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The Cryosphere Discussions

Interactive comment on "Lateral meltwater transfer across an Antarctic ice shelf" *by* Rebecca Dell et al.

Anonymous Referee #2

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This manuscript describes the evolution of surface meltwater on the Nivlisen Ice Shelf in Antarctica during the 2016-2017 melt season. The authors describe in detail their adaptation of the FAST algorithm for tracking water on ice shelves, and apply the method to two optical satellite datasets. They develop four categories of ice-shelf water bodies, and use them to discuss water transport across the Nivlisen Ice Shelf. Two main systems emerge on the ice shelf along linear surface depressions as the surface hydrology system transitions from isolated lakes to a connected network.

As explained in the introduction, ice-shelf surface hydrology is a critical component of ice-shelf stability, and thus important in predictions of ice-sheet mass loss. Being able to map and analyze the development of ice-shelf surface hydrology is important for understanding how future warming and subsequent ice-shelf melting will influence ice-

shelf behavior. There is a significant gap in our knowledge of water transport across ice shelves, and the goals of this manuscript are both timely and within the scope of TC. In general this manuscript is well written and should be published in TC with some revisions applied. The topic of ice-shelf meltwater transport is important, and the results of this study will certainly be of interest to the TC audience.

This manuscript builds on previously developed tools (water-tracking algorithms, band ratios, etc) and applies them to an ice-shelf whose surface hydrology has not to my knowledge been analyzed in detail. The authors have adapted these methods and tools to suit ice shelves, and combined this algorithm with previously validated methods of water volume retrieval from satellite imagery. However, the authors do not clarify why the FAST algorithm is not suitable for use on ice shelves and do not explain the differences between the FASTER algorithm and their new FASTISh.

The authors clearly demonstrate an evolving meltwater system on the Nivlisen Ice Shelf, and clearly describe why these observations are important for ice-shelf stability. However, the conclusions could use some clarification and possibly additional analysis. First of all, the difference between a meltwater lake and a stream is defined here only geometrically. Streams and rivers are defined by water flow, but the definition used here does not include a water flow condition. Rivers and streams described here could technically be linear lakes that fill up from percolation through the firn. The authors seem to support this, since they describe two mechanisms for water transport 1) movement through firn and 2) movement via overtopping lakes, but then claim there is no evidence of overtopping lakes. There is not sufficient data or analysis to confirm water is flowing in these features precisely because water transport in the firn cannot be tracked from optical satellite imagery. Satellite radar could be used to track melt in the upper firn layers and might provide insights into exactly how water is moving. Additionally, the authors have not explained where firn is located on the ice shelf or how it is detected. I think it was visually identified. That should be briefly described and indicated on one or more maps (along with blue ice areas). The connection between

temperature and surface hydrology development could be enhanced by including data from a climate model that covers the entire ice shelf as opposed to a single weather station. The development of air and ground temperatures could be tracked through space and time and then be compared to the development of the surface hydrology system that the authors already quantified.

The general structure of the manuscript could be improved by including some of the more important conclusions and implications in the abstract and introduction. For example, the comparison to the surface lakes of Larsen B in the discussion could be highlighted to provide some motivation for the study, as opposed to limiting the goal of the study to developing an algorithm and tracking water on one ice shelf. Some more context for the Nivlisen Ice Shelf would be helpful in Section 2. In terms of the methods, providing context for the FASTISh algorithm would go a long way. A lot of time is spent in the beginning discussing a method that is at this point standard in ice-shelf/ice-sheet hydrology, and it's not clear how FASTISh differs from FAST.

Figures:

Titles would help the reader interpret figures more easily.

Figure 1. Add coordinates to Nivlisen map, include location of weather station. Annotate blue ice areas, water bodies and firn extent. The caption refers to a red star to locate the Nivlisen Ice Shelf, but I don't see it. Also, is this image mosaicked? From the description of data preparation, it seems like the entire ice shelf cannot be captured by a single Landsat scene, and that pairs of scenes were mosaicked.

Figure 2. This is a nice workflow diagram. One very detail-oriented comment: It is a little confusing to have "Cloud Mask" in an input, and then the next line be the "Apply Cloud Mask" processes in the same workflow. From my understanding of the workflow, cloud masks are generated from a separate workflow followed in Google Earth Engine and are then an output of that workflow. Maybe delete the "Cloud Mask" input from the top.

Figure 3. Include the paths of the DEM that were extracted and shown in Figure 8. Consider combining this figure with Figure 8 and maybe Figure 7. It would be nice to have an "elevation figure" to synthesize everything.

Figure 4. This shows the water transport really nicely. Consider having the scale bar on only one image so that the eye can focus more on the water. Also, consider making the color of lakes and streams more distinct- it is hard to distinguish in print and only slightly easier on screen. Also, the text references streams a and b on line 343, but I think you should keep names and labels consistent. Label them here, since it is the first time we see the hydrologic system. Maybe add labels to row D.

Figure 5. Great figure! Move the WS and ES labels so they don't overlap the nice masks. Is the basemap Landsat? Include that in the caption. Is it necessary to include a category for water that isn't mapped if the background shows a satellite image? It makes me want to look for what features with a gray outline.

Figure 6. Get rid of white space after 01-04-17 since nothing is plotted there. Actually, if I'm correct in this interpretation, it seems like this figure shows a period of water deepening– in the All Water Bodies and Envelopment Transitions categories, the volume increases at a greater rate than the area from $\sim$ 01-12-16 to 01-02-17.

Figure 7. This figure basically tells me that water flows downhill. This is very encouraging, but I think that's communicated in the combination of Figures 3 and 4.

âĂČ Specific comments:

Line 1: change "stored" to "can form"

Line 31: I don't think it's clear that water transfer is "facilitated by two large surface streams." In fact, the discussion seems to indicate lateral transport of water through firn.

Line 80: I agree it is important to assess the variability of ice-shelf surface hydrology over the course of a melt season, but the year-to-year change is also critical. As just

one example, the Nansen River does not form every year (Bell et al. 2017). If meltwater transport is such an important part of ice-shelf stability, then its variable behavior must be important, too. What if water didn't move across Nivlisen one year?

Line 92: Why is it necessary to produce FASTISh? It would be very helpful to include a description of FAST, highlighting its strengths and weaknesses.

Line 98: In general I would like more description of the ice shelf here. A discussion of the firn would be useful.

Line 103: Be more specific about where the ice thickness reaches 700 m. Is 700 m a grounding line thickness? Taking a look at Horwath et al., referred to in the text, it looks like it might be.

Line 105: It would be helpful to include a reference to Fig. 1 here with some annotations provided.

Line 110 (Study Area in general): Discuss meltwater features in more detail than "meltwater features show changes over time." Kinglsake et al. 2015 specifically say that lakes drain on the Nivlisen Ice Shelf. You may disagree with the classification of the meltwater identified by Kingslake et al. 2015 – the images there look like what you call an "envelope transition." However, "changes over time" doesn't communicate enough information to the reader. This description could include basic information from your analysis, too. Knowing up front how large the extent of melting is compared to the total area of the ice shelf, for example, would be helpful in orienting the reader. Also including some basic climate information would be good, especially since you talk about temperature data later.

Line 139: Converting from DN to TOA values is important for analyzing spectra anywhere, not just at high latitudes.

Line 156: I appreciate that clipping each scene to the same extent is a required step in the algorithm, but I don't understand the reason. Although you say "when com-

paring images," but you can compare scenes that have overlapping areas but not the same extent. This makes me think there is some other requirement that you haven't mentioned.

Line 168: It might be good to describe bands in terms of their spectral range rather than color, since you are using imagery from two different platforms. Clearly this is not critical, just a thought.

Line 171: The division by a "quantification value" comes out of nowhere. Is there a paper you could cite that explains this as a part of data processing? I would delete "expected" since it can imply that something is wrong with Sentinel-2, when it seems like it's just a convention of how they deliver their data. I haven't worked much with Sentinel-2, however, so if this really is an unexpected discrepancy then ignore my suggestion.

Line 178: Is the thresholding approach the same as before?

Line 179: How can a value exceed 10,000 if all bands were divided by 10,000?

Line 233: While I know it is correct to say that errors in lake depth estimates have been calculated as zero (Pope et al. 2016), I think it is misleading to have this be the only mention of error about this method. To a reader who isn't already familiar with this method, the claim that error is zero will be shocking, and probably lead to skepticism. I think that if you are going to describe the method to help the reader understand what you did, it is important to give a little bit more detail about the sensitivity to A and g, the dependence of the band chosen, and that physical qualities of the system are known (water column attenuation, surface roughess of the lake, etc.)

Line 265: I'd really like to see a figure of the thresholds and different water body shapes. I think it would help me understand the categories you introduce in section 3.5.

Line 286: There should definitely be a figure for this. It could be Figure 5, but I would almost prefer a zoomed-in high detail of an area with one of each type.

Line 308: Is the figure for this Fig. 7? If so, refer to it. But also, be clear about which water bodies. I was expecting an elevation profile with different colors representing your four water body categories, whereas Fig. 7 shows the Eastern and Western Systems.

Section 3.7: Plot this on a map- I can't figure out where it is! Also I think a single point of temperature is insufficient for this analysis. It would be useful to see modeled (maybe RACMO) temperature and energy balance across the extent of the surface hydrology system.

Line 326 and Section 4.1: Give a general synthesis. Instead of only having four paragraphs that describe the observations, tell the reader the overall trend. I can't really grab on to a take-away message the way it is written.

Line 328-29: Ice shelves are flat places- what does relatively flat mean and how do you know how thin the winter snow cover is?

Line 343-344: Refer to Fig. 5.

Line 353: Again, how do you know the extent of the firn? If it is visually identified, consider digitizing it. I'd be curious to see how the firn extent changes as the system evolves, especially given your discussion section.

Line 357-358: I am now getting confused between lakes and streams- are the two "large streams" just linear lakes? Your distinction between the two is only geometric. It is not clear that water flows in these water bodies the way water flows in streams. I am convinced water is transported, but I don't think there is clear evidence for how. Except that you later say you have no evidence for water overtopping lakes, which makes me think you are concluding most water moves through firn.

Line 385-387: The FASTISh algorithm itself does not produce a time series of water body properties- it only does you have used it on a time series of images.

Line 392-397: While you refer to Fig. 7 for this, that figure only shows migration to lower elevations, not lower latitudes. I am not sure what trends you refer to in section

4.1 – rewriting that section to include a general point would help. Then refer to it here by saying "In line with the XYZ trends described in section 4.1. . ..."

Line 399: I got confused between the Eastern System and Western System and the water body categories. When I looked at Fig. 7 I was expecting to see the four categories, since the title of the section is "Tracking Individual Water Bodies." Why have you not done this? Is it because most of the water is in the ES and WS? It would make sense to focus on these two, given that there is also migration of both systems. But I think that needs to be clarified in the text. It is even more confusing in the rest of the paragraph because on line 404 you say "most of the surface water" and it's not clear if you mean "most of the surface water in each meltwater system" (and I don't even know which meltwater system it is, east or west?) or if you mean "most of the surface water on the ice shelf".

Line 418-419: I'm not sure this sentence matters. What is rhythmic variance? What do these properties mean for the surface water?

Line 448: You say surface water area and volume correspond with rising temperatures, but Fig. 9 shows volume loss is associated with temperature increase, and only in the category of "always a lake" when most of the water is contained in the ES and WS. It would be helpful to include a figure showing what is claimed on line 453 "As temperatures rise and surface water bodies increase in area and volume. . .." It seems like the point you are trying to make in this section is that temperature controls the evolution of the system, so showing the decreasing lakes with increasing envelopment transition might make that clearer. Although later it seems like you are claiming the opposite.

Line 463: How do you know water is flowing along linear depressions as opposed to those depressions being filled from the sides due to transport in the firn? Especially since you mention on line 470-472 that the growth of ES and WS are more likely to be fed by increased meltwater production and movement through firn. In general, I think

you argue well for meltwater transport through firn. I would highlight that, but it would require a little more discussion and analysis of how you track firn on the surface.

Line 464-468: You have not demonstrated that the ES and WS are “fed by smaller surface lakes and streams both above and below the grounding line.”

Line 470-472: Is it really possible to infer this when there are no images between Dec. 27th and Jan 26th? I assume that evidence of a “lip” would be the development of a stream forming out of a lake. How do you know this didn’t happen? Also, refer to Fig. 4 here.

Line 480-482: You claim it is possible that meltwater could be transported to the front of the ice shelf in the future. That would require water to organize in a river that can flow off the ice-shelf edge (unless there is some meltwater evacuation through firn that I don’t know about, but that’s another can of worms). You could potentially demonstrate this by assuming at some point the firn will saturate and water will follow surface depressions (you have already argued that this is happening). You could perform a water routing analysis on the full DEM, or at least see if you can visually identify linear surface depressions out to the edge of the shelf.

Line 488-501: “The relatively extensive snow and firn cover . . .likely prevents the development of. . .meltwater. . .on the Larsen B.” This is a very important distinction that I think you should highlight (maybe include it in the abstract and allude to it in the introduction?). This is definitely an important conclusion, because it defines a type of meltwater type and evolution that stands in contrast to the “ponds break ice shelves” style of meltwater without needing to remove water.

Line 515-518: Earlier you said that the transfer of water was *not* due to overtopping of surface lakes.

Line 508-526: It seems like now you are saying temperature does not control the evolution of the surface hydrology system. Earlier it seemed like you were saying the

opposite.

Line 530-552: What are the implications for the stability of Nivlisen? Could you tie your analysis more explicitly to our general understanding of ice-shelf stability? Your refreezing calculation is really interesting, but has nothing to do with the rest of the paper. It makes me again want to know more about firn on this ice shelf.

Line 558-576: I would lead with the conclusions you reach about the ice shelf, not with a description of your method, and also include a summary of the implications of your analysis.

Line 570: Again, how do you know there is a thin snow band and firn pack?

âĂČ Technical comments

Line 20: hyphenate “ice-shelf”

Line 59: hyphenate “ice-shelf”

Line 76: hyphenate “ice-shelf”

Line 210: change “two” to “2” since it follows a mathematical symbol, even though it is a number less than ten.

Line 294: “identified and tracked”

Line 306-307: Spell out acronyms when you use them for the first time REMA and DEM.

Line 548: hyphenate “ice-shelf”

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