Author's response to anonymous reviewer #1

Summary:

In this study the authors combine observations from SAR (Sentinel 1) and optical (Sentinel 2) satellite imagery to generate a record of Antarctic supra-glacial lake coverage with high spatial and temporal resolution. The record covers six Antarctic ice shelves between 2015 and 2021. Three of the ice shelves are located on the Antarctic Peninsula (George VI, Wilkins, Bach) and three are located in East Antarctica (Amery, Nivilsen, Riiser-Larsen). The authors use machine learning to identify lakes from imagery, with the machine learning methods described in two previous papers (Dirscherl et al., 2020 & 2021). The authors investigate the coverage and reoccurrence of the lakes and perform a statistical analysis of the correlations between lake coverage and atmospheric conditions and global climate indicators.

For the Antarctic Peninsula ice shelves, they find peak lake coverage in January, with the largest lake coverage in the 2018-2019 and 2019-2020 seasons. The most significant correlation is found for George VI Ice Shelf where lake coverage is positively correlated with air temperature, with a lag of approximately 14 days. There appears to be a negative correlation of lake coverage with the Southern Annual Mode for the Antarctic Peninsula ice shelves.

For the East Antarctic ice shelves, there is a less prominent peak in lake coverage, with coverage extending from late December to early February. Furthermore 2020-2021, saw the smallest lake coverage for these East Antarctic ice shelves. Positive correlations are observed for temperature and solar radiation with a range of lag times.

The manuscript is a natural progression from the two previous papers describing the machine learning methods. Here these methods are applied to 6 years' worth of data from 6 Antarctic ice shelves, thereby providing one of the most (if not the most) comprehensive records of recent Antarctic supra-glacial lake coverage. The analysis is thorough and generates a set of noteworthy/interesting conclusions. However, my one major criticism is that the results and discussion sections are a bit of a jumble, this is mainly due to the volume of information the author tries to convey. This could be addressed by adding more structure to the text, possibly by splitting it into six sections for each ice shelf and limiting the text to reporting the significant results with the figures contain extra details.

This work makes a worthwhile contribution to the field and I feel it will be of interest to many in the glaciology community.

I have included a commented PDF as part of my review. Here I include some more detailed points that require addressing:

We thank the reviewer for the time and efforts spent in reviewing our manuscript in so much detail. The additional comments are very much appreciated and were of great help to provide an improved version of the manuscript. We addressed all points raised in the supplementary pdf. Moreover, we improved the results and discussion section and limited the text to the most important information and key conclusions. Please find our responses to the individual comments below. All line indications refer to the "track changes" version of the manuscript.

Comments:

- Use of term average:
    - At times I was confused by the use of average, which in some contexts refers to: the mean of the data included in the bi-weekly value; the spatial average over the ice shelf; or the mean of multi-year data. It would be good to clarify what is mean each time average is used.

Many thanks for this helpful comment. We clarified on the meaning of the term “average” in the main text each time it was referred to.

    - Secondly average is used in the abstract and conclusion with reference to the mean values from the 6 years of data. However, on first reading this gives the impression that it is a long-term record. Saying something is above or below the average, when that is only based on 6 years of data lacks the long-term context. For instance, it may be the case that 2015-2016 was a high lake year in comparison to the 20 years beforehand, but not in comparison to the following 5 years. This point needs to be considered throughout the text when reporting differences between annual results.

Thank you for this suggestion. We agree that the short observational period provided by Sentinel-1 and Sentinel-2 does not capture long-term trends. To clarify on this, we improved the corresponding wording throughout the manuscript.

- If I am interested in an ice shelf not included in this investigation what can I learn from this paper? Are there any general statements that can be applied to all lakes following the evidence generated here?

Despite some minor variations in lake coverage resulting from varying local control factors (e.g., albedo feedbacks, ice surface topography or local microclimatic conditions), our study revealed similar lake evolution over all three Antarctic Peninsula (API) ice shelves. In fact, lake coverage over all three ice shelves was highest during the past two melting seasons compared to the previous four melting seasons. Likewise, also the detected driving factors agreed well among the three regions (Table 2) making it likely that other Antarctic Peninsula ice shelves in the vicinity of the Bellingshausen Sea Sector responded similar to the present regional environmental conditions particularly during the 2019/2020 and 2020/2021 summers with high meltwater coverage. This information has been integrated in the discussion section (line 861-863) as well as in the conclusion (line 1108).

For East Antarctic ice shelves, lake evolution was far more variable due to the larger distance among them and thus, the different environmental conditions. At the same time, it has to be noted that over all three East Antarctic ice shelves, temperature conditions, the amount of incoming solar radiation and katabatic winds showed strong influence on lake evolution making it likely that these are primary control factors also for other East Antarctic regions. Furthermore, the past melting season 2020/2021 revealed very low lake extents over all three ice shelves in agreement with the timing of an atypical Amundsen Sea Low (ASL) leading to low temperature conditions. This highlights the significant influence of large-scale atmospheric modes on entire ice sheet sections where similar trends in lake evolution can be expected, e.g., in terms of low lake extents over other East Antarctic ice shelves during the 2020/2021 summer. In fact, the atypical ASL was also found to cause comparatively low lake extents during the late 2020/2021 melting season over the API suggesting that Southern Hemisphere atmospheric modes can exert continent-wide influence. Likewise, also the influence of SAM and IOD was shown to influence entire ice sheet sections (Table 2) over the API and East Antarctica in a similar manner. In order to provide this information in the manuscript, we expanded the corresponding paragraph starting in lines 1002-1006 and lines 1027-1035.

Considering all six investigated ice shelves, the summary in Table 2 highlights that local control factors show good agreement with respect to the direction of detected relationships. Therefore, similar relationships can likely be observed over other Antarctic ice shelves. Moreover, also temperature, radiation and wind conditions show consistent significance over all ice shelves highlighting their strong influence on lake evolution. To provide more general statements in the main text, we addressed the described patterns in the discussion section (line 1027-1035).

- How are datasets (Sentinel 1 & 2) combined? What is the time resolution of the pre-aggregated data? Is this consistent for each bi-weekly value? How does the performance with each dataset compare? i.e. are same lake features identified? Are there any differences? How does this impact your results?

Sentinel-1 and Sentinel-2 classifications were combined through decision-level fusion, i.e., the mosaicking of all obtained Sentinel-1 and Sentinel-2 classification products. Mosaicking was performed to obtain the maximum lake extent during a given time interval thus, considering all classified lake pixels in each single classification map as valid. To clarify on this, we modified the corresponding text in line 321.

The time resolution of the pre-aggregated data thus, of the single classification maps corresponds to the repeat interval of the individual satellite sensors reaching up to daily revisit frequencies over Antarctica due to overlapping orbit tracks in polar regions (the general revisit time at the equator is 5 and 6 days for Sentinel-2 and Sentinel-1, respectively). This information has been inserted in line 218 and 230.

The data availability for each bi-weekly interval fluctuated only slightly over an ice shelf whereat the number of available acquisitions varied with respect to the timing within the melting season (sometimes more acquisitions were available during the peak of the melting season (January) than in months before and after, particularly for Sentinel-2; see Supplementary Figure S1). At the same time, data availability was restricted during few months over Riiser-Larsen and Nivlisen Ice Shelf requiring interpolation with the bi-weekly long-term mean of 2016-2021 (see Supplementary Figure S1, lines 220-222 and 322-325 in the manuscript).

Comparing classifications from Sentinel-1 and Sentinel-2, the same lake features can generally be identified. However, due to sensor-specific characteristics, lake sizes and lake visibility may vary. For example, lakes in SAR data oftentimes appear larger than in optical imagery due to the penetration capability of microwave sensors through thin ice and snow. Hence, even buried and slightly/partly frozen lakes can be detected with SAR. On the other hand, lakes that are subject to particularly strong refreezing or wind roughening cannot be detected with our deep learning classification method. Regarding optical data, buried lakes cannot be detected while wind roughening does not affect lake visibility. Further, cloud cover hinders lake visibility in optical imagery while SAR data are unaffected by meteorological and illumination conditions. Therefore, the combination of optical and SAR data was particularly beneficial allowing to obtain a more complete mapping record than with single-sensor classifications. At the same time, these differences in mapping capabilities may lead to some variability in intra-annual and inter-annual lake extent mappings particularly when only one sensor type delivers information. For example, data availability during cloud cover or at the onset of Antarctic winter purely results from Sentinel-1 SAR. This could lead to a slight underestimation of the total lake area in case of lakes being subject to strong wind roughening. Likewise, when only optical data are available, lakes covered in snow are not detected and 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. In order to provide information on the abovementioned points in the manuscript, we complemented the paragraph in lines 63-66.

- This new combined dataset is a great contribution to the field and this is not emphasized enough in the main text. It would be great if the usefulness of the new dataset could be highlighted more, i.e. 2D dynamics of lakes, lake geometries, etc. But maybe this is the focus for future papers?

Many thanks for this positive feedback and helpful suggestion. We inserted a paragraph on the usefulness as well as on potential future applications of the combined dataset in the conclusion section (line 1104-1106). Since all data were made publicly available via DLR's GeoService (the link was added in line 1126 of the data availability section), future studies on 2D lake dynamics etc. can be easily performed.

- It would good to add details about how machine learning training data was generated and how classification was tested. Are there any feature that might be missed?

Due to the lack of a pan-Antarctic mapping record and an operational monitoring service providing supraglacial lake extent classifications for Sentinel-1 and Sentinel-2 data, the machine learning training data consisted of the original satellite acquisitions as well as manually created labels. For Sentinel-1, only classes "water" and "non-water" were labeled while Sentinel-2 data were labeled for classes "water", "rock", "shadow" and "snow/ice". Regarding Sentinel-2, the availability of multi-spectral data allowed to obtain rock classification maps as side-product, e.g., for further geo-scientific analyses as well as an improved discrimination between shadow and lakes being one of the biggest challenges to overcome. Classification was tested by means of the prediction of independent test scenes distributed across the entire Antarctic continent and not presented to the machine learning models before. For evaluation, an accuracy assessment was performed on basis of randomly sampled and manually labeled points in the test data that were evaluated as part of a confusion matrix. For both classification methods, the main remaining limitations were related to false positive lake classifications (line 303, 314). False negative lake classifications occurred less frequently but mostly over mixed pixels at lake edges for Sentinel-2 (line 314) and over particularly large lakes for Sentinel-1. This information can also be found in our preceding papers describing the methods for Sentinel-1 and Sentinel-2 in more detail. To indicate how the stated training/test data and accuracy values were obtained, we slightly expanded the corresponding paragraphs (lines 291, 297-299, 307, 312-313).

Transport of meltwater:

- You say that water is transported across the ice shelf (and I believe you) but what evidence do you have of actual water movement? It would be really interesting to see the flow of meltwater and subsequent growth of lakes in a time series.

Many thanks for this comment. While we did not provide any direct evidence of water movement across the ice shelves in the manuscript itself, this process is partly reflected in the maps providing details on temporal lags thus, the temporally delayed response of meltwater accumulation to climate drivers in regions that are most distant from initial meltwater accumulation in the early melting season, e.g., near the grounding line (Figure 7;

Figure 8). Further, also Figure 3 reflects the temporal growth of the surface hydrological network over time and Figure 2 and Figure 5 show the existence of inter-connected surface hydrological networks. Since the manuscript already contains a comparatively large number of figures, we decided not to include an additional figure on time series over individual lake features in the manuscript itself. However, we added an exemplary Figure showing a time series of the January maximum lake extent over central Nivlisen Ice Shelf in 2017-2021 to the Supplement (see below, Supplementary Material). Here, the progressive expansion of the surface hydrological network towards the north-east can be observed. Moreover, the bi-monthly data were made publicly available online and can be easily used for further time series analyses.

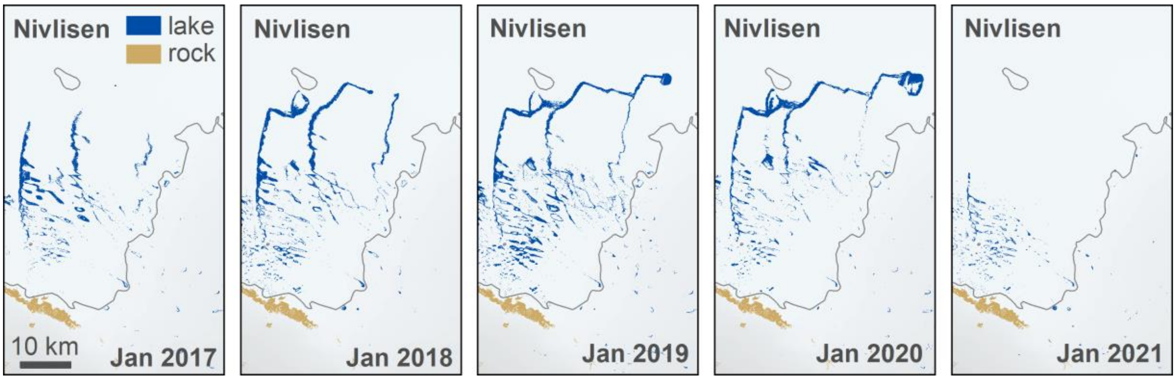

Figure 1 January maximum lake extent mapping products for years 2017-2021 over Nivlisen Ice Shelf. The grounding line data (grey) are from Mouginot et al. (2017) and Rignot et al. (2013) and Sentinel-2 bedrock data are from Dirscherl et al. (2020).

- You say that there is a lag between melt and lake growth where water has been transported across the shelf. How far has meltwater been transported? Can you investigate the lag between ERA5 data where the melt is formed and the formation of the lake?

As can be seen in Figure 2 and Figure 5, the surface hydrological networks extend over long distances particularly on Nivlisen, Riiser-Larsen, George VI and Amery ice shelves. For example, the elongated meltwater features stretching from west to east on Nivlisen Ice Shelf (see Figure 1 above) reach up to >30 km in length in 2020 until they reach the furthest meltwater pond in the north-east. Moreover, Figure 7 and Figure 8 provide details on the location and strength of temporal lags where meltwater has been transported.

- Figure 5: It's difficult to make out colours representing over 2 or 3 years of reoccurrence. This is possibly due to the small areas where lakes are frequently present. It would be good if bigger map plots were available, possibly in a supplement? There's so much great data here, it's a shame not to be able to see it more clearly.

Thank you for this helpful comment. It is correct that supraglacial lakes on the Antarctic Peninsula rarely reached recurrence frequencies >2 years in 2015-2021. Here, supraglacial lakes were mainly present during the past two melting seasons. In East Antarctica, lakes tend to reoccupy the same surface depressions during multiple years even though the overall area with recurrence frequencies >3 years remains comparatively small. We followed your suggestion and improved the choice of colours in Figure 5 in our revised manuscript version. Moreover, we enlarged the map plots for each ice shelf in the manuscript (line 495) and provided additional plots in the Supplement.

- Results section: As mentioned earlier, the results section can be difficult to read in places because there is so much information about 6 different ice shelves. One way to make this easier to read would be to have a small section dedicated to each one, and then use the discussion to summarise similarities and differences between them. It would also be helpful to only report the statistical significant results and point the reader to the figures for more details.

Many thanks for this important suggestion. We improved the results section and limited it to the most relevant information highlighting only the most significant results (line 356). Moreover, we improved the discussion section (line 741) by highlighting similarities and differences among the ice shelves more clearly and by reducing its general information content.

- Correlation analysis sections: Again these two sections are difficult to read because there is so much information. I like figure 6 – maybe it would be good to use this figure to guide the reader through the results. Similarly with Figures 7 and 8, but possibly here you can be more selective about what plots you choose to show, leaving the others to the supplement.

We followed your suggestion and shortened the text in Section 4.2. In particular, we limited the text to the key results and reference the figures and supplementary tables for more detail (line 466). Therefore, we decided to keep Figures 7-8 in the main text.

- Similarly, the discussion section includes a lot of repetition of the results section and frequently jumps from one ice shelf to another and back again – this could be trimmed down.

Many thanks for this important comment. We limited the discussion to the most relevant information and key messages and highlighted similarities and differences among the ice shelves (line 741).

Comparison with large-scale climate indicators such as:

- DMI: Lines 589-591: I don’t understand what is meant by this sentence.

With this sentence, we wanted to state that - in contrast to the 2019/2020 melting season - the 2020/2021 melt event was not caused by a strong positive Indian Ocean Dipole event. In fact, the IOD returned to neutral values during 2020 (shown in Figure 10) suggesting other driving factors for increased meltwater accumulation during 2020/2021. We improved the wording of the corresponding sentence in the manuscript (line 851).

- SAM: Line 429: “correlation with annual SAM (Table 1) indicates a significant negative linear relationship (r=-0.82*) over George VI Ice Shelf.” This is the only significant correlation identified. Can you draw any API-wide conclusions from this?

Many thanks for this comment. Returning correlation values of -0.78 and -0.74, Bach and Wilkins Ice Shelf similarly showed strong negative correlations. Here, the low number of observations (n=6) used for correlation might have caused unreliable values of p resulting in statistically insignificant values. Hence, rather the r-value should be considered. This is also stated in lines 737-738: “Due to the low number of observations used for correlation, the p-value might not be representative and rather r should be used for interpretation“. To summarize, the influence of SAM can likely be observed across most of the API despite some minor variations due to local factors. We improved the corresponding wording in line

490 and highlighted potential implications for other API regions in the discussion (line 1027-1035).

> I found it difficult to discern the take away conclusions about the interaction with these climate indicators. Lines 642-652 do discuss this, but the explanation is very vague, with few references to other studies that have thoroughly investigated these dynamics.

We improved the discussion on large-scale climate drivers and highlighted their potential implications for other Antarctic regions in line 1027-1035.

- Melt-albedo feedbacks (Line 678): not sure whether you have mentioned any particular examples of this from your results. It would be great to see some examples.

To highlight the influence of low-albedo surfaces on lake formation, we included our Sentinel-2 rock classification product in Figure 5. As can be seen, lakes on George VI, Wilkins, Nivlisen and Amery Ice Shelf are clustered close to rock. Even though this only provides indirect evidence of melt-albedo feedbacks, it highlights the spatial proximity of lakes to low-albedo surfaces. The same applies to lakes appearing near blue ice regions over Riiser-Larsen, Nivlisen and Amery Ice Shelf (comparison of Figure 5 to Figure 1d-f; Figure 2d-f). This is also reflected in Figure 7 and Figure 8 showing a shorter response time of lake formation in regions close to low-albedo features. As a more detailed analysis of melt-albedo feedbacks would go beyond the scope of this study and require detailed investigation of the spatial proximity of lakes to blue ice or rock over time, we decided not to expand this section.

- Table 2: “Local controls” how have you determined these correlations? It’s easy to miss this in the text, so it would be good to have a dedicated results section on this (similar to point above).

As mentioned, local controls were mainly analysed for completeness through the visual comparison of supraglacial lake extent classification maps to rock classification maps, blue ice occurrence (in optical imagery) as well as DEM data (Figure 2, Figure 5). For analysis of the influence of the firn air content, we used previous year precipitation data, as shown in Table 1 and Figure 9 (also see lines 492-493, 606-615). We improved the corresponding descriptions in Section 3.2.3 (line 353-355) as well as in Section 4.1 (line 356) and Section 4.2 (line 466).

- Buried lakes: This is mentioned in the conclusion and abstract, but not in the main text. How important/common are they? Where are they found? Is this one difference between sentinel 1 & 2? Are you missing them in Sentinel 2? How does this impact your results?

While information on the distribution of Antarctic buried lakes is so far limited with only few confirmed observations over Larsen C Ice Shelf on the Antarctic Peninsula (Hubbard et al., 2016) as well as over Roi Baudouin and Fimbul ice shelves in East Antarctica (Dunmire et al., 2020; Lenaerts et al., 2017; Liston et al., 1999), they likely exist over other parts of the ice sheet as well, similar as expected for firn aquifers (van Wessem et al., 2021, 2016). In addition, it has to be noted that we also refer to buried lakes when only parts of lake surfaces are covered by thin ice and/or snow, as visible in Figure 12 of our preceding paper (Dirscherl et al., 2021).

Considering the penetration of radar sensors into snow and ice, buried lakes can only be mapped in SAR data. In fact, this represents one of the major advantages of Sentinel-1 allowing to obtain a more complete mapping record than with single-sensor Sentinel-2 mappings. In the latter, buried lakes cannot be detected. To improve the understanding of advantages of SAR sensors for supraglacial lake extent mapping in Antarctica, we inserted the corresponding information in the introduction (line 64-66).

- ERA5-Land climate reanalysis – you haven't included any discussion on the potential shortfalls of using this data. For instance, are small scale effects around blue ice or exposed bedrock included? How does this impact your results?

Please find information on the general quality of the ERA5-Land climate variables in Section 3.1.2 (line 233). Even though small-scale effects were not investigated as part of this study, it is not likely that small-scale effects are visible in gridded data at a spatial resolution of 9 km. While the main advantages of ERA5-Land data were addressed in Section 3.1.2 (line 233), we briefly addressed corresponding drawbacks in the discussion section (line 1040-1041).

Minor Comments:

Line 101-102: Use of space when quoting numerical values to separate thousands from hundreds, i.e. 10 000. (i) I'd usually choose to use a comma; 10,000. (ii) I'd apply this to 1,000 and 10,000. I'm not sure what the formatting choices of the journal are.

Many thanks for noticing that. We changed numerical values to the suggested format.

Line 287-288: "We observe a rapid onset of supraglacial lake formation in late January" Fig 3 shows that the peak lake coverage is in late January not the onset of lake formation.

Thank you for this important comment. We improved the wording in the corresponding sentence (line 363).

Line 292-293: "More specifically, lake extents during the 2019-2020 and 2020-2021 melting season were above average during their peak and slightly below average in parts of early 2019-2020 and late 2020-2021" Does this imply faster than usual lake formation? Do you think this is a result of shallower lakes?

Due to the comparatively short length of the time series it is difficult to say whether lake formation was faster than usual. This particularly applies, as lake formation during preceding years was comparatively low overall thus, values above average simply reflect lake extents that were higher than in the preceding four low-melt years. As stated in the manuscript, specific atmospheric drivers were responsible, e.g., for the early end of melting season 2020-2021 and not a generally shifted melting season. Similarly, to evaluate whether the overall pattern of lake evolution is a result of shallower lakes, longer time series would be required. Another requirement would be to accurately discriminate between frozen lakes and open water lakes in optical data in order to retrieve lake volumes (see lines 315-317).

Line 371: "lakes spreading across Nivlisen Ice Shelf": Can you detect whether this spreading is occurring in time? i.e. lakes spread during melt season or lakes spread year on year?

In fact, lakes were spreading across Nivlisen Ice Shelf both, within melting seasons as well as from year to year (see Figure 1 above). Within melting seasons, lakes first developed close to the grounding line and progressively expanded in north-easterly direction towards the late melting season. Similarly, the maximum January lake extent mapping products (Figure 1 above) show a progressive advance of the surface hydrological network towards the north-east over the years with exception of the 2020-2021 melting season where lake coverage was generally low. We added a brief sentence on this in the manuscript (line 460). Furthermore, we included the Figure shown above in the Supplement.

Line 377: “average and maximum air temperature” What average is this? The spatial average across the whole shelf? The average of the aggregated data? The multi-year average?

In this context, “average” refers to the bi-weekly average air temperature and “maximum” to the maximum air temperature during a bi-weekly interval (see line 328). In Figure 6, these pixel-based bi-weekly average and maximum values are summarized as spatial averages. In order to clarify on the respective quantities, we improved the corresponding wording throughout the manuscript and in the caption of Figure 6 (line 644).

Lines 429-434: It might be easier for the reader if you only report the significant results in the text, as otherwise there is too much information to take in.

While we generally agree with this comment, the correlations for SAM and previous year precipitation result from only few observations potentially leading to unreliable values of p. Therefore, also correlations above the determined significance level should be considered and the r-value should be used. This is also stated in line 608 and 737. For all other correlations results, we shortened the corresponding sections (line 466).

Line 613: I don’ understand what you mean by “north(-easterly)”

Please excuse this ambiguous wording. Here, we wanted to state that winds were blowing predominantly from north-easterly direction with the corresponding directional value being inclined more towards northerly direction. We clarified on the meaning of this the first time it was referred to (line 808).

Line 638 -639: “firn air depletion potentially contributing to facilitated melt in 2020-2021” do you mean lakes rather than melt?

Many thanks for this important comment. That is correct, with this statement we actually wanted to refer to facilitated “meltwater ponding”. We corrected the sentence accordingly (line 749).

Line 665: “latitudinal flow stripes” I don’t think latitudinal is the best word to use here as the structure of the flow stripes is so complex. I suggest just removing latitudinal.

Thank you for this suggestion. We reworded the sentence accordingly (line 751).

Line 667: “surface slopes” do you mean low surface slopes?

Many thanks for noticing that. That is correct, this should be “low surface slopes”. We corrected the sentence accordingly (line 752).

Line 781: Include reference to: Gilbert, E., & Kittel, C. (2021). Surface Melt and Runoff on Antarctic Ice Shelves at 1.5°C, 2°C, and 4°C of Future Warming. Geophysical Research Letters, 48(8), 1–9. https://doi.org/10.1029/2020GL091733

Thank you for this suggestion. We inserted the reference in the corresponding sentence (line 1045).

Lines 803-804: Example of how you are using your short record to talk about anomalous years, without any context of long-term values.

We improved the wording throughout the whole manuscript.

Line 807: “record low lake coverage” same as point above.

Many thanks for noticing that. We improved the wording throughout the whole manuscript.

Line 808: “Lateral meltwater transport” where is the evidence for water flow/movement?

As mentioned earlier, we included an exemplary Figure in the Supplement showing lateral meltwater transport across Nivlisen Ice Shelf. Moreover, all bi-weekly mappings were made publicly available (line 1126).

Line 829: “Reduced firn air content” How is this measured? Are you inferring this from the records of low snow accumulation?

As stated in line 335, we use previous year precipitation as indirect indicator for the FAC of snow thus, for analysis of relationships between supraglacial lake formation and the state of the snowpack.

Figure 1: “the large lake feature at the western grounding line was excluded from analyses”

I’m not sure what is meant here. (i) This is not mentioned anywhere else in the text. (ii) It is not clear what feature/lake you are referring to. (iii) What impact does excluding this area have on you results?

Please excuse the lack of information in Figure 1. The large lake feature referred to is Beaver Lake at the western edge of Amery Ice Shelf. Since Beaver Lake is a permanent lake feature that is frequently covered by smooth, see-through ice, it might cause misclassifications in Sentinel-2 data when the melting season is already over. To avoid this, we decided to exclude this permanent lake feature from our analysis. We clarified on this in the caption of Figure 1 (line 153).

Figure 2: Looking at Figure 2e I wonder how much of this region is classified as a lake? There seems to be a high bright patch of open water and then an elongated drainage pathway. In the main text there is no discussion about meltwater volumes and how this might affect correlations with temperature and radiation, etc.

For a region as shown in Figure 2e, the round lake feature in the middle would be classified as lake area while the drainage structure would only partly be classified as lake. In particular, only the small streams visible in the middle of the drainage structure would be classified as lake while the rest would be masked. This mostly occurs due to the similarity to slush being masked as part of our slush elimination strategy (see line 311). As stated in lines 315-316, lake volumes were not derived due to the difficulties in differentiating between open water and slightly frozen lakes in optical satellite imagery, as also stated in other studies (e.g.,Moussavi et al., 2020). On the other hand, lake depth retrieval in SAR data is not possible.

Figure 5: As mentioned above, visibility of plots could be improved.

Many thanks for this suggestion. We improved the colour scheme in Figure 5 and included larger maps for each ice shelf in the manuscript (line 495) and Supplement.

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 were of great help to provide an improved manuscript version. In particular, we followed your suggestion and limited 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. All line indications refer to the “track changes” version of the manuscript.

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 improved the wording of the corresponding sentence in line 41.

Pg 3 – Ln 65: (v): should be (iv)

Thank you for noticing that. We corrected the wording accordingly (line 74).

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

We rephrased the sentence accordingly (line 181).

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 189-196, 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 revised the corresponding paragraph (line 189, 195-196) and improved the understanding of Figure 1 (line 151).

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 expanded the corresponding description in line 216.

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 306). 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 309-311). 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 expanded the paragraph in lines 297-300 and 312-313.

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. This information was complemented in the introduction (line 63-66).

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 improved the wording in line 323-324 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 corrected that accordingly (line 326).

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. In Figure 5, we improved the color scheme in order to improve the visibility of year-to-year lake extent dynamics over the ice shelves. 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 added 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 were made publicly available online (line 1126).

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

Many thanks for this suggestion. We shortened the whole paragraph and excluded this detailed information.

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

Please excuse the unclear wording. We mean wind magnitude and corrected the text accordingly (line 595).

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 was corrected accordingly (line 749).

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

With latitudinal 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 corrected this to "…meltwater accumulates in flow stripes controlled by…" (line 751).

Pg 21 -Ln 673: is among: are among

Many thanks for noticing that. We corrected that in the revised manuscript version (line 860).

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,b). In order to clarify on this, we reformulated the corresponding paragraphs (lines 750-756).

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) (see line 954, 980-982).

Pg 23 – Ln 732: near the Wohlthat Mountains

Many thanks for noticing that. We corrected the sentence accordingly (line 964).

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

The mapping products were made available online as part of our revisions (Section on data availability, line 1126) via the DLR GeoService. Further, we included 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 corrected the sentence accordingly (line 1067).

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., 2016), 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 were made publicly available via DLR's GeoService. We included a link in the data availability section as part of our revisions (line 1126).

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 improved the color scheme of the figure as part of our revisions (line 520). Moreover, we enlarged the individual map plots in the manuscript (line 520) and inserted additional, even larger plots in the Supplement.

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

Since Figure 5 has been modified in order to provide bigger map plots, the corresponding labels do not exist anymore.

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