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Capsizing and impact wave detection - Case study of iceberg A-76A

Constance Hjort[1], Ole Baltazar[1], Bjarke Nilsson[1]
[1]Department of Space Research and Space Technology, Technical University of Denmark, Kgs. Lyngby, Denmark

INTRODUCTION

Iceberg calving is increasing as global temperatures rise, producing massive tabular icebergs that can fracture and generate powerful iceberg-tsunamis. These waves pose risks to ecosystems and coasts, yet have rarely been observed directly. Traditional satellites capture only narrow tracks across the ocean, making it nearly impossible to resolve these wave fields. In 2023, iceberg A-76A, a London-sized iceberg, drifted into SWOT's one-day orbit swath and fractured, creating a unique opportunity to analyse these waves using SWOT's sea surface height anomaly (SSHA) data.

In this study:

- We analyse the breakup of iceberg A-76A near South Georgia (2023).
- Using SWOT data, we detect XX iceberg-tsunamis generated during disintegration.
- We develop a method to characterise these iceberg-tsunamis.
- Comparing SWOT measurements to controlled laboratory experiments [3].

This case study demonstrates SWOT's unique ability to capture iceberg-ocean interactions and offers new insights into how calving processes generate waves.

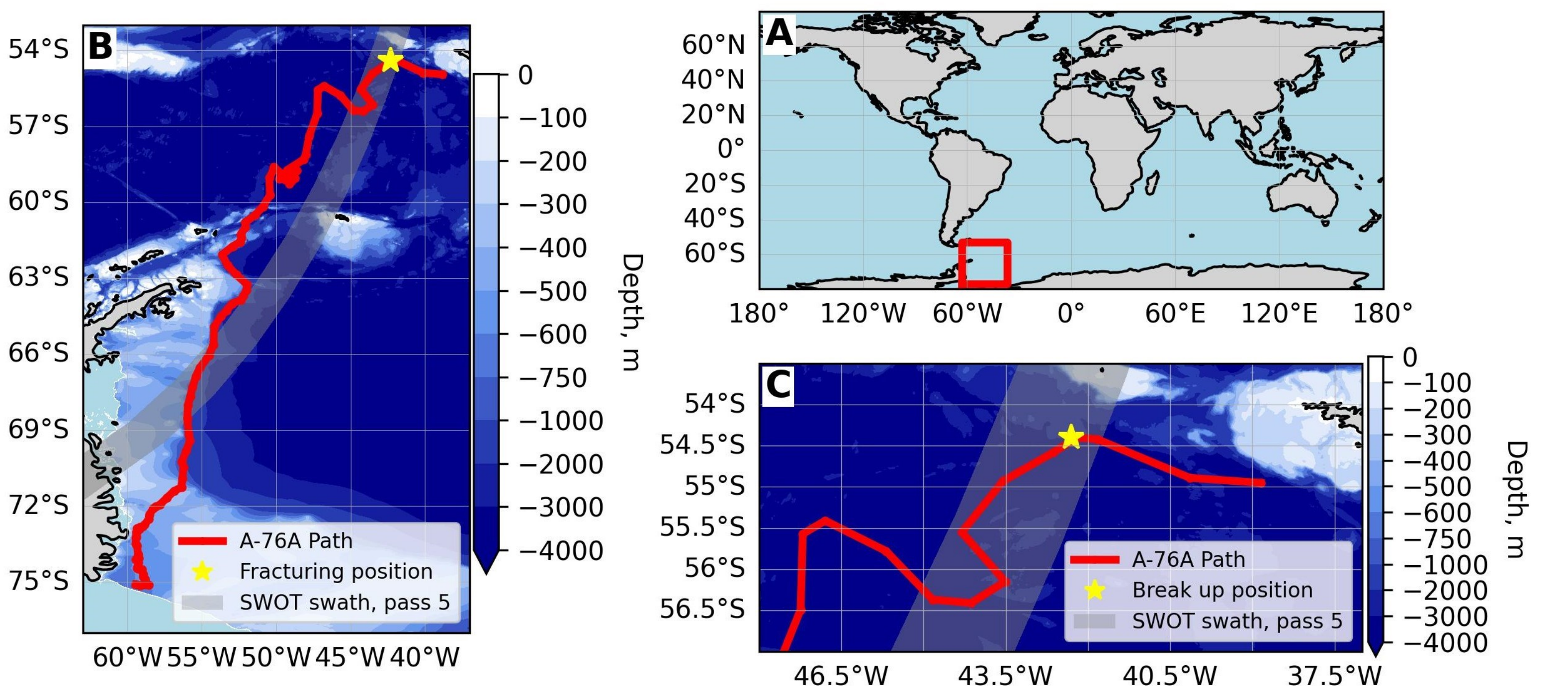

Figure 1: a) Overview map indicating the region where iceberg A-76A drifted. b) Drift tra-jectory of iceberg A-76A as provided by the U.S. National Ice Center [1].The background is the depth from the GEBCO 2024 bathymetry dataset [2]. Pass 5 swath is shown in grey, and the approximate location of fracturing is marked with a yel-low star. c) Close-up view of the fracturing area, showing the path of A-76A, the SWOT pass 5swath, and the position of the break-up event. Figure produced for paper [4].

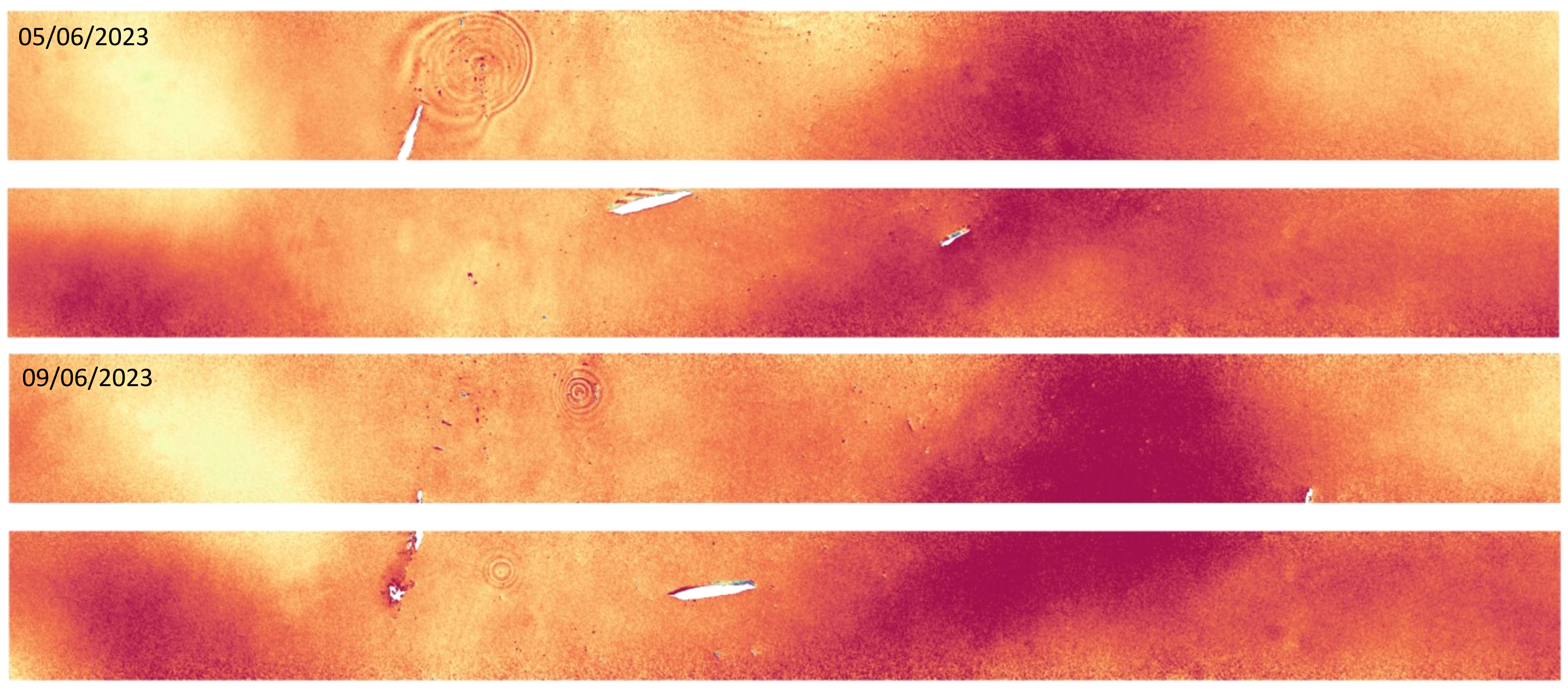

Figure 2: Examples of SSHA swath captures by SWOT, where the presence of iceberg-tsunamies is clear. The data is from pass 5 from 50°S to -55°S from (top) the 5th of June 2023 and (bottom) the 9th of June 2023.

Characterising Iceberg-Tsunamis

Purpose

The goal of characterising iceberg-tsunamis is to understand what kind of waves they are and how they interact with the ocean environment.

- *Wave steepness* (H/L): Describes how energetic and nonlinear the waves are. High steepness indicates breaking potential and stronger local impacts.
- *Dimensionless depth* (h/L): Determines whether the waves behave as deep-water, intermediate, or shallow-water waves, which controls their speed, dispersion, and coastal impact.

How we measured iceberg-tsunamis

- Convert SWOT SSHA to radial coordinates around the impact site.
- The wave height, H, read from SSHA, is defined as the wave height of the dominant wavelength.
- The water depth, h, is read from GEBCO bathymetry [2].
- Apply wavelet transform to identify dominant wavelengths and dispersion relationship.
- Fitting linear dispersion relationship, to identify time-of-impact, t_0.
- Calculate dimensionless depth (h/L) and steepness (H/L).

Key Findings

- Typical wavelengths: 2–5 km.
- Wave heights: 10–30 cm.
- Dimensionless depth: 0.4–3.5 → mostly intermediate/deep water.
- Steepness ~ 10^{-4} → highly linear.
- Younger waves = higher steepness, older waves = broader.

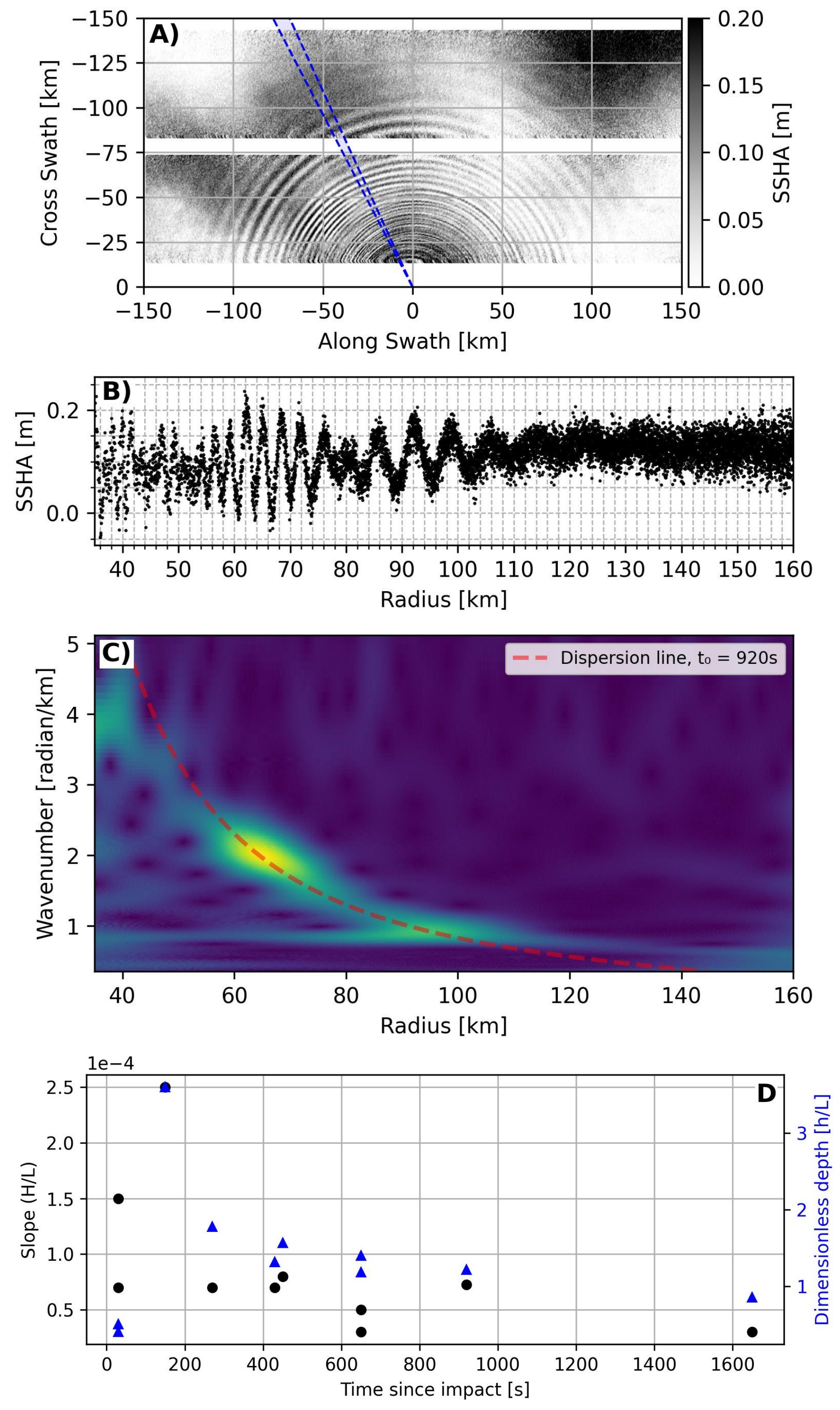

Figure 3: a) Sea Surface Height Anomaly (SSHA) from pass 5 on the 11th of May 2023 at -41.85° longitude and -52.2° latitude, highlighting the section used for wave analysis. b) SSHA data from the highlighted section in (a) shown in radial coordinates. c) Corresponding scalogram of (b) using a complex Morlet wavelet with a central frequency of 2 Hz and a bandwidth of 1.5Hz, overlayed by the predicted wavenumber dispersion after 920 s. d) Slopes (black axis) and dimensionless depth (blue axis) for 12 analysed iceberg-tsunamis over time since impact. . Figure produced for paper [4].

Linking to Laboratory Experiments

Purpose

To validate SWOT observations and better understand iceberg-tsunami generation, we compare satellite results with controlled calving experiments by Heller et. al. (2019) [3]. These tank experiments provide the only systematic reference for iceberg-calving waves. Providing temporal surface elevation data at different radial and angular distances from the calving direction.

Comparision methods

- Extracted wave steepness (H/L) and relative depth $(h/L)$from lab data.
- Compared laboratory wave regimes with those derived from SWOT (linear, intermediate–deep water).
- Analysed temporal evolution: wave decay, dispersion, and trailing patterns.
- Used wavelet scalograms to compare observed iceberg-tsunamis with the different calving mechanisms from the laboratory results.

Key Findings

- Laboratory steepness: 10^{-2}–10^{-1} and Dimensionless depth: 0.2–5 → consistent with SWOT results, thus the two datasets are comparitativ.
- Distinct calving signatures observed in wavelet scalograms:
  Capsizing: directional differences, two dominant wavelengths vs. dispersed tail.
  Gravity-dominated fall: multiple pulses, strong dispersion.
- SWOT waveforms show similarities to capsizing and fall events, suggesting calving mechanisms may be inferred from space. Shown in Figure 4, where (a) a break-off from a larger iceberg generates a scalogram, similar to those found for gravity falls (f), same for the iceberg-tsunami shown in Figure 3. While (b-c) shows a tsunami caused by capsizing, where the directionality change in the wave matches observation for capsizing in laboratory data (d-e), indicating not just what type of calving mechanism, but also calving direction.

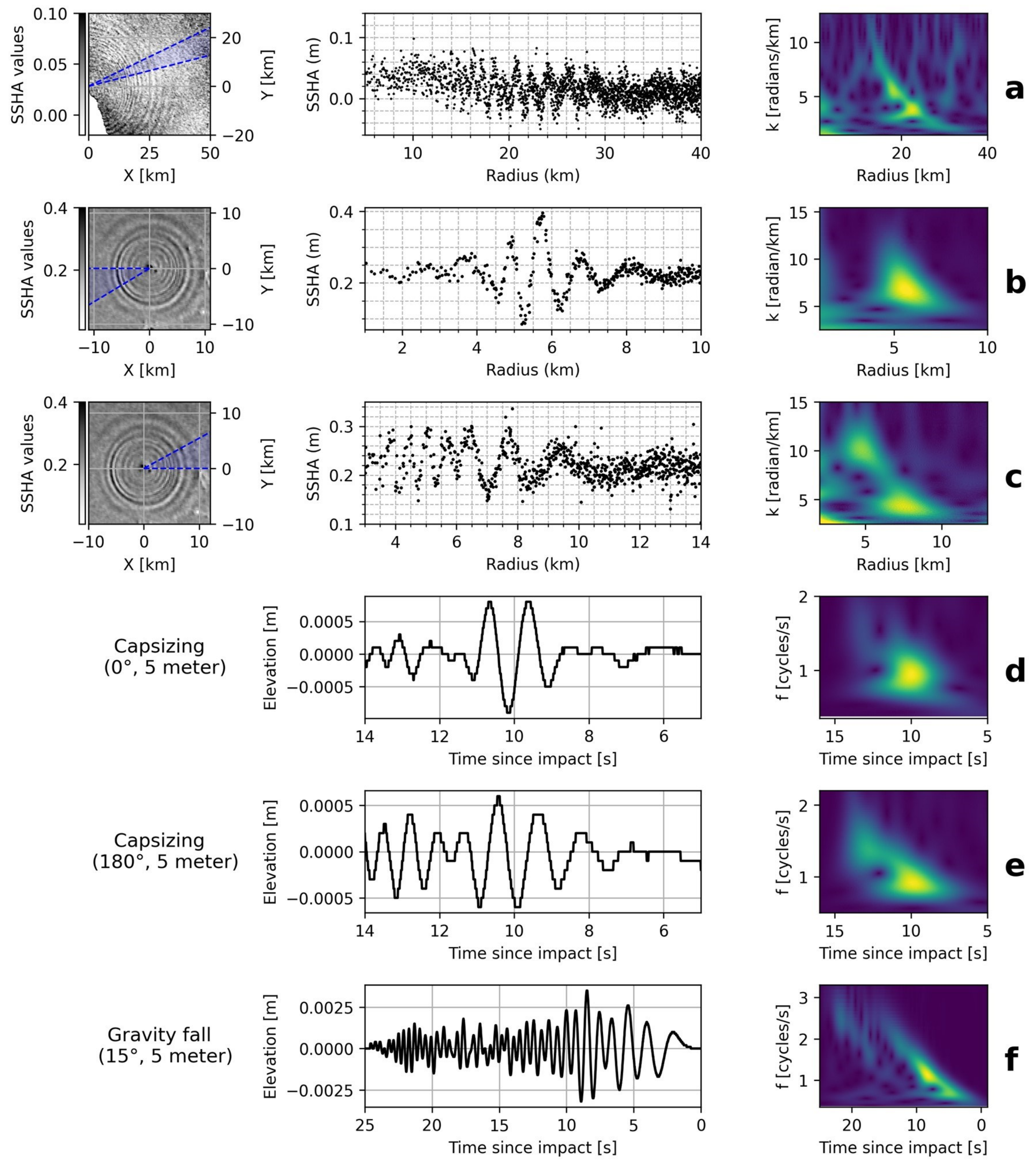

Figure 4: a) Left: SSHA from April 26, 2023, at 41.5◦S, 53.8◦W; wave analysis from0.25–0.45 rad. Middle: Corresponding radial waveform. Right: Scalogram (Complex Morlet 2.5-1). b, c) Left: SSHA from May 3, 2023, at 41.85◦S, 52.2◦W, wave analysis from −π to −2.6 rad (b) and 1.25–1.75 rad (c). Middle: Corresponding radial SSHA data. Right: Scalograms (Com-plex Morlet, 1-1.5). d, e) Left: Probe positions in polar coordinates. Middle: Surface elevation from experiment t1b (capsize in 1m depth; using a 0.8m x 0.5m x 0.25m, 92.43km ice block).Right: Wavelet scalograms (Complex Morlet 1–1.5). f) Left: Probe positions in polar coordinates. Middle: Surface elevation from experiment t11 (gravity-dominated fall; using a 0.8 m x 0.5m x 0.25 m, 93.62kg ice block). Right: Wavelet scalogram (Complex Morlet 1–1.5). Figure produced for paper [4].

CONCLUSION & KEY TAKE-AWAYS

- SWOT directly captured iceberg-tsunamis from the breakup of A-76A.
- The tsunamies are characterised by long, low, highly linear waves, consistent with deep/intermediate-water behaviour.
- A combination of Wavelet scalograms and dispersion relation allows estimation of time since impact.
- Scalogram patterns align with laboratory experiments, suggesting the potential to infer calving direction and mechanism.
- Few events, short-lived signals, and data noise make detection challenging.
- Improve signal processing and explore how SWOT's orbit change affects the ability to capture iceberg–wave interactions.

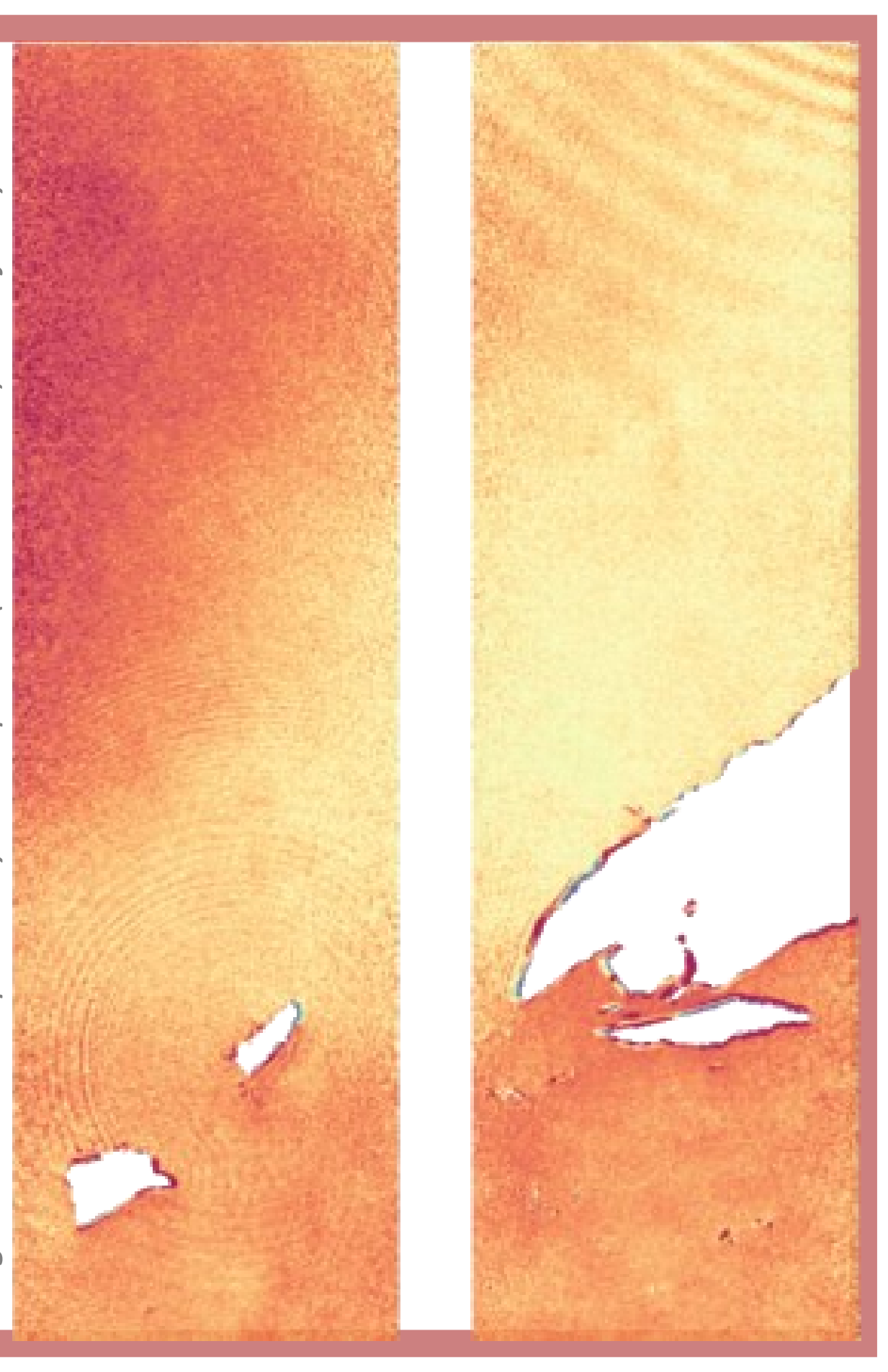

Figure 5: SSHA captures by SWOT pass 5 (50°S to -55°S) 11th of May 2023.

[1] U.S. National Ice Center. (2025). Antarctic icebergs csv archive [Dataset]. NERC EDS British Oceanographic Data Centre NOC.

[2] GEBCO. (2024). The gebco 2024 grid - a continuous terrain model of the global oceans and land. [Dataset]. NERC EDS British Oceanographic Data Centre NOC. doi: https://doi.org/10.5285/1C44C9E99-0A0D-5F4F-E063356-7086ABC0EA0F

[3] Heller, V., Chen, F., Bühl, M., Gabl, R., Chen, X., Wolters, G., & Fuchs, H. (2019). Large-scale experiments into the tsunamigenic potential of different iceberg calving mechanisms. Scientific reports, 9 (1). doi: https://doi.org/36310.1038/s41598-018-36634-3

[4] Constance Hjort, Ole Baltazar Andersen, Bjarke Nilsson. Early Analysis of Iceberg-Tsunamis in the Southern Ocean: The Breakup of A-76A Observed by SWOT. *ESS Open Archive.* October 06, 2025. doi: 10.22541/essoar.175976127.76763033/v1

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