



Atmospheric forcing and winter landfast sea ice fracture activity near Tuktoyaktuk, Arctic Canada

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Abstract. Landfast sea ice (LFSI) is a crucial socio-ecological component of the Arctic climate system, regulating ocean-atmosphere fluxes, buffering against coastal erosion, and providing a vital travel medium for hunting and transportation in Indigenous communities such as Tuktoyaktuk in the Northwest Territories of Canada. However, accelerated Arctic warming is reducing the extent, thickness, and strength of sea ice. These changes make the ice more susceptible to mechanical failure and breakup. This study investigates the atmospheric drivers and associated LFSI-pack ice interactions around Tuktoyaktuk Northwest Territories, Canada. Using satellite-based Synthetic Aperture Radar (SAR), we identified 48 discrete fracture events between 2016 and 2023. These events exhibited substantial interannual variability, ranging from 3 events in 2016-2017 to 15 events in 2022-2023, out of which 38 of the 48 events (79.2%) occurred between December and March. Based on the midpoint-based nominal dates, 68.8% of LFSI fractures occurred during, or within three days following, enhanced synoptic-scale pressure-gradient forcing. Matched-control analysis showed significantly higher wind speeds on nominal fracture dates than on matched non-fracture dates (median difference = 4.9 km h^{-1} , $p = 1 \times 10^{-4}$). Fracture events were also commonly associated with elevated wind speeds and predominantly offshore wind directions (ESE, SE, and E). These fractures highlight the sensitivity of the LFSI edge to synoptic weather patterns and may provide indicators of localized LFSI instability.

1 Introduction

Sea ice plays a crucial role in the Earth's climate system, acting as a barrier between the ocean and atmosphere while also serving as an important indicator of climate variability and change (Liu and Horton, 2018). Since the late 1970s, Arctic sea ice has undergone significant declines in extent and thickness, with anthropogenic forcing identified as the primary driver of the observed long-term loss (IPCC, 2021). This decline has accelerated warming in the Arctic, referred to as Arctic Amplification (AA), causing the region to warm nearly four times faster than the global average (Rantanen et al., 2022). Within Northern Canadian Waters (Canadian Arctic Domain: Kane Basin, Foxe Basin, Baffin Bay, Beaufort Sea, and the Canadian Arctic Archipelago), overall annual sea ice extent has declined at 7.2% per decade between 1968 and 2024 (Environment and Climate Change Canada, 2025). The regional loss of this sea ice has increased the vulnerability of Arctic coastlines to erosion from enhanced wave action, together with coastal permafrost thaw (Nielsen et al., 2022).



Within these vulnerable coastal regions, sea ice that remains attached to the shoreline is classified as landfast sea ice (LFSI). Following the operational definition of Mahoney et al. (2005), LFSI can be defined as sea ice that remains stationary for at least 20 consecutive days. LFSI has a maximum thickness at the end of winter of about 1-2 meters, and it accounts for approximately one-third of Arctic coastal sea ice (Maslanik et al., 2011; Li et al., 2019), and contributes 13% of the total Northern Hemisphere sea-ice area during winter (Zhai et al., 2022). As such, LFSI is a defining feature of the Canadian Arctic. LFSI keeps ocean waves away from the shoreline, significantly reducing coastal erosion (Rachold et al., 2000; Radosavljevic et al., 2016; Zhai et al., 2022). Northern communities depend on LFSI stability for activities such as hunting, navigation, connecting isolated communities to the mainland, and preserving their cultural heritage (Laidler et al., 2009; Cooley and Ryan, 2024). LFSI also serves as a crucial habitat for breeding, movement, and feeding of marine species such as polar bears and seals (Zhai et al., 2022). Moreover, it fosters regional economic growth and supports traditional Indigenous fishing practices (Eicken et al., 2009).

Pack ice and LFSI represent two dynamically distinct yet physically interconnected components of the Canadian Arctic sea ice system. Unlike the relatively immobile LFSI, pack ice responds rapidly to external forcing from winds, ocean currents, and tides. The interface between these two regimes, the Seaward LFSI Edge (SLIE), acts as a critical region of mechanical coupling, where stresses generated by the drifting pack ice are transmitted toward the stationary LFSI. While a portion of this stress is absorbed or redistributed by grounded ridges, hummocked ice, or rough brash zones acting as mechanical buffers, excessive localized stress can lead to deformation and fracturing near the interface (Kowalik and Proshutinsky, 1994; Wang et al., 2020; Chang et al., 2024; Muilwijk et al., 2024).

A breakout event occurs when a large section of LFSI detaches from the stable coastal ice cover and transitions into drifting pack ice under atmospheric and oceanic forcing (Jones et al., 2016; Jensen et al., 2023). Before a full breakout occurs, internal ice stress may exceed the local mechanical strength of the ice, producing fractures and leads parallel to the LFSI boundary (Jones et al., 2016; Dammann et al., 2018; Loewen et al., 2024). These features do not necessarily result in immediate detachment, but they can indicate localized instability, boundary weakening, or stress concentration at the LFSI edge (Jones et al., 2016; Dammann et al., 2018). Such wintertime fractures can alter the mechanical stability of the boundary ice, increasing stress within the interface zone (Steffen, 1987; Vevatne et al., 2014). Arctic communities are already observing an increase in premature fracturing events during spring and winter (Cooley et al., 2020), while later LFSI formation and earlier breakup are shortening the stable ice window (Mahoney, 2006; Howell et al., 2024). These changes can trigger thinner, mechanically weaker ice, increasing susceptibility to sudden breakouts.

Managing travel safety risks on LFSI in northern communities requires enhanced spatiotemporal monitoring capabilities (Dammann et al., 2019), a need increasingly met through satellite remote sensing. Early efforts relied on optical imagery. For example, Cooley et al. (2020) used visible MODIS satellite data to examine seasonal LFSI variability in northern Canada, while Zhai et al. (2022) combined MODIS imagery with thermodynamic modeling to study breakup patterns in the East Siberian Sea. However, optical imagery is effective only under clear-sky conditions and during sunlit periods. Consequently, microwave remote sensing is favored for sea ice studies due to its capacity to penetrate cloud cover and operate during the polar night. Satellite-based SAR has proven particularly effective for mapping these active LFSI boundaries. Dammann et al. (2019) utilized Sentinel-1 SAR data to map pan-Arctic LFSI stability and identify fracture-prone zones. Expanding on this, Chen et al.



(2021) employed a multi-sensor, multi-frequency interferometric dataset (L-band ALOS-2, C-band Sentinel-1, and Radarsat-2) to derive time-series measurements of surface deformation. Satellite-based SAR has also been applied to investigate coastal sea-ice conditions in other Arctic regions, including Kongsfjorden and Rijpfjorden, Svalbard (Johansson et al., 2020). More recently, Jensen et al. (2023) analyzed a 23-year time series of C-band SAR imagery to quantify breakout events in the northern Bering Sea, demonstrating the value of long-term SAR archives for resolving patterns of boundary instability.

Despite these advancements, there remains a critical need to isolate how short-term atmospheric forcing is associated with localized fracturing at the community scale before full breakouts occur. Building on the SAR-based characterization of LFSI fracture activity near Tuktoyaktuk presented by (Chaudhary et al., 2025), this study integrates Sentinel-1 SAR observations from 2016 to 2023 with local meteorological records and ERA5 reanalysis data. Here, we extend the previous analysis by focusing specifically on the atmospheric forcing associated with fracture occurrence. Our objective is to investigate the atmospheric forcing mechanisms associated with fracture events near the SLIE in Tuktoyaktuk, an Inuvialuit community situated at the mouth of the Mackenzie River's eastern channel in the Beaufort Sea (see Figure 1). We hypothesize that atmospheric forcing drives the motion of the adjacent pack ice, concentrating stress within the transition zone and causing fractures to occur preferentially near the SLIE. Rather than evaluating large-scale seasonal breakups, we focus on resolving the high-frequency dynamics within the transition zone to better understand the immediate environmental precursors of local LFSI failure. Ultimately, resolving these short-term drivers is a crucial step toward developing localized, short-term fracture-risk monitoring frameworks for community-scale ice-safety applications.

2 Materials and Methodology

2.1 Study area

Tuktoyaktuk, a community in Canada's Northwest Territories, is one of the six settlements within the Inuvialuit Settlement Region (ISR). Tuktoyaktuk plays a vital role as a harbor, enabling the transport and delivery of essential supplies to Inuvialuit communities across the region and further east (Andrachuk and Smit, 2012). The Tuktoyaktuk region is primarily characterized by seasonal first-year sea ice and is among the northwest communities experiencing earlier sea ice break-up and increasingly ice-free summers (Cooley et al., 2020; Gully et al., 2023). With no summer sea ice to protect the shores from waves, the coastline has been eroding due to strong wind events and storm-induced waves (Aveco, 1986; UMA Engineering Ltd., 1994; Manson and Solomon, 2007; Andrachuk and Pearce, 2010; Beveridge, 2013; Whalen et al., 2022). As a result, it is one of the first Canadian Arctic communities to face relocation due to severe coastal erosion (Baird, 2019; Scott et al., 2023).

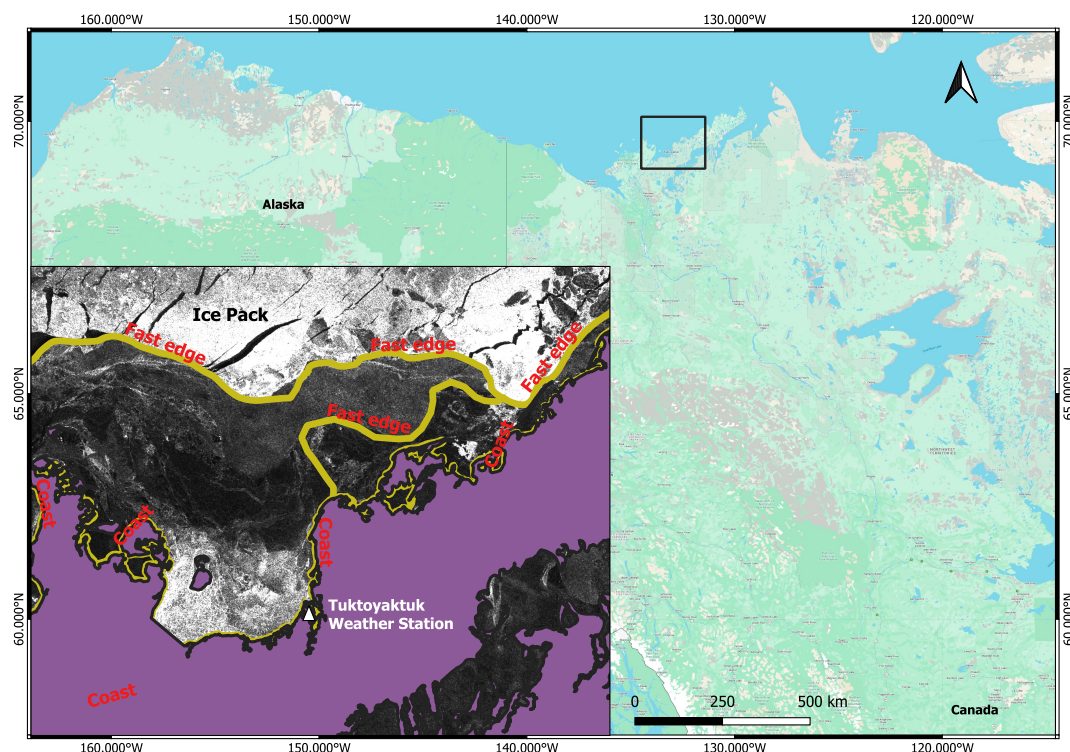


Figure 1. Map showing the Tuktoyaktuk community (indicated by a triangle in the inset), overlaid on a SAR backscatter image acquired on 15 February 2019. The map includes shapefiles from the ECCC Canadian Ice Service delineating LFSI and pack ice boundaries. The background provides a geographic context of the wider Northwest Territories region in Canada.

During winter, the Tuktoyaktuk coastline is mostly covered by LFSI, which extends to the Beaufort Sea and persists until break-up in early July (Environment and Climate Change Canada, 2023). Tuktoyaktuk has historically supported a persistent winter LFSI cover; however, between 1983 and 2009, the region experienced delayed ice formation, resulting in a noticeably shorter LFSI season (Galley et al., 2012). In this region, sea ice typically begins to form around the first week of October, and a stable LFSI cover generally develops by late November or early December. Break-up generally occurs during the first week of July, marking the end of the LFSI season (Environment and Climate Change Canada, 2019). At the SLIE, a transition zone develops between the attached LFSI and the adjacent mobile pack ice (Carson, 2014; Weingartner et al., 2017). This boundary is characterized by recurrent lead formation and enhanced mechanical activity and therefore represents a region where fractures are commonly observed.

2.2 Datasets

This study uses the European Space Agency's C-band dual-polarized Sentinel-1A Ground Range Detected (GRD) SAR product to detect fractures, which are further examined using Landsat 8/9 optical imagery for visual validation of fracture location. In



100 addition, to investigate the environmental conditions associated with fracture occurrence, meteorological observations from local weather station and ERA5 reanalysis data (Copernicus Climate Change Service, 2023) were used to characterize air temperature, near-surface wind conditions, mean sea-level pressure (MSLP), and pressure-gradient forcing associated with fracture events. Pressure-gradient forcing was subsequently derived from the mean sea-level pressure fields and used as a diagnostic of synoptic-scale atmospheric forcing. A summary of the datasets used in this study is provided in Table 1, with further discussion in the following sections.

Table 1. Characteristics of the datasets used to detect fracture events and examine associated sea-ice and meteorological conditions around Tuktoyaktuk from 2016 to 2023.

Dataset	Properties	Purpose in Study
Sentinel-1	C-Band Dual-pol (HH/HV) Medium resolution Extra Wide Swath: 20 m × 40 m Swath width: ≈ 400 km	Detection and mapping of sea-ice fracture events.
Landsat 8/9	Blue (Band 2): 482 nm Green (Band 3): 561.5 nm Red (Band 4): 654.5 nm Spatial Resolution: 30 m	Visual confirmation and spatial context of fracture and flaw-lead features during cloud-free periods.
Sea Ice Charts	Weekly ice charts (GIF and E00 formats) Sea Ice Concentration Sea Ice Stage of Development	Identification of LFSI extent, SLIE position, seasonal ice conditions, and ice-season duration.
ECCC Weather Station Data	Hourly data Station Name: TUKTOYAKTUK A Climate ID: 2203911 Variables: Wind and Temperature	Local measurements of wind speed, wind direction, and air temperature.
ECMWF reanalysis v5 (ERA5)	Hourly data Spatial Resolution: 0.25° × 0.25° Variables: 10-m Wind, 2-m Temperature, Mean Sea Level Pressure	Regional atmospheric forcing analysis through mean sea-level pressure gradients and wind-condition assessment
DFO Tide Gauge	Hourly observed and predicted water levels; derived tidal range and residual water-level anomaly	Assessment of tidal and residual water-level effects on fracture occurrence



2.2.1 SAR Data

We acquired 267 Extra Wide (EW) swath Sentinel-1 C-band Synthetic Aperture Radar (SAR) scenes from the Alaska Satellite Facility (Alaska Satellite Facility, 2023). The dataset spans December through May for six winter seasons between 2016 and 2023. The 2017–2018 season was excluded because insufficient coverage (only 1–2 scenes between January and May 2018) prevented continuous analysis. We note, however, that due to the revisit interval of Sentinel-1 acquisitions (12 days), short-duration fracture events occurring between consecutive SAR observations may not have been detected. The EW mode imagery features a spatial resolution of roughly $20\text{ m} \times 40\text{ m}$ and covers an incidence angle range of approximately 18.9° to 47° , depending on the sub-swath and target location. In these scenes, the backscatter coefficient (σ^0 , in dB) reflects surface roughness and varies as a function of incidence angle (Segal et al., 2020; Zhang et al., 2021; Macdonald et al., 2024). Specifically, smooth undeformed sea ice and calm open water exhibit low backscatter (σ^0) values because specular reflection directs radar energy away from the sensor. In contrast, rough or pressure-ridged ice and wind-roughened open water enhance diffuse scattering, resulting in higher σ^0 values (Johannessen et al., 2006; Isleifson et al., 2010; Partington et al., 2010; Dierking, 2013). While this contrast at C-band enables reliable discrimination between open water, sea ice, and lead formation, potential ambiguities such as smooth ice or damp snow appearing dark alongside calm water were accounted for during visual inspection (Partington et al., 2010).

2.2.2 Ice Chart Data

To contextualize ice types and identify key fast ice dynamics, such as the timing of LFSI formation and breakup around Tuktoyaktuk, we additionally integrated regional Canadian Ice Service (CIS) ice charts (Environment and Climate Change Canada, 2023). Operationally, ice conditions are derived from satellite imagery, aerial observations, and ancillary data (Environment and Climate Change Canada, 2023). Using these charts, we estimated the timing of new-ice formation, fast-ice establishment, ice-free conditions, and the location of the LFSI boundary. Therefore, the LFSI edge is mapped as the interface between shore-attached fast ice and adjacent mobile pack ice. To account for seasonal evolution, the chart closest in time to each SAR observation date was selected to represent the concurrent LFSI extent (see Figure 3). This boundary serves as a spatial reference for analyzing fracture occurrence relative to the adjacent pack ice regime. Because ice charts are issued weekly, the exact onset of a specific ice condition may fall anywhere between consecutive observation dates. To address this temporal uncertainty, the midpoint between the target chart date and the preceding week was adopted as the approximate timing for LFSI development.

2.2.3 Meteorological Data

The weather station data were obtained from an Environment and Climate Change Canada (ECCC) TUKTOYAKTUK A station, located at 69.43°N , 133.03°W . Hourly measurements of air temperature, wind speed, and wind direction were used in the analysis. However, because the weather station represents conditions at a single coastal location, ERA5 atmospheric reanalysis (Copernicus Climate Change Service, 2023) data were additionally used to characterize broader regional atmospheric variability. With ERA5 data, we first evaluated how well ERA5 agreed with the weather station data (see Figure S2 in



the Supplements). ERA5 MSLP fields were also analyzed to investigate the large-scale atmospheric pattern associated with regional wind variability observed from the ECCC stations.

To evaluate potential oceanographic influences on fracture occurrence, hourly water-level observations and predicted astronomical tides from the Fisheries and Oceans Canada (DFO) (Fisheries and Oceans Canada, 2026) tide gauge at Tuktoyaktuk was also
 140 analyzed. These data were used to derive tidal range and non-tidal residual water level anomalies.

2.3 Methodology

Building on the datasets described above, an automated workflow was developed to detect ice fractures from SAR imagery and subsequently examine their relationship with meteorological conditions. The overall processing and analysis framework is summarized in Figure 2. All Sentinel-1 SAR data were first pre-processed using SNAPPY, the Python interface to the
 145 ESA SNAP toolbox (European Space Agency, 2023). Standard processing steps, including the application of precise orbit files, speckle filtering, radiometric calibration, and terrain correction, were applied to generate calibrated backscatter (σ^0) products following established Sentinel-1 processing workflows (Copernicus Data Space Ecosystem, 2024). These steps were implemented to minimize geometric and radiometric distortions and to ensure that backscatter values are comparable across acquisitions throughout the study period.

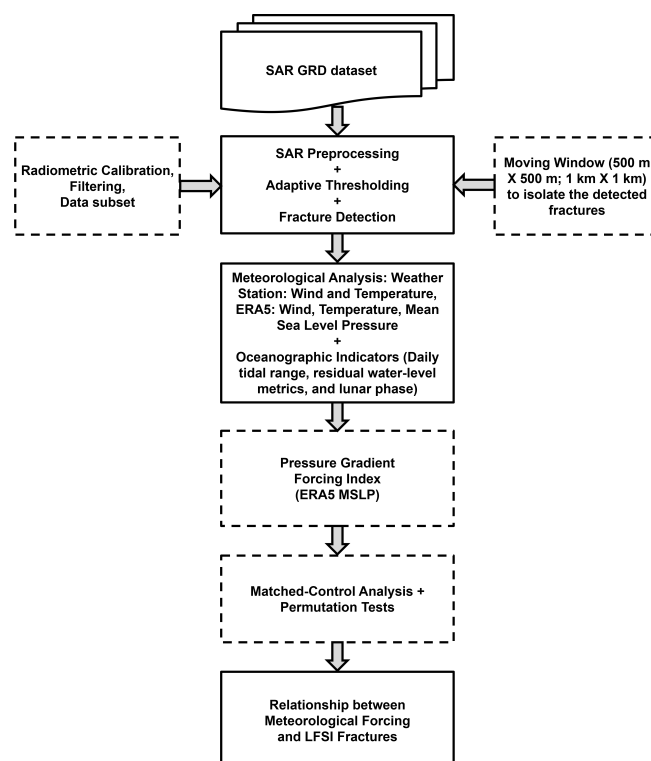


Figure 2. Schematic overview of the fracture detection and meteorological analysis workflow used in this study.



150 Following pre-processing, a spatial subset was extracted around Tuktoyaktuk to capture the LFSI–pack ice interface (Figure 4). This subset includes both the shore-attached LFSI and the adjacent mobile pack ice, providing the spatial context necessary to examine fracture occurrence along the boundary zone. Landsat 8/9 imagery was also integrated with the ice charts to qualitatively interpret fracture features (Figure S1).

To identify potential fracture zones, an automated adaptive thresholding technique was applied to the SAR subsets. Unlike
155 conventional global thresholding approaches, such as the Otsu method (Otsu, 1979), that apply a single threshold value across an entire image, adaptive thresholding determines locally varying thresholds based on pixel intensity within smaller neighborhoods (Bradley and Roth, 2007; Liu and Yu, 2009; Roy et al., 2014). This approach is well-suited to SAR imagery, where backscatter varies spatially due to differences in ice type, geophysical properties, surface roughness, incidence angle, and polarization. The resulting binary classification highlights regions of low backscatter associated with fractures and open-water
160 features relative to the surrounding ice cover.

Because fractures occur during the LFSI season, variations in the duration of the ice season can influence the temporal window over which fracture events occur (discussed in Section 3.1.1). To place the observed fractures within the broader seasonal evolution of the ice cover, we examine the duration of each LFSI season and compare it with the corresponding number of detected fracture events that season.

165 Building on the SAR-based fracture-detection approach developed in Chaudhary et al. (2025), an automated moving window analysis was implemented using window sizes of 500 m × 500 m and 1 km × 1 km. These window sizes were selected to evaluate the sensitivity of fracture detection to spatial scale. The windows were moved across the entire image, calculating the proportion of low-backscatter pixels within each mask grid. A window was classified as a fracture zone when more than 80% of its pixels exhibited low backscatter, indicative of open water or fractured ice; such regions are classified in
170 black, and surrounding ice in white. This approach reduces the influence of small segmentation errors by evaluating local neighborhoods rather than individual pixels. Since the moving window analysis identifies grid cells rather than discrete fracture geometries, neighboring cells classified as fractures were grouped and treated as a single fracture event. Examples of the resulting classifications are shown in Figure 4.

Due to the discrete temporal sampling of SAR acquisitions, fracture-opening events were treated as interval-censored
175 between the last SAR acquisition without a visible fracture (t_0) and the first acquisition where the fracture was detected (t_1) (Turnbull, 1976; Sun, 2006). The fracture-opening time is thus constrained within the interval $(t_0, t_1]$. For all subsequent analyses in this study, we assigned the midpoint, $t_{\text{nom}} = (t_0 + t_1)/2$, with an associated timing uncertainty of $\Delta t = (t_1 - t_0)/2$, converted to hours Δt_h . Monthly events were calculated based on t_{nom} to identify dominant fracture periods within each season. Hereafter, fracture day refers to the midpoint-based nominal fracture date rather than the exact time of fracture opening.
180 This approach standardizes irregular SAR sampling into a consistent event timeline suitable for subsequent meteorological attribution (Johnson and Eicken, 2016).

Following the identification of fracture events, we analyzed the associated meteorological parameters, focusing first on wind regime. Monthly wind rose plots were generated to evaluate prevailing wind dynamics across the multiple winter seasons (see Figure S7 in Supplement). For further directional attribution, wind sectors were grouped into approximate land-originating



185 (off-shore) and ocean-originating (on-shore) categories based on the local coastline orientation around Tuktoyaktuk. Off-shore sectors were defined as E, ESE, SE, SSE, S, SSW, SW, WSW, and W, while on-shore sectors were defined as WNW, NW, NNW, N, NNE, NE, and ENE. For each fracture date or pre-fracture window, the dominant sector was assigned from the larger percentage of hourly wind directions falling within these two groups.

For visualization of fracture-day and pre-fracture wind conditions, ERA5 u_{10} and v_{10} components were spatially averaged
190 over the study region and temporally averaged over each calendar day. Daily wind speed and meteorological wind direction were then calculated from the daily mean wind components, with values extracted on the nominal fracture date and 1, 2, 3, and 7 days beforehand.

To assess whether fractures occurred under anomalous forcing, wind and temperature conditions on fracture dates were compared with matched non-fracture control periods. ERA5 10-m wind components (u_{10} , v_{10}) and temperatures were spatially
195 averaged over the study area and temporally averaged for each calendar day, with daily wind speed calculated from the resulting mean wind components. Wind speeds on midpoint-based nominal fracture dates were then compared with season- and month-matched non-fracture control days.

Background conditions were estimated by selecting control days drawn from the same season and calendar month as the event. For the wind analysis, we tested multiple matched-control configurations using $k = 3, 5, 7$, and 9 control days per
200 fracture event, with exclusion buffers of ± 1 , ± 2 , and ± 3 days around fracture dates to avoid including days influenced by the same synoptic event responsible for the fracture. The $k = 7$ configuration with a ± 2 -day exclusion buffer was selected for final attribution because it provided a balance between reduced control variance and close calendar day matching. For temperature, a parallel matched-control analysis was performed using season- and month-matched non-fracture days, with a ± 1 -day exclusion buffer around fracture dates.

205 Further, to determine if conditions on fracture days were systematically anomalous, we applied a stratified permutation test to the matched pairs. For each event set (one fracture day with its corresponding control days), the event label was randomly reassigned among the days. This randomization was repeated 10,000 times, and the overall median difference was recalculated for each to construct a null distribution of median differences. The observed median difference was then compared against this distribution to calculate a two-sided p-value, with bootstrap confidence intervals and weighted means computed to characterize
210 the typical thermal conditions during fracturing, while wind vectors were evaluated to isolate the specific magnitude and direction of anomalous forcing during fracturing.

In addition to these local wind and temperature comparisons, we used ERA5 mean sea-level pressure fields to characterize broader synoptic-scale atmospheric forcing. The pressure-gradient magnitude was calculated over the Tuktoyaktuk coastal domain and expressed in hPa km^{-1} . Daily pressure-gradient values were smoothed using a 3-day running mean to define
215 the pressure-gradient forcing index. Enhanced synoptic forcing was identified when this smoothed index exceeded the 75th percentile of the pressure-gradient distribution across the analyzed ice-season periods.

This pressure-gradient index was then used to assess how synoptic forcing varied in the days surrounding fracture occurrence. For this, we constructed event-centered composites of ERA5-derived sea level pressure (SLP)-gradient forcing and 10-m wind speeds. For each of the 48 fracture dates, daily values were extracted from seven days before to seven days after the nominal



220 fracture date (day 0). Mean composite values and ± 1 standard error were calculated for each relative day. Finally, a paired Wilcoxon signed-rank test was used to compare event-level mean values between a pre-fracture window (days -3 to -1) and a background window (days -7 to -4).

Because fractures at the LFSI edge may also be influenced by water-level variability and tidal forcing, we additionally examined potential oceanographic controls. Observed water levels, predicted astronomical tides, and residual water-level
 225 anomalies were compiled from the Tuktoyaktuk tide gauge. Daily tidal ranges, residual water-level metrics, and lunar phases on fracture dates were compared against the matched controls using the same permutation framework applied to the meteorological variables. Additionally, composite analyses tracked residual water-level behavior during the 7 days surrounding fracture occurrence.

3 Results

230 3.1 General Environmental Conditions

Comparison between ERA5 and the Tuktoyaktuk weather station (69.430°N , 133.03°W) showed good agreement, with temperatures strongly correlated ($r = 0.98\text{--}0.99$), while wind speed correlations were lower but still strong ($r = 0.85\text{--}0.90$) across all study years (2016-2017 to 2022-2023; see Figure S2 in Supplements), supporting the use of ERA5, particularly in regions where observational coverage is limited.

235 The regional wind regime exhibits a predominantly bimodal orientation along an E-W/NW-SE axis. However, distinct seasonal variations emerge; winter months (January–February) frequently exhibit strong NW components, while late spring (April–May) marks a transition toward higher-frequency, high-velocity wind events (see Figure S7 in Supplements). Notable interannual anomalies are also apparent, such as the extreme high-wind events captured in December 2022.

3.1.1 Seasonal Ice Evolution and SAR-Detected Fracture Occurrence

240 The timing of new and fast ice formation around the community was relatively consistent from year to year. New ice appeared on average around 11 October ± 7.4 days, followed by fast-ice establishment approximately three weeks later on 03 November ± 6.4 days. Following fast ice formation, the LFSI cover persisted until 15 June ± 8.3 days. The timing of ice-free conditions also showed moderate interannual variability, ranging from as early as 10 June 2019 to as late as 3 July 2017. During break-up, melting typically begins near the entrance of Tuktoyaktuk Bay, leaving the community ice-free while a temporary ice bridge
 245 remains between the nearshore region and the Beaufort Sea (see the enclosed region in the Ice Free column of Figure S3). The remaining offshore ice subsequently disintegrates over the following days, marking the end of the seasonal ice cover.

In total, 48 fracture events were identified across the six-year record (Chaudhary et al., 2025), and fracture occurrence varied substantially between seasons (see Table 2). While the nominal LFSI duration remained relatively consistent across the study period, varying by only about three weeks, the number of detected fracture events ranged from 3 events in 2016-2017 to 15
 250 events in 2022-2023. The longest ice season (2016-2017) recorded the fewest fractures, whereas the shortest season (2022-

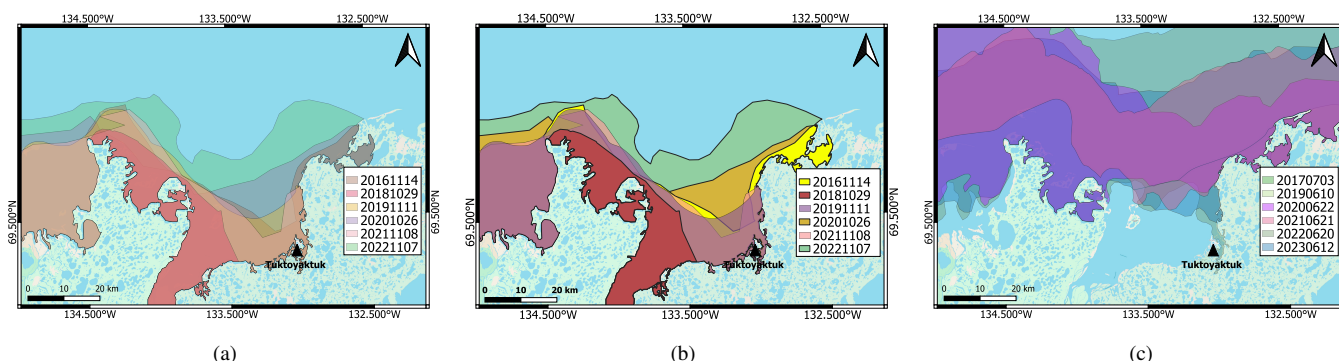


Figure 3. Sea ice charts showing the spatial distribution of (a) New Ice, (b) Fast Ice, and (c) Ice-Free conditions around Tuktoyaktuk for different years. Each figure is derived from Canadian Ice Service sea ice charts, with the dates corresponding to the first appearance of the respective sea ice condition in the ice charts for each year. The location of Tuktoyaktuk is marked with a triangle. The maps illustrate the interannual variability in sea ice conditions and the seasonal progression of sea ice development and retreat across the study period.

2023) recorded the highest number of fractures. This contrast indicates that fracture occurrence is not simply proportional to ice-season duration. However, differences in SAR sampling also need to be considered. The lower event count in 2016-2017 may be partly influenced by the larger SAR revisit interval in that season, with a median gap of ~ 216 h, which would reduce the likelihood of detecting short-lived or rapidly refreezing fractures. In contrast, seasons from 2019 onward generally had shorter median SAR gaps of 48 – 95 h, reducing the nominal timing uncertainty to 24 – 47 h and improving the detection of transient fracture events.

Nevertheless, the discrepancy between ice-season duration and fracture occurrence suggests that community-scale fracturing is not a linear function of seasonal ice duration or gradual thermodynamic weakening alone. Instead, the high interannual variability points to the importance of short-term atmospheric forcing and local boundary conditions at the LFSI-pack-ice interface. Because reported fracture counts rely on discrete Sentinel-1 acquisitions, they should be interpreted as conservative estimates; short-lived openings or rapidly refreezing leads occurring between successive overpasses may go undetected. Higher-frequency time-series observations would help resolve these rapid dynamics while also distinguishing newly formed leads from persistent smooth ice features. Figure 4 shows that the detected fractures predominantly occur as linear features oriented approximately parallel to the SLIE and are concentrated within the mechanically active transition zone. This spatial clustering at the interface of the stable LFSI and mobile pack ice is consistent with the hypothesis that ice-edge interactions generate enhanced mechanical forcing and localized deformation.

Fracture timing evaluated using the midpoint-based nominal dates shows that 38 of the 48 events (79.2%) occurred between December and March, indicating a strong mid-winter concentration of fracture activity. The original SAR-detection dates produced the same December-March total, but the midpoint correction slightly shifted the monthly distribution, with December, February, and March each containing 10 events. Not all detected fractures resulted in a breakout event. Breakout events,



Table 2. Seasonal sea-ice conditions, fracture occurrence, and SAR dating precision for the Tuktoyaktuk ice seasons. New-ice, fast-ice, and ice-free dates are based on the first observation of each condition in weekly CIS ice charts. The ice-covered season duration is estimated from the first new-ice observation to the first ice-free observation and carries an uncertainty of approximately ± 7 days due to the weekly temporal resolution of CIS charts. This duration should not be interpreted as the duration of stable LFSI, which begins only after fast-ice establishment. Fracture events are interval-dated between the last SAR scene without fracture and the first SAR scene with fracture; the nominal fracture date is assigned as the midpoint of this interval.

Season	New Ice	Fast Ice	Ice Free	Ice- covered season duration (days)	Fractures (<i>N</i>)	Median Gap (h)	IQR Gap (h)	Median Uncertainty (h)	First Fracture	Last Fracture	Dominant Months
2016– 2017	2016-10- 17	2016-11- 14	2017-07- 03	~259	3	215.59	191.72– 251.79	107.79	2016-12- 19	2017-02- 12	Feb
2018– 2019	2018-10- 01	2018-11- 05	2019-06- 10	~252	8	95.45	47.73– 120.14	47.73	2018-11- 29	2019-05- 04	Mar, Dec
2019– 2020	2019-10- 21	2019-11- 11	2020-06- 22	~245	9	47.73	47.73– 72.41	23.86	2019-12- 06	2020-04- 16	Mar
2020– 2021	2020-10- 19	2020-10- 26	2021-06- 21	~245	4	47.73	47.73– 47.73	23.86	2021-01- 05	2021-03- 04	Jan
2021– 2022	2021-10- 18	2021-11- 08	2022-06- 20	~245	9	95.45	47.73– 120.14	47.73	2021-12- 04	2022-05- 08	Apr
2022– 2023	2022-10- 17	2022-11- 07	2023-06- 12	~238	15	95.45	60.07– 156.34	47.73	2022-12- 06	2023-05- 03	Jan, Mar

therefore, represent a subset of the detected fractures and are highlighted in bold in Table 3. Given the strong year-to-year variability and relatively short record, these variations cannot yet be linked to long-term climate trends.

3.2 Synoptic and Local Conditions Associated with Fracturing

3.2.1 Synoptic-Scale Pressure-Gradient Forcing

275 To evaluate the larger-scale atmospheric systems responsible for generating regional winds capable of causing fractures, pressure-gradient magnitudes were calculated from regional SLP fields (Figure 5). The regional SLP fields exhibit strong temporal variability across all observed ice seasons. To quantify the relationship between synoptic events and ice failure, we evaluated whether fractures occurred during or within three days after an intense pressure-gradient episode (defined by the 75th percentile threshold). Under this criterion, 33 of the 48 fracture events (68.8%; 95% Wilson CI: 55–80%) were

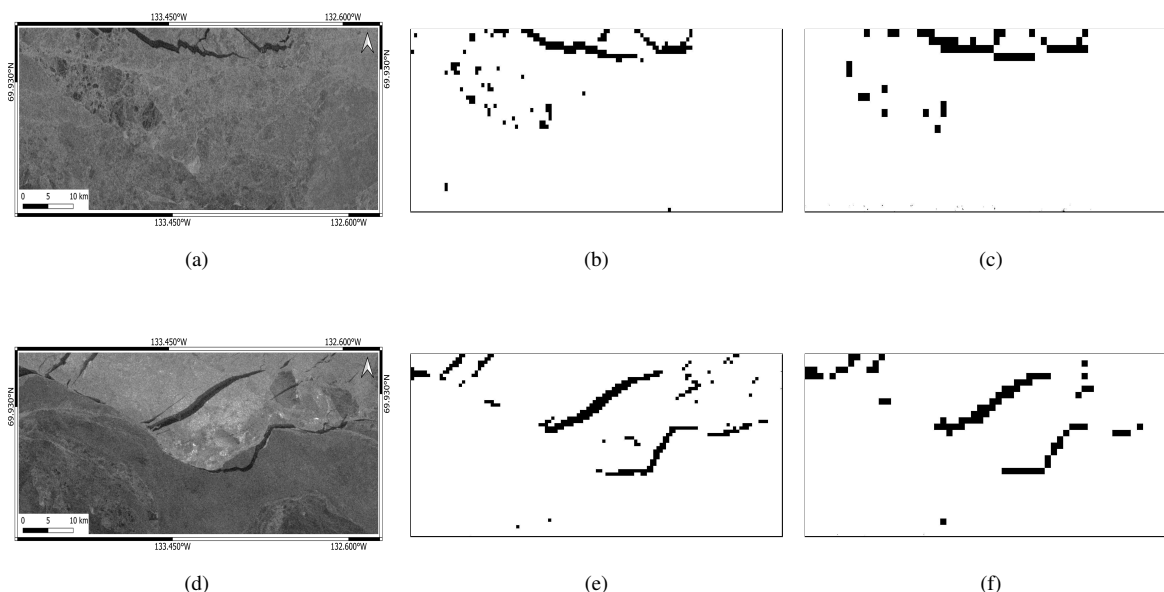


Figure 4. HH Sigma0 (σ^0) image, threshold output with $500 \text{ m} \times 500 \text{ m}$, and $1 \text{ km} \times 1 \text{ km}$ grid outputs for (a-c) 11 February 2017, and (d-f) 15 February 2019. The displayed regions are spatial subsets of the larger Sentinel-1 scenes centered on the SLIE, where fracture and flaw lead features are most prominent (with LFSI in the lower part of each image and the adjacent mobile pack ice in the upper part).

280 associated with enhanced synoptic forcing. This pressure-gradient percentage is therefore interpreted separately from the seasonal fracture-frequency percentages, which describe the timing distribution of fracture occurrence rather than atmospheric attribution. Conversely, 15 of the 48 fracture dates (31.2%) occurred outside these high-forcing periods.

These residual events may reflect localized processes, unresolved internal pack-ice stress, or delayed mechanical responses. Concurrent tide-gauge observations showed no statistically significant relationship between fracture occurrence and tidal
 285 range, tidal phase, or lunar cycle, suggesting that tides are unlikely to be the primary triggering mechanism (see Section 5 in Supplement).

While the highly active 2022-2023 season exhibited the most persistent high-SLP gradient episodes, similar temporal clustering occurred throughout the 2018-2019, 2019-2020, and 2021-2022 seasons, suggesting a multi-year signature. We evaluated whether atmospheric forcing systematically intensified in the days preceding the midpoint-based nominal fracture
 290 date. Event-centered composites generated across a 14-day window around the fracture dates show elevated atmospheric forcing near the nominal fracture date, with the strongest composite values occurring close to day 0 (Figure 6). Matched-control analysis showed no statistically significant difference in ERA5 2-m air temperature between fracture and non-fracture control days, indicating that wind forcing was a stronger event-day discriminator than temperature.

Both regional pressure-gradient forcing and ERA5 10-m wind speed showed elevated composite values near fracture occurrence.
 295 Pressure-gradient forcing increased most clearly during the final 2-3 days before the nominal fracture date and reached its highest composite value around day 0. ERA5 wind speed showed a similar short-term increase, rising sharply immediately



Table 3. Original SAR-detected fracture dates identified in (Chaudhary et al., 2025), and corresponding midpoint-based nominal fracture dates calculated for the present analysis. Original dates represent the first SAR observation in which a fracture was identified, while midpoint dates represent the midpoint between the last no-fracture SAR acquisition and the first fracture-detection acquisition. Dates shown in bold in the original-date column correspond to breakout events, defined as cases where the seaward LFSI edge detached and transitioned into mobile drifting ice. The bold number at the end of each entry in the second column indicates the total number of fracture events for that ice season.

Year	Original fracture date	Midpoint-based nominal fracture date
2016-2017	2016-12-25, 2017-02-11, 2017-02-13 - (3)	2016-12-19, 2017-02-08, 2017-02-12
2018-2019	2018-12-05, 2018-12-17, 2018-12-29, 2019-02-10, 2019-03-06, 2019-03-16, 2019-04-21 , 2019-05-05 - (8)	2018-11-29, 2018-12-15, 2018-12-27, 2019-02-08, 2019-03-04, 2019-03-15, 2019-04-20, 2019-05-04
2019-2020	2019-12-07, 2019-12-19, 2020-01-17, 2020-02-05, 2020-02-17, 2020-03-08, 2020-03-20, 2020-04-01, 2020-04-17 - (9)	2019-12-06, 2019-12-18, 2020-01-15, 2020-02-04, 2020-02-16, 2020-03-07, 2020-03-19, 2020-03-31, 2020-04-16
2020-2021	2021-01-06, 2021-01-16, 2021-02-11 , 2021-03-05 - (4)	2021-01-05, 2021-01-15, 2021-02-10, 2021-03-04
2021-2022	2021-12-06, 2021-12-18, 2022-01-23, 2022-02-23, 2022-02-28, 2022-04-07, 2022-04-24, 2022-05-01, 2022-05-09 - (9)	2021-12-04, 2021-12-17, 2022-01-22, 2022-02-21, 2022-02-27, 2022-04-05, 2022-04-22, 2022-04-29, 2022-05-08
2022-2023	2022-12-08, 2022-12-15, 2023-01-01, 2023-01-04 , 2023-01-08, 2023-01-13, 2023-01-20, 2023-02-23, 2023-02-25, 2023-03-09, 2023-03-19, 2023-03-21, 2023-03-26, 2023-04-02 , 2023-05-04 - (15)	2022-12-06, 2022-12-13, 2022-12-30, 2023-01-03, 2023-01-06, 2023-01-11, 2023-01-18, 2023-02-22, 2023-02-24, 2023-03-08, 2023-03-18, 2023-03-20, 2023-03-24, 2023-04-01, 2023-05-03

before the nominal fracture date and also peaking around day 0. Comparing the pre-fracture window (days -3 to -1) with the background window (days -7 to -4), the mean pressure-gradient forcing increased from 0.0138 to 0.0151 hPa km⁻¹, while ERA5 wind speed increased only slightly from 15.94 to 16.39 km h⁻¹. Paired Wilcoxon signed-rank tests indicated that these increases were not statistically significant for the selected pre-fracture window ($p = 0.159$ for pressure-gradient forcing; $p = 0.681$ for wind speed). These results therefore suggest elevated atmospheric forcing near the estimated fracture-opening window, but the pre-fracture increases over days -3 to -1 were not statistically significant relative to the background window. The largest composite values occurred close to day 0 and should be interpreted as forcing near the nominal fracture date rather than at the exact moment of failure.

3.2.2 Event-Day Meteorological Conditions

On the nominal fracture dates, while regional winter baselines exhibit standard seasonal variations (Figure S7) and winter air temperatures show no significant interannual anomalies (Figure S9), distinct atmospheric anomalies characterize fracture

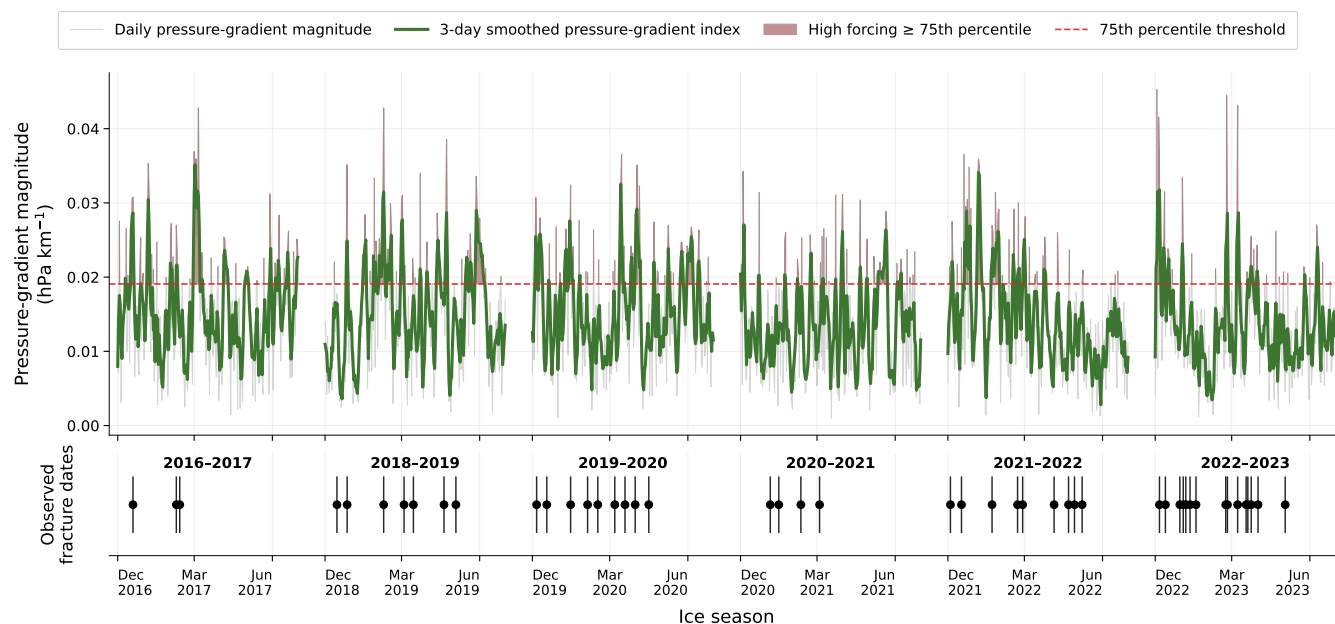


Figure 5. Sea-ice fracture dates and corresponding atmospheric pressure-gradient forcing derived from ERA5 MSLP data for the Tuktoyaktuk coastal region during the 2016-2017 to 2022-2023 ice seasons. The upper panel shows the regional pressure-gradient magnitude (hPa km^{-1}), including the daily forcing signal (grey), the 3-day smoothed pressure-gradient index (green), and the 75th percentile threshold (red dashed line). Periods exceeding the threshold are highlighted by shading, indicating enhanced synoptic-scale atmospheric forcing. The lower panel shows the timing of observed sea ice fracture events identified from SAR observations, calculated via midpoint-based nominal dates. Fracture events frequently coincide with, or occur shortly after, periods of elevated pressure-gradient forcing, indicating that fracture occurrence was frequently associated with elevated atmospheric forcing.

days. Analysis of the wind conditions associated with fracture events (Figures 7 and S7) showed that fracture-day winds were most frequently associated with land-originating sectors rather than predominantly western or northwestern flow. Based on the midpoint-based fracture dates, the most frequent mean wind directions on fracture dates were ESE (11 cases; 22.9%), SE (8 cases; 16.7%), and E (6 cases; 12.5%). When classified by sector origin (see Table S1), 43 of the 48 fracture days (89.6%) were dominated by land-originating winds, whereas 4 events (8.3%) were dominated by ocean-originating winds and 1 event (2.1%) showed an equal land–ocean split. The maximum fracture-day wind speed was 39.92 km h^{-1} on 8 February 2019, associated with land-originating winds. Among the strongest wind-speed cases ($\geq 30 \text{ km h}^{-1}$) within the pre-fracture to fracture-day windows, 7 of 9 events were dominated by land-originating wind sectors, defined here as easterly to westerly offshore-flow directions from the landward side of Tuktoyaktuk, whereas only 2 were dominated by ocean-originating sectors. Table 4 summarizes the individual events contributing to the strongest wind-speed cases. These results suggest that, for the midpoint-based event dates, offshore/land-originating wind forcing was more commonly associated with fracture occurrence than ocean-originating flow.

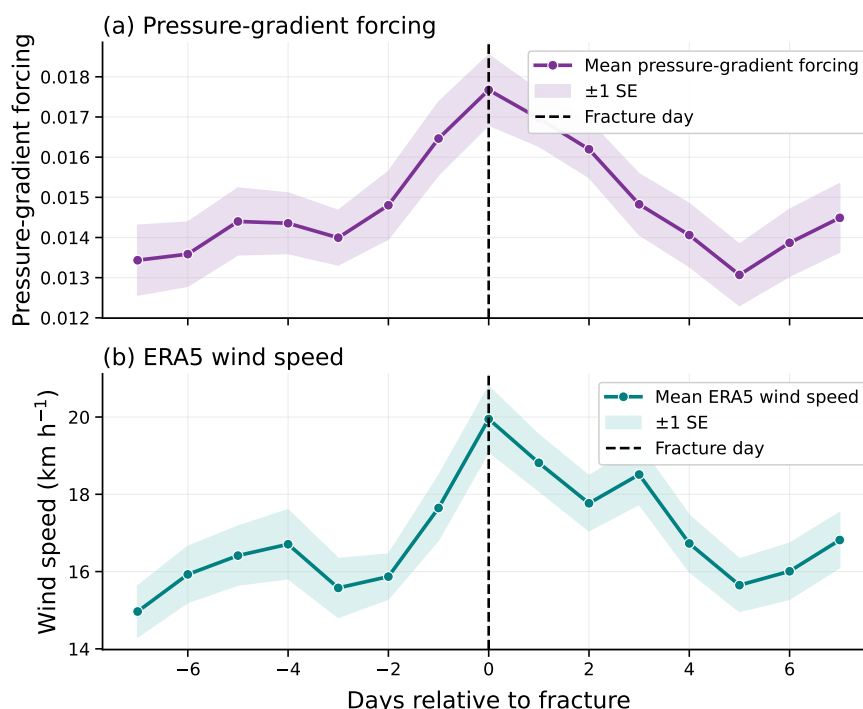


Figure 6. Event-centered composites of atmospheric forcing around fracture events. (a) Composite ERA5-derived pressure-gradient forcing and (b) composite ERA5 10-m wind speed from seven days before to seven days after each nominal fracture date. Day 0 represents the midpoint-based fracture date. The solid colored lines show the mean composite values across all fracture events, and the shaded regions represent ± 1 standard error. Both pressure-gradient forcing and wind speed show elevated composite values near the nominal fracture date and reach their highest composite values around day 0, indicating enhanced synoptic-scale atmospheric forcing near the estimated fracture-opening window.

3.3 Statistical Signatures via Matched-Control Permutation

To confirm that these event-day conditions were truly anomalous rather than typical seasonal fluctuations, a stratified permutation test was executed against matched non-fracture control days (refer to Table S3). Across all matched-control configurations, ERA5 wind speeds were significantly higher on nominal fracture dates than on matched non-fracture dates ($p < 0.05$), with median differences of 3.3–5.2 km h^{-1} , demonstrating robustness to the number of control days and temporal exclusion buffer. We selected the $k=7, \pm 2$ -day configuration for final attribution because it balanced reduced control variance with close calendar-day matching while avoiding the broader temporal spread associated with larger control sets. Under this configuration, all 48 fracture events were successfully matched to seven control days, and wind speeds on nominal fracture dates were a median of 4.9 km h^{-1} higher than on matched non-fracture days ($p=1 \times 10^{-4}$).

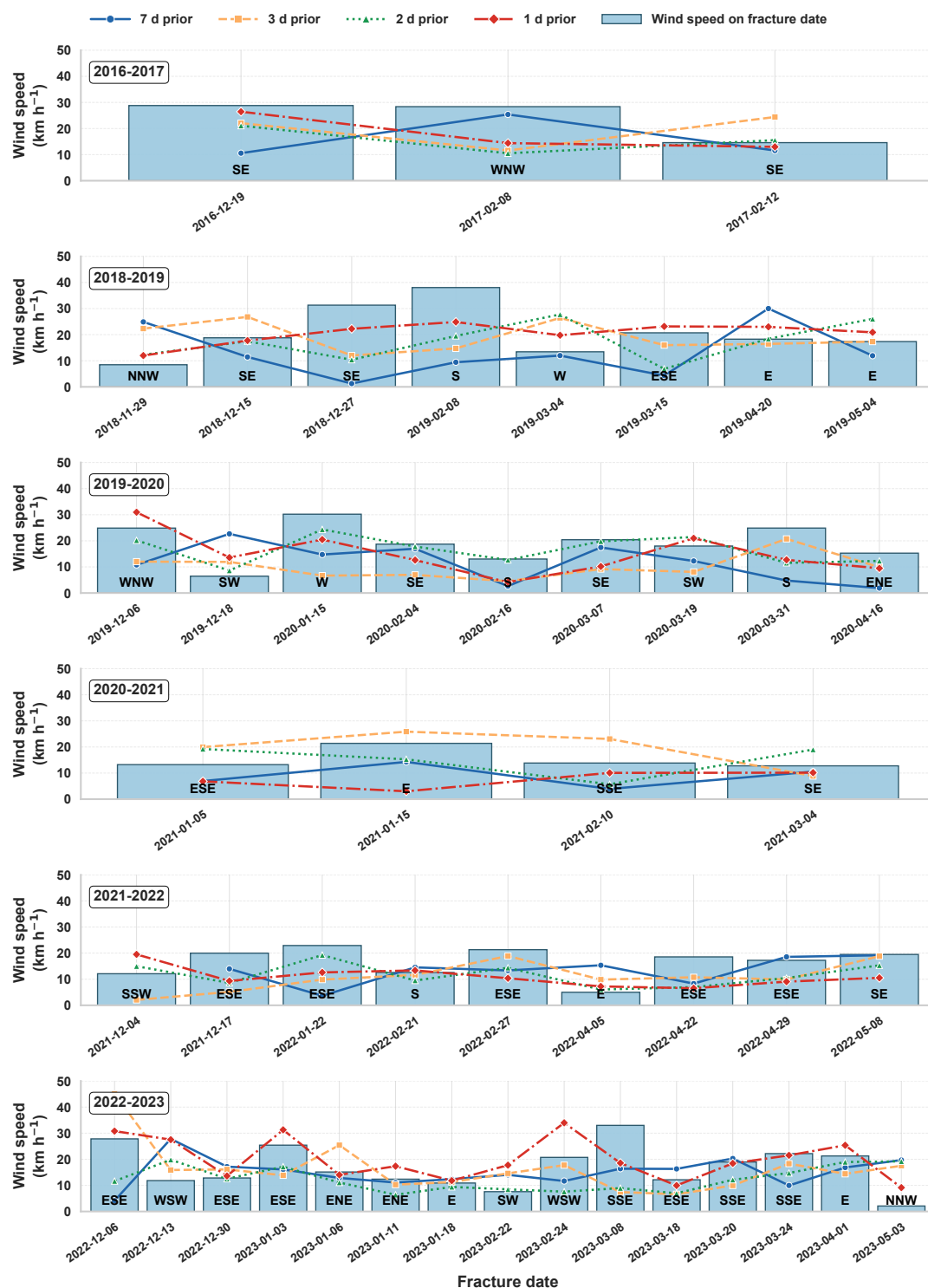


Figure 7. ERA5 wind speed and wind direction on the midpoint-based nominal fracture dates and during the preceding 7, 3, 2, and 1 days. Dates correspond to the nominal fracture dates defined from SAR interval-censoring.



Table 4. Strongest wind-speed cases associated with midpoint-based nominal fracture dates. The table lists fracture events for which the highest mean wind speed among the 7-, 3-, 2-, and 1-day cumulative pre-fracture windows or the nominal fracture day was $\geq 30 \text{ km h}^{-1}$. Land-originating sectors are defined as E, ESE, SE, SSE, S, SSW, SW, WSW, and W; ocean-originating sectors are defined as WNW, NW, NNW, N, NNE, NE, and ENE.

Nominal fracture date	Highest WS (km h^{-1})	Window of highest mean WS	Dominant direction group	Land/Ocean %
2019-02-08	39.92	On fracture day	Land sector	100 / 0
2022-12-06	33.12	3 days before	Land sector	66.67 / 33.33
2023-02-24	33.07	1 day before	Land sector	100 / 0
2017-02-08	31.76	On fracture day	Ocean sector	41.67 / 58.33
2023-03-08	31.56	On fracture day	Land sector	100 / 0
2018-12-27	31.31	On fracture day	Land sector	100 / 0
2019-12-06	30.54	1 day before	Ocean sector	8.33 / 91.67
2020-01-15	30.31	On fracture day	Land sector	54.17 / 45.83
2023-01-03	30.13	1 day before	Land sector	100 / 0

4 Discussion

330 The primary result of this study is that mid-winter LFSI fractures near Tuktoyaktuk are most strongly associated with mechanical forcing rather than short-term thermodynamic weakening or oceanographic variability. Across all matched-control configurations, local wind speed emerged as the single clearest event-scale discriminator ($p = 1 \times 10^{-4}$ under the baseline seven-control configuration). Fracture events were also predominantly associated with land-originating wind sectors, particularly ESE, SE, and E, indicating that both the magnitude and direction of atmospheric forcing are relevant to mechanical loading near the

335 LFSI edge. In contrast, ERA5 2-m air temperatures, tidal ranges, lunar phases, and residual water-level anomalies showed no statistically significant differences between fracture and control dates. These findings support the interpretation that mid-winter fracturing events represent localized mechanical failure at the ice edge rather than premature seasonal breakup.

4.1 Mechanical Failure Across the Fast-Ice Edge

Event-scale fracturing near Tuktoyaktuk is best understood as a nested atmospheric-ice dynamic, where synoptic-scale pressure

340 gradients drive the regional wind fields that result in differential stress across the fast ice edge (Chang et al., 2024; Muilwijk et al., 2024). Nearly 70% (33 of 48) of detected fractures occurred during or within three days after the regional pressure-gradient index exceeded the 75th-percentile threshold. Together with the matched-control evidence for anomalously high wind speeds on fracture days, this suggests that large-scale pressure gradients provide the synoptic conditions for enhanced regional winds that drive mechanical loading and fracture occurrence at the fast-ice edge.



345 This finding is not surprising as it stems from the contrast in mobility between relatively stationary LFSI and the adjacent Beaufort Sea pack ice (Steffen, 1987; Vevatne et al., 2014; Jensen et al., 2023). While LFSI is anchored by coastline geometry, shallow bathymetry, and grounded ridges, the unconstrained pack ice responds rapidly to atmospheric drag. Fracture-day winds were most frequently from the ESE, SE, and E sectors, while seven of the nine strongest wind events ($\geq 30 \text{ km h}^{-1}$) were dominated by land-originating sectors. Such wind forcing can promote differential motion between mobile pack ice and relatively stationary LFSI, generating shear and tensile loading across the transition zone. The strong association between elevated wind speeds and fracture occurrence therefore supports the interpretation that short-term wind forcing provides the mechanical loading associated with failure along the SLIE.

4.2 Pre-conditioning vs. Threshold Triggers

The absence of significant short-term air temperature or oceanographic anomalies on fracture dates suggests a distinction
355 between background preconditioning of the ice cover and the event-scale mechanical forcing associated with fracture occurrence.

Tides and non-tidal water-level fluctuations can contribute to flexural and mechanical stresses along LFSI boundaries (Kowalik and Proshutinsky, 1994; Wang et al., 2020), while cumulative thermodynamic processes, such as ice growth and snow accumulation, influence the evolving mechanical state of LFSI (Li et al., 2019). However, because neither temperature nor oceanographic metrics differed significantly between fracture and matched-control dates, these variables were not significant
360 event-scale discriminators of fracture occurrence in the present analysis.

Instead, thermodynamic state, coastal bathymetry, and pre-existing ice structure may promote failure within mechanically vulnerable sections of the LFSI–pack-ice transition zone, particularly along recurrent leads and pre-existing weaknesses near the SLIE, whereas elevated wind forcing is more closely associated with the timing of fracture opening. Spatial variations in coastline geometry, LFSI stability, and pre-existing structural weaknesses can produce heterogeneous mechanical responses
365 to similar atmospheric forcing, concentrating stress and fracture susceptibility within particular sections of the LFSI–pack-ice transition zone (Chen et al., 2021; Jensen et al., 2023). Thus, local ice conditions may influence where fractures occur, whereas strong wind events appear more closely associated with when fracture opening occurs.

4.3 Observational and Temporal Considerations

Several observational constraints must be considered when interpreting these event-timing relationships. First, because nominal
370 fracture dates are defined as the midpoint between the last SAR observation without a visible fracture and the first observation in which a fracture is detected, day-0 maxima represent forcing near the estimated fracture-opening window rather than at the exact time of crack propagation. Although both pressure gradient forcing and wind speed increased toward day 0, conditions during the pre-event window (days -3 to -1) did not differ significantly from the background window (days -7 to -4). This suggests that atmospheric forcing does not show a consistent multi-day buildup before fracture, but instead tends to strengthen
375 close to the estimated fracture-opening period, consistent with the significantly higher wind speeds observed on fracture days.

Median observation gaps ranged from 48–95 h in most seasons to more than 216 h in 2016–2017, resulting in substantial uncertainty in the timing of individual fracture events. Short lived openings or rapidly refreezing fractures may also occur



entirely between successive SAR acquisitions and therefore remain undetected. Consequently, the observed seasonal counts of 3-15 fracture events should be interpreted as conservative estimates of fracture occurrence rather than absolute measures of interannual variability.

4.4 Implications for Predictive Hazard Monitoring

Distinguishing mid-winter mechanical fracturing from seasonal thermal breakup is important for coastal hazard management. Mid-winter discontinuities often create localized, high-risk open-water leads while the broader LFSI cover remains intact (Cooley et al., 2020). The strong association between elevated wind speeds and fracture occurrence found here suggests that combining SAR-based monitoring of LFSI conditions with short-term weather forecasts could provide a basis for developing fracture-risk monitoring (Jones et al., 2016; Loewen et al., 2024). High-resolution Sentinel-1 imagery can map baseline LFSI geometry and identify vulnerable SLIE segments. At the same time, weather models forecast elevated wind events aligned with critical directional vectors (e.g., offshore SE–E flows exceeding regional thresholds), and high-susceptibility zones can be flagged for upcoming periods of increased fracture risk. Integrating these directional wind-risk models with Indigenous and local knowledge regarding active travel routes, sea-ice behavior, and ice safety (Eicken et al., 2009; Laidler et al., 2009) bridges the gap between satellite revisit delays and real-time community safety on the ice.

5 Conclusions

This study investigated the environmental conditions associated with wintertime LFSI fracture near Tuktoyaktuk using Sentinel-1 SAR imagery and atmospheric reanalysis data across six of seven ice seasons (2016-2017 to 2022-2023). Our findings show that mid-winter fracturing is most strongly associated with short-term mechanical atmospheric forcing rather than short-term thermodynamic weakening or the oceanographic variability examined here. Local wind speed emerged as the clearest event-scale discriminator, while fracture events were predominantly associated with land-originating winds, particularly from the SE–E sectors. Synoptic-scale pressure gradients provide the broader atmospheric context for fracture occurrence by driving regional surface winds that can promote differential motion and mechanical loading between relatively stationary LFSI and the adjacent mobile Beaufort Sea pack ice. Crucially, over 79% of detected fractures occurred between December and March, well before seasonal melt. This seasonal concentration, together with the lack of a significant short-term temperature signal, indicates that the observed mid-winter fractures are localized mechanical failure events within an otherwise established ice cover rather than early seasonal breakup. Local ice and boundary conditions, including coastal morphology, LFSI stability, and pre-existing structural weaknesses, may further influence fracture susceptibility along the LFSI–pack-ice transition zone.

These results provide a physical foundation for predictive risk monitoring near Arctic coastal communities. SAR observations of ice-edge conditions with directionally targeted wind forecasts could help identify periods of increased fracture risk and contribute to hazard assessment between satellite observations. Integrating these physical risk thresholds with Indigenous and local knowledge regarding active travel routes and sea-ice behavior could help address satellite revisit limitations and improve the relevance of hazard information for community safety on the ice. Future efforts should focus on combining higher-frequency



410 satellite constellations with localized under-ice current measurements and mechanical stress modeling to resolve fine-scale
dynamics at the fast-ice boundary further.

Data availability. All datasets used in this study are publicly available from open-access sources. The SAR imagery was obtained from the Alaska Satellite Facility (ASF) and can be accessed at <https://search.asf.alaska.edu/>. Landsat imagery is available through <https://glovis.usgs.gov/app>. Weather station data for Tuktoyaktuk is accessible at https://climate.weather.gc.ca/historical_data/search_historic_data_e.html. ERA5 reanalysis data can be freely downloaded from <https://cds.climate.copernicus.eu/>, and ice chart data are

415 available at <https://iceweb1.cis.ec.gc.ca>.

Author contribution. VC performed the data analysis and led the manuscript writing. VC and VN developed the methodology, and VN contributed to revisions. JS and DI supervised the project and contributed to interpretation and revisions.

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