Summary

The manuscript aims to detect landlocked lakes in Antarctica fusing optical and SAR imagery and using a U-net based method.

We would like to thank the Referee 2 for reviewing and commenting the manuscript. Below, we present a detailed response to each of your comments, with the original comments in italics and the responses in blue. All the recommended modifications will be implemented in the revised paper that will be uploaded.

Novelty/Relevance

I'm not aware of another method addressing land-locked Antarctic lakes. However, the methods used are standard methods, or in the case of thresholding the SAR imagery outdated within the field of research. The thresholding method also means that the lakes under different wind states can't be separated. Moreover, the method can't separate these lakes from other types of lakes, not surprising, but if that was the goal the method needs to be further improved.

We agree that the thresholding method is significantly affected by wind interference. The thresholding method didn't perform well with SAR images and separate landlocked lakes from other lakes, such as supraglacial lakes. But using potential landlocked lakes' open water (LLOW) areas derived from

Landsat images can extract landlocked lakes from other types of lakes in our workflow.

Strengths

Study of land-locked lakes in Antarctica, where the method is designed to detect a specific type of lakes. Could this method be applied to other landlocked lakes to monitor water resources? If so then it might become a more viable method.

Thanks for your suggestions for the potential application of this method. The landlocked lakes distributed in Antarctica are situated in diverse natural environments, such as cloud covers, terrain, mountain shadows and temperature variation. We trained the U-Net model to adapt these different conditions using various training data, such as thin clouds, mountain shadows and floating ice, which leads to the robust workflow for other study areas. What's more, the 6-day time interval of Sentinel-1 images contributes to the LLOW change monitoring. Thus, our method is able to monitor the variation of other LLOW areas in Antarctica.

Weaknesses

The manuscript is weak in the technical details, in particular there is an apparent lack of understanding of satellite images and details around them are missing. How is the SAR data pre-processed? Is the different spatial resolution between the optical and SAR images accounted and corrected for? The incidence angle *dependency in SAR data will result in higher incidence angles having a lower backscatter response. How is this accounted for in the method? Are only repeat orbits used? How will the incidence angle affect the results here?*

Thanks for your suggestions for the pre-process of SAR images.

1) We used the Sentinel-1 level-1 GRD data as SAR images, which had undergone preprocessing steps such as radiometric calibration and thermal noise removal (https://sentinel.esa.int/web/sentinel/technical-guides/sentinel-1-sar/products-algorithms/level-1-algorithms/overview). We only conducted terrain correction on them. 2) The spatial resolution of Sentinel-1 images is 10 m. Landsat images maintained at a 30-m resolution until they are resampled to 10-m resolution after being processed into potential LLOW areas. 3) We didn't take measures to mitigate the effects of incidence angles. Considering the pre-process method proposed by Wangchuk et al. (2019), we will use the same relative orbits to reduce the influence of incidence angles. Fortunately, all SAR images we used are acquired in descending orbits except images in Schirmacher Oasis (SO). Thus, we will check the images in SO region. 4) The backscattering threshold between water and non-water are usually affected by the incidence angle (Wakabayashi et al., 2019). We will evaluate the influence in our results.

Radar shadows (e.g. mentioned on P12 R271) are a well-known issue within SAR images. A method should be designed to deal with them or at least quantify the scale of the issue.

A part of radar shadows has been excluded by the mask of potential LLOW areas during the identification of LLOW. We will evaluate the influence of radar shadows with DEM datasets in the revised version.

Wind may cause a wind roughened (high backscatter) surface, it appears that the model can only deal with low backscatter surface scattering surfaces. The method would then only be applicable in a limited number of SAR images and this limitation would hinder an operationalization or a processing chain with a larger number of images. Moreover, separation of open water areas from surrounding is challenging due to the varying backscatter values under different wind conditions. To make a method applicable to be used in an ML/DL/operational setting all wind states need to be accounted for in the method. Something that is challenging for a threshold-based method.

Thanks for your suggestion on the impact of wind. We agree that the threshold algorithm can't deal with complex wind condition and subsequent unstable backscatters. We had attempted to train deep learning models to identify water rather than threshold method. However, limited by technology and the size of training datasets, the deep learning model performed not well.

Thus, we used threshold method to extract water and focused on the identification of LLOW.

The text should be significantly shortened to avoid unnecessary repetitions, focus the message on what was done here (without repetitions). E.g. among other things can section 3.4 be significantly shortened by removing repetitions. As the other reviewer has already pointed out that the text is verbose and provided examples I'll not do so further here.

Thanks for your suggestion. We will make the article more concise and avoid repetitions.

Stating that "best" analysis etc has been used should be strengthened to indicate what makes this the "best".

Thanks for your suggestion. The U-Net model shows good performance across various terrains and conditions. For example, it is able to overcome the interference from the clouds, shadows and floating ice. The robust U-Net model contributes to the generation of potential LLOW areas for the entire Antarctica. The thresholding method also performs similarly across all regions. Thus, we proposed that our workflow for LLOW identification is robust and can be applied to the entire Antarctic area. This point will be clarified in the revised manuscript.

The correlation between PDD and lake area is long established and is not new, and neither is different lake shape evolution with different PDD evolution. The fact that lakes melt first from the edges is fundamental knowledge and not new knowledge established here. Combined can these results easily be referred to in existing literature, and this manuscript should highlight what is new knowledge aside from these well-established results.

We appreciate your comments. We acknowledge that these concepts are indeed well-established within the scientific community and are not presented as novel findings within our manuscript. In the original version of the manuscript, we simply provided a comprehensive background. We will remove these points in the revised manuscript.

Figure 9 show significant amount of lake area before the start of the study, in order to show time series of lake evolution at least for 3 of the sites the time series needs to be expanded to include data from at least one month earlier. How is the time series affected by removing all the troublesome images, e.g. the wind affected and those where the method failed? Lack of useful data at the start and end of the season will lead to under/over estimation of the lake area. Can the method (time series) be said to satisfactory deal with rapid changes? Or is there a need to increase sampling frequency? P20R402. How does the lack of data in December affect this? It appears that for at least the CWM side data from earlier months is *needed to establish maximum lake area and probably also the LH site judging from Figure 9.*

1) Affected by strong wind and floating ice, there are often large areas of backscatter increase in lakes. The backscatter of the entire lake can rise to a level similar to the surrounding rocks or ice, making them indistinguishable. This phenomenon can lead to a decrease in the identified LLOW area by 10% to 50%. Therefore, when we remove these images, the time series become much more stable. 2) We agree that lack of valid data at the start and end of the season will lead to little understanding about minimum LLOW areas in frozen state. However, due to the 6-day interval between consecutive Sentinel-1 images, the LLOW time series can capture the maximum of LLOW areas. Thus, the current sampling frequency is sufficient. 3) The sustained high LLOW areas in the CWM from January to February indicate that the area in January is already the maximum extent of the lakes. The lakes won't freeze in January, suggesting that the area in December is expected to be smaller than that in January. Therefore, the absence of data for December does not lead to an underestimation of the maximum lake area.

There are 3 different lakes presented here, how can this method separate the three types if they all exist in one satellite image?

These three types of lakes, supraglacial lakes, epiglacial lakes, and landlocked lakes, have distinct characteristics. Supraglacial lakes are surrounded by ice rather than the rock. Epiglacial lakes have only a partial contact with rocks but is not within a rocky area. Landlocked lakes are entirely situated within a rocky area. After land cover classification with the U-Net model, BFS can distinguish their relative positions to rocks in one image. The positional information of LLOW obtained from Landsat can be used as a reference for identifying the location of LLOW in Sentinel-1 images. Finally, landlocked lakes can be distinguished from other types of lakes in Sentinel-1 images.

P13R290-292. If the LLOW are underestimated who does this affect the biological component that has been used as an argument for conducing the entire study?

We appreciate your attention to this. If LLOW are underestimated, it could lead to a conservative assessment of available habitats for various aquatic species. This, in turn, could affect our understanding of biodiversity, ecological interactions, and the potential for conservation efforts within these ecosystems. Such underestimation might also impact the accuracy of ecological modeling and predictions regarding the distribution and abundance of species, which are crucial for formulating effective conservation strategies and understanding ecosystem dynamics in coastal Antarctica.

P14R317. It is stated that using the thresholding method produces large amount of errors. Establishing an improved method should therefore be a goal of this manuscript. Open water areas that are either sea water, melt lakes on the ice *sheet or lakes on land is not possible using simple thresholding in the SAR images as the radar signal interprets each as water.*

Thanks for your suggestion. The interpretation of SAR imagery is challenging due to ambiguous backscatter returns and image geometry effects (Li et al., 2021). Due to technological limitations and the scale of training datasets, we were unable to implement the deep learning for water identification with SAR images. Thus, we selected the thresholding method to replace it. In addition, the utilization of the potential LLOW areas also aids in the thresholding method to eliminate the interference from shadows and other types of water like supraglacial lakes.

P21R411-420. Lake growth after temperatures start exceeding 0 has been well studied on the Greenland ice sheet for well over 10 years now. And PDD was used by, e.g. Johansson et al, (2013) to study lake evolution.

Johansson, Jansson and Brown (2013): Spatial and temporal variations in lakes on the Greenland Ice Sheet, J. Hydrology, https://doi.org/10.1016/j.jhydrol.2012.10.045

We greatly appreciate the reviewer's insightful comment and the reference to the seminal work of Johansson, Jansson, and Brown (2013) on the spatial and temporal variations in lakes on the Greenland Ice Sheet. We acknowledge the importance of this prior research and its relevance to our study, which explores the growth of lakes' open water area in response to exceeding zero-degree temperatures, utilizing Positive Degree Days (PDD) to assess lake evolution. We will include this work in our reference list.

Presentation

There is a substantial amount of details about chemical and biological importance of these lakes in the introduction. Shorten this to one paragraph, up to 4 sentences and highlight instead how this work fits into lake detection using satellite images, ML/DL of lake detection, or similar. The work should be set into the context of existing science with the topic presented here not in a different scientific field.

Thanks for your suggestions about the introduction. We will condense the mentioned details into one concise paragraph, comprising up to four sentences. This revision will emphasize how our work integrates with and contributes to the existing body of research on satellite-based lake detection and the application of ML/DL methodologies in this field.

P7R145-150. If dual-polarization data is not available, why is it being discussed here where the method is presented? This would then fit better in the introduction or the discussion.

Thanks for your suggestions. We will move this section to introduction.

Minor comments

P2R12 what is "reliable" in this context?

We appreciate the reviewer's question concerning the use of the term "reliable" in the context of Antarctic landlocked lakes' open water (LLOW) serving as a climate indicator. In our manuscript, the term "reliable" is intended to convey the consistent and predictable nature of LLOW as an indicator of climatic conditions in the Antarctic ecosystem. LLOW's sensitivity to climatic variables, such as temperature and precipitation, enables it to indicate the broader climate information. This sensitivity is based on the direct relationship between climatic factors and the physical, chemical, and biological processes occurring within these lakes, making them effective indicators of climate change.

P2R16. Why did you choose ice-free areas? And what do you mean with ice-free here, no glacier ice, no inland ice sheet, no sea ice.

Thank you for your question. The ice-free areas refer to the coastal Antarctic continental areas without ice or snow during the austral summer; these are regions without glacier ice and inland ice sheets. In these ice-free areas, lakes undergo freezing and melting cycles, playing a crucial role in maintaining the ecosystems of Antarctica. Moreover, changes in the areas of these lakes may be sensitive to climate warming. Thus, a thorough understanding of the areas of these lakes is of great significance for assessing the impact of climate change on Antarctic ecosystems. However, current methods for detecting this kind of lakes are unavailable. Thus, we aim to develop new techniques and methodologies to improve the detection and analysis of this type of lakes, contributing to the broader field of climate and ecological research in Antarctica.

P4R63. Rapidly -> change to a more scientific wording.

Thanks for your suggestion. We will correct.

Section 2.2. The number of optical images are introduced as 79 and then there is the discussion about removing image. It later transpires that 79 images were used. The text must be amended so that it is clear how many images were being used.

Thanks for your comment. We used 79 Landsat images and 390 Sentinel-1 images at the beginning. Then in post-processing section, we remove 45 Sentinel-1 images which are affected by strong wind or other factors. Thus, we used a total of 345 Sentienl-1 images. We will correct the text in the revised paper.

P5R103. Specify what "superior in many aspects" means.

Thanks for your suggestion. We will add the explanation about it.

P6R113. This is well known remove this reference to fundamental radar knowledge.

Thanks for your suggestion. We will remove this reference.

P6R117. Define high-resolution

Thanks for your suggestion. We will clarify the temporal resolution.

P6R125-127. Why is there a reference attached to one of the weather stations and not the other? Is it possible to give credit to the data providers instead? The text about "temperature" is confusing, is this not actual temperatures but some kind of simulated temperatures or why has been used?

Thank you for your comments. Regarding the Davis station data, it is from the Australian Government Bureau of Meteorology's official website at http://www.bom.gov.au/climate/data/stations/, with the station number being 300000.

As for the term "temperature", it refers to "daily mean air temperature" and "daily mean near-surface temperature". The quotation marks here emphasize this abbreviated expression. Please be assured that the station data represents actual observations. It is not derived from reanalyzed data sources like ERA-5.

Chapter 3. The ground truth should be presented in the data and not as a part of the results in chapter 3. This also goes for parts of chapter 3.2 that should also be moved to the data section.

Thanks for your suggestion. We will move description of ground truth to chapter 2. Chapter 3.2 is about the process of open water identification, so it's not suitable for the data section.

P11R226-229. Very well known (fundamental radar) remove reference.

Thanks for your suggestion. We will remove this reference.

Within this manuscript Sentinel-1 has been used, this is essential to call it or make an acronym if it's preferred to call it Sentinel. This as there are many ESA Sentinel satellites, and there is also the Asian Sentinels.

Thanks for your suggestion. We will uniformly replace "Sentinel" with "Sentinel-1".

P12R270. Many methods detect glacier outlines etc. A more thorough method should be able to at least attempt to separate ice (moving materiel) from the more stationary rocks.

Thanks for your suggestion. We will revise this incorrect description.

P13R297-299. Well known fundamental radar knowledge, remove reference.

Thanks for your suggestion. We will remove this reference.

P16R348. Remove "

Thanks for your suggestion. We will remove it.

Reference

Li, W., Lhermitte, S., and López-Dekker, P.: The potential of synthetic aperture radar interferometry for assessing meltwater lake dynamics on Antarctic ice shelves, The Cryosphere, 15, 5309-5322,https://doi.org/10.5194/tc-15-5309-2021, 2021.

Wakabayashi, H., Motohashi, K., and Maezawa, N.: Monitoring lake ice in Northern Alaska with backscattering and interferometric approaches using Sentinel-1 Sar Data, IGARSS 2019-2019 IEEE International Geoscience and Remote Sensing Symposium, 4202-4205,

Wangchuk, S., Bolch, T., and Zawadzki, J.: Towards automated mapping and monitoring of potentially dangerous glacial lakes in Bhutan Himalaya using Sentinel-1 Synthetic Aperture Radar data, Int. J. Remote Sens., 40, 4642-4667,https://doi.org/10.1080/01431161.2019.1569789, 2019.