1. Reply to the editor

Dear Dr. Piccolroaz,

thank you again very much for handling our manuscript! We have revised the manuscript again considering all the comments from the last iteration given by the two reviewers. A detailed reply to all their comments is included below.

On behalf of all the authors

Sincerely

Georg Pointner

2. Reply to Anonymous Referee #1

Dear Anonymous Referee #1,

we thank you very much for taking the time to review our manuscript again and for providing new comments that helped us to improve the manuscript again!

Comments:

Abstract: The first sentence of the abstract needs to be modified. The sentence is already in past tense "Siberia have been suggested", therefore the word 'before' at the end can be removed.

Reply: We have removed the word 'before'.

Line 34: 'throughout each year' should be removed and the two sentences combined. It should read "Western Siberia frequently cross frozen lakes in winter."

Reply: The sentence now reads: "The Yamal-Nenets are reindeer herders that travel across the Yamal Peninsula in Western Siberia and frequently cross frozen lakes in winter."

Line 39: "use two main terms" change to "uses to main terms".

Reply: Changed to "uses two main terms".

Line 125 to Line 132: These 8 lines read very similar to a statement of objectives/goals of the paper. This should be moved or combined with the final paragraph of the introduction section.

Reply: Thank you for pointing this out! We have combined it with the final paragraph of the introduction section.

OLD:

Introduction section:

"In this study, we demonstrate a connection between potential signs of gas emissions in SAR and optical very high resolution (VHR) imagery of lake Neyto and quantify their spatial relations. We provide a direct link between the locations of clusters of low backscatter on lake Neyto from Sentinel-1 SAR data and potential seep sites that we could identify as open holes in lake ice in a single VHR WorldView-2 image. Similar holes in VHR imagery were described and shown in detail for lake Otkrytie, located approximately 60 km to the east of lake Neyto by Bogoyavlensky et al. (2019a)"

Study site section:

"Here, we present methods to map the backscatter anomalies from Sentinel-1 SAR imagery and the holes from WorldView-2 data with state-of-the-art image processing techniques and compare their locations spatially. Our study provides a first quantitative assessment of spatial relations between features in SAR and VHR imagery potentially related to subcap gas emissions on lake Neyto. Further, we provide time series of classified area of anomalies, quantify the expansion over time and discuss the use of other remote sensing data that could help to advance the understanding of the mechanisms involved. In this regard, investigations of ALOS PALSAR-2 fully polarised L-band SAR data were carried out, which could reveal the dominant scattering mechanisms of backscatter anomaly regions and regular floating lake ice."

NEW:

Introduction section:

"In this study, we demonstrate a connection between potential signs of gas emissions in SAR and optical very high resolution (VHR) imagery of Lake Neyto for the first time. We provide a direct link between the locations of clusters of low backscatter from Sentinel-1 SAR data and potential seep sites that we could identify as open holes in lake ice in a single VHR WorldView-2 image. Similar holes in VHR imagery were described and shown in detail for Lake Otkrytie, located approximately 60 km to the east of Lake Neyto by Bogoyavlensky et al. (2019a). We present methods to map the backscatter anomalies from Sentinel-1 SAR imagery and the holes from WorldView-2 data with state-of-the-art image processing techniques and compare their locations spatially. Further, we provide time series of classified area of anomalies, quantify the expansion over time and discuss the use of other remote sensing data that could help to advance the understanding of the mechanisms involved. In this regard, investigations of ALOS PALSAR-2 fully polarised L-band SAR data were carried out, which could reveal the dominant scattering mechanisms of backscatter from anomaly regions and regular floating lake ice."

3. Reply to Anonymous Referee #3

Dear Anonymous Referee #3,

we thank you very much for taking the time to review our revised manuscript, especially going through the long list of revisions and suggestions from the previous round and for providing new comments that helped us to improve the manuscript again!

Comments:

Overall, this revised manuscript presents a novel method of examining holes in lakes ice that are presumed to be associated with methane release. The introduction section presents the context for the research problem very well; the methods section is extremely detailed for reproducibility; the results are clearly and explicitly presented; and the discussion/conclusions wrap up the 'story' of the research well. I enjoyed reading this manuscript and feel that it provides a substantial contribution to lake ice remote sensing overall and stands to make major contributions towards the ability to detect and eventually through using this method on the large scale in combination with methane work, improve the quantification of total methane release from arctic lakes.

I have read the previous reviewer comments along with the author responses and believe the authors have more than adequately addressed all concerns. The main issues raised were the physical process of the slushing not being correctly identified and the overly 'assertive' statements regarding what the

findings were showing considering there is no ground data to confirm. The authors revised the suggested mechanisms of the backscatter anomaly formation following the Reviewer's advice and revised the content throughout to present the findings as hypothesis that needs to be confirmed in the field, though I do agree, what they are suggesting is quite plausible and physically makes sense given what I have observed from slushing on lakes that experience mid-winter temperature climbs above freezing. We also occasionally see warmer temperatures in the lower layers of the on-ice snowpack.

Reply: We thank you very much and we appreciate this positive feedback very much! We are glad that you think our revisions are sound. Thank you also for your comments regarding the presented hypothesis! It is very interesting to hear that you also occasionally observed warmer temperatures in the lower layers of the snowpack.

Lines 81-85: The very detailed dielectric information requested by Reviewer 1 is interesting, but the authors might consider adding a few words to clarify for the reader why they are listing those GHz ranges at those temperatures (I did realize in the data section that this list aligns with the data sets but that was not clear to me at that stage of reading the introduction).

Reply: Thank you for pointing this out! We have added the following sentence:

"The reported values were chosen since they were most representative for the SAR data (C- and L-band) used in this study."

Line 145 – 151: this doesn't fit in study area section, it reads as intro/objectives and should probably be combined with the last section of the introduction section.

Reply: Yes, thank you! This was also suggested by the other anonymous referee. We have combined it with the last paragraph of the introduction.

OLD:

Introduction section:

"In this study, we demonstrate a connection between potential signs of gas emissions in SAR and optical very high resolution (VHR) imagery of lake Neyto and quantify their spatial relations. We provide a direct link between the locations of clusters of low backscatter on lake Neyto from Sentinel-1 SAR data and potential seep sites that we could identify as open holes in lake ice in a single VHR WorldView-2 image. Similar holes in VHR imagery were described and shown in detail for lake Otkrytie, located approximately 60 km to the east of lake Neyto by Bogoyavlensky et al. (2019a)"

Study site section:

"Here, we present methods to map the backscatter anomalies from Sentinel-1 SAR imagery and the holes from WorldView-2 data with state-of-the-art image processing techniques and compare their locations spatially. Our study provides a first quantitative assessment of spatial relations between features in SAR and VHR imagery potentially related to subcap gas emissions on lake Neyto. Further, we provide time series of classified area of anomalies, quantify the expansion over time and discuss the use of other remote sensing data that could help to advance the understanding of the mechanisms involved. In this regard, investigations of ALOS PALSAR-2 fully polarised L-band SAR data were carried out, which could reveal the dominant scattering mechanisms of backscatter anomaly regions and regular floating lake ice."

NEW:

Introduction section:

"In this study, we demonstrate a connection between potential signs of gas emissions in SAR and optical very high resolution (VHR) imagery of Lake Neyto for the first time. We provide a direct link between the locations of clusters of low backscatter from Sentinel-1 SAR data and potential seep sites that we could identify as open holes in lake ice in a single VHR WorldView-2 image. Similar holes in VHR imagery were described and shown in detail for Lake Otkrytie, located approximately 60 km to the east of Lake Neyto by Bogoyavlensky et al. (2019a). We present methods to map the backscatter anomalies from Sentinel-1 SAR imagery and the holes from WorldView-2 data with state-of-the-art image processing techniques and compare their locations spatially. Further, we provide time series of classified area of anomalies, quantify the expansion over time and discuss the use of other remote sensing data that could help to advance the understanding of the mechanisms involved. In this regard, investigations of ALOS PALSAR-2 fully polarised L-band SAR data were carried out, which could reveal the dominant scattering mechanisms of backscatter from anomaly regions and regular floating lake ice."

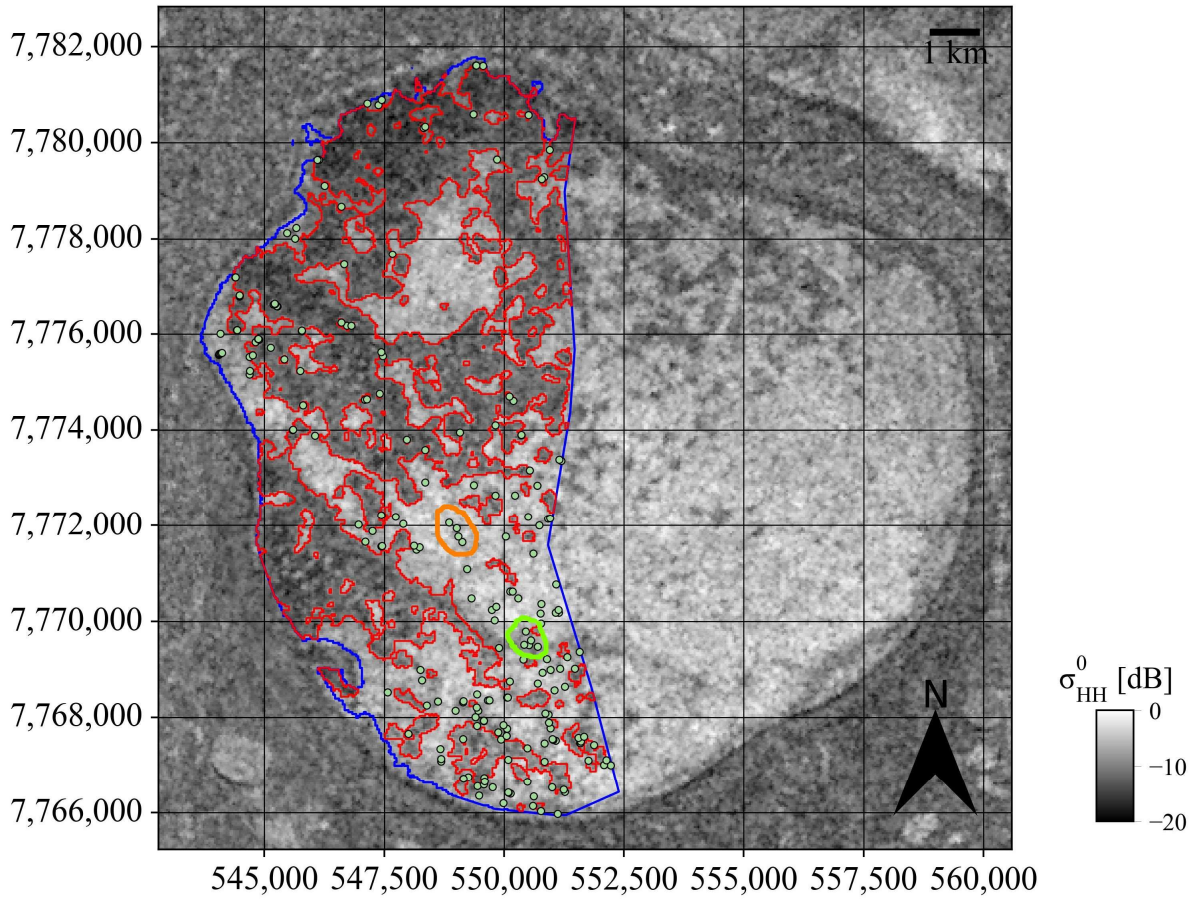
In the methods, the summary of most important methods with the flow chart is great, it really helps bring together all the steps happening in the detailed pre-processing.

Reply: Thank you very much for this positive feedback! We are glad to hear that the summary helps to better follow the methodology.

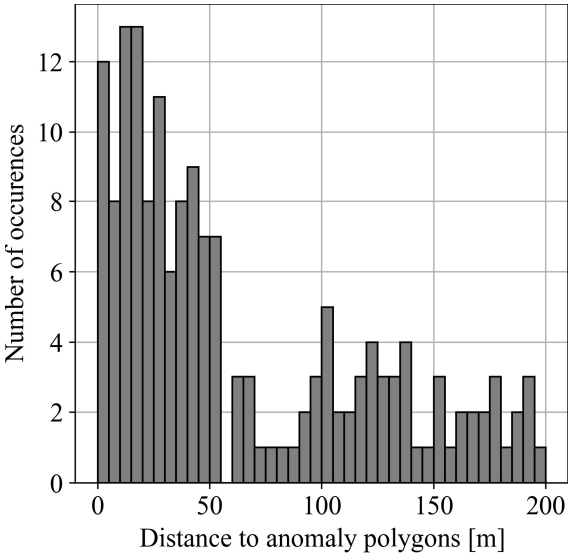
Lines 560 – 580, Discussion section: I think the revions here are great, I was nodding along agreeing as I read this. The one thing I did not see in the discussion that I was hoping to see (perhaps I missed it in the results section) is why the other 29% of the holes are not in the anomalous backscatter regions. Could a sentence be added to the discussion with thoughts/comments on why this might be (perhaps the time difference? The snow had not flooded yet? or variations in the snow depth and hence moisture amounts affect the backscatter? Or more technical reasons related to the processing? Or yet unknown reasons?).

Reply: Thank you for this comment! You already provided very good suggestions and we think in many cases it could be a combination of more factors, but also possibly influenced by yet unknown factors.

Map of locations of the holes that were not inside the classified anomalies:



What is noticeable is that the distance between many locations of holes and the anomalies is rather small. 37% of all points outside are less than 40m (one S1 pixel width) away from the anomaly polygons, 52% less than 80m.

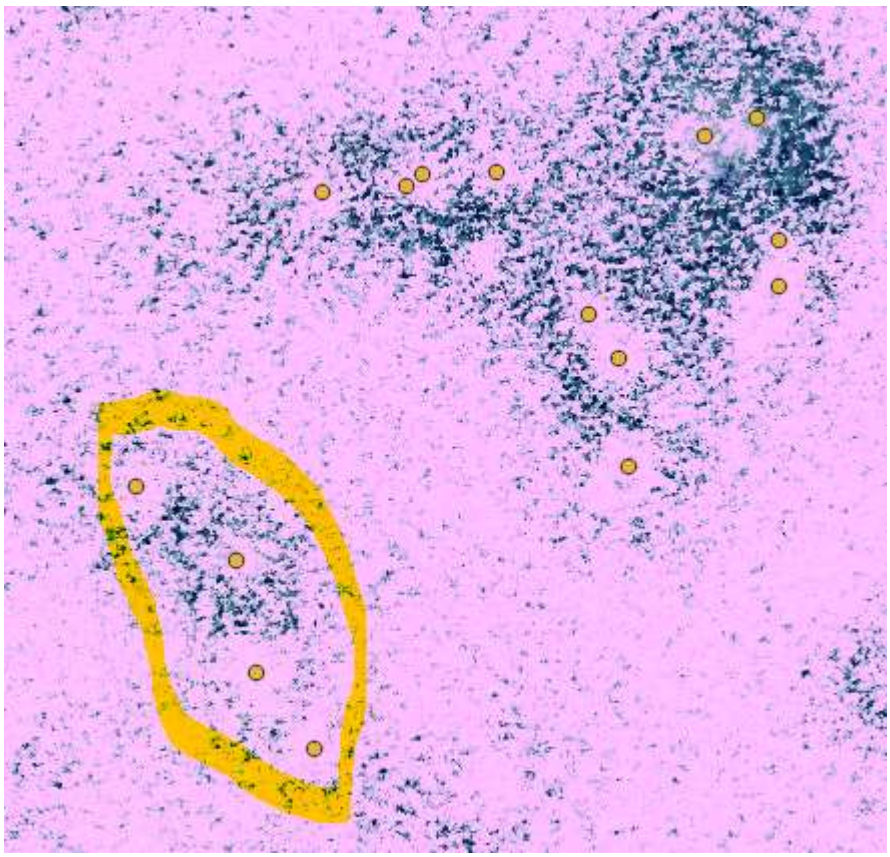


One idea would be that flooding leads to accumulations of slush and/or wet snow around something like a common centre of mass for a group of holes (compare also to Fig. 11) and the snow around holes further away from that centre may have flooded later than for the other holes (and later than the S1 image was acquired) since the surface might get pushed below hydrostatic water later (only after

enough slush/wet snow had accumulated). Also, if only a part of a pixel was flooded, the limited spatial resolution may prevent the pixel from being classified as anomalous. Speckle that cannot be perfectly removed might further contribute.

The processing itself seems to also play a role. Since no in-situ data were available, the algorithm was in the first place designed to only capture anomalies with a strong contrast to regular floating lake ice. Marked in green in the map are example locations of holes where a medium contrast can be identified in the SAR imagery. The algorithm likely classified the pixels around those holes not as anomalies because it was designed to only capture anomalies with higher contrast, but the same factors regarding speckle and spatial resolution mentioned earlier may also play a role here.

For other holes (for example the ones marked in orange in the map, the same locations are marked in yellow below) less and/or later flooding seems to have occurred even when looking at VHR image acquired a few days later than the SAR image:



The reason for this is not clear, but variations in snow depth may also lead to less flooding. As you can see, some interconnected factors seem to play a role for most points, but we cannot rule out other yet unknown factors.

We have added the following to the discussion section.

"Some potentially interconnected factors might possibly explain why 29% of detected holes are located outside the classified anomaly regions. It is noticeable that the distances between many detected holes and the anomaly region polygons is relatively short (median 67 m). The snow around these holes might have flooded after the time of the Sentinel-1 acquisition and/or the limited spatial resolution might also play a role. Other potential reasons for holes outside classified anomaly regions may include remaining speckle, the imperfectness of the classification method in general or variations in snow depth leading to less flooding around some holes, but other unknown reasons might also contribute."

Minor typographical observations:

Throughout, lake is not capitalized when part of a name. This is perhaps normal for the naming convention of the region? The study map however does capitalize Lake, so consider revising this to match the lowercase lake throughout the manuscript.

Reply: We indeed think it is more appropriate to capitalize lake when part of a name, so we changed it throughout the manuscript and kept the study map as it is. Thank you for pointing this out!

Line 32: Placement of 'only poorly' reads strangely to me in that sentence, you might consider rewording that sentence, or perhaps just use 'poorly' if you keep the current sentence structure.

Reply: We have reworded the sentence. The sentence now reads: "Global climate models may currently underestimate carbon emissions from permafrost environments significantly and cannot account for methane ebullition from geological lake seeps"

Line 123: Consider second 'largest' rather than second 'biggest'

Reply: Changed to "second largest".

Line 124: You say 'about' 60 km but used 'ca.' in the previous sentence, consider using the same term.

Reply: We have changed "ca." to "about".

Line 130: Snow Depth Liquid Water Equivalent (SDLWE), I was not familiar with that term so explored the reference, which I see is for ERA5 data. Consider mentioning that this is from reanalysis, I don't think the acronym is used elsewhere in the paper so consider rephrasing as something along the lines of ' Snow depth (liquid water equivalent) from ERA5 is …'.

Reply: The sentence now reads: "Snow depth (liquid water equivalent) from ERA5 reanalysis data generally increases gradually in winter and spring until melt-onset and typically ranged between 15 cm and 20 cm at its maximum in recent years"

Section 3.6 heading – I think you can just call it ERA5 2 m air temperature since that's all you used from the dataset, more consistent with the other headings that way. You mention here that it is from the 1979-present single level hourly data. Later in the paper you again mention its the 1979-present single level data, I don't think you need that detail. If it's explained in section 3.6 you can just refer to it as Era5 2 m hourly air temperature after section 3.6. This is how I am more used to seeing reanalysis data presented, however, this is my opinion not a fact to follow! Revise as you see fit.

Reply: Thank you! Indeed, it is more consistent this way. We changed the heading to "ERA5 2 m air temperature". Later in the paper we changed "air temperature from the ERA5 hourly data on single levels from 1979 to present" to "2 m air temperature from ERA5".

Lines 251: Word missing? Over the lake? Or over lake Neyto?

Reply: Changed to "over the lake".

Line 339: I think a word is missing: Yen-thresholding was in the following performed using skimage.filters.threshold_yen with default parameters.

Reply: We are not sure if a word was missing, but maybe the sentence was unclear. We have changed it to: "Yen-thresholding was in the following applied to the imagery using skimage.filters.threshold_yen with default parameters".

Line 347: Figure 2 gives, or shows … (remove shall)

Reply: Changed to "gives" (without "shall").

Line 563: "leakage of liquid water" I would say flooding – but its just semantics. To me, leaking implies 'dripping' while flooding implies 'over the surface'.

Reply: Thank you for pointing this out! Flooding sounds a lot better. We have changed it to "consequent flooding through the holes over the ice top".