Reviewer 1

R1A - Description of methods:
I am not confident I understand what you have done strictly based on this manuscript. As I think it would be good if this paper stands by itself, I am suggesting that you spend some more time elaborating on the methods.

We have made an extensive overhaul of the datasets and methods section. The "difference" document reveals the extensive changes to this section, but to summarise here:

a) Almost all "methods" suggestions from all reviewers incorporated

b) New flow-chart figure depicting processing pipeline provided as Fig. 1

c) Outcomes of each method step now explicitly stated.

Changes: extensive changes throughout lines 73 to 247. More detail is provided for each specific point below.

- For instance, it is not clear to me how you create the composites. Could you be clearer in terms of this being a mosaic of overlapping imagery or if you are considering just one acquisition for each location and this being a composite of the two channels. Either way, it would be helpful with a couple of sentences addressing how they are created and the number of images typically incorporated.

Addresses, as suggested.

New text at Line 103:
"(i.e., a TIR composite at all times of the year, and a visible composite when solar illumination was present)"

Much more detail now added on the number of images used at Line 112:
"Here we rank all cloud-mask granules by their cloud content, and choose the 100 least cloudy granules in each of six regions (each approximately 60 degrees of longitude wide) around the Antarctic coast for compositing and further processing, i.e., 600 MOD/MYD02 granules in total per 15 day window. This regional consideration was implemented in an effort to ensure a more even distribution of MOD02 granules. We found that without this consideration, the ranking algorithm resulted in a high concentration of granules in a limited number of cloud-free regions at the expense of cloudy regions."

- The steps in the methods are quite clear in of themselves, but it would help if the outcome of each steps is described as well.

Addressed, as suggested. Outcomes are given for each step in Lines 139 to 182. The flow chart (new Fig. 1) also aids clarity in this regard.

- This is how I interpret your initial steps: - For any given location and for all 15-day periods in your dataset, you download all available images and create multiple composite images based on available channels (how do you do this?).

More detail provided, as suggested. This detail is included within Lines 100 to 125 (not pasted here, for brevity).

- Hence, for this location, you have several images (how many roughly?)

For each 15 day window we use 600 images as an input to all processing. This is now made clearer at Line 112:

"Here we rank all cloud-mask granules by their cloud content, and choose the 100 least cloudy granules in each of six regions (each approximately 60 degrees of longitude wide) around the Antarctic coast for compositing and further processing, i.e., 600 MOD/MYD02 granules in total per 15 day window."

- Then you detect the edges in all these composites resulting in multiple 1 km resolution (binary datasets?) indicating locations of edges in each composite.

Addressed – both within the text description, i.e., Line 139 to 182, and the new flow chart (Fig. 1).

- Then you sum the binary datasets and thus higher numbers more strongly indicate persistent edges at the timescale of 15 days. By doing this you reduce the number of composites down to one product?

That's right. Well, not quite one product, but we vastly reduce the input images by this process. We retain the Canny vs Sobel edges in separate summary images, for example.

This detail is described within the new flow chart.

- You then multiply the edges with the median-filtered composite. But which one, if you have multiple composites for this region?

That's right. This is Step 6 detailed in line 161. Only the (summed) Canny edges are used in this process to construct the edge probability map. This is because the Canny edges have excellent localisation.

- Also, please spend a sentence on describing how this results in confidence as opposed to just the edge product.

Addresses, as suggested. Please see Line 167:
"These thresholds are used to construct a grey-scale representation of the edge confidence for each pixel on the grid."

- What is the range of values prior to normalization?

Good question. I haven't thought to check, because the normalised product is so much more useful when deploying this algorithm across the whole continent. The lower range is 0 (no Canny edges * a zero value for the median-filtered composite image). The upper range is typically the product of ~60 Canny edges (a particularly obvious edge with frequent, clear views of the surface throughout the whole period in both Terra and Aqua MODIS) and a composite gradient-median-filtered value of around 5, for the infrared case, or 0.75, in the visible channel case. The IR value is higher due to the numerical value of the brightness temperature difference between cold ice and warm water being much higher than the difference in reflectance of a dark vs light surface. But these details are helpfully abstracted away thanks to the normalisation.

Since these values are not used in their pre-normalised state, we didn't change the manuscript.

- Finally, the result is a product of landfast ice edge with 1 km spatial and 15-day temporal resolution. However, how do you eliminate lower confidence edges based on the histogram analysis?

Edges with a lower confidence than the lowest threshold (which is 98% of the cumulative probability distribution – i.e., the upper 2 percentile of pixels) are eliminated by simple thresholding.

This is made clearer in Line 166-169.

- If you could attempt to clear up any of misunderstandings and make this a little easier to follow, it would be great. I suggest a figure where the reader can associate each step with a figure panel (or alternately a schematics). Basically, modifying Figure 1 to incorporate the other steps as well

With these changes, along with the flow diagram suggested by Reviewer 3, we think that a much clearer explanation is now provided.

R1B:

Specific points:
-At line 190 you describe: "In the case of a manually-extracted ice edge pixel, it reflects the sum of the ice edge change plus the digitisation error." And you seem to imply that there are no errors in this data?

I think you meant to type that this implies that there is no error in the automatic digitisation, is that right? This (that the auto-determined pixels have no error) was our initial assumption – since the Canny edge localisation is very good – however you're right - we have implicitly ignored any sub-pixel digitisation error with this assumption.

Performing a quick random point simulation, I can see that the sub-pixel error averages to zero, but has an RMS value of 0.288 px. It could be argued that this value is a better one to use here.

We now use a value of 0.288 px for the automated edge error, and the quadrature sum of this value plus the previously-determined value of 5.47 px (i.e., no 5.48 px) for manually-determined edges. This has now been incorporated into the Methods (Line 223 onward) and Results (Line 300 onward) sections.

- Could you elaborate about this in the manuscript and discuss the accuracy of the Canny edge detection in general based on your pixel spacing and in terms of misclassification in the case of slow moving non-stationary ice in fjords

The accuracy of the Canny edge detection is described in the above comment.

Misclassification of melange as fast ice probably occurs in a few limited regions around the coast. We haven't mentioned this in the manuscript because it probably occurs in such limited regions as to be negligible on a circum-Antarctic scale. But I agree that it's worth noting this caveat in the revised manuscript. Another related error is in regions of densely-packed icebergs, which we pointed out in line 215 of the original manuscript, so this would be a good place to discuss melange misclassification.

This is now included at Line 246: "Regions of ice mélange at the front of ice shelves are another source of uncertainty here, but remain unquantified due to their negligible areal extent on a continental scale."

- and stationary drifting ice pinned between icebergs or by onshore winds over consecutive 15-day periods? I suggest as before to move some of this discussion into either a discussion section or as a subsection to the methods section and discuss caveats a little more deliberately.

Yes, as you indicate, both issues are probably present to some extent. Regarding the drifting sea ice pinned between grounded icebergs, we have experienced this but only in limited areas in the Antarctic (e.g., visible from stations but at a spatial scale much smaller than one km, our pixel size). Regarding the ice temporarily advected against the shore or existing, genuine fast ice, we still believe that 15 days is long enough to preclude most of this ice from consideration. The coastal flow is generally offshoreward to westward (Turner and Pendlebury, 2001). Blocking anticyclonic pressure systems do occur in southern midlatitudes and these can result in persistent onshoreward winds in particular regions of the Antarctic coast, although the residence time for such systems is rarely longer than one week (Massom et al., 2004).

New text at Line 126:
"The 15 day time-step is chosen by balancing a desire for finer resolution against the potential for pack ice temporarily advected against the coast to be misclassified as fast ice despite no mechanical fastening taking place. Around most of coastal Antarctica, the climatological near-surface wind direction is generally offshoreward to westward (Turner and Pendlebury, 2004), thus promoting advection of pack ice away from the coast. Blocking anticyclonic pressure systems do occur in southern mid-latitudes and these can result in persistent onshoreward winds in particular regions of the Antarctic coast, although the residence time for such systems is rarely longer than one week (Massom et al., 2004). As such, a time-step of 15 days is sufficiently long to preclude most of these cases. Drifting sea ice pinned between grounded icebergs may also be misclassified as fast ice, though our earlier work showed that the persistent advection of pack ice into pre-existing coastal features is likely to be a larger problem, and that pack ice held fast between grounded icebergs may quickly become fastened (Fraser et al., 2010)."

J. Turner; S. Pendlebury (Eds.) The International Antarctic Weather Forecasting Handbook, British Antarctic Survey, Cambridge, UK. ISBN: 1855312212, 2001.

R. A. Massom; M. J. Pook; J. C. Comiso; N. Adams; J. Turner; T. Lachlan-Cope; T. T. Gibson. J. Climate (2004) 17 (10): 1914–1928

- You define landfast ice as stationary for 15 days as opposed to earlier 20 days. A 3-week timeframe is to my knowledge more common. Why did you make this choice and how will this impact the analysis and the potential misclassification of temporarily stationary pack ice etc.

As above – the circumpolar trough generally permits swift passage of low-pressure systems from west to east. Blocking events can occur north of the ice edge, but these rarely persist more than one week, so 15 days is probably sufficient to exclude this except for extreme cases. Discussion added to the text at around Line 126, including rationale for the 15 day choice, as in the previous comment.

- Is the manual delineation very labor intensive e.g. is it sometimes difficult to determine where to draw the line with potentially large consequences for the ice extent? Do you have suggestions for how to mitigate this or how your approach could be improved in the future resulting in a larger than 58\% success rate?If you could discuss this slightly in the manuscript, that would be very interesting.

The manual delineation ranges from being relatively straightforward (in the case of high quality composite imagery, where few judgement calls need to be made) to quite labour intensive (in the case of heavy cloud obscuring the surface, resulting in ambiguous fast ice edge delineation, and requiring the use of the previous and next 15 day period's composite imagery for guidance). On occasion, such judgement calls have the potential to significantly impact a single period's fast ice extent retrieval in a limited region.

We have taken steps to mitigate this here compared to our earlier work (e.g., by now considering edges visible even under thin cloud; by including more MODIS data per 15-day period). Multisensor fusion would help alleviate this to some extent (we used AMSR-E in our previous work) but limits the time period able to be considered (e.g., AMSR-E was launched 2.5 years after Terra MODIS). Here, our approach is still limited by poor MOD35 cloud mask product accuracy at times. We are interested in implementing state-of-the-art machine-learning cloud masking to mitigate this (e.g., Paul and Huntemann, The Cryosphere Discussions, 2020). This improvement may lead to an automation percentage in excess of the 58\% reported here.

I agree that this kind of discussion is a great addition to the manuscript. We have added text at Lines 281 and 295:
"Manual delineation ranges from being relatively straightforward (in the case of high quality composite imagery, where few judgement-calls need to be made) to quite labour intensive (in the case of heavy cloud obscuring the surface, resulting in ambiguous fast ice edge delineation, and requiring the use of the previous and next 15 day period's composite imagery for guidance). On occasion, such judgement-calls have the potential to significantly impact a single period's fast ice extent retrieval, albeit in a limited region."

and

"We have taken steps to mitigate this here compared to our earlier work (e.g., by now considering edges visible even under thin cloud; by more intelligently selecting the least-cloudy MODIS data for each 15 day period). Here, our approach is still limited by relatively poor MOD/MYD35 cloud mask product accuracy at times. In the future, we are interested in implementing state-of-the-art machine-learning cloud masking algorithms to mitigate this (e.g., Paul and Huntemann, 2020). This improvement may lead to an automation percentage in excess of the 58% reported here."

Ref: Paul, S. and Huntemann, M.: Improved machine-learning based open-water/sea-ice/cloud discrimination over wintertime Antarctic sea ice using MODIS thermal-infrared imagery, The Cryosphere Discuss., https://doi.org/10.5194/tc-2020-159, in review, 2020.

- Could you even provide some speculation into whether other sensors could enhance the analysis?

Yes – as above, AMSR-E has been used to complement this technique in our previous work (Fraser et al., 2010, which was purely manually-digitised), although it isn't clear how the multisensor fusion could be achieved in the framework of the present paper. Again, we would like to reiterate that few sensors match the very long observational lifetime of MODIS, so a multisensor fusion becomes less attractive in this sense.

Text added at Line 336:
"Multi-sensor fusion would help to further mitigate the subjective elements of this dataset to some extent. As an example, we used AMSR-E, in our previous work (Fraser et al., 2010). However, mission overlap generally limits the time period able to be considered in multi-sensor fusion algorithms (e.g., AMSR-E was launched 2.5 years after Terra MODIS, and was effectively decommissioned in 2011)."

- I realize and appreciate that you have written a quite concise paper and don't want to delve too much into the details. However, I suggest some more clarity and elaboration around these two points.

We agree that some more detail in these sections would be a useful addition at the cost of a few sentences.

R1 - Minor comments:

1) Line 65 - 74 move to discussion

Yes, now moved to discussion: Lines 346 to 359.

2) Line 78: I don't see the "in prep" reference in the bibliography. If not included there, take out.

Yes, this is still in prep so we will remove it from here.

3) Table 1: Avoid the word very as in "very high"

OK – changed in Table 1.

4) Line 81: Replace "the new" with something like "the fast ice time series presented here" to make it clear that it is not a new one described in Table 1.

Changed. Now Line 73.

5) Line 95: Can you clarify how the composites are created? Do you mean creating a mosaic or merging the channels?

Yes, addressed in the main comment above.

6) Line 97: Is this manual updating done every year and for the entire coastline? Is this labor intensive if to be done with necessary accuracy?

Yes, every year for the entire coastline, using the two MOA products (produced in 2004 and 2009) as a baseline. It is relatively quick in comparison to the manual parts of fast ice retrieval. Detail added to the text in Line 92: “Although this process is entirely manual, it occurs only once per year so is not particularly laborious.”

7) Line 112: “layer of clouds”?

Amended. Now Line 107.

8) Line 115: Here as well as prior in the manuscript, the use of parenthesis could be toned down by reformulating.

Thank you – we note that Reviewer 2 has recommended a parenthesis overhaul too. We have revisited all occurrences in line with these comments.

9) Line 123: Again, not sure if parenthesis is needed here.

As above.

10) Line 126: I am not familiar with the plural form “cloud”. Clouds?

Yes, changed as with comment 7.

11) Line 125: You have already said this. Take out.

Thank you - done.

12) Line 133: Missing oxford comma

Inserted.

13) Line 139 and 140: It would be great if you could elaborate here on what you mean by summing edge products. Do you just sum binary pixel values of edge/no edge?

That’s correct. Elaborated on at Lines 151 – 158 by describing outcome:
“– Produce Canny edge images for each granule: Canny edge-detect MOD/MYD02 granules and sum within the current 15 day period. Outcome: Canny edge sum image for automated edge extraction.
– Produce Sobel edge images for each granule (Sobel, 2014): Sobel edge-detect MOD/MYD02 granules and sum within the current 15 day period. Outcome: Sobel edge sum image to guide manual fast ice edge interpretation.”

14) Line 139: Do you mean successive 15-day periods, meaning several periods? If so, how many?

Sorry, this sentence was explained terribly! Thank you for picking it up. Will be changed from “and sum over successive 15-day periods.” to “and summed within the current 15-day period.” Same for the following dot point. Line 151.

15) Line 142: Try to limit redundancy, you have already stated that the composites are cloud-free

Thank you, redundancy removed.

16) Line 143: Could you provide a short explanation for the Median filter. For instance, what is this gradient value range? Is there a threshold used to determine whether the edge is stationary and for how long?

Partly addressed in the response to your main comment above, but to explicitly answer here: The gradient of the median of the composites ranges from 0 to around 5 (for the Channel 31 thermal IR brightness temperature composite) or 0.75 (for the Channel 01 reflectance composite). There is no consideration of time-scale finer than the compositing window of 15 days, since few regions are spoiled for cloud-free imagery throughout the entire 15 day window. The adaptive threshold is applied only to the product of the Canny summed edges and the gradient-median-composite images.

Changes to the main text as described above: Line 155.

17) Line 148: Is this something you define. If so, make that clear. Otherwise, please provide reference.

Yes, this is our original algorithm. Made clear in Line 163: "Compute the per-pixel product of the Canny edge image and the gradient-median-composite image described above, which was found to accurately and correctly locate many fast ice edges (i.e., this is an original algorithm)."

18) Line 162: In the methods section below Line 162 looks like the start of a discussion to me. I recommend creating a discussion section and placing much of this there. Some of it also belongs more in the introduction perhaps.

This has now been moved to Section 3.2 (the results/discussion)

19) 185: Like before, no need for parenthesis

Complete parenthesis overhaul for whole manuscript!

20) Line 215: Missing space

Thank you.

21) Line 244: What indicates this in the plot? The discontinuity in the plot?

Ah, no – apologies for the confusion. Regions with low automation fraction indicate this. This has now been made clear in Line 291: "By showing longitudes with a low automation fraction, this plot also indicates areas which tend to be most affected by inherent issues detailed in the Methods Section, i.e., persistent cloud cover and/or persistent advection of pack ice toward fast ice that reduces the contrast (in reflectance and surface temperature) between pack and fast ice." Reviewer 4 also wondered about the discontinuities. These are now described in the figure caption.

22) Line 248: What do you mean with edges vary? The detected edges or the actual ice edge? You mean vary over time when the ice edge is assumed constant? Please explain better.

This has been clarified at Line 302:

"We find that, on average, manually-determined edges change in location by 5.47 pixels more than that for automatically-determined edges (auto-determined = 10.06 pixels vs manually-determined = 15.53 pixels) in subsequent 15 day windows."

23) Line 263: Please be consistent with the use of notations for in-line lists e.g. 1, a, or i.

Thank you – all made consistent now.

24) Line 266: Missing space

Thank you.

25) Line 271: Please clarify this sentence as it is not clear what you mean by complexity dataset and linkages between what.

The dataset we refer to is a dataset of Antarctic coastal margin complexity and configuration, though I agree it doesn't read particularly well as written. Has been clarified:
"Moreover, we plan to study the spatial distribution of fast ice extent in the context of a new dataset describing the multiscale complexity and configuration of the coastline (including aspect) around Antarctica (Porter-Smith et al., in review, 2019), under the hypothesis that the coastal configuration is a first-order determinant of fast ice extent in many regions."

Reviewer 2: General notes

R2A) I think the spatiotemporal dimensions of the landfast ice datasets you create (1km, 15-day interval) could be better justified. It's entirely reasonable to cite the data product and repeat interval of the satellite as reasons for these dimensions. However, because the purpose of this publication is to present a novel dataset for others to use, it would be a good idea to include some discussion of the advantages/disadvantages of these spatiotemporal dimensions.

As you indicate, our spatial resolution was indeed influenced by the sub-satellite (i.e., nominal) resolution of the thermal infrared channels. Our previous work using fewer swaths per compositing period was limited to a 2 km spatial resolution, but here with more swaths, we were able to get good results with a 1 km spatial resolution.

Regarding the temporal resolution of 15 days, we were driven by a desire to get a finer time-step while still precluding pack ice temporarily advected against the coast from being counted as fast ice. Another factor limiting a finer time-step is cloud coverage. We find that with a 15 day window we are generally able to build high-quality cloud-free composite imagery. We think this is near the limit though – a finer time-step is likely to result in "holes" in the cloud-free composite imagery corresponding to persistently cloudy regions.

New text added:
Line 99: "We choose a 1 km spatial resolution to match the nominal resolution of the MODIS TIR channels."
Line 126: "The 15 day time-step is chosen by balancing a desire for finer resolution against the potential for pack ice temporarily advected against the coast to be misclassified as fast ice despite no mechanical fastening taking place. Around most of coastal Antarctica, the climatological near-surface wind direction is generally offshoreward to westward (Turner and Pendlebury, 2004), thus promoting advection of pack ice away from the coast. Blocking anticyclonic pressure systems do occur in southern mid-latitudes and these can result in persistent onshoreward winds in particular regions of the Antarctic coast, although the residence time for such systems is rarely longer than one week (Massom et al., 2004). As such, a time-step of 15 days is sufficiently long to preclude most of these cases. Drifting sea ice pinned between grounded icebergs may also be misclassified as fast ice, though our earlier work showed that the persistent advection of pack ice into pre-existing coastal features is likely to be a larger problem, and that pack ice held fast between grounded icebergs may quickly become fastened (Fraser et al., 2010). Cloud coverage, which can be persistent in some regions, is a further barrier to a finer time-step when producing visible and
TIR composite images of the surface (Fraser et al., 2009)."

R2B) I understand you are intending to apply this dataset in an analysis for future publication. I would advise you either discuss how these dimensions apply to your intended use of the dataset, or how you envision others using your dataset.

This would be a good addition to the summary section. We have added a couple of sentences around this:

Line 315:
"Indeed, it is expected to generate and contribute to multiple cross-disciplinary studies of the Antarctic coastal environment. Examples include behavioural ecology of charismatic megafauna (e.g., emperor penguin colony presence/absence), the effects of fast ice on the physical oceanography of the continental shelf (e.g., influencing coastal polynya location, and subsequent sea ice production and water mass modification), and a quantification of the fresh water, nutrients

and biomass within the fast ice itself. Logistical uses are also envisioned (e.g., informing base resupply schedules). Moreover, this dataset directly addresses a key gap identified in major high-level IPCC reports, enabling improved analysis of trends and variability of this key element of the highly-vulnerable Antarctic coastal environment (Vaughan et al., 2013; Meredith et al., 2019)."

R2C) In your results section, for example, you observed an 8.3% increase in fast ice extent compared to Fraser et al.'s (2012) study, which you attributed to the switch from a 20 to 15-day stationary criterion used to identify fast ice. How do these differences in outcomes due to changes in temporal window affect what this data might be used for?

An extremely good point! We are happy to elaborate on this.

This work has shown that a finer time-step is likely to produce a larger fast ice extent, as expected. This has implications not only for the current work, but also for the next generation of SAR-based observations of fast ice, which, depending on the algorithm, can rely on two observations obtained in subsequent repeat passes. In the case of ESA's SENTINEL-1, this involves a 12-day repeat cycle. TerraSAR-X is shorter still at 11 days, although it has yet to be exploited for fast ice retrieval. Other SAR algorithms which don't rely on exact repeat orbits are able to retrieve fast ice extent over even shorter baselines (e.g., feature-tracking algorithms can deal with any baseline, as long as features are present). These are all likely to retrieve higher fast ice extents than the product here, simply due to the shorter observational baseline.

As you indicate, this probably has implications for end users. This is probably particularly true in regions of ephemeral or volatile fast ice extent. We can mitigate this to some extent with a temporally-continuous dataset such as that presented in this work. For example, we can assess the presence of fast ice across several contiguous time-steps to assess whether a particular region is likely to have volatile fast ice. In such regions, we might suspect that the reported fast ice extent in the region is likely to be higher for a finer time-step.

Text added to the manuscript: Line 266:
"This sensitivity of fast ice extent to observation time-step has implications not only for the current work, but also for the next generation of SAR-based observations of fast ice, which, depending on the algorithm, can rely on two observations obtained in subsequent repeat passes. In the case of ESA's SENTINEL-1, this involves a 12 day repeat cycle. The temporal baseline of DLR's TerraSAR-X is shorter still at 11 days, although it has yet to be exploited for fast ice retrieval. Other SAR-based fast ice retrieval algorithms which don't rely on exact repeat orbits are able to retrieve fast ice extent over even shorter baselines (e.g., feature-tracking algorithms can deal with any baseline, as long as features are present). Such methods are all likely to retrieve higher fast ice extents than the product here, simply due to the shorter observational baseline. As indicated here, differences are particularly strong in regions containing volatile fast ice. As such, end-users of fast ice products in such regions should be cognizant of this phenomenon."

R2 - Minor comments:

1) Line 67: Perhaps provide some examples of these scientific and operational uses?

As above – added at Line 315:
"Indeed, it is expected to generate and contribute to multiple cross-disciplinary studies of the Antarctic coastal environment. Examples include behavioural ecology of charismatic megafauna (e.g., emperor penguin colony presence/absence), the effects of fast ice on the physical oceanography of the continental shelf (e.g., influencing coastal polynya location, and subsequent

sea ice production and water mass modification), and a quantification of the fresh water, nutrients and biomass within the fast ice itself. Logistical uses are also envisioned (e.g., informing base resupply schedules)."

2) Line 81: The use of parenthesis to clarify the imagery dating back to the year 2000 seems out of place. It would help the flow of the introductory sentence to this section to find a way to integrate this into the sentence without the use of parenthesis.

Agreed – all bracket use now amended.

3) Line 96: I'm unsure of why "(coastline)" and "(change in)" were inserted into this sentence. Please edit the sentence to make their purpose clear.

Amended along these lines.

4) Line 98: The wording of this sentence is a little redundant. You can change it to "Temporal compositing was carried out to create cloud-free. . ." or "Temporal compositing is required to create cloud-free. . .". Since this is the methods section, the reader will already assume this is what you've done, so I would recommend the latter. It is also in keeping with the present tense used in the writing.

A good point – now amended.

5) Line 106: Because the authors are the same for the two studies cited, you can change the in-parenthesis citation to Fraser et al. (2009, 2010).

Now amended – thank you.

6) Line 107: If you are referring to both cited Fraser et al. studies, say "The earlier works", if you are referring to only one of the cited studies, specify which one.

Thanks – this is a good way to clarify.

7) Line 110: Per my comment on line 107, if Fraser et al. 2010 is the work being referenced, make mention of it earlier. Perhaps move this parenthesis citation to the end of the previous sentence that starts with "The earlier work".

OK – clarified.

8) Line 111: Overall the writing in this manuscript is well done. However there is the tendency to use parenthesis when they are not necessary. The clarification that cloud cover is a challenge for optical remote sensing in polar regions can either be integrated into the sentence, or stand as its own sentence. I would recommend the latter, as this would allow for the inclusion of study citations where optical remote sensing was challenging in polar environments.

Thank you for suggesting we revisit our use of parentheses. We have taken a more considered look at them all in the revised manuscript.

9) Line 118: Please integrate parenthesis into sentence, or create new sentence.

OK

10) Line 123: Please integrate parenthesis into sentence.

Yes, amended.

11) Line 126: Please change to “thin clouds” or “thin cloud cover”.

Done – this is in line with Reviewer 1’s comment too.

12) Line 168: Figure 1 is really well done, and does a good job complimenting the written description of the data collection process.

Thank you! We have also incorporated a flow chart as suggested by Reviewer 3, to further improve comprehension.

13) Line 182: Parenthesis integrate or remove

OK

14) Line 187: Parenthesis integrate or remove

OK

15) Lines 192 - 205: I am personally a supporter of numbered lists in publications, especially methods sections, as they are a great help for the audience. However I would recommend some consistency in how these numbered lists are used. From lines 192-205 there are two numbered lists, the first list is independent from the text in a line-by-line format. The second list is integrated in the text. I advise you pick a method of numbering and stick with it. If you choose to integrate both lists into the text, I suggest you separate them into different paragraphs so the readers do not get them confused.

Good idea. We have changed the format of the second to match the first.

16) Line 215: Add a space between the final word and the parenthesis containing the citation.

Thank you, done.

17) Line 220-223: This sentence needs work. I would advise either choosing between “ground-breaking” and “new” to avoid redundancy. Remove the parenthesis (across East Antarctica) and integrate into text. Rearrange to improve the flow. For example: “We restrict our presentation of results to the illustration of key attributes in this new pan-Antarctic fast ice dataset, and evaluate its improvements over earlier datasets created for East Antarctica (Fraser et al. 2012).

Thanks for your help with this paragraph, we agree. This has been amended.

18) Line 223-224: Remove parenthesis and integrate into text, or delete it. In this case I would advise the latter because the audience already knows you are talking about the dataset you created. Also, the comma separation breaks the flow of the sentence. Try something like: “More in-depth analysis of spatial-temporal patterns and drivers of fast ice distribution is outside the scope of this journal, but is underway for future studies (Fraser et al., in prep.).”

Thanks – that sounds better.

19) Line 227: I would remove "important new" adjectives in this sentence when you are referring to the data. The importance has already been demonstrated in the intro and discussion sections, and the purpose of the article is to introduce a novel dataset, so the audience already knows it is new.

OK

20) Line 230: Please integrate the parenthesis text into the sentence.

OK

21) Line 233: Please integrate the parenthesis text into the sentence

OK

22) Line 236: Please integrate the parenthesis text into the sentence

OK

23) Line 259-260: Can you specify any ongoing or anticipated study topics of the Antarctic coastal environment this dataset is expected to help? It's okay if there aren't any that can be specified at the present time, but it would be interesting to include if there are.

I'm happy to add some examples in the text: Line 317

"Examples include behavioural ecology of charismatic megafauna (e.g., emperor penguin colony presence/absence), the effects of fast ice on the physical oceanography of the continental shelf (e.g., influencing coastal polynya location, and subsequent sea ice production and water mass modification), and a quantification of the fresh water, nutrients and biomass within the fast ice itself. Logistical uses are also envisioned (e.g., informing base resupply schedules)."

24) Line 260: As I make clear in my summary of this manuscript above, I have no doubt this dataset is a very important contribution to Antarctic fast ice research, and will be heavily cited for years to come. However there is a certain promotional tone in this manuscript that seems out of place in a scientific article. In line 260, "major high-level" is used to emphasize the importance of IPCC reports. However, readers of ESSD will already know the importance and weight of IPCC reports, and will not need these adjectives. Unless "major" and "high-level' are established terms used to organize IPCC reports by importance, I would advise leaving them out. Throughout the manuscript you qualify mentions of your data with terms such as "new" and "ground-breaking". While this dataset is indeed new and ground-breaking, it would be better to reserve these terms for sentences when the actual importance of the data is directly addressed, rather than somewhat indiscriminately throughout the manuscript. I understand the purpose of this paper is to make the availability and utility of this new dataset known to the scientific community. I would argue, on your behalf, that the importance of the dataset you created is already evident in your paper, and the scientific community will readily understand this without the need for promotional adjectives.

Thanks for this perspective. On reflection this language does seem a little out of place here, and would be more suited to a press release, for example. We have reworked the text throughout the manuscript to tone it down.

25) Lines 263-267: Previously you used numbers when listing steps taken to accomplish a goal. I suggest using numbers here instead of letters, to maintain consistency in the paper.

OK, we have adopted this suggestion.

26) Line 269: In this paper you use the terms “spatial-temporal patterns” and “spatio-temporal patterns”. Both are valid terms, but for the sake of consistency I would pick one and use throughout.

Thanks for picking up on this inconsistency. We have chosen to use “spatio-temporal” throughout.

Reviewer 3

Main comments R3A-D:

R3A) I found the description of the algorithm in the methods section somewhat difficult to follow. I would recommend creating a flow-diagram to better illustrate how the algorithm is applied in general This diagram could then refer to Figure 1 to illustrate outputs at various steps in the algorithm. I would also like to see more detail on some aspects of the algorithm. For example, how does the algorithm deal with cases where both thermal and visible imagery are available when generating the 15-day cloud-free composite images? I would also like to see some discussion in the results section on whether there were observed differences between fast ice area products generated from visible and thermal composite images. Further, I would like to see more justification for choosing a 1-km, 15-day epoch for identifying landfast sea ice, and more discussion on how the choice of this epoch influences the generated fast ice extent products.

Similar suggestions were made by Reviewers 1 and 2. The flow chart is a great idea which we have implemented (Fig 1).

Regarding your request for more detail, this has also been requested by Reviewers 1 and 2. To specifically answer your questions here:

When visible channel information is available we parallel-process all algorithms for both the Channel 01 (visible) and Channel 31 (thermal IR) cases. Edge guesses are produced for both channels, and combined at the very last step before manual edge completion. We have added this detail to the manuscript. We are also happy to add discussion about the improvements to automation possible when visible channel information is incorporated. The 1 km, 15 day justification has been requested by Reviewer 2 as well – I paste the reply to their comment here for convenience:

As you indicate, our spatial resolution was indeed influenced by the sub-satellite (i.e., nominal) resolution of the thermal infrared channels. Our previous work using fewer swaths per compositing period was limited to a 2 km spatial resolution, but here with more swaths, we were able to get good results with a 1 km spatial resolution.

Regarding the temporal resolution of 15 days, we were driven by a desire to get a finer time-step while still precluding pack ice temporarily advected against the coast from being counted as fast ice. Another factor limiting a finer time-step is cloud coverage. We find that with a 15 day window we are generally able to build high-quality cloud-free composite imagery. We think this is near the limit though – a finer time-step is likely to result in "holes" in the cloud-free composite imagery corresponding to persistently cloudy regions.

We didn't perform independent retrieval on visible vs thermal IR input data in times of both being available. However we note that the performance of the cloud mask is generally better during times of solar illumination, leading to better quality composite images, so expect that the automation fraction is generally higher during the summer.

Changes made:
Figure 1 is new flow chart.
Complete overhaul of methods section: Line 73 to 247 – too numerous to list - see "diff" document for complete list.

R3B) I would also like to see more discussion on the fast ice distributions shown in Figure 2. Antarctic fast ice extent can be temporally variable on a regional scale, and I would argue that this variability is not captured by presenting pan-Antarctic maximum and minimum distributions. For example, the fast ice edge in McMurdo Sound in 2016 was significantly farther from the coast than shown in Figure 2 (see, for exampleMYD02.A2016350.0410.006).

We completely agree with this! However such analysis will appear in our later work, since it is out of scope for ESSD: "Articles in the data section may pertain to the planning, instrumentation, and execution of experiments or collection of data. Any interpretation of data is outside the scope of regular articles." (from https://www.earth-system-science-data.net/about/manuscript_types.html)

R3C) The authors state that the number of images contributing to the composite was increased relative to the Fraser et al. (2019) algorithm (Lines 114 + 115). I would like to see more details on how this was accomplished, particularly since the epoch was reduced from 20 to 15 days. If I understand correctly, the auto-determined fast ice edge moved an average of ∼ 10 km in a 15-day period. How does this compare to previous regional studies?

Happy to elaborate on this. Upon clarifying that statement I discovered that our earlier work (actually Fraser et al., 2010) did indeed use a slightly smaller input image density (number of images per day). However in our earlier work we considered only half as much coast (10 degrees west to 172 degrees east) so the density was in fact probably higher. However in the present work we rank our relatively fewer images more intelligently to ensure more even coverage in all regions (see response to Reviewer 1, relevant response pasted here in italics). We also use the full swath width here, whereas we trimmed in our previous work (which was more susceptible to cloud-mask inaccuracies). Thus we prefer to rewrite point 1 to state "1) ensuring a more even distribution of cloud-free scenes, thereby increasing the chance of a cloud-free view of the surface".

In line 132 we state that 600 images are incorporated into the composite images for each 15 day period, but we are happy to elaborate on this in the text by saying that these 600 images are separated into 6 regions of 100 images. Without this regional consideration, we found that there is a concentration of images in one or more particular regions based on cloud conditions, since we rank and select the 600 least cloudy granules.

New text added to manuscript: (Line 112)
"Here we rank all cloud-mask granules by their cloud content, and choose the 100 least cloudy granules in each of six regions (each approximately 60 degrees of longitude wide) around the Antarctic coast for compositing and further processing, i.e., 600 MOD/MYD02 granules in total per 15 day window. This regional consideration was implemented in an effort to ensure a more even distribution of MOD02 granules. We found that without this consideration, the ranking algorithm resulted in a high concentration of granules in a limited number of cloud-free regions at the expense of cloudy regions."

Yes, we found the auto-determined fast ice edge moves around 10 km in a 15 day period. We aren't aware of any previous regional, automated, long-term datasets but are interested in performing this kind of comparison in future work. Automated SAR products exist but are sporadic in coverage and temporal baseline, so are likely to have a confounded statistic in this regard.

R3D) The authors state that four adaptive thresholds are set when computing fast ice edge confidence, but then do not describe how these thresholds are utilised in the algorithm. Please provide this detail.

Apologies for this oversight! These thresholds are used to assign four levels of edge confidence in the automatically-determined edge map. This is the main input to the manual processing step. The manual processing links automatically-determined edges. This map showing four levels of confidence (as a grey-scale) are particularly helpful in guiding edge completion. This dot point has been changed to:
“Produce a normalised histogram of edge confidence, setting four adaptive thresholds at 0.995 (highest-confidence edge), 0.990, 0.985 and 0.980 (lowest-confidence edge). These thresholds are used to construct a grey-scale representation of the edge confidence for each pixel on the grid. Outcome: Confidence-classified automated fast ice edge map.”

1) Line 7: visible-thermal infrared imagery – change to “compositing visible and thermal infrared imagery”.

OK

2) Line 38: change “, but at a poorer spatial resolution of 6.25 km (Nihashi and Ohshima, 2015) to limit its” to “, but a poorer spatial resolution of 6.25 km (Nihashi and Ohshima, 2015) limits its”

Good suggestion, thank you.

3) Lines 65 – 75: this would fit better in the results section.

Reviewer 1 also suggested this. We moved it to the results/brief discussion section.

4) Line 66: suggest re-order “It also has a multitude of potential scientific and operational uses, given the wide-ranging importance of fast ice” to “Given the wide-ranging importance of fast ice, it also has a multitude of potential scientific and operational uses.”

Good suggestion, we have amended it.

5) Line 68: remove “developed”

Agreed.

6) Line 95: Can you estimate how time intensive it is to update the coastlines and ice shelf edge positions on an annual basis?

Also a suggestion of Reviewer 2. This update (conducted once per year, or 18 times) was small in comparison to edge completion of the 432 fast ice maps. Detail has been added: Line 92: “Although this process is entirely manual, it occurs only once per year so is not particularly laborious.”

7) Line 96: it is not clear what is meant by “change in”.

Also suggested by Reviewer 2. Has been amended.

8) Line 104: where are the data provided?

This is detailed in the abstract, the data availability section and in the reference list, and all three places are mandated by ESSD. We decided not to add this detail around Line 104 because of this.

Instead, we moved the sentence “All data are provided as Climate and Forecast (CF)-compliant NetCDF files.” to the “data availability” section (Line 273).

9) Line 139: what is meant by “successive”?

A mistake by me – also picked up by reviewer 2! This has been amended.

10) Line 139 + 140: provide more detail by what is meant by “sum over”.

As above – this mistake has now been rectified.

11) Line 142: Provide more detail on how the absolute value of the gradient for the composite image was calculated.

OK. For each pixel in each composite image (i.e., for the visible composite and the thermal IR composite images separately) the median pixel value was calculated from a 7*7 pixel neighbourhood. Then for each pixel in the median-filtered composite, the magnitude of the gradient vector was obtained. This is now explicitly stated at Line 142: “Produce gradient-median-composite images: Median-filter (using a 7*7 pixel sliding window) each composite image (i.e., visible and TIR), then take the absolute value of the gradient of this image, indicating edges in the composite image. Outcome: Gradient-mean-composite images for automated edge extraction.”

12) Line 149: remove “are set”.

Thank you – removed.

13) Lines 154 – 158: how time intensive is it (on average) to undertake manual processing of fast ice edges? How are the lead-detection images used in the manual processing?

Reviewer 1 also requested this detail. It is the most time-intensive part of the work. One year of manual processing (i.e., 24 maps) can be completed in about one week of approximately full-time work. The aim for the manual processing is to complete the auto-determined edges, so as to provide a contiguous fast ice edge which can be “bucket-filled” to represent fast ice. This detail has been added to the text, Line 172: “Carry out necessary manual processing (relatively labour-intensive, one year takes approximately 40 hours):”

14) Line 178: replace “Here and” with “Here, “

OK

15) Lines 195 + 197: provide more detail on how the mean fast ice edge separation between composite subsequent images is calculated, e.g. how do you determine which pixel in the second image to “match” with the pixel in the first image?

We find the nearest edge of similar type (manually- or automatically-determined). Cross-type edges are ignored (i.e., auto to manual, or manual to auto) to avoid confounding results. A cutoff of +/- 50 px (i.e., a 100 km window) is used as an extremely conservative upper bound to avoid the rare case of pixels matching with distant pixels. This detail has been added to the text. Line 214: “We find the nearest edge of similar type. In this step, we match automatically-determined edge pixels with the nearest automatically-determined edge in the subsequent image. Cross-type edge matches are ignored (i.e., auto to manual, or manual to auto) to avoid confounding results. A cutoff of +/- 50 px (i.e., an ∼100 km window) is used as an extremely conservative upper bound to avoid the rare case of pixels matching with distant pixels.”

16) Line 202: explain what is meant by “. . . all remaining manually-determined pixels . . .”

“Remaining” was a poor choice of word. Sentence changed to “weighting all skeletonised manually-determined pixels by their respective area”. (Line 229)

17) Line 223: replace “journal” with “manuscript”.

We did actually mean “journal” here – ESSD is only for presentation of datasets, not their scientific analysis – but agree that “manuscript” would fit equally well in this case. Changed to “manuscript”.

18) Line 248: confirm whether the time period over which these variations have been calculated is 15-days.

You’re right. This clarification has been added.

Comments on the data set

19) In the data set’s README file, it states that the latitude of true scale is 70 N. This should read 70 S.

Thank you for picking up on this error. I have amended it at the data centre.

Reviewer 4

1) How have authors distinguished between fast ice and ice shelves from satellites data? with fast ice, it is expected to occasionally collapse at the edge of the ice shelves.

This process is explained at lines 84 to 94. Particular care was paid to this process, although it is possible that multiyear fast ice was classified as ice shelf in some regions. This caveat has been added to the text: "It is possible that some very persistent multi-year fast ice is misclassified as ice shelf in limited regions, although particular care was paid to avoid this." (Line 93)

2) Regarding the Figure 4, why are the solid line discontinuous in some places in this figure?

This is a good question. This discontinuity was described in an early draft of the manuscript but was removed in an effort to keep the manuscript concise! We can spend a few words to describe this in the figure caption. "To remove noise in regions with little fast ice, 1-degree longitude bins with less than 5,000 total fast ice edge pixels across the 18 year dataset were not plotted."

3) Also, in the discussion section 3.2, the authors have described the results of the comparison between the East and West Antarctic regions. Is it possible to consider the reasons for the differences in terms of sea ice, ocean processes and/or atmospheric fields?

Absolutely – we strongly agree, and this is very high priority for future work. It's out-of-scope for an ESSD paper, unfortunately (and we think it's good to separate out the science drivers from the dataset anyway): "Articles in the data section may pertain to the planning, instrumentation, and execution of experiments or collection of data. Any interpretation of data is outside the scope of regular articles." (from https://www.earth-system-science-data.net/about/manuscript_types.html)

High-resolution mapping of circum-Antarctic landfast sea ice distribution, 2000-2018

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Abstract. Landfast sea ice (fast ice) is an important component of the Antarctic nearshore marine environment, where it strongly modulates ice sheet-ocean-atmosphere interactions and biological and biogeochemical processes, forms a key habitat, and affects logistical operations. Given the wide-ranging importance of Antarctic fast ice and its sensitivity to climate change, improved knowledge of its ~~distribution (and~~ change and variability ~~therein)~~ in its distribution is a high priority. Antarctic fast-ice mapping to date has been limited to regional studies and a time series covering East Antarctica from 2000 to 2008. Here, we present the first continuous, high ~~spatiotemporal~~ spatio-temporal resolution (1 km, 15 day) time series of circum-Antarctic fast ice extent; this covers the period March 2000 to March 2018, with future updates planned. This dataset was derived by compositing cloud-free satellite ~~visible-thermal~~ visible and thermal infrared imagery using an existing methodology, modified to enhance automation and reduce subjectivity in defining the fast ice edge. This ~~ground-breaking~~ new dataset (Fraser et al., 2020) has wide applicability, and is available at http://dx.doi.org/doi:10.26179/5d267d1ceb60c. The new algorithm presented here will enable continuous large-scale fast ice mapping and monitoring into the future.

1 Introduction

Landfast sea ice (fast ice) is a pre-eminent feature of the Antarctic near-coastal environment, where it forms a relatively narrow (several tens to ~200 ~~kms~~ km wide) zone of consolidated ice attached to grounded icebergs, coastal margins (including sheltered embayments), floating glacier tongues and ice shelf fronts (World Meteorological Organization, 1970). Depending on location, it can be either annual (forming each austral autumn-winter and melting back each spring-summer) or perennial

(Fraser et al., 2012), with multi-year fast ice attaining thicknesses up to several tens of metres (e.g., Massom et al., 2010). By forming a recurrent, persistent and highly-consolidated substrate of sea ice and snow, fast ice strongly modulates important physical and biological processes occurring at the Antarctic coastal margin - including stabilisation of ice shelves that moderate ice sheet mass loss to the ocean and resultant sea level rise (Massom et al., 2018). Given these factors, there is strong motivation for improved knowledge of its circum-Antarctic distribution, change and variability. Indeed, the lack of ~~such information~~ a long-term and continent-wide Antarctic fast ice dataset from which to accurately gauge change and variability has been highlighted as a major gap by the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (Vaughan et al., 2013) and the Special Report on ~~Oceans and the~~ the Ocean and Cryosphere (Meredith et al., 2019).

The consistent large-scale and long-term monitoring of Antarctic fast ice from space necessitates overcoming a number of inherent challenges relating to detection and resolution (both spatial and temporal), given the attributes of the satellite data themselves, and the nature of fast ice itself. For one thing, fast ice is a narrow remote-sensing target compared to the more extensive moving pack-ice zone (that is regularly monitored by coarse-resolution satellite passive-microwave sensors), and advection of pack ice against adjacent fast ice can lead to a relatively indistinct boundary between the two. Table 1 summarises the current status of Antarctic fast ice detection and mapping from space, and the advantages and disadvantages of the techniques used (see also Lubin and Massom, 2006). Wide-swath moderate-resolution satellite visible and thermal infrared (TIR) imagery offers excellent geographical coverage at kilometre-scale resolution and on daily time-scales, but it is strongly affected by persistent cloud cover year-round and polar darkness~~(~~,the latter precluding use of visible imagery in winter ~~)~~ (Fraser et al., 2009). While this limitation can theoretically be circumvented by using high-resolution Synthetic Aperture Radar (SAR) imagery (Giles et al., 2008; Li et al., 2018; Kim et al., 2020), the application of SAR to large-scale fast-ice mapping and time-series analysis has to date been limited in space and time by its relatively-narrow swath coverage and uneven image acquisition around coastal Antarctica. Satellite passive-microwave data, on the other hand, offer complete circumpolar coverage on a daily basis (largely unaffected by clouds and darkness), but ~~at~~ a poorer spatial resolution of ∼6.25 km (Nihashi and Ohshima, 2015) ~~to limit~~ limits its capability for accurate fine-scale mapping of fast ice.

As a result of these challenges and factors relating to scientific focus, the mapping of Antarctic fast ice from space has to date been largely confined to limited geographical regions (e.g., around Antarctic bases and penguin colonies) and also relatively short time series or snapshots. These are based on manual interpretation of ad hoc digitizations of satellite SAR and cloud-free visible/TIR imagery ~~(e.g., Mae et al., 1987; Ushio, 2006; Massom et al., 2009; Aoki, 2017; Kim et al., 2018; Li et al., 2018; Giles et al., 20~~ A significant advance in continuous coverage was made by Fraser et al. (2012) in their analysis of fast ice across East Antarctica (10° W to 172° E) based on compositing of cloud-free imagery from the MODerate-resolution Imaging Spectro-radiometer (MODIS) sensors onboard NASA's Aqua and Terra satellites, for the period 2000-2008. This study also used a more rigorous definition of fast ice that included a temporal criterion e.g., that sea ice must remain stationary for 20 days to be classified as fast ice (Fraser et al., 2010), but still ~~had~~ involved a significant amount of time-consuming and intensive manual analysis. Considerable progress has since been made in the automated extraction of the fast-ice edge in both MODIS (Fraser et al., 2019) and SAR image products (e.g., Kim et al., 2020; Li et al., 2018), in parallel with advancements in SAR-based fast ice detection in the Arctic e.g., Mahoney et al. (2007), Meyer et al. (2011) and Dammann et al. (2019). Improved automation is particularly important given the volume of data involved and the considerable effort that is required to manually digitize the fast ice edge using non-automated techniques (Fraser et al., 2012).

To date, large-scale and long time-series mapping of Antarctic fast ice has been confined to two datasets. These are: ~~(~~1) the manually-classified MODIS-based dataset (Fraser et al., 2012); and ~~(~~2) a fully automated Advanced Microwave Scanning Radiometer for EOS (AMSR-E)-derived time series for the time period 2003 to 2012 from Nihashi and Ohshima (2015). While the latter dataset is circumpolar in its coverage, an analysis by Fraser et al. (2019) shows a tendency of passive-microwave radiometry to underestimate fast-ice extent due to an inherent insensitivity to young fast ice <90 days old, and its relatively poor spatial resolution.

Here, we introduce and provide details of a new ~~gap-filling~~ algorithm and dataset - the first high spatio-temporal resolution (1 km; ~~15-day~~15 day) long-term time series (currently 2000 to 2018 with regular updates planned) of complete circum-Antarctic fast ice extent. This new technique is based on the compositing of MODIS cloud-free visible and TIR images using a technique described by Fraser et al. (2009), but improved and with automated extraction (as far as possible) of the fast ice edge through addition of edge-detection logic. This reduces the amount of manual interpretation required while increasing the level of objectivity in retrieving the fast ice maps. ~~Importantly from both science and logistical perspectives, this ground-breaking new dataset enables improved analysis of trends and variability in the coastal Antarctic sea ice environment - to address the major knowledge gap in IPCC reports (Vaughan et al., 2013; Meredith et al., 2019). It also has a multitude of potential scientific and operational uses, given the wide-ranging importance of fast ice. Moreover, the new algorithm developed will provide an important means of mapping and monitoring fast ice into the future and in a continuous fashion, given its applicability to the new generation of medium-resolution spectroradiometers. These include the Visible Infrared Imaging Radiometer Suite (VIIRS) on NASA's Suomi National Polar-orbiting Partnership (NPP) platform (launched October 2011); the Sea and Land Surface Temperature Radiometer (SLSTR) and Ocean and Land Colour Instrument (OLCI) on ESA's Sentinel-3 platform (launched February 2016); and the Second-generation Global Imager (SGLI) on JAXA's Global Change Observation Mission (GCOM)-C1 platform (launched December 2017).~~

In the next sections, we present a description of the datasets and updated methods used to transform MODIS imagery into consistent fast ice maps. Following this, we present the fast ice dataset and provide a comparison with the earlier East Antarctic fast ice time series from Fraser et al. (2012). Analysis of the time series, anomalies and trends for the entire circumpolar record is beyond the scope of this paper, and is the subject of ~~another study (Fraser et al., in prep.)~~a study in preparation. A major aim here is to make this dataset available to the wider scientific community, thereby facilitating collaborative fast ice-related research across disciplines.

Table 1. Table detailing techniques used to detect and/or map Antarctic fast ice, encompassing both large-scale and case studies. MODIS: Moderate Resolution Imaging Spectroradiometer (NASA). AVHRR: Advanced Very High Resolution Radiometer (NOAA). SAR: Synthetic Aperture Radar. SSM/I: Special Sensor Microwave/Imager (Defence Meteorological Satellite Program). AMSR-E: Advanced Microwave Scanning Radiometer for Earth Observation System (Japan Aerospace Exploration Agency). AMSR-2: Advanced Microwave Scanning Radiometer-2 (Japan Aerospace Exploration Agency). ALOS: Advanced Land Observing Satellite (Japan Aerospace Exploration Agency). PALSAR: Phased Array type L-band Synthetic Aperture Radar (onboard ALOS). Envisat: Environment Satellite (European Space Agency). ASAR: Advanced Synthetic Aperture Radar (onboard Envisat). RADARSAT: Radar Satellite (Canadian Space Agency).

Product	Large scale dataset or case study?	Instrument	Technique	Timespan	Temporal resolution	Spatial resolution	Spatial coverage	Advantages	Disadvantages	Publications
This work	Large scale dataset; ongoing	MODIS visible/ thermal IR	Semi-automated, composite-based	Mar 2000 – Mar 2018; updates planned	15 day	1 km	Circum-Antarctic	High spatio-temporal resolution; close agreement with Fraser et al. (2012); long and continuous time series; semi-automated	A degree of subjectivity remains; considerable manual overhead	This work
MODIS manually-digitised dataset	Large scale dataset; discontinued	MODIS visible/ thermal IR	Fully manual, composite-based	Mar 2000 – Dec 2008	20 day	2 km	East Antarctica	Medium spatio-temporal resolution; continuous time series	Fully manual	Fraser et al. (2009, 2010, 2012)
Ad-hoc MODIS and AVHRR digitisations	Case studies	MODIS and AVHRR visible/ thermal IR	Fully manual, snapshots	Nov 1978 – present	Snapshots	1 to 4 km	Focus regions	Long time series	Poor georeferencing and resolution at times (AVHRR), cloud-affected, fully manual, snapshots	Mae et al. (1987); Massom (2003); Ushio (2006); Massom et al. (2009); Aoki (2017); Kim et al. (2018); Labrousse et al. (2019)
National Ice Center charts	Large scale dataset; ongoing	Various sources (SAR, visible, TIR, scatterometer)	Fully manual, snapshots	Jul 1998 – present	Snapshots within one week	Data- and year-dependent	Circum-Antarctic	Long time series; near-real time	Unvalidated; fast ice retrieval of variable accuracy; not a consistent circumpolar product; format changes; many analysts; fully manual; coarse spatial resolution at times	N/A
Passive microwave spectral	Large scale dataset; ongoing	SSM/I, AMSR-E, AMSR-2	Principal component analysis	Dec 1990 – present	90 day	6.25 to 12.5 km	Circum-Antarctic	Fully automated	Insensitive to young (<90 day old) fast ice; coarse spatial resolution	Tamura et al. (2007, 2016); Nihashi and Ohshima (2015)
Object-based SAR	Case study	ALOS PALSAR	Object-based definition	Snapshots in 2007 and 2010	5 day	100 m	Various west Antarctic sites	High spatial resolution; reasonable accuracy; potential for extensive automation	Limited time series of underlying data	Kim et al. (2020)
SAR gradient difference	Case study	Envisat ASAR, Sentinel-1	Automated ice edge from gradient difference	Snapshots in 2008 and 2016	13 to 20 day	40 m	Prydz Bay	High spatial resolution; high accuracy; potential for extensive automation	Requires reference fast ice climatology to remove spurious edges; limited time series of underlying data	Li et al. (2018)
Motion-based SAR	Case Study	RADARSAT	Maximum cross-correlation	Snapshots in 1997 and 1999	1 to 20 day	100 m	Western Pacific Ocean sector	High spatial resolution; potential for extensive automation	Limited time series of underlying data	Giles et al. (2008)
~~Multisensor~~ Multi-sensor fusion	Large scale dataset; discontinued	MODIS, AMSR-E, SSM/I	Machine learning	2003 to 2008	20 day	25 km	Circum-Antarctic	Novel technique; automated	Low spatial resolution; apparent fast ice overestimate	Kim et al. (2015)

2 Dataset and methods

The ~~new~~ fast ice time series presented here for the entire Antarctic coastline uses imagery ~~(dating back to 2000) from NASA's~~ from the MODIS sensors on both the Terra (MOD) and Aqua (MYD) satellites, and obtained from NASA's Level-1 Atmosphere Archive & Distribution System Distributed Active Archive Center (https://ladsweb.modaps.eosdis.nasa.gov). The first ∼2 years of this dataset was produced using only Terra MODIS imagery, prior to the July 2002 commissioning of Aqua MODIS. Specifically, the algorithm uses data from the following:

- Channel 1 (visible, 620 to 670 nm) from the MOD/MYD02QKM dataset, the 250 m resolution level 1B product being available during times of solar illumination;

- Channel 31 (thermal infrared, 10.78 to 11.28 μm) from MOD/MYD021KM, the 1 km resolution level 1B product being available regardless of sunlight and providing information during periods of polar darkness;

- The high resolution georeferencing arrays from the MOD/MYD03 product; and

- The level 2 cloud mask product (MOD/MYD35_L2).

A crucial feature of the new algorithm and time series is accurate masking of the Antarctic continent, ice shelves and nearshore islands. For this, we use the MODIS-based Mosaic Of Antarctica (MOA) coastline digitisation – both the 2003-04 product (Haran et al., 2005; Scambos et al., 2007) and the 2008-09 product (Haran et al., 2014). Change in ice-shelf front location over time due to ice-sheet advance or iceberg calving necessitates progressive updates to the MOA coastline product. For this, we make annual modifications to the location of the ice-sheet margin ~~(coastline)~~ by manually digitising ~~(change in)~~ the change in the position of the ice shelf front ~~in successive 15-day visible composite images~~ once per year, at the time of annual climatological minimum fast ice extent i.e., day of year 061-075 (Fraser et al., 2012). Temporal compositing is required ~~, and carried out,~~ to create cloud-free images of the entire Antarctic coastal zone. The MOA-derived annual coastline rasters are also manually edited to correct an artefact in the coastline in the Vestfold Hills region, near Davis Station (68.5° S, 78.25° E). Although this process is entirely manual, it occurs only once per year so is not particularly laborious. It is possible that some very persistent multi-year fast ice is misclassified as ice shelf in limited regions, although particular care was paid to avoid this.

All swath-to-grid projection of the level 1 and 2 imagery is performed with the MODIS Swath-To-Grid Toolkit (MS2GT, version 0.26), available at https://nsidc.org/data/modis/ms2gt. We grid all level 1 and 2 products to a 1 km resolution polar stereographic grid with a latitude of true scale set to 70° S (grid size: 5625 * 4700 pixels, covering the expected maximum circumpolar fast ice extent), to maximise compatibility with other sea ice datasets from the NSIDC. ~~All data are provided as Climate and Forecast (CF)-compliant NetCDF files~~We choose a 1 km spatial resolution to match the nominal resolution of the MODIS TIR channels.

We broadly follow the fast ice mapping methodology developed by ~~Fraser et al. (2009) and Fraser et al. (2010)~~Fraser et al. (2009, 2010), but with significant improvements to enhance automation and objectivity in delineation of the fast ice edge. The earlier ~~work~~

~~(which focused on East Antarctica only)~~ East Antarctic work first constructed cloud-free composite images of the surface over consecutive 20 day periods, based on MODIS visible and TIR imagery and the NASA MODIS cloud mask product (Fraser et al., 2009). These composites (i.e., a TIR composite at all times of the year, and a visible composite when solar illumination was present) were then used for manual delineation of the fast ice edge (Fraser et al., 2010). The authors noted regions and times of lower composite image quality when persistent cloud obscured the surface in the majority of component images (cloud is a major issue for optical remote sensing of the surface in polar regions). In the Fraser et al. (2009) algorithm, even an optically-thin layer of ~~cloud~~ clouds in which the surface features were still discernible was excluded from the cloud-free composite image, sometimes resulting in "data holes" in the image time series. Here, we mitigate this shortcoming by: 1) ~~increasing the number of images contributing to the composite (~~more intelligently ranking cloud content and ensuring a more uniform distribution around the Antarctic coast, thereby increasing the chance of a cloud-free view of the surface~~)~~; and 2) implementing automated determination of the fast ice edge location in an independent image processing pathway which does not rely on the cloud mask product. ~~In this~~ Here we rank all cloud-mask granules by their cloud content, and choose the 100 least cloudy granules in each of six regions (each approximately 60 degrees of longitude wide) around the Antarctic coast for compositing and further processing, i.e., 600 MOD/MYD02 granules in total per 15 day window. This regional consideration was implemented in an effort to ensure a more even distribution of MOD02 granules. We found that without this consideration, the ranking algorithm resulted in a high concentration of granules in a limited number of cloud-free regions at the expense of cloudy regions.

In the latter processing pathway described above, we perform edge detection on all individual gridded MOD/MYD02 granules~~(~~, exploiting the difference in both albedo and infrared brightness temperature between ice, cloud and ocean~~)~~. This is based on the fact that both cloud and pack ice edges are dynamic between images whereas fast ice edges are likely to be relatively persistent in location (i.e., stationary). We use the ~~Canny~~ Canny (1986) edge detection method ~~(Canny, 1986)~~ to ensure that edges are correctly localised and detected only once. We then sum all edges within a ~~15-day~~ 15 day window, thereby determining which edges are ~~(most)~~ most persistent. These persistent edges are then interpreted to be either the fast ice edge or the continental margin. Since the ~~locations of continental margin change are~~ location of the continental margin is well-known~~(on much longer time-scales)~~, we exclude these edges from consideration and are thus left with a representation of the fast ice edge. This map of persistent edges over each ~~15-day~~ 15 day window forms the basis for subsequent automated circum-Antarctic fast ice edge detection. ~~An advantage of this approach is that it is less affected by thin cloud compared to the earlier image preparation techniques in Fraser et al. (2009), leading to a more complete time series~~

The 15 day time-step is chosen by balancing a desire for finer resolution against the potential for pack ice temporarily advected against the coast to be misclassified as fast ice despite no mechanical fastening taking place. Around most of coastal Antarctica, the climatological near-surface wind direction is generally offshoreward to westward (Turner and Pendlebury, 2004), thus promoting advection of pack ice away from the coast. Blocking anticyclonic pressure systems do occur in southern mid-latitudes and these can result in persistent onshoreward winds in particular regions of the Antarctic coast, although the residence time for such systems is rarely longer than one week (Massom et al., 2004). As such, a time-step of 15 days is sufficiently long to preclude most of these cases. Drifting sea ice pinned between grounded icebergs may also be misclassified as fast ice, though our earlier work showed that the persistent advection of pack ice into pre-existing coastal features is likely to be a larger problem, and that pack ice held fast between grounded icebergs may quickly become fastened (Fraser et al., 2010). Cloud coverage, which can be persistent in some regions, is a further barrier to a finer time-step when producing visible and TIR composite images of the surface (Fraser et al., 2009).

Our image processing pipeline is outlined below, and is depicted by flow-chart in Figure 1. For each ~~15-day~~ 15 day window in the March 2000 to March 2018 study period, we:

1. Download and grid all MOD/MYD35_L2 (cloud mask) granules covering the Antarctic coastal zone (approximately 1,800 granules per ~~15-day~~ 15 day interval). Outcome: A complete library of gridded cloud mask granules.

2. Rank granules by cloud content. Outcome: Ranked list of least-cloudy scenes.

3. Select the top 600 cloud-free granules, cognizant of granule location (to ensure sufficient coverage in all coastal regions). Outcome: List of 600 least-cloudy scenes with relatively even coverage around the continent.

4. Download and grid all corresponding MOD/MYD02QKM (reflectance; available during periods of solar illumination), MOD/MYD021KM (TIR brightness temperature; available year-round), and MOD/MYD03 ~~granules.~~ (high-resolution geolocation data) granules. Outcome: Library of least-cloudy reflectance and TIR brightness temperature scenes, gridded.

5. Process gridded MOD/MYD02 images for manual and automated edge-detection purposes:

   – Produce cloud-free composite images from 600 input granules: Construct thermal infrared and (when solar illumination available) visible cloud-free composite images from the gridded MOD/MYD02 and MOD/MYD35_L2 granules, following ~~Fraser et al. (2009) and Fraser et al. (2010)~~Fraser et al. (2009, 2010). Outcome: Composite images.

   – Produce Canny edge images for each granule: Canny edge-detect MOD/MYD02 granules and sum ~~over successive 15-day periods~~within the current 15 day period. Outcome: Canny edge sum image for automated edge extraction.

   – Produce Sobel edge images for each granule (Sobel, 2014): Sobel edge-detect MOD/MYD02 granules and sum ~~over successive 15-day periods (for use with manual edge delineation)~~within the current 15 day period. Outcome: Sobel edge sum image to guide manual fast ice edge interpretation.

   – Produce gradient-median-composite images: Median-filter (using a 7*7 pixel ~~window) cloud-free composite images and calculate~~ sliding window) each composite image (i.e., visible and TIR), then take the absolute value of the gradient of this image, indicating edges in the composite image. Outcome: Gradient-mean-composite images for automated edge extraction.

   – Produce modified lead-detection images after Willmes and Heinemann (2015), but with a larger filtering window of 251 pixels (originally 51 pixels) to enhance contrast in regions of fast ice. Outcome: lead-detection images to guide manual fast ice edge interpretation.

6. Construct an automated classification base image:

   – Compute the per-pixel product of the Canny edge image and the gradient-median-composite image described above, which was found to accurately and correctly locate many fast ice edges (i.e., this is an original algorithm). This product represents a continuous measure of fast ice edge confidence. Outcome: base image for automated fast ice edge extraction.

   – Produce a normalised histogram of edge confidence, setting four adaptive thresholds ~~are set~~ at 0.995 (highest-confidence edge), 0.990, 0.985 and 0.980 (lowest-confidence edge). These thresholds are used to construct a grey-scale representation of the edge confidence for each pixel on the grid. Outcome: Confidence-classified automated fast ice edge map.

   – Mask ~~an~~ the edge confidence map ~~by~~ using the rasterised MOA coastline and write out as the automated classification base image. Multiple spurious edges exist at this point. Outcome: Coast-masked automated edge image.

7. Carry out necessary manual processing (relatively labour-intensive, one year takes approximately 40 hours):

   – Close inspection ~~of~~ and completion of edges in automated classification base image, guided by: a) the Sobel edge image; b) cloud-free composites; and c) modified lead-detection images. This is used to: i) verify automated fast ice edge extraction, and ii) manually complete/add edges where automated extraction fails to detect the fast ice edge. Sobel edge detection is used in this manual step, rather than Canny edge detection, because it produces a broader (i.e., several pixels wide) edge which is tolerant of small changes in ice edge location. Outcome: Image of completed fast ice edges.

   – "Bucket fill" those pixels between the continental margin and the ~~(~~now-continuous ~~)~~ ice edge to represent fast ice coverage (extent). Outcome: Near-final image of fast ice edge and "filled" pixels.

8. Automatically remove spurious edges (i.e., edges not adjacent to fast ice) remaining from the ~~base image.~~ classified image. Outcome: Final classified fast ice image.

~~Both the cloud-free composite images and the automated classification base images are susceptible to a number of factors which can reduce their quality/utility as fast ice edge discriminators. These include: 1) persistent/heavy cloud obscuration of the surface; and 2) instances where moving pack ice is advected toward the fast ice edge, thereby reducing the fast ice-pack ice contrast in both visible and TIR images, as noted in Fraser et al. (2009). Since the final~~

Since the "bucket fill" step requires a continuous fast ice edge, and because the automatically-determined fast ice edge is often incomplete, manual intervention is frequently required both to form a continuous fast ice edge and to validate the position of the automatically-determined fast ice edge. An example classification showing both manual and automated ice edge detection is shown in Figure 2. This manual intervention is relatively time-consuming and reduces objectivity to some extent, but is considered to be a fundamental step in visible/TIR fast ice extent retrieval. It should be reiterated here that the inclusion of automatic edge determination is a considerable advance from the original fully-manual final step of edge extraction described by Fraser et al. (2010). In order to mitigate the possibility of manual edge definition contributing to false trends in the dataset and following Fraser et al. (2012), all edge verification and manual edge completion is performed in a random order.

When manual edge delineation is not possible in any given region for a particular ~~15-day~~ 15 day period (e.g., due to persistent thick cloud), the method employs a subjective definition of the location of the fast ice edge based on imagery from the immediately previous and/or subsequent ~~15-day~~ 15 day periods, following Fraser et al. (2010). An extreme example relates to the fast ice map from DOY 166-180 in 2001, during most of which the Terra MODIS instrument was in “safe mode” and acquired no data. Here~~and~~, in the interest of providing a temporally-contiguous dataset, we opt to use the fast ice map from the following timestep (DOY 181-195, 2001) but mark all edges as “manually-determined” to indicate higher uncertainty in the fast ice edge retrieval for DOY 181-195 (2001).

Determination of uncertainty for this dataset (in both edge location and resulting fast ice areal extent) requires careful consideration. The primary uncertainty arises from digitisation error~~(~~, typically given in pixels~~)~~, in areas of manual ice edge determination, which then propagates to an areal uncertainty value. However, neither the digitisation error nor the propagation to an areal uncertainty are straightforward to determine/quantify. Prior work made broad estimates of the manual digitisation error by carrying out an independent re-digitisation of a subset of the fast ice edge and resolving differences in the resulting fast ice area (Fraser et al., 2010). This approach, however, requires both extrapolation of errors from a small subset to the entire dataset and duplication of time-consuming manual edge extraction. In our modified approach ~~(presented here)~~presented here, we employ a novel alternative approach for uncertainty estimation which addresses these shortcomings. This involves analysis of the per-pixel difference in ice edge location in two consecutive fast ice maps, for all pairs of consecutive images in the entire dataset. In the case of an automatically-extracted fast-ice edge pixel, this difference purely reflects the change in location of the ice edge (plus or minus a small, sub-pixel scale digitisation error, which we also quantify). In the case of a manually-extracted ice edge pixel, it reflects the sum of the ice edge change plus the digitisation error. Thus, to estimate the digitisation uncertainty, we:

1. assume that automatically-determined edges are accurate in location (an appropriate assumption due to excellent edge localisation of the Canny edge detection filter underpinning the automation);

2. quantify the mean fast ice edge separation between subsequent images only for automatically-determined edge pixels~~, to~~. We find the nearest edge of similar type. In this step, we match automatically-determined edge pixels with the nearest automatically-determined edge in the subsequent image. Cross-type edge matches are ignored (i.e., auto to manual, or manual to auto) to avoid confounding results. A cutoff of +/- 50 px (i.e., an ~100 km window) is used as an extremely conservative upper bound to avoid the rare case of pixels matching with distant pixels. We thereby produce a mean measure of ice edge location change between two consecutive ~~15-day~~ 15 day time periods;

3. ~~quantify the mean fast ice edge separation between subsequent images only~~ as above but for manually-determined edge pixels, to produce a mean measure of ice edge change plus digitisation error; and

4. subtract the former from the latter, resulting in a digitisation error estimate for manually-determined ice edge pixels.

We also estimate the sub-pixel error in digitisation, i.e., grid-scale effects in the digitisation error. This estimation is achieved by performing 10,000 simulations of a one-dimensional random edge position and compare it to the centre location of a sample pixel. The RMS of the residual between the genuine pixel centre and the simulated centre is taken to be the sub-pixel error. Thus, the automatically-determined edge error is taken to be the sub-pixel error only, and the manually-determined edge error is taken to be the quadrature sum of the sub-pixel and manual digitisation errors. Following estimation of ~~the manual digitisation error~~both the manual and sub-pixel digitisation errors, we estimate areal uncertainty for each fast ice map by: ~~1) ensuring that the manually-determined fast ice edge is~~

1. ensuring that all fast ice edges are one pixel wide by performing a morphological skeleton operation; ~~2) weighting all remaining manually-determined~~
2. weighting all skeletonised edge pixels by their respective area; then ~~3)~~
3. multiplying by the ~~digitisation~~ appropriate error, as estimated above.

This approach to areal uncertainty calculation is highly conservative (i.e., likely an overestimate) since it assumes that all errors occur in the same direction; in reality, digitisation errors are likely to produce both underestimates and overestimates of fast ice extent in equal measure. Furthermore, cyclonic systems which may cause wind-blown regional fast ice breakout (Massom et al., 2009) also typically bring extensive cloud cover. In this way, image subsets requiring manual fast ice edge delineation are more likely to be produced during times of wholesale ice edge change, thereby falsely inflating the uncertainty estimates.

Regarding the fast ice dataset product, we provide the method of edge determination (“automatic” or “manual”) in the output dataset, for each pixel of fast ice edge. We also compute the mean percentage of automatically-determined ice edge pixels in each 1° longitude bin. As a further indication of dataset integrity, we quantify differences between the new fast ice dataset and the Fraser et al. (2012) East Antarctic-only dataset for the period and region of overlap (10° W to 172° E, north of 72° S, March 2000 to December 2008). Large tabular icebergs are removed from the fast ice classification where independent iceberg information is available and/or the icebergs are clearly visible, but manual discrimination between fast ice and large tabular icebergs is difficult at times due to a lack of contrast in the satellite imagery (Fraser et al., 2010). Similarly, myriads of small icebergs embedded/grounded in places in the fast ice (Massom et al., 2009) are difficult to distinguish and remove, but form an integral part of the fast ice matrix. Following Fraser et al. (2010), we classify such regions of fast ice containing many small grounded icebergs as fast ice. Regions of ice mélange at the front of ice shelves are another source of uncertainty here, but remain unquantified due to their negligible areal extent on a continental scale.

3 Results and brief discussion

~~Here, we~~ We restrict our presentation of results to ~~illustrating~~ illustration of the key attributes of this ~~ground-breaking new dataset in its circumpolar entirety, while also evaluating improvements compared to the earlier mapping of fast-ice extent (across East Antarctica) by Fraser et al. (2012) and~~ new pan-Antarctic fast ice dataset, and evaluate its improvements over earlier datasets created for East Antarctica (Fraser et al., 2012). We also present quantification of uncertainties. More in-depth analysis of ~~spatial-temporal patterns~~ spatio-temporal patterns and drivers of fast ice distribution ~~(based on this dataset), and their drivers,~~ is outside the scope of this ~~journal~~ manuscript, but is underway ~~(Fraser et al., in prep.)~~for future studies.

3.1 Circumpolar distribution of fast ice at maximum and minimum extent, and cross-comparison with earlier work

We illustrate the envelope of circum-Antarctic fast ice extent throughout the 18-year dataset time series by showing its spatial distribution at maximum (occurring in 2006, at DOY 271-285) and minimum (2009, DOY 061-075) extent in Figure 3. Figure 4 then shows a cross-comparison of this ~~important new~~ dataset with that of Fraser et al. (2012), covering the area and period of overlap. The total East Antarctic fast ice extent in the new dataset is 8.3 % greater than that reported in Fraser et al. (2012), on average. This difference is attributed to two factors: 1) a "relaxation" of the temporal fast ice condition in the new algorithm ~~(from the 20-day~~ from the 20 day criterion used in Fraser et al. (2012), i.e., more ice remains "fast" ~~(stationary)~~ for 15 days than for 20 days~~)~~; and 2) the enhanced ability of the new "persistence of edges" algorithm to retrieve fast-ice extent under cloud cover. The largest differences between the two datasets are encountered at $\sim$118° E and 152° E. These two longitudes correspond to areas of dynamically-formed "semi-fast ice", i.e., regions where pack ice is blocked from westward advection~~(and intercepted)~~, and intercepted by upstream obstacles e.g., large grounded iceberg B9B prior to its ungrounding in 2010 (Massom et al., 2010). In such regions, fast ice tends to be more exposed and ephemeral i.e., it can intermittently break out to become pack ice but then reform, on a synoptic scale. As such, reducing the temporal "fastness" condition ~~(~~to 15 days ~~)~~ produces relatively large differences in these regions.

This sensitivity of fast ice extent to observation time-step has implications not only for the current work, but also for the next generation of SAR-based observations of fast ice, which, depending on the algorithm, can rely on two observations obtained in subsequent repeat passes. In the case of ESA's SENTINEL-1, this involves a 12 day repeat cycle. The temporal baseline of DLR's TerraSAR-X is shorter still at 11 days, although it has yet to be exploited for fast ice retrieval. Other SAR-based fast ice retrieval algorithms which don't rely on exact repeat orbits are able to retrieve fast ice extent over even shorter baselines (e.g., feature-tracking algorithms can deal with any baseline, as long as features are present). Such methods are all likely to retrieve higher fast ice extents than the product here, simply due to the shorter observational baseline. As indicated here, differences are particularly strong in regions containing volatile fast ice. As such, end-users of fast ice products in such regions should be cognizant of this phenomenon.

3.2 Quantification of dataset objectivity and error estimation

Both the cloud-free composite images and the automated classification base images are susceptible to a number of factors which can reduce their quality/utility as fast ice edge discriminators. These include: 1) persistent/heavy cloud obscuration of the surface – particularly during times of no solar illumination when the cloud mask product is less accurate (Ackerman et al., 2006);

and 2) instances where moving pack ice is advected toward the fast ice edge, thereby reducing the fast ice-pack ice contrast in both visible and TIR images, as noted in Fraser et al. (2009).

Manual delineation ranges from being relatively straightforward (in the case of high quality composite imagery, where few judgement-calls need to be made) to quite labour intensive (in the case of heavy cloud obscuring the surface, resulting in ambiguous fast ice edge delineation, and requiring the use of the previous and next 15 day period's composite imagery for guidance). On occasion, such judgement-calls have the potential to significantly impact a single period's fast ice extent retrieval, albeit in a limited region.

A broad measure of objectivity in fast ice extent retrieval is the percentage of edges that could be retrieved automatically. This is plotted in Figure 5. The circum-Antarctic mean automation percentage is 58%. East Antarctica is characterised by generally high automation percentages ($\sim$50 to 90%) – with the exception of localised pockets (down to 37%) located in Wilkes (98° to 108° E and 126° to 138° E) and George V lands (150° to 153° E). In West Antarctica, automation percentage is high (generally 70 to 90%) in the eastern Weddell Sea and Ross Sea (50 to 85%), but low in the Bellingshausen and Amundsen seas sector (40 to 60%) and along both flanks of the Antarctic Peninsula (as low as 22%). ~~This~~ By showing longitudes with a low automation fraction, this plot also indicates areas which tend to be most affected by inherent issues detailed in the Methods Section, i.e., persistent cloud cover and/or persistent advection of pack ice toward fast ice that reduces the contrast ~~in (~~(in reflectance and surface temperature) between pack and fast ice.

We have taken steps to mitigate this here compared to our earlier work (e.g., by now considering edges visible even under thin cloud; by more intelligently selecting the least-cloudy MODIS data for each 15 day period). Here, our approach is still limited by relatively poor MOD/MYD35 cloud mask product accuracy at times. In the future, we are interested in implementing state-of-the-art machine-learning cloud masking algorithms to mitigate this (e.g., Paul and Huntemann, 2020). This improvement may lead to an automation percentage in excess of the 58% reported here.

As detailed in the Methods Section, we estimated the sub-pixel error, applicable to both automatically- and manually-determined edges, as well as the manual-only error in digitisation. By simulation, the sub-pixel error is determined to be 0.288 pixels. We developed a novel technique to quantify the error in manual estimation of fast ice edges. We find that, on average, manually-determined edges ~~temporally vary~~ change in location by 5.47 pixels more than that for automatically-determined edges (auto-determined = 10.06 pixels vs manually-determined = 15.53 pixels) in subsequent 15 day windows. Thus, the automatically-determined edge error is 0.288 pixels, and the manually-determined edge error is the quadrature sum of 0.288 and 5.47 pixels, i.e., 5.48 px. For each ~~15-day~~ 15 day epoch, we obtain a conservative estimate of the fast ice areal uncertainty by multiplying ~~the number of manually-determined pixels by the equivalent distance of 5.47~~ each skeletonised edge pixel by the appropriate error estimate, in km, assuming that the nominal resolution of 1 km/pixel applies everywhere in the domain. This uncertainty in fast-ice area has a mean value of ~~7.3~~ 7.8% when averaged across the entire circum-Antarctic dataset. This is ~~similar to~~ somewhat larger the value of 4.38% uncertainty obtained in regions requiring >10% manual edge delineation, as detailed in Figure 5 from Fraser et al. (2010) using traditional re-digitisation-based error estimation, confirming that the new method is conservative.

4 Summary

Here we have both introduced: 1) a new improved technique for mapping and monitoring coastal fast ice coverage around Antarctica at high resolution, and 2) the most complete time series of Antarctic fast ice extent to date. This ~~ground-breaking product represents an important~~ product represents a new baseline against which to gauge change and variability in both the ice and climate, and has wide applicability. Indeed, it is expected to generate and contribute to multiple cross-disciplinary studies of the Antarctic coastal environment. ~~Moreover, it~~ Examples include behavioural ecology of charismatic megafauna (e.g., emperor penguin colony presence/absence), the effects of fast ice on the physical oceanography of the continental shelf (e.g., influencing coastal polynya location, and subsequent sea ice production and water mass modification), and a quantification of the fresh water, nutrients and biomass within the fast ice itself. Logistical uses are also envisioned (e.g., informing base resupply schedules). Moreover, this dataset directly addresses a key gap identified in major high-level IPCC reports~~regarding~~, enabling improved analysis of trends and variability of this key element of the highly-vulnerable Antarctic coastal environment (Vaughan et al., 2013; Meredith et al., 2019).

The new algorithm also provides an important means of mapping and monitoring fast ice into the future and in a continuous fashion, given its applicability to the new generation of medium-resolution spectroradiometers. These include the Visible Infrared Imaging Radiometer Suite (VIIRS) on NASA's Suomi National Polar-orbiting Partnership (NPP) platform (launched October 2011); the Sea and Land Surface Temperature Radiometer (SLSTR) and Ocean and Land Colour Instrument (OLCI) on ESA's Sentinel-3 platform (launched February 2016); and the Second-generation Global Imager (SGLI) on JAXA's Global Change Observation Mission (GCOM)-C1 platform (launched December 2017).

Although an element of subjectivity remains in the large-scale retrieval of fast ice coverage from satellite visible/thermal infrared imagery, we have mitigated this to some extent. This has been achieved by: ~~a~~1) implementing an automated ice edge-retrieval algorithm~~(~~, resulting in successful extraction of ∼58% of ice edge pixels~~); b~~; 2) performing random manual extraction to eliminate false trends; ~~c~~3) quantifying the uncertainty associated with manual edge delineation (~~7.3~~ 7.8 % of fast ice area retrieval, on average); and ~~d~~4) performing a cross-comparison with a similar (but independent) spatially- and temporally-overlapping dataset (Fraser et al., 2012). Crucially, this new MODIS-based dataset provides the longest contiguous time series of this key element of the Antarctic cryosphere while offering complete circum-Antarctic coverage for the first time at high resolution.

Multi-sensor fusion would help to further mitigate the subjective elements of this dataset to some extent. As an example, we used AMSR-E, in our previous work (Fraser et al., 2010). However, mission overlap generally limits the time period able to be considered in multi-sensor fusion algorithms (e.g., AMSR-E was launched 2.5 years after Terra MODIS, and was effectively decommissioned in 2011).

Analysis of spatio-temporal patterns, variability and trends in circum-Antarctic fast ice coverage is underway, using this dataset (Fraser et al., in prep.), as is related work determining and evaluating the drivers of these observed patterns. Moreover, we plan to study the spatial distribution of fast ice extent in the context of a ~~major new coastal configuration and complexity dataset for~~ new dataset describing the multiscale complexity and configuration of the coastline (including aspect) around

Antarctica (Porter-Smith et al., in review, 2019), ~~to explore possible linkages~~under the hypothesis that the coastal configuration is a first-order determinant of fast ice extent in many regions.

5 Data availability

The dataset has been made available at the Australian Antarctic Data Centre at http://dx.doi.org/doi:10.26179/5d267d1ceb60c, as a series of Climate and Forecast (CF)-compliant NetCDF files (Fraser et al., 2020). This dataset contains the following fields:

- Fast ice time series - presented as classified maps of the surface type (fast ice interior pixel; automatically-determined fast ice edge; manually-determined fast ice edge); and
- Latitude, longitude and area of each pixel.

There are plans to regularly update and extend the time series forwards in time, on a biennial basis, until the demise of both MODIS platforms but continuing with next-generation imaging spectroradiometers after this time.

Author contributions. ADF led the study, acquired the data, developed automation algorithms, manually digitised fast ice, produced figures, and wrote the manuscript. RAM and KIO contributed equally toward project genesis and direction. SW contributed to algorithm automation development. PJK assisted with manual digitisation. JC and RP-S packaged the dataset for distribution. All authors edited the manuscript.

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

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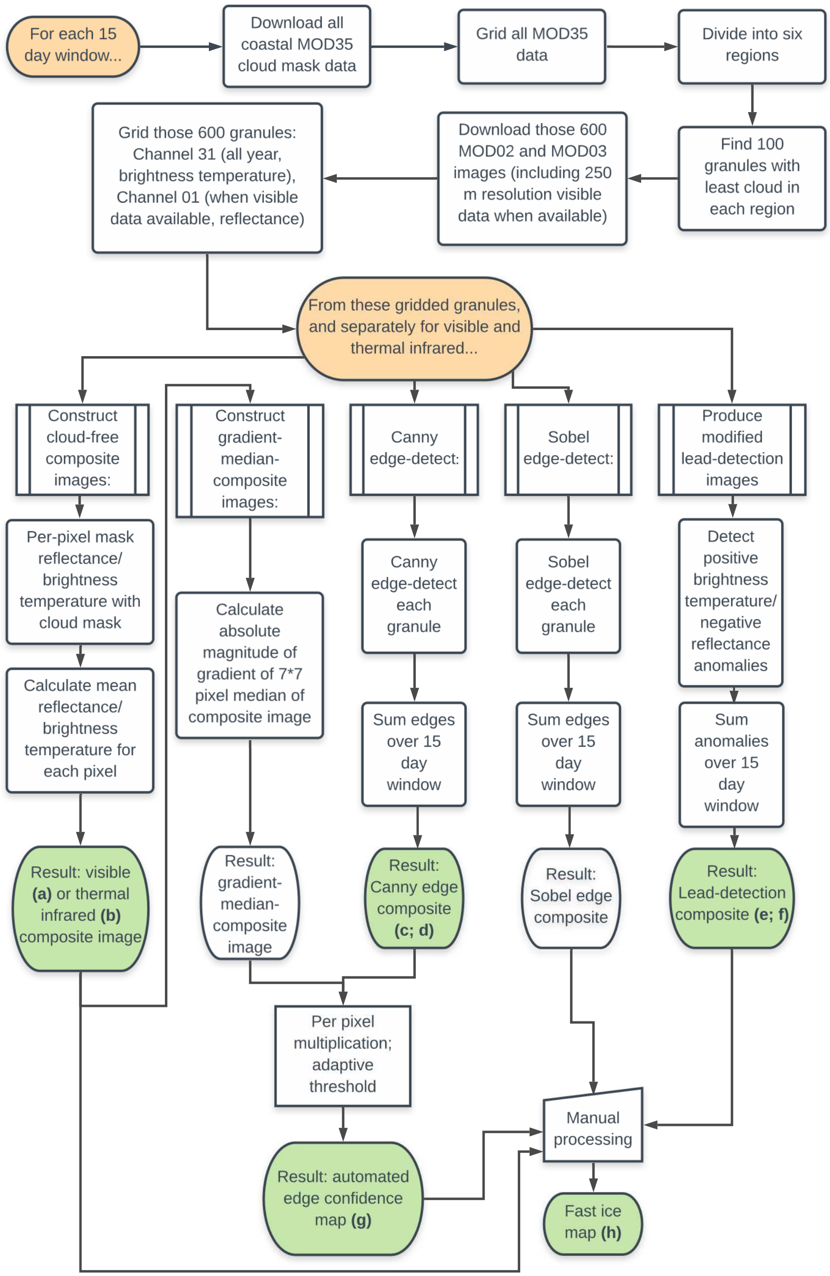

Figure 1. Flow chart depicting the image processing pipeline. Bold letters within the green-coloured elements refer to individual panels in Figure 2.

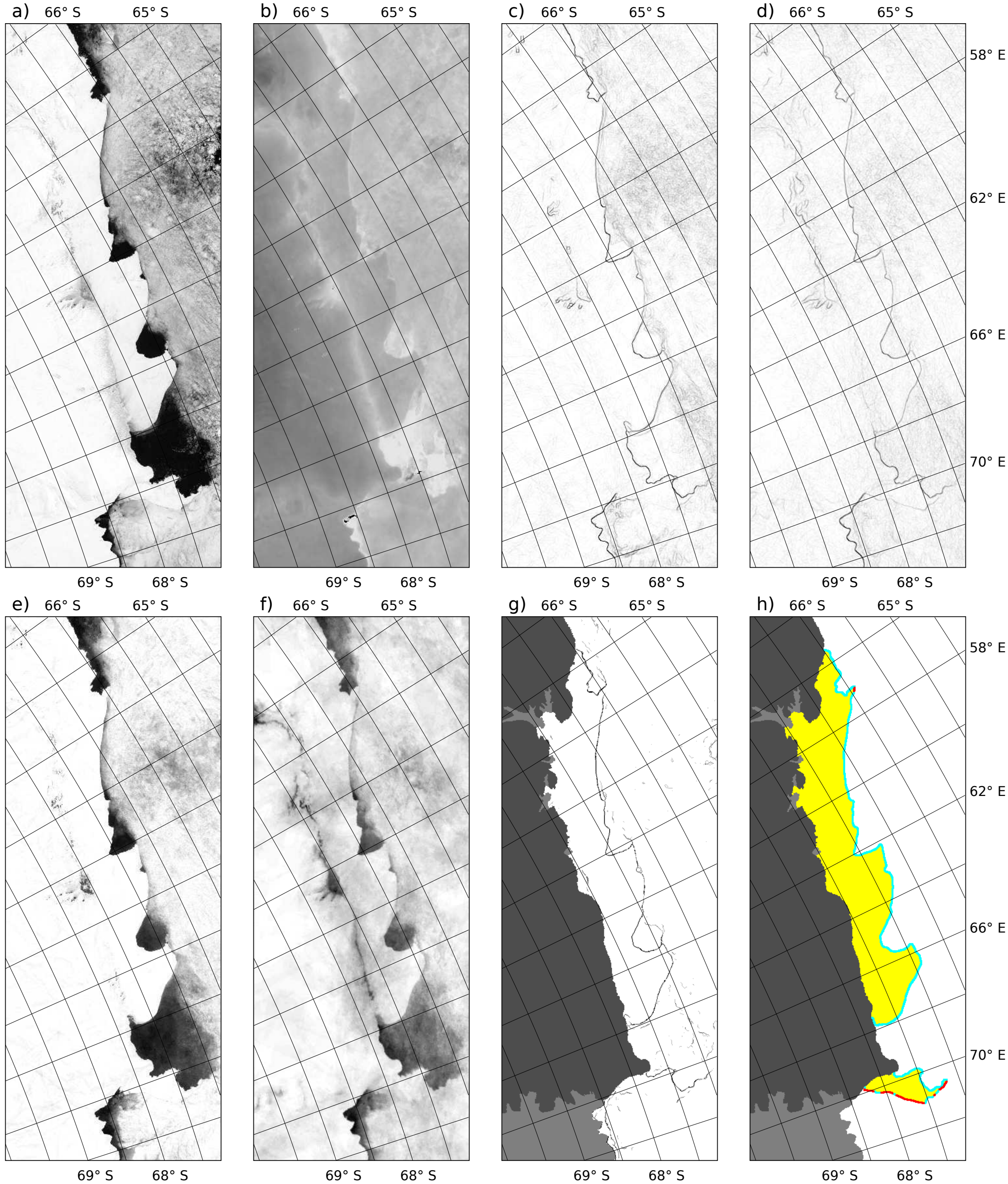

Figure 2. Figure depicting an example of the automated fast ice edge detection along the Mawson Coast, East Antarctica, for DOY range 316-330, 2005. See the red rectangle in Figure 3 for spatial context. a) and b): ~~15-day~~ 15 day channel 1 (visible) and channel 31 (thermal infrared) cloud-free composite images, respectively. c) and d): Sum of Canny algorithm-detected edges in individual channel 1 and channel 31 images respectively, for the ~~15-day~~ 15 day period. e) and f): Modified lead-detection for channel 1 and channel 31 images, respectively (after Willmes and Heinemann, 2015, but with an enlarged filtering window to enhance fast ice detection). g) Results of the combined edge detection algorithm (black line). Light and dark grey areas represent grounded and floating glacial ice, respectively, and are masked out. h) Fast ice classified map after manual edge inspection/correction and filling. Cyan and red represent automatically- and manually-completed edges, respectively, and the width of these lines has been expanded in this example to enhance visibility. Yellow represents infilled fast ice area.

Figure 3. Fast ice distribution at times of maximum (occurring in 2006, DOY 271-285; shown in yellow) and minimum (2009, DOY 061-075; shown in orange) extent over the ~~18-year~~ 18 year dataset period. The grounded Antarctic Ice Sheet and floating ice shelves are shaded light and dark blue, respectively. The red rectangle shows the region used to illustrate the automation in Fig. 2.

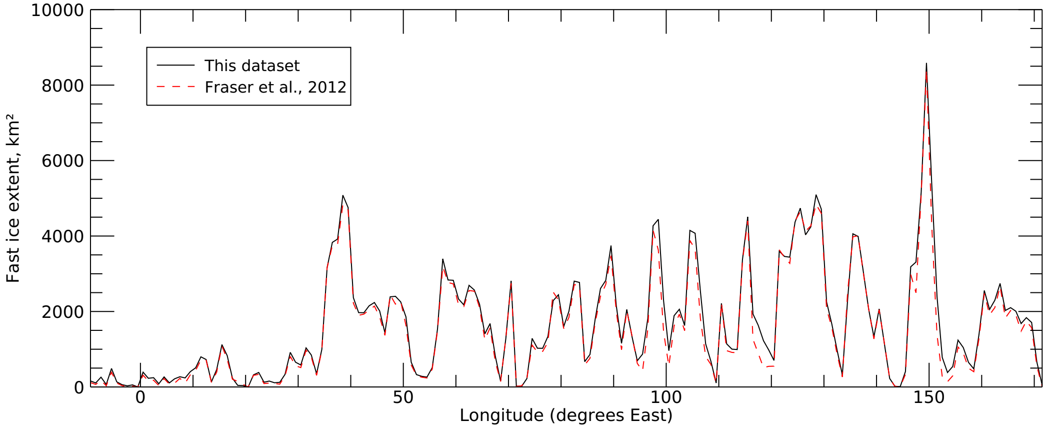

Figure 4. Mean fast ice extent per degree of longitude for this new improved dataset (black solid line) and Fraser et al. (2012) (dashed red line), for the period and region of time series overlap (March 2000 to December 2008, 10° W to 172° E).

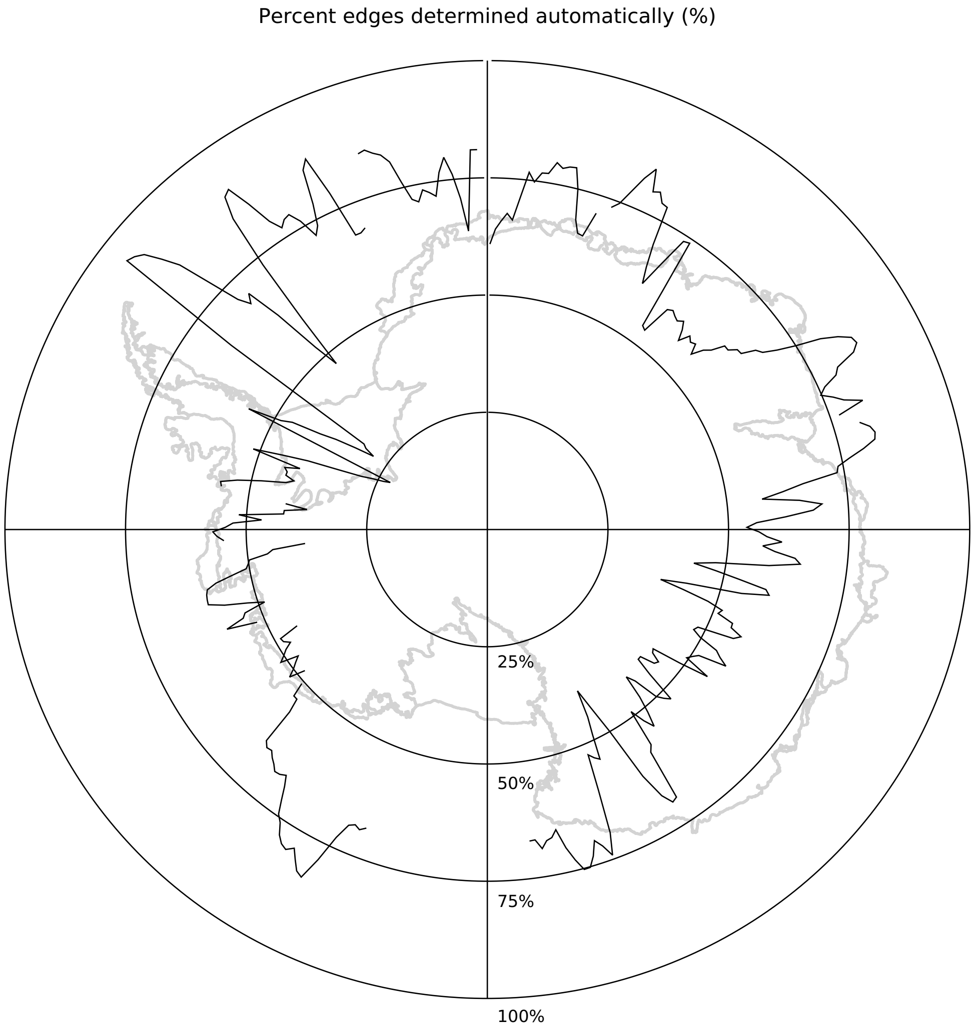

Figure 5. Polar plot showing the percentage of edges determined automatically, as a function of longitude. The Antarctic continent is outlined in grey for spatial context. To remove noise in regions with little fast ice, 1° longitude bins with less than 5,000 total fast ice edge pixels across the 18 year dataset were not plotted.