

Thank you Dr. Rott for your comments and suggestions. I really enjoyed our conversation. We have addressed your comments below marked with **[Author Response]**.

Short Comment on “Antarctic Peninsula ice shelf collapse triggered by föhn wind-induced melt” by M. K. Laffin et al., submitted to *The Cryosphere Discussions*, 25 Oct. 2021.

Commenter: Helmut Rott

The authors explored mechanisms triggering the rapid collapse events of the Larsen A and B ice shelves, using a regional climate model and Machine Learning analysis in order to investigate the influence of föhn winds and associated melt on the surface liquid water budget. They conclude that increased surface melt due to föhn supplied water to melt lakes, inducing the crossing of a critical stability of water depth that triggered the rapid Larsen A collapse. The authors claim a lack of high resolution satellite imagery during the collapse and deduce estimates on melt lake surface area from an AVHRR image (1 km spatial resolution) of 8 December 1992. In fact, high resolution synthetic aperture radar (SAR) images (ca. 25 m resolution) of the ESA ERS-1 satellite were acquired during the disintegration event, on 25, 28 and 30 January and 2. February 1995. Some of the ERS-1 SAR images acquired over Larsen Ice shelf are shown in Rott et al., 1998 (paper cited by Laffin et al.). Furthermore, Rott et al., 1996 (not cited), show ERS SAR images acquired during the event and present a report on the state of Larsen A Ice Shelf two months before the collapse, built on field observations.

[Author Response] - Thank you for bringing some of these images to our attention. We knew of the images but did not know they were at a high resolution. We will be sure to better study these high resolution images.

The ERS SAR images, as well as the report on the field observations in October and November 1994 disprove the hypothesis of Laffin et al. that the Larsen A collapse in January 1995 was triggered in the short-term by hydrofracture processes. According to the ERS image of 25 Jan. 1995, close to the start of the main disintegration event, the extent of surface lakes on Larsen A Ice Shelf amounted to about 1% of the total area (Fig. C1 below). In Oct./Nov. 1994 the ice shelf was already heavily fractured. Cold temperatures and an extended pre-frontal cover of fast ice kept the ice shelf from breaking apart. Details are reported in Rott et al., 1996, e.g. referring to an ice wedge protruding from the level ice shelf several km inland of the front (Fig. C2), on cracks along the border between the Larsen A and Seal Nunataks ice shelves, and rifts along the coastline line to the peninsula.

[Author Response] - We agree that some of the images, specifically the 25 Jan 1995 do not show that melt ponds are present on the Larsen A Ice Shelf prior to collapse. As you suggest this shows that at the time of collapse, the ice shelf could not support melt ponds and did not experience large scale hydrofracture cascades as we and others have suggested. However, as we discussed in our zoom meeting, the ERS image from 28 Jan 1995, shows that melt ponds are present on what remains of the ice shelf before total collapse (See the Figure A1 below). There are a multitude of reasons why there are no melt ponds in the 25 Jan image but are in the 28 Jan image, but it does show that to some capacity the Larsen A ice shelf was able to support melt ponds even though its surface was no longer smooth and cracks were present.

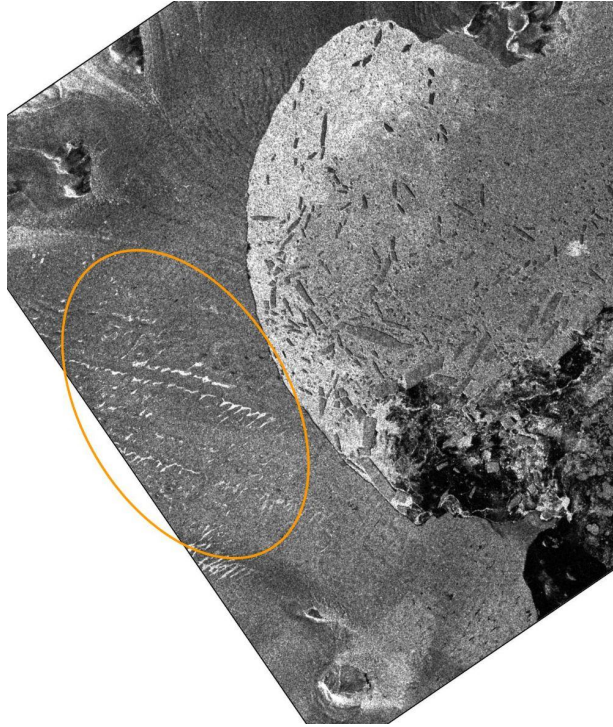


Figure A1: ERS 1 SAR image from 28 Jan 1995 of the Larsen A ice shelf with melt ponds/lakes circled in orange.

Regarding the temporal sequence of the collapse event, the ice shelf section downstream of Dinsmoor Bombardier-Edgeworth (DBE) glaciers retreated to the grounding line faster than downstream of Drygalski Glacier along which Laffin et al. show the location of the LA föhn jet. The pre-collapse crack density was highest on the DBE ice shelf section. Another striking incident was the rapid off coast drift of detached icebergs and growlers, gaining 40 km in distance between 28 and 30 January 1995, an indication for oceanic mechanic forcing as main factor for the rapidity of disintegration.

[Author Response] - Yes, you are correct that the sequence of events of collapse began with a faster disintegration of the downstream section of DBE outlet glaciers, however as we discussed this would make sense because of the already fractured nature of that portion of the ice shelf. The DBE section of the ice shelf surface was inherently rough and cracked due to the suturing of the three glaciers and flow direction.

As far as the rapid off coast drift of the detached icebergs, you are correct that there was some form of ocean forcing. Also however, the powerful föhn winds that were present during the collapse as identified in this and other studies also pushed the icebergs off coast leading to this iceberg travel pattern. As we discussed it is unfortunate that ocean observations are not available during this time, but this theory may benefit from modeling studies to better understand what was happening from an ocean standpoint.

This comment is not a review of the paper. Nevertheless I want to address some further issues:

Melt pattern on Larsen A Ice Shelf: The model simulations (Figs. 3 and 6) indicate reduced melt in the northern section of the ice shelf (downstream of DBE glaciers). ERS SAR images, acquired in years preceding the collapse, as well as the 25 Jan. 1994 image (Fig. C1), do not show any significant difference in melt intensity between different ice shelf sections.

[Author Response] - This is certainly a good point. One way to corroborate if the föhn jet locations simulated by RACMO2 are in the correct place is to confirm the location of other jets, such as those found on the Larsen C ice shelf and studies extensively using airborne observation, surface

observations, and model simulations (Kuipers Munneke et al., 2014; Elvidge et al., 2016). When we compare the RACMO2 identified locations of föhn jets on the Larsen C with those observed, we confirm they are in the correct location.

Position of föhn jets: The uniqueness of the föhn jets on Larsen A (Drygalski Glacier) and on Larsen B (Hektor – Green glaciers) needs to be reconsidered. ERS SAR images during the Larsen A event show high reflectivity of the ocean surface and rapid off-coast displacement of ice downstream of DBE glaciers, indications for strong off-shore winds. During the Larsen B disintegration event rapid off coast drift of icebergs was observed also downstream of Crane and Jorum glaciers (Rack et al., 2004).

[Author Response] - You are correct about the images showing strong winds, but this does not disqualify the location of the föhn jets identified in this study. The location of the föhn jets are indicated by föhn-induced surface melt and not wind speed. It is entirely possible that the winds north and south of these föhn jets on both Larsen A and B are just as strong as within the jet, but the warming and melt effect may be different. Additionally, even though a location is not affected by a föhn jet, it is still possible to experience a weaker föhn wind that produces a similar wind/wave roughness identifiable for SAR imagery.

Line 289: “... the LAIS and LBIS collapsed catastrophically within weeks and not through long-term thinning and retreat like other ice shelves...” The gradual retreat of the Larsen A front between Seal Nunataks over 20 years up to the collapse is documented by means of satellite images starting in 1975 (Skvarca, 1993; Rott et al., 1996).

[Author Response] - Thank you for your comment, I will make sure to mention the gradual thinning of the ice shelves prior to rapid collapse.

References:

- Rack, W. and H. Rott, H.: Pattern of retreat and disintegration of the Larsen B ice shelf, Antarctic Peninsula, *Ann. Glaciol.*, 39, 505 – 510, 2004.
- Rott H., Skvarca, P., and Nagler, T.: Rapid collapse of northern Larsen Ice Shelf, Antarctica, *Science*, Vol. 271, Issue 5250, 788-792, 1996.
- Skvarca, P.: Fast recession of the northern Larsen Ice Shelf monitored by space images, *Ann. Glaciol.*, 17, 317-321, 1993.

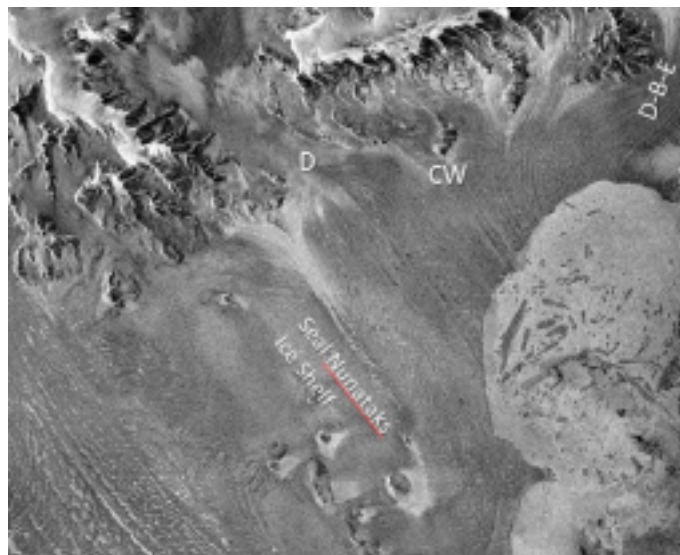


Fig. C1. Section of ERS-1 SAR image, covering Larsen A Ice Shelf, 25 January 1995. CW – Cape Worsley, D – Drygalski Glacier, DBE – Dinsmoor-Bombardier-Edgeworth glaciers, S - Sobral Peninsula.



Fig. C2. Ice wedge on Larsen A Ice Shelf, located several km inland of the front (left). Cracks near the ice front (right). Photos H. Rott, 24 Oct. 1994.