32-year record-high surface melt in 2019/2020 on north George VI Ice Shelf, Antarctic Peninsula

Banwell et al.

Anonymous referee

General comments:

This manuscript presents a quantitative analysis of surface meltwater on the George VI Ice Shelf, Antarctic Peninsula, focusing on the most recent melt season (2019/2020) and setting this in the longer-term record of melt. The authors use data from a number of sources, including microwave radiometer and scatterometer, automatic weather station measurements and a previously published algorithm to classify surface meltwater ponding from Landsat 8 and Sentinel-2 imagery.

Meltwater has been linked to the instability and collapse of Antarctic Peninsula ice shelves. Although the focus and methods of this study are not novel, it quantifies the recent anomalous melt event on this ice shelf, which is important given that such record-high melt events are set to become more frequent in future. Therefore, it is my view that the findings from this manuscript are of broad interest to the cryospheric community.

In general, I would like to complement the authors on their well-written and clearly-structured manuscript, and the study rationale and methods are well-justified. The results build upon previous work that has reported surface meltwater lakes on this ice shelf by providing a time series of ponded surface meltwater together and analysing this alongside microwave observations of melt together with local climatic controls.

The authors use optical Landsat 8 and Sentinel-2 imagery to derive ponded meltwater volumes. However, I wonder why historical satellite imagery pre-2013 was not used to supplement this record and set 2019/2020 within the longer-term context of surface ponding? I suspect this may be related to difficulties applying the lake depth radiative transfer model to historical imagery, but it would be worth justifying.

There could be more of a discussion on the fate of surface meltwater during and at the end of the melt season. For example, is the decrease in meltwater volume in mid-late January associated with refreezing, or is there any evidence of englacial lake drainage? Similarly, do the authors observe any rapid drainage events, and if so at what point in the melt season?

There is also a lack of discussion of uncertainties, especially melt detection uncertainty using the microwave brightness temperature product and the ASCAT product. In addition, the reader should be made aware of the limitations in using the depth retrieval algorithm applied to optical satellite imagery (see Sneed and Hamilton, 2011 and Pope et al., 2016).

I think it could also be highlighted more clearly in the manuscript that this record surface melt in 2019/2020 was unrelated to foehn-driven melting (see specific comments).

Once the authors address these issues and my specific comments below, I can therefore recommend that this manuscript is suitable for publication in The Cryosphere.

Specific comments:

Line 25: consider quantifying ‘low-speed’ winds here, i.e. $\leq 7.5\ ms^{-1}$

Line 63: Consider adding either an additional sentence here or an additional panel in Figure 1 showing which other ice shelves experienced increased meltwater ponding in 2019/2020 to provide further context. Although it is mentioned in the Figure caption that Larsen C, Wilkins and Bach also experienced ponding, this is not immediately clear from Panel A.

Line 66: I suggest either enlarging the latitude-longitude labels on Panel A, or adding them to Panel B. In addition, I think it would be helpful to add an arrow labelling ice flow direction.

Line 87: Quantify surface summer melt rates (e.g. up to ~400 mm w.e. yr^{-1}, Trusel et al., 2013).

Line 90: Reynolds (1981) discusses observations of moulins on George VI, so consider modifying this sentence.

Line 91: Quantify ‘high’ basal melt rates and thinning rates.

Line 93: Consider adding one line in this paragraph quantifying ice flow speeds on northern GVIIS, since ponding preferentially occurs on slower-moving ice.

Line 95: I suggest also citing Lucchitta and Rosanova (1998) here as well.

Line 99: I suggest making it clearer in this paragraph that these three types of surface lakes form every austral summer to make it clearer you are not just referring to 2019/2020. In addition, consider adding sub-panels to Figure 1 to show examples of these three types, or a separate Supplementary Figure.

Line 100: I suggest you also cite Hambrey and Dowdeswell (1994) here, and perhaps add to the end of this sentence that ice flowlines are surface manifestation of longitudinal foliation.

Line 104: Please consider also citing Langley et al. (2016) and Arthur et al. (2020b) here, which record observations of down-ice lake advection on Langhovde Glacier and Shackleton Ice Shelf, East Antarctica.

Line 111: I suggest continuing the final sentence with: ‘as described above, enabling it to support a large surface area of surface meltwater (Alley et al., 2018).

Line 117: Be consistent with the use of northern/north GVIIS; I think northern is used most frequently throughout.

Line 125: What is the uncertainty associated with this microwave brightness temperature product and the ASCAT product in Section 3.2? There could be more discussion of this.

Line 129: I suggest adding one sentence after this along the lines of: the sensor measures the emitted energy from the surface and sub-surface, proportional to the brightness temperature (which increases with the presence of liquid water and which increases absorption and emissivity).

Line 142: Briefly state why grid cells > 1700 m a.s.l. were masked out, presumably to only show data corresponding to ice shelf areas.

Line 148: Consider adding a citation here?

Line 161: I suggest adding a sentence explaining where this threshold comes from i.e. was based on empirical comparisons with QuikSCAT-derived melt (Ashcraft and Long, 2006).

Line 166: Add ‘scatterometer-derived’ before ‘cumulative melt days’.

Line 177: Perhaps briefly outline here the threshold-based algorithms other than NDWI that this method uses, i.e. NDSI and others, or else list which bands are used.

Line 182: Consider also citing Bell et al. (2017) and Arthur et al. (2020b) here.

Line 184: This depth-reflectance algorithm makes a number of assumptions which I think are worth briefly outlining in an additional sentence, including the assumption of homogenous lake bottom albedos, minimal wind-driven light scattering, etc (Sneed and Hamilton, 2007).

Line 185: There is no discussion currently in this section of false positives. How did you deal with these (if there were any), and were they manually removed?

Line 218: I think 'warm' here more accurately describes foehn winds than 'hot'. Also suggest adding at the end of this sentence 'and commonly occur on the AP', and citing Luckman et al. (2014).

Line 219: I suggest adding an indication here of how steep the topography is, e.g. maximum slope.

Line 339: This is an interesting finding. I wonder whether it would be worth adding an additional sentence (either here or at the end of this section) explicitly summarising these observations demonstrate you can still get record melt when conditions are generally warmer, with no involvement of foehn wind events.

Line 393: Are there any measurements of firn air content/thickness on George VI?

Line 410: I don't think you can necessarily suggest that surface melt volumes were highest in 2019/2020 out of the prior 31 seasons without having explicitly derived volume estimates from imagery pre-2013.

Line 419: Change 'zero re-freeze' to 'no refreezing occurred'.

Line 434: Explain 'shoulder seasons' – do you mean colder seasons (autumn/winter?).

Line 446: Change 'back to 2013' to 'from 2013 to 2020' and suggest adding to the last part of the sentence: 'was also exceptional in areal extent and volume [..]'.

Line 454: Add AOI area here in brackets to remind readers of its size in comparison with Larsen B in the next sentence. Also, what was the maximum lake depth?

Line 458: I suggest also citing Alley et al. (2018) here.

Line 460: Consider showing in a Supplementary Figure the lakes mapped in this study overlaid onto the areas classed as vulnerable to hydrofracture by Lai et al. (2020).

Figure S5: I notice there are two particularly deep lakes – why, out of interest, do you suggest this is?

Technical corrections:

Line 31: minor point, but check here and throughout that citations are listed chronologically.

Line 49: Add comma after 'However'.

Line 100: 'most extensive' rather than 'the largest'?

Line 106: Change en-echelong to '*en-echélon*' and consider adding a brief description for those unfamiliar with this term, e.g. closely spaced, sub-parallel.

Line 120: Change '(from 2013)' to 'from 2013-2020' and the same with '(from 2017)'.

Line 125: Insert 'passive' before 'microwave radiometer'.

Line 132: Hyphenate 25 km.

Line 157: Hyphenate 4.45 km and consider briefly outlining the SIR algorithm.

Line 159: Hyphenate 'SMMR-based'.

Line 173: Rephrase to 'to selected multispectral imagery (see paragraph below)'.

Line 197: Are italics needed in this paragraph?

Line 216: Remove 'periods'.

Line 220: citation should be Wiesenneker et al., 2018 (full reference is correct).

Line 291: remove commas after 2020 and AOI.

Line 327: Change 'refreeze' to 'refreezing'

Line 390: Re-word sentence to 'meltwater ponding is not observed in the optical imagery until mid-December'.

Line 495: Please add volume, issue and page numbers: 44(6), 837-869.

References:

Alley KE, Scambos TA, Anderson RS, et al. (2018) Quantifying vulnerability of Antarctic ice shelves to hydrofracture using microwave scattering properties. *Remote Sensing of Environment* 210: 297–306.

Arthur, J. F., Stokes, C. R., Jamieson, S. S. R., Carr, J. R., and Leeson, A. A.: Distribution and seasonal evolution of supraglacial lakes on Shackleton Ice Shelf, East Antarctica, *The Cryosphere Discuss.,* https://doi.org/10.5194/tc-2020-101, 2020b.

Hambrey MJ and Dowdeswell JA (1994) Flow regime of the Lambert Glacier-Amery Ice Shelf system, Antarctica: Structural evidence from Landsat imagery. *Annals of Glaciology* 20: 401–406

Langley ES, Leeson AA, Stokes CR, et al. (2016) Seasonal evolution of supraglacial lakes on an East Antarctic outlet glacier. *Geophysical Research Letters* 43(16): 8563–8571.

Lucchitta BK and Rosanova CE (1998) Retreat of northern margins of George VI and Wilkins Ice Shelves, Ant- arctic Peninsula. *Annals of Glaciology* 27: 41–46.

Luckman A, Elvidge A, Jansen D, et al. (2014) Surface melt and ponding on Larsen C Ice Shelf and the impact of fohn winds. Antarctic Science 26(6): 625–635.

Reynolds RW (1981) Lakes on George VI Ice Shelf. *Polar Record* 20(128): 425–432.

Sneed WA and Hamilton GS (2007) Evolution of melt pond volume on the surface of the Greenland Ice Sheet. *Geophysical Research Letters* 34(3): 4–7.