Contents:

1. Reply to the editor

Dear Dr. Piccolroaz,

thank you very much for taking the time to handle our manuscript and for providing additional comments! We have carefully revised the manuscript considering all comments given by the two reviewers. Please find a specific reply to your comments below:

In particular, they ask to i) revise the methods section adding more information about the data and the image processing techniques used in the study.

Reply: We have added more information about the used data and specifically provide now lists containing the IDs of all the images used in this study and additional metadata in the supplement. These lists are also referenced in the manuscript. We have revised and expanded the description of the image processing techniques indicating all relevant Python packages along with their versions and listed the exact methods used from these packages together with their parameters.

ii) present, interpret, and discuss the results more critically, properly commenting the limitations of the analysis, and better supporting the hypothesis about the mechanisms involved.

Reply: We have now re-written, re-phrased and re-arranged large parts of the discussion and conclusion sections. Following the discussion with anonymous referee #2, we have discarded the hypothesis that anomalies are related to cavities, as this does indeed not seem practical considering the arguments presented in the referee comment. As suggested, we have now discussed the slushing/wetting explanation using our in-situ data to support this hypothesis but have used more cautious formulations throughout the manuscript. We have now acknowledged that in-situ data of lake Neyto are needed to understand the mechanisms and verify that holes are caused by up-welling gas in many parts of the discussion and conclusion sections.

In light of the description of the Special Issue to which this manuscript has been submitted, I also ask the authors to expand their comment at lines 119-128 about the implications of their study for understanding the lake-climate interaction, by recalling it in the Discussion section.

Reply: We have added the following paragraph to the discussion section:

"Here, we have shown the potential connection between open holes in lake ice potentially caused by gas emissions and patches of anomalously low backscatter in C-band SAR imagery for the first time, but in situ data are needed to understand the phenomenon in detail. Upon the verification of the presented hypothesis, the capability of SAR instruments to collect useful data under almost all weather conditions, high revisit rates and high coverage may allow the identification of other lakes with subcap gas emissions from C-band SAR data in future studies at larger spatial extents. This might then aid our understanding of how much methane is released from West Siberian lake seeps and might possibly contribute to an incorporation of emissions from these seeps in climate models."

2. Reply to Anonymous Referee #1

Dear Anonymous Referee #1,

we thank you again very much for taking the time to review our manuscript and for providing detailed and constructive comments!

General comments:

The article 'Mapping potential signs of gas emissions in ice of lake Neyto, Yamal, Russia using synthetic aperture radar and multispectral remote sensing data' provides an extensive analysis of backscatter anomalies linked to possible gas emissions for Lake Neyto, Yamal, Russia. Multiple image products and processing techniques were used to support the authors' hypothesis and the results are supported by the existing literature. The study is particularly interesting due to its connection to gas emission from the warming Arctic and the multiple recent publications addressing similar elements from Alaska and northern Canada.

Reply: We are pleased to hear that. Thank you again!

The literature review provided in the article is well constructed and provides a good background. Furthermore, the discussion is well organized and outlines how the results in this study reflect and differ from similar work.

Reply: Thank you again for this positive feedback!

The methods section requires the most revision in the current manuscript. There must be further documentation of the Sentinel-1 catalog used (dates, number of images, and gaps between images). There are small concerns about the Sentinel-1 image processing done regarding how noise in the images was addressed. While many image processing techniques are used, the description given is not adequate. These techniques should be better described to ensure that the method can be replicated in future studies. Specific comments are provided regarding these issues, in addition to short comments about figures and sentence structure.

Reply: We have now included a table showing the years of data, the number of images and the average temporal gap. Additionally, we provide detailed tables as supplement listing all images by ID together with metadata (local and UTC sensing time, mean average incidence angle over the lake). We have now listed all relevant software libraries used (including their versions) and explicitly indicated the methods used from these libraries along with the chosen parameters and given a more detailed description of the methods. Please see the replies in the following for details, also regarding the handling of the noise.

Specific Comments

Line 11: Include the actual percentage of holes mapped in the VHR data that relate to the SAR anomalies.

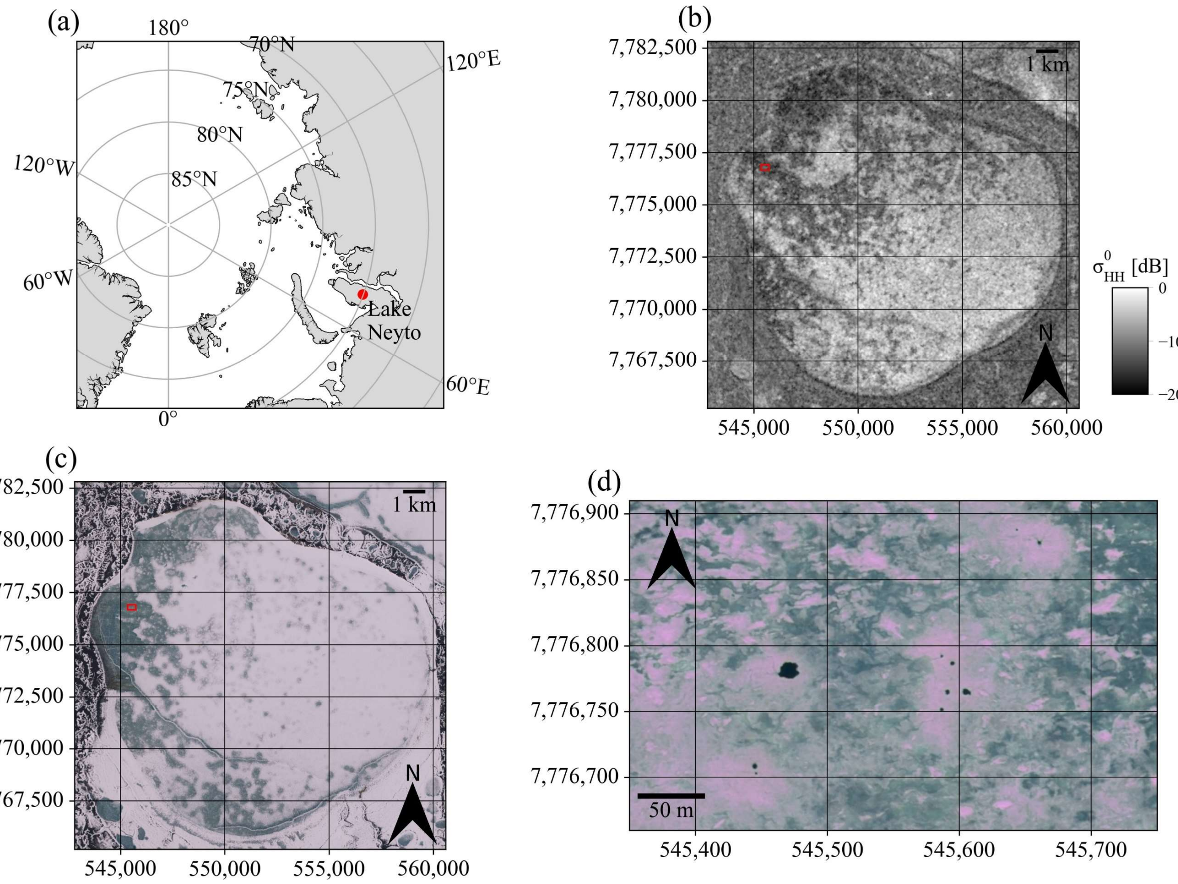
Reply: We have added the number (71% now with the revised methodology).

Lines 100-118: These lines are more suited for a study site section, an additional section could be added before 'Data' or as a subheading of the same section to present the information. Some additional information about lake Neyto would also strengthen the description of the study site (temperature, precipitation, lake properties, distance to major settlements/coordinates). This could also be addressed in Figure 1 by adding a fourth frame that provides a geographic context.

Reply: We agree. The inclusion of a study site section was also suggested by Anonymous Referee #2. We transferred the mentioned lines and added the following before the transferred lines:

"Lake Neyto (other title: Neyto-Malto), 70.073 °N, 70.350 °E, is located in the central part of the Yamal Peninsula, ca. 80 km away from the closest settlement Seyakha and ca. 80 km away from the Bovanenkovo gas field. The lake has the second biggest area (214 km^2) in Yamal after Yaroto-1 lake. The length of the shoreline is about 60 km and the lake measures approximately 17.8 km in the south – north direction and 16.5 km from west to east. The lake is relatively shallow, reaching 17 m at the north-west corner, but the average depth does not exceed 3 m, which results in a significant mixing of water masses during summer (Edelstein et al., 2017). Wide shelf areas up to 800 m can be found within the lake, whereas at the deepest part, several depressions with diameters up to 500-800 m are documented (Edelstein et al., 2017). Lake shores are mostly cliffs up to 25 m high, sometimes with tabular ground ice exposures. The ground temperature at 2 m depth in the surroundings of the lake is approximately -1.5 °C (Obu et al., 2020). The Snow Depth Liquid Water Equivalent (SDLWE) 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 (Hersbach et al., 2018)."

As suggested, we included a fourth frame in Figure 1. This is the new Fig. 1:



Section 2.1: Further discussion on the Sentinel-1 images used is needed. While the other imagery sources use one or a handful of images, Sentinel-1 appears to be the focus of this study. Therefore, a table listing the years of data, the number of images, and the average temporal gap between imagery would be good to include. Alternatively, a calendar plot showing the dates of the study period with associated acquisitions (Sentinel-1, Worldview, PALSAR, Sentinel-2, and Landsat-8) would be a good way to convey the amount/temporal resolution of the imagery used to the reader.

Reply: We have added a table listing the years of data, the number of images, and the average temporal gap between imagery directly in the manuscript:

Year	Number of images	Average temporal gap
2015	29	4d 7h
2016	88	1d 13h
2017	112	1d 7h
2018	52	2d 23h
2019	41	3d 14h

Anonymous Referee #2 also suggested to include a table of all acquisitions, but together with metadata (local sensing time, mean projected local incidence angle). Since altogether more than 300 Sentinel-1 acquisitions were used, we now provide detailed tables including the scene ID, acquisition time and mean incidence angle as supplementary .csv-files and also indicate the exact scenes that were used for calculating the lake masks and the shelf masks. In particular, we now include 4 tables in total for the Sentinel-1 data: One for all EW scenes used for calculating the time series, one for all IW scenes used, one for the EW scenes used for calculating the lake masks and one for the EW scenes used for calculating the shelf masks. Additionally, we provide a similar table for the other satellite data used in this study.

We have added the following to the Sentinel-1 data section:

"Lists of the used scenes including the mean projected local incidence angle over the lake, acquisition times in local time and Universal Time Coordinated (UTC) and an indicator showing if the scenes were assembled due to slicing (see Sect. 4.1.1)) are provided in the Supplement (S1-S4) to this article in ".csv"-format. "S1__scene_metadata_list_Sentinel1_EW_main.csv" contains a list of the main Sentinel-1 EW data (342 scenes) used in this study. "S2__scene_metadata_list_Sentinel1_EW_lake_masks.csv"and "S3__scene_metadata_list_Sentinel1_EW_shelf_masks.csv" contain lists of the Sentinel-1 EW data used for calculating lake masks (5 scenes) and shelf masks (5 scenes), respectively (see Sect. 4.2.1 for details). "S4__scene_metadata_list_Sentinel1_IW.csv" contains a list of all Sentinel-1 IW data used for the validation (10 scenes). "S5__scene_metadata_list_other_sensors.csv" contains a similar list for the other satellite data (4 scenes in total) used in this study, which are described in the following paragraphs."

We have now also added a description that some products had to be assembled using the "slice assembly" operator in SNAP, when products have been sliced directly over the lake in the "Pre-processing of Sentinel-1 SAR data"-section:

"Some products have been sliced directly over lake. In these cases, the slice-assembly operator was applied to those products in gpt as the first processing step. Products to which this operator was applied are indicated in the supplementary tables S1-S4."

Line 192-193: No mention of speckle filtering or multi-looking is made. Was this not done? How do the authors address the issue of noise within the SAR images? The process was done for the PALSAR-2 images as stated on line 208.

Reply: The following is a copy of what we stated in the author comment. We argued that by using a bilateral mean filter as part of the classification workflow, we were able to achieve better results than *by using a conventional speckle filter. We have added the following sentence to the "Classification of backscatter anomalies from Sentinel-1 data" section:*

"The bilateral mean filter was chosen to handle noise with the aim of binary classification in mind, as opposed to a conventional speckle filter."

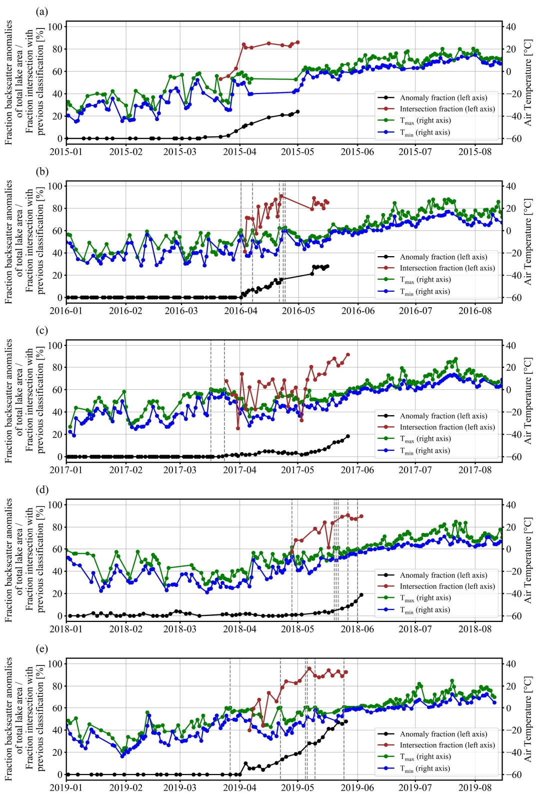
Start of copy from author comment:

For the ALOS-PALSAR-2 fully polarized data, speckle filtering was considered necessary for the polarimetric classification. The "Polarimetric Speckle Filter Operator" in SNAP was used here, as opposed to a conventional speckle filter.

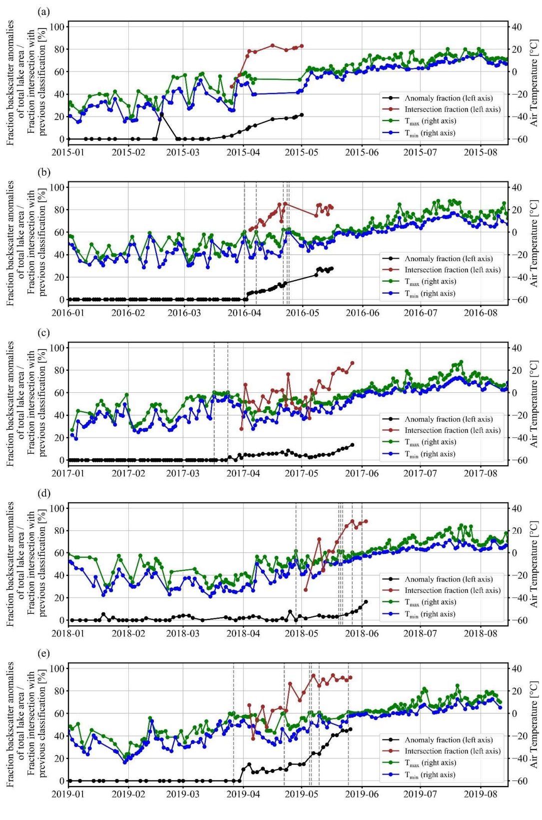
For the Sentinel-1 data, we chose a more custom approach to handle the noise as part of the classification workflow. We agree that speckle filtering is conventionally done in SAR geometry with filters specifically tuned to the theoretical statistical distribution of the speckle. However, for a flat surface (such as a lake), effects of the topography can be considered negligible and conventional speckle filters often blur the image and reduce the spatial detail a lot. With the objective of binary classification in mind, we chose to use a bilateral mean filter from the scikit-image (version 0.15.0) python library ([skimage.filter.rank.bilateral_mean]) to handle the noise after the pre-processing steps.

For comparison, we have now re-calculated results using the Refined Lee-filter from SNAP, which is usually considered to be good at preserving edges in the imagery. Here, for the comparison, the Refined Lee filter was applied before the terrain-correction in SNAP and the bilateral mean filter in the classification workflow was omitted. Except an obvious misclassification in February 2020, the time series appear relatively similar to those in the preprint (with bilateral mean).

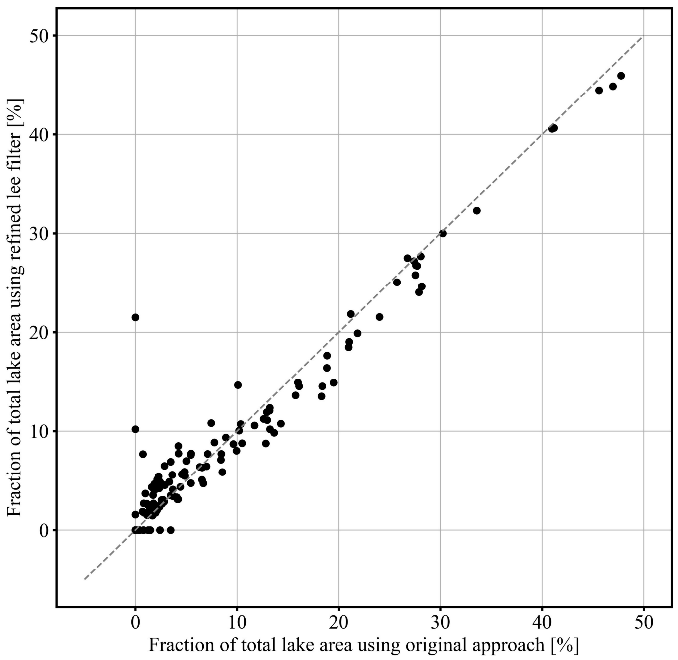
Original (with bilateral mean filter):



For comparison (with refined Lee filter):



A scatterplot for identified fractions of anomalies of total lake area (black data points in the time series plots above) using the two approaches is also illustrating similar results:



The validation metrics compared between the two approaches:

	Original (with bilateral mean filter)	**For comparison (with refined Lee filter)**
Matthews Correlation Coefficient	0.78	0.73
Cohen's Kappa Coefficient	0.78	0.73
F1 score binary	0.8	0.75
F1 score macro	0.89	0.86

Since the Matthews Correlation Coefficient, Kappa and the F1 score binary are by approximately 5% lower than for the original approach, we would prefer to keep the original workflow.

End of copy from author comment

Line 194: Further explanation of the incidence angle normalization process is needed. According to Pointer et al., 2019, backscatter was normalized to 30◦ , was the same value used here? The normalization process requires further attention so that it is clear to the reader.

Yes, backscatter was also normalized to 30°. A more thorough description has now been added:

"The incidence angle normalisation methodology used here is described in Pointner et al. (2019) and uses empirically derived normalisation functions in the form second degree polynomials to normalize

backscatter in dB to a common reference incidence angle of 30°. The normalisation function can be written as

$$\sigma^0_{norm}(\Theta)\ [dB] = a * \Theta^2 + b * \Theta + c \qquad (1)$$

where $\sigma^0_{norm}(\Theta)$ is the normalisation function, Θ is the local projected incidence angle, and a, b and c are the polynomial coefficients. The polynomial coefficients in Eq. (1) used for the incidence angle normalisation with respect to the sensor mode and polarisation are given in Table 3.

Table 3. Polynomial coefficients used for the incidence angle normalisation with respect to sensor mode and polarisation.

	a	b	c
EW HH	0.0067	-0.6784	1.7417
EW HV	0.0026	-0.3976	-16.2692
IW VV	0.0123	-1.1955	12.297
IW VH	0.0148	-1.4496	10.1781

Based on these coefficients, the final normalisation to the reference incidence angle of 30° was applied using (Pointner et al., 2019):

$$\sigma^0(30) = \sigma^0(\Theta) - (\sigma^0_{norm}(\Theta) - \sigma^0_{norm}(30)) \qquad (2)$$

where $\sigma^0(30)$ is the backscatter coefficient normalised to 30°, $\sigma^0(\Theta)$ is the backscatter coefficient before normalisation, $\sigma^0_{norm}(\Theta)$ is the value of the normalisation function at the incidence angle concerned and $\sigma^0_{norm}(30)$ is the value of the normalisation function at 30°."

Line 200: Line 201 states that the Sentinel-2 images were atmospherically corrected, were the Worldview-2 images also corrected?

Reply: Below is a copy of what we stated in the author comment:

Start of copy from author comment

The WorldVIew-2 images were not atmospherically corrected. Openly available atmospheric correction algorithms for WorldView-2 such as "6S" require detailed information on atmospheric conditions at the acquisition time that are simply not available to us. As an example, we refer here to the GRASS GIS implementation of the algorithm: https://grass.osgeo.org/grass76/manuals/i.atcorr.html

It does not include an atmospheric model for the Arctic and the aerosol concentration that is required cannot be estimated accurately for the study site and acquisition date. The reason we applied atmospheric correction to the Sentinel-2 data was that this could readily be done using the sen2cor tool. However, upon further review of literature, sen2cor also seems to fail in the automatic image-based retrieval of atmospheric parameters such as aerosol optical thickness or water vapor (König et al., 2019). Based on this, we think that sen2cor would also require parameterization based on external data to produce reliable results and as for the WorldView-2 data, this data is not available to us.

A shortcoming on our side we identified based on your comment is that we only used uncalibrated digital number (DN) data from the WorldView-2 data. We think it would be more meaningful to calibrate these data to top of atmosphere reflectance before the pan-sharpening.

Since the Sentinel-2 images are only used for visual comparisons, we would therefore propose to use top of atmosphere reflectance for both, Sentinel-2 and WorldView-2 and show recalculated results *based on the calibrated data derived from WorldView-2 if we were asked to submit a revised version of the manuscript.*

End of copy from author comment

We have now used Top of Atmosphere (TOA) reflectance for both, Sentinel-2 and WorldView-2 data. The sentence stating that Sentinel-2 images were atmospherically corrected was removed. The following sentence was added instead:

"Sentinel-2 data were downloaded in level 1C (L1C) format and directly used for visual comparisons."

WorldView-2 data has now been calibrated to Top of Atmosphere Reflectance and pan-sharpening has now been performed using all available bands, as this was required to address a comment by anonymous referee #2. We have modified the description of the pre-processing of the WorldView-2 data:

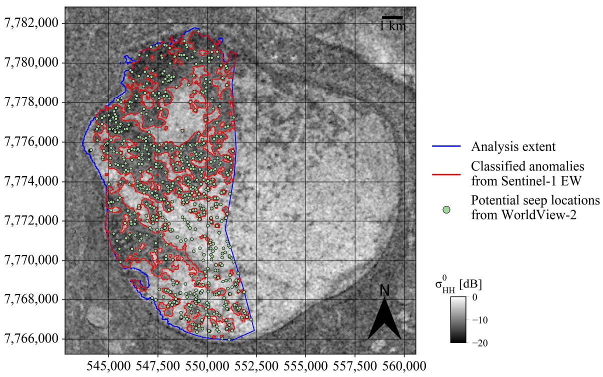
OLD: "We applied pansharpening based on the GDAL command line utilities which uses the Brovey method (GDAL/OGR contributors, 2020) to the WorldView-2 scene from 22 May 2016. As input for the pansharpening algorithm, we used all bands whose wavelength range lies completely within the wavelength range of the panchromatic band."

NEW: "We calibrated the WorldView-2 data from 22 May 2016 to top-of-atmosphere (TOA) reflectance following the methodology given by Updike and Comp (2010) and applied pan-sharpening from the Geospatial Data Abstraction Library (GDAL) command line utilities (version 2.2.4) which is based on the Brovey method (GDAL/OGR contributors, 2020) using all available bands."

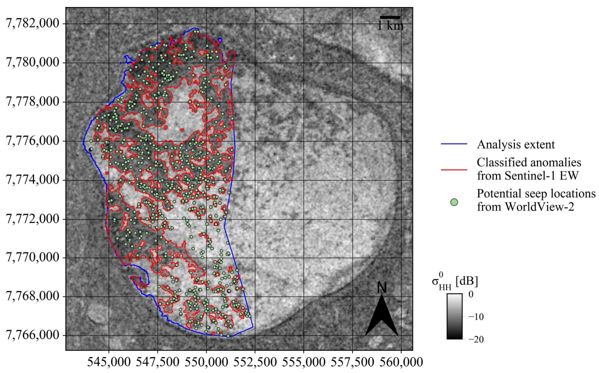
Start of copy from author comment

Results are similar to the ones in the preprint. For example, please see the recalculated Fig. 7:

Old:



New:



Please find comparisons of statistics between the old (with DN) and new (with TOA reflectances and pan-sharpened using all bands) approach below:

	Old	New
Number of detected holes	715	718
Number of hole polygons excluded for calculating histogram using area threshold	5	10
Median hole area	4.25 m^2	4.0 m^2
Percentage of holes inside classified anomaly regions	68%	71%
Mean minimum distance between the points (detected holes) and the polygons (anomaly regions)	48m	38m
Median distance of all points (detected holes) lying outside the polygons (anomaly regions)	97m	67m

End of copy from author comment

We have updated all figures and values the were affected by using the updated methodology.

Line 229: A short description of the Otsu thresholding method should be included. Were backscatter values used for thresholding or were images converted to greyscale?

Reply: We have added the following to the section 4.1.1. Pre-processing of Sentinel-1 SAR data as the subset extent is required to know which pixels were used for Otsu thrsholding:

"The well-known-text (WKT) representation of the subset extent in World Geodetic System 84 (WGS84) geographical coordinates is: POLYGON ((69.2277 69.7650, 70.9744 69.7650, 70.9744 70.3610, 69.2277 70.3610, 69.2277 69.7650, 69.2277 69.7650))."

We have added the following to section 4.2.1. Classification of backscatter anomalies from Sentinel-1 data:

"For the extraction of the lake masks, we used Otsu-thresholding (Otsu, 1979) on the HH-polarisation band (σ^0 in dB) implemented in scikit-image (skimage.filters.threshold_otsu, default parameters) of the late autumn acquisitions. Here, no incidence angle normalization was applied, as the incidence angle range over the lake was small and the backscatter values were only used to create the masks and were not compared to those of other acquisitions. After thresholding, we used the method scipy.ndimage.morphology.binary_fill_holes (default parameters) to fill holes in the classification result, polygonised the result using gdal_polygonize.py (default parameters) and extracted the polygon of lake Neyto."

Line 236: How were images rescaled? Was this done using a min-max normalization?

Reply: We used this method: skimage.exposure.rescale_intensity. As noted in the manuscript, the out_range interval was [-1,1] for all polarizations since this was a requirement for the other methods that were applied in the following. The choice of the in_range was more arbitrary, but since the rescaling result might be strongly affected by outliers in single images, we considered it best to use the same in_range for all images. To avoid too much clipping of the high and low values, the in_range should contain all sigma nought values that we would usually expect from the lake. On the other hand, the in_range should not be too large, to avoid too much precision loss. We decided to use a in_range of [-40 dB, 0 dB] for the co-polarized images and [-50 dB, -10 dB] for the cross-polarized images (the cross-polarized signal is usually significantly lower). We agree that this should be noted in the manuscript.

OLD: "After masking, pixel values were re-scaled to the interval from -1 to 1, as required by the image processing algorithms applied in the following."

NEW: "After masking, pixel values were re-scaled from dB to the interval from -1 to 1 using skimage.exposure.rescale_intensity (out_range=(-1,1), in_range=(-40,0) in case of co-polarization, in_range=(-50,-10) in case of cross-polarization), as required by the image processing algorithms applied in the following."

Line 272: Similar to above, more information should be provided about the watershed segmentation. Additional settings used for the process and the software packages used to perform both blob detection and segmentation should be included.

Reply: We have added the following:

"The method skimage.feature.blob_log (min_sigma=0.69, max_sigma=10, num_sigma=200, threshold=0.187) was used on the negative of the green band image."

And changed:

OLD: "Markers for the hole class were set on single pixels on which the centres of detected blobs were located. Markers for the background class were set on pixels with digital number (DN) larger than 1300. After the definition of the markers, the watershed segmentation was applied and individual hole objects were extracted and vectorised."

NEW: "Markers for the hole class were set on single pixels on which the centres of detected blobs were located. Markers for the background class were set on pixels with pan-sharpened TOA reflectance larger than 0.45. The marker image was defined with the same size as the original image, with value 1 for the hole markers, value 2 for the background class and value 0 elsewhere. After the definition of the markers, the watershed segmentation (skimage.segmentation.watershed, default parameters) was applied using the original image and the marker image, and individual hole objects were extracted and vectorised."

Figure 4: The boxplots for 2017-05-22 and 2019-05-24 are initially confusing when you look at the plot. Could the y-axis labels be dropped on the middle frames and 2019- 05-24 frame so that there is only one shared axis? Additionally, a better demonstration that the outside frames are part of the dataset shown in the middle frame would help improve the figure.

Reply: We dropped the y-axis labels on the middle and right frames and merged all frames. Please find the new figure below:

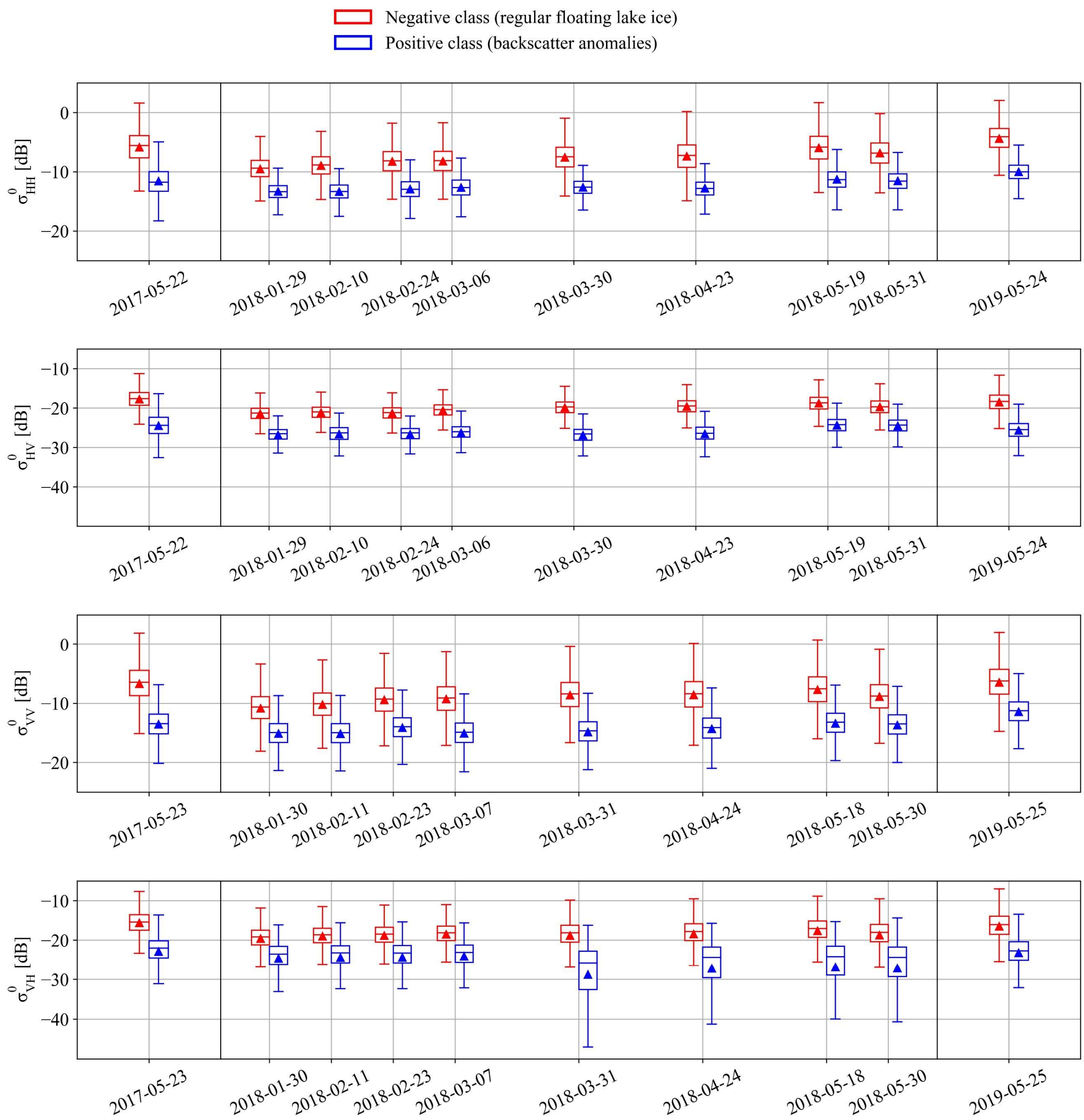


Figure 5: It would be better to show the same image/area for both a) and b) – that way the reader could see how the watershed was used to best identify the holes in the ice.

Reply: Agreed. Please find the new figure below:

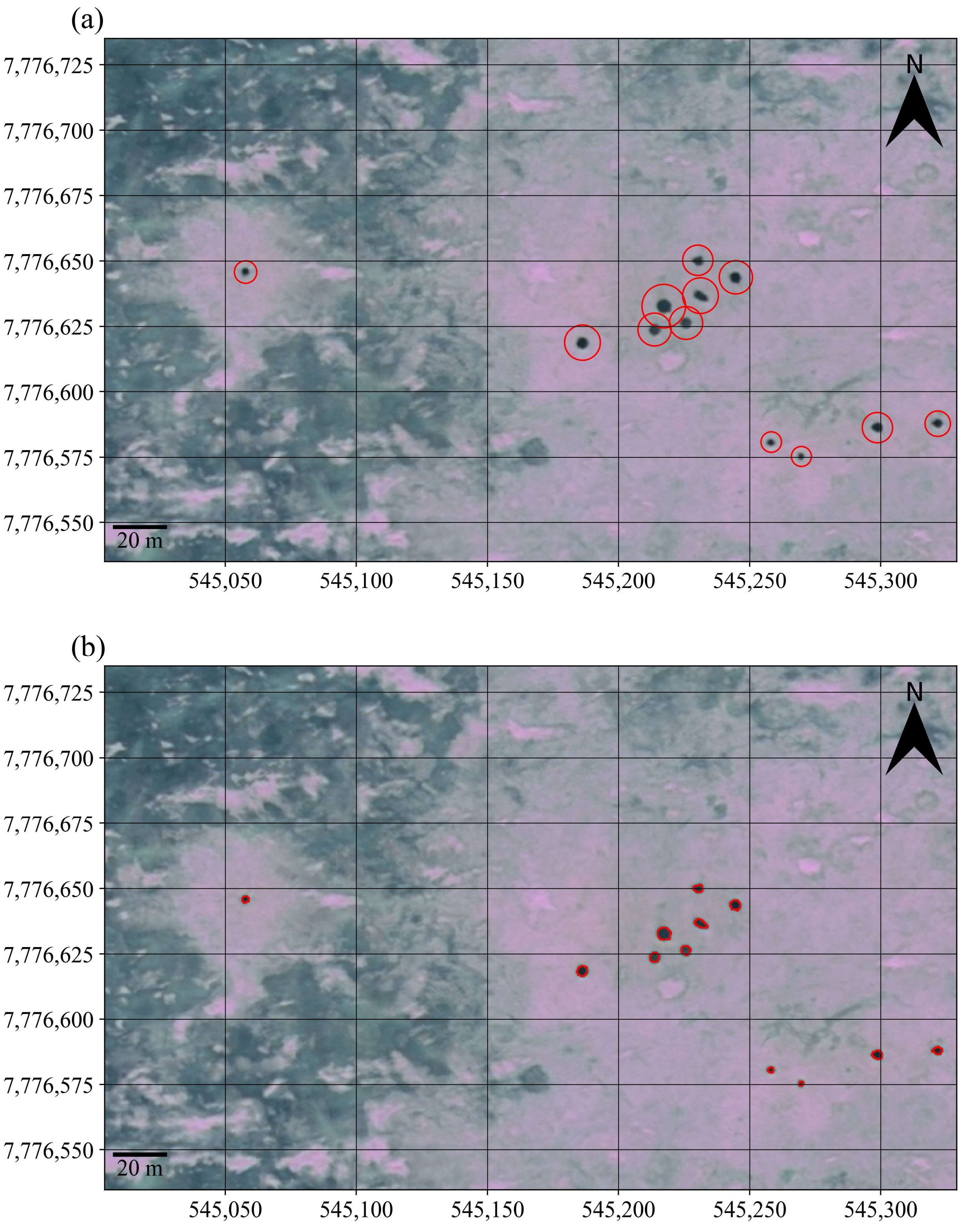


Figure 9: The intersection fraction is confusing, the explanation needs to be changed so that the metric is clear to readers. The repeated mention of 'positive class' makes the explanation wordy, possibly it could be changed to anomaly regions.

Reply: We followed your suggestion to change "positive class" to "anomaly regions". Additionally, the explanation was changed. The new name is "fraction of overlap between anomaly regions on consecutive dates".

The following changes in the text were made:

OLD: In order to assess the expansion of anomaly regions, the fraction of intersection of the positive class of the previous classification in time with the positive class of the classification at the timestamp indicated is shown in brown (area of intersection divided by area of the anomaly regions at the previous timestamp).

NEW: In order to assess the expansion of anomaly regions, the fraction of overlap between anomaly regions on consecutive dates is shown in brown (area of intersection between classified anomaly regions on the timestamp indicated and that of the previous timestamp, divided by area of the classified anomaly regions at the previous timestamp).

OLD CAPTION: Time series of fraction of area of anomaly regions with respect to total lake area (black, (Pointner and Bartsch, 2020)), fraction of intersection of the previous classification with the classification at the timestamp indicated (brown) for the time period after no anomalies were detected for the last time in the years concerned, maximum (green) and minimum (blue) air temperature recorded at the Seyakha weather station. The left axis indicates the fraction of anomaly region areas to total lake area and fraction of intersection. The right axis indicates air temperature. Fractions of intersection were calculated as area of intersection between anomalies detected at the timestamp indicated and that of the previous timestamp, divided by the area of anomalies detected at the previous timestamp. Gray dashed lines indicate dates where maximum air temperature exceeded 0 °C during the analysis periods of the SAR data.

NEW CAPTION: Time series of fraction of area of anomaly regions with respect to total lake area (black, (Pointner and Bartsch, 2020)), fraction of overlap between anomaly regions on consecutive dates (brown) for the time period after no anomalies were detected for the last time in the years concerned, maximum (green) and minimum (blue) air temperature from the ERA5 hourly data on single levels from 1979 to present (Hersbach et al., 2018). The left axis indicates fraction of area of anomaly regions with respect to total lake area and the fraction of overlap between anomaly regions on consecutive dates. The right axis indicates air temperature. Fractions of overlap were calculated as area of intersection between classified anomaly regions on the timestamp indicated and that of the previous timestamp, divided by area of the classified anomaly regions at the previous timestamp. Gray dashed lines indicate dates where maximum air temperature exceeded 0 °C during the analysis periods of the SAR data.

Minor Typography

Line 4: ‘so far’ can be removed to improve conciseness, and it should be changed to ‘due to a lack of...’

Reply: Agreed. We changed it accordingly.

Line 22: ‘remain’ should be changed to are.

Reply: Agreed. We changed it.

Line 28: ‘distinguish’ should be changed to ‘distinguished’

Reply: Agreed. We changed it accordingly.

Line 122: ‘threads’ should be threats?

Reply: Yes, ‘threats’ was meant. Changed.

Line 361-362: “temperature is often approaching or slightly exceeding” should be changed to “often approaches or slightly exceeds”.

Reply: Agreed. Changed.

Line 375: “is by approximately”, the ‘by’ can be removed.

Reply: Agreed. Changed.

Line 404: A citation is needed for the causes of holes on Lake Baikal.

Reply: We have changed the sentence and added the following references:

“However, other causes of holes in lake ice were identified for lake Baikal, for example, such as seal breathing holes, hot springs or oil seepage (Galaziy, 1987; Petrov, 2009).”

References:

Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C., Radu, R., Rozum, I., Schepers, D., Simmons, A., Soci, C., Dee, D., Thépaut, J-N.: ERA5 hourly data on single levels from 1979 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). (Accessed on 30-10-2020), https://doi.org/10.24381/cds.adbb2d47, 2018.

Bartsch, A., Pointner, G., Leibman, M. O., Dvornikov, Y. A., Khomutov, A. V., and Trofaier, A. M.: Circumpolar Mapping of Ground-Fast Lake Ice, Frontiers in Earth Science, 5, 12, https://doi.org/10.3389/feart.2017.00012, 2017.

Galaziy, G. I.: Baikal in questions and answers. Eastern-Siberian Publishing. (In Russian.). 380 pp., 1987.

König, M., Hieronymi, M., and Oppelt, N.: Application of Sentinel-2 MSI in Arctic Research: Evaluating the Performance of Atmospheric Correction Approaches Over Arctic Sea Ice, Frontiers in Earth Science, 7, 22, https://doi.org/10.3389/feart.2019.00022, 2019.

Obu, J., Westermann, S., Barboux, C., Bartsch, A., Delaloye, R., Grosse, G., Heim, B., Hugelius, G., Irrgang, A., Kääb, A., Kroisleitner,C., Matthes, H., Nitze, I., Pellet, C., Seifert, F., Strozzi, T., Wegmüller, U., Wieczorek, M., and Wiesmann, A.: ESA Permafrost ClimateChange Initiative (Permafrost_cci): Permafrost ground temperature for the Northern Hemisphere, v2.0, Centre for Environmental Data Analysis, 02 November 2020, https://doi.org/10.5285/6ebcb73158b14cd5a321b7c0bc6ed393., 2020.

Petrov E.A.: The Baikal seal. « ECOS », Ulan-Ude, 2009, 176 pp. (In Russian). ISBN 978-5-85693-340-5, 2009.

Pointner, G., Bartsch, A., Forbes, B. C., and Kumpula, T.: The role of lake size and local phenomena for monitoring ground-fast lake ice, International Journal of Remote Sensing, 40, 832–858, https://doi.org/10.1080/01431161.2018.1519281, 2019.

3. Reply to Anonymous Referee #2

Dear Anonymous Referee #2,

we thank you again very much for taking the time to review our manuscript and for providing detailed comments! We also thank you again for sharing your expertise related to the flooding/slushing/wetting of the snowpack that helped to improve the manuscript.

General comments:

The manuscript presented is a detailed study of a single lake (Lake Neyto) in the Yamal Peninsula, which if the hypotheses are correct, present a method that could be used to monitor multiple lakes across a much larger area of both the Yamal and likely Siberian region. The methods presented in the study are technically sound, but the results are presented and interpreted to fit the narrative and at times, are cavalier by placing too much weight on hypotheses that do not have in-situ observations to back them up. The narrative of the paper hinges on the fact that methane ebullition is creating hotspots that are tens to hundreds of metres in area. The hot spots are spatially co-located with areas of open water that are observed in high resolution spring time optical acquisitions (WorldView 2), and when overlaid on SAR imagery, are also collocated with larger regions of lower backscatter.

Reply: Thank you again for the positive feedback regarding the used methods. We have now significantly re-arranged, re-written and changed many parts of the discussion and conclusion sections using more cautious formulations. We have discarded the explanation related to cavities, as based on your comments and further internal discussion, this does not seem practical indeed.

The authors propose that the regions of lower backscatter are the result of methane ebullition that is creating large cavities in ice thickness, creating a specular reflection away from the sensor. This is difficult to agree with for a few reasons: First, as evidence in the Discussion section where the authors present evidence of surface slushing as a result of a hole being augered into the ice, the water level went approximately 40cm over the ice surface. This is significant, because if methane ebullition is creating holes or areas of thin ice, then the surface will undoubtedly become wet as the ice is depressed passed the hydrostatic water level. The slushy snow will either absorb incoming microwave radiation, or it will refreeze as snow ice (and become a greater backscatter). Since most of the lower backscatter areas increase throughout the winter season, it is more likely that the surface is becoming wetter as the ice is depressed by the increasing weight of the snowpack and water floods the ice surface. This is consistent with Figures 7, 8, and 9, as the area impacted by the hole is nearly always a concentric circle, consistent with water spreading on a (relatively) flat surface.

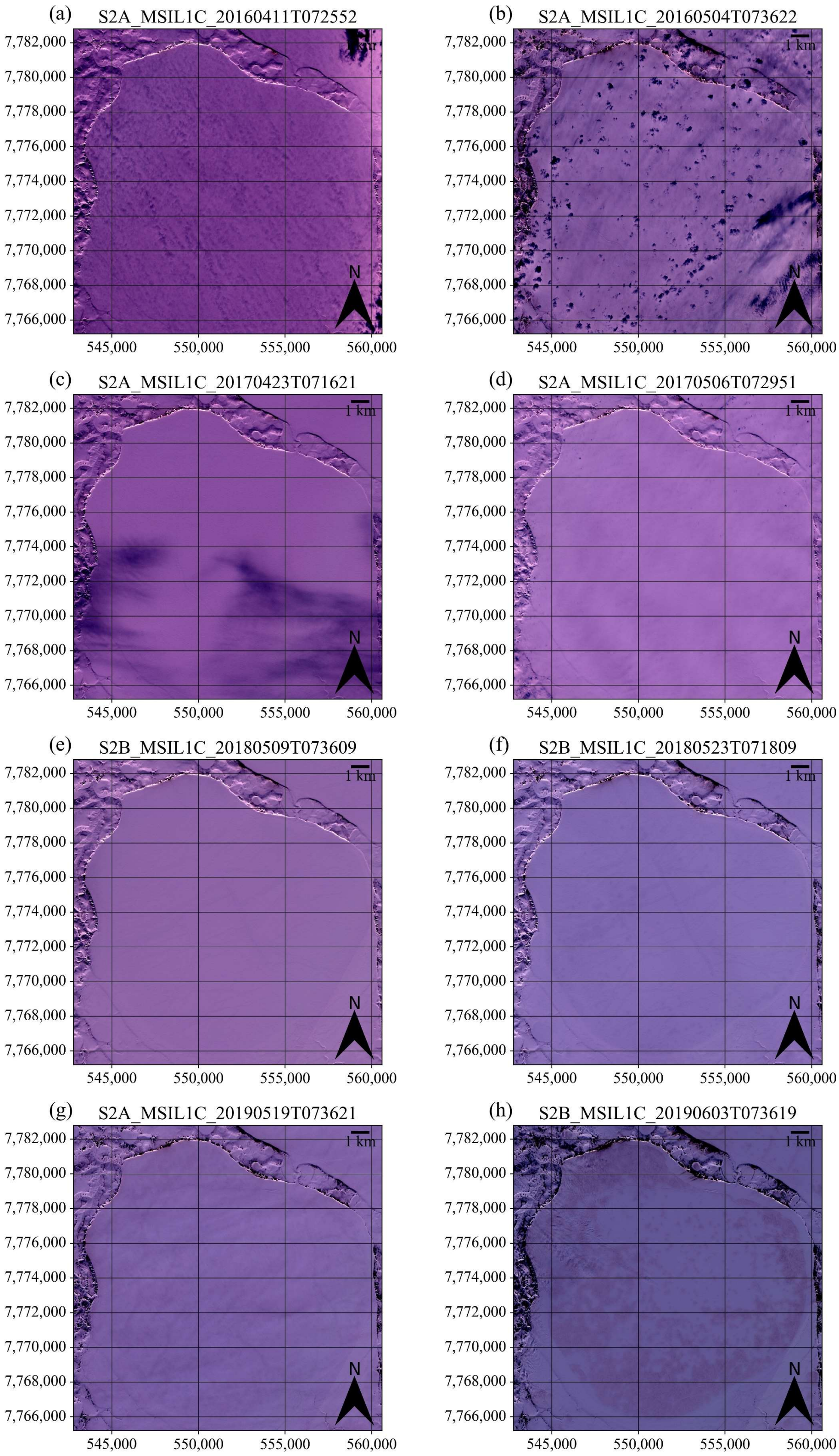
Reply:

Below is a copy from our author comment. We assumed that significant changes in TOA reflectance would occur if the ice surface were flooded in April medium resolution images. We now think that this assumption was not appropriate.

Start of copy from author comment:

Based on your comments and further internal discussion, we think that flooding of the surface and consequent slushing/wetting of the snow is the most probable explanation for the observed patterns in the imagery. At first, it seemed puzzling that wet and/or slushy snow areas could expand so gradually over weeks to months. But given that with time the ice will get further depressed below hydrostatic water level with increased loading of (wet) snow and slush, this makes a lot of sense. Our expectation was that if flooding was responsible for the observed anomalies, we would be able to see indicators *for flooding of the ice layer and/or slushing/wetting of the snow in most of the cloud-free medium resolution optical imagery acquired during late winter and spring (Sentinel-2 and Landsat).*

Below is a figure with cloud-free Sentinel-2 images of different years (TOA reflectance, scaling for visualization between 0.7 and 1 to enhance contrast). The acquisition date and time is indicated in title (UTC). Local time is 5h later, so these images were acquired around 12:30 local time. Only in the latest acquisitions before or during melt onset we can clearly see similar patterns as in the SAR images.



The description in the manuscript was based on the expectation that there is significantly different reflectance in the flooded or slushed regions also in the earlier April images. This expectation might be therefore not adequate in this context.

Actually, a photo was taken (please see below) when the wheel of the all-terrain vehicle fell into the patch of very thin ice on of the lakes on Yamal (as stated in the preprint), which shows that there was fresh snow above the seep location. Before it was hit by the wheel, the site was indistinguishable from the surrounding snow-covered ice. The vertical structure before it was hit by the wheel cannot be described with confidence. There was certainly fresh show on top, below that might have been a layer of melted or frozen slush, but this cannot be stated with confidence. The ice below was very thin. These observations might be related to what we see in the Sentinel-2 imagery, but further observations are needed to understand this in detail.

End of copy from author comment

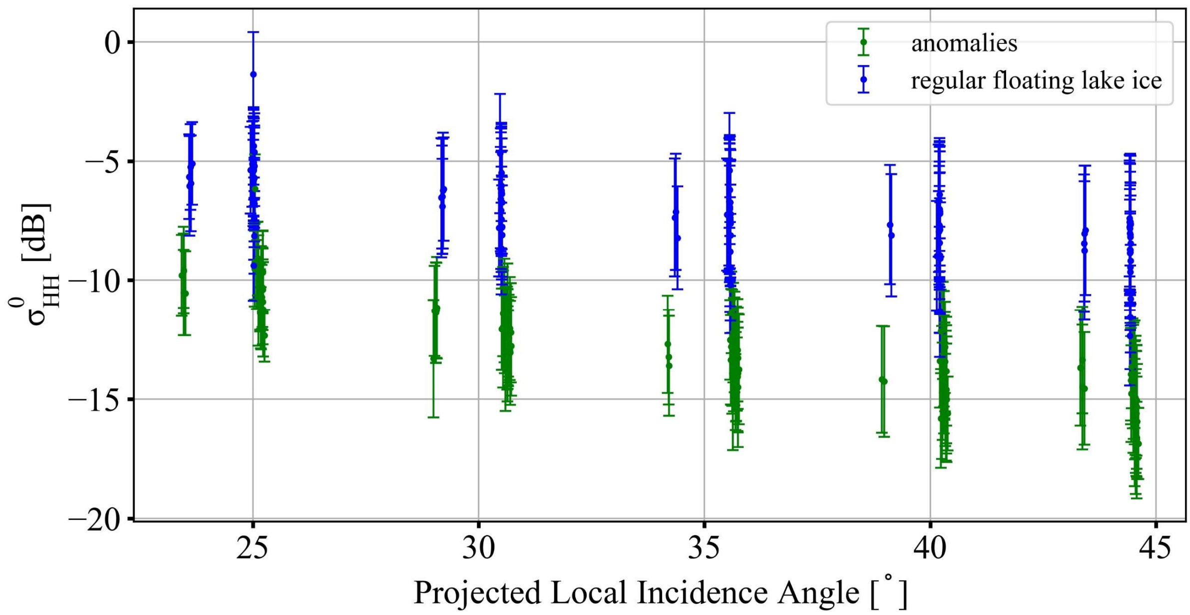
We again thank you for providing this alternate hypothesis and for encouraging us to think more about slushing/wetting of the snow. We have now included a discussion on this hypothesis and also refer to your referee comment in the manuscript. We have used the in-situ observations of lake ice drilling on the other lake to support this hypothesis. We have now included another figure that might show accumulations of slush and wet snow around the holes, as this might be of relevance for future field-based studies.

Second, if cavities that are present in the ice are large enough to act as a spectral reflector as opposed to roughness, then based on scattering theory the radar cross section from the target would be consistent regardless of incidence angle. The authors have normalized the incidence angles in this study, and it would be interesting to see if the NRCS is consistent across the incidence angle range observed.

Reply:

***Start of copy from author comment**:*

For a prefect specular reflector, the NRCS would be consistent across the incidence angle range, but then we would expect the magnitude of the backscattered signal to be below the noise floor of the sensor. What we proposed was that the main mechanism could be specular reflection, but the backscattered signal could still include contributions from the rough ice-water interface in smaller regions of regular floating lake ice inside the resolution cell. We do not think that we can differentiate between cavities and wet snow based on the incidence angle dependence alone in this case. This has become less important now, as we agree with you that wet snow or slush is most likely responsible for the observed low backscatter. We have nevertheless plotted the incidence angle dependence for all acquisitions for which anomalies have been identified for both classes. The points indicate the median sigma nought, the whiskers the standard deviation. Blue is the regular floating lake ice class; green is the anomaly class. There seems to be a similar dependence for both classes. The backscatter-incidence angle relationship would be better assessable by taking samples from a single scene (assuming similar environmental conditions over the entire scene) over the whole incidence angle range, but this was not possible here (because we could not sample anomalies over an entire scene extent).



End of copy from author comment

Third, there are no in-situ observations. The authors rightly mention that this area is extremely difficult to get to, and that direct personal observation of the holes are not safe due to thin ice. This acknowledgement of the limitation needs to also bring with it a lessening of the claims/assumptions that the source of the hotspots is definitely methane ebullition, and the mechanism that influence the SAR scenes.

Reply: We agree. We have updated, re-arranged and re-written many parts of the discussion and conclusions and used more prudent formulations.

That being said, there is considerable scientific merit to this paper in the methods, statistical tests, and results that it shows. In my opinion I believe that the paper will become acceptable after significant revision to ensure that interpretation of imagery lacking in-situ data remains inquisitive as opposed to prescriptive.

Reply: Thank you again! We have changed the parts regarding the interpretation significantly and tried to keep it inquisitive.

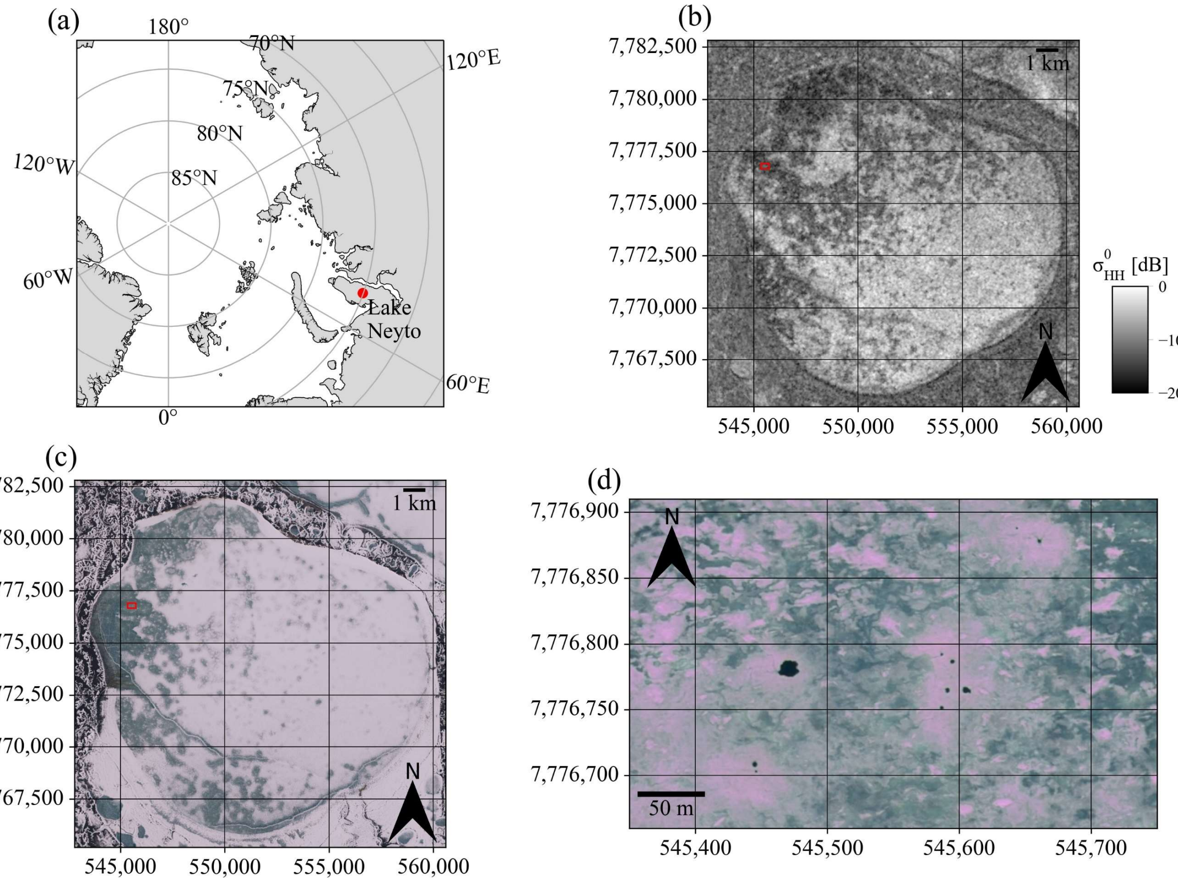
Specific comments:

I will list line #s in this section, but firstly – this manuscript did not have a Study Site section. This is integral to this paper as it consistently references the surround region, and studies that have been done on other lakes. Please include.

Reply: This was also criticized by the other referee. We have now added a study site section, transferred lines 100-118 into that section (as suggested by referee #1) and added the following additional information before the transferred lines:

"Lake Neyto (other title: Neyto-Malto), 70.073 °N, 70.350 °E, is located in the central part of the Yamal Peninsula, ca. 80 km away from the closest settlement Seyakha and ca. 80 km away from the Bovanenkovo gas field. The lake has the second biggest area (214 km^2) in Yamal after Yaroto-1 lake. The length of the shoreline is about 60 km and the lake measures approximately 17.8 km in the south – north direction and 16.5 km from west to east. The lake is relatively shallow, reaching 17 m at the north-west corner, but the average depth does not exceed 3 m, which results in a significant mixing of water masses during summer (Edelstein et al., 2017). Wide shelf areas up to 800 m can be found within the lake, whereas at the deepest part, several depressions with diameters up to 500-800 m are documented (Edelstein et al., 2017). Lake shores are mostly cliffs up to 25 m high, sometimes with tabular ground ice exposures. The ground temperature at 2 m depth in the surroundings of the lake is approximately -1.5 °C (Obu et al., 2020). The Snow Depth Liquid Water Equivalent (SDLWE) 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 (Hersbach et al., 2018)."

Additionally, we included a fourth frame in Figure 1 indicating the location of lake Neyto following a suggestion by anonymous referee #1:



The Introduction section is very detailed but extremely long. Paragraphs between lines 55 and 95 can be further summarized to provide key points to the reader.

Reply: We have tried to summarize these paragraphs as much as possible. However, a thorough description of the relative permittivity required additional content. We have transferred lines from the introduction to the study site section (see previous comment). The length of the introduction has now changed from 129 lines to 100 lines.

OLD: "Promising in this context are space-borne synthetic aperture radar (SAR) data. SAR has proven to be very useful for the monitoring of lake ice phenology (e.g. Duguay and Pietroniro, 2005; Surdu et al., 2015). Several studies have successfully used SAR data to distinguish between ground-fast (ice that froze to the lakebed) and floating lake ice (e.g. Bartsch et al., 2017; Duguay and Lafleur, 2003; Engram et al., 2018; Grunblatt and Atwood, 2014; Surdu et al., 2014). Ground-fast ice usually occurs around the shallow shelf or over the whole lake area, if the lake is shallow enough. In C-band SAR images, low backscatter is observed from ground-fast lake ice and high backscatter is usually observed from floating lake ice (Duguay and Pietroniro, 2005). The magnitude of the reported differences between backscatter from ground-fast and floating lake ice varies across studies and depends on radar frequency, polarisation, incidence angle and geographic region (Antonova et al., 2016). Lake ice is nearly transparent for the radar signal. Low radar return is observed from ground-fast lake ice due to low dielectric contrast between ice and the lake sediments (Duguay et al., 2002). On the other hand, strong reflection of the radar signal occurs at the ice-water interface of floating lake ice because of high dielectric contrast between ice and liquid water (Duguay et al., 2002; Engram et al., 2013). The dominant mechanism for high backscatter from floating lake ice observed by SAR sensors has long been described to be double-bounce scattering from the ice-water interface and columnar bubbles trapped within the ice (e.g. Duguay et al., 2002; Jeffries et al., 1994; Wakabayashi et al., 1993). More recent *studies, however, provide strong evidence that the dominant mechanism is direct backscattering from a rough ice-water interface (Atwood et al., 2015; Engram et al., 2020, 2013; Gunn et al., 2018). Coming back to gas emissions, Engram et al. (2020) showed a significant correlation between whole lake methane emissions and whole lake L-band backscatter from ice-covered Alaskan lakes in case of superficial seeps (see Sect. 5 for details). For a number of lakes on the Yamal Peninsula, regions characterised by low C-band backscatter that very likely belong to the floating ice regime have been identified (Bogoyavlensky et al., 2018; Pointner et al., 2019). Patterns of low backscatter have especially been pointed out for lake Neyto in Central Yamal using C-band Sentinel-1 SAR data (Bogoyavlensky et al., 2018; Pointner et al., 2019). Lake Neyto is one of the largest lakes on Yamal and also the region of interest in this study. Here, regions of anomalously low backscatter mainly appear in late winter and spring in regions previously characterised by significantly higher backscatter, are often of circular or linear shape, seem to successively expand over time in a single year before melt-onset and appear predominantly in different locations of the lake in different years (Pointner and Bartsch, 2020). Based on the analysis of data of boreholes in the vicinity of lake Neyto, Bogoyavlensky et al. (2018) described a gas field that stretches out under lake Neyto. They showed Sentinel-1 scenes acquired in different years, compared them visually to optical Sentinel-2 scenes and suggested that backscatter anomalies are related to zones of very thin or no ice which resulted from gas bubble inclusions within the ice. They further suggested that the gas potentially migrated from the gas field or that it could have also resulted from gas-hydrate decomposition within permafrost, or both. Pointner et al. (2019) also suggested that the regions of low backscatter may be a result of upwelling gas released through the sediments, which might lead to local thinning of the ice layer and form cavities in the ice. Significantly lower backscatter would be observed because of increased specular reflection at the water-surface at the bottom of the cavity. They discussed the phenomenon showing time series of Sentinel-1 imagery from 2016 and 2017, but did not provide further analyses concerning the connection between anomalies and gas emissions. Engram et al. (2020) and Greene et al. (2014) showed that hotspot bubbling of methane (ebullition capable of maintaining open holes in the ice) can form cavities at the ice-water interface throughout winter and spring. So far, these cavities have only been identified for superficial seeps in Alaskan lakes and their size is in the order of decimetres (Engram et al., 2020; Greene et al., 2014) . In order to explain the observed regions of low backscatter on lake Neyto, cavities would have to be significantly larger and potentially caused by higher emission rates. Another possible explanation for the phenomenon given in Pointner et al. (2019) was that eddies could cause a local thinning of the ice layer, similar to the cause of ice rings on lakes Baikal, Hovsgol and Teletskoye reported by Kouraev et al. (2019, 2016)."*

NEW: "Promising in this context are space-borne synthetic aperture radar (SAR) data. SAR has proven to be very useful for the monitoring of lake ice phenology (e.g. Duguay and Pietroniro, 2005; Surdu et al., 2015). Several studies have successfully used SAR data to distinguish between ground-fast (ice that froze to the lakebed) and floating lake ice (e.g.,Bartsch et al., 2017; Duguay and Lafleur, 2003; Engram et al., 2018; Grunblatt and Atwood, 2014; Surdu et al., 2014). In C-band SAR images, low backscatter is observed from ground-fast lake ice and high backscatter is usually observed from floating lake ice (Duguay and Pietroniro, 2005). The magnitude of the reported differences between backscatter from ground-fast and floating lake ice varies across studies and depends on radar frequency, polarisation, incidence angle and geographic region (Antonova et al., 2016). Lake ice is nearly transparent for the radar signal. Low radar return is observed from ground-fast lake ice due to low dielectric contrast between ice and the lake sediments (Duguay et al., 2002). On the other hand, strong reflection of the radar signal occurs at the ice-water interface of floating lake ice because of high dielectric contrast between ice and liquid water (Duguay et al., 2002; Engram et al., 2013). The dielectric contrast is determined by differences in the complex-valued relative permittivity ε, that in general depends on the radar frequency and temperature. The real part ε' of ice is approximately 3.17 and nearly independent of radar frequency and temperature (Mätzler and Wegmüller, 1987). The imaginary part ε" is below

10^{-3} for pure and impure freshwater ice at C- and L-band frequencies (Mätzler and Wegmüller, 1987). Meissner and Wentz (2004) providea detailed list of ε of water at various frequencies and temperatures. At 1.7 GHz and 25 °C, ε' is 78 and ε" is 6. At 5.35 GHz and 25 °C, ε' is 73 and ε" is 19. At 5 GHz and -4 °C, ε' is 65 and ε" is 38. ε of frozen soil largely depends on the temperature, and water, clay, silt and sand content (Zhang et al., 2003). At 10 GHz, ε' ranges approximately from 3.2 to 8, ε" from 0.1 to 2 (Hoekstra and Delaney, 1974). Little sensitivity of ε of frozen soil to the radar frequency between 1.4 and 10.6 GHz is suggested by estimates in Zhang et al. (2003). The dominant mechanism for high backscatter from floating lake ice observed by SAR sensors has long been described to be double-bounce scattering from the ice-water interface and columnar bubbles trapped within the ice (e.g. Duguay et al., 2002; Jeffries et al., 1994; Wakabayashi et al., 1993). More recent studies, however, provide strong evidence that the dominant mechanism is direct backscattering from a rough ice-water interface (Atwood et al.,852015; Engram et al., 2020, 2013; Gunn et al., 2018). Engram et al. (2020) showed a significant correlation between whole lake methane emissions and whole lake L-band backscatter from ice-covered Alaskan lakes in case of superficial seeps (see Sect. 6 for details). For lake Neyto on the Yamal Peninsula, regions characterised by low C-band backscatter that very likely belong to the floating ice regime have been identified (Bogoyavlensky et al., 2018; Pointner et al., 2019). Based on the analysis of data of boreholes in the vicinity of lake Neyto, Bogoyavlensky et al. (2018) described a gas field that stretches out under lake Neyto. They showed Sentinel-1 scenes acquired in different years, compared them visually to optical Sentinel-2 scenes and suggested that backscatter anomalies are related to zones of very thin or no ice which resulted from gas bubble inclusions within the ice. Pointner et al. (2019) also suggested that the regions of low backscatter may be a result of up-welling gas released through the sediments, which might lead to local thinning of the ice or that eddies might cause a local thinning of the ice layer, similar to the cause of ice rings on lakes Baikal, Hovsgol and Teletskoye reported by Kouraev et al. (2019, 2016)."

Page 1, Line 20: "Methane (CH4) is a powerful greenhouse gas and the global trend of its atmospheric concentration has shown significant changes over the last decades (Nisbet et al., 2014)." What changes" The concentration of Methane, or its effects? Please be specific.

Reply: The concentration was meant. We have added the following:

"Methane (CH4) is a powerful greenhouse gas and the global trend of its atmospheric concentration has shown significant changes over the last decades. The concentration increased significantly until 1998 and since 2007 until today, while between 1999 and 2006, it remained nearly constant (Nisbet et al., 2014)."

Page 2, Line 38: "150 thousand"

Please write as 150 000

Reply: We agree. Changed to 150 000.

Page 2 Line 48: "… that gained a lot of attention in the scientific community recently."

What sort of attention? Newspaper? Scientific studies? Please provide references, and if they were the references earlier in the sentence, please provide at the end.

Reply: Basically both, newspaper and scientific studies. We now think this phrase sounds a bit odd. We changed it to: "…such as a number of gas emission craters (GECs) that were discovered and described in recent years (e.g. Bogoyavlensky et al., 2016; Dvornikov et al., 2019; Kizyakov et al., 2020, 2017; Leibman et al., 2014)."

Page 3 Line 62: “Low radar return is observed from ground-fast lake ice due to low dielectric contrast between ice and the lake sediments (Duguay et al., 2002). On the other hand, strong reflection of the radar signal occurs at the ice-water interface of floating lake ice because of high dielectric contrast between ice and liquid water (Duguay et al., 2002; Engram et al., 2013).”

Provide the actual real and imaginary values of the relative permittivity so the reader can understand what a high and low dielectric contrast are.

Reply: We agree. These values are dependent on the radar frequency and temperature and consequently needed a more precise description. We have added the following:

“The dielectric contrast is determined by differences in the complex-valued relative permittivity ε, that in general depends on the radar frequency and temperature. The real part ε’ of ice is approximately 3.17 and nearly independent of radar frequency and temperature (Mätzler and Wegmüller, 1987). The imaginary part ε” is below 10^{-3} for pure and impure freshwater ice at C- and L-band frequencies (Mätzler and Wegmüller, 1987). Meissner and Wentz (2004) provide a detailed list of ε of water at various frequencies and temperatures. At 1.7 GHz and 25°C, ε’ is 78 and ε” is 6. At 5.35 GHz and 25°C, ε’ is 73 and ε” is 19. At 5 GHz and -4°C, ε’ is 65 and ε” is 38. ε of frozen soil largely depends on the temperature and water, clay, silt and sand content (Zhang et al., 2003). At 10 GHz, ε’ ranges approximately from 3.2 to 8, ε” from 0.1 to 2 (Hoekstra and Delaney, 1974). Little sensitivity of ε of frozen soil to the radar frequency between 1.4 and 10.6 GHz is suggested by estimates in Zhang et al. (2003).”

Page 3 Line 68: “Coming back to gas emissions”,

Remove – this is unnecessary

Reply: Removed.

Page 5 Lines 119 – 128: Understanding such phenomena can be important for numerous reasons, such as climate modelling, where global models 120 currently incorporate methane release from permafrost environments only poorly (Turetsky et al., 2020) and only consider ebullition from superficial seeps, or the understanding of sub-lake permafrost dynamics (Pointner et al., 2019). Another important point is that gas emissions can pose serious threads to humans, e.g. people working in the gas industry or local indigenous people. The Yamal-Nenets are reindeer herders that travel across the Peninsula throughout each year. They frequently crossfrozen lakes in winter. In June 2017, a powerful explosion from a gasinflated mound that formed under a riverbed near Seyakha 125 on the Yamal Peninsula has been documented by Bogoyavlensky et al. (2019c), scattering debris over a radius of a few hundred metres. For lake Otkrytie, an eruption that seems to have been capable of breaking lake ice of 1.5 m thickness was described by Bogoyavlensky et al. (2019a). Understanding where different forms of gas release happen may be favorable for identifying areas of increased risk for humans.”

This paragraph is out of place here. It should be moved to the beginning of the Intro or in the Discussion section to provide information about the impact of the study.

Reply: We have moved it to the beginning of the introduction (second paragraph) and modified it to:

“Global climate models currently incorporate methane release from permafrost environments only poorly and cannot account for ebullition from geological lake seeps (Turetsky et al., 2020). Gas emission related phenomena can pose serious threats to humans, e.g. people working in the gas industry or local indigenous people. The Yamal-Nenets are reindeer herders that travel across the Yamal Peninsula in Western Siberia throughout each year. They frequently cross frozen lakes in winter. Patches of thin ice, caused by emissions of natural gas, may be present on some of these lakes (e.g. Bogoyavlensky et al.,

2016, 2019a). In June 2017, a powerful explosion from a gas-inflated mound that formed under a riverbed near Seyakha on the Yamal Peninsula has been documented by Bogoyavlensky et al. (2019c), scattering debris over a radius of a few hundred metres. Understanding where different forms of gas release happen may be favourable for identifying areas of increased risk for humans."

Page 6 Line 129: The Data section should have a table of the acquisitions that were used in this analysis for reproducibility. It's also important to list the relevant metadata about those acquisitions, specifically the local time of acquisition and the incidence angle. For example, you have several scenes that were acquired during days in which the temperature exceeded 0C. A daytime/nighttime acquisition time becomes quite crucial to your study then.

Reply: We have added a table listing the years of data, the number of images, and the average temporal gap between imagery directly in the manuscript (as suggested by referee #1):

Year	**Number of images**	**Average temporal gap**
2015	29	4d 7h
2016	88	1d 13h
2017	112	1d 7h
2018	52	2d 23h
2019	41	3d 14h

Since altogether more than 300 Sentinel-1 acquisitions were used and we think that the table would be too large to fit in the data section, we now provide detailed tables including the scene ID, acquisition time and mean incidence angle as supplementary .csv-files and also indicate the exact scenes that were used for calculating the lake masks and the shelf masks. In particular, we now include 4 tables in total for the Sentinel-1 data: One for all EW scenes used for calculating the time series, one for all IW scenes used, one for the EW scenes used for calculating the lake masks and one for the EW scenes used for calculating the shelf masks. Additionally, we provide a similar table for the other satellite data used in this study.

We have added the following to the Sentinel-1 data section:

"Lists of the used scenes including the mean projected local incidence angle over the lake, acquisition times in local time and Universal Time Coordinated (UTC) and an indicator showing if the scenes were assembled due to slicing (see Sect. 4.1.1)) are provided in the Supplement (S1-S4) to this article in ".csv"-format. "S1__scene_metadata_list_Sentinel1_EW_main.csv" contains a list of the main Sentinel-1 EW data (342 scenes) used in this study. "S2__scene_metadata_list_Sentinel1_EW_lake_masks.csv"and "S3__scene_metadata_list_Sentinel1_EW_shelf_masks.csv" contain lists of the Sentinel-1 EW data used for calculating lake masks (5 scenes) and shelf masks (5 scenes), respectively (see Sect. 4.2.1 for details). "S4__scene_metadata_list_Sentinel1_IW.csv" contains a list of all Sentinel-1 IW data used for the validation (10 scenes). "S5__scene_metadata_list_other_sensors.csv" contains a similar list for the other satellite data (4 scenes in total) used in this study, which are described in the following paragraphs."

We have now also added a description that some products had to be assembled using the "slice assembly" operator in SNAP, when products have been sliced directly over the lake in the "Pre-processing of Sentinel-1 SAR data"-section:

“Some products have been sliced directly over lake. In these cases, the slice-assembly operator was applied to those products in gpt as the first processing step. Products to which this operator was applied are indicated in the supplementary tables S1-S4.”

Page 7 Line 154: 1236.5 MHz and 1278.5 MHz Use GHz or MHz – be consistent.

Reply: Agreed. We suggest using GHz. Changed to: 1.237 GHz and 1.279 GHz.

Page 7 Line 180: “closest to lake Neyto and located on the east coast of the Yamal Peninsula at a distance of approximately 80 km, to assess potential temporal relationships between backscatter anomalies and air temperature”

80km is a significant distance when considering air temperature, and the fact that the Seyakha station is located on the coast and lake Neyto is located in land of the Yamal Peninsula. Is it possible that a gridded reanalysis product would be better representative?

Reply: We now use “ERA5 hourly data on single levels from 1979 to present 2m temperature” data (Hersbach et al., 2018) for the nearest gridpoint (70°N, 70.25°E) instead (please see also the reply to this comment in our previous author comment). We have recalculated results using these data. We have added the following dataset description:

“ERA5 is the fifth generation of European Centre for Medium-Range Weather Forecasts (ECMWF) global climate and weather reanalysis. Reanalysis uses combined model data and observations on a global scale to derive a complete and consistent dataset (Hersbach et al., 2018). The ERA5 hourly data on single levels from 1979 to present product contains hourly estimates for a variety of atmospheric, ocean-wave and land-surface parameters on a regular latitude-longitude grid of 0.25° (Hersbach et al., 2018). In this study, we used the "2m temperature" variable, which represents near-surface air temperature, for a comparison to the temporal dynamics of the backscatter anomalies. The "2m temperature" data for the nearest grid point to lake Neyto (70°N, 70.25°E) were therefore aggregated to daily minima and maxima using the cdstoolbox.geo.extract_point, and cdstoolbox.climate.daily_min and cdstoolbox.climate.daily_max methods of the Python Application Programming Interface (API) of the Copernicus Climate Change Service (C3S) Climate Data Store (CDS). The data was subsequently downloaded and converted to °C.”

Page 8 Lines 183 – 187: “2.7 ArcticDEM digital elevation model V3.0 The ArcticDEM is a high-resolution, high quality, digital surface model (DSM) of the Arctic created by the Polar Geospatial Center (PGC) at the University of Minnesota from optical stereo imagery acquired by the WorldView-1, WorldView-2, 185 WorldView-3 and GeoEye-1 satellites using photogrammetric methods (Porter et al., 2018). Its spatial resolution of 2 m is unprecedented for digital elevation models (DEMs) with a pan-Arctic extent. The ArcticDEM was used for the terrain-correction of all SAR data presented in this study.” This just doesn’t need to be in here. The mention of ArcticDEM can be provided in Section 3.1.1., but is not necessary to the level of detail

Reply: We agree. This section was removed. The use of the ArcticDEM is now given in the preprocessing section (now 4.1.1):

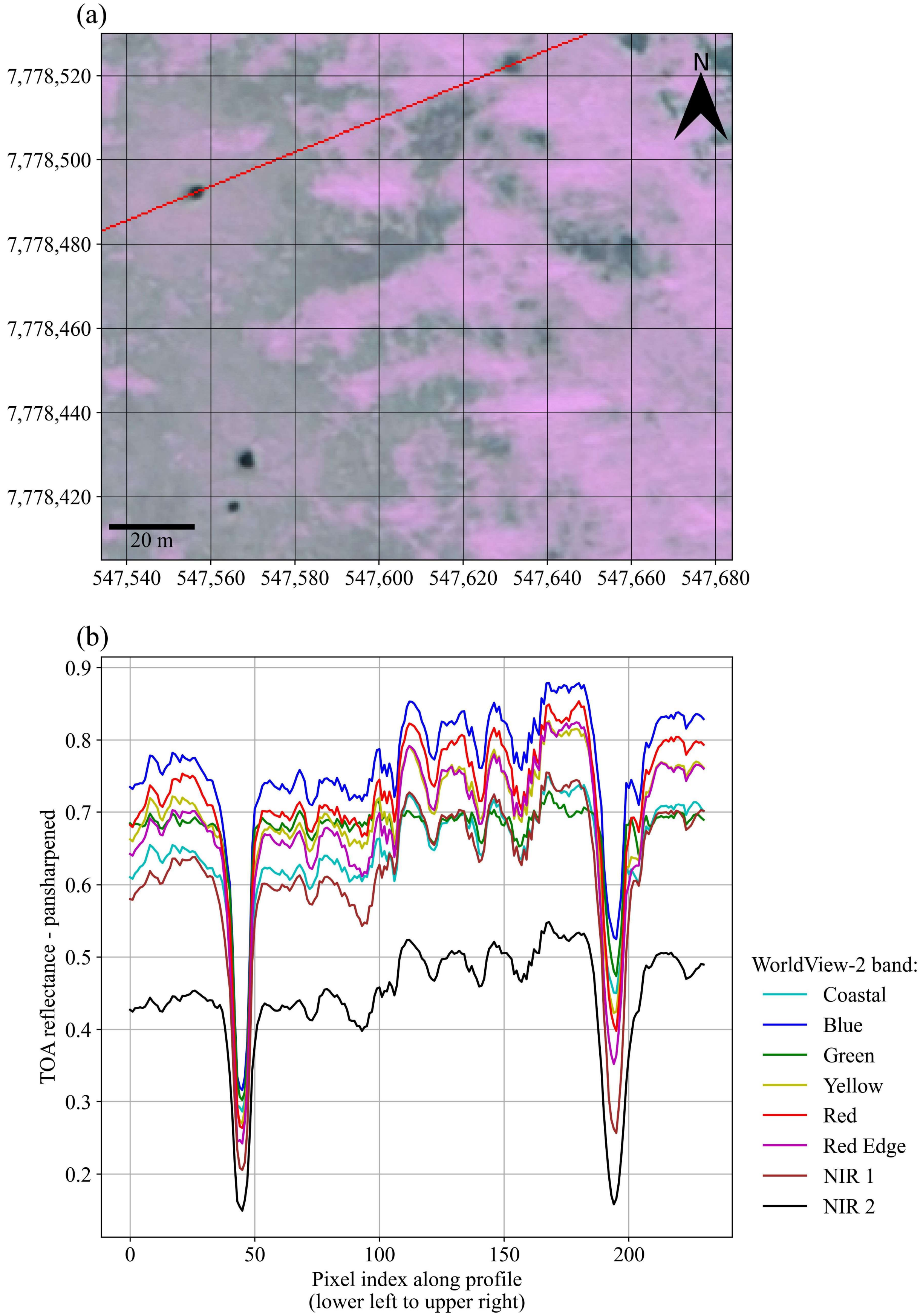
“In the following, the applied operators within gpt were sub-setting, radiometric calibration, thermal noise removal and terrain correction using the external ArcticDEM digital elevation model version 3.0 (Porter et al., 2018).”

Page 10 Lines 265-266: “We used the green band as the input as it showed the highest contrast between the holes and areas of surrounding ice” This is surprising. Not the NIR band? It would be good to see a breakdown with a profile of reflectance, for instance.

Reply: We think we have not used the appropriate formulation here.

We changed the sentence to "We used the green band as the input as it allowed for the best separation between holes and other features that we did not interpret as holes but could have been confused with holes by the blob detection algorithm".

We have added a new figure and accompanying text to give an example what was considered a hole and what not and an associated spectral profile:



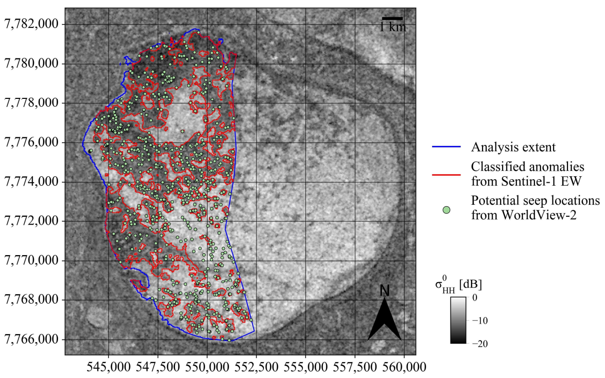
Caption: "Examples of features in WorldView-2 imagery acquired on 22 May 2016 and associated spectral profile. (a) WorldView-2 true-color composite with red line indicating the pixels used for plotting the profile. Spectral profile indicating variations between contrast for the two main minima.

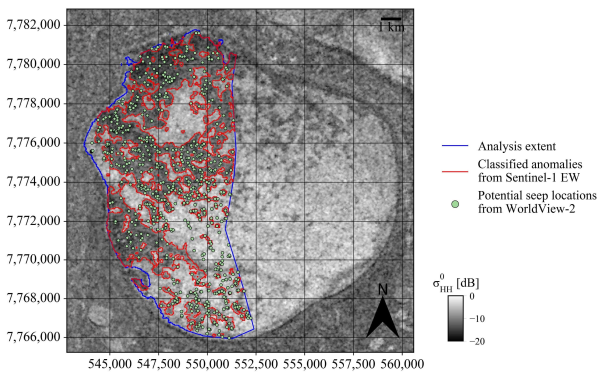
The left main minimum was considered as a hole that should be detected, while the right minimum was not considered as a hole and its detection should be avoided."

Text: "Fig. 2 shall give an example of what we interpreted as holes and what features we sought to prevent from detecting as holes. Fig. 2 (a) shows a true-color composite and Fig. 2 (b) shows an associated spectral profile. The red line in Fig. 2 (a) indicates the pixels used for plotting the profile in Fig. 2 (b) (lower left to upper right). Two main minima can be identified. The left minimum was interpreted as hole that should be detected by the algorithm (and also the other two dark spots in the lower left of the image), while the right minimum was not considered as hole and it should not be detected by the algorithm. In most bands, the contrast between both minima and the surrounding pixels is similar, while the smallest contrast for the right minimum is observed in the green band."

In the preprint, we have used digital numbers (DN) and used the 5 bands whose wavelength range lies completely within the wavelength range of the panchromatic band for the pansharpening. We have now re-calculated results using calibrated TOA reflectances with the use of all bands in the pan-sharpening (as this was required to produce the profile described above). Results are similar to the ones in the preprint. For example, please see the recalculated Fig. 7 below:

Old: *New:*





Please find comparisons of statistics between the old (with DN) and new (with TOA reflectances and pan-sharpened using all bands) approach below:

	Old	**New**
Number of detected holes	715	718
Number of hole polygons excluded for calculating histogram using area threshold	5	10
Median hole area	4.25 m²	4.0 m²
Percentage of holes inside classified anomaly regions	68%	71%
Mean minimum distance between the points (detected holes) and the polygons (anomaly regions)	48m	38m
Median distance of all points (detected holes) lying outside the polygons (anomaly regions)	97m	67m

Page 11: Table 1

This needs to be in the Data section

Reply: We agree. It was moved to the data section. Local acquisition times are now also included.

Page 11 Lines 295-296: "We estimate the total number of pixels in the negative class (regular floating lake ice) to be about one order of magnitude larger than the total number of pixels in the positive class (anomalies) in the validation dataset (Table 1)" Where is this assumption coming from? Please provide.

Reply: This assumption comes from the confusion matrix used for calculating the validation metrics shown in table 2 of the preprint. We have changed it to:

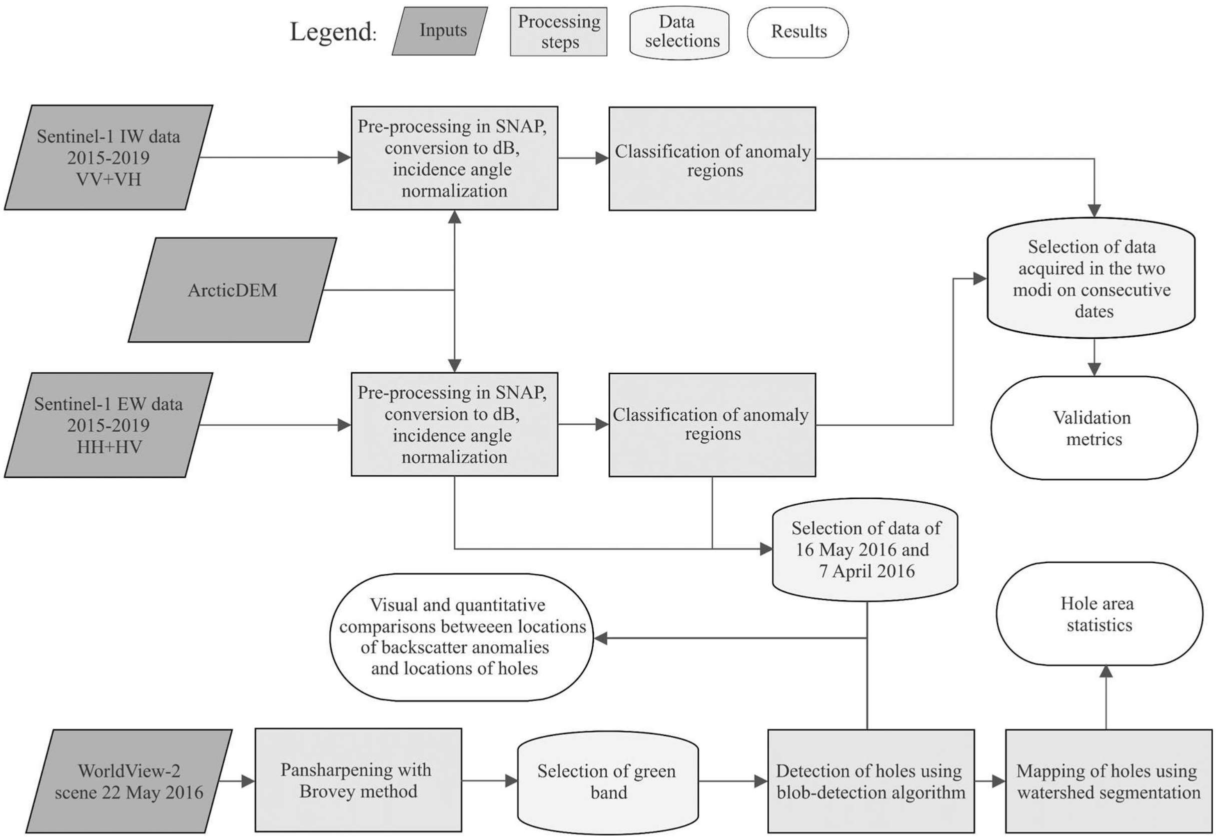
"From the confusion matrix calculated from the EW and IW classification results, we estimate the total number of pixels…"

Page 12 Lines 311 – 318: In order to compare levels of σ 0 from anomalies when lake ice was present to those of open water on lake Neyto, we used all available Sentinel-1 EW and IW scenes acquired in July and August from 2015 to 2019, when the lake can be assumed to be largely ice-free. We masked the images using the same lake masks as described in Sect. 3.2.1 and calculated the mean σ 0 315 for the whole lake on single dates and averaged it over time, similarly to the calculations described in Sect. 3.3 above. We calculated the difference between this temporal mean of assumed open-water backscatter and the temporal mean of the positive (anomaly) class backscatter (see last paragraph in Sect. 3.3). Again, all calculations were performed separately for each polarisation channel." This method has some pretty important flaws. As mentioned later in this article, open water backscatter is likely to be influenced by Bragg scatter due to waves, and slight waves on the order of 3cm can cause considerable bbackscatter of the signal. Holes in the ice would not exhibit this same kind of wave action. How can it be certain that we're comparing apples to apples here?

Reply: You are right about the influences. Since we now agree that scattering most probably comes from wet snow and/or slush, we think this comparison of backscatter levels is not useful anymore. We have removed the paragraph and associated parts in the results and discussion section.

Figure 2: The workflow is not referenced anywhere in the paper. Also, it's confusing. The input data and actions are the same colour/shape, and the other symbols don't follow a similar structure. Please revise to be consistent. It also needs a legend to delineate input/output/method.

Reply: This section was intended to provide an overview of the most important methodological steps using the Sentinel-1 and WorldView-2 data. We agree that the figure should be better described in the text. We have changed the heading "Workflow visualisation" to "Summary of the most important methodological steps" and now provide a short summary text on this section. This is the new figure:



The following description was added:

"A flowchart diagram depicting the most important processing, selection and analysis steps associated with Sentinel-1 and WorldView-2 data is shown in Fig. 3. Sentinel-1 EW and IW were both pre-processed and classified using a similar methodology. Classification results of IW and EW data acquired on consecutive dates (Table 2) were used to calculate validation metrics. Polygons of detected holes deduced from the blob-detection and subsequent watershed segmentation on the green band of the pan-sharpened WorldView-2 image acquired on 22 May 2016 were used to calculate statistics of hole area. Detected locations of holes as produced by the blob detection algorithm were visually and quantitatively compared to single Sentinel-1EW acquisitions and associated anomaly classification results from 16 May 2016 and 7 April 2016."

Page 19 Lines 345-346: "The majority of holes is characterised by an area smaller than 5 m2 , the median is 4.25 m2 . Few holes with areas larger than 100 m2 were identified."

How is it that we can detect holes that are smaller than 5 square metres? Also, that would mean that you're assuming that the cavities in the ice are much, much greater than 5 square metres based on the area of low backscatter surrounding each hole. This does not seem practical compared to the likelihood that the surface snow is being wetted, and is absorbing the incoming microwave signal.

Reply: One pan-sharpened WorldView-2 pixel is 0.25 m² in area. What we replied above was that we (probably wrongly) had assumed that we would have been able to see effects of flooding more often on medium resolution optical images. Based on this assumption, the most probable explanation left was that the low backscatter had to do with the under-ice properties (cavities). We now agree that this does not seem practical and discarded this explanation and provided a discussion on wetting and slushing of the snow.

Page 20 Line 354: “Figure 8 shows the same locations of detected holes deduced from the WorldView-2 image acquired on 22 May 2016 as in Fig. 7 on top of a Sentinel-1 EW HH-polarised acquisition from 7 April 2016, taken more 355 than a month earlier than the image in Fig. 7.”

What was the temperature on 22 May 2016?

Reply: According to the ERA5 data, minimum temperature was -2°C and maximum temperature was 1.2°C. We have added the following:

“Maximum and minimum air temperature on 22 May 2016 were 1.2 °C and -2.0 °C, respectively, according to the ERA5 data (Hersbach et al., 2018). Apart from 1 April and three days from 22 April to 24 April, maximum air temperature remained below 0 °C until 16 May in 2016 (Hersbach et al., 2018).”

Page 21 Line 359: “A steady increase of area of backscatter anomalies in late winter and spring is evident. The maximum extent of backscatter 360 anomalies was especially high in 2019, where on the last useful acquisition date, its area was approximately half of the whole lake area (Fig. 9, compare also to Fig. 3 (a)). “ Its evident that the intersection also increases when the air temperature is close to 0C or higher. This is very important, because slushy snow would be present during the same period, especially if they are located next to holes that are 40cm below the hydrostatic water level.

Reply: Yes, thank you for pointing this out. We have added the following: “The fraction of overlap often increases when the air temperature approach or exceed 0°C.” and included it in the discussion section.

Page 21 Line 361 – 362: “The total lake area is approximately 200 km2 . Maximum air temperature is often approaching or slightly exceeding 0 ◦C throughout the analysis periods” Seyatha station is also coastal, which is in contrast to the region surrounding the lake. I’m not confident that a direct comparison is appropriate.

Reply: Yes, we have now used ERA5 data instead and recalculated results using these data, please see the reply to the other comment above.

Page 25 Lines 378-382: Potential signs of gas emissions might also be seen in Sentinel-2 optical acquisitions of the lake during melt and lake ice break-up. In 2019, a comparably high number of cloudfree Sentinel-2 acquisitions were taken during these time periods. 380 Figures 11 (a)-(e) show Sentinel-2 true-color composites for a section in the Northern part of the lake during melt and lake ice break-up in 2019. Irregularities in snow cover on top of the lake ice may be seen in Fig. 11 (a) and (b), while diminishing patterns of bright ice and dark spots not much larger than the pixel resolution are likely depicted in Fig. 11 (c)-(e).”

This is a leap, as the pattern in these images is very consistent with breakup of lakes with no methane ebullition.

Reply: Thank you for sharing your expertise and for pointing this out! We removed the figure and the accompanying text.

Page 27 Lines 394 – 396: “This result appears especially 395 significant when considering that the holes were mapped at 0.5 m pixel-spacing and anomaly regions from Sentinel-1 at 40 m pixel-spacing.” Why could this be? Sentinel 1 acquisitions with a 40m pixel spacing could not resolve the holes, no. And it’s unlikely that the cavities will be over 200m in diameter. You have also presented that when augering into the ice that the ice is so depressed that the surface is wetted up to 40cm above the ice level. This evidence makes me invoke Occam’s razor that the most likely result here is that the hole is influencing flooding of the ice surface and slushing events.

Reply: Based on what we stated above, we thought cavities might be the most likely explanation, but we agree now that flooding and slushing events are the most likely explanation. We have now included paragraphs about the hypothesis related to flooding/wetting/slushing in the discussion section and removed this sentence.

Page 27 Lines 397 – 400: "As snow seems to have melted earlier in zones where anomalously low backscatter was observed before and the blob-detector algorithm was especially used to detect holes characterised by high contrast to surrounding bright ice, there could be more seeps that either do not form holes in the ice, are characterised by lower 400 contrast in zones with more snow, or both." This is less likely than ice pushed below the hydrostatic water level with a hold nearby.

Reply: We agree. We have removed this paragraph and rewritten and rephrased many parts of the discussion section.

Page 27 Lines 404-406: "However, we are not aware of any 405 studies reporting such causes for shallow Arctic lakes and based on studies by Bogoyavlensky et al. (2019a, 2018, 2016) and Kazantsev et al. (in review), we consider gas emissions as the most likely explanation." This line is carrying a lot of weight, and needs to be validated.

Reply: You are right. We changed it to "Ebullition of geologic methane as the cause of the holes in the ice of lake Neyto would be consistent with studies by Bogoyavlensky et al. (2019a, 2018, 2016) and Kazantsev et al. (2020), but in-situ measurements are needed to confirm this hypothesis."

Page 27 Lines 411 – 414: "Continuous seeping with durations of at least weeks to months, associated with continuously expanding cavities might be an explanation. On the other hand, it seems surprising that the strongest expansions occur in spring, where the largest ice thicknesses can be assumed." See snow slushing example

Reply: Yes. We have removed this paragraph and rewritten and rephrased many parts of the discussion section.

Page 28 Lines 418 – 421: "In case of cavity formation, it could be that the backscatter level of many pixels in the anomaly regions in the Sentinel1 EW imagery (40 m pixel-spacing) is caused by a combination of lower backscatter from cavity regions (due to increased 420 specular reflection from the gas/water-interface) and higher backscatter from zones of regular floating lake ice, as the resolution is comparably coarse."

This sentence is hyperbole – Can you support this with other references or studies? If not, I suggest its removal.

Reply: We have removed it.

Page 28 Lines 422 – 429: "In 2016 in late April and early May, very low backscatter from the entire lake surface was observed, which suggests wetting or melting of snow on top of the ice took place during that period and backscatter was mainly governed by interaction with the wet snow (Duguay and Pietroniro, 2005). Consequently, images acquired during that time were excluded from the analysis 425 (Fig. 9 (b)). One ALOS PALSAR-2 fully polarised scene in 2016 was available, which was unfortunately acquired during this period and was thus also not used for the analysis of scattering mechanisms. However, ALOS PALSAR-2 fully polarised data from 2015, one year earlier than the WorldView-2 scene was acquired, were available. The shape and locations of backscatter anomaly regions vary significantly between different years (Bogoyavlensky et al., 2018; Pointner and Bartsch, 2020) (compare also to Fig. 1, Fig. 3 and Fig. 10), but the characteristic expansion is similar in all years analysed, as discussed above." I'm not sure what we as the reader get out of this paragraph because you're discussing data that you did not analyze.

Reply: The following part has now been removed: "In 2016 in late April and early May, very low backscatter from the entire lake surface was observed, which suggests wetting or melting of snow on top of the ice took place during that period and backscatter was mainly governed by interaction with the wet snow (Duguay and Pietroniro, 2005). Consequently, images acquired during that time were excluded from the analysis 425 (Fig. 9 (b)). One ALOS PALSAR-2 fully polarised scene in 2016 was available, which was unfortunately acquired during this period and was thus also not used for the analysis of scattering mechanisms. However, ALOS PALSAR-2 fully polarised data from 2015, one year earlier than the WorldView-2 scene was acquired, were available."

Page 28 Lines 439 – 440: "At L-band, backscatter from anomaly regions is higher than from regular floating lake ice (Fig. 10 (c)), which is the opposite effect as for C-band (Fig. 10 (a) and (b))." That is not what you presented in Figure 10 though, you presented the T11 parameter which is not "the backscatter"

Reply: You are right, of course. We have removed this sentence. If we look closely, what is evident is that the high values of T_{11} are mainly observed from the outlines of the anomaly regions, what might potentially relate to scattering mechanisms from slush and/or wet snow. We have replaced the sentence by:

"While T_{11} values are similar between many centres of anomaly regions and regular floating lake ice, high values of T_{11} are observed mainly from the outlines of anomaly regions, which might potentially relate to different scattering mechanisms for slush and wet snow, but in-situ data are required to assess this and understand scattering mechanisms at both, C-band and L-band frequencies."

Additionally, we have made the following changes:

OLD: "The observation that C-band backscatter is generally higher than L-band backscatter in the case of regular floating lake ice may be explained by the longer radar wavelength in L-band."

NEW: "The observation that C-band backscatter is relatively high and L-band T_{11} is relatively low in the case of regular floating lake ice may be explained by the longer radar wavelength in L-band."

Page 28 Lines 450-451: "Another obvious difference between C-band and L-band is that backscatter from anomaly regions is higher at L-band (Fig. 10 (a), (b) and (c))." This was already stated above.

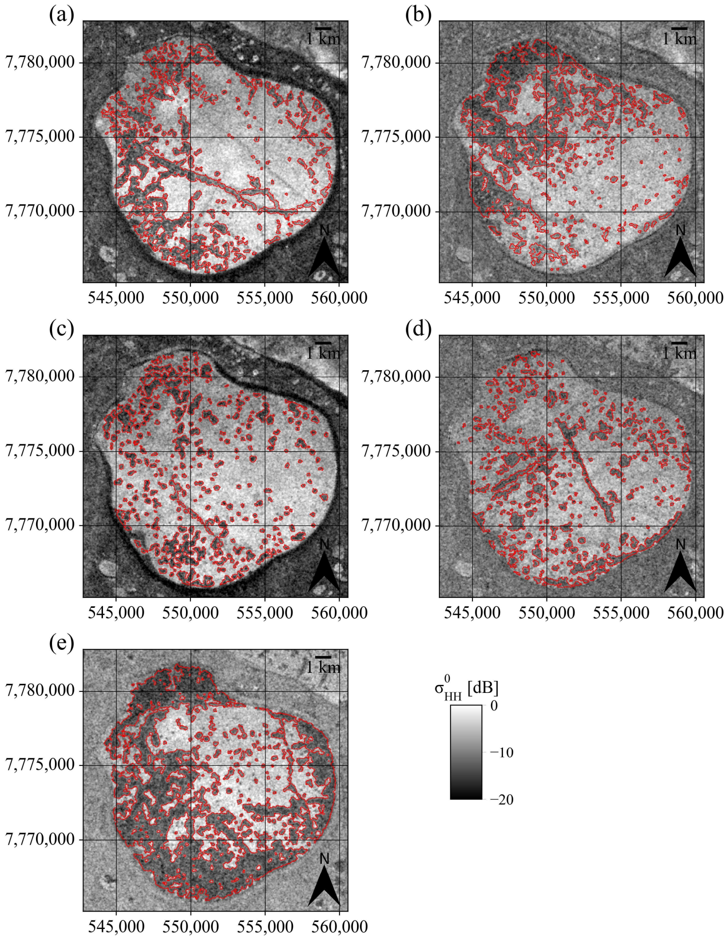
Reply: We have removed this sentence.

Page 29 Lines 458 – 462: "As a consequence of slowed ice growth, the cavities are filled by water, partly filled by gas or completely filled by gas (Engram et al., 2020). Resulting rough surfaces are the ice-water interface or the gas-water interface (Engram et al., 2020). For lake Neyto, formation of potential cavities (anomaly regions) could start in late winter or 460 spring and then the cavities may successively expand over time (compare to Fig. 9). Bogoyavlensky et al. (2018) and Pointner and Bartsch (2020) showed that locations of potential cavity zones (backscatter anomalies) vary significantly between years for lake Neyto."

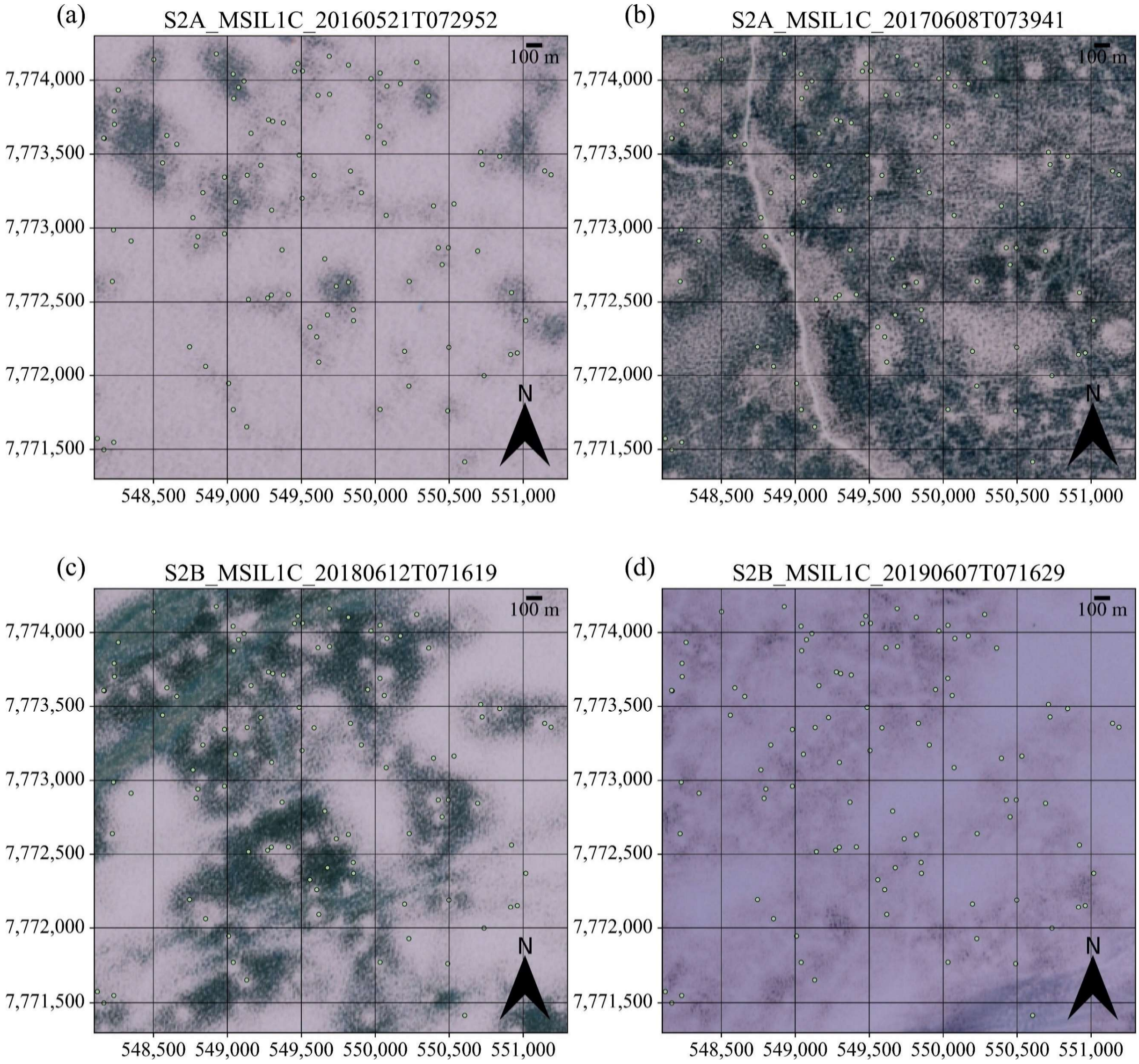
It would make sense that the location of ebullition would remain consistent based on the source of ebullition. What biogeochemical process is there that you can justify the movement of the methane source? This needs to be addressed.

***Start of copy from author comment**:*

Reply: Indeed, this would make much more sense. Given that we assumed that it had to do with the under-ice properties, this was the only explanation for the large variations of locations of anomaly regions between the years. The following figure shows the anomaly regions in Sentinel-1 HH-polarized images of the last useful acquisition date in the years concerned, (a) 2015 to (e) 2019 (Pointner and Bartsch, 2020):



We now think that given what was discussed earlier, the changes in locations could be a result of different flooding/wetting/slushing patterns. So, the locations of ebullition sources could indeed most likely remain stable throughout all the analysed years. We have looked again on Sentinel-2 images acquired during melt-onset and there are (at least some) similarities between the identified points and patterns in the optical images in 2016 to 2019. The best explanation seems to be that the locations remain stable, but as you noted, of course it has yet to be verified that the holes are related to gas emissions.



End of copy from author comment

We have now removed this sentence:

*"*For lake Neyto, formation of potential cavities (anomaly regions) could start in late winter or spring and then the cavities may successively expand over time (compare to Fig. 9).*"*

And changed:

*"*Bogoyavlensky et al. (2018) and Pointner and Bartsch (2020) showed that locations of potential cavity zones (backscatter anomalies) vary significantly between years for lake Neyto.*"*

To:

Bogoyavlensky et al. (2018) and Pointner and Bartsch (2020) showed that locations of backscatter anomalies vary significantly between years for lake Neyto.

Page 29 Lines 463 – 465: "Features related to ebullition responsible for increased L-band backscatter in PALSAR-1 SAR imagery in Engram et al. (2020) are of much smaller spatial scale than features that are expected to be responsible for anomalies in SAR imagery of lake Neyto." What are the features responsible in Engram et al., 2020?

Reply: The features are cavities at the ice-water interface that are (partially or completely) filled with water or gas. We have changed the sentence to:

"Cavities related to ebullition responsible for increased L-band T_{11} in PALSAR-1 SAR imagery in Engram et al. (2020) are of much smaller spatial scale than the holes in the VHR imagery of lake Neyto."

Additionally, we made the following change:

OLD: "Diameters of reported cavities in (Engram et al., 2020) are in the order of decimetres, while regions of bright ice around holes (potentially cavities) in WorldView-2 imagery of lake Neyto extend to tens or hundreds of metres".

NEW: "Diameters of reported cavities in (Engram et al., 2020) are in the order of decimetres, while the median area of 718 open holes identified in this study is 4 m^2"

Page 29 Lines 483-485: "Ice metamorphism processes related to increased solar radiation and air temperatures in spring such as the the formation of bubbles and air channels on the ice surface or the formation of ice needles 485 (Kouraev et al., 2015) may play a role, but this could not be assessed." Slushing of the ice would happen during the winter season as well, not just the spring

Reply: Yes, have now removed this sentence.

Page 30 Lines 490-491: "During lake ice drilling on Yamal in April 2019, several lakes were found to have water level up to 40 cm higher than the level of lake ice. In situ observations of the lake ice of lake Neyto in winter or spring would be required to understand the cause of the anomalously low backscatter in detail."

YES. This really provides evidence of what you're seeing in the SAR scenes. Based on the location of the holes and the area of low backscatter, the interaction has much less to do with the under-ice roughness/cavity, and much more to do with the absorption. Keep in mind that absorbed signals generally also show that they are the result of surface roughness in polarimetric decomposition (see target decomposition of first year sea ice, for instance). This sentence above supports the slushing hypothesis with in-situ observations of the snow/ice dynamics in the region.

Reply: Indeed. Thank you very much again for sharing your expertise! We have re-arranged and re-written parts many parts of the discussion section and we used these in-situ observations as the support of what we see in the SAR images.

We have changed the sentence above to:

"During lake ice drilling on Yamal in April 2019, the water level on several lakes rose up to 40 cm higher than the level of lake ice (Fig. 13). This could be a similar effect as the one that might be responsible for the observed anomalies on lake Neyto, but in-situ data collected on the ice of lake Neyto would be required to verify this."

Page 30: Figure 12 In the caption, please provide the exact date of the observation, and the lake name (with coordinates)

Reply: We have added the following in the caption:

"The lake in the photo is termed LK-013, observed and drilled on April 6, 2019 (ca. 14:00 local time). The coordinates (WGS84 geographic) are 70.262123°N, 68.884803°E. Ice thickness at the time of drilling was approximately 1.5 m."

Page 31 Lines 503 – 510: “A steady increase of area of backscatter anomalies in late winter and spring can be seen in Fig. 9 for all years analysed. Especially high is the fraction of lake area covered by areas of anomalously low backscatter in 2019 (compare also to Fig. 3). 505 Also in 2019, a comparably high fraction of cloud-free Sentinel-2 observations were acquired during lake ice break-up. These acquisitions may show additional signs of degassing (Fig. 11, northern part of the lake). Regions that seem to have become snow-free earlier in Fig. 11 (a) and (b) partially match regions with increased frequency of dark spots in Fig. 11 (c), (d) and (e). Especially noticeable are diminishing patterns of apparently bright ice in Fig. 11 (c), (d) and (e). These bright patterns may show similar features as the WorldView-2 image acquired on 22 May 2016, but the limited spatial resolution of Sentinel-2 does 510 not allow to draw firm conclusions” Based on the discussion about this study, I believe that this paragraph is really too inconclusive to make any assumptions, and suggest its removal.

Reply: We have removed this paragraph.

Page 32 Line 539: “We do not claim that anomalies on these lakes are necessarily caused by gas emissions.”

It appears that you have the same amount of evidence for these lakes as you do for Lake Neyto. It would be appropriate for you to state that the patterns are consistent with methane ebullition, but needs to be verified throughout the paper.

Reply: We have changed the sentence to:

“Anomalies on these lakes appear similar to those on lake Neyto, but if they (including those on lake Neyto) are indeed related to methane ebullition has yet to be verified.” We have now also included additional remarks that this hypothesis needs to be verified throughout the paper and used more prudent formulations.

Page 33 Line 550: “anomalies are indeed likely caused by gas emissions through the lake sediments.” Consider rewriting to read “anomalies are consistent with previous studies that quantify gas emissions…”

Reply: We have largely re-written the conclusions section.

*OLD: “*The spatial relationship between 715 holes detected from Worldview-2 imagery and anomalies mapped from Sentinel-1 EW imagery acquired a few days apart suggests that anomalies are indeed likely caused by gas emissions through the lake sediments. Statistics of areas of mapped holes support the explanation of subcap seepage of methane as the most likely origin. The successive expansion of anomaly regions observable mainly during late winter and spring in all of the analysed years (2015 to 2019) might be explained by cavities formed by the gas emissions that successively hollow out the lake ice around seep locations over time. This could also explain the outcomes of our polarimetric analyses that suggest scattering in potential cavity regions occurs primarily from an open water surface (or the gas-water interface). However, fluctuations in the time series of area of anomaly regions and the bright color of ice around the holes in the WorldView-2 image also raise further questions about this hypothesis and in situ data of the lake ice in winter or spring would be needed to understand the dominant C-band SAR scattering mechanism in detail. Additionally, a detailed explanation for the significant uptrend in late winter and spring would also require the analysis of in situ data on talik and lake ice conditions. The proposed method to automatically map backscatter anomalies delivered good results in relation to the chosen validation strategy and could allow to monitor gas emissions on lake Neyto also in the future. The spatial and temporal properties of Sentinel-1 SAR data might also allow for the identification of lakes with similar gas emissions as lake Neyto over larger spatial extents in the near future.*”*

NEW: "The spatial relationship between 718 holes detected fromWorldview-2 imagery and anomalies mapped from Sentinel-1 EW imagery acquired a few days apart and more than a month earlier suggests that anomalies expand from the locations of many holes. Expanding anomalies might be caused by flooding of the ice and subsequent slushing and/or wetting of the snow around the holes, as the ice surface around the holes might get depressed below hydrostatic water level due to increased snow loading in spring. This explanation is inferred from observed flooding of the ice layer during ice drilling on another lake in Central Yamal in spring, but in-situ observations of ice of lake Neyto are needed to test this hypothesis. Statistics of areas and spatial clustering of mapped holes are consistent with observations related to subcap seepage of methane reported in previous studies, but it has yet to be verified that the holes in ice of lake Neyto are indeed caused by up-welling gas. The proposed method to automatically map backscatter anomalies delivered good results in relation to the chosen validation strategy and could potentially allow to monitor gas emissions on lake Neyto also in the future upon the verification of this hypothesis. The spatial and temporal properties of Sentinel-1 SAR data may also allow for the identification of lakes with similar anomalies as lake Neyto over larger spatial extents in the near future and, if the given hypothesis is correct, this might potentially aid our understanding of how much methane is released by West Siberian lake seeps."

Page 551 – 553: ". The successive expansion of anomaly regions observable mainly during late winter and spring in all of the analysed years (2015 to 2019) might be explained by cavities formed by the gas emissions that successively hollow out the lake ice around seep locations over time." I disagree with this based on the evidence I have seen for the wetting of the snowpack due to overflow or through holes in the ice.

Reply: Yes, we have removed this sentence.

Page 33 Line 560: "to the chosen validation strategy and could allow to monitor gas emissions on lake Neyto also in the future." Consider adding "also in the future upon the verification of this hypothesis.

Reply: Yes, we changed it accordingly.

References:

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