Responses to Lucas Beem for: "Subglacial lakes and hydrology across the Ellsworth Subglacial Highlands, West Antarctica" (MC No: tc-2020-68).

We very much appreciate the insightful comments from Dr. Lucas Beem (*italic* and highlighted in grey) and for his constructive and helpful reviews of our manuscript. Below we respond (non-highlighted text) to the comments.

Lucas Beem comments

This article makes the contribution of expanding the inventory of subglacial lakes, specifically in West Antarctica, and discusses the basic characteristics of these lakes. Through the use of radar echo sounding observations that were collected in 2004/2005 bed echoes that could be characterized as a reflection off of an ice/water interface were identified. These reflections were further classified in four categories that relate to the confidence that the echo is from an ice/water interface. The analysis used established approaches for the identification and classification of subglacial water bodies, namely bright, low variance reflections that have flat hydraulic potential.

Overall I found this to be a fine article. I believe the methodology needs clarification in a multiple locations. There are many specific instances that I note within the line comments below. In particular the specularity methodology has left me scratching my head (see line comments 81,122 below). Also, I don't think specularity is being measured/observed, but instead consistency of bed echo is being used as a proxy, in combination with other observables (relative and absolute brightness), to infer specularity. I think that distinction should be clear in the methodology

We will alter the text to make it explicit that we use the consistency of the bed echo as a proxy to infer the specularity with reference to key papers (e.g., Peters et al., 2005; Carter et al., 2007).

I am unmoved by the lake volume estimates. This attempt is highly unconstrained to the point of being untrustworthy. I understand the desire for volume balances beneath the ice sheet and that others have made similar assumptions within the literature, but a volume range from 8 to 125 km^3 with fully contrived shorelines isn't a rigorous or defensible result.

We agreed. This estimation may be an overinterpretation of the data we have. We will remove the area and volume estimations due to the high uncertainties and will modify the discussion to account for this. It is a small component of the analysis and will not impact the key findings of the paper in terms of the new inventory or lakes.

The ice catchment boundaries made it to the abstract, so it must be considered an important detail, but the boundaries (ice verse subglacial hydrology nor old subglacial hydrology verse updated subglacial hydrology) are never directly compared. A figure should be modified to allow the reader to understand this reported observation. The change in 'known' subglacial hydrology catchment beneath Thwaites Glacier may be an important contribution, but the reader has no opportunity to assess this finding and to evaluate the implications to an important region of West Antarctica. Including these boundaries would support the conclusions of the authors and, if truly significant, increase the impact of this article.

We will include more detail in the results and discussion about the subglacial hydrological catchment. In particular we will include a figure with the subglacial hydrological drainage system simulated with Bedmap2 and our new DEM and will provide quantitative differences. Additionally, we will include more discussion on this point.

When I read though an article I note places where I get confused. Certainly, not every reader would share my confusion, but perhaps some readers would. There are many suggestions below that ask for clarity and specificity. There are also comments that relate to the broader points outlined above.

We address each comment below and in addition we will work on further proof reading the manuscript to ensure clarity throughout. Our responses to the specific comments are detailed below.

Specific comments:

Line 7) 'region': Not sure a region has been defined yet. 60% increase for Ellsworth Highlands or West Antarctica? While it certainly becomes evident later, the abstract should stand alone.

We will change to West Antarctica.

23) 'most likely': Hypothesized, maybe?

We will change this so it will be clear we are hypothesizing this.

27)'many that': should it be 'that many' or 'many'?

We will change to "that many".

27,36) 'highly': What is the threshold between dynamic and highly dynamic?

We will delete the word "highly", in both cases.

*36) Maybe high dynamism *is* the filling and draining, not highly dynamic *and* fills and drains?*

Yes, the word should be "is". We will amend the text.

39-40) This is at the edge of my grammatical confidence, but are these semi-colons correct?

We will change the semi-colons on lines 39 and 40 to commas.

47) 'Not fully understood': Is anything? Perhaps; "many hypothesis remain untested" or something else

We will alter the text to: 'many hypotheses remain untested'.

48) 'fastest changing': In what regard? Certainly if we choose differing metrics we could identify different glaciers that are fastest changing. Maybe generalize this statement. If PIG and THW are the fastest changing then e.g. should be i.e.

We will change this from e.g. to i.e.

52) 'ice basal water': perhaps just 'basal water'?

We will be more concise and will change the text as suggested.

52-53) 'edge of the continent': This might not be accurate as the ice sheet grounding zone is not coincident with the continental margin.

We will alter the text to "ice sheet grounding zone".

56) First time PIG is used and acronym is not defined.

PIG will be defined at first mention.

62) 'subset of this data-set': Which subset? Just the data over ESH? Why was this done? The justification for this work talks about the importance of analyzing existing data sets? Why wasn't the entire data set analyzed / why restrict it?

We analysed the available BBAS data from season 2004/2005. We will make it clear in the text.

65) How parenthetical abbreviations with parenthetical references are formatted varies. For example: Line 65 they are within the same parenthetical. Line 39-40 they are in independent parenthetical. Should this be consistent throughout, or maybe rewrite to not require the combination of parentheticals?

We will change the referencing to make it consistent throughout the text.

66-69) Maybe explicitly enumerate the list, e.g. i) ii), for clarity

We will change to an enumerated list.

73-75) I think the sentence would read more clearly if the final clause was moved closer to the beginning of the sentence, maybe 'Following previously published methods, these reflections were then...'

We will change as suggested.

78) Point 2 is that the lake surface is has a flat hydraulic potential, right? Should it use those terms? The hydraulic potential water surface should not be inclined in a lake context. I wonder if 'potential', means a candidate site and not a potential energy surface, if so, that is leading to my confusion. Also it's unclear what 11 times opposite means. Perhaps it's, 11 times the magnitude in the opposite direction?

We will rewrite this and make it clearer. We will change the text so that it will be clear that we mean a candidate site and that the 11 times does indeed mean 11 times magnitude in the opposite direction.

79) What's distinguishes between points 2 and 3? Appears to be describing the same characteristic in differing terms, flat hydraulic potential.

Point 2 is referred to the ice surface, whereas point 3 is referred to the hydraulic potential. We will clarify this in the text.

81) First time BRPr is used and it is not defined. If BPRr is a proxy for specularity, the term BPRr is not used in section 2.3. On line 121, BPRr appears to be absolute reflectivity

It should be read BRP. The BRPr will be removed and replaced by BRP instead.

82) '<3sigma BRPr': See line 122 comment

We will clarify this point in the text so that it will be clear that is 3 dB sigma BRP.

88) Is BRPe attenuation in ice or energy loss more generally? In this line, BRPe is defined by the methodology used to quantify it.

BRPe refers to energy corrected for both geometrical spreading and ice attenuation. We will make this clear in the text.

90,97) Is there an inconsistency in variables used for geometrical spreading (L_t and L_g)? L_t never appears in an equation. Also, with the placement of the parenthetical L_i, in line 90, it suggests it is defined differently than in line 97. Is L_i attenuation, system gains, or attenuation and system gains? I would look to make this nomenclature consistent and unambiguous. Also, the terms are repeatedly defined, maybe simplify to reduce repetition.

L_t should not be on the equation. We will review this section so that this point will be clear. We will check the parenthesis and all the variables included in the equation. Similarly, we will check the nomenclature is consistent throughout manuscript.

102) 'height': Is that height of the antenna above the ice surface?

We will rewrite this in the text so that it will clear that we meant the height of antenna above the ice surface.

104) Is an indent missing?

Indent will be added.

104) 'section': What is a 'section'? How long/how many samples? This should be clear how calculated attenuation values vary within the survey and over what length scale. Understanding attenuation application could be significant to using BPR as an identifier for bright bed. On line 376, attenuation rate is reported as 'constant'. But here on 104, its seems to be calculated on a 'section' by 'section' basis. Which is it? Also, reporting the magnitude of attenuation rate will be of interest to the community.

The attenuation rate was calculated using variable numbers of sample points depending on the particular area. For example, it ranges from 120 samples in the smallest section (within steep terrain) to more than 500 samples before and after a subglacial lake candidate depending on the basal interface.

111) 40 samples on either side or 20 samples are either side. What is a nominal sample spacing? If statistics are calculated for 40 meters of bed verses or hundreds of meters or kilometers it will influence significance/usability of the results

The standard deviation was calculated 20 samples either side of a point. The horizontal resolution of the radar is ∼21 m. We will explicit this in the text.

Section 2.4) Which of the categories require hydrologic-potential flatness? Only 'definite' explicitly includes hydrologic-potential. Can a sloped hydraulic-potential surface be considered a lake with the other classifications?

All the categories require a hydropotential surface that is more linear than its surroundings, but the smoother the lake, the more likely it is to be defined as 'definite'. However, we also note that this surface may be tilted if the subglacial lakes are smaller than 4-5 km. As a consequence, the term 'flat' may not be appropriate and instead we suggest we will apply the term 'smooth' or 'linear'. We will clarify this in the text.

122) '3σ BRPr': Maybe the threshold magnitude of specularity proxy should be defined here. It is unclear to me. Partially as I am confused about the distinction between BRP and BRPr (see line 81 comment) and what '3 BRPr' means. I understand that the analysis requires a low magnitude of standard deviation to be a definite lake, but that magnitude is not defined. Does the threshold vary between lakes, or is a universal threshold applied? Looking at Carter et al., 2007 those authors used 3 db standard deviation in bed echo strength as a threshold for a specularity proxy. Should '<3σ BRPr' be a 1sigma threshold of less than 3 db?

We used the same threshold for every subglacial lake candidate. This threshold should have been written as 3 dB σ BRPe. Thank you for noticing this important detail.

123) 'flat hydraulic surface': flat hydraulic potential surface

We will change the text as suggested.

133) 'distinguish': What characteristics are not distinct? Should the clause be more specific?

We will change the clause to make it so that it will be clear that we meant the difficulty to recognise each subglacial lake reflectivity from the surrounding bed reflectivity.

Section 2.5) Lake shape assumptions seem poorly justified. Why should lakes have the same aspect ratio? The average of two lakes (SLE, SLC) does not revel much about a distribution of lake sizes. How do aspect ratios of pater-noster lakes vary within a subaerial valley, does this lend credence to this assumption? Not all the candidate lakes are within a trough. Are the trough assumptions applied to all environmental settings? If so, how can that be justified? Perhaps making volume estimates from a single RES crossing exceeds the capacities of the data.

We recognise there are a large variation in the estimation of each potential subglacial lakes volume. We will delete these estimations in the manuscript to avoid overinterpretation.

147) A mention of the tectonic environment (like the details discussed near line 235) in these section would support the choice of a side slope lake depth assumption.

We will remove the depth estimations of subglacial lakes.

156) 'replaced them with Bedmap2': Bedmap2 is 1km grid product. Which bedmap2 value was chosen for inclusion in the new 2km grid DEM? What methodology was employed

We use the nearest pixel to interpolation and create the downsampled output pixel value (nearest neighbor algorithm). We will include this in the text

158) 'downsampled': How?

We use the nearest neighbor routine. We will clarify this in the text.

162-163) Why include units for some variables?

We will include the units for all the variables and indicate what density we use for water and ice.

167) equation 5, g is a different typeface

We will change the typeface.

171) These citations are specific to the middle of Whillans ice stream. The lakes in this article are in a different glaciological setting. How does hydrology in fine grained subglacial substrate in the middle of a fast flowing ice stream relate to the hydraulics in a fault bounded subglacial highland trough beneath an ice divide?

We will rewrite this paragraph and indicate that we followed previous investigations in Ellsworth Subglacial Highlands (e.g., Vaughan et al 2007; Rivera et al., 2015) where water pressure was assumed to be close to the overburden ice pressure in subglacial flow path calculations.

177) 'tends': Does it ever not?

Yes - it does. We will remove the word tends.

218) 'very close' is greater than 20 km? What does 'very close' mean?

We will change "very close" to "less than 50 km".

220) '17': 17 is the total number of 'small lakes' or the number of small lakes near the divide? Maybe if it said (17 of x) or (x of 17) whichever is correct. Would that be clearer if the numeric values of this section where not parenthetical but part of the sentence, e.g. 'Seventeen of the small lakes. . .',?

We will change the numeric value of this example and include it in the sentence.

221) 'these': Which lakes are 'these'? only the 3 largest?

We referred to the small subglacial lakes. We will change this to "over small subglacial lakes".

228) 'mean': What do we learn from the mean? Would the mode be more descriptive?

We will include the mode in the supplementary material. Thanks for the suggestion.

241) Where is the ET? Geographical names should be locatable with labels on figures. Particularly with a reference to figure 9 which does not have any locatable basal topographic features.

We will include more geographical names in the figure to provide a clearer spatial reference.

246) All the others have a count, why use percentage here? Is it better to be consistent?

We will change it to a count.

246-253) Seems like some of this is repetitious. Velocity description occurs on line 228, lowland description occurs on line 238. Length appears on line 227.

We will review this paragraph and we will make it clearer and to avoid repetition.

262) Percentage or count? consistency?

We will change this to count.

269) '(Figure 7c and 7d)': These panels do not show catchment boundaries, so it is not possible to detect how the subglacial hydrology catchments and ice catchments differ and how that might be an important insight.

We will include the catchment boundaries in suggested figures and will also bolster the text to refer to the figure and describe the way they differ.

275) Is an indent missing?

Yes – we will add it.

277) 'channelization': Is channelization an assumption? How is the geometry of the system known? Perhaps 'routing' is a better word?

Thank you for this clarifying suggestion. We will change the wording to "routing".

289) How deep is 'deep'?

We will clarify this in the text by changing the sentence to "(. . .) deeper than 100 m as are SLC and SLE".

290) What is the evidence of melting over the lake? Perhaps present as a hypothesis?

Thank you for noting this – you are correct that we do not have any measurements so we will therefore introduce this as a hypothesis.

293) What is a 'variable' distribution? Can a more specific statement be used?

The distribution of the subglacial lakes does not have an evident pattern to its distribution. We will clarify this in the text.

301) How is the shape of these lakes known? They are assumed to be circular or elliptical. How can these shapes be compared to the shapes in the Wright and Siegert inventory? In Wright and Siegert inventory a single length value is reported except for 8 lakes which have an additional width value. How is any meaningful shape comparison accomplished with these data?

We recognize this may be too speculative since we don't have a fully understand of the subglacial water bodies. We will delete these conjectures as it distracts from the main focus of the paper which is to simply identify the lakes and discuss their spatial distribution.

306-308) It is ambiguous if this statement is an inclusive list (all are necessary) or are three independent criteria. I might rewrite to have the distinction be explicit.

This is not an inclusive list. These are single criteria suitable for the occurrence of subglacial water. We will rewrite it to make it clearer. Thanks for the suggestion.

330) 'trough': Capitalize?

We will capitalize T.

334)'cascade-type system': This term is used a few times (line 352,418) without a clear definition of what characterizes this system or what other systems might exist. I presume 'cascade' refers to a temporal correlation between respective draining and filling events? My understanding only becomes a possibility after reference to Thwaites lakes from Smith et al. as cascade. Maybe clearer terminology is needed?

We will clarify this concept at its first mention.

349) Is an indent missing? Section 4.5) Much of this section appears to be methodology to me. Consider moving the text.

Indent will be added.

370) No space after 'energy.'

Space will be added.

376) 'focused'/'single portions': Isn't BRP calculated everywhere? What does 'single portions' mean? Is it a length of flight line, or a certain number of samples? If so, that should be explicitly stated with the magnitude (e.g. # samples) of data used.

The BRP was calculated for each subglacial candidate within a determined number of samples for each subglacial candidate. This number of samples is variable, and it will be added in the Annex table.

396) 'elevation': should it be 'altitude'?

We will change this to altitude.

398) 'appropriate': What is 'appropriate'? Denser (more closely spaced) survey lines are needed?

We meant an optimized survey to characterize the subglacial interface, considering the geometry of the subglacial topography. In other words, we would ideally have lines going across topographical features directly as opposed to diagonally (e.g., across subglacial trough).

406)'124' and '7.7': Different magnitudes than reported on line 257

All these estimations will be deleted.

408) ''dim'': Dim in quotes here, but not elsewhere. Which way should it be?

Quotes will be deleted.

Figure 1) Colorbar: 3000 is white. But back ground is white as are the masks for ice shelfs. Maybe change the end member color or background.

We will change the colour of the ice shelves and the end member of the elevation scale.

Figure 1) Colorbar: Mapping of elevation order with negative elevations closer to top of page is counter to more intuitive mappings of high elevation above lower elevation.

We will change as suggested. Thanks.

Figure 1) Figure 1 should include all the places referenced in the text. Should all abbreviations used in the figure be defined in the caption? This might assist the reader

Thanks for this suggestion. We will complement the caption.

Figure 6) 'a&b' and 'c&d',: maybe include reference to Figure 7.

We will include the reference to Figure 7.

Figure 8) Caption 'regional distribution in Antarctica': What does that mean? Is this the ice thickness distribution for the BBAS survey, all of Antarctica?

This is the regional distribution for all of Antarctica (values taken from Bedmap2). We will remove it to avoid confusion.

Figure 9) Why group a histogram of surface velocities with a map of hydrology routing? Figure 9b, should be in Figure 8.

We thought it would be more useful for the reader to have this histogram to add context to the hydrology map. The spatial distribution of the velocity are shown in the map of the study area so we did not wish to repeat it. We will move this histogram with the other histograms.

Table 2) The use of both BRP (in caption) and BRPr (table header) without a clear definition of difference.

We have now deleted the BRPr term in the text.

Responses to Reviewer 2 for: "Subglacial lakes and hydrology across the Ellsworth Subglacial Highlands, West Antarctica" (MC No: tc-2020-68).

We are grateful to reviewer 2 for the helpful reviews of our manuscript and for the references provided. Below we respond (non-highlighted text) to the comments of reviewer 2 (*italic* and highlighted in grey).

Anonymous referee #2

This paper identifies 37 new subglacial lakes in West Antarctica from ice-penetrating radar data. Radiometric properties were used to classify the confidence of these lakes. A volume estimate was made for these lakes. New topography measurements were used to make an updated DEM of the Ellsworth region so that a water routing model could be generated to investigate the potential for drainage. This work is an important contribution to lake inventories and hydrological understanding, though some areas of this paper require clarification or further discussion. The volume estimates do not seem particularly meaningful given the assumptions made in the methods and the uncertainty of the results (see comments below). Given that the water routing model is the primary evidence for connected drainage, it would be useful to include more information on the topography data (e.g. survey spacing, data density). Also, improved topography is an important contribution, and the impact could be enhanced by providing quantitative information on the improvement or showing comparisons to Bedmap2. There are some statements that seem to conflate active and stable lakes (see comments on lines 37-40), and I believe there could be more discussion on which category the newly discovered lakes fall into. Generally speaking, active lakes identified with satellite observations do not have a clear radar signature, and RES-detected lakes are not observed to have surface elevation changes. The authors hypothesize that these lakes are part of a dynamic drainage system and speculate about cascade-type drainage. It is fine to suggest this, but the fact that many of the lakes in this study are "definite" RES-detected lakes indicates that they could very well fall into the inactive RES lake category. So far, no active drainage has been observed in this region. Previous investigations of SLC and SLE have concluded that these lakes are stable. Perhaps there is a more nuanced stance where RES lakes can be part of a drainage system without the dramatic ice surface drop of active lakes, and the authors do acknowledge that satellite observations of change would be required to confirm drainage. But I think it is important that the authors discuss these contradictory pieces of evidence..

We appreciate all the elements and resources for improving this manuscript that the referee is offering in this review.

Specific comments:

Line 16: "reported acceleration of ice velocity" Reported an acceleration of ice velocity?

We will amend the sentence.

It is unclear what is meant by the identification of lakes through the "characterisation of the subglacial topography from ice surface data." Bell et al. (2007) detected active lakes using satellite data, similarly to Wingham et al. (2006) and Smith et al. (2009). Bell (2008) reviews subglacial lakes gathered from a variety of different sources and surveys, including active lakes detected from satellite data, and non-active lakes detected with radar. The Jamieson et al. (2016) study does not identify lakes. Rather, they hypothesize about potential lake locations by running a water routing model on estimated bed topography.

Was this intended to be a statement about active lakes, or subglacial lakes in general? To the best of my knowledge, neither Robin et al. (1970) or Popov and Masolov (2003) have identified active lakes; the lakes they found are considered stable. The Rivera et al. (2015) study also concluded that their lake was stable. The only study that I am aware of that has seen any radiometric evidence for active lakes is Langley et al. (2011):

Langley, K., Kohler, J., Matsuoka, K., Sinisalo, A., Scambos, T., Neumann, T., ... & Albert, M. (2011). Recovery Lakes, East Antarctica: Radar assessment of subglacial water extent. Geophysical Research Letters, 38(5).*Line 37-40: "These active subglacial lakes have been identified using a range of techniques including satellite measurements of ice surface elevation changes (e.g., Wingham et al., 2006; Smith et al., 2009), characterisation of the subglacial topography from ice surface data (e.g., Bell et al., 2007; Bell, 2008; Jamieson et al., 2016); airborne radio echo sounding (RES) (e.g., Robin et al., 1970; Popov and Masolov, 2003); and/or ground-based RES (e.g., Rivera et al., 2015)."*

It is unclear what is meant by the identification of lakes through the "characterisation of the subglacial topography from ice surface data." Bell et al. (2007) detected active lakes using satellite data, similarly to Wingham et al. (2006) and Smith et al. (2009). Bell (2008) reviews subglacial lakes gathered from a variety of different sources and surveys, including active lakes detected from satellite data, and non-active lakes detected with radar. The Jamieson et al. (2016) study does not identify lakes. Rather, they hypothesize about potential lake locations by running a water routing model on estimated bed topography.

Was this intended to be a statement about active lakes, or subglacial lakes in general? To the best of my knowledge, neither Robin et al. (1970) or Popov and Masolov (2003) have identified active lakes; the lakes they found are considered stable. The Rivera et al. (2015) study also concluded that their lake was stable. The only study that I am aware of that has seen any radiometric evidence for active lakes is Langley et al. (2011):

Langley, K., Kohler, J., Matsuoka, K., Sinisalo, A., Scambos, T., Neumann, T., ... & Albert, M. (2011). Recovery Lakes, East Antarctica: Radar assessment of subglacial water extent. Geophysical Research Letters, 38(5).

We refer to subglacial lakes in general as opposed to just 'active' lakes. We will rewrite this paragraph to clarify how subglacial lakes in general are identified, and also will clarify the methods by which active lakes have been defined. We will check the specific papers as we do this.

Rignot, E., Mouginot, J., Morlighem, M., Seroussi, H., & Scheuchl, B. (2014). Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011. Geophysical Research Letters, 41(10), 3502-3509.

Rignot, E., Mouginot, J., Scheuchl, B., van den Broeke, M., van Wessem, M. J., & Morlighem, M. (2019). Four decades of Antarctic Ice Sheet mass balance from 1979– 2017. Proceedings of the National Academy of Sciences, 116(4), 1095-1103.

Joughin, I., Smith, B. E., & Medley, B. (2014). Marine ice sheet collapse potentially under way for the Thwaites Glacier Basin, West Antarctica. Science, 344(6185), 735- 738*Line 47-49: "Given the fact that this region is located up-ice of the fastest-changing ice streams in the world (e.g., Pine Island Glacier and Thwaites Glacier), and that they are some of the most vulnerable glaciers to ongoing climate change (Martin et al., 2019)..." This statement could be better cited. Some options:*

Rignot, E., Mouginot, J., Morlighem, M., Seroussi, H., & Scheuchl, B. (2014). Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011. Geophysical Research Letters, 41(10), 3502-3509.

Rignot, E., Mouginot, J., Scheuchl, B., van den Broeke, M., van Wessem, M. J., & Morlighem, M. (2019). Four decades of Antarctic Ice Sheet mass balance from 1979– 2017. Proceedings of the National Academy of Sciences, 116(4), 1095-1103.

Joughin, I., Smith, B. E., & Medley, B. (2014). Marine ice sheet collapse potentially under way for the Thwaites Glacier Basin, West Antarctica. Science, 344(6185), 735- 738

We appreciate the suggested references, and we will include some, or all of them in the text.

Line 85: The BBAS acronym is not defined Section

BBAS is the name (Basin Balance and Synthesis) used to refer to flight lines from the 2004/2005 PASIN survey over PIG (Vaughan et al., 2006). We will be explicit about this in the text.

2.3: There are two different definitions of specularity. It might be helpful to explain that the method in this manuscript is different from the specularity calculation method in Schroeder et al. (2014) to avoid confusion.

We will clarify in the text that we use Carter et al. (2007) definition for specularity.

Line 139: "in a GIS" In a GIS software?

We will change this in the text complementing GIS with the word software.

Section 2.5: The methods for surface area and volume calculation are not convincing. The dimensions of two lakes (SLC and SLE) do not provide a statistically robust or representative basis for the dimensions of other lakes. The lake geometry outlined in Figure 3 seems unrealistic, especially if a lake does not happen to fall within a trough or if there is sediment infill. And since the data is not SAR processed, isn't it possible that the hyperbola slopes are different from the actual topography?

Although, previous studies have made similar assumptions on the shape (i.e., circular shape) in calculating the area for their hypothesised subglacial lakes we do acknowledge the area and volume estimations are subject to very large uncertainties. The other reviewer also made this comment. As a consequence, we will remove this from the text – it will not significantly impact the overall findings of the paper.

Section 2.6: Given that the water routing model is the primary piece of evidence for the connected drainage hypothesis, I think you can elaborate on the topography. It would be helpful to include information on radar grid spacing, changes from Bedmap2, or percentage of grid cells within 5km of a data point.

We will make sure we describe the generation for the new DEM fully and that we describe the features within it carefully with an eye on how they end up controlling the drainage and connections between lakes. We will make explicit in the text the references where details on the BBAS survey can be found and will show the unpublished radar survey grid from CECs in a figure. Also, we will show a figure with the differences in the new DEM model (this work) and Bedmap2.

Lines 255-256: Is the order of magnitude uncertainty in cumulative lake volume really make this a meaningful result, especially given the assumptions in volume calculation?

We do acknowledge these uncertainties in the different methods applied. Therefore, will remove this estimation from the text.

Line 302: "the range of length notably smaller" The range of length is notably smaller?

We will add the word "is".

Line 310: "poorly constrained" Are poorly constrained?

We will reword this to point out that Geothermal Heat Flux values are variable depending on the selected technique to model it; and also, that the resolution of the models may not show localized highs in the Heat flux.

MacKie, E. J., Schroeder, D. M., Caers, J., Siegfried, M. R., & Scheidt, C. (2020). Antarctic Topographic Realizations and Geostatistical Modeling Used to Map Subglacial Lakes. Journal of Geophysical Research: Earth Surface.*Section 4.2: Is it being hypothesized that these lakes are active lakes? It should be discussed that radar-detected lakes do not have drainage that can be observed from the surface. Or maybe radar-detected lakes are more dynamic than previously expected, but not active enough to be seen from the surface? If you are hypothesizing a more active regime, it might be helpful to cite the MacKie et al. (2020) study which predicts that there are active lakes in the Ellsworth region.*

MacKie, E. J., Schroeder, D. M., Caers, J., Siegfried, M. R., & Scheidt, C. (2020). Antarctic Topographic Realizations and Geostatistical Modeling Used to Map Subglacial Lakes. Journal of Geophysical Research: Earth Surface.

Thanks for your suggestion and for the reference. In this article we hypothesize that some of these subglacial lakes may be part of wider active subglacial hydrological drainage system without ice surface changes, provided that hydrological system is in steady state. As long as the rates and locations of flowing water at the base of the ice do not change, it would not affect the surface elevation or they may not be noticed on the surface. We will discuss this more fully in the text.

Line 335-335: "The identification of any such episodic draining (e.g., Wingham et al., 2006) would require analysis of ice elevation changes to capture water infilling/drainage through time."
Following on the comment above, there'll have to be a thoughtful statement about why you think these lakes could be detected by satellite, when so far all other radar-detected lakes (with a possible few exceptions) have not.

You are correct, very few subglacial lakes detected by radar have also been identified by satellite means. It may be the case that the lake is too small relative to the ice thickness or the recharge period is too long, and the modern satellite have not been able yet to observe one of the drainage events. We remove this statement.

Line 337: "down-ice" Downstream?

We will change it to downstream.

423-424: Why is it assumed that the observed lake lengths are the minimum length?

We made two different assumptions to produce two different ideas of lake size because the radar may pick up at most, the longest dimension of the lake, and at a minimum, it would pick up the shortest dimension of the lake – thus we'd produced two end member estimates (with very large uncertainties). However, we recognise these assumptions have a considerably imprecision (both reviewers commented on this) and therefore we will remove the section of lake dimensions because it does not significantly impact our key findings for the paper.

Relevant changes made in the manuscript

We have done everything we said in the responses of the referees comments.

We amended the number of subglacial lakes identified (from 37 in the previous version to 33 in this version) and their classification, according to our degree of confidence.

Subglacial lakes and hydrology across the Ellsworth Subglacial Highlands, West Antarctica

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Abstract. Subglacial water plays an important role in ice sheet dynamics and stability. ~~It is~~ Subglacial lakes are often located at the onset of ice streams and have the potential to enhance ice flow downstream by lubricating the ice-bed interface. The most recent subglacial lake inventory of Antarctica mapped nearly 400 lakes, of which ∼14% are found in West Antarctica. Despite the potential importance of subglacial water for ice dynamics, there is a lack of detailed subglacial water characterization in West Antarctica. Using radio-echo sounding data, we analyse the ice-bed interface to detect subglacial lakes. We report ~~37~~ 33 previously uncharted subglacial lakes and present a systematic analysis of their physical properties. This represents a ∼ 40% increase in subglacial lakes in ~~the region~~ West Antarctica. Additionally, a new digital elevation model of basal topography was built and used to create a detailed hydropotential model of Ellsworth Subglacial Highlands to simulate the subglacial hydrological network. This approach allows us to characterize basal hydrology, subglacial water catchments and connections between them. Furthermore, the simulated subglacial hydrological catchments of Rutford Ice Stream, Pine Island Glacier and Thwaites Glacier do not match precisely with their ice surface catchments.

1 Introduction

Subglacial water is important for ice sheet flow, with the potential to control the location of ice stream onset (e.g., Siegert and Bamber, 2000; Vaughan et al., 2007; Winsborrow et al., 2010; Wright and Siegert, 2012) by lubricating the ice base and reducing basal friction (Bell et al., 2011; Pattyn, 2010; Pattyn et al., 2016; Gudlaugsson et al., 2017). Some studies have reported an acceleration of ice velocity in different regions of Antarctica as a result of basal hydrologic conditions (e.g., Stearns et al., 2008). Subglacial water piracy has been invoked to explain the on and off switching of streaming flow (e.g., Vaughan et al., 2008; Anandakrishnan and Alley, 1997; Diez et al., 2018). Additionally, small changes in the ice sheet surface or ice thickness can lead to significant changes in basal hydrology; causing water flow to change direction (Wright et al., 2008). Significant glaciological change is known to have taken place in West Antarctica over the last few thousand years (Siegert et al., 2004b, 2019). For example, there is evidence of a well-organized and dynamic subglacial hydrological system which formed paleo-channels and basins underneath the present Amundsen Sea Embayment (ASE) (Kirkham et al., 2019). This subglacial hydrological system was ~~most likely~~ hypothesized to be caused by episodic releases of meltwater trapped in upstream subglacial lakes (Kirkham et al., 2019).~~But these changes have not been uniform~~ However, changes to subglacial hydrology associated with ice surface elevation changes have not been identified across ~~WAIS~~ the Ellsworth Subglacial Highlands (ESH). Ross et al. (2011) demonstrated that the ice divide and ice flow across ~~the Ellsworth Subglacial Highlands (ESH)~~ ESH have been stable for more than 20 ky. The ESH are located within the Ellsworth-Whitmore Mountain (EWM) block (Figure 1). Some studies have demonstrated the potential variability of subglacial flow routing and ~~many that~~ that many subglacial lakes form part of a ~~highly~~ dynamic drainage network (e.g., Siegert, 2000; Fricker et al., 2014; Pattyn et al., 2016). However, our understanding of the subglacial hydrology in ESH is relatively limited. ~~: only 2 subglacial lakes (i.e. subglacial lake Ellsworth and CECs) have been recognized within the troughs of this region~~ Understanding the current hydrological network, and assessing its evolution and sensitivity through time, is therefore essential for an improved understanding of Antarctic ice-sheet dynamics. Additionally, a better comprehension of this relationship is also important for studies of ice sheet mass balance and supplies of water to the ocean potentially affecting circulation and nutrient productivity (Ashmore and Bingham, 2014).

The most recent inventory identified ∼400 subglacial lakes across Antarctica (Wright and Siegert, 2012, Figure 1), ∼14% of which are located beneath the West Antarctic Ice Sheet (WAIS). Studies have shown that some of these subglacial lakes are connected (Wingham et al., 2006; Fricker et al., 2014) and ~~that some are highly dynamic, and drain and refill~~ that they drain and refill dynamically (e.g., Fricker et al., 2007, 2014). ~~These~~ Active subglacial lakes have been identified using a range of techniques including satellite measurements of ice surface elevation changes (e.g., Wingham et al., 2006; Smith et al., 2009).~~characterisation of the subglacial topography from ice surface data (e.g., Bell et al., 2007; Bell, 2008; Jamieson et al 2016);~~Stable deep water subglacial lakes have been identified using airborne radio echo sounding (RES) (e.g., Robin et al., 1970; Popov and Masolov, 2003)~~;~~ and/or ground-based RES (e.g., Rivera et al., 2015).

Previous work in the ESH area identified Subglacial Lake Ellsworth (SLE) and Subglacial Lake CECs (SLC) (Figure 1) by interpreting specular basal reflections in RES data as an indicator of deep (>10 m) subglacial water (e.g., Siegert et al., 2004a; Rivera et al., 2015) and although Vaughan et al. (2007) identified other potential subglacial lakes near SLE, none of these candidates were quantitatively confirmed and they were not included in the last subglacial lake inventory (Wright and Siegert, 2012). Subglacial Lake Ellsworth's water depth, geometry and lake floor sediments were characterised using seismic reflection surveys (Woodward et al., 2010; Smith et al., 2018). SLE and SLC are components of a subglacial hydrological network in the upper reaches of multiple West Antarctic ice streams and in the ESH (e.g., Vaughan et al., 2007). However, despite the evidence of subglacial water, and a potential subglacial network connecting multiple subglacial water bodies, ~~is not fully understood~~ many hypotheses remain untested in terms of subglacial ~~hydrological~~ hydrology dynamics. Given the fact that this region is located up-ice of the fastest-changing ice streams in the world (~~e.g.~~ i.e. Pine Island Glacier and Thwaites Glacier),

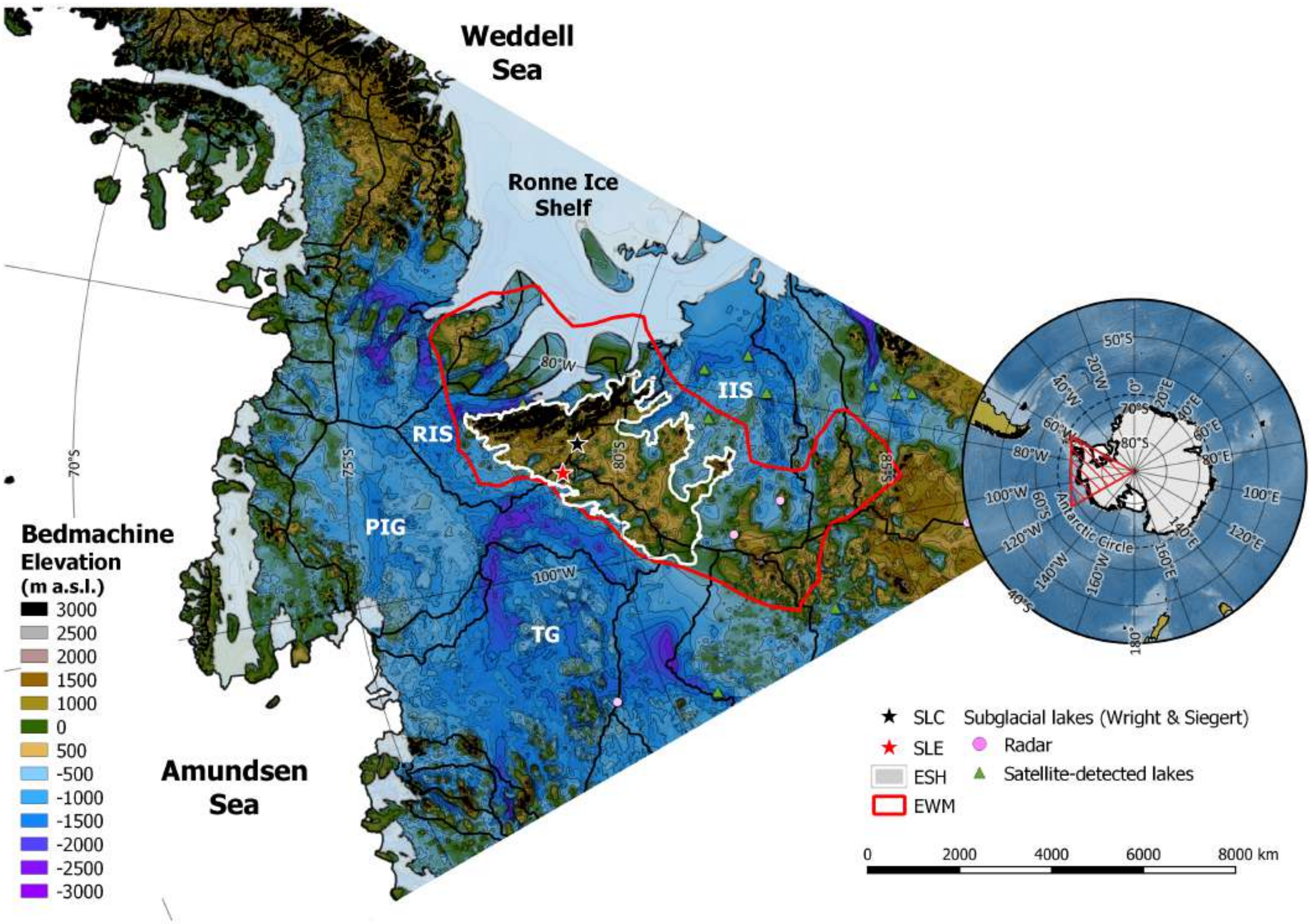

Figure 1. The distribution of West Antarctic subglacial lakes between 60°W and 120°W (Wright and Siegert, 2012). EWM: Ellsworth-Whitmore Mountain (in red, polygon from Jordan et al. (2013)); ESH: Ellsworth Subglacial Highlands (in white); Black lines: catchment boundaries produced using data from the SCAR Antarctic Digital Database (https://www.add.scar.org/). ; TG: Thwaites Glacier; PIG: Pine Island Glacier; RIS: Rutford Ice Stream; IIS: Institute Ice Stream. In the background is Bedmachine elevation model (500 m) (Morlighem et al., 2019), with contour lines every 500 m. Projection: Antarctic Polar Stereographic (EPSG 3031).

and that they are some of the most vulnerable glaciers to ongoing climate change ~~Martin et al., 2019~~ (e.g., Rignot et al., 2014, 2019; Joughin et al., 2014), a more detailed study of the subglacial hydrological system using existing RES data is of particular importance. Our aim is to produce an inventory of subglacial lakes for the ESH, and to model the modern subglacial hydrology in the ESH draining towards the ASE. We then assess the connectivity of these new subglacial lakes and the potential drainage flow of the ~~ice~~ basal water to the edge of the ~~continent~~ grounded ice sheet.

2 Methods

During the 2004/2005 austral summer the British Antarctic Survey collected $\sim 35,000$ km of airborne RES data (Vaughan et al., 2006), mostly over the catchment of ~~PIG~~ Pine Island Glacier (PIG) (Figure 5), during the Basin Balance and Synthesis (BBAS) aerogeophysical survey (Vaughan et al., 2006). The survey aircraft was equipped with dual-frequency carrier-phase GPS for navigation, a radar altimeter for surface mapping, magnetometers and a gravimeter for potential field measurements and the Polarimetric radar Airborne Science INstrument (PASIN) ice-sounding radar system (Vaughan et al., 2006, 2007; Corr et al., 2007). The radar system was configured to operate with a transmit power of 4 kW around a central frequency of 150 MHz. A 10-MHz chirp pulse was used to successfully obtain bed-echoes through ice more than 4200 m thick (Vaughan et al., 2006). Here, we use the radar data processed as a combination of coherent and incoherent summation without SAR processing to obtain ice-bed interface information (Vaughan et al., 2006). We analyse ~~a subset of this data-set~~ the available BBAS data from 2004/2005 to characterize the bed conditions of the northern margin of the ESH. We focus on three main tasks: first, identifying subglacial water at the ice base; second, defining and characterizing the modern subglacial hydrological network; and third, simulating the subglacial flow routing. We identify subglacial lakes by analysing the power of the reflected energy from the ice-bed interface ~~(Bed Reflection Power or BRP, Gades et al. (2000)) using four steps. We use the radar data to identify bright reflections underneath the ice (Section 2.1) and then we correct the ice attenuation of the radar power to obtain absolute reflections (Section 2.2). We then classify the identification confidence of each potential water body (Section 2.4) according to the methodology of Carter et al. (2007). Lastly, we analyse the hydraulic potential and ice surface slope of each bright reflection (Section 2.6).~~ (Gades et al., 2000), i.e. Bed Reflection Power or BRP, using four steps:

1. We use the radar data to identify bright reflections underneath the ice (Section 2.1).
2. We correct the ice attenuation of the radar power to obtain absolute reflections (Section 2.2).
3. We classify the identification confidence of each potential water body (Section 2.4) according to the methodology of Carter et al. (2007).
4. Lastly, we analyse the hydraulic potential and ice surface slope of each bright reflection (Section 2.6).

2.1 Identification of subglacial lakes

Nearly 7500 km of the BBAS airborne radar (i.e. flight lines: B01, B02, B03, B05, B08, B09, B22, T04) data were analysed to identify high amplitude basal reflections potentially associated with a subglacial lake signature. A preliminary qualitative approach allowed us to identify a variety of bright surfaces at the base of the ice sheet. ~~These reflections were then quantitatively analysed to determine the BRP in order to classify them as potential subglacial lake candidates, saturated sediments and/or smooth surfaces following previous methods (e.g., Robin et al., 1970; Oswald and Robin, 1973; Popov and Masolov, 2003; Siegert, 2005; Rivera et al., 2015)~~ Following previous methods (e.g., Robin et al., 1970; Oswald and Robin, 1973; Popov and Masolov, 2003; Siegert, 2005; Rivera et al., 2015), these reflections were then quantitatively analysed to determine the BRP in order to classify them as potential subglacial lake candidates, saturated sediments and/or smooth surfaces. We looked for lake candidates that satisfy the following five criteria:

1. Ice surface above subglacial lake candidate must be smooth and planar (Kapitsa et al., 1996; Siegert, 2005).
2. The ~~potential water surface should incline at~~ subglacial lake candidate reflection should have a slope ~ 11 times magnitude opposite to the ice surface slope (Oswald and Robin, 1973).
3. There should be a ~~constant hydrological low~~ flat hydraulic potential along the length of the lake (Vaughan et al., 2007).
4. The lake should have BRP values that are significantly higher than the surrounding surface return (15-20 dB) Siegert (2000).
5. There should be a low amplitude strength variation (specularity) of the ice-water interface (i.e. < $3dB\sigma$ ~~BRPr~~ BRP). We followed previous approaches (e.g., Carter et al., 2007) to obtain a specularity proxy using the dispersion of the Bed Reflected Power measured (BRPm). We then used a threshold of 3 dB σ to define a specular surface over all the sublglacial lake candidates.

2.2 Bed Reflection Power (BRP)

The returned power measured, $BRPm$, from the ice/bed interface is computed within a defined sampling window using eq.1.

$$BRPm = \frac{1}{n_{\mathbf{2}} - n_{\mathbf{1}} + 1} \sum_{n=n_1}^{n_2} s_{\mathbf{n}}^2 \tag{1}$$

where $s_{\mathbf{n}}$ is the amplitude (V) of the signal, and $n_{\mathbf{1}}$ and $n_{\mathbf{2}}$ defines the samples number in the calculation window.

To distinguish the potential lakes from their surroundings,~~the normalized depth-corrected BRP was computed for the BBAS data~~ we use a normalized depth-corrected BRP over each candidate lake.~~following previous studies (e.g., Gades et al., 2000; Jacobel et al., 2009; Matsuoka et al., 2012; Schroeder et al., 2016; Young et al., 2016)~~ We calculate the BRP following previous studies (e.g., Gades et al., 2000; Gacitúa et al., 2015), as the ratio of the locally measured power of the basal echo ($BRP_{\mathbf{m}}$) to the energy ~~estimated from the ice thickness and the empirical fit~~ corrected by geometrical spreading and ice attenuation loss ($BRP_{\mathbf{e}}$):

$$BRP = \frac{BPR_{\mathbf{m}}}{BRP_{\mathbf{e}}} \tag{2}$$

~~In calculating the BRP we account for the geometrical spreading ($L_{\mathbf{g}}$), attenuation loss ($L_{\mathbf{t}}$), and system gains ($L_{\mathbf{i}}$) encountered during the survey. In addition, we account for the height of the airborne BBAS system over the ice surface and for the ice thickness. The $BRP_{\mathbf{e}}$ quantification was adopted from previous work (e.g., Bentley et al., 1998). A simplified version of the model can be written as follows:~~

$$\underline{BRP_{\mathbf{e}} = (P_{\mathbf{tx}} + G_{\mathbf{a}} + G_{\mathbf{ant}}) - (L_{\mathbf{g}} + L_{\mathbf{i}} + T_{\mathbf{ai}})}$$

Here $P_{\mathbf{tx}}$ is the power emitted by the radar energy source, $G_{\mathbf{a}}$ corresponds to the gain of the receiver without including the antenna gain; $G_{\mathbf{ant}}$ is the gain of the antenna (Heliere et al., 2007), and $T_{\mathbf{ai}}$ is the transmission coefficient at the first interface (air-ice). $L_{\mathbf{g}}$, is the geometrical spreading loss; $L_{\mathbf{t}}$, is the ice attenuation loss. These latter parameters are modelled separately and substituted into (3) for each subglacial lake candidate.

In this study, we used as a general expression for the estimated power, $BRP_{\mathbf{e}}$, the eq. 3 (e.g., Gacitúa et al., 2015):

$$BRP_{\mathbf{e}} = P_{\mathbf{tx}}\, G\, L_{\mathbf{g}}\, T_{\mathbf{ai}}^2\, L_{\mathbf{i}}^2\, R_{\mathbf{ib}} \tag{3}$$

where $P_{\mathbf{tx}}$ is the transmitted power; G, is the system gain; and $L_{\mathbf{g}}$, geometrical spreading losses. Additionally, the transmission coefficient at the air/ice interface is defined as $T_{\mathbf{ai}}$; and the reflection coefficient of the ice/bedrock interface as $R_{\mathbf{ib}}$. Lastly, $L_{\mathbf{i}}$ represents the ice attenuation loss.

The geometrical spreading loss ($L_{\mathbf{g}}$) is calculated after Bentley et al., (1998) as: We then calculated the geometrical spreading loss ($L_{\mathbf{g}}$) modifying the original approach by Bentley et al. (1998) as:

$$L_{\mathbf{g}} = \frac{(G_{\mathbf{ant}}\lambda)^2}{[8\pi(h_{\mathbf{a}} + \frac{h_{\mathbf{i}}}{\sqrt{\varepsilon_{\mathbf{i}}}})]^2} \tag{4}$$

where $G_{\mathbf{ant}}$ is the antenna gain (11 dBi), λ is the wavelength of the radar signal at the air medium (1.935 m), and $h_{\mathbf{a}}$ is the height of the antenna above the ice surface (values taken from Corr et al. (2007)). $h_{\mathbf{i}}$ is the ice thickness, derived from BBAS ice thickness picks, and $\varepsilon_{\mathbf{i}}$ is the relative dielectric permittivity of ice (3.188) (Glen and Paren, 1975).

For each section of radar profile, we compute the ice attenuation loss, calculating a depth-averaged attenuation rate. In this approach we use an empirical relationship between the ice thickness ($Z_{\mathbf{s}}$) and the BRP, and then normalize the received power to a constant depth (jacobel et al., 2009) (Figure 2). For each section of the radar profile with a subglacial lake candidate, we quantify the ice attenuation loss ($L_{\mathbf{i}}$) following previous studies (e.g., Winebrenner et al., 2003; MacGregor et al., 2007; Matsuoka et al., 2012; Schroeder et al., 2016) on a 'section' by 'section' basis. We first use an empirical relationship between the ice thickness ($Z_{\mathbf{s}}$) and BRP; and we then apply a depth-averaged attenuation rate to correct for the power loss (Figure 2). To calculate the Bed Reflection Power estimated (BRPe) we substitute the $L_{\mathbf{g}}$ calculation and the $L_{\mathbf{i}}$ estimation into eq. 3.

2.3 Specularity calculation

In this work we use theThe standard deviation (σ) of the BRP was used as a proxy to determine infer how specular the surface of each potential water body is (Carter et al., 2007). This was is used as a threshold to determine whether the surface of each subglacial lake candidate was smooth or rough is smooth or not (Peters et al., 2005). The standard deviation (σ) was calculated within 40 samples around 20 samples either side of a particular point, i.e. ~400 m each side, to ensure a representative number of radar observations are included. A low value of σ indicates a smooth surface is present at the base of the ice as would be expected for the surface of a water body (Rivera et al., 2015; Gacitúa et al., 2015; Carter et al., 2007; Bowling et al., 2019).

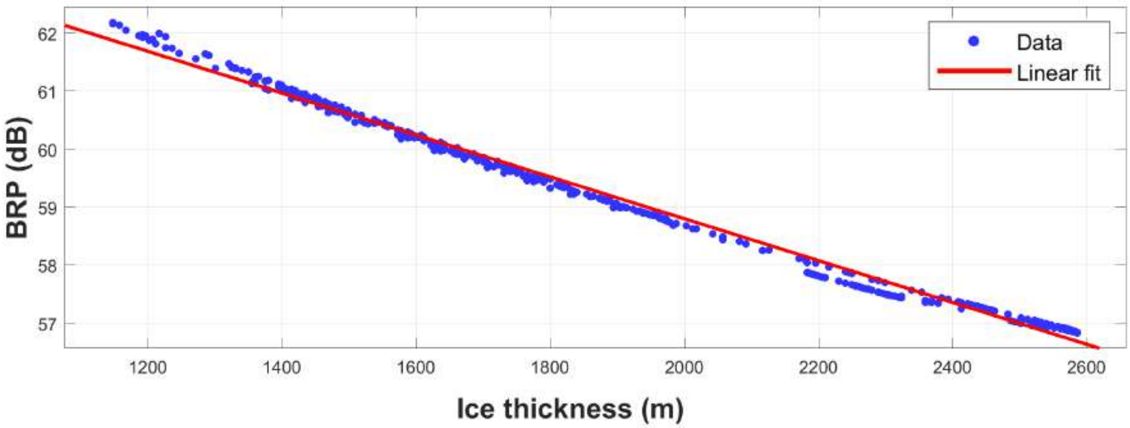

Figure 2. Example of the ice-attenuation correction for a radar line window of PASIN radar data (BBAS line B01: SL2 in Fig.7). linear fit: the red line is a log of normalized power representing the BRP dependency to ice thickness.

(e.g., Peters et al., 2005; Carter et al., 2007).

2.4 Subglacial Lake classifications

Having identified the candidate subglacial lakes, we determine the degree of confidence in our identification by ranking them from the most to least likely to be a subglacial lake. To achieve this we initially use the BRP values for each lake candidate following previous work (Carter et al., 2007), comparing these values to already known subglacial water bodies such as Subglacial Lakes Ellsworth, CECs and Vostok. This leads to a suite of four physically-based categories to which each potential subglacial lake is assigned, ranging from definite to indistinct as follows:

1. **Definite subglacial lakes**. This category has an absolute reflectivity higher than the surroundings (BRP 15db higher) and displays a low variation in the BRP (high specularity: < 3 dBσ ~~BRPr~~ BRP). Therefore, this category is defined by a high absolute reflection power and a low standard deviation (σ) across the subglacial lake candidate surface ~~, and a flat hydraulic surface~~.

2. **Dim subglacial lakes**. These candidates have a high relative reflection strength and surface specularity, but lack the absolute reflectivity values of definite lakes in that their BRP is no more than 10db higher than the surroundings.

3. **Fuzzy subglacial lakes**. These candidates show higher relative and absolute reflection coefficients than the surroundings, but are not specular along their surfaces (i.e. $> 3\sigma$ BRP). We note that a challenge with such candidates is that they could also potentially be interpreted as saturated basal sediments. (Dowdeswell and Siegert, 2003; Peters et al., 2005; Siegert, 2000). In addition, if the water is less than 8 m deep, reflections from the water-lake bottom interface may interfere with

the signal from the ice-water interface (Gorman and Siegert, 1999). Furthermore, exceptionally smooth surfaces with no water present could also have similar signal characteristics to these fuzzy subglacial lakes (Carter et al., 2007).

4. **Indistinct subglacial lakes**. This category is composed of lake candidates that are specular but ~~are~~ their reflectivity is difficult to distinguish from the surroundings. Although these could still represent subglacial lakes, such characteristics are also common to transient water systems or to exceptionally smooth beds with fine grained sediments surrounded by rougher saturated sediments (Carter et al., 2007).

2.5 ~~Subglacial Lake dimensions~~

~~To measure the size of the water bodies we calculated the length of the bright reflector in each radargram associated with a potential subglacial lake. We then selected each trace within the potential subglacial lake radar window and visualised it in a GIS software to examine its spatial extent. We consider the spatial extent as being either a minimum or maximum lake length since we do not know the full 2-dimensional shape of the water body due to the reconnaissance nature of the airborne survey. For each subglacial lake we then estimated the area in two different ways:~~

1. ~~Assuming a circular shape with a radius equal to half of the lake length.~~

2. ~~Assuming an elliptical shape and using the length of the trace as either the width (a) or the length radius (b). We then use SLE and SLC, as trough-confined examples of subglacial lakes, to obtain an average of the a:b ratio (i.e. ∼4:1) and we calculate the area in each case.~~

~~Using the method proposed by Dowdeswell and Siegert (1999), we estimated the depth by extrapolating the observed side-slope topography at the margin of each subglacial lake (Figure 3)~~.

2.6 Hydropotential (Φ) calculation

To determine the subglacial hydrological characteristics of the EWM region we produced a new bed Digital Elevation Model (DEM). We use existing gridded bed elevation data from: BedMap2 (Fretwell et al., 2013); ice thickness measurements from DELORES (2007-2009) and CECs (2005/2006) (Siegert et al., 2012); new along-track ice thickness measurements from the 2014 CECs RES campaign (Rivera et al., 2015); and new unpublished radar measurements from the CECs 2017 RES field campaign in ESH region (Zamora et al., 2019; Uribe et al., 2019). In January 2014 radar data collected by CECs over an area of ∼7000 km^2 were acquired with a line spacing of ∼8 km, completing a total of ∼1100 km. The survey during December of the same year was collected over a nested grid around the SLC and along the host trough further north towards RIS, surveying a total of ∼1050 km. During December 2017 the CECs radar survey measured a total of ∼700 km along the same trough where SLC is located (Figure 3).

We use a 2 km grid mesh with a continuous curvature tension spline algorithm (Paxman et al., 2017; Wessel et al., 2013) to grid the data. We masked the grid to remove interpolated values more than 5 km from the nearest measured data point, and replaced them with BedMap2 bed elevation values. Since BedMap2 has a resolution of 1 km, we used the nearest neighbor

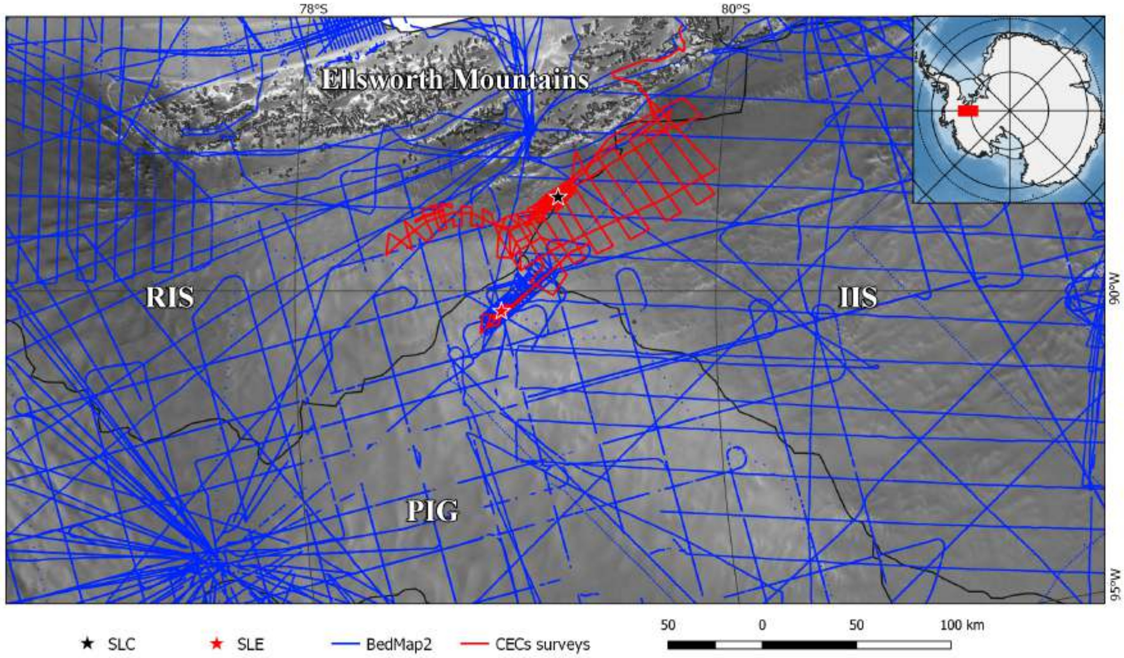

Figure 3. Coverage of data sets used in the construction of the Bed Digital Elevation Model. Blue lines shows radar lines from BedMap2; Black lines: catchment boundaries produced using data from the SCAR Antarctic Digital Database (https://www.add.scar.org/). Projection: Antarctic Polar Stereographic (EPSG 3031).

algorithm to downsample the DEM cell size to 2 km. We also masked the ice shelves from the radar measurements and replaced these values with those from BedMap2 to obtain offshore bathymetry. The 1 km resolution CryoSat2 ice surface DEM (Slater et al., 2018) was down-sampled to 2 km to match the new bed DEM using the nearest neighbor routine. This enabled us to use the ice surface elevation and subglacial bed to determine the hydrological head, Φ, following Shreve (1972).

At the ice sheet bed, water flows in the direction of steepest descent of the hydraulic potential. Hydropotential ($\Phi_\mathbf{h}$) is the sum of the water pressure, P_w (Pa), and water density, $\rho_\mathbf{w}$ (1000 and 1020 kg m^{-3}for fresh and sea water, respectively), normalized by gravitational acceleration, **g** (9.8 m s^{-2}) and the water system bed elevation, Z (m) (e.g., Shreve, 1972; Cuffey and Paterson, 2010; Livingstone et al., 2013) as follows:

$$\Phi = P_\mathbf{w} + \rho_\mathbf{w}\, g\, Z \quad (5)$$

Equation 5 can usefully be rewritten into an alternative equation in terms of subglacial bed and ice surface elevation (Shreve, 1972).

$$\Phi = \rho_\mathbf{w}\, g\, Z + k\, \rho_\mathbf{i}\, g\, H \quad (6)$$

where $\rho_\mathbf{i}$ is the density of ice (917 kg m^{-3}), H is the ice thickness (m) and k is a dimensionless factor, representing the influence of ice overburden pressure on the local subglacial water pressure.

Assuming the water pressure is close to the ice overburden pressure (k ∼ 1) from seismic and borehole observations (e.g., Blankenship et al., 1986, Tulaczyk et al., 2001) We assumed the water pressure is close to the overburden ice pressure as suggested for Ellsworth Subglacial Highlands in previous studies (e.g., Vaughan et al., 2007; Rivera et al., 2015), so equation 6 can be rearranged as follows:

$$\Phi = \rho_{\mathbf{w}}\, g\, Z + \rho_{\mathbf{i}}\, g\, H \tag{7}$$

This approach has been widely used across Antarctica to model the subglacial hydrological drainage (e.g., Livingstone et al., 2013; Carter et al., 2017; Kirkham et al., 2019).

2.7 Subglacial water flow routing

Since subglacial water tends to moves from areas of high to low subglacial water pressure, following the hydropotential (Φ) gradient (Shreve, 1972), we can determine present-day large-scale subglacial flow routing and identify whether the candidate subglacial lakes connect into this subglacial hydrological network. We modelled the subglacial flow routing using the hydropotential (Φ) and followed Schwanghart and Scherler (2014) to calculate the flow routing using the following steps:

1. Lows (sinks) in hydropotential (Φ) were filled to their lowest pour point.

2. The channelized network was then determined using a multiple flow direction (MFD) algorithm (Schwanghart and Scherler, 2014). The subglacial hydraulic drainage basin was then delineated, and we computed the flow accumulation in order to understand the upstream contributing area above the lakes.

3. The stream network was then defined using an up-slope area threshold for channel initiation. We set an arbitrary threshold of 50 25 connected cells (100 50 km^2) as defining a channel.

3 Results

3.1 New bed elevation model

The new bed DEM of the ESH provides new detail on two major subglacial troughs and shows that they are much deeper than shown in existing DEMs (e.g. BedMap2 and BedMachinev1): Ellsworth Trough (ET) and a parallel trough east of ET, informally referred to here as CECs Trough (CT) (Figure 4). These troughs extend parallel to the Ellsworth Mountains and are extensive linear features that appear to connect the interior of the ESH to the deep basins that lie beneath the WAIS. These are a common feature within the ESH and likely reflects a topography which has evolved under conditions of alpine erosion and, before glacial inception, fluvial erosion (Jamieson et al., 2014; Sugden et al., 2017; Vaughan et al., 2007; Ross et al., 2014) steered by tectonic influences. This area may have been subject to a mix of areal scour and selective linear erosion beneath the WAIS (e.g., Jamieson et al., 2014; Sugden et al., 2017; Paxman et al., 2019). The main difference from BedMap2 and

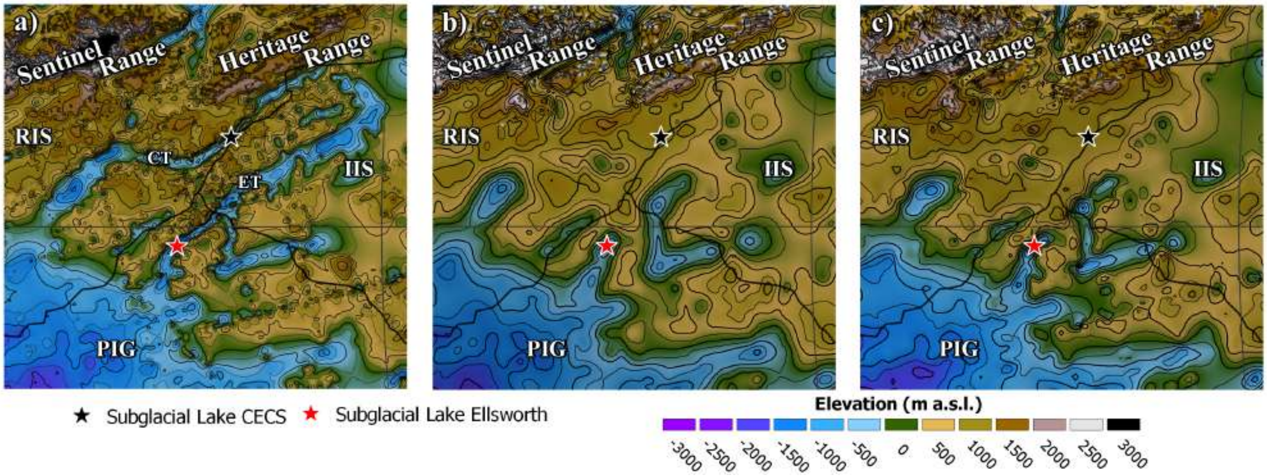

Figure 4. Comparison between three different bed Digital Elevation Models. a) New DEM gridded in this work; b) BedMap2 DEM; c) BedMachine Antarctica v1. White lines show the catchment boundaries produced using data from the SCAR Antarctic Digital Database (https://www.add.scar.org/). ET: Ellsworth Trough; CT: CECs Trough; RIS: Rutford Ice Stream; PIG: Pine Island Glacier; IIS: Institute Ice Stream. Projection: Antarctic Polar Stereographic (EPSG 3031).

BedMachine Antarctica v1 are the two parallel subglacial troughs that run from IIS to RIS and PIG, and a subglacial range between the new troughs with a perpendicular transection valley near SLE (Figure 4). In Figure 4, we compare these new features in our DEM against BedMap2 and BedMachine Antarctica v1.

3.2 Subglacial lakes

Using qualitative ~~viewing~~ visual analysis of the BBAS radar data, we identified 107 bright reflections potentially caused by subglacial lakes within the BBAS dataset (Figure 5). These reflections were further analysed by comparing the characteristics of these features with other Antarctic subglacial lakes (Siegert, 2005; Carter et al., 2007) in order to either confirm or reject each feature as a subglacial lake (Figure 6).

The lakes are largely distributed within a series of subglacial valleys that emerge from the ESH into the Bentley Subglacial Trench near the ice divide between PIG, RIS and IIS at the northern edge of the ESH (Figure 7). We observe two clusters of subglacial lakes and one potential chain of subglacial lakes in the ESH region. The first cluster is near SLE, <100 km from the ice divide between IIS, RIS and PIG (Figure 8a). Most of the subglacial lakes in this first cluster are located in ~~the same trough as SLE~~ ET, or are connected to the same trough system. However, in some cases the drainage of subglacial water in this cluster may be in two distinct directions, i.e. towards Weddell Sea Embayment (WSE) or ASE (Figure 8c). The second cluster is located in a valley upstream of the PIG catchment near the water divide between ASE and WSE Sea (Figure 8b). In this cluster, the hydraulic modelling suggests the lakes connect and drain into the modern hydrological network flowing towards the WSE (Figure 8d). The chain of subglacial lakes is in a trough located upstream of IIS and PIG, less than 50 km from the

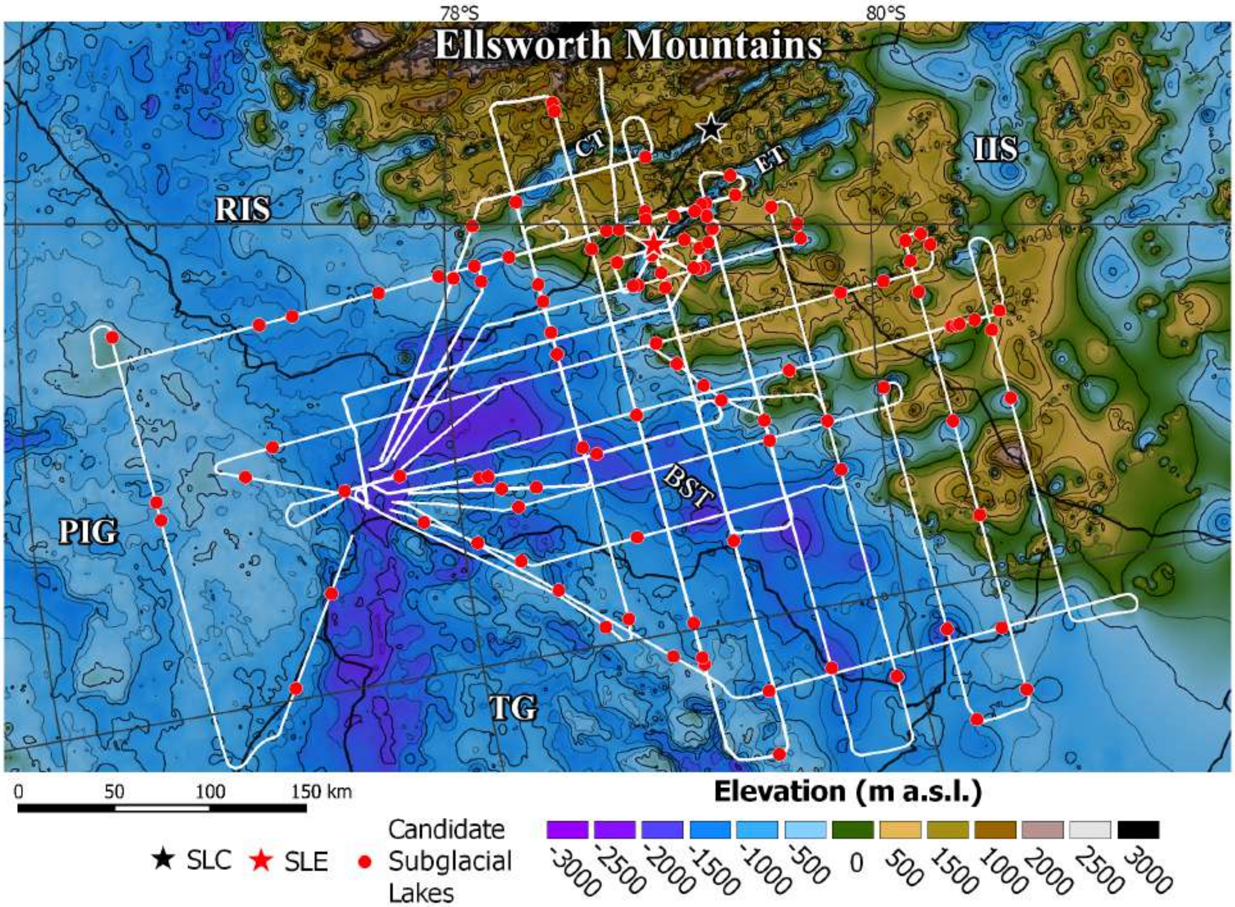

Figure 5. Qualitative analysis of high amplitude reflection (blue circles) identified using eight flight lines of the BBAS radar set. The black and red star show the position of Subglacial Lake CECs (SLC) and Subglacial Lake Ellsworth (SLE), respectively. The red star also marks the radar section shown in Figure 6. Data from the BedMachine Elevation model (500 m) (Morlighem et al., 2019) is shown in the background. White lines show the 7500 km of analysed BBAS radar lines. Black lines: catchment boundaries produced using data from the SCAR Antarctic Digital Database (https://www.add.scar.org/). ET: Ellsworth Trough; CT: CECs Trough; RIS: Rutford Ice Stream; PIG: Pine Island Glacier; TG: Thwaites Glacier; BST: Bentley Subglacial Trench; ~~BIS: Bindschadler Ice Stream;~~ IIS: Institute Ice Stream. Projection: Antarctic Polar Stereographic (EPSG 3031).

ice divide. These subglacial lakes are in between ET and the valley that hosts the second cluster of lakes, near the PIG-IIS ice divide (Figure 8b). Furthermore, the subglacial hydrological simulation also shows that part of the drainage flowing beneath the PIG is diverted to flow beneath Thwaites Glacier (TG), collecting the water of these ice catchments and draining to the ASE.

Using the quantitative analysis of the bed reflectivity at 107 sites, and classifying accordingly, we confirm the presence of ~~37~~ 33 previously unrecognised subglacial lakes (Supplementary information: Table 1), which is a ∼40% increase in the

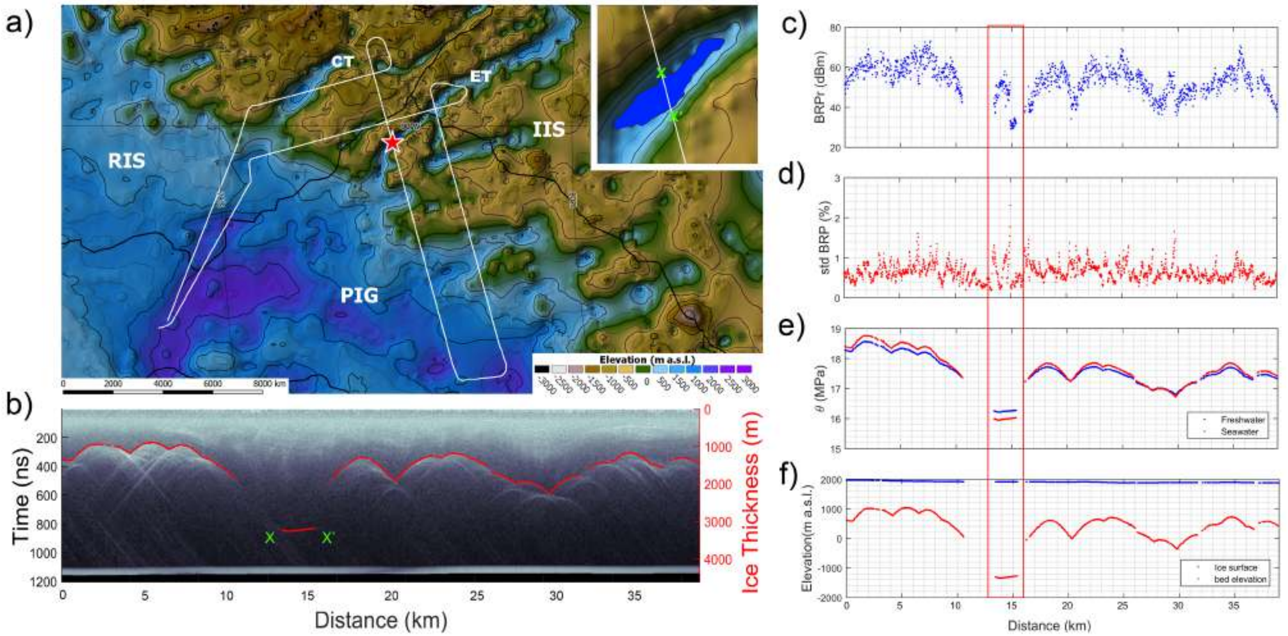

Figure 6. Example of subglacial lake identification in a radargram from the BBAS survey (Flight line B05) and its location in WAIS. a) Shows the location of the flight line (B05, white-line) and the position of the radargram (red star) in the line overlain on the new subglacial DEM (2 km). Ice catchment boundaries produced using data from the SCAR Antarctic Digital Database (https://www.add.scar.org/) are shown in black. The inset on 'a' shows the Subglacial Lake Ellsworth bed topography contour, and the portion highlighted in green represents the subglacial lake in 'b'. ET: Ellsworth Trough; CT: CECs Trough; RIS: Rutford Ice Stream; IIS: Institute Ice Stream; PIG: Pine Island Glacier. Projection: Antarctic Polar Stereographic (EPSG 3031). b) Shows the bright reflection (red line) classified as a subglacial lake. The radargram is corrected for elevation and shows both the time (ns) for the returned echo from the ice/bed interface (Y1) and the ice thickness (m) calculated using a radio wave propagation through the ice of 0.168 m ns^{-1} (Y2). c) Bed Reflection Power (dBm). d) Specularity (σBRP). e) Hydropotential considering fresh (blue) and salt (red) water densities. f) Ice surface elevation (blue line) and bed elevation (red line).

total number of subglacial lakes known to exist beneath the WAIS (Wright and Siegert, 2012). Although a small number of these subglacial lakes were hypothesised or identified by other studies (e.g., Livingstone et al., 2013; Vaughan et al., 2007), none of these water bodies were included in the most recent subglacial lake inventory of Wright and Siegert (2012). Using the categories described above, we categorise these subglacial lakes into 4 groups with different confidence levels (Figure 7). We identify ~~16~~ 7 definite subglacial lakes (very high confidence), ~~13~~ 5 dim subglacial lakes (high confidence), ~~3~~ 20 fuzzy subglacial lakes (medium confidence) and ~~3~~ 1 indistinct subglacial lake (low confidence).

3.3 Distribution of subglacial lakes

The ESH hosts ~~28~~ 24 of the new subglacial lakes, 7 others are in the Bentley Subglacial Trench, and 2 lakes are located in the region of relatively high topography between tributaries 3 and 5 of PIG, between Byrd Subglacial Basin and the outlet of PIG

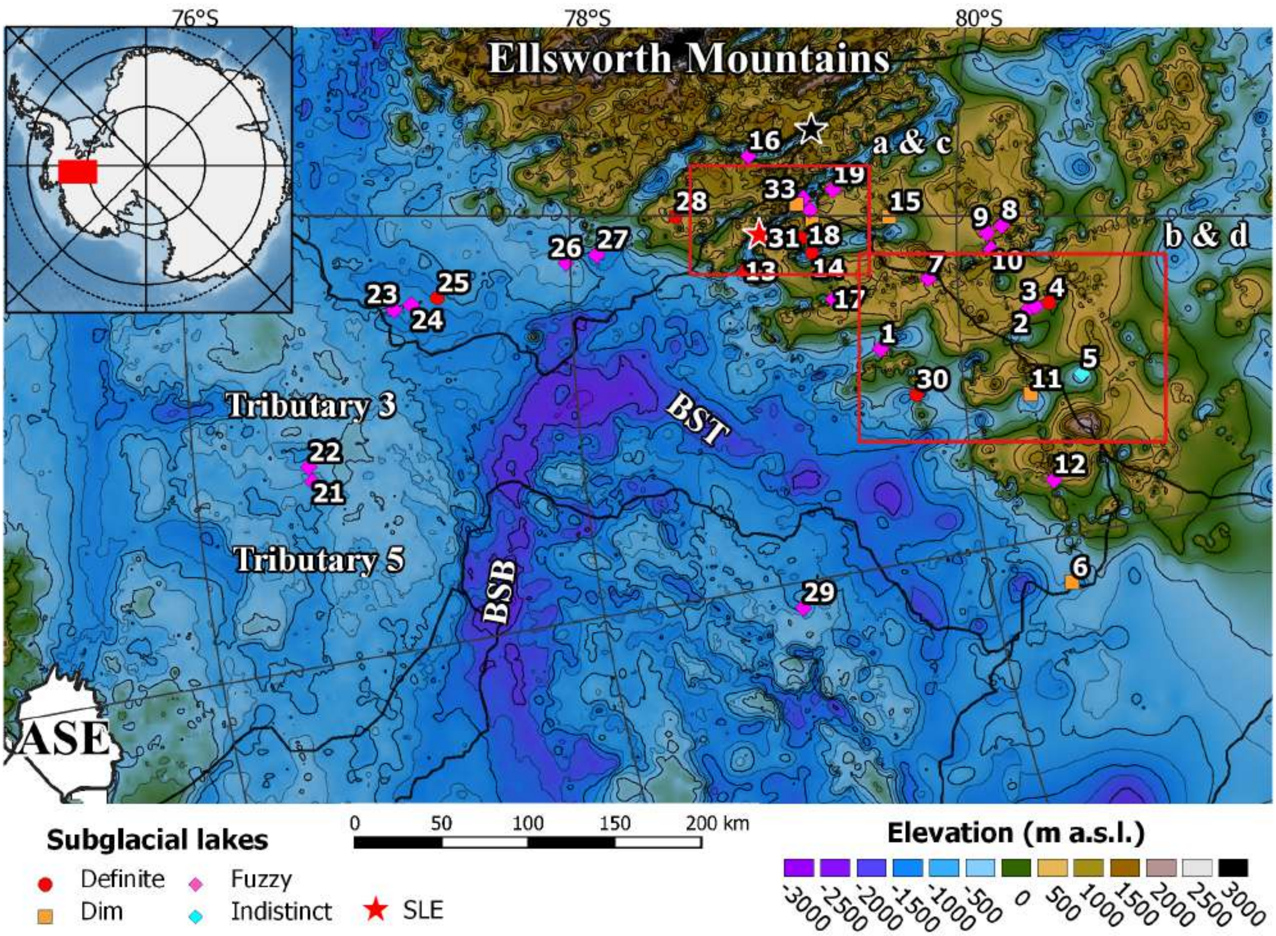

Figure 7. Location of subglacial lakes within the Ellsworth Subglacial Highlands. Inset: Location of ESH in Antarctica. The subglacial lakes are represented by different shapes and colours according to the classification of their BRP. The subglacial lakes are classified from a greater to a lesser degree of confidence, as follow: red dots for definite; yellow squares for dim; pink diamonds for fuzzy; and cyan diamonds for indistinct subglacial lakes. The black and red stars represent SLC and SLE, respectively. In the background the new subglacial DEM and the PIG tributaries are numbered according to the scheme given by Stenoien and Bentley (2000). Contours every 500 m. The red rectangle shows the location of panel a and b (also c and d) in Figure 8. Ice sheet boundaries produced using data from the SCAR Antarctic Digital Database (https://www.add.scar.org/) are shown in thick black lines. ASE: Amundsen Sea Embayment; BST: Bentley Subglacial Trench; BSB: Byrd Subglacial Basin. Projection: Antarctic Polar Stereographic (EPSG 3031).

(SL ~~28 and 29~~ 21 and 22 in Figure 7). The majority of these subglacial lakes (~~34~~ 30) are ~~very close to an~~ located less than 50 km from the ice divide and thirteen ~~most of them (15)~~ are located within 20 km from the ice divide between IIS and RIS (Figure 9a). ~~Most of the small (less than 3 km length) subglacial lakes (17) lie within 50~~ Sixteen small subglacial lakes (less than 3 km length) lie within 30 km of an ice divide, whereas the two largest subglacial lakes (~~SL 28-27-19~~ SL6 & SL23) are all located

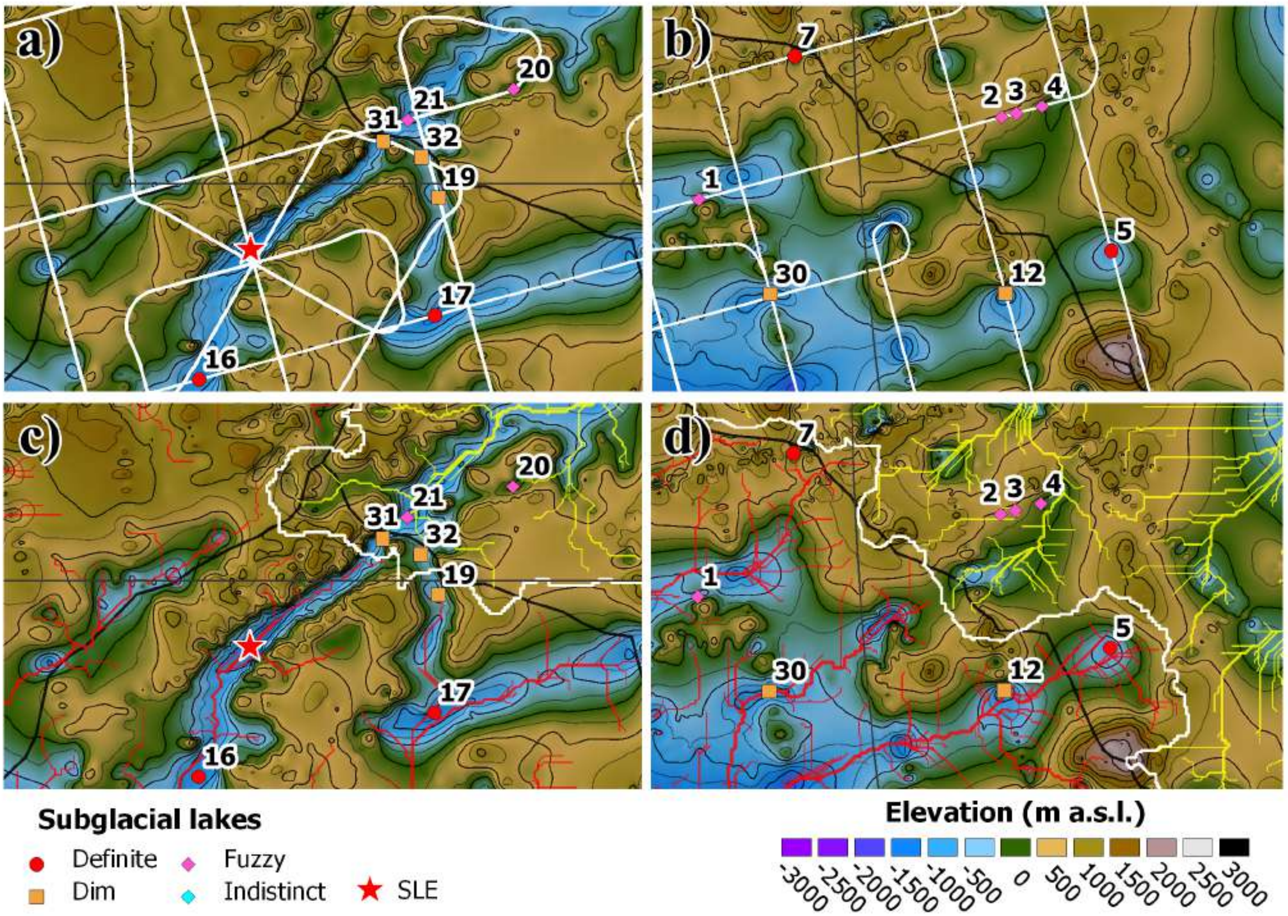

Figure 8. Two main subglacial lakes clusters: Ellsworth Trough and western ESH. The location of this cluster is delimited by red squares in Figure 7. a) First cluster of subglacial lakes in Ellsworth Trough. b) second cluster of subglacial lakes identified in upstream Institute area. The new subglacial DEM is shown in the background. In a) and b) white lines are airborne RES survey tracks. Elevation contours lines at 500 m intervals. c) and d) shows the subglacial water hydrological network, for the same areas of a) and b), plotted in different colours depending the flow direction. The red lines show modelled subglacial drainage towards Amundsen Sea Embayment; the yellow lines, drainage to the Weddell Sea Embayment.In c) and d) the white lines shows the subglacial water catchment boundaries and the thick black lines the ice sheet boundaries produced using data from the SCAR Antarctic Digital Database (https://www.add.scar.org/). Projection: Antarctic Polar Stereographic (EPSG 3031).

within 25 km of the PIG ice divide and $\sim$ 3 km, respectively. The ice thickness over ~~these~~ the small subglacial lakes is variable ~~and ranges~~ ranging from 1600 m to 4000 m with an average thickness of $\sim$ 2600 m (Figure 9b). ~~Few subglacial lakes (13)~~ Five subglacial lakes are covered by ice thicker than 3000 m thick and ~~even fewer (7)~~ ten lie underneath thinner ice (~~1500-2000 m thick~~ less than 2000 m thick). Most subglacial lakes associated with thinner ice columns are located south of the IIS-PIG ice

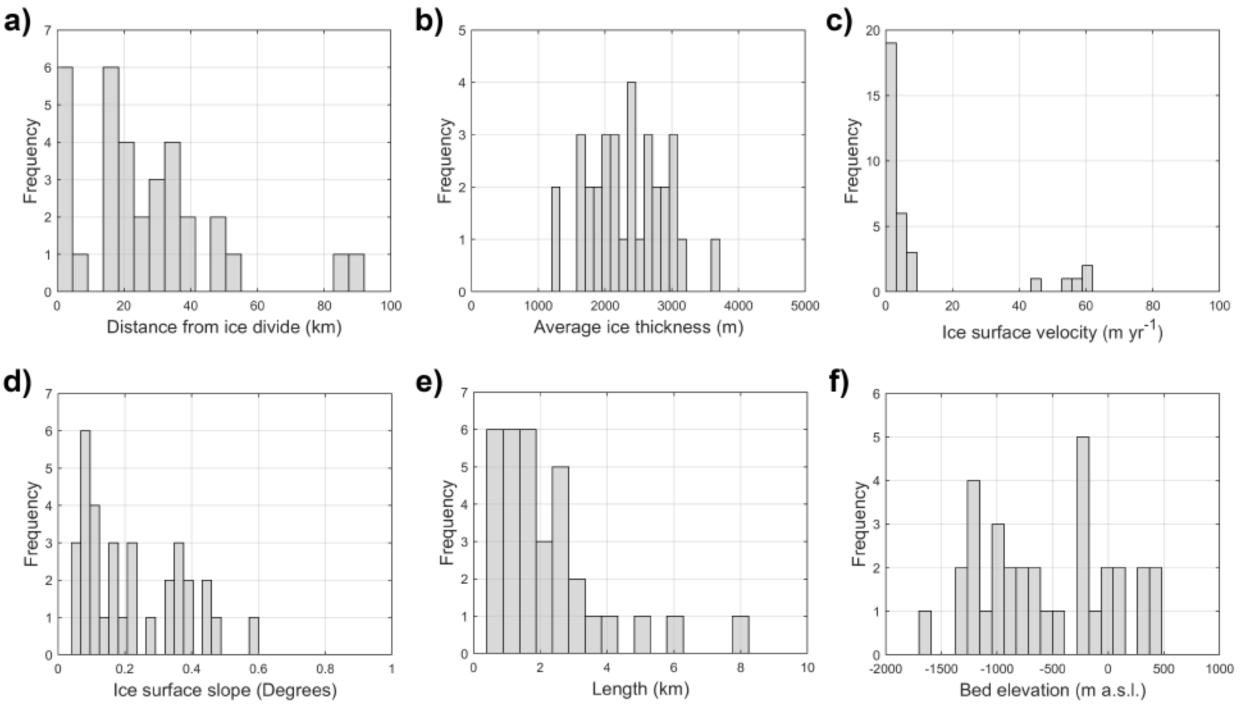

Figure 9. Frequency-distribution histograms of subglacial lakes identified in this study. a) Distance from major ice divides. b) Average ice thickness, obtained from BBAS ice thickness measurements.The blue line shows the regional distribution of the ice thickness in Antarctica (Fretwell et al., 2013) for a continental reference. c) Ice surface velocity (Mouginot et al., 2019). d) Ice surface slope, obtained using Cryosat-2 (Slater et al., 2018). e) Minimum length of identified subglacial lake, calculated by measuring the horizontal extent of the lake reflection. Subglacial lakes bed elevation (new DEM).

divide, while those underneath thicker ice columns are distributed at the head of PIG. The majority of subglacial lakes with an overlying ice thickness of between 2000 and 3000 m are situated close to the triple ice divide between IIS-RIS and PIG and along the border between PIG and RIS, where the ice surface slope is near zero (Figure 9d) and, hence, the subglacial hydraulic gradient is also close to zero. Those subglacial lakes located near the PIG-RIS-IIS ice divide, lie beneath very slow flowing ice (Figure9c and Figure 10). However, the ice surface velocity is higher (between 50 myr^{-1} and 60 myr^{-1} in 4 subglacial lakes) above those subglacial lakes located in lower topography (Figure 10). The location of the newly discovered subglacial lakes and the distribution of ice surface velocities are shown in Figure 10. The length of subglacial lakes is variable, ranging from a minimum of ~ 0.35 km to a maximum of ~ 8 km, but most of them (18) are less than 2 km in length (Figure 9e). Some of the subglacial lakes (13) are larger than 2 km and two of them (SL6 and SL23), near PIG ice divide (Figure 7), are relatively large lakes (~ 8 km). with a mean of ~ 4. In general, ice surface velocities over subglacial lakes is never higher than 60 myr^{-1} and most of the subglacial lakes (25) lie beneath ice flowing less than 6 myr^{-1} (Mouginot et al., 2019).

~~The new bed DEM of the ESH provides new detail on two key subglacial troughs and shows that they are much deeper than shown in existing DEMs (e.g. BedMap2 and BedMachinev1). These troughs extend parallel to the Ellsworth Mountains which faces the Weddell Sea and are extensive linear features that appear to connect the interior of the ESH to the deep basins that lie beneath the WAIS.Additionally, the DEM reveals that subglacial lakes are hosted within two different subglacial topographic contexts. Many exist in linear subglacial troughs with steep side walls. These are a common feature within the ESH and likely reflects a topography which has evolved under conditions of alpine erosion and, before glacial inception, fluvial erosion (Jamieson et al., 2014; Sugden et al., 2017; Vaughan et al., 2007) steered by tectonic influences. Other lakes are located within terrain with reduced relief and a mean elevation below sea level in an area constrained by subglacial hills (Figure 7). This area may have been subject to a mix of areal scour and selective linear erosion beneath the WAIS (e.g., Jamieson et al., 2014; Sugden et al., 2017; Paxman et al., 2019).~~

The new DEM reveals that subglacial lakes are located within two different subglacial topographic contexts: within linear subglacial troughs with steep side walls, and within lowland terrain constrained by subglacial hills (Figure 4).

~~Subglacial lakes located in the Ellsworth Trough (Ross et al., 2014), in a parallel trough to the west and in adjacent subglacial valleys lie beneath very slow flowing ice near the ice divide (Figure 9). In contrast, those located in are distributed along the head of TG, on tributaries 3 and 5 of PIG (SL 28 and 29 in Figure 9), in some topographic depressions beneath the PIG, and at the northern end of the Ellsworth Mountains beneath the RIS where there is currently a slightly higher annual average velocity than elsewhere in the ESH. In a small number of cases ($\sim 10\%$) however, some subglacial lakes located closer to the PIG outlet over the subglacial topographical barrier do have average overlying velocities close to 60 m/yr (Figure 10). Most of the subglacial lakes (26) are located within the subglacial trough system of the ESH.These subglacial lakes are variable in size but most of them (13) are larger than 2 km. This region also hosts SLC and SLE. In contrast, 11 of the total identified subglacial lakes are situated along the lowland terrain (below sea level) and are more uniform and larger in size (Figure 9c). Most of these subglacial lakes (21) are greater than 2 km in length and two (26 and 25) relatively large lakes ($\sim$ 15 km) are found in the Bentley Subglacial Highlands towards RIS (Figure 7) Analysis of the ice surface indicates mostly a flat area over the subglacial lakes and a maximum value < 1 degree (Figure 9d) above any of the subglacial lakes. Based on the assumptions about the shape of subglacial lakes (circular/elliptical) and extrapolation of the observed side-slope topography at the margin of the subglacial lakes, we estimate a total volume for circular shapes of $\sim$31km^3 (Supplementary information: Table 2) and either $\sim$125 km^3 or $\sim$8km^3 for elliptical shapes (depending on the use of radius a or b, respectively) stored in all the subglacial lakes, excluding SLE ($\sim$1.4 km^3, Woodward et al.(2010)) and SLC ($\sim$2.5 km^3, Smith et al. (2019).~~

3.4 Subglacial flow routing

The modern configuration of the ice sheet and the improved bed DEM allowed us to calculate a new hydropotential map around ESH. This hydropotential model suggest that the subglacial water catchment differs in shape to that previously calculated. The new hydraulic potential model suggests an increase of $\sim$1500 km^2 in the water catchment area of TG (in comparison with

BedMap2), mainly because the contribution of the newly discovered CT. Figures 4 show this difference in the shape of the subglacial water catchments. The water flow routing in the hydrological network initiates near the major ice divides in the region (i.e. RIS-IIS-PIG) and flows to the margin of the continent (Figure 7d and e). The hydraulic model assumes a wet bed throughout the ESH and the geometry of the subglacial hydrological network is classically dendritic. It extends almost from the major ice divide (RIS-IIS-PIG) to the ~~continental margin~~ edge of the ice sheet, connecting the majority (~~70%~~ i.e. 30 subglacial lakes) of the subglacial lakes identified in this work into a wider subglacial hydrological network. We identify 2 main drainage systems: WSE and ASE. There are ~~18~~ 15 subglacial lakes draining towards the WSE ~~one subglacial lake (dim) draining towards the Ross Sea~~ and ~~15~~ 18 draining towards the ASE. In ASE, most of the subglacial lakes are connected into a single drainage network flowing underneath PIG and TG, and partially beneath RIS. Only two subglacial lakes are disconnected from the main ASE drainage system: they originate near the border between RIS and PIG over the subglacial highland (SL28) and within a valley sub-parallel to ET (SL31). Only one subglacial lake, located in the upper catchment of IIS (SL10), is disconnected from WSE drainage system. ~~in the Bentley Subglacial Highlands and drain completely underneath PIG.~~ Significantly, we note that the surface flow patterns of ice and the flow patterns of subglacial water are not always co-incident. The most evident difference between hydrological and ice flow catchments are observed underneath the PIG-TG catchments (Figure 8c and 8d). Here, the ice flows from the PIG-IIS ice divide into the PIG catchment, however the subglacial drainage catchment flows first into the head of the PIG catchment and then diverts into the TG catchment. We find that the area of the subglacial hydrological catchments of PIG and TG are $\sim$1.35 x10^5 km^2 and $\sim$2.83 x10^5 km^2 respectively (and if calculated using BedMachine are $\sim$1.25 x10^5 km^2 and $\sim$2.88 x10^5 km^2 respectively) and that the ice surface catchment of PIG and TG have areas of $\sim$1.76 x10^5 and $\sim$1.86 x10^5 respectively (Mouginot et al., 2017).

We find that the majority of the known subglacial lakes in the region coincide with channels delineated in our subglacial hydraulic modelling. This gives additional confidence to the assessment of the lakes because it provides an indication that there would be upstream areas which might capture enough water to fill a lake, but also that the ~~channelization~~ routing would be appropriately directed to deliver that water into the lake positions. A challenge with the subglacial flow routing is that the bed DEM is based on sparse data due to the reconnaissance nature of the primary airborne RES data-sets across the study area. As a consequence, the spline interpolation and the use of potential field data to fill gaps in the DEM means that the routing is subject to uncertainty associated with overly smooth data in some areas, and potentially noisy data in others. The latter issue would have most influence in terms of potentially enabling streams to be diverted, but because we use tension spline interpolation we believe that noise is minimised.

4 Discussion

4.1 Subglacial lakes and the production of basal water

We have identified several bright basal reflections, which we interpret as West Antarctic subglacial lakes. Many of these are located at the head of the catchments of PIG and TG. Many of these subglacial lakes are found in the ESH very close to

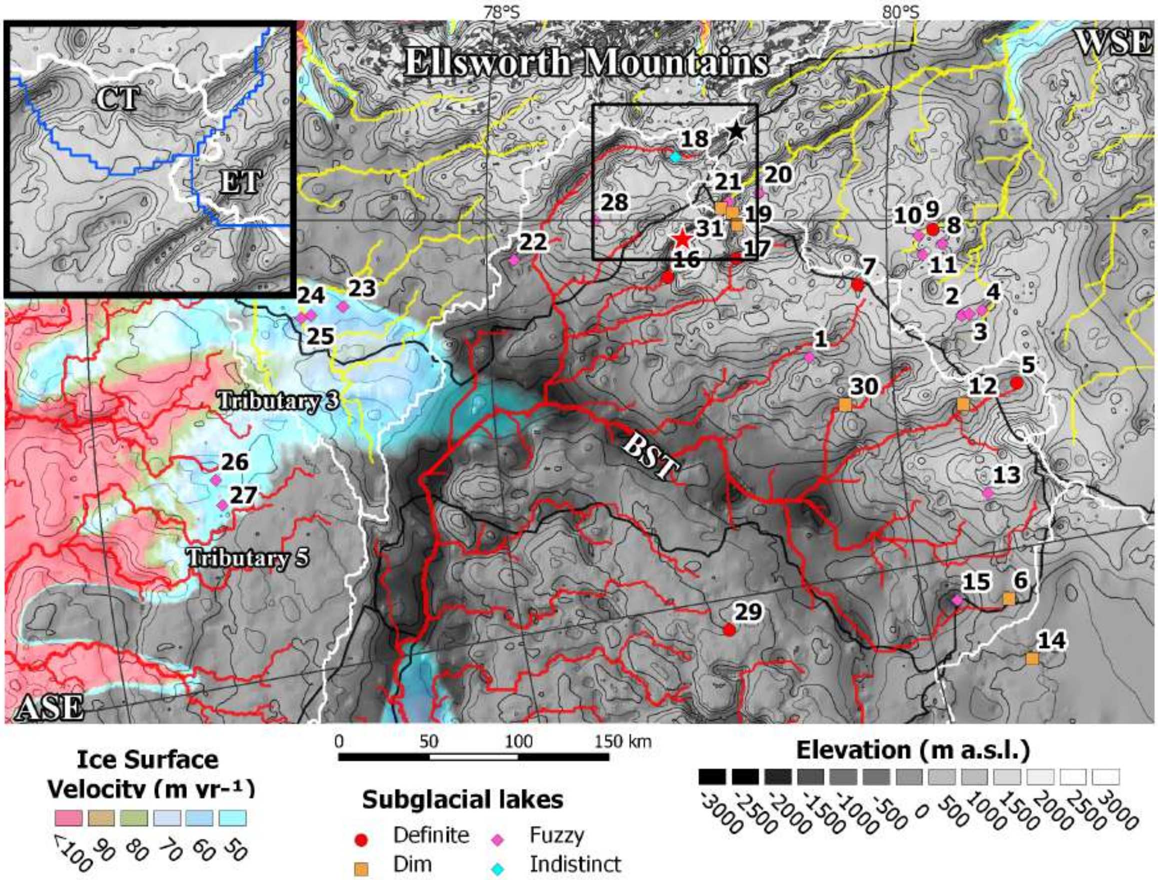

Figure 10. Mean annual ice surface velocity (Mouginot et al., 2019) of Pine Island Glacier, Rutford Ice Stream, Institute Ice Stream and Thwaites Glacier. The red lines show the subglacial water towards Amundsen Sea Embayment (ASE), while the yellow lines indicate the drainage towards Weddell Sea Embayment (WSE). The inset in the upper corner (black square in main panel), shows details in the water catchment boundary between ASE & WSE. ET: Ellsworth Trough; CT: CECs Trough~~Black line shows ice surface velocities higher than 250 myr^{-1}~~. The white line indicates the boundary of the water catchment (this work) and the blue line indicates the previous boundary (BedMap2). ~~The blue lines show the subglacial water drainage and the arrows indicates the general flow direction. The Cryosat-2 Elevation model (1 km), virtual hillshade (Helm et al., 2014)~~ Ice surface velocity (Mouginot et al., 2019) and the new DEM are shown in the background, with elevation contour every 500 m (thin black lines). Velocities lower than 50 myr^{-1} are not displayed. ~~ASE: Amundsen Sea Embayment; BSB: Byrd Subglacial Basin;~~ BST: Bentley Subglacial Trench. Projection: Antarctic Polar Stereographic (EPSG 3031). ~~B) shows the histogram of surface ice velocity over the central part of each subglacial lakes.~~

the ice divide between IIS, PIG and RIS (Figure 7). Because ~~many~~ some of these were classified as 'definite' lakes, we have confidence that they are likely to be ~~deep water~~ lakes deeper than 100 m like SLC and SLE. The subglacial water ~~is likely~~ may be produced by a combination of basal melting directly over subglacial lakes and from the input of water produced elsewhere in the subglacial catchment (e.g., Ross and Siegert, 2020).

The spatial distribution of subglacial lakes in terms of size ~~is variable~~ does not have a evident pattern to its distribution. The RES data shows that ~~36%~~ most of the subglacial lakes (∼60%) ~~of the subglacial lakes~~ are smaller than 2 km and only ~~8%~~ ∼10% are bigger than ~~10~~ 5 km. ~~Most of the subglacial lakes (56%)~~ Only the ∼30% of the subglacial lakes are between 2 km and ~~10~~ 5 km in length and are distributed within a region of steep subglacial topographic relief (Ellsworth Subglacial Highlands); while the smaller subglacial lakes are found in much lower subglacial terrain. However, the largest new subglacial lakes are also located in a low ~~subglacial region~~ elevation area, underneath RIS. The distance from the lakes already inventoried to the ice divide is similar to our findings, confirming the tendency of subglacial lakes to be located close to the thick, flat ice and rough basal topography associated with ice divides (Dowdeswell and Siegert, 1999). The ice thickness also has a similar distribution to that described by Wright and Siegert (2011), very close to the average ice thickness in Antarctica, and most of the subglacial lakes are found beneath an ice thickness around 3000 m. ~~These reported subglacial lakes have the same shape as those identified by Wright and Siegert (2011) but the range of length notably smaller.~~ While Wright and Siegert (2011) mapped subglacial lakes as large as ∼10 km, the subglacial lakes identified in this work are all less than 8 km in length. Despite this, the predominance of lake length < 3km is similar to the distribution noted by Wright and Siegert (2011).

Subglacial lakes are likely to form beneath areas suitable for it, for example: areas of thick ice (i.e. > 2.5 km) where the pressure-melting temperature is enough to maintain liquid water (Dowdeswell and Siegert, 1999; Gorman and Siegert, 1999), in areas of internal ice deformation and sliding that contribute heat to produce melting (Siegert et al., 1996), ~~and~~ or areas of elevated geothermal heatflux (GHF). Although observations of GHF are absent in the ESH, and modelling efforts (e.g., Shapiro and Ritzwoller, 2004; Maule et al., 2005; An et al., 2015; Martos et al., 2017) are significant, GHF estimates vary depending on the technique used. Model resolution may not show localized highs in the GHF.~~poorly constrained there are.~~ This allows possibilities for localized elevated GHF, and therefore enhanced production of basal water in the ESH. One potential localised source of elevated basal heat is enhanced radiogenic heat flux from granite intrusions known to exist within the EWM block (Burton-Johnson et al., 2017; Leat et al., 2018). In addition, the high relief basal morphology of ESH (e.g., Vaughan et al., 2007; Ross et al., 2014; Winter et al., 2015) with its narrow and deep subglacial troughs, will enable a localised intensification of GHF via topographic focusing (van der Veen et al., 2007). Continent-wide models of the basal thermal regime (e.g., Pattyn, 2010) suggest that the ESH are warm-based throughout, although given the thin ice located between the deep subglacial troughs, it is more likely to have a patchwork of basal thermal regime, with warm-based ice within the deep troughs and cold-based ice on the subglacial interfluves. Beyond the ESH (e.g. PIG, RIS, TG) it is likely that the bed is predominantly warm-based in line with continent-scale models (e.g., Pattyn, 2010). The discrepancy between the Pattyn model and actual basal conditions in the ESH is likely to be due to the coarse resolution of Bedmap (Lythe and Vaughan, 2001) used by Pattyn (2010). Future numerical modelling of basal thermal regime using our new high-resolution DEM and newly identified subglacial lakes would therefore be an important aspect of improving assessments of the basal thermal regime in this region.

4.2 Large-scale subglacial drainage network and lake connectivity

In the ESH, the subglacial water network is mainly controlled by subglacial topography and pre-existing troughs and deep valleys (e.g., ET and CT) (Siegert et al., 2012). Flow routing into Bentley Subglacial Trench, RIS, IIS and TG is determined by the combination of the very steep-sided trough walls and the overall form of the ice sheet surface, which partially aligns with ice flow ~~and drives subglacial water flow along the axis of the deep troughs (Mouginot et al., 2019)~~.The new hydropotential map suggest that the subglacial water in ESH is flowing along the axis of the new deep subglacial troughs (i.e. CT and ET) and is likely connected with the northern edge of the ESH. This implies that more water than previously expected is draining through TG subglacial water catchment.

It is likely that the subglacial lakes identified in the Ellsworth Trough (Figure 8c) are connected in a very well-defined local drainage system (Siegert et al., 2012; Ross and Siegert, 2020) which may be more dynamic than previously thought. Modelling of modern hydropotential shows that diversion of subglacial water within this trough (Figure 8c and 8d) is upstream from SLE and most of the seven subglacial lakes in this system are connected or very close to a subglacial water path. It is possible that some episodic events could link these subglacial lakes by draining subglacial water from one hydropotential sink to another, ~~forming a cascade-type system~~ from high hydraulic areas (i.e. modern ice divide between PIG and IIS) to lower hydraulic areas (i.e. the Bentley Subglacial Trench), forming a cascade-type system (e.g., Smith et al., 2017). However, these bridging events may not be large enough to displace the necessary subglacial water along this routing to be detected by satellite measurements. Another possibility is that these episodes occurs in the time scale of tens of years and therefore it may not be noticed from the surface. ~~The identification of any such episodic draining (e.g., Wingham et al., 2006) would require analysis of ice elevation changes to capture water infilling/drainage through time.~~ We also identify a dim subglacial lake (SL16) in the ~~CECs Trough~~ CT, ~~down-ice~~ downstream of SLC toward the RIS (Figure 7). Although the current hydraulic modelling does not show a clear connection between this new lake and SLC, it is possible that under different ice sheet configurations both subglacial lakes were connected hydrologically.

4.3 The subglacial hydrological catchments of Pine Island and Thwaites Glaciers

We observe that most of the subglacial water draining towards ASE is routed through the Bentley Subglacial Trench in the upper part of the hydrological catchment and driven through the Byrd Subglacial Basin towards the trunk of TG. The high topography in the mid PIG catchment (Vaughan et al., 2006) means that the hydrological drainage system does not link to the faster flowing trunk of PIG. Instead, the basal hydrological system is captured by TG. This drainage pattern has two main implications. Firstly, the subglacial hydrological catchments of PIG and TG do not correspond to the ice catchments; they do not coincide either in position or size. Secondly, the hydrological system of TG trunk (Schroeder et al., 2013) may be fed by water sourced in the upper glaciological catchment of PIG, within the ESH.

Any change in the water catchment of the TG, at the head of PIG, could therefore have important glaciological consequences for the ice dynamics of TG and the wider ASE. This is particularly critical since the subglacial water drainage area of TG is bigger than previously thought and recent investigations (e.g., Smith et al., 2017) have demonstrated the presence of active subglacial lakes, in a cascade system-type, beneath the trunk of TG. Any water accumulation/drainage (e.g., chain of active subglacial lakes) in this area may affect the basal friction of the ice and therefore the ice flow velocity. Conversely, this pattern may have a reduced importance for PIG in terms of magnitude or timing due to the topographic barrier disconnecting the drainage upstream with the lower/marginal section of PIG. If we are to clearly understand the potential role of subglacial water on the ice dynamics of the PIG and TG systems, then more investigations of the detailed subglacial and hydrological conditions are required.

4.4 The spatial relationship between subglacial lakes and ice flow in West Antarctica

Almost 90% of the newly identified subglacial lakes in West Antarctica are located in areas of slow ice flow velocity (<20 m/yr) (Mouginot et al., 2019). There are two likely reasons for this: Firstly, the ice surface slope, which is a crucial driver of basal hydraulic conditions, is typically low in these regions (Supplementary information: Table 1), thus enabling ponding to occur even in relatively low magnitude topographic depressions. Secondly, given the ice flow is slow in this area, we can infer that the subglacial network may be an efficiently draining system that does not enable the pressurization of a deforming bed, but instead may allow efficient water transport.

4.5 Limitations of the RES data, the bed DEM and hydropotential modelling

The BBAS radar data were processed as un-focused SAR images and were based on 1-D reflection (Heliere et al., 2007). In some areas (e.g., subglacial troughs), this provided a poor constraint on the subglacial bed because of the presence of diffracted hyperbolae caused by an unfocused return of the energy. This means the ice-bed interface is not clear enough to identify in some of the radar lines, and it is especially difficult to detect the bed topography in areas where the strength of the radar return is low. This way of processing could have influenced the BRP calculation, misleading some subglacial lake classification, or underestimating the size of the recognized subglacial lakes due to an uncertainty on which axis (longitudinal or transversal) had been identified.

The BRP calculation was focused in single portions with bright reflectors on each radar profile; and we assume a constant ice attenuation rate by considering the attenuation within these portions as proportional to the ice thickness. Although this attenuation is proportional to the dielectric attenuation, and therefore to the ice temperature and to solute content in the ice (Gudmandsen, 1971; Corr et al., 1993), we did not include any temperature model, which resulted in limited capacity to distinguish differences in reflectance.

We categorized every subglacial lake based on their physical characteristics using the classification method proposed by Carter et al. (2007) as a guideline. However, specularity criteria could be modified increasing the threshold to 6 dB sigma as suggested in previous studies (e.g., Gudmandsen, 1971; Peters et al., 2005) allowing some roughnes in the ice/bed interface and considering the values for the same criteria in SLE and SLC. In this case, the number of definite subglacial lakes would rise to 17; while the number of fuzzy lakes would decrease to 10 subglacial lakes (Supplementary information: Table 2). ~~some criteria were modified using higher thresholds (e.g., BRP and σBRP) as proposed by previous studies (Dowdeswell and Siegert, 2003).~~

Our new subglacial DEM improves our previous knowledge of subglacial bed condition in the Ellsworth Subglacial Highlands (BedMap2 (Fretwell et al., 2013), and Bedmachine Antarctica (Morlighem et al., 2019)) and, despite the relatively coarser resolution, it does account for topographic features which connect the WSE with the ASE that are not yet present in other models (Figure 4). We note that our hydropotential model was derived from this new gridded DEM at a resolution of 2 km, and therefore it may not detect some smaller (< 2km) subglacial flow pathways. Although new and/or more detailed subglacial water or drainage systems could be identified in future RES campaigns, the main drainage pattern would not be substantially different to that which we have identified under the modern ice sheet configuration.

Additional targeted surveys across the newly identified lake reflections would better constrain the size and area of the subglacial lakes and therefore improve our estimations of the potential volume of subglacial lakes within this region of WAIS. Moreover, for the parts of the survey closest to the ESH the BBAS survey collected airborne RES using a regular 30-km grid flown at constant ~~elevation~~ altitude (Vaughan et al., 2006), which could have missed some features and/or subglacial lakes hosted in areas between each flight line. Therefore, the number of subglacial lakes discovered in this work could increase with more RES data surveyed using ~~an appropriate flight geometry~~ a grid optimized to characterize the subglacial interface, considering the geometry of the subglacial topography. Ideally, this grid would have lines aligned perpendicularly to topographical features directly as opposed to diagonally (e.g., across subglacial troughs).

5 Conclusions

1. We used RES data from the 2004/5 BBAS survey to locate subglacial lakes within the ESH region of West Antarctica. This analysis allowed us to identify ~~37~~ 33 new subglacial lakes to add to the existing inventory (Wright and Siegert, 2012). ~~Assuming a circular shape, we estimate a total subglacial water volume of $\sim$31 km^3 (excluding Subglacial Lake Ellsworth and Subglacial Lake CECs, which are $\sim$1.8 km^3 and $\sim$2.9 km^3, respectively). While assuming an elliptical shape, we obtained a volume of $\sim$124 km^3 and $\sim$7.7 km^3.~~ We then classified these subglacial lakes according to how confident we are in their detection. Using this classification, we identify 7 subglacial lakes with a very high degree of confidence. A further 5 dim subglacial lakes, 20 fuzzy lakes and 1 indistinct subglacial lake were also identified.

2. We observed that the majority (~~75%~~ 28 subglacial lakes) of the lakes are situated underneath or close (< 40 km) to the modern ice divide between Institute Ice Stream and Rutford Ice Stream, Pine Island Glacier and Thwaites Glacier. Furthermore, we also detected that slow ice flow is associated with these lakes and that there are always low gradient ice surfaces above them.

3. We developed a new bed DEM based on recently collected survey data that was not previously incorporated in Antarctic topographic models. This allowed us to recognize new topographic features such as the long and linear subglacial trough systems (i.e. CT and ET) which connect to multiple sub-catchments and which therefore may play an important role in the basal hydrology and dynamics of the West Antarctic Ice Sheet.

4. Using the new DEM and the up to date surface elevation model from Cryosat-2 (Slater et al., 2018) we analysed the subglacial hydraulic network. We identified the potential for connection between the subglacial lakes and the wider subglacial hydrological system, thus providing a mechanism for cascading and active lake drainage. Most importantly, however, we show that the hydrological catchments of RIS, PIG and TG do not correspond precisely with glaciological catchments. Indeed, TG's hydrological catchment appears larger than previously thought, capturing basal water from the upper region of PIG.

5. ~~The detection of subglacial lakes was carried out by means of RES, which is based on 1-D reflections. These 1-D reflections do not fully capture the whole body of the subglacial lakes, but we assumed the length presented as a minimum value for each subglacial water body. Consequently, additional targeted surveys across the newly identified lake reflections would better constrain the size of the subglacial lakes.~~

Author contributions. The study was conceived by FN, MB, SJ, NR and AS. BBAS RES data was originally collected and provided by DV, NR, MS. CECs RES data was collected and provided by AR, RZ and JAU. RES processing was undertaken by FN, NR, GG and JAU. DEM was created by FN and GP. RES analysis was undertaken by FN, NR, SJ and MB. The manuscript was written by FN with input from all authors.

Competing interests. The authors declare that they have no conflict of interest.

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