

The role of atmospheric blocking on the calving of Greenland's marine-terminating glaciers

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Den atmosfäriska blockeringens inverkan på kalvningen hos Grönlands havsnära glaciärer

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Physical Geography and Ecosystem Analysis

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Abstract

The Greenland Ice Sheet (GrIS) is seeing an accelerated rate of ice melt, which increasingly contributes to global sea-level rise. Studies have reported a growing mass imbalance coinciding with a widespread retreat of the island's glacial termini. The associated discharge of ice is driven by submarine melting and ice breaking off glacial fronts, a process known as calving. The rate at which calving occurs is influenced by large-scale oceanic and atmospheric factors. Therefore, this study aims to explore the impact of atmospheric blocking on ice calving from 2013 to 2021. To analyze this, a dataset of glacial fronts delineated by a novel machine learning algorithm is used in combination with the relatively new parameter of extreme Greenland Blocking Episodes (GBEs). A Superposed Epoch Analysis (SEA) is performed for a visual analysis of the effect of extreme GBEs on calving, strengthened by several Mann-Whitney U tests to analyze the influence of blocking on surface air temperatures and weekly and yearly rates of calving.

Despite high variability of the glacial response across the study period, a widespread glacial retreat is found, with a mean withdrawal of 106 m year^{-1} per glacier. Ten occurrences of extreme GBEs are identified throughout the study period, during which the temperature anomalies are shown to be significantly higher than outside of the episodes. No relationship to blocking is found for the short-term calving rates of the pooled and individual set of glaciers. The year 2019 sees double the amount of extreme GBEs as any other year, but there is no significant increase in calving. Although atmospheric blocking is known to induce glacial surface melt, my study finds no clear link to the process of calving. Understanding how atmospheric conditions influence processes on the GrIS is key to improving models of ice melt and sea-level rise estimates.

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1.3 List of abbreviations

Abbreviation	Meaning	Page
ESA	European Space Agency	3
ESOTC	European State of the Climate	3
GBE	Greenland blocking episode	3
GrIS	Greenland ice sheet	3
IPCC	Intergovernmental Panel on Climate Change	3
NOAA	National Oceanic and Atmospheric Administration	7
SAR	synthetic aperture radar	22
SEA	superposed epoch analysis	7

2 Introduction

2.1 Context

The Greenland Ice Sheet (GrIS) is seeing an accelerated rate of shrinkage in the 21st century due to the effects of climate change, characterized by an increase in mass loss, a rapid thinning along the island's margins, and accelerating outlet glaciers (IPCC, 2021; ESA, n.d.). The system exhibits a mass imbalance, as the 2025 hydrological year was the 29th consecutive year of a net mass loss (ESOTC, 2026). Between 1972 and 2025, 5747 ± 467 Gt of ice was lost, contributing 16.0 ± 1.3 mm to the global average sea level rise. Projections indicate that, regardless of emission scenario, the loss of mass is expected to continue throughout this century.

The total GrIS mass balance is determined by the surface mass balance, ice flow, and basal melt (ESOTC, 2026). The surface processes generally have a positive contribution to the mass balance and primarily consist of snow accumulation and meltwater runoff driven by solar radiation, air temperature, and precipitation. The ice flow dynamics are driven by ice moving under its own weight towards the ocean. Ice flow naturally has a negative impact on the mass balance, and most of the ice discharge occurs through submarine melt and glacial calving.

Glacial calving is the process of ice breaking off the terminus of a glacier into water. Widespread calving front retreats have been detected in Greenland, and nearly every marine-terminating glacier has thinned or seen a retreat over the past few decades (Mottram et al., 2019; Moon et al., 2020; Murray et al., 2015). The highest rates of mass loss through ice discharge are found along the western coast and in southeastern Greenland, concentrated at a few major outlet glaciers (Mouginot et al., 2019; Khan et al., 2020). For individual outlets, the primary controls of calving are sea ice and ice mélange, fjord geometry, bed topography, and terminus type (Carr et al., 2013; Morlighem et al., 2019). Large-scale drivers of calving include oceanic and atmospheric forcing (Vieli & Nick, 2011).

Atmospheric circulation over Greenland is a driver of short-term changes in ice sheet mass balance due to the effects on snowfall and melt rates (IPCC, 2021). An example of this is the large-scale patterns in the atmospheric pressure field known as atmospheric blocking, which are known to “block” or redirect migratory cyclones (Hanna et al., 2014, 2015). These strong and persistent anticyclonic systems can be defined by the appearance of an anomalous center of high pressure and are known to cause exceptional atmospheric conditions, such as harsh cold episodes in winter and extreme droughts and heat waves in summer. Over the GrIS, these events are referred to as Greenland Blocking Episodes (GBEs). They often form along the western margin of the ice sheet, and can stay in place for days or weeks. The year 2019 is an example of the extreme conditions that GBEs are known to induce, as a combination of low snowfall and dominant anticyclonic conditions caused a record annual mass loss of 532 ± 58 Gt yr⁻¹ for the GrIS (Sasgen et al., 2020; Tedesco & Fettweis, 2020). Although the effects of blocking on surface melt are well-studied in literature, it is relatively unknown what the effect on calving is, as the drivers and controls related to atmospheric forcing are relatively indirect and difficult to study (Vieli & Nick, 2011).

This study looks at extreme GBEs and their impact on the short-term ice mass loss from glacial calving. The existence and effects of extreme GBEs have only been described relatively recently (Hanna et al., 2013, 2014, 2015). As a result, the studies that have so far been conducted in this field have focused on the role of individual atmospheric parameters and did not consider blocking (Moon et al., 2020; Mouginot et al., 2019; Murray et al., 2015). Additionally, previous

studies either consider a very limited number of glaciers extensively, or they consider a large number of glaciers whose retreat is measured by distance rather than area. My study uses a dataset published by Loebel et al. (2024), which consists of 23 delineated calving fronts from 2013 to 2021 that have been extracted using new machine-learning techniques and Landsat-8/9 imagery. Due to this novel method, area of change can be used as a metric for a large sample set of glaciers. Therefore, this study considers the relatively new parameter of extreme GBEs in combination with the area of change of a larger sample of glacial fronts in the GrIS.

2.2 Research aim and questions

The aim of this study is to explore the impact of extreme GBEs on ice mass loss from glacial calving across a spatially representative sample of Greenland's outlet glaciers. The research question of this study is as follows: what is the relationship between extreme GBEs and glacial calving in a representative sample of Greenland's outlet glaciers from April to September between 2013 and 2021?

To answer that, this study addresses the following questions:

1. How did Greenland's outlet glaciers develop from 2013 to 2021?
2. What is the effect of extreme GBEs on surface air temperature?
3. How do extreme GBEs relate to short-term glacial calving?
4. To what extent did the 2019 anomalous melting year impact glacial calving?

3 Background

The ice-ocean boundary of the GrIS is constantly changing due to the melting and calving of marine-terminating glaciers. Two distinct ice calving styles defined in literature are serac failure and buoyant flexure (Fried et al., 2015, 2018; Goliber & Catania, 2024). The former type is shaped by high-frequency, low-volume calving events. Submarine melting from the seawater undercuts the terminus, connects to surface crevasses, and creates smaller icebergs. The latter calving style creates low-frequency, high-volume ice bergs. Buoyant flexure is more common in glaciers with relatively deep beds, where the termini create floating tongues that can break off as large glacial slabs.

After the calving process breaks off a section of the terminus, it ends up in the sea. If the resulting sea ice and ice mélange (the mixture of sea ice types and snow) are not broken up, they can play a buttressing role, which stabilizes the glacier (Sun et al., 2017; Benn & Åström, 2018). Factors that influence the sea ice and ice mélange can therefore have an effect on the calving rate. Carr et al. (2013) describe that fjord width can restrict the calving rate, as narrower fjords slow down the removal of sea ice. The melting of ice mélange also reduces the buttressing effect and can therefore destabilize outlet glaciers. Additionally, Morlighem et al. (2019) find that bed topography and fjord bathymetry influence how much sea water reaches the glacial terminus. Nearby glaciers might therefore experience similar oceanic conditions but show different responses. Basal pinning points, i.e., rock outcrops that marine-terminating glaciers can attach themselves to, are also able to stabilize the glacial calving (Carr et al., 2013). Thus, the calving rate of individual outlet glaciers is influenced by factors specific to each glacier. However, atmospheric conditions are able to influence entire regions of the entire GrIS.

Studies have shown that Greenland's outlet glaciers react strongly to changes in atmospheric temperatures (Howat et al., 2008; Moon & Joughin, 2008). Vieli & Nick (2011) describe the primary effects of atmospheric forcing on glacial calving, which is mainly driven by surface ice melt. Meltwater can percolate from the surface to the glacier's basal layer, which increases glacial velocity towards the sea through basal lubrication. Water can also drain into glacial crevasses, increasing the water pressure as it fills up (Van der Veen, 1998). This process weakens the glacial ice and makes calving more probable. Additionally, the surface meltwater can percolate and warm the ice from within, weakening the ice shelf and making calving more likely to occur (Vieli & Nick, 2011). Furthermore, the glacial surroundings can have a buttressing effect, where a glacier is held in place by friction with its surroundings (Carr et al., 2013). Atmospheric warming can soften the ice on the sides, reduce the buttressing, and thereby increase glacial flow (Vieli & Nick, 2011). In addition to that, the calving process is complicated by the fact that calving events can cause the glacial stresses and forces to be redistributed, causing an instantaneous acceleration at the terminus. This effect is known to ripple further inland, increasing the glacial velocity kilometers upstream. Therefore, atmospheric warming-induced effects on calving are uncertain due to the difficulty of studying inner glacial mechanisms. The related atmospheric variables are strongly influenced by the occurrence of extreme GBEs (Hanna et al., 2015, 2018).

Atmospheric blocking over the GrIS can be measured by the occurrence of extreme GBEs. Hanna et al. (2013) find that recent temperature records over Greenland are characterized by unprecedented levels of high pressure, especially at the 500 mb geopotential height. The pressure corresponds to warm-air advection, reducing the cloudiness especially in the south (Fettweis et al., 2013; Hanna et al., 2014). This causes an increase in incoming shortwave radiation and a decrease in albedo, thereby causing an increase in atmospheric temperatures.

McLeod and Mote (2016) find that extreme GBEs are increasing predominantly in the spring (MAM) and summer (JJA) months, and cite it as a driver of interannual variability of the GrIS sea ice melt. Due to the buttressing role sea ice has on marine-terminating glaciers (Sun et al., 2017; Benn & Åström, 2018), atmospheric blocking can indirectly impact calving through the melting of sea ice and ice mélange.

4 Methods

The methods describe the quantitative approach this study uses to analyze the relationship between extreme GBEs and glacial calving. First off, the data description contains the explanations for the calving, blocking, and temperature variables, as well as a description of the study area. The data processing section then delineates how these variables are used in this study to acquire normalized values for the statistical testing, as well as a definition of extreme GBEs. Lastly, the statistical methods define the usage of the Superposed Epoch Analysis (SEA) and the Mann-Whitney U tests, whereby a Bonferroni correction is applied to account for the number of statistical tests utilized.

4.1 Data description

4.1.1 Glacial calving dataset

This study uses a glacial calving front dataset from Loebel et al. (2024). Their dataset consists of 23 glacial fronts across Greenland from 2013 to 2021, represented as line layers in shapefile format. Their data is gathered by use of software that automatically delineates calving front locations from Landsat-8 and Landsat-9 Level-1 archives using a deep learning approach. The delineated line layers act as a proxy for glacial calving, making it suitable to study calving in the long term. The time periods of the measurements are irregular, as the Landsat satellites capture images of each area of Greenland every eight days (USGS, n.d.). Additionally, Loebel et al.'s (2024) software uses Landsat's optical imagery as input, meaning it does not use photos taken in the dark or in cloudy conditions. For Greenland, this effectively limits the period of this study to the months that have the most sunlight and least amount of clouds, from April to September.

4.1.2 Greenland Blocking Index

The Greenland blocking data is downloaded from NOAA (n.d.-a), who provide a Greenland Blocking Index (GBI) timeseries from 1948 to the near present. The data is presented as daily values of the geopotential height at 500 mb, area averaged over 60-80°N and 20-80°W. The values are calculated from NOAA's (n.d.-b) NCEP/NCAR Reanalysis, averaged from 4x daily measurements.

4.1.3 Temperature data

Greenland's temperature data is downloaded from the Danish Meteorological Institute (DMI), report 25-08 (Cappelen, 2025). Their report contains the data for 91 stations with weather observations in the period 1958-2024. This study uses the temperature data from station 04124 – Nuussuaq. It is a Greenland Isolated Weather Station (GIWS), an automatic station with hourly data for dry-bulb temperature. Station 04124 has operated from September 18th, 1982 up to the present. It is chosen due to its approximate central location of the GBI, it being along Greenland's coast, and it containing data from 30 years before the start of the study period in 2013, meaning it can provide an adequate climatological baseline. The data is given as mean air temperature [°C] two meters above the ground. Due to the irregular measurement times across the years of operation, only the daily measurements at 12 UTC are used for consistency.

4.1.4 Study area

Figure 1 shows a map of the study area. Of the 23 glaciers in Loebel et al.'s (2024) dataset, four are filtered out due to being outside of the GBI's coordinates, and nine outlets are not used due

to consisting of several fronts. This leaves ten marine-terminating calving fronts (Table 1), including glaciers from a large portion of Greenland's coastline.

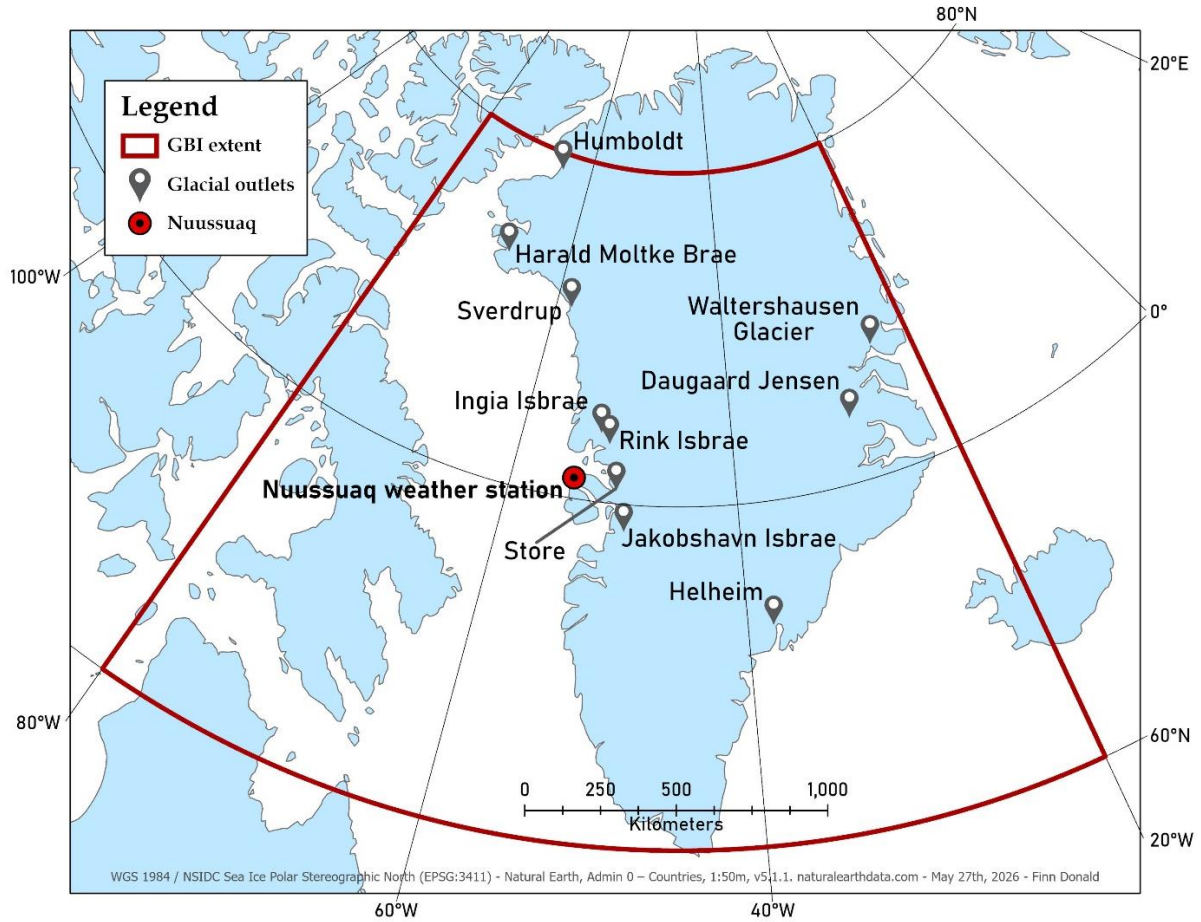


Figure 1: Map showing the extent of the GBI, the ten glaciers in this study, and weather station used for the temperature data.

Table 1: Coordinates and terminus width for each glacier.

Glacier	Latitude	Longitude	Measured terminus width (km)
Daugaard Jensen	71.77°N	-29.25°W	5.43
Harald Moltke Brae	76.60°N	-67.78°W	6.12
Helheim	66.35°N	-38.20°W	5.42
Humboldt	79.50°N	-63.00°W	85.90
Ingia Isbrae	72.13°N	-52.45°W	3.05
Jakobshavn Isbrae	69.17°N	-49.83°W	20.94
Rink Isbrae	71.75°N	-51.67°W	4.53
Store	70.40°N	-50.60°W	4.95
Sverdrup	75.60°N	-58.10°W	6.28
Waltershausen glacier	73.90°N	-24.42°W	10.22

4.2 Data preprocessing

4.2.1 Rectilinear box method

The rectilinear box method (Loebel et al., 2024) is used to calculate the glacial areal change caused by calving. This method, first described by Moon and Joughin (2008), is provided as a Python script that requires three inputs. These are line layer shapefiles that represent the rate of calving, a Landsat-8 basemap, and a box drawn from 4 vertices, which was drawn in ArcGIS Pro for this study. Additionally, the script needs to know the EPSG code of the basemap and line layers to accurately make the areal change calculations and plot each outlet glacier's location. The software's output consists of a text file with the date and areal change in square kilometers, as well as a map and graph of areal change over time.

4.2.2 Calving anomaly rate normalization

An anomaly normalization is applied to the calving rate values. After computing the area of change for each glacier, the daily calving rate [km^2/day] is calculated:

$$Calving\ rate = (area[t] - area[t - 1]) / (date[t] - date[t - 1]) \quad (1)$$

Where $[t]$ is a given measurement, and $[t-1]$ is the previous one. The calving rate's new date is the midpoint between the two measurements, which is rounded down for any half-days.

Thereafter, a monthly anomaly normalization is applied to the calving rates. The observations for each glacier are grouped by calendar month, and the calving rate's means and standard deviations are computed across all years. Each observation is then calculated as a z-score anomaly:

$$Calving\ anomaly = \frac{rate - monthly\ mean}{monthly\ standard\ deviation} \quad (2)$$

The resulting calving anomaly is expressed as how many standard deviations it is away from the glacier's typical calving rate for a given month. This means that each observation can be compared to its own typical state and can be compared to other glaciers regardless of seasonality.

4.2.3 Temperature anomaly normalization

A z-score anomaly normalization is also applied to the temperature data. The difference to the calving anomaly calculations is the use of a climatological baseline. First, the baseline is defined from 1982 to 2012, with leap days counted as February 28th. Then, the mean and standard deviations are calculated for all 365 day-of-year combinations across the baseline. Thereafter, the baseline mean for the corresponding day-of-year is subtracted from each measurement between 2013 and 2021 and divided by the standard deviation. The result is z-score temperature anomalies.

4.2.4 Extreme GBEs

To define extreme GBEs, a definition from literature needs to be used. Hanna et al. (2018) define an extreme episode as the GBI exceeding 3 standard deviations for at least three consecutive days. However, due to the irregular temporal sampling of the calving dataset that

results in a study of the long-term effects of blocking on calving, this definition could lead to blocking episodes that are too short to properly analyze.

Instead, McLeod and Mote's (2016) definition is used, where a blocking episode is defined as having 5 days above the 97th percentile of a 7-day window centered on a date. The 97th percentile GBI value is calculated for every day of the year from 1948 to 2012 as a climatological background (with leap days being counted as February 28th) and is thereafter compared against the daily values from 2013 to 2021 to find occurrences of extreme GBEs. Days that are consecutively flagged according to this definition are aggregated into single episodes, with the peak GBI value in a series used as the event date.

4.3 Statistical methods

With the calving and extreme GBE data processed, this study performs a SEA to visually analyze trends of all the glaciers combined. Additionally, a Mann-Whitney U test is used for the first research question, testing for the relationship between blocking episodes and temperature anomalies. Three more Mann-Whitney U tests are used between the blocking episodes and calving data. This consists of a pooled analysis of glaciers, a per-glacier evaluation, as well as an examination of the melting year 2019. A Bonferroni correction is applied to the significance level α , as performing several Mann-Whitney U tests increases the chance for a false positive result to occur.

4.3.1 Superposed Epoch Analysis

The SEA is a statistical tool used by Chree (1913) to detect patterns in time series relative to specific epochs or events. The technique is described in detail by Singh and Badruddin (2006). It has been used before by Adams et al. (2003) to study the relationship between an atmospheric variable and a physical phenomenon. Due to the mathematical complexity of the technique, this study uses a simpler approach based around compiling blocking and calving data and extracting a visual relationship. The result is used as a visual tool, rather than extracting statistical values from the data like the previously mentioned articles. Nevertheless, the resulting graph still contains valuable information about our study.

First off, the SEA defines each extreme GBE as epoch = 0. A time window of 28 days is defined before and after each epoch, and each calving anomaly observation that falls within this window is grouped into one of the eight 7-day bins. The bins are defined as seven days, as that is the same amount of time of McLeod and Mote's (2016) definition of an extreme GBE. Then, the mean of each bin's calving anomaly observations is calculated. The result is a graph with lag on the x-axis and mean calving anomalies on the y-axis, where a post-event negative calving anomaly dip would indicate that this study's expected relationship between blocking and calving is present.

4.3.2 Mann-Whitney U test

4.3.2.1 About the test

The Mann-Whitney U test is chosen over the Student's t-statistic, as it is a non-parametric statistical test used to examine the difference between two groups that does not assume a natural distribution in the underlying population distributions (Chicco et al., 2025; Mann & Whitney, 1947). Rather than comparing group means directly, Mann-Whitney ranks subjects from their lowest to highest value, whereafter each of the two groups' cumulative rank is summed. The

test is based on the assumptions that the two samples are independent, the observations are continuous, and the distributions are similar in shape. Each Mann-Whitney U test defines a null hypothesis (H_0), where no difference is found between two groups, as well as an alternative hypothesis (H_1), where the distributions of the two groups differ. The test then computes a p -value and compares it to the significance level α to determine whether test significance is reached.

4.3.2.2 Performed tests

This study relies on three Mann-Whitney U tests for its results. A Bonferroni correction is applied to these tests, giving an adjusted significance level of $\alpha (= 0.050 / 3) = 0.017$. The null hypothesis for all tests is that there is no difference between the two groups.

1. Temperature anomalies within seven days of an extreme GBE are compared against those outside of this window to assess the relationship between air temperature and blocking (*one-tailed, H_1 : anomalies in GBE group > non-GBE group*);
2. A pooled analysis of all glaciers, where calving rate anomalies within seven days of an extreme GBE are compared against measurements outside of this window (*one-tailed, H_1 : anomalies in GBE group < non-GBE group*);
3. The calving measurements of the melting year 2019 compared against all other years (*one-tailed, H_1 : anomalies in 2019 group < non-2019 group*).

Several exploratory Mann-Whitney U tests are also performed to aid in the interpretation of the results. These tests are not accounted for in the Bonferroni correction, as they are either an extension of the main tests' time windows, or they are part of the per-glacier analysis, which in the case of its inclusion would create an impractically low significance threshold. Two exploratory tests are the temperature-blocking and pooled calving analyses repeated using a 14-day window to assess the choice of window size using the same alternative hypotheses. Furthermore, a per-glacier analysis is performed, comparing the calving rate anomalies within seven days of an extreme GBE against those outside for each individual glacier to assess the individual response of outlet glaciers (*H_1 : anomalies in GBE group < non-GBE group*).

5 Results

The results are structured through the sub-questions. First off, an analysis of the results from Loebel et al.'s (2024) rectilinear box method is performed to study the behavior of the ten outlet glaciers of this study. Secondly, the distribution of extreme GBEs is assessed in addition to the statistical testing of blocking and surface air temperature. The results from the SEA, as well as the pooled and per-glacier statistical tests, follow to study the short-term effects of blocking on glacial calving. Lastly, the calving anomalies during the record-breaking melt year of 2019 are evaluated.

5.1 Outlet glacier developments

There are 2904 observations across the 10 glaciers from 2013 to 2021. Figure 2 shows the glacial areal change of Sverdrup, one of this study's outlet glaciers, and it is based on 419 calving front inputs. Both the visual output and timeline highlight a receding glacial front. A typical seasonal trend for the glaciers is visible in the timeline, with a period of steady growth earlier in the year and a steep melting event later in the year. Figures for all other glaciers can be found in Appendix 9.1.

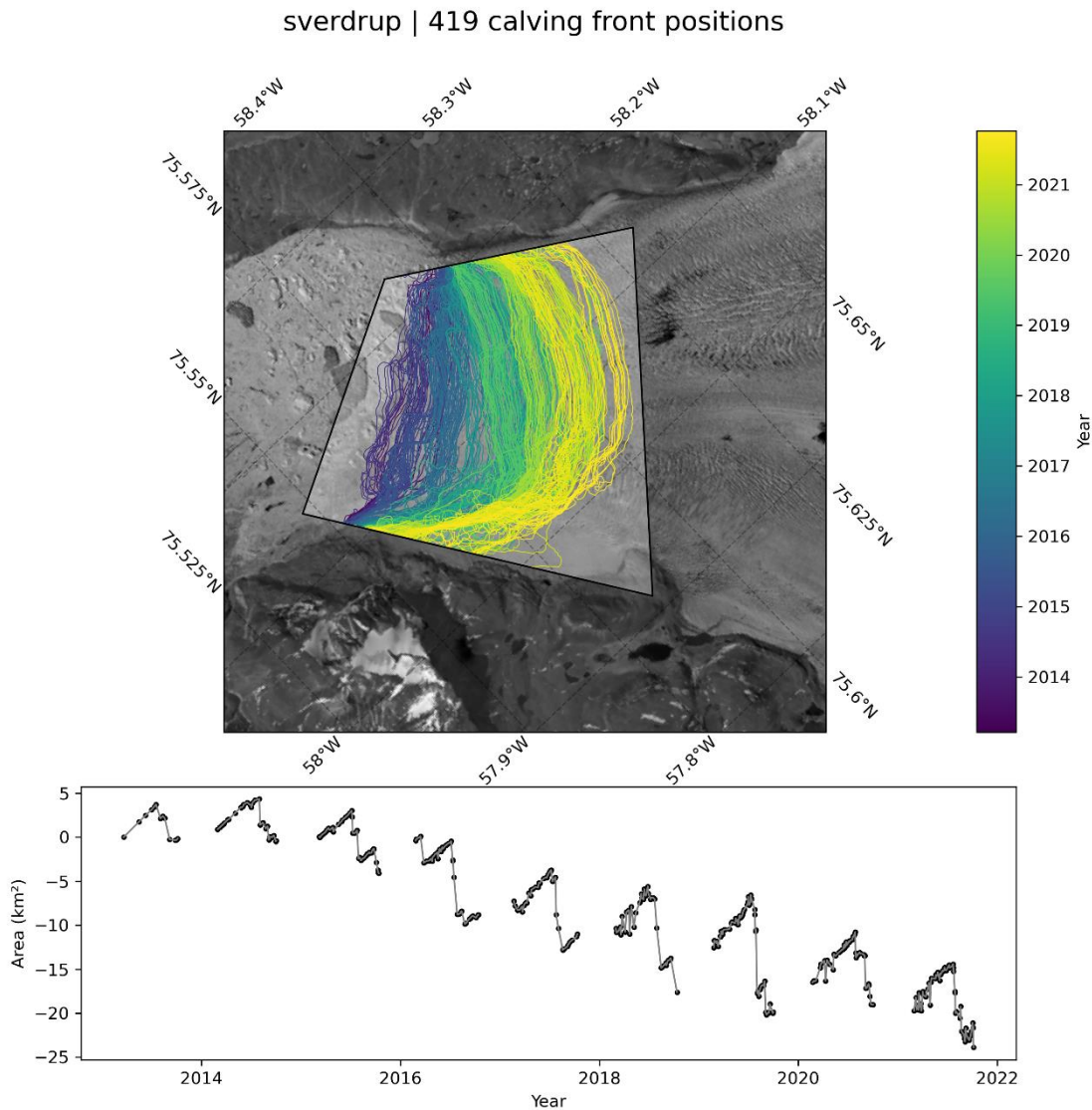


Figure 2: Visual output of Sverdrup's outlet glacier using the rectilinear box method. Each line represents one delineated calving front position, with the color indicating the year that it is from between

2013 and 2021. The bottom graph shows the change in area using each individual measurement of the timeline of the glacial development.

From 2013 to 2021, eight of the ten calving fronts see a decrease in area, with Rink Isbrae and Store growing in size by less than a square kilometer (Table 2). The median areal change of the glacial fronts from 2013 to 2021 is -4.58 km^2 . Accounting for the difference in terminus length of all glaciers, the mean front advance is 950 m. Across the study period, this is a retreat of 106 m year^{-1} per glacier. The fronts that retreated the most are Sverdrup and Ingia Isbrae: 3120 meters and 2710 meters respectively. The glaciers show some differences in seasonality, with some fronts growing and others shrinking in spring. All fronts retreat in summer, except for Waltershausen, which has a mean glacial advance in both spring and summer. Eight outlets portray a higher rate of calving during the summer (JJA) than during the spring (MAM). The fronts that calve more in spring are Helheim and Jakobshavn Isbrae, the two southernmost glaciers of this study.

Table 2: Each glacier's areal change from 2013 to 2021 (mean areal change of 2021 minus 2013), the total front advance (total areal change divided by terminus length), the mean calving rate in spring (MAM), and the mean calving rate in summer (JJA).

Glacier	Areal change from 2013 to 2021 [km^2]	Total front advance [m]	Mean spring areal change [$\text{km}^2/\text{season}$]	Mean summer areal change [$\text{km}^2/\text{season}$]
Daugaard Jensen	-3.14	-580	0.70	-5.02
Harald Moltke Brae	-2.99	-490	0.95	-1.00
Helheim	-7.96	-1470	-4.27	-3.45
Humboldt	-83.76	-980	-2.00	-18.38
Ingia Isbrae	-8.28	-2710	0.23	-1.73
Jakobshavn Isbrae	-6.02	-290	-8.11	-1.29
Rink Isbrae	0.61	130	0.94	-2.57
Store	0.33	70	2.64	-1.79
Sverdrup	-19.61	-3120	3.24	-6.42
Waltershausen glacier	-0.89	-90	0.27	1.76
Mean	-13.17	-0.95	-0.54	-3.99

5.2 Temperature and blocking

There are 10 distinct extreme GBEs that occur between 2013 and 2021. Four of these happen in 2019, which is twice as many episodes as any other year (Figure 3). There are no extreme GBEs in 2013, 2018, and 2020. The remaining years each have one episode. Additionally, the monthly analysis shows that most of the episodes occur in July ($n = 3$). April and May see two

episodes each, while June, August, and September each have one extreme GBE throughout 2013 to 2021.

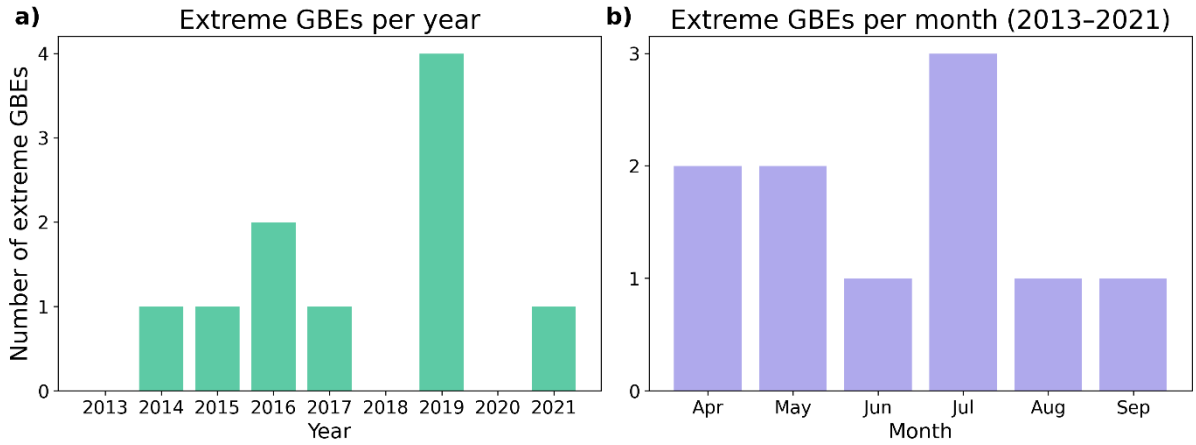


Figure 3: a) Bar chart featuring the extreme GBEs on a yearly basis, and b) the months that extreme GBEs occur in.

Figure 4 shows the number of extreme GBE days ($n = 52$) within the values of the daily GBI. Despite 2013 and 2020 having measurements outside of the 97th percentile climatological background threshold, the conditions do not persist for long enough to meet the criterion for an extreme GBE. 2018 is the only year that did not have any individual observations that exceed the 97th percentile. An enlarged version of this graph is attached in Appendix 9.2.

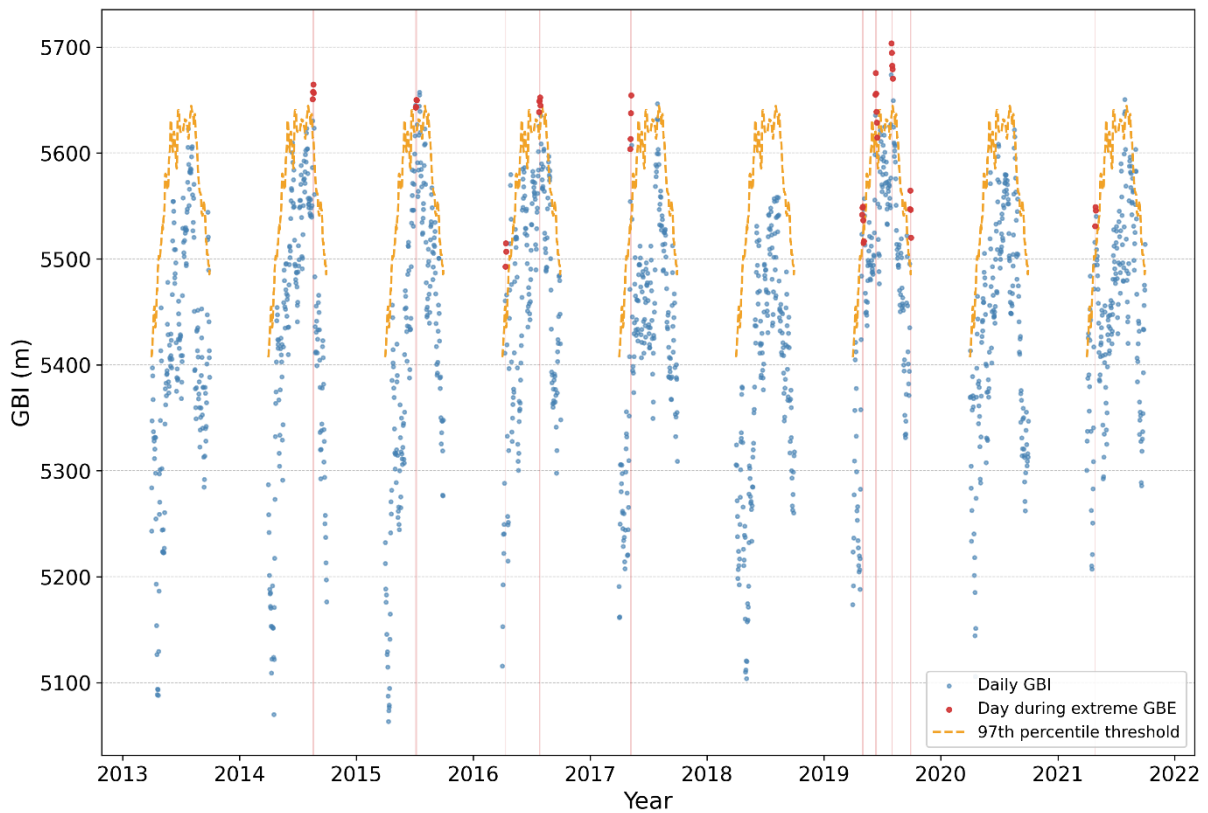


Figure 4: Daily GBI with extreme GBE days highlighted (April-September from 2013-2021).

The temperature anomalies are higher during extreme GBEs than outside of them for both the 7-day ($p = 0.000$) and 14-day ($p = 0.000$) windows. This yields a statistically significant result

($p < 0.017$), rejecting H_0 . The mean temperature anomalies within 7 and 14 days of extreme GBEs are z-scores of 0.687 and 0.548 respectively, and mean anomalies outside of this are 0.215 and 0.208. The total amount of noon observations is 1443, with 64 and 121 measurements recorded for the GBE groups of the respective time windows. The box plots of these results can be seen in Figure 5, where it is visible that the percentiles for the observations during extreme GBEs are consistently higher than those outside of these periods.

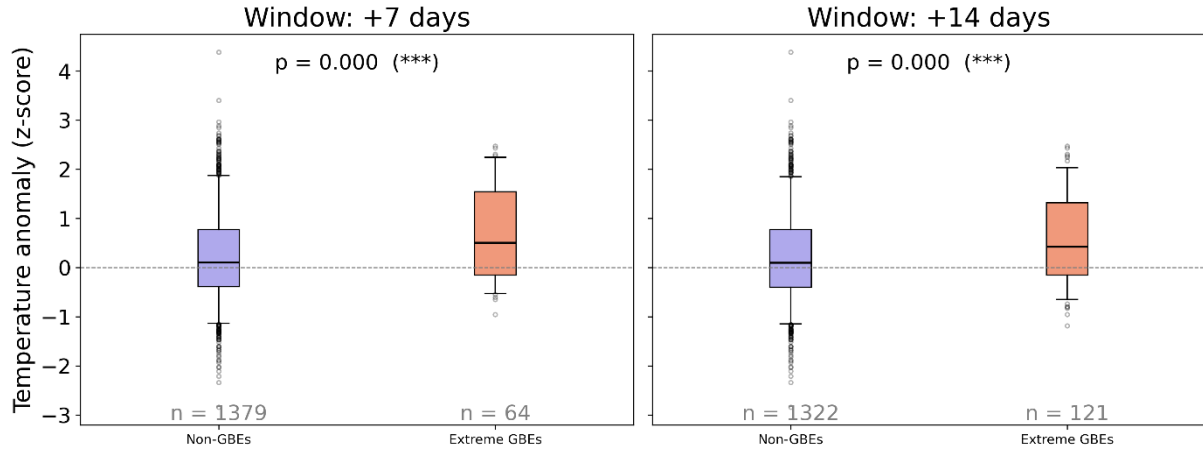


Figure 5: Boxplot showing the distribution of temperature anomalies for both time windows. The black line represents the median value (50th percentile), the boxes themselves represent the 25th to 75th percentile range, and the whiskers signify the 5th to 95th percentiles. Individual observations outside of these ranges are shown as dots.

5.3 Short-term glacial calving

5.3.1 Superposed Epoch Analysis

Figure 6 portrays the glacial calving rates around one of the ten extreme GBEs. The calving values in this episode are fairly typical, with more calving rate values closer to $y = 0$. Each of the ten blocking episodes and the calving rates around it can be found in Appendix 9.3.

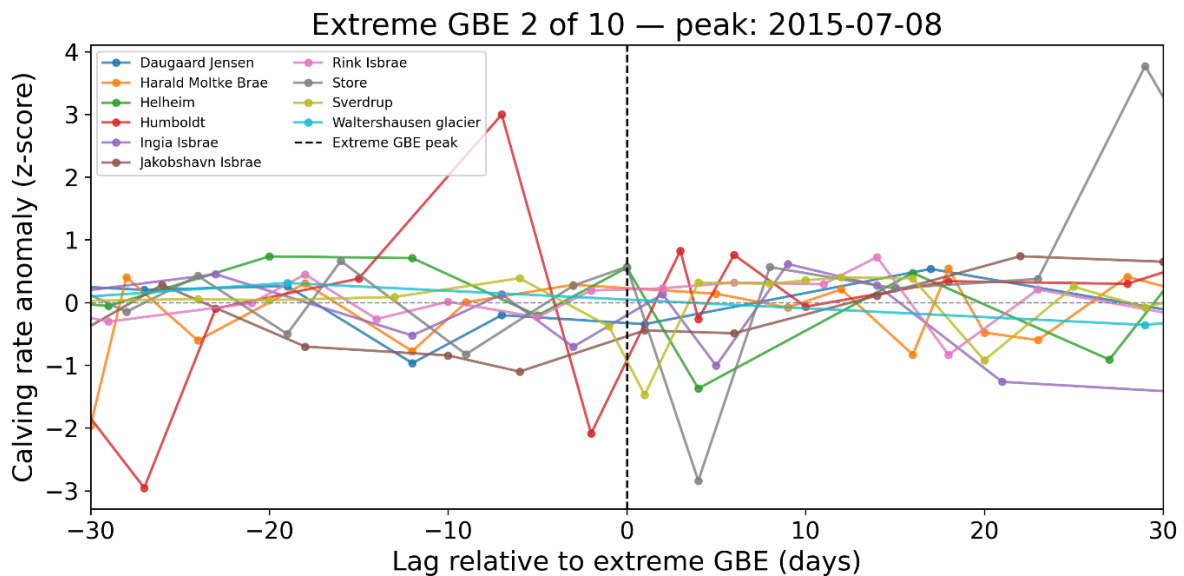


Figure 6: The dotted line at $x=0$ represents the occurrence of one of the ten extreme GBEs in this study. The x-axis shows the 30-day window in both directions from the episode, and the y-axis has the calving rate anomalies for the ten studied glaciers. Each colored line represents one outlet glacier.

The mean calving anomalies for the ten blocking episodes are compiled into 7-day bins for the SEA (Figure 7). The SEA shows all calving anomalies occurring around extreme GBEs, with 1063 calving observations falling within the ± 28 -day window. The pre-event bins have a negative tendency, hovering around a mean calving rate anomaly between 0.0 and -0.3, meaning glaciers are on average losing area to calving before the blocking episodes. The post-event bins seem to portray some variability, with the signal fluctuating to a positive level before dipping negatively again. Overall, the expected signal of a post-event negative dip is absent.

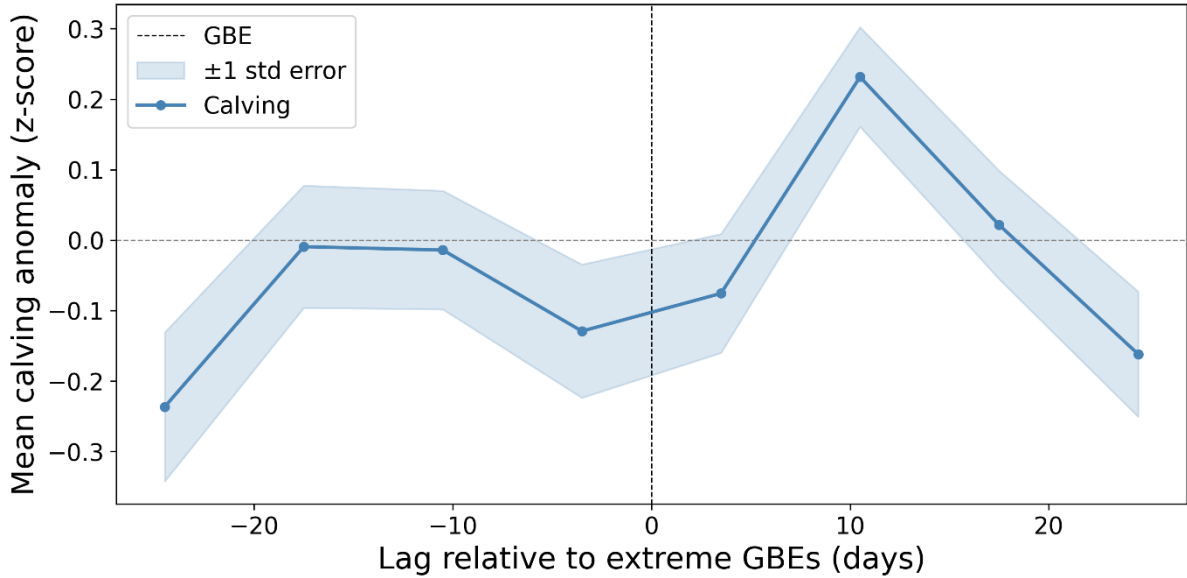


Figure 7: The SEA showing the signal of the mean calving anomaly z-scores occurring around all extreme GBEs. Each dot on the calving line indicates the center of a 7-day bin. The mean calving line is portrayed with a ± 1 standard deviation error around it.

5.3.2 Pooled analysis

Combining all glaciers, calving anomalies are not significantly lower during GBEs than outside of them for both the 7-day ($p = 0.270$) and 14-day windows ($p = 0.718$). Therefore, the result is non-significant ($p \geq 0.017$), failing to reject H_0 . The boxplots in Figure 8 highlight the similarities between the two groups.

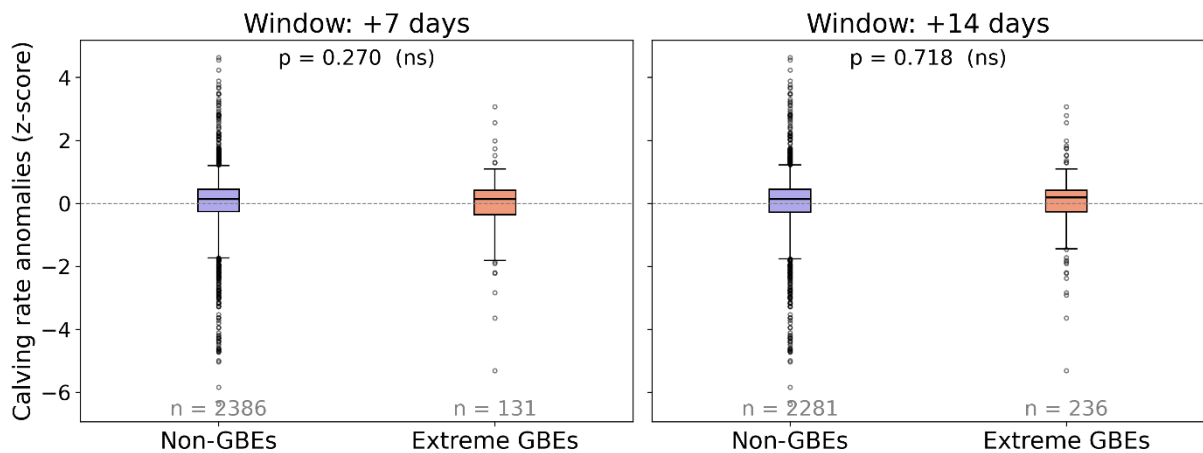


Figure 8: Boxplots of the calving rate anomalies during extreme GBEs and non-GBEs. Left shows the boxplot with a 7-day window, and on the right a 14-day window.

5.3.3 Per-glacier analysis

Table 3 shows that none of the glaciers considered individually have a significant response to extreme GBEs ($p \geq 0.017$). The result therefore fails to reject H_0 .

Table 3: Results from the Mann-Whitney U tests on the individual outlet glacier's calving anomaly rates. "N (GBE)" contains the amount of measurements within an extreme GBE for a glacier, as well as the measurements outside of this window with "N (non-GBE)". The p-values are given, as well as whether or not they reach significance.

Glacier	N (GBE)	N (non-GBE)	p-value	Significant ($p < 0.017$)
Daugard Jensen	9	231	0.350	No
Harald Moltke Brae	20	326	0.441	No
Helheim	10	156	0.842	No
Humboldt	17	267	0.568	No
Ingia Isbrae	17	251	0.193	No
Jakobshavn Isbrae	7	160	0.056	No
Rink Isbrae	14	265	0.484	No
Store	12	212	0.607	No
Sverdrup	16	323	0.456	No
Waltershausen glacier	9	195	0.303	No

5.4 The 2019 melt year

There are 353 calving observations in 2019. With a p-value of 0.461, there is no significant difference between 2019 and other years ($p \geq 0.017$), failing to reject H_0 . Figure 9 shows that 2019's mean calving anomaly of -0.038 is typical and does not deviate from the other years.

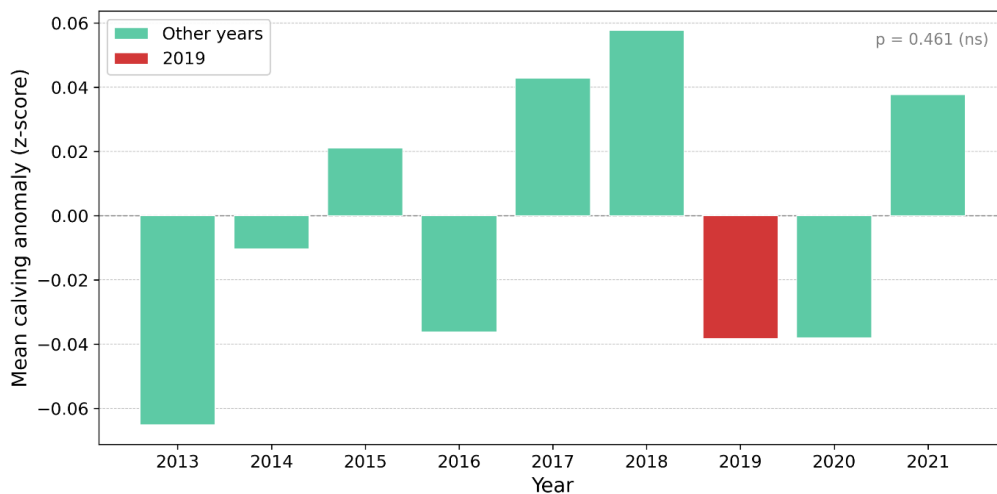


Figure 9: A bar chart comparing the mean calving anomaly of the 2019 melt year to the other years' values.

6 Discussion

This paper studies the relationship between extreme GBEs and glacial calving areal change in Greenland's outlet glaciers from April to September between 2013 and 2021. The sections of the discussion are structured by the sub-questions:

1. How did Greenland's outlet glaciers develop from 2013 to 2021?
2. What is the effect of extreme GBEs on surface air temperature?
3. How do extreme GBEs relate to short-term glacial calving?
4. To what extent did the 2019 anomalous melting year impact glacial calving?

6.1 Glacial changes

6.1.1 Widespread glacial retreat

The ice mass of the GrIS is balanced between the generally positive contributions of surface processes and the naturally negative impacts of ice flow towards the ocean (ESOTC, 2026). For the past several decades, the system has been out of balance, and existing literature reports a widespread glacial retreat across the ice sheet (Mottram et al., 2019; Moon et al., 2020; Murray et al., 2015). The results from this study mirror the existing literature, as a median glacial area loss of 4.58 km^2 is found between all ten glaciers, with a mean retreat of 106 m year^{-1} glacier⁻¹. Murray et al. (2015) report a retreat of 267 km across 199 glaciers between 2000 and 2010, or 122 m year^{-1} glacier⁻¹. Considering the different study periods, as well as my study considering only ten glaciers, these two values are sufficiently similar to provide a consistent pattern of the ice sheet's glacial retreat.

6.1.2 Minor glacial stabilization

Two glaciers are found to have advanced from 2013 to 2021 – Rink Isbrae by 14 m year^{-1} and Store by 8 m year^{-1} . Murray et al. (2015) and Mottram et al. (2019) study a large sample of glaciers and similarly find a small number of glaciers that retain stability (11 out of 199 & 2 out of 28, respectively). Both studies agree on Store stabilizing with reported growth at respectively 3 and 0 m year^{-1} . Contrary to my results, Rink Isbrae is reported to retreat by 38 and 27 m year^{-1} . This difference could stem from the different time periods that are considered, as Mottram et al. (2019) study Rink Isbrae from 1993-2015 and Murray et al. (2015) from 2000-2010. Medrzycka et al. (2016) point to terminus geometry (including fjord topography, crevasse density, and ice thickness) as the primary drivers of calving for Rink Isbrae, with ice mélange as a mitigating factor. I speculate that the discrepancy could be due to natural long-term variation in the ice discharge. Glacier-specific factors could also be at play, such as settling into a deeper bed or entering a narrower part of the fjord. Murray et al. (2015) report that their advancing glaciers portray no pattern of regionality, which highlights that glacial advance is driven by factors unique to each glacier. Overall, the reasons behind glacial advance are poorly understood. A more accurate view may be one of glacial stabilization, as the only known mechanism for glacial advance is a surplus in surface mass, which is not known to systematically occur on the GrIS.

The most surprising result is perhaps that Waltershausen is found to have an overall glacial retreat but is found to advance in spring and summer. It is found that there are some methodological inconsistencies for this glacier that are discussed in section 6.5. Despite this,

Mottram et al. (2019) report that Waltershausen's glacial advance is stable at 0 m year⁻¹. My study finds a retreat of 10 m year⁻¹. The small discrepancy does not indicate a systematic error in the dataset. I would consider Waltershausen Glacier as a relatively stable glacier due to the findings from literature and my results.

6.1.3 Spring advance

Jakobshavn Isbrae and Helheim are the only glaciers in this study that portray a higher rate of calving during the spring rather than during the summer. They are also the two southernmost glaciers of this study.

For the past several decades, Jakobshavn Isbrae is described as the fastest-flowing and largest contributor to ice discharge in the GrIS (Mouginot et al., 2019). The glacier's rapid retreat that started in the 1990s can be largely explained by the warming of the sea water that occurred in Disko Bay (Myers & Ribergaard, 2013). The intrusion of anomalously high deep-water temperatures causes more submarine melting to occur, the effect of which strengthened after the glacier entered a deeper bed trough around 2010 (Rashed et al., 2025). Additionally, the ice mélange by Jakobshavn Isbrae plays an important role in controlling the rate of ice discharge through ice shelf buttressing. I speculate that Jakobshavn Isbrae and Helheim experience earlier and higher deep-water temperatures in spring, resulting in earlier and more intense calving. There could also have an effect on the sea ice and ice mélange, breaking it up earlier due to the increased temperatures in Disko Bay, causing an increase in glacial velocity. Overall, despite the variability in the seasonality and development of marine-terminating glaciers on the GrIS, most outlets are retreating, with a minority stabilizing.

6.2 Temperature and blocking

Surface air temperature anomalies at Nuussuaq station are significantly higher during extreme GBEs than outside of them for both the 7-day ($p = 0.000$) and 14-day ($p = 0.000$) windows. This result is consistent with the established physical mechanism linking Greenland blocking to surface warming. The blocking creates anticyclonic conditions over Greenland, which induces southerly warm air advection (Fettweis et al., 2013). The result therefore validates McLeod and Mote's (2016) definition of extreme GBEs, as there is a measured increase in surface air temperatures during the blocking episodes.

However, the magnitude of the measured anomaly should be interpreted cautiously. The Nuussuaq weather station sits on the west coast, and blocking episodes do not present uniform changes to the weather across the GrIS. The advection of southern, warmer air typically occurs along the west coast, with a lesser effect on the east coast (Fettweis, 2013; Hanna et al., 2014). The effects also differ across the ice sheet, as it tends to create cloudless conditions in the south but actually produces clouds in the north (Tedesco & Fettweis, 2020). Even in regions where blocking-induced warming does occur, the associated dryness allows temperatures to decrease during the night-time, partially offsetting the enhanced warming and surface melt. The temperature result should therefore be interpreted cautiously, capturing one dimension of a more complex atmospheric signal.

A climatological baseline from 1982 to 2012 is used as a background to analyze the temperature data from 2013 to 2021. Both the GBE and non-GBE group temperature anomalies are positive, with values ranging from 0.208 to 0.687. I interpret this as a result from the accelerated warming that the GrIS and Arctic have experienced in the past decades (IPCC, 2021). It is also possible that the positive GBI trend in recent decades described by Hanna et al. (2015, 2018) can

systematically cause higher surface air temperature anomalies. Despite both groups experiencing higher anomalies, the GBE group is still significantly higher, which shows that the effects of blocking are still distinguishable in the noise.

These findings show that anticyclonic blocking creates measurable environmental effects that can occur unevenly across the GrIS. The question is, how do the effects of atmospheric blocking relate to glacial calving?

6.3 Calving and blocking

There is no detectable visual pattern to calving in the SEA. The Mann-Whitney U test for the pooled set of glaciers also fails to reject the null hypothesis, meaning that calving anomalies are not found to be significantly lower during extreme GBEs than outside of them for both the 7-day and 14-day windows. The finding of there being no detectable signal is in agreement with literature. Holland et al. (2016) use a similar time period of seven days to study a marine-terminating glacier and finds that no atmospheric properties (i.e., air temperature, radiation, wind, and precipitation) have any bearing on glacial calving. Murray et al. (2015) also do not find a relationship between atmospheric variables and glacial calving, citing the complex effects of the processes involved, as well as the individual glacial response to the same environmental fluxes. These findings are also consistent with the per-glacier assessment of blocking. If blocking is a driver of glacial calving, then at least some positive results would be expected. However, none of the ten outlet glaciers record a significant response to extreme GBEs, indicating that the relationship between calving and atmospheric forcing is more complex than my study would indicate. These null results are therefore consistent with literature, and there is a high uncertainty and variability of the processes involved.

The atmospheric warming-induced effects on calving are uncertain and rather indirect (Vieli & Nick, 2011). I speculate that the physical state of the ice plays an important role in the timing of calving. For example, a small increase in temperature might cause surface ice to melt, but a large increase might not reach the same tipping point. These dynamics also change based on variables individual to each glacier, despite being influenced by the same atmospheric conditions. This study's null result is therefore consistent with literature, as there is uncertainty and variability of the processes involved.

In addition to that, the calving process is complicated by the fact that calving events can cause the glacial stresses and forces to be redistributed, causing an instantaneous acceleration at the terminus (Vieli & Nick, 2011). This effect is known to ripple further inland, increasing the glacial velocity kilometers upstream. Since my methodology looks at the calving front position as a proxy for calving rate, the amount of calving could increase at the same time as an advance in calving front position occurs. To compute the rate of calving on shorter timescales, the glacial velocity should be accounted for, which falls outside of the scope of this study.

In short, the role of atmospheric forcing on surface ice melt is well-described in literature. There are some mechanistic links between atmospheric conditions and glacial calving, but these operate through indirect controls that weaken the overall glacial structure, such as meltwater percolation, basal lubrication, and sidewall softening (Van der Veen, 1998). These factors can additionally increase the glacial velocity so that the front does not retreat but can even temporarily advance, despite an increase in mass loss. Furthermore, conditions specific to each individual glacier also create differences in the response to the same environmental factors they might experience. Even the physical condition of glacial ice plays an important role, as it might

reach certain tipping points. However, it is possible that atmospheric blocking operates on longer timescales than the 7-day and 14-day windows of this study.

6.4 Record melt in 2019

As established by Sasgen et al. (2020) and Tedesco & Fettweis (2020), the year 2019 saw record-breaking ice melt rates across the GrIS. Anti-cyclonic conditions dominated throughout the summer, reducing cloudiness in the south and consequently causing below-average summer snowfall and albedo for the region. McLeod & Mote's (2016) definition of extreme GBEs captures four episodes occurring in 2019, validating the findings from literature of an exceptional year of blocking. If atmospheric forcing has any bearing on calving rates on longer seasonal timescales, then one would expect the record-breaking melt year of 2019 to have a higher rate of calving than other years. Holland et al. (2016) do not rule out this finding in their study. However, my study finds no significant difference between the calving rates of 2019 versus all other combined years. This null result is consistent with literature's characterization of 2019, as the anomalous conditions caused surface melt to occur (Sasgen et al., 2020; Tedesco & Fettweis, 2020).

Therefore, the analysis of the melting year 2019 confirms that surface ice melt and glacial calving are at the very least partially decoupled processes. There are indirect links that theoretically weaken the ice and can increase calving readiness, but the most significant controls of glacial calving are oceanic forcing and sea ice (Vieli & Nick, 2011).

6.5 Limitations and improvements

First off, there are some errors present in the Waltershausen glacier terminus front line layers from Loebel et al.'s (2024) dataset. Several lines are incorrectly delineated by the machine-learning software, and after looking at the underlying Landsat-8 imagery, it looks like it got confused by light cloud coverage. The errors are minor, but they could have led to a miscalculation of the mean spring and summer calving rates. Errors such as these can be detected by using the visual calving output and looking for line layers that detour from the main calving front.

Secondly, the results of this study did not account for a margin of error. Loebel et al.'s (2024) dataset defines three mean delineation errors of 61.2, 73.7, and 73.5 meters from different tests, meaning that the error range for a given terminus front is 61-74 m. Including a margin of error into the study can improve the validity of the results.

Additionally, Loebel et al.'s (2024) line layer dataset uses Landsat-8 and Landsat-9 images to delineate calving fronts. These are optical sensors (USGS, n.d.) and can be blocked by clouds and night-time measurements, effectively restricting the study period to spring and summer. Li et al. (2024) published a calving front dataset for Svalbard that incorporates multiple optical and Synthetic Aperture Radar (SAR) satellite images. With the use of SAR, it is possible to get a year-round image acquisition interval of 1-3 days. Their mean distance error is also lower at 31 ± 30 m compared to Loebel et al. (2024) at 61-74 m.

Lastly, the rectilinear box method published by Loebel et al. (2024) requires a 4-vertex polygon for each glacier. The requirement of using a box does not capture the full glacial extent, as all lines are partially cut off, the severity of which depends on the shape of the terminus. It could be worth investigating an improvement to the script so that it accepts more complex polygons

as inputs or it could make a polygon shape out of the input line layers so that it always captures the full glacial extent.

This study takes the measurements in terminus front change from Loebel et al.'s (2024) dataset and converts the output to a daily rate of calving. However, this approach assumes that calving occurs linearly and in small batches, which is not necessarily the case. Some marine-terminating glaciers exhibit either serac failure or buoyant flexure, while others have both (Fried et al., 2015, 2018). The daily rate of calving that my study uses is suitable for outlets dominated by serac failure and is less suitable for buoyant flexure. For the latter type, any real atmospheric effect on calving could therefore go undetected due to a misrepresentation of calving. I speculate that simply using the difference in area between two measurements without dividing by the difference in time and assigning that value of areal change to the whole time range between two measurements could account for buoyant flexure.

7 Conclusions

This study confirms the widespread retreat of marine-terminating glaciers that is reported in literature. Most of the outlet glaciers showed an overall retreat, with a minority of glaciers remaining stable throughout the period of 2013 to 2021. There is a high variability of glacial response to experiencing the same environmental conditions. Only the two southernmost glaciers see a higher rate of calving during the spring months, rather than during the summer. This highlights that factors individual to each glacier, such as fjord width, bed topography, bathymetry, and basal pinning points, play an important role in the calving front development. However, calving glaciers are still known to respond strongly to atmospheric forcing.

The extreme GBEs of this study are shown to cause significantly higher temperature anomalies on both the 7-day and 14-day time windows. This is consistent with literature's characterization of blocking in Greenland and helps validate McLeod and Mote's (2016) definition of extreme GBEs. However, this result should be interpreted cautiously, as Greenland blocking is known to create an uneven signal across the GrIS. All temperature anomalies during the study period are also found to be higher than the climatological background, which is likely an indication of the warming that the Arctic has experienced in the past several decades. Despite that, the measured surface warming does not cause an increase in glacial calving.

No relationship is found between the calving anomalies and extreme GBEs for the 7-day and 14-day time windows. Additionally, the per-glacier analysis reveals that none of the ten glaciers have a significant increase in calving in a 7-day period after an extreme GBE. This result is consistent with literature that finds no increase in short-term glacial calving as a response to any atmospheric variable. Nonetheless, there are some mechanistic links that could increase the rate of calving as a response to atmospheric conditions that operate mainly through surface meltwater. These links are rather indirect and have a high uncertainty due to the difficulty of studying inner glacial mechanisms. There is no indication that these mechanisms operate on a yearly timescale.

Four GBEs are found to occur during the melting year of 2019, double the amount of any other year during this study, confirming the dominating anti-cyclonic conditions that are described in literature. However, no difference is found in the rate of calving between the year 2019 and any other year of this study. This indicates that even on a yearly timescale, the influence of blocking-induced surface melt is non-significant on the rate of calving.

In short, no relationship is found between extreme GBEs and glacial calving in Greenland's outlet glaciers from April to September between 2013 and 2021. Although atmospheric blocking is known to influence the glacial surface conditions, there is no clear indication that this effect influences calving. Future research could incorporate imagery from SAR to study the terminus front to decrease the margin of error and widen the studied time frame. Also, including the glacial velocity into the analysis of calving front development would provide a more accurate assessment of the calving rate. Furthermore, analyzing the spring calving patterns of the southern glaciers could reveal a pattern of calving occurring increasingly earlier in the year. As the GrIS continues to lose mass at an accelerated rate, understanding the role of how atmospheric conditions influence the ice mass balance is essential to providing accurate sea level rise estimates.

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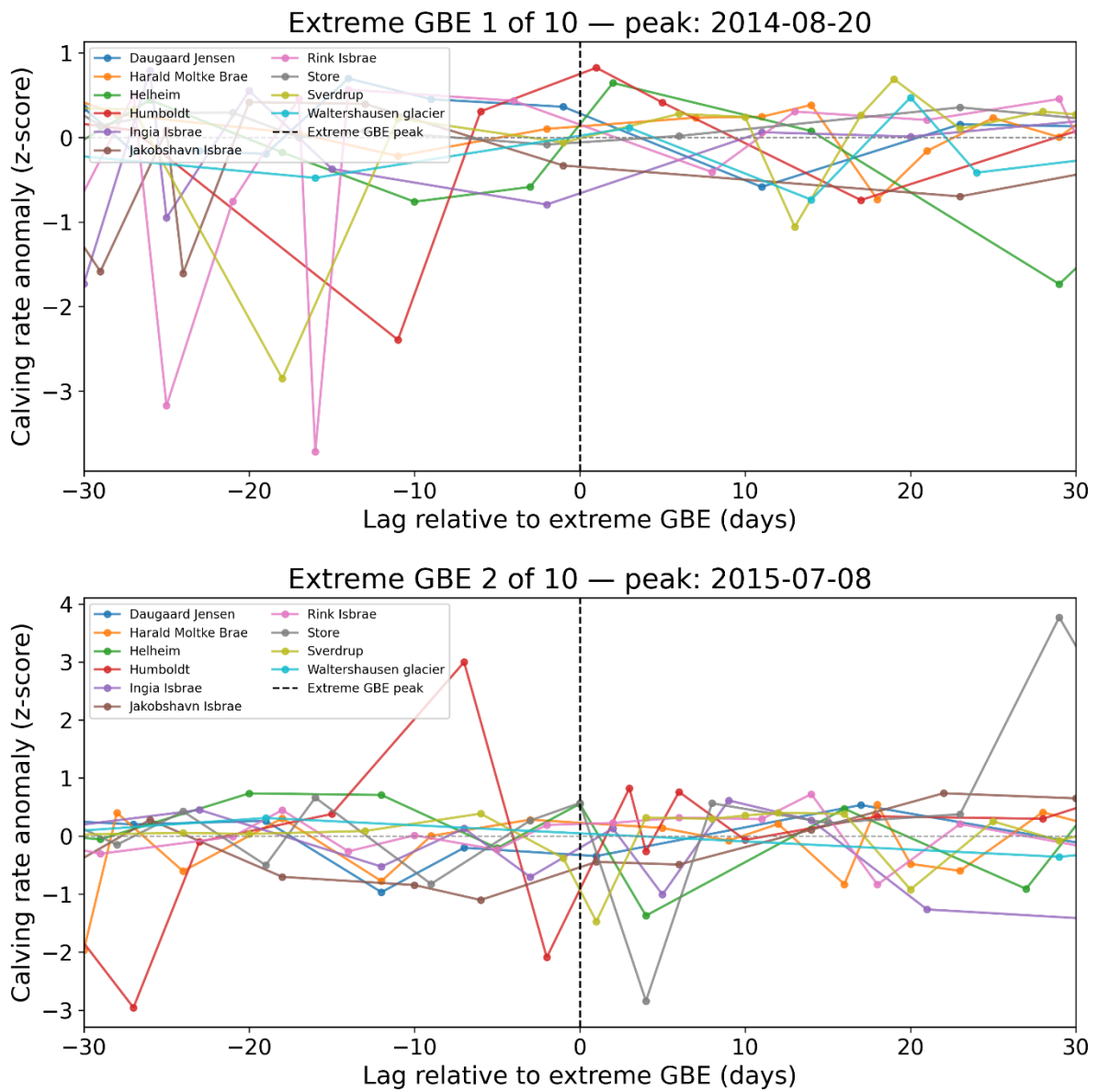
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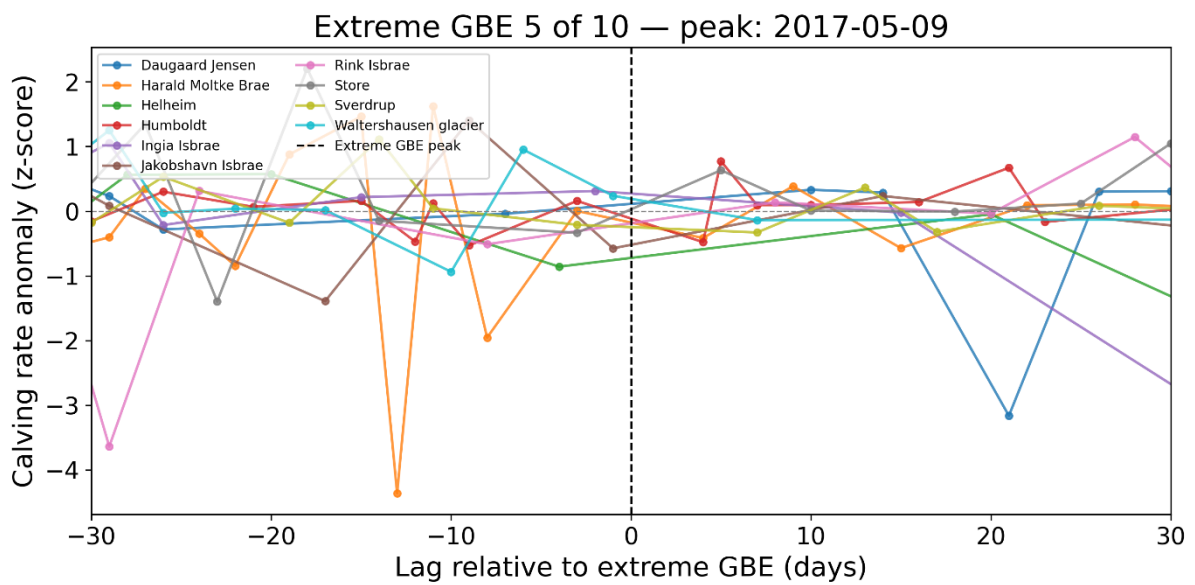
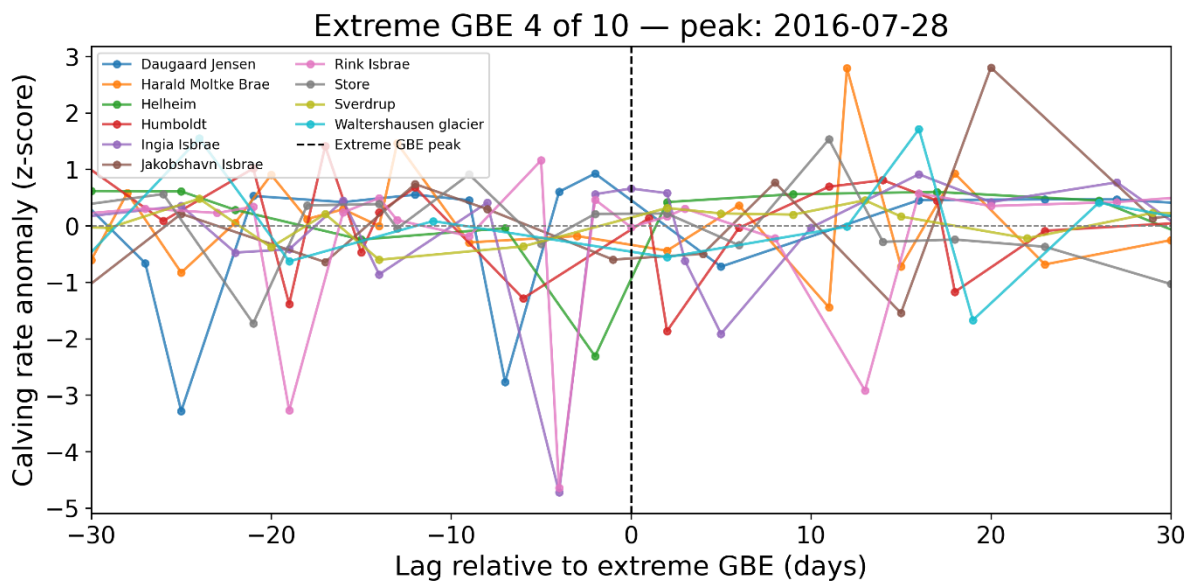
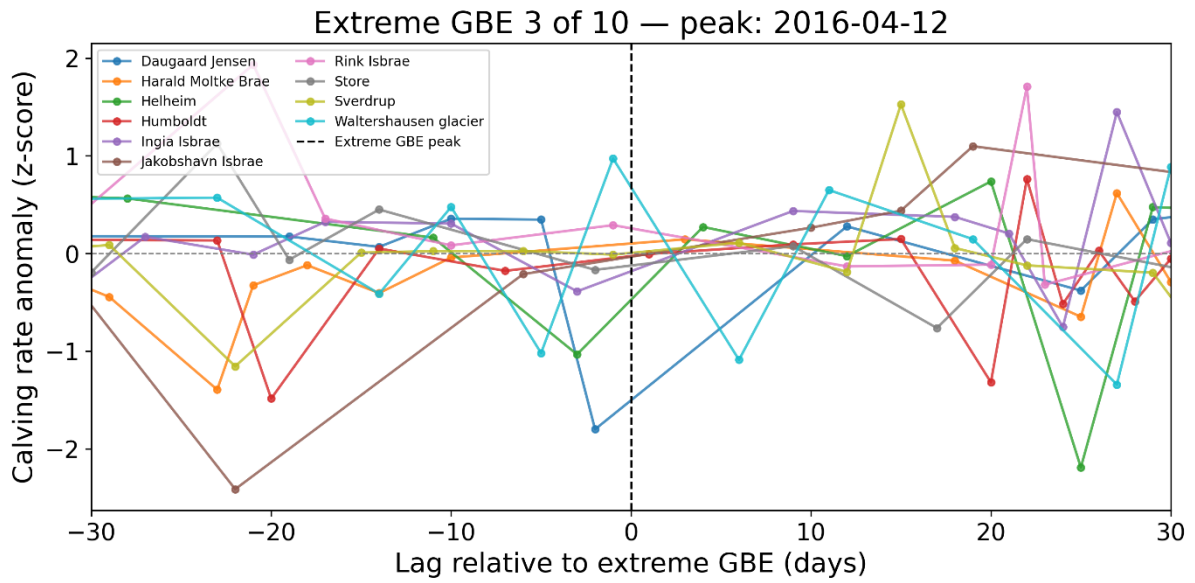
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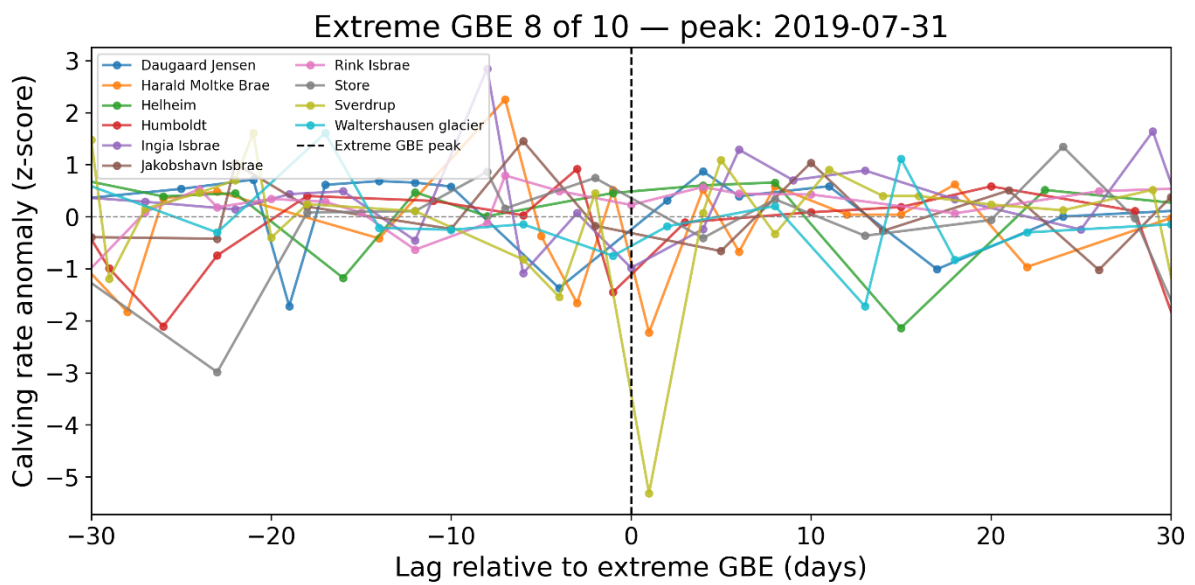
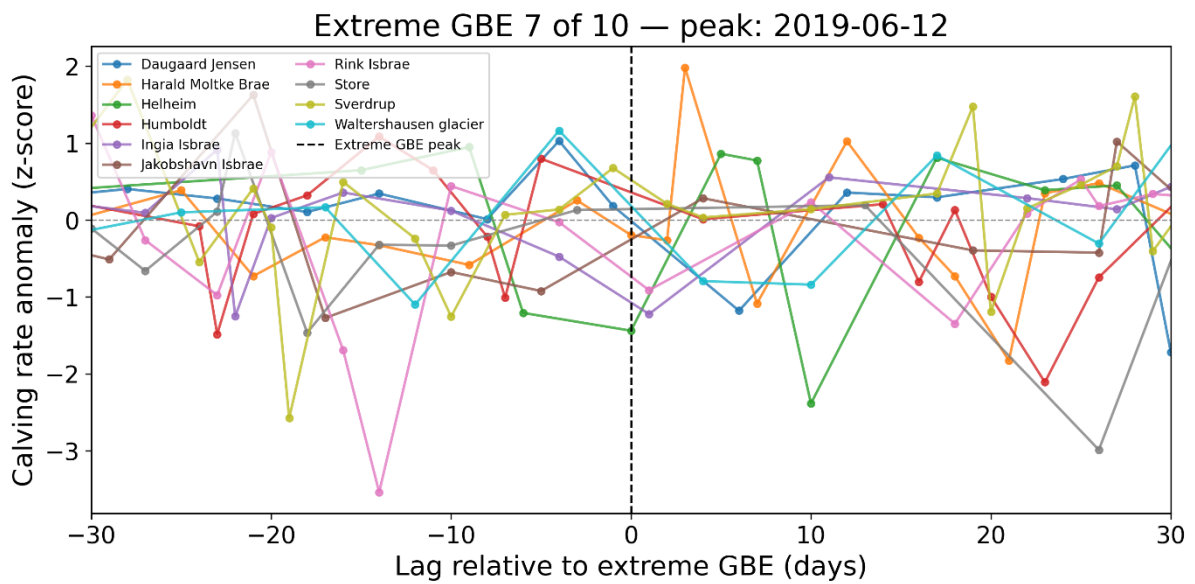
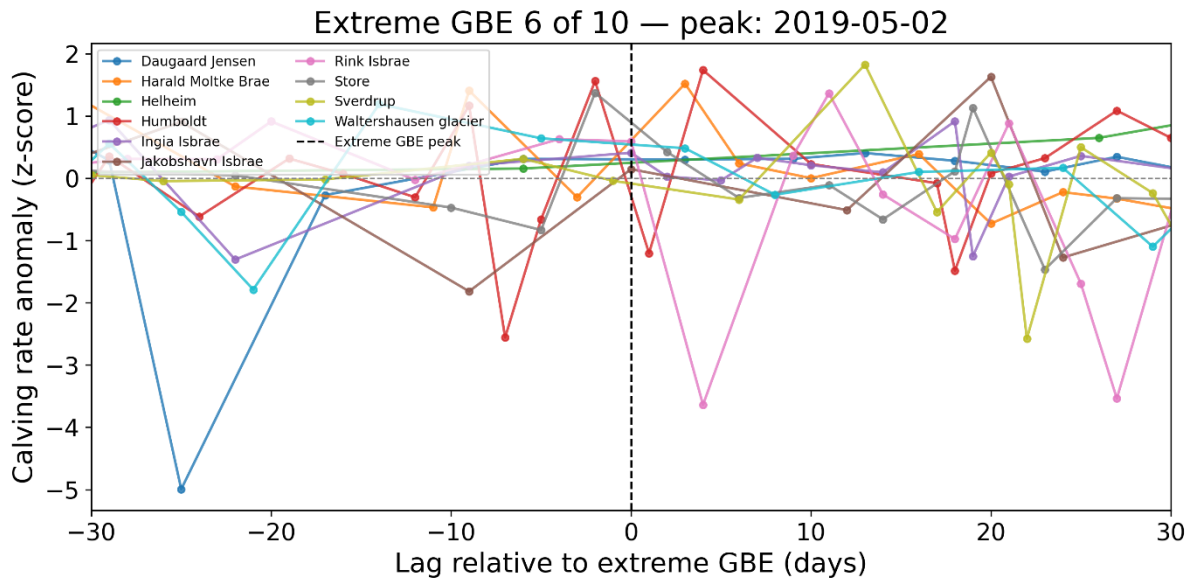
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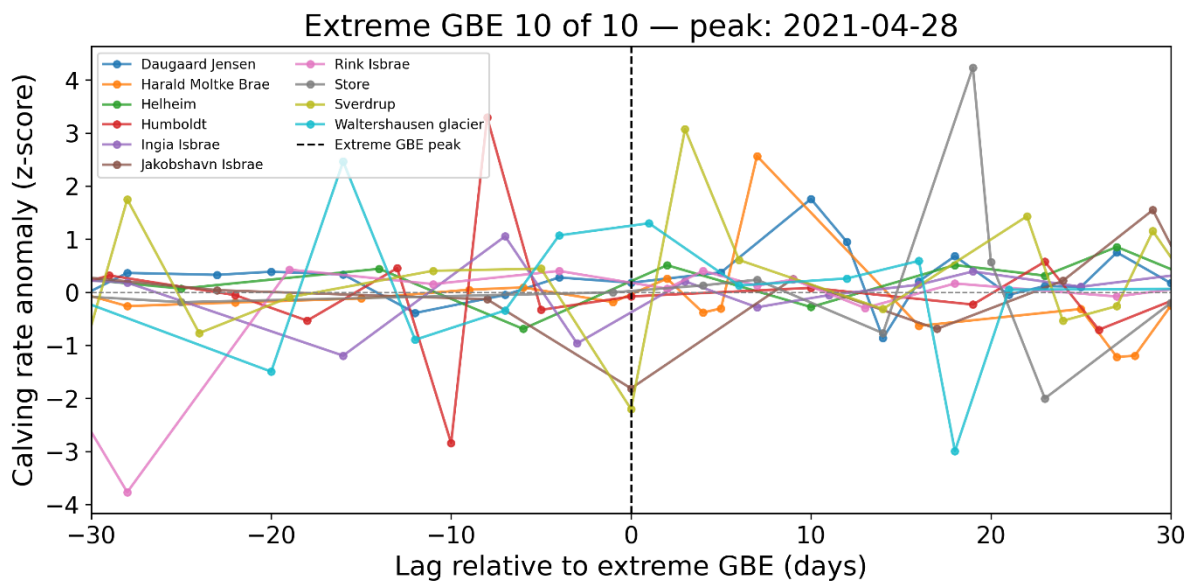
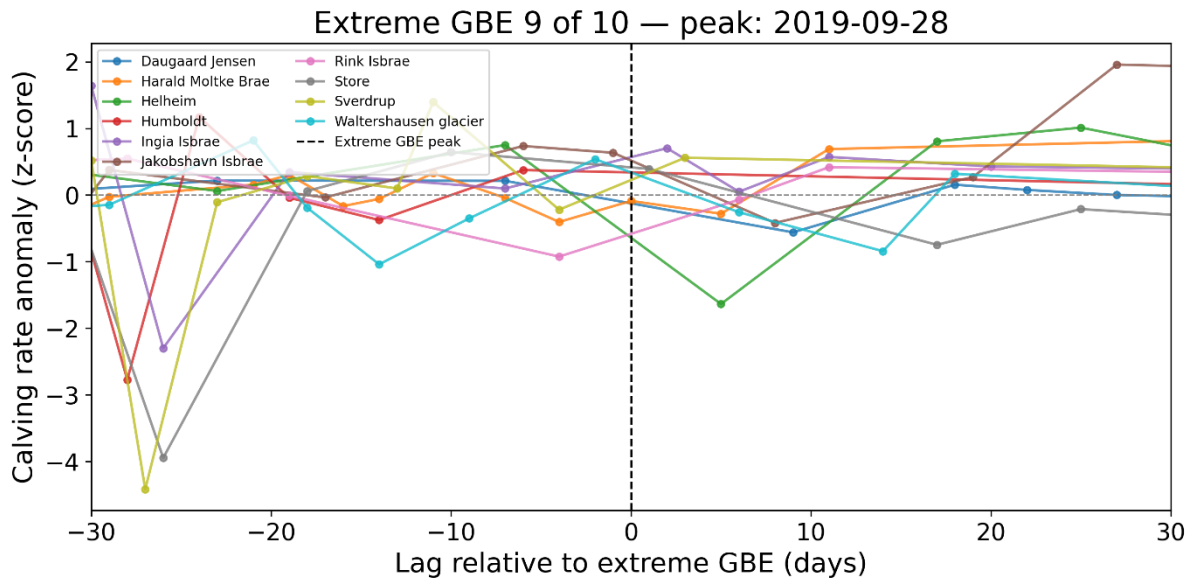
9 Appendix

9.1 Extreme GBE data and calving rate anomalies

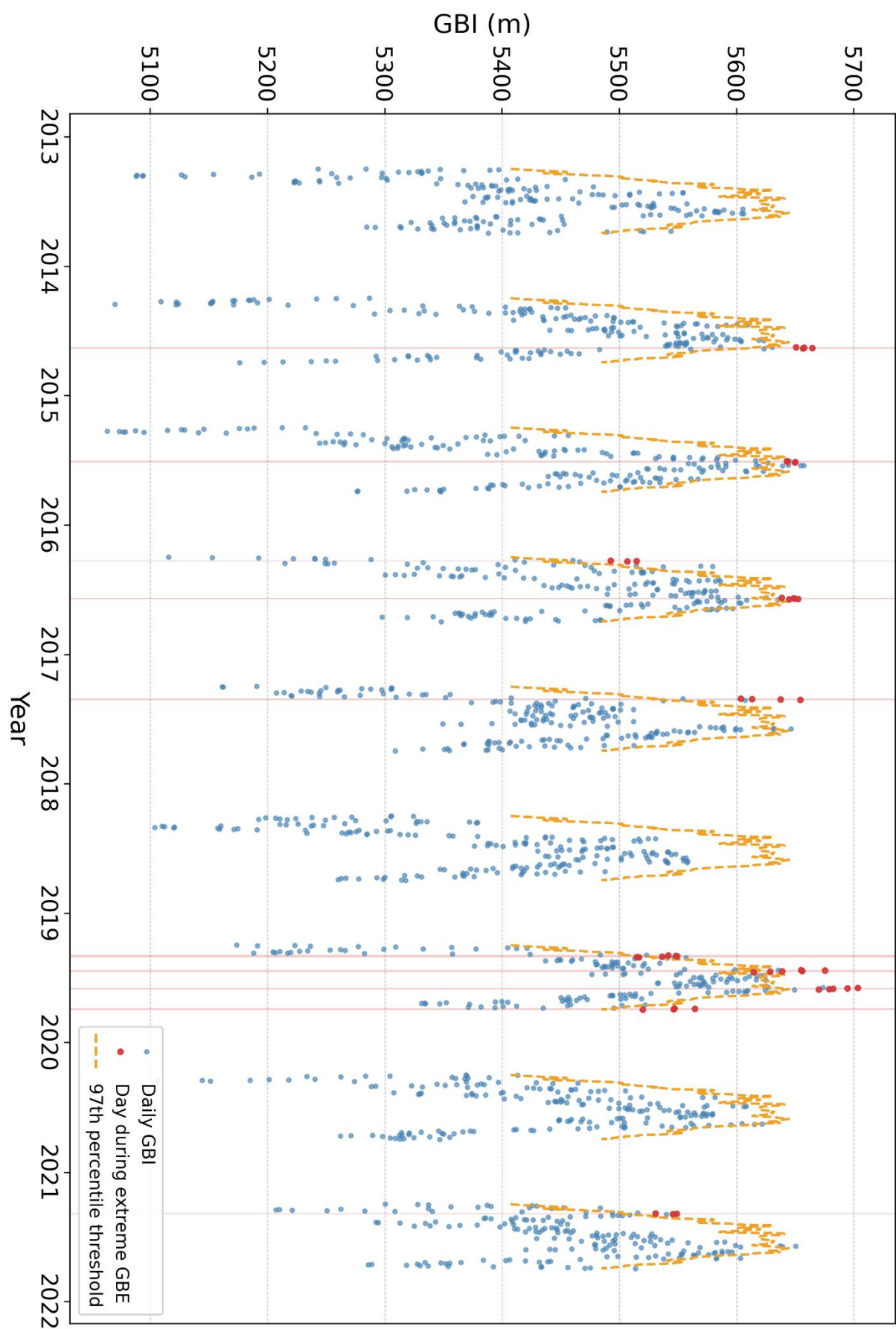






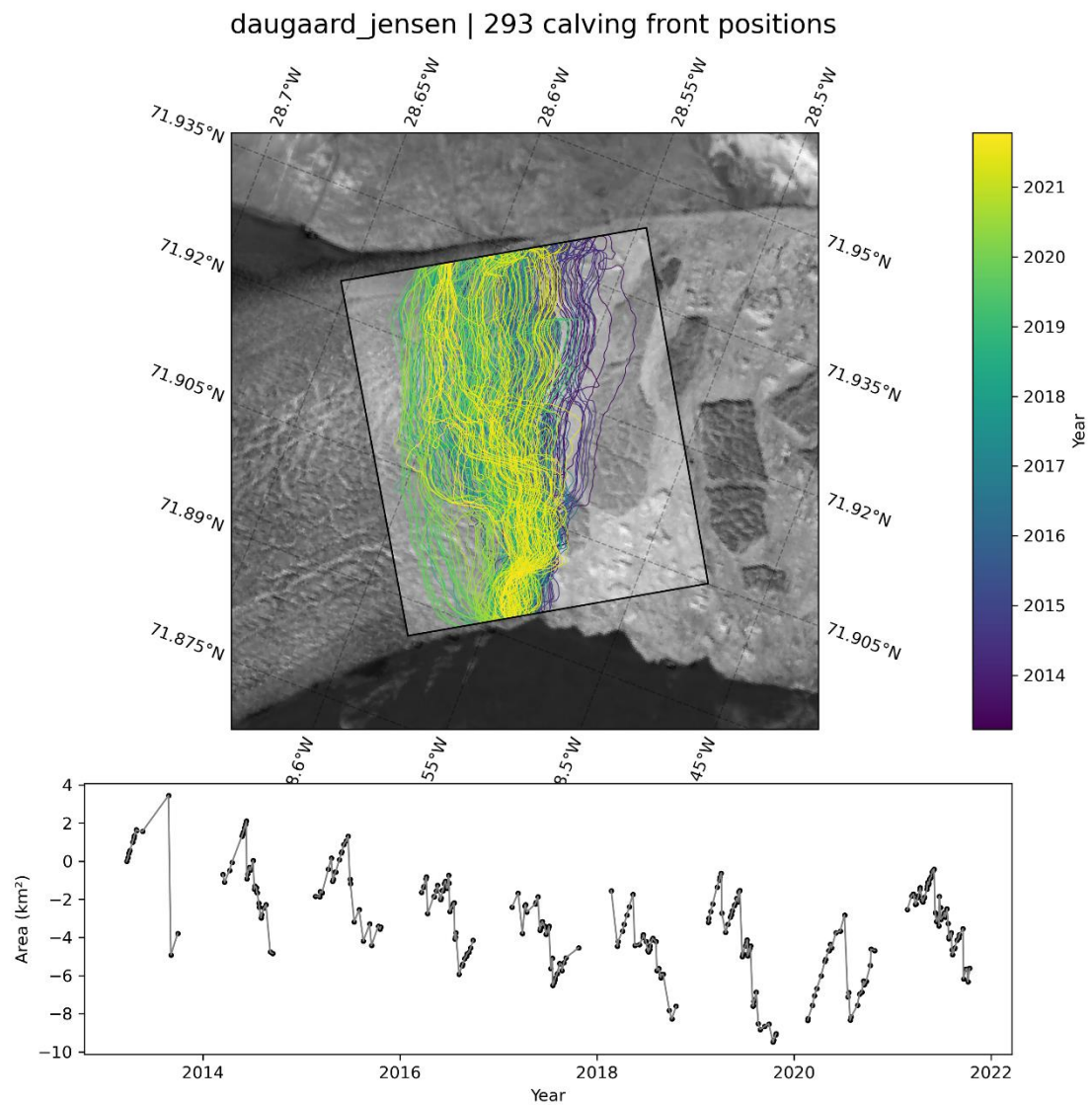


9.2 Enlarged GBI values



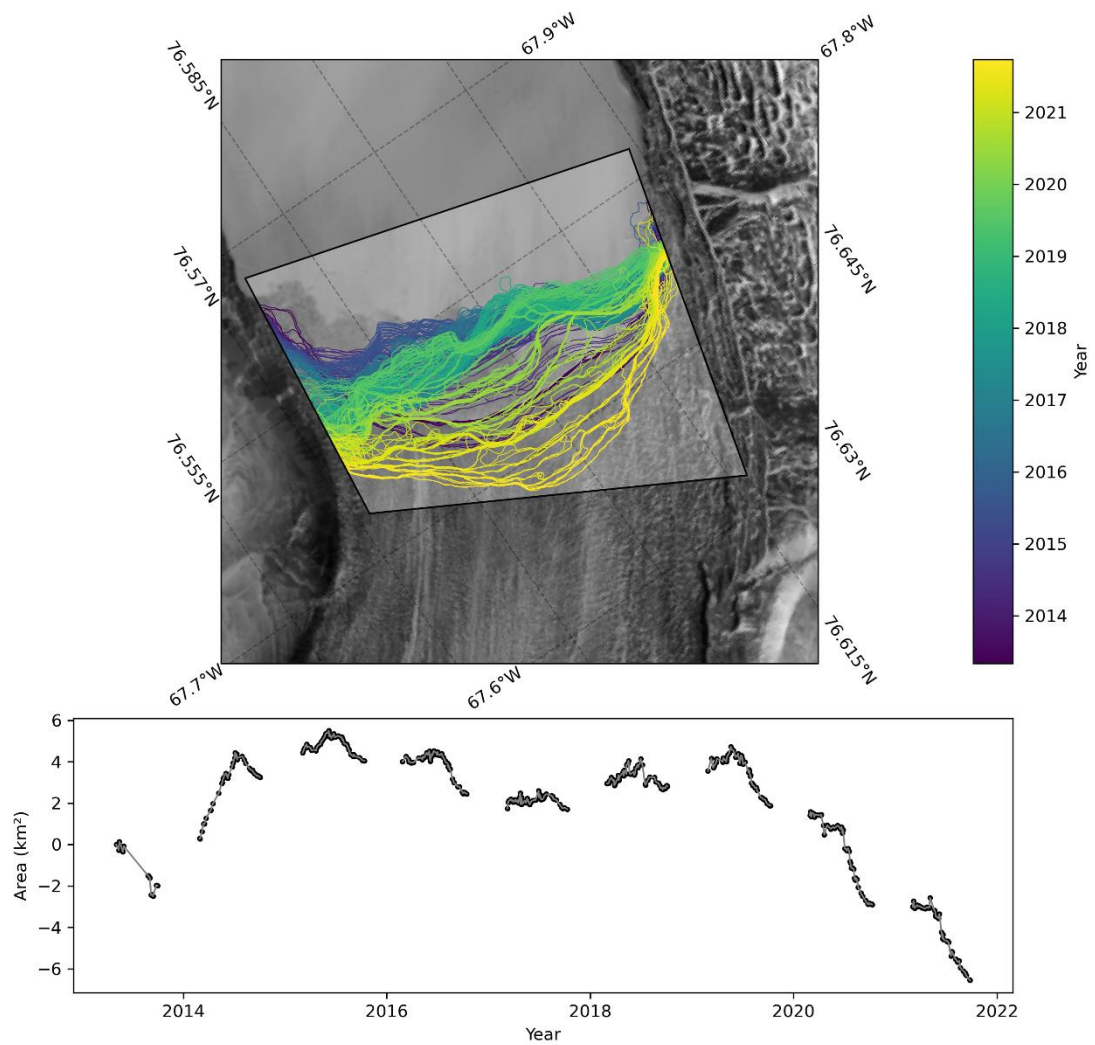
9.3 Rectilinear box method outputs

Daugaard Jensen



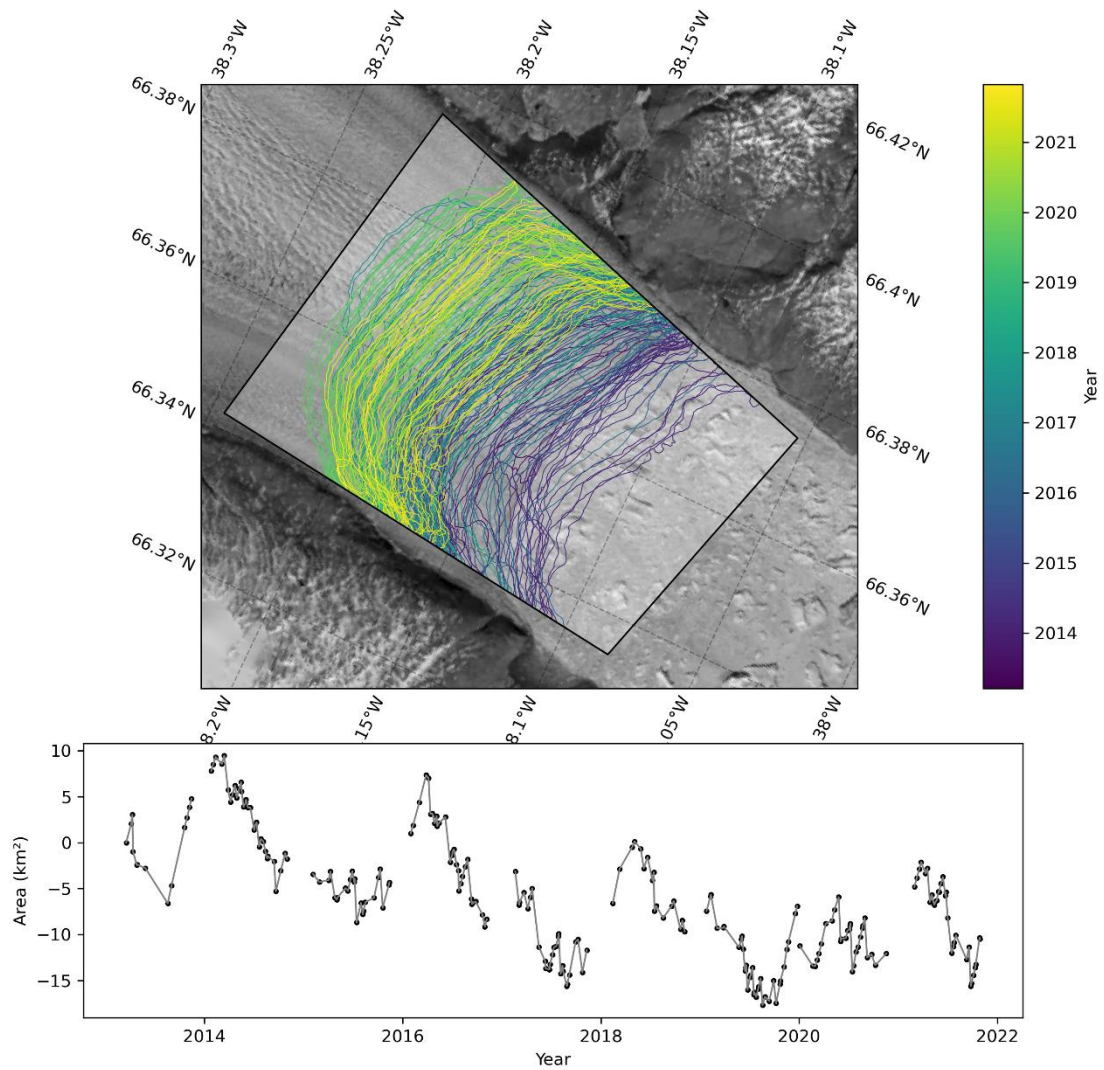
Harald Moltke Brae

harald_moltke_brae | 420 calving front positions



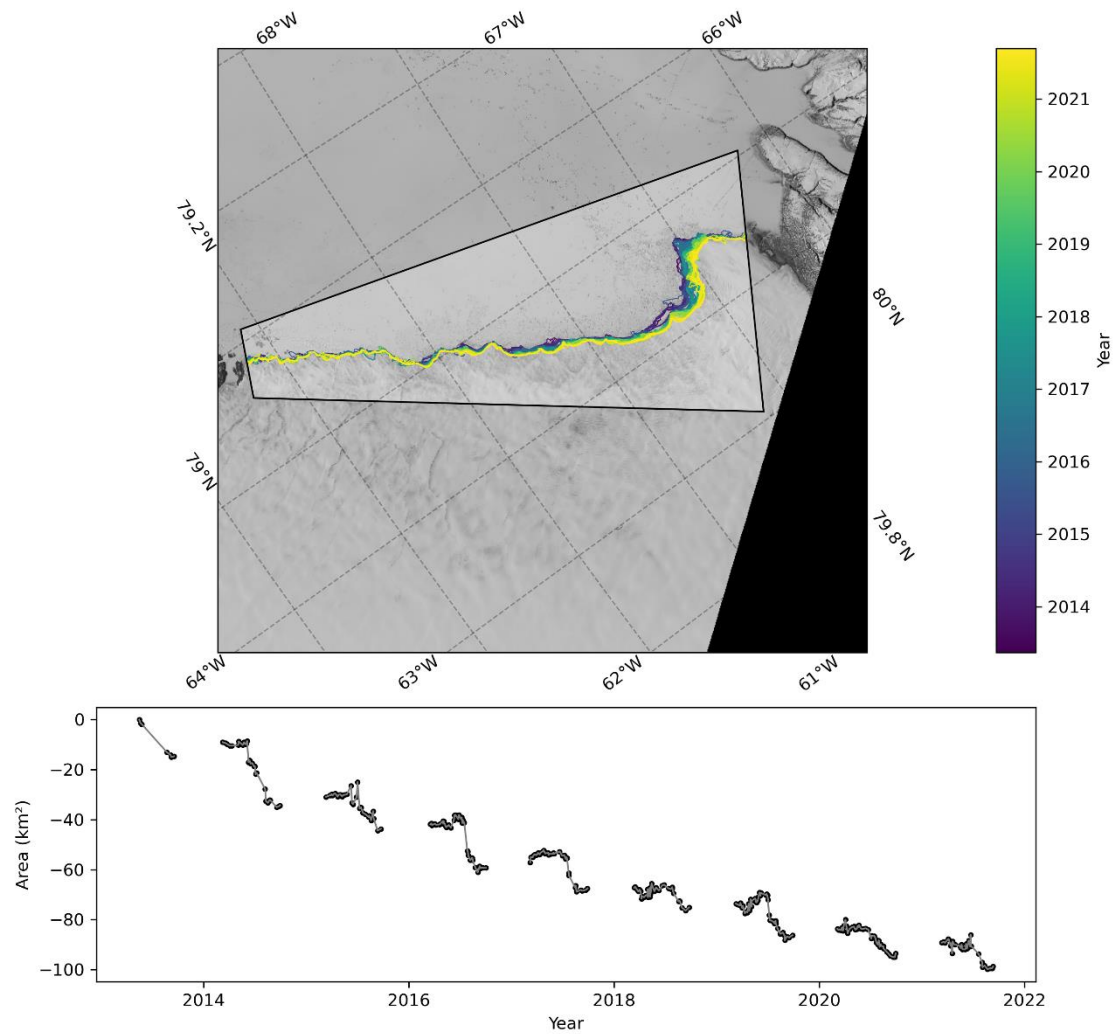
Helheim

helheim | 238 calving front positions



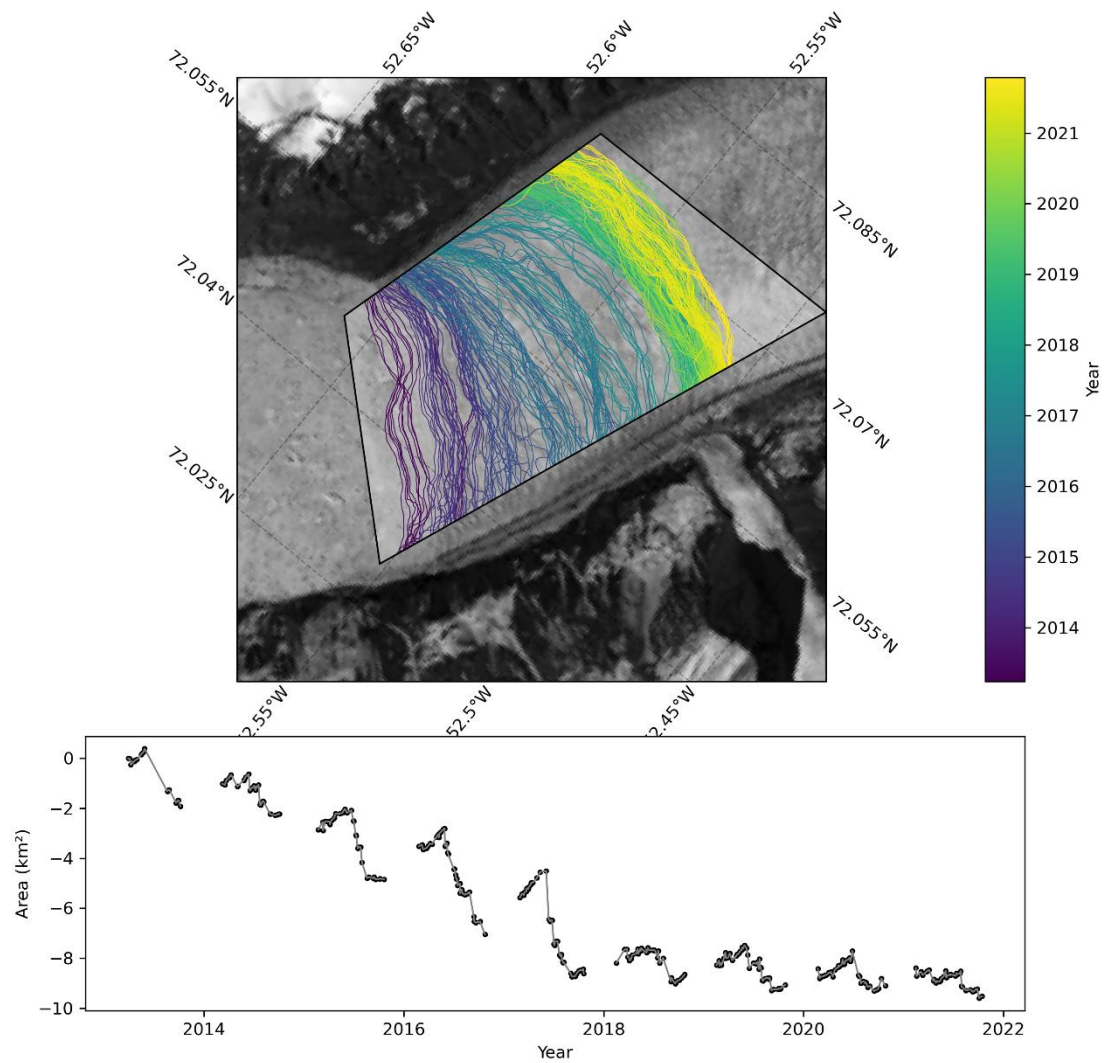
Humboldt

humboldt | 326 calving front positions



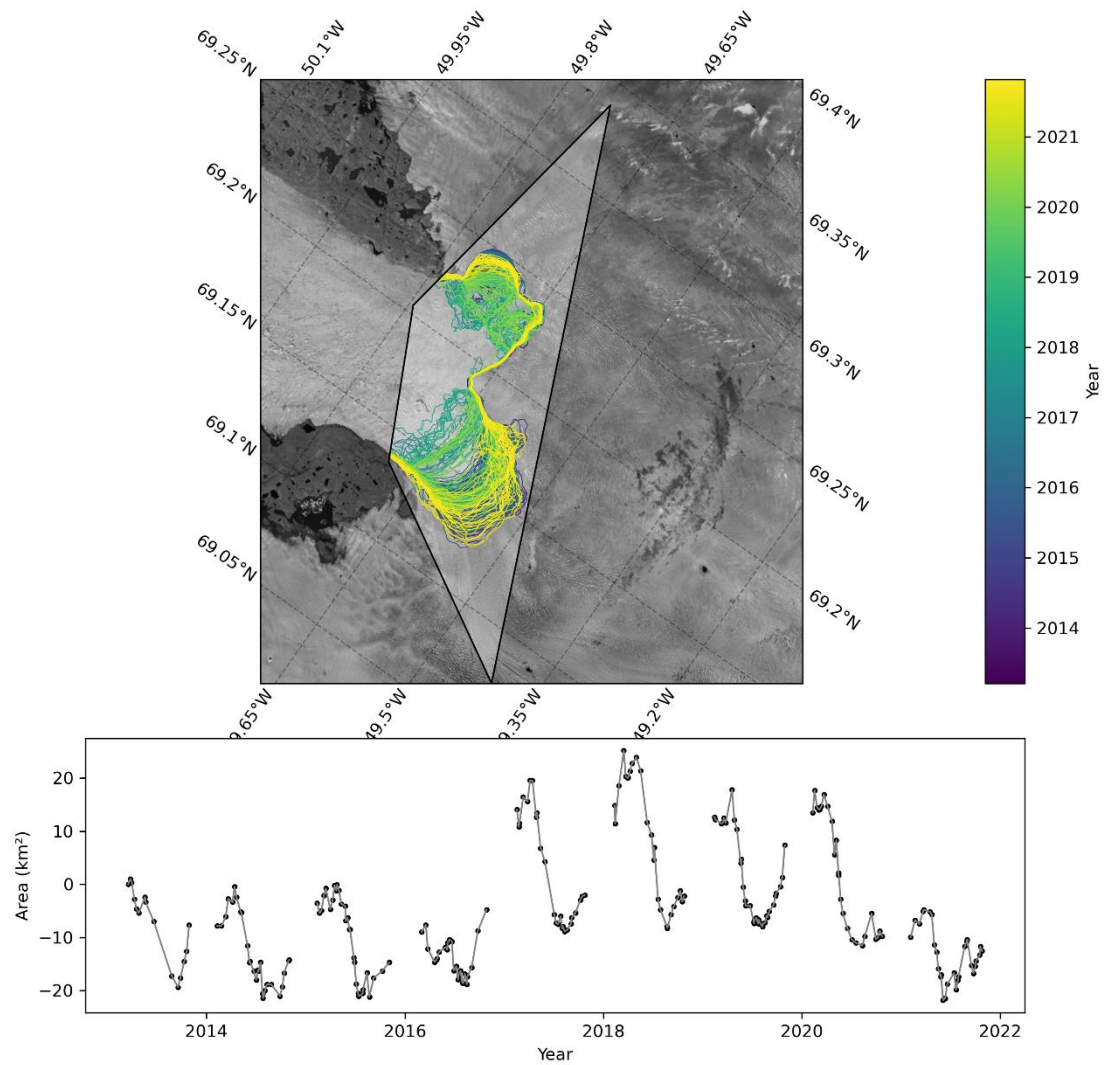
Ingia Isbrae

ingia_isbrae | 344 calving front positions



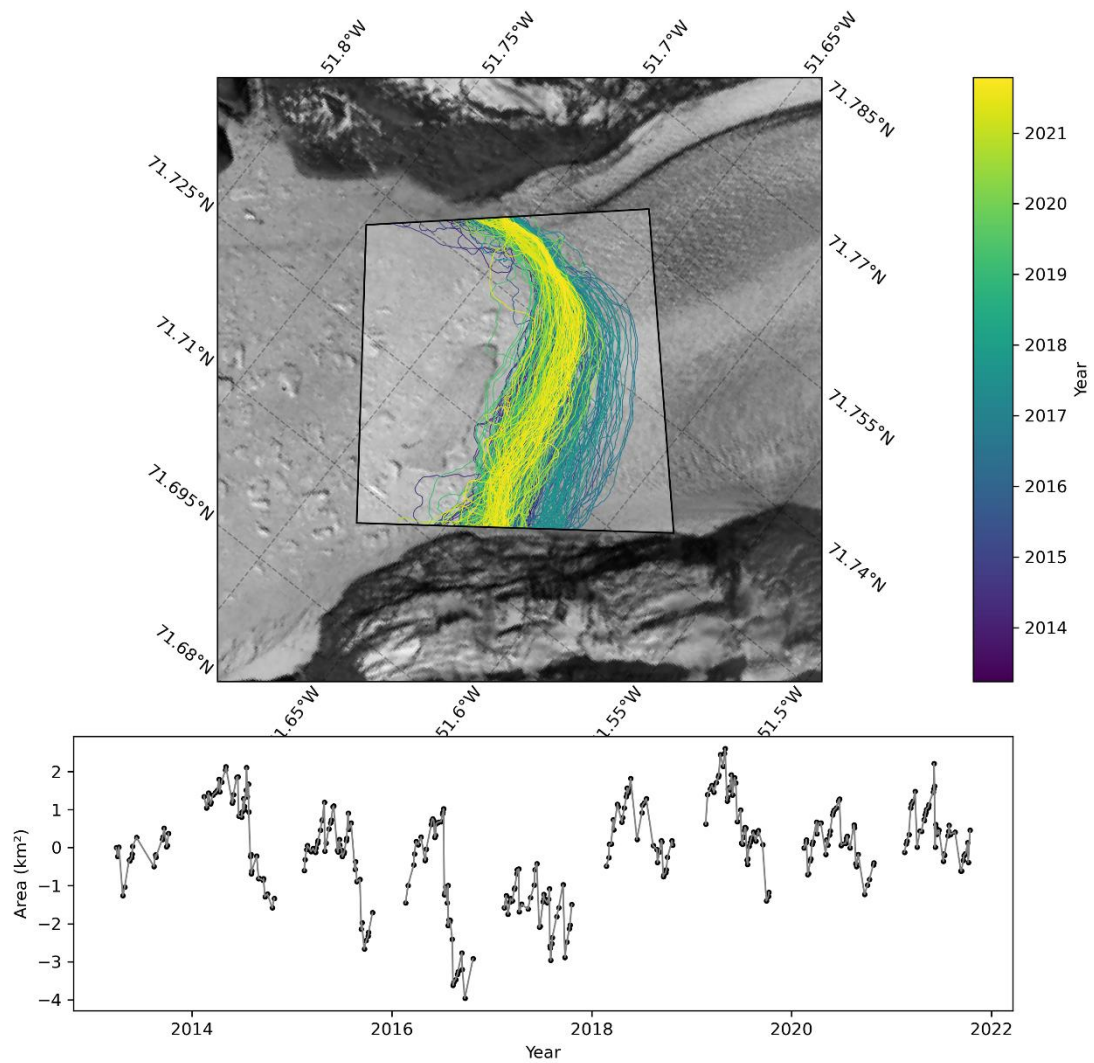
Jakobshavn Isbrae

jakobshavn_isbrae | 238 calving front positions



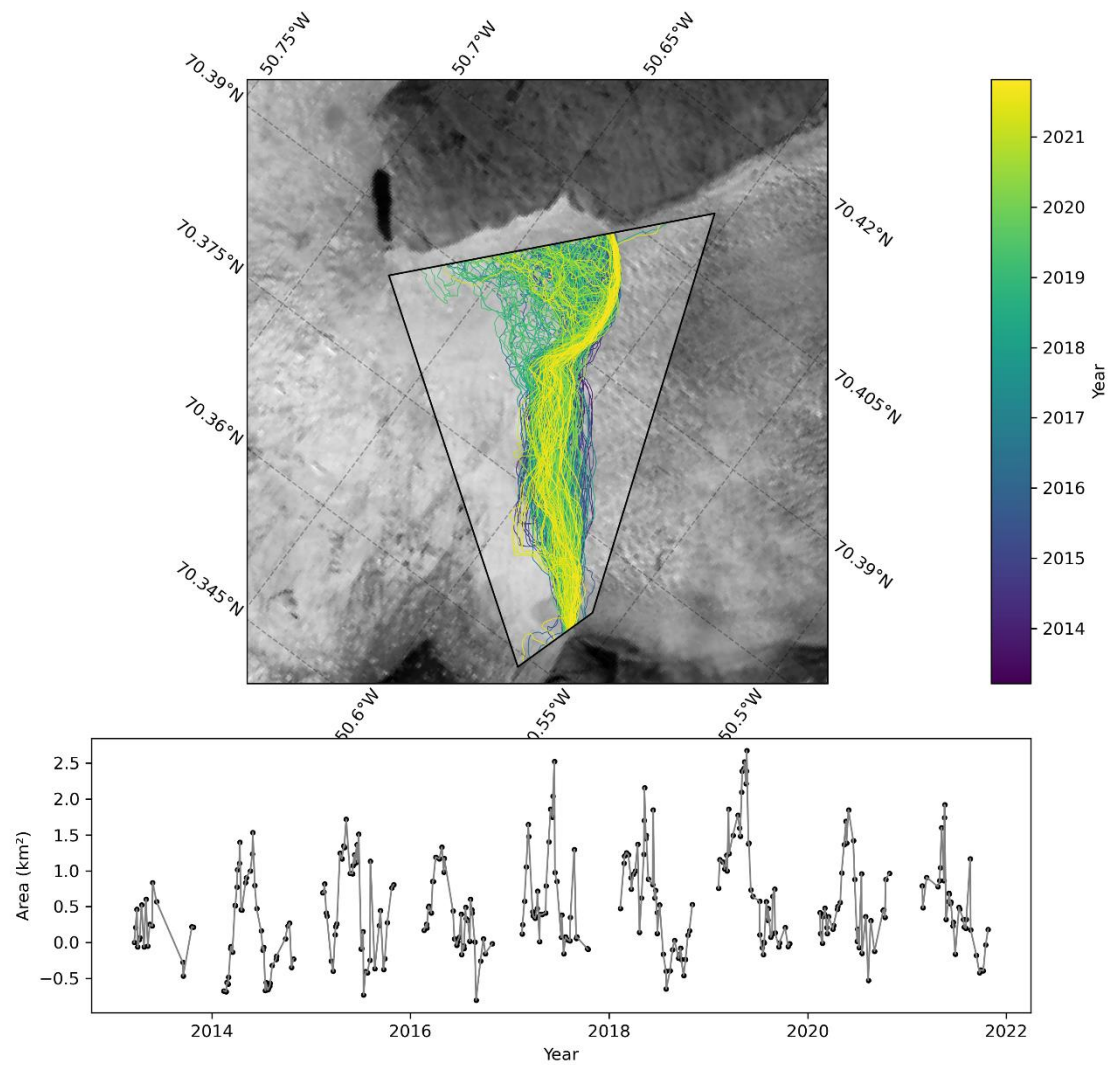
Rink Isbrae

rink_isbrae | 364 calving front positions



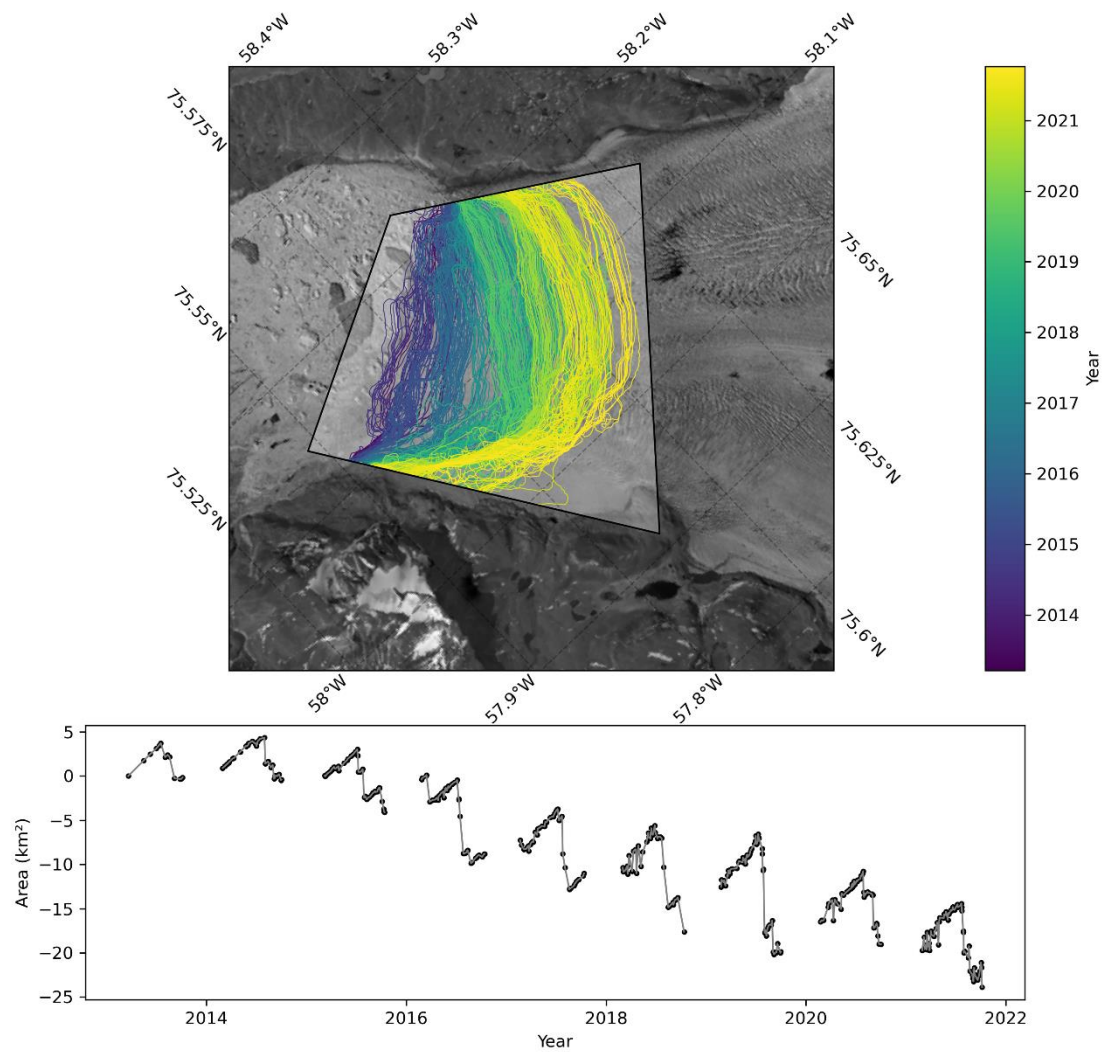
Store

store | 320 calving front positions



Sverdrup

sverdrup | 419 calving front positions



Waltershausen Glacier

waltershausen_glacier | 269 calving front positions

