumulation values there are low compared to Juvfonne.” to emphasise the difference between the surrounding and the ice patch. After making this statement more clear we believe it fits best here to round off the subsection and keep the details here, because the discussion also emphasises wind driven redistribution, but focuses more on connecting the different mass balance drivers.*

L409 significant melt days —> I believe this has not been introduced, consider defining this term in the methods section *Response: Thank you for this helpful suggestion. We agree that the term should be formally introduced and defined in the Methods section where the Summer Melt Potential Index is presented. We have added the definition to Section 3.5 (Meteorological data) as follows:*

"To quantify changes in the frequency of high-intensity melt events, we define 'significant melt days' as days where the daily Summer Melt Potential Index exceeds the 75th percentile of its May–September daily distribution over the observation period."

Paragraph starting in L496: I suggest moving this to the discussion.

Response: We agree that this could be part of the discussion as well, and we looked for a proper place to put it, but we prefer to keep it here not to alter the discussion too much and to keep it here together with the results.

L548 It should be noted that CPDD does not account for nighttime refreezing, crucial for possible refreezing of melt water. Do you assume this to play a significant role here? If so, I suggest stating that. *Response: Thank you for this comment. Yes, we assume that meltwater refreezing - both surface refreezing and internal refreezing within the cold snowpack and ice - plays a significant role at Juvfonne, particularly given its high-elevation and permafrost setting.*

During spring and early summer (May-June), as well as during clear-sky summer nights, radiative cooling and sub-zero nighttime temperatures frequently cause meltwater generated during the daytime to refreeze. Because CPDD relies solely on positive daily mean temperatures, it cannot account for these diurnal freeze-thaw cycles or internal energy sinks, which partly explains why degree-day sums alone do not fully capture the interannual variance in mass loss.

We have expanded the discussion in Section 5.1 (Mass balance drivers of Juvfonne) to explicitly state this:

"The comparison of the CPDD calculated from the air temperature data from Juvvasshøe and the point mass balance at Juvfonne revealed correlations between CPDD and summer and annual balance, although variations in CPDD alone do not explain the variance in melting. It should be noted that CPDD does not account for nighttime or internal refreezing of meltwater. At a high-elevation permafrost site like Juvfonne, nocturnal sub-zero temperatures and radiative cooling frequently promote meltwater refreezing—particularly during May–June and clear late-season nights. This process retains mass locally and reduces effective ablation, contributing to the discrepancy between temperature-only indices and observed mass balance."

L573 Consequently, the suppression of subsurface melting significantly enhances the longevity of ice patches —> all ice patches or just those above permafrost?

Response: Thank you for highlighting this important distinction. This mechanism applies specifically to ice patches situated in permafrost environments. In non-permafrost settings, the ice-ground surface interface typically reaches 0°C during the melt season, facilitating basal melt. In contrast, underlying permafrost maintains sub-zero temperatures at the base, suppressing subsurface melting and thereby enhancing ice patch longevity. We have clarified the sentence to specify the permafrost setting: "Consequently, in a permafrost setting, the suppression of subsurface melting significantly enhances the longevity of ice patches."

L581 Thus, a feedback loop exists: the underlying permafrost delays the degradation of the ice patch, while the ice patch concurrently prevents the degradation of permafrost in its

immediate vicinity during periods of climate change. As above, not clear from the text if you mean that this is true of all ice patches (i.e., are all of them on permafrost?) or if you are speaking specifically of Juvfonne here?

Response: See above point, it is probably not true for all ice patches, but for many. There is of course a difference of snow patches and ice patches. To develop real ice-patches one must have a cold reservoir in depth to maintain refreezing of melt water producing the ice in the ice patch. This increases the thermal conductivity, which adds to the cold reservoir during winter. We added the following sentence: "This process is certainly valid for all ice-patches in high mountain environments in permafrost"

From L585 onwards, section on LIA extent: This mixes methods and results that have not been introduced yet. Consider restructuring somewhat and mentioning this earlier. .

Response: We prefer to keep LIA results in discussion as now as this is a contribution to discussion and not any results we report on in Fig 5 or Table S1 or in abstract or conclusion, it is just two estimates for discussion.

Technical corrections

L46 with numerous signs from hunting and travelling Consider rephrasing for clarity - what kinds of "signs" or these? Archaeological artefacts? *Response: We changed to 'Archaeological finds from ice patches are known from North America, Mongolia, the European Alps and Scandinavia, providing extensive evidence of past hunting and travelling' and hope this makes it clearer. See also comment from Reviewer 2.*

L74 repetition from L58, is this needed again or can redundancies be removed?

Response: Good catch, we removed some content from both to reduce the repetition.

L77 recent inventories —> specify "glacier inventories" if that is what they are. Why was it not included in the earlier inventories?

Response: glacier added to specify glacier inventories. We also added based on semi-automated methods versus manual digitisation as this likely explains the differences and many more items were included in the satellite based inventories based on automatic mapping.

Fig1: why are there two "front" markers? Do they indicate the position of the front at different times? *Response: that for notifying that this was not explained. we added explanation 'Front marks points used for front observation measurements.'*

L136 and other instances: ensure all abbreviations are explained (lidar, UAV, RTK,...)

Response: checked and added explanations for these abbreviations first time used and checked for other non-explained.

L155 except for Kjelen and Juvfonne that were digitised orthophotos acquired on 26 August 2019 —> "..., for which outlines digitised from orthophotos acquired on were available"? (If this what you mean? otherwise, what are "digitised orthophotos"?)

Response: here 'outlines' were missing, thanks for spotting it. We updated this 'except for Kjelen and Juvfonne, for which outlines were digitised from orthophotos acquired on 26 August 2019 (See Table 1 for details).

L168 Global Navigation Satellite System (GNSS) Introduce abbreviation where it first occurs. *Response: Done, moved explanation to first occurrence.*

L187 Model data were also included —> which model data and for what? (I suggest removing this here since you explain it in the next paragraph). *Response: Done*

L234 Mass balance for the entire ice patch was not calculated for all years, but only for the first year of measurements (2009/2010), when more stakes were available. This was already stated in the methods, no need to repeat here unless you include the glacier wide MB from that year. *Response: Agreed and removed.*

Fig. 4: the black and blue lines are hard to see. Consider using brighter colours. *Response: we have increased the thickness of the lines and used a brighter blue color for the 2010 outline.*

L301 volume of 20 m³ and an estimated volume of 73 m³ in 2011 Is this meant to be the entire volume of the ice patch (??) Check the units. *Response: thanks for spotting this blunder, it is 0.20 km² and 0.73 km³.*

L312 bw —> winter mass balance? Was this abbreviation defined? *Response: it was defined in the figure but we now also have added it to the text where used.*

Fig 9 caption: “around before and after a cold front” rephrase for clarity (omit around?) *Response: Thank you for pointing this out. We have updated the caption to read: "...of Juvvasshøe before and after a cold front."*

Paragraph starting in L 334: check tenses and homogenise them (should probably be past tense throughout) *Response: We have checked and corrected to past tense several places.*

Fig S5: Unclear from the caption and legend what “3 . Snow depth” is and how it differs from the dark blue snow depth. Please clarify. *Response: Thank you for the additional perspective. The thin blue line shows the snow depth measured next to Juvfonne multiplied by a factor of three. It helps in identifying years where the snow accumulation on Juvfonne is particularly high compared to the surrounding. To make this more clear we added this sentence to the caption: “ The thin blue line is the snow depth next to Juvfonne multiplied by three. ”*

Windrose plots (Figs 10, S6) can the scale of the y axis (%) be homogenised across the subplots? It is hard to compare them if the scales differ. *Response: Thank you for pointing that out. We are already aware of this problem and tested it both ways before deciding to keep the version with unhomogeneous axes. When the axes are the same, Fig. 10 a) and Fig. S6 2016 and 2023 are reduced to 56% and roughly 25% (both years) of their current size (considering that the area is proportional to the squared of the radius). That makes it extremely hard to distinguish the distribution of wind speeds and for Fig. S6 even the wind direction distribution becomes hard to compare to others. Furthermore, we focus more on the shape of the distributions instead of the occurrence frequency of the peak, although of course both are connected, and we think this visualization fits that purpose better.*

L376 aligning —> aligns? *Response: Done*

L377 Precipitation obtained from seNorge_2018 and observed at nearby Bøverdalen station is evenly distributed throughout the year, with the lowest amounts in April and May, and the highest in January and November. The second part of the sentence seems to contradict the first. *Response: Thank you for pointing this out. We agree that describing the precipitation as "evenly distributed" was misleading given the observed seasonal variability (with spring precipitation being less than half of the winter/late-summer peaks). We have rephrased the sentence as follows:*

"Precipitation obtained from seNorge_2018 and observed at the nearby Bøverdalen station shows a distinct seasonal pattern, with the lowest amounts in April and May, and peak precipitation occurring during late summer (August) and winter (December–January)."

Fig S7: What is the difference between the solid black line and the dotted line? Explain in caption. *Response: Thank you for finding this. We extended the caption to clearly explain the different lines: "Incoming shortwave radiation is shown as 10 days running mean (rm, solid colored lines) for selected years with high or low summer mass balances. The black dotted line and grey shading show the mean of 2000 to 2022 and minimum and maximum values, respectively. The black solid line is the 10 day running mean of the mean irradiance."*

L393 The annual variations in air temperature is illustrated —> are illustrated
Response: Done

L408 Over this 16-year observation period, the exhibits a consistent positive trend —> incomplete sentence? *Response: Thank you for spotting this typo. We have corrected the sentence by adding the missing noun: "Over this 16-year observation period, the index exhibits a consistent positive trend ($p = 0.086$)."*

L418 leading to the largest summer balance recorded of nearby Storbreven —> consider rephrasing for clarity to something like "...leading to the most negative summer balance recorded at nearby Storbreven.." *Response: Done*

L472 To assess how the changes of Juvfonna are compared to other ice bodies in the region, we assessed the repeat lidar surveys covering Juvfonna and the Galdhøpiggen massif over the period 2011-2020 To assess we assessed — consider rephrasing
Response: thanks, we changes we assessed to we analysed to make the wording better

Table 1: what are the bold values in the last line? I assume sums and averages, but it should be stated somewhere (caption) *Response: Good point. we added an explanation that these are area sums and area weighted averages.*

L555 missing ' symbol to end the quote *Response: actually, the quote is long and we removed the ' in the middle to avoid*

L573 remove extra period after the parentheses *Response: Done. This now closes the sentence due to removal of other text*