Author's response to anonymous Reviewer #2

General Comment

Dirscherl et al. present a study on the evolution of supraglacial lakes on six Antarctic ice shelves between 2015-2021 based on a comprehensive and newly generated data set of lake extents and investigate the main environmental drivers of the meltwater ponding. The primary source data for generating high-resolution time series of supraglacial lake extents are Sentinel-1 (S1) SAR and Sentinel-2 (S2) optical satellite imagery, which are processed building on previously developed machine learning methods. The resulting supraglacial lake extent maps are merged and converted to fractional water coverage time series for further statistical analysis. For the analysis of climatological controls a number of variables derived from the ERA5-Land reanalysis data set are used as well as large scale atmospheric indices.

In the Antarctic Peninsula the authors find anomalous high lake coverage in the last two melt seasons and low lake coverage in preceding years, while in East Antarctica this seemed to be reversed and also generally more variable. The correlation analysis showed that climatological controls (temperature, solar radiation, snow melt, wind) varied for each iceshelf both spatially as well as temporally, illustrating the complex interplay between different climate variables at different time lags. Also the Southern Annular Mode and the local glaciological setting was found to exert a strong control on supraglacial lake formation.

The topic of this paper, supraglacial lake evolution in Antarctica and its main climatological controls, is very interesting and relevant, in particular thanks also to recent advances in modern computing technology and increasing availability of satellite EO data. This paper by Dirscherl et al. is a well written, illustrated and referenced manuscript and a valuable and original contribution of interest for the glaciology community. The authors give a good motivation for their work, a detailed description of their methods and results and provide a thorough discussion. The outcome provides new insights on present-day Antarctic surface hydrology and main environmental drivers in particular relevant for ice sheet and climate modelers.

That said, I do think there is some room for improvement, in particular with respect to the readability, as at times the amount of information in (particular in) the results and discussion section is somewhat overwhelming. Maybe it is better here to not describe and discuss each and every detail but focus on the key points and let the figures/tables tell the rest. Further comments and suggestions for improvements are provided below.

We thank the reviewer for the constructive feedback and detailed review of our manuscript. We appreciate your useful remarks and suggestions which will be of great help to provide an improved manuscript version. In particular, we will follow your suggestion and limit the text in the results and discussion section to the most important information and key conclusions. Please find below a more detailed response to your specific comments.

Specific Comments

Pg 2 – Ln 34-36: With… Antarctic: I think the wording in this sentence is a bit too strong or not clear. In particular the notion that surface hydrological features will become the dominant driver for Antarctic ice mass loss. This is currently overshadowed by basal melting and iceberg calving.

Many thanks for this important comment. We will improve the wording of the corresponding sentence:

"With surface melting expected to double by 2050 (Trusel et al., 2015), Antarctic surface hydrological features will expand and likely contribute to future ice shelf instability and ice mass loss from the Antarctic (Arthur et al., 2020a; Lai et al., 2020)."

Pg 3 – Ln 65: (v): should be (iv)

Thank you for noticing that. We will correct the wording accordingly.

Pg 5 – Ln 137: through Wohlthat mountains: through the Wohlthat Mountains

We will follow your suggestion and rephrase the sentence accordingly.

Pg 5 – Ln 146-148: The AOI outlines look a bit random to me. Does this mean that no lakes occurred in the other areas? Why not investigate the entire ice shelf?

As stated in lines 146-151, the AOI outlines were determined in agreement with supraglacial lake occurrence during at least one time step within our bi-weekly time series. Therefore, we only considered pixels where supraglacial lakes were mapped during November to March in 2015-2021. Consequently, no lakes were detected over the remaining ice shelf area. While these AOI outlines were mainly relevant for statistical correlation analysis, satellite data acquisition and lake extent mapping were performed on basis of the entire ice shelf area. We will revise the corresponding paragraph and improve the understanding of Figure 1.

Pg 5 – Ln 156: Sentinel-1: I assume you have used the GRD product?

That is correct. We used Level-1 GRD High Resolution (HR) data products in IW swath mode. We will expand the corresponding description in line 156.

Pg 5 – Ln 163: Sentinel-2: Did you use any particular spectral band/combination? What resolution?

Thank you for this comment. For Sentinel-2, we used a range of spectral bands and indices for model training (and scene prediction) (see line 238). While specifications on the machine learning method and used bands and indices can be found in our preceding study (Dirscherl et al., 2020), the Sentinel-2 classification algorithm used in the present study was slightly modified (see lines 241-243). The pixel spacing of used Sentinel-2 data was either 10 m or 20 m whereat the 20 m bands were resampled to 10 m.

Pg 8 – Ln 231-232: The ... regions: This needs some more elaboration on how the test data sets was generated.

For creation of the test dataset, we selected Sentinel-1 scenes that were distributed in space and time covering regions around the Antarctic continent that were not presented to the model during training. This ensures a representative evaluation of the classification performance. At the same time, scenes (/regions) were selected based on confirmed supraglacial lake occurrences (e.g., Stokes et al., 2019; Dell et al., 2020; Kingslake et al., 2017) and where particularly "difficult" surface features (e.g. wet snow) and lakes of varying appearances were present. This is outlined in detail in our preceding study (Dirscherl et al., 2021). In order to improve the corresponding description in the manuscript, we will expand the paragraph starting in line 231.

Pg 8 – 251-252: This also needs some elaboration on to what extent do the Sentinel-1 and Sentinel-2 datasets agree? Can some of the intra- and inter-annual variability be explained by differences between the sensors, in particular since you mention that S1 can also observe buried lakes, not visible with S2?

While Sentinel-1 and Sentinel-2 data generally reveal the same lakes, their sizes and visibility may vary depending on sensor-specific characteristics. As indicated, lakes in SAR data can appear larger than in optical imagery due to the penetration capability of microwave sensors into thin ice and snow. Hence, even buried or slightly frozen lakes can be detected. On the other hand, strongly frozen lakes or lakes that are subject to severe wind roughening cannot be detected in SAR imagery. Therefore, the inclusion of Sentinel-1 SAR is particularly beneficial in order to obtain a more complete mapping record, also with respect to cloud cover and polar darkness affecting lake visibility in optical imagery. Regarding optical data, buried lakes cannot be detected while wind roughening does not affect lake visibility. Optical Sentinel-2 data therefore deliver important information on supraglacial lake coverage during cloud-free conditions in Antarctic summer. To summarize, only the combination of optical and SAR data allows to obtain a more complete mapping record than is possible with single-sensor classifications.

That said, the observed intra-annual and inter-annual variability in lake extents may partly result from differences in used sensor types particularly where data from only one sensor type delivers information. For example, mappings during cloud cover or at the onset of Antarctic winter purely result from Sentinel-1 SAR. This could lead to a slight underestimation of the total lake area in case lakes are subject to strong wind roughening. Likewise, when only optical mappings are available, buried lakes are not detected which may lead to slightly smaller lake outlines. Overall, the described effects are not believed to bias the overall detected temporal signature of lake evolution since wintertime lake extents are generally small and since a conjoint occurrence of severe wind roughening in SAR data and cloud cover in optical imagery is unlikely.

Pg 8 – Ln 252: interpolate: do you mean spatial or temporal interpolation?

Thank you for this comment. With interpolation, we refer to the temporal interpolation of the generated time series shown in Figure 3. In detail, satellite data were not available during specific months over Riiser-Larsen and Nivlisen Ice Shelf, also apparent in Figure S1. This required an interpolation of the respective time periods with the bi-weekly long-term mean 2016-2021 (shown in red in Figure 3). In order to clarify on this, we will improve the wording accordingly.

Pg 8 – Ln 255: fractional water coverage: elsewhere this is referred to as fractional lake extent, do you mean the same?

Many thanks for noticing this. Fractional water coverage and fractional lake extent refer to the same variable. We will correct that accordingly.

Pg 9 – Ln 285: The results section starts with a graph/description on supraglacial lake extent dynamics, what I miss are actually some (examples of) high-resolution supraglacial lake extent maps generated in 3.2.2.

While we did not include individual lake extent mappings in the manuscript, Figure 5 shows the inter-annual recurrence frequency of lakes on each ice shelf being generated from aggregated January lake extent mapping products. As a more detailed description of the individual mapping products goes beyond the scope of this paper, we will not expand the number of Figures in the manuscript but add an exemplary time series of January lake extent mappings (2017-2021) over Nivlisen Ice Shelf to the Supplement. Furthermore, all bi-weekly lake extent mapping products will be made publicly available online as part of our revisions.

Pg 14 – Ln 447: 0-1, 2-4 and 0-1, respectively

Many thanks for this suggestion. We will correct the sentence in line 447 accordingly.

Pg 14 – Ln 452: Wind: Do you mean wind magnitude?

Please excuse the unclear wording. We mean wind magnitude and will correct the text accordingly.

Pg 20 – Ln 638: How does firn air depletion lead to facilitate melt? Seems like a step is missing here.

Thank you for this important comment. We actually mean "facilitated meltwater ponding". The sentence will be corrected accordingly.

Pg 21 – Ln 665: latitudinal: do you mean longitudinal?

With longitudinal we wanted to refer to the occurrence of meltwater lakes and streams stretching from west to east (or east to west). However, in agreement with the comment of Reviewer #1, we will correct this to "…meltwater accumulates in flow stripes controlled by…".

Pg 21 -Ln 673: is among: are among

Many thanks for noticing that. We will correct that in the revised manuscript version.

Pg 21 – Ln 678: ice shelf geometry: In what way does the ice shelf geometry play a role for supraglacial lake evolution?

Here, we primarily refer to the compressive flow regime over George VI Ice Shelf that largely determines the location of supraglacial meltwater ponding on the ice shelf. Further, also the location of the grounding line and thus, the shape of the ice shelf were shown to determine supraglacial lake locations, e.g., on Bach or George VI Ice Shelf (see Figure 5a,c). In order to clarify on this, we will reformulate the corresponding sentence to "ice shelf morphology and geometrical setting".

Pg 23 – Ln 717-718: How does prevailing low wind speeds following periods of anomalous high wind speeds dictate lake formation, what mechanics are at play here?

Supraglacial lake formation on Riiser-Larsen Ice Shelf appears to follow episodes of particularly strong north-easterly winds. These strong winds could reflect katabatic winds, a known control on East Antarctic supraglacial lake formation. In fact, easterly katabatic winds warm adiabatically through vertical mixing and can lead to the exposure of albedo-lowering blue ice and firn through wind scouring further enhancing surface melt (Lenaerts et al., 2017).

Pg 23 – Ln 732: near the Wohlthat Mountains

Many thanks for noticing that. We will correct the sentence accordingly.

Pg 25 – Ln 800: As before, where can we see an example of this product at unprecedented 10 m spatial resolution?

The mapping products will be made available online as part of our revisions (Section on data availability) via the DLR GeoService. Further, we will include exemplary maps highlighting inter-annual lake spreading across Nivlisen Ice Shelf in the Supplement.

Pg 25 – Ln 801: surface hydrological features -> supraglacial lake extent

We will correct the sentence accordingly.

Pg 26 – Ln 802: buried lakes: Can you elaborate on how deep buried lakes can be detected

While radar penetration at C-band (the operating frequency of Sentinel-1) can reach up to 20 m in fresh snow (Nagler et al., 2015), the actual penetration depth of the signal depends on factors such as the snow conditions with varying moisture contents leading to different radar penetration (i.e., dry snow yields higher penetration than wet snow), the terrain slope and orientation as well as the radar incidence angle. Therefore, the depth of detected buried lakes strongly depends on the environmental setting whereat lakes that are buried by dry snow can generally be detected at greater depths.

Pg 27 – Ln 842: Data availability: Are the generated products going to be made publicly available?

As mentioned above, all supraglacial lake extent mapping products will be made publicly available via DLR's GeoService. We will include a link in the data availability section as part of our revisions.

Figures

Fig 5: This is a nice plot showing fine-scaled details, but unfortunately it is hard to distinguish the different colours.

Many thanks for this helpful comment. We will improve the color scheme of the figure as part of our revisions.

Fig 5: I would suggest switching the labels b & a to a & b, same for h/g, f/e

We will correct the labelling of Figure 5 accordingly.

Additional references cited:

Dell, R., Arnold, N., Willis, I., Banwell, A., Williamson, A., Pritchard, H., and Orr, A.: Lateral meltwater transfer across an Antarctic ice shelf, The Cryosphere, 14, 2313–2330, https://doi.org/10.5194/tc-14-2313-2020, 2020.

Dirscherl, M., Dietz, A. J., Kneisel, C., and Kuenzer, C.: Automated Mapping of Antarctic Supraglacial Lakes Using a Machine Learning Approach, Remote Sens., 12, https://doi.org/10.3390/rs12071203, 2020.

Dirscherl, M., Dietz, A. J., Kneisel, C., and Kuenzer, C.: A Novel Method for Automated Supraglacial Lake Mapping in Antarctica Using Sentinel-1 SAR Imagery and Deep Learning, Remote Sens., 13, 197, https://doi.org/10.3390/rs13020197, 2021.

Kingslake, Ely, J. C., Das, I., and Bell, R. E.: Widespread movement of meltwater onto and across Antarctic ice shelves, Nature, 544, 349–352, https://doi.org/10.1038/nature22049, 2017.

Lenaerts, J. T. M., Lhermitte, S., Drews, R., Ligtenberg, S. R. M., Berger, S., Helm, V., Smeets, C. J. P. P., Broeke, M. R. van den, van de Berg, W. J., van Meijgaard, E., Eijkelboom, M., Eisen, O., and Pattyn, F.: Meltwater produced by wind–albedo interaction stored in an East Antarctic ice shelf, Nat. Clim. Change, 7, 58–62, https://doi.org/10.1038/nclimate3180, 2017.

Nagler, T., Rott, H., Hetzenecker, M., Wuite, J., and Potin, P.: The Sentinel-1 Mission: New Opportunities for Ice Sheet Observations, 7, 9371–9389, https://doi.org/10.3390/rs70709371, 2015.

Stokes, C. R., Sanderson, J. E., Miles, B. W. J., Jamieson, S. S. R., and Leeson, A. A.: Widespread distribution of supraglacial lakes around the margin of the East Antarctic Ice Sheet, Sci. Rep, 9, 1–14, https://doi.org/10.1038/s41598-019-50343-5, 2019.