

Comments on “Triggers of the 2022 Larsen B multi-year landfast sea ice break-out and initial glacier response” by N.E. Ochwat et al., tc-2023-88

This paper presents an important case-study analysis of the region of perennial fast ice that formed in the embayment previously occupied by the former Larsen B Ice Shelf following its disintegration in 2002. Specifically it uses a combination of observational, reanalysis and remote-sensing data to examine the causes (“triggers”) of a major fast-ice break-out event in 2002, and shows the effects of the latter on the speed, elevation and calving behaviour of various outlet glaciers feeding into the embayment. In so doing, it confirms the findings of a number of recent studies that highlight the important role of fast ice in mechanically buttressing adjacent glaciers and ice shelves, and the linkage between fast ice loss and changes glacier/ice shelf dynamics and calving behaviour - with this effect being modulated by surrounding pack ice that damps the impact of waves in breaking up the fast ice. An additional important finding of this study is that substantial decreases in glacier elevation occurred in response to loss of the fast ice buttress, in concert with major floe speed increases – in much the same way as occurred following the Larsen B disintegration.

In summary, this paper makes a valuable contribution to a growing corpus of work that highlights previously overlooked and poorly-quantified though crucially-important linkages between sea ice (change) – both in the form of stationary coastal fast ice and moving pack ice – and (change in) glacier and ice-shelf dynamics. This is particularly timely, given the current state of Antarctic sea ice and the increasing concern over Antarctica’s contribution to sea-level rise. Having said this, there are a number of issues that I feel need to be addressed in order to improve the paper.

The science questions addressed are well within the scope of TC, and I recommend publication subject to substantial revisions, as laid out below.

Please find below my overall comments, followed by a more detailed listing of suggestions. I hope these are useful and help improve the paper.

Overview Comments

1. The paper itself is generally well written, apart from minor issues relating to inconsistent use of tense and minor grammatical errors. However, the text seems overly long, and could benefit from being substantially shorter and more concise. This would make it more readable while telling the story more clearly – leading to greater impact in this journal.
2. The terms “sea ice” and “fast ice” are used interchangeably. Explain the difference between fast ice and pack ice upfront in the introduction, then refer specifically to fast ice and pack ice as appropriate (or overall sea ice – which is what the passive microwave dataset gives). See my Comment against Line 41 below (in Specific Comments).
3. May I suggest that the Data and Methods Section be shortened and restructured around the variables and phenomena being investigated – with these being grouped accordingly – rather than listing (working through) the individual datasets themselves. This would also help focus the paper more fully on the story being presented, which is certainly a good one, while also minimising repetition and improving the “readability” of the paper. For example, an introductory sentence or two/three (preface) could be added immediately after the Section 3 heading (between lines 99 and 100), along the lines of – “The linkages between fast ice..... and glacier events were detected and analysed using a combination of observational, reanalysis and remote-sensing data. (NB then briefly adding the high-level information about the individual datasets i.e., what they are/names, where they are obtained from).” Then, subsequent sub-sections could consolidate information currently scattered across the sub-sections by focussing on the different sub-topics - in a more logical sequence than is currently the case, and with

emphasis on the techniques used. Section 3.1. could/would then become “Sea Ice Change and Variability” – pulling together information relating to how the fast ice breakout event was detected and monitored; detection of open-ocean corridors in the adjacent pack ice; and fast ice surface melt was determined and mapped. Then Section 3.2 could be “Glaciological Characteristics”; and Section 3 “Atmospheric and Oceanic Factors”.

4. The Results (Section 4) is very long and contains detailed information about the timings of the different events (corridor formation, fast ice breakup, calving, glacier acceleration, elevation change etc. for each glacier) that is difficult to follow. This section could be shortened substantially by (1) condensing the results into a Table (or two), and by (2) adding a timeline schematic along the lines of Figure 11 in <https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2014JF003223>. This would again substantially improve the readability of the findings and increase their impact. It’s hard to follow the different timings and events – and how they line up – in the current text.
5. The Discussion (Section 5) is also very long in the way that it works through all of the topics in sequence. This could be substantially shortened – and repetition of Results avoided – by focussing on synthesising the main findings into a coherent story around why the fast ice breakout did not occur until 2002, and what the effects were then on the glacier systems – referring back to the suggested timeline schematic figure and associated Tables.
6. The claim in Lines 315-316 and elsewhere (e.g., Lines 495-496, 503-504) that in January 2022, a relatively ice-free corridor connected the fast ice front area to the open Southern Ocean for the first time since persistent fast ice formed in 2011 needs backing up with further evidence. This assertion is based on Figure 6b, which gives sea ice area in an offshore box for January 19 only for the years 2010 to 2022 (I’m sorry but I don’t have access to Figure S5 which is also referred to). I did a quick search through past satellite sea-ice concentration images and also found the persistent occurrence of a corridor in February 2021 (for example). This begs the question – why did the fast ice breakout only occur in January 2022 and not earlier? It also suggests that the fast ice breakout in 2022 may be due to a combination of factors, and not only exposure to ocean swells (as stated in Lines 27-29 of the Abstract and elsewhere).
7. Section 5.3 should specifically refer back to, and compare the new findings with, other studies from elsewhere around Antarctica by Miles et al. (2018), Arthur et al. (2021), Greene et al. (2018) and Gomez-Fell et al. (2022) regarding relationships between fast ice presence/absence and both (1) glacier calving and (2) speedup (i.e., buttressing).
8. Re the Figures – may I recommend marking key phenomena/events referred to in the text directly on the figures (e.g., X, Y or the like), such that pointers can then be given in the text e.g., “....this event is marked X in Fig. XXa”. This will greatly help the reader.
9. General comment re the Figures – the colours are challenging to differentiate (at least for me) – e.g., Figures 8 and 9. Also, Figure 9 is too complicated – too many lines. This could be substantially simplified by reducing the number of lines (while including the results in a table). The satellite image in Figure 10 is indistinct and difficult to interpret – this could be improved by adding boundaries and marking key features.
10. The paper is generally well referenced, but I’ve made suggestions regarding adding a few key references that are missing. Also, the order of referencing is neither chronological nor alphabetical e.g., Lines 527-528

Just one other thing – I note that the authors (or rather the lead author and 2 others) have also submitted a shorter version of this topic for publication as a “sidebar” in the annual State of the Climate Report for 2022 (in press in the Bulletin of the American Met Soc) – and with a similar title. It may be best if the authors refer to this other publication upfront in this new paper. May I suggest that this information be added in a sentence at the very end of the Introduction (onto Line 72) –

stating that a shortened version is in press in BAMS (and referencing that). However, this will also need to briefly state how this paper differs from that sidebar i.e., why this new paper is necessary.

Specific Comments and Suggestions

Line 36 – 2008 and 2009 (add Braun, M., Humbert, A. & Moll, A. Changes of Wilkins Ice Shelf over the past 15 years and inferences on its stability. *Cryosphere* **3**, 41–56, 2009)

Line 41 – “...and outer-margin calving due to ocean swell-induced flexure (Massom et al., 2018). Massom et al. (2018) further implicate loss of attached landfast sea ice (fast ice) in the Wilkins Ice Shelf breakup events, following loss of a protective pack ice buffer offshore – due to the vulnerability of fast ice to ocean swells (Crocker and Wadhams, 1989). While fast ice is consolidated sea ice that remains stationary attached to the coast (Fraser et al., 2021), pack ice refers to sea ice that is constantly in motion under the influence of winds and ocean currents.” REFERENCE - G.B. Crocker, P. Wadhams, Breakup of Antarctic fast ice, *Cold Regions Science and Technology*, 17 (1), 61-76, [https://doi.org/10.1016/S0165-232X\(89\)80016-3](https://doi.org/10.1016/S0165-232X(89)80016-3), 1989.

Line 45 – what is meant by “increase ocean swell”?

Line 50 – replace “catastrophically” with “substantially”.

Lines 56-58 (“Fast ice.....”) – remove.

Lines 58-60 – inappropriate to have this Result in the Introduction – move this to the appropriate place. It’s also not clear how these thicknesses were derived. ALSO – line 60 – “containing both fast ice and glacial ice”.

Lines 65-68 – this should also refer to other studies relating fast ice to glacier calving and advance/speed e.g., Miles et al. (2018), Arthur et al. (2021), Greene et al. (2018) and Gomez-Fell et al. (2022).

There is a need to introduce the concept of the damping of waves by pack ice, with references. This is central to the ocean corridor concept proposed by Massom et al. (2018).

Lines 68-72 – define buttressing.

Line 67 – add Massom et al. (2010) after “collapse”.

Line 76 – “south”.

Line 78-79 – To the east, the northwestern Weddell Sea is generally covered by pack ice.

Line 83 – NB there’s more to the Larsen B breakup than this (hydrofracture) alone – refer back to Lines 37-41, and my Comment on Line 41 above. RE THIS, Lines 80-84 could probably be merged into Lines 33-36.

Line 102-103 – remove “a climate...ECMWF”.

In Section 3 and in the appropriate place, add – “Following Massom et al. (2018) and Teder et al. (2022), we investigate the occurrence of open-ocean corridors across the sea ice zone, enabling ocean swells to interact in an unobstructed fashion with the Larsen B embayment fast ice”.

Lines 139-141 – not clear what this means.

Line 147 “several...images”

Line 152 – image cross-correlation

Line 161 – images

Line 162 “estimated from the location of a break in slope”

Line 164 – what is listric faulting?

Lines 179-180 – different tenses. Be consistent throughout the paper.

Line 181-182 – what is meant by “Assuming snow is negligible”? Also, what is this assumption based on?

Line 183 – why were these density values chosen (based upon what)?

Lines 189-194 – Did AMIGOS also provide meteorological information?

Line 202-210 – how was fast ice area determined. Were there any difficulties in distinguishing the boundaries?

Line 205 unclear – how does an edge reform?

Line 209 – not clear what “the edge broke out” means.

Lines 2002-210 – this needs a figure to show the sequence of events discussed, as a series of outer margin lines.

Line 212 – “occupation of”

Line 218 – “reformed into”

Line 219 – “advanced 16 km from February 2011 to XXXX”

Line 220 – “while Punchbowl”

Lines 223-224 – why is there a seasonal cycle in the Scar Inlet Ice Shelf flow speed? And is this a feature of all of the glaciers investigated? Please add this information.

Line 232 – it’s hard to see the fractures in Figure 1b and 1b – the images are very small. Also – it’s not clear what Figures 1d-f show – maybe consider leaving these out.

Line 238 – not clear what re-enter means here - is this floes from outside moving into, or the formation of new ice within?

Line 238 – “sea ice coverage”

Line 239 – “winter 2022”

Line 240 – what is meant by “apparent coherency”?

Lines 242-243 – this sentence needs rewriting. Also, change plates to floes. Regarding “sea ice concentration varied” – over what area, and does this refer to pack ice or fast ice (noting that a feature of fast ice is its consolidated nature i.e., 100% concentration)?

Lines 245 and 246 – should “climate” be “meteorological” here?

Line 245 onwards – need to refer to Crocker and Wadhams (1989) and Langhorne et al. (2001) here, regarding the fact that fast ice is particularly vulnerable to breakup by ocean waves. REFS: Langhorne, P., Squire, V., Fox, C., and Haskell, T. (2001). Lifetime estimation for a land-fast ice sheet subjected to ocean swell. *Annals of Glaciology*, 33, 333-338. doi:10.3189/172756401781818419

G.B. Crocker, and P. Wadhams (1989). Breakup of Antarctic fast ice. *Cold Regions Science and Technology*, 17(1), 61-76, [https://doi.org/10.1016/S0165-232X\(89\)80016-3](https://doi.org/10.1016/S0165-232X(89)80016-3).

Figure 3 and Line 261 – make the blue box more prominent. Also, why was this location chosen, and why is 4 grid cells the size chosen?

ALSO – is “surface temperature” surface air temperature?

Line 262-264 – unclear. Occurring when?

Lines 271-273 – not clear as written.

Lines 292-295 – ungrammatical – rewrite as 2 sentences.

Figure 5 – make the solid and dashed lines thicker.

Line 307 etc. – is sea ice extent based on the 15% ice concentration threshold? (add this information to the appropriate Data and Methods sub-section).

Line 307 – why is January 19 chosen? This is the date of initial fast ice breakout, but what were sea-ice conditions like in the previous and subsequent days?

Figure 6b – the text above and y axis state “sea ice area”, but the text talks about sea ice extent only. In Line 308 – should “time series of sea ice extent (concentration multiplied by area of pixel)” be “time series of sea ice area (concentration in each pixel multiplied by the number of ice-covered pixels)”?

Figure 6b – also, why is the value given only for January 19 in all of the years? This could be misleading to interpretation of when and how long open-ocean corridors occurred. Also in lines 315-316 – Figure 6b does not back up the statement that no other corridors occurred over the period from 2011, as it shows January 19 only. For example, I had a quick look at the satellite data and this shows the persistent occurrence of a corridor in February 2021 (for example). This leads to the question – why did the fast ice breakout only occur in January 2022 and not earlier? Therefore, the claim in Lines 315-316 that “This pathway, which allows for wave action to access the front of the Larsen B fast ice, had not been present since the fast ice’s formation in 2011” needs backing up with further evidence. This comment also applies to Lines 495-496 – “Therefore, for the first time since the formation of the persistent fast ice cover in 2011, a relatively ice-free corridor connected the fast ice front area to the open Southern Ocean.” (I’m sorry but I don’t have access to Figure S5 which is also referred to). Also Lines 503-504 etc.

Line 325 – open-ocean (sea ice-free) corridor

Line 329 – equivalent to a wavelength

Line 343 – change “4.3.1 Initial retreats of landfast ice and glacier fronts” to “4.3.1 Retreat of glacier fronts”

Line 347 evidenced by

Line 356-358 – what does this mean, and why is it important?

Line 372 – what is meant by “Hektoria and Green Glacier responded to the collapse in later months following the fast ice break-out”? What collapse?

Lines 374-376 – unclear as written.

Figure 8a and 8c – length scales are missing.

Section 5 Discussion. This section seems overly long, and may repeats much of what has been stated before. Much of this information could be captured more concisely in a well-formulated schematic along with Tables – see my General Comment 6 above.

Lines 390-391 and Section 4.3.2 – Did Evans Glacier also show a speed change?

Line 396 – what is meant by noise levels in the data? What are they?

Figure 10 – the satellite images are indistinct and difficult to distinguish. Please mark of features and important boundaries.

Line 462 onwards - As stated above in General Comments, the Discussion (Section 5) is also very long in the way that it works through all of the topics in sequence. This could be substantially shortened – and repetition of Results avoided/minimised – by synthesising the main findings into a coherent story around why the fast ice breakout did not occur until 2002, and what the effects were then on

the glacier systems. This would then naturally refer back to the suggested new timeline schematic figure and associated Tables.

Line 463 – “Synoptic scale climate patterns” may be confusing, as synoptic is a meteorological term referring to the approximate horizontal scale of cyclones. Maybe replace with “Meteorological conditions. This comments also applies to other places where “climate” is used e.g., Line 464.

Line 477 – “eastern (lee) side”

Line 480 – should low concentration be zero concentration?

Line 496 - damping

Lines 498 and 507-509 – need to add the references to Langhorne et al. (2001) and Crocker and Wadhams (1989) here.

Lines 507-509 – not clear whether this is referring to fast ice or glacier ice.

Line 511 – ‘the broken-out fast ice had drifted 9-16 km’

Lines 515-517 – again, it is not clear whether this is referring to fast ice or glacier ice, or both. Hydrofracturing a process associated with crevasses on ice shelves/glacier, and has yet to be observed on fast ice.

Lines 517-519 – This is similar to the finding of Massom et al. (2018). They found that strong and persistent offshore westerly/northwesterly winds in late 2001 through early 2002 both (1) created a persistent sea-ice free corridor offshore from the Larsen B Ice Shelf to enable swell penetration that contributed to the ice-shelf breakup, then (2) blew the resultant icebergs and melange out of the Larsen B embayment. Please refer to this parallel here.

Line 520 onwards (Section 5.3) – please specifically refer back to, and compare the new findings with, other studies from elsewhere around Antarctica by Miles et al. (2018), Arthur et al. (2021), Greene et al. (2018) and Gomez-Fell et al. (2022) regarding relationships between fast ice presence/absence and both (1) glacier calving and (2) speedup (i.e., buttressing).

Line 524 – replace “despite” with “contrary to”.

Lines 525-529 – I didn’t quite understand these 2 sentences, and how these factors relate to the findings of this paper.

Line 569 – effects on glacier flow and decreased surface elevation. Also reference Rignot et al. (2004) and Scambos et al. (2004) here.

Line 560 – that the sea ice concentration in the Weddell Sea in 2022 was the lowest recorded is somewhat ambiguous. When did this occur (in the year)? Also, does this refer to the entire Weddell Sea?

ALSO – there was a large sea-ice free corridor prior to and during the Larsen B disintegration event in 2002 (see Massom et al., 2018)

Line 555 onwards (Conclusions) – again, please place the current findings more in the context of previous studies.

Lines 557-559 – where is it shown that high temperatures (alone) caused the ice-free corridor? Is it more likely to be wind-driven?

Lines 559-561 – this may not be the case – refer to Massom et al. (2018) regarding the extraordinary opening in late 2001 through early 2002. Also see my comments above and in the Overall Comments.

Lines 563-564 “pack ice-free corridor”

Lines 564-565 – fast ice flexure would not be confined to the outer margins – see Langhorne and Crocker and Wadhams papers.

Line 565 – hydrofracture is not a process that has been associated with fast ice.

Line 571 – replace “The fast ice was clearly buttressing...” to “This suggests that the fast ice slab was acting to buttress...”

Line 571-572 – this is a place to reference previous studies i.e., “confirming the findings of previous studies e.g., Massom et al. (2018), Miles et al. (2018), Arthur et al. (2021), Greene et al. (2018) and Gomez-Fell et al. (2022).

Lines 576-586 – Suggest combining the 2 paragraphs into one coherent paragraph.

Line 576 – move the Fraser reference to “...fringed with multi-year fast ice (Fraser et al., 2021)...”

Line 577-578 – this is not a new trigger mechanism. Suggest changing to “Antarctica’s coastal fast ice may become more susceptible to breakup due to increasing exposure to ocean swells via open-ocean corridors through pack ice (Reid and Massom, 2022; Teder et al., 2022).”

REF: Reid, P.A., and R.A. Massom. 2022. Change and variability in Antarctic coastal exposure, 1979–2020. *Nature Communications*, **13**, 1164, <https://doi.org/10.1038/s41467-022-28676-z>

Line 580 – change “are” to “will likely be”. Also, what is meant by “similar to ice shelf tributary glaciers”? – suggest removing this.

Lines 584-586 – change to: “It is important to continue monitoring not only the glaciers feeding into the Larsen B embayment in terms of their response to changing fast-ice conditions, but also other key glacier-/ice shelf-fast ice interactive systems around Antarctica and their response to increased coastal exposure (Massom et al., 2022; Teder et al., 2022)”. I added these references as this is what they propose.

Line 602 Data Availability – change “data is” to “data are”, and in line 607 add “data”.