Greenland Ice Sheet (GrIS) margin retreat driven by marine outlet glacier activity

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Abstract. The Greenland Ice Sheet retreat is a very clear and quantifiable metric by which climate change can be evaluated. Recent studies have suggested that the ice sheet will continue to contribute to sea level rise, meaning that mapping the future expectations for changes in the ice sheet are vital. In this study, satellite and aerial imagery of the region around the Jakobshavn Glacier spanning from 1985 to 2020 was loaded into and analyzed in QGIS, with the areas of ice retreat to both the north and the south being mapped out manually. The data analysis yielded results indicating that the areas of fastest retreat are closest to the fast-moving marine outlet glacier. A significant acceleration in the retreat of the ice sheet between the two periods was also noted. The study shows that the vicinity to a glacier likely impacts the retreat rate of the ice sheet around it, specifically muting ice-climate feedback further away, a factor which ought to be investigated further in the future to better model such regions.

1 Introduction

The near-future evolution of the Greenland Ice Sheet (GrIS) is of considerable scientific and societal interest, given the expectation that GrIS will significantly contribute to global sea-level rise in the coming decades and centuries (IPCC, 2019). In addition to affecting sea level rise rates, the retreating GrIS will expose new land area along its margins, leading to changes in regional surface albedo and soil carbon storage (e.g., Robinson et al., 2010; Leng et al., 2012). Analyses of the changes that GrIS experienced in the last several decades when it was forced by warming atmospheric and oceanic conditions (Ettema et al., 2009; Wood et al., 2018) contribute to improving scientific models used to predict the future trajectory of GrIS evolution (e.g., Robinson et al., 2010).

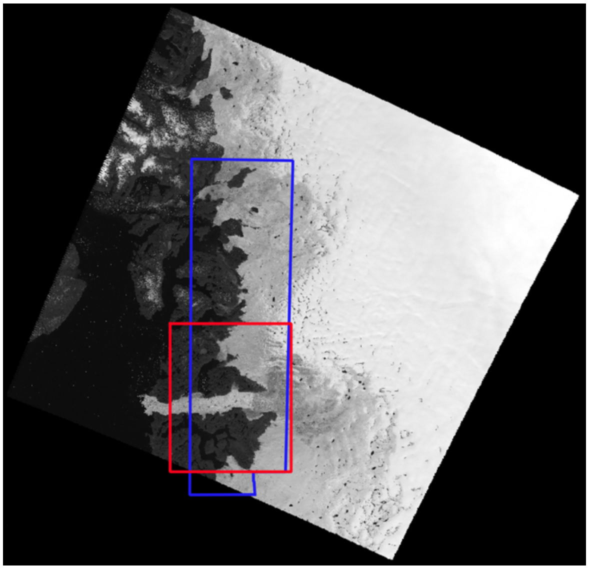

Figure 1: The area covered by the Landsat 7 (ETM+) (2001) dataset, with the area covered by the DEM and orthophotographs of Greenland based on aerial photographs (1985) and the Sentinel-2 Satellite (2020) outlined in blue and red respectively.

2 Methods

We used satellite images and aerial photographs to track the margin retreat between 1985, 2001, and 2020. The images were processed and analyzed using QGIS 3.10, in WGS 72 / UTM zone 22N.

2.1 Satellite and Aerial Image Data

Basic information for each dataset used in the study is compiled in Table 1.

Dataset Name (Year)	Region (UTM Zone 22W)	Resolution	Source	Additional Info
Sentinel-2 Satellite (2020)	X: 504017-559471 Y: 7642099-7709695	20 m	sentinel-hub.com	the SWIR product (665, 842, 2190 nm): bands 4, 8, and 12
Landsat 7 (ETM+) (2001)	X: 430060-681565 Y: 7603774-7846031	15 m		the panchromatic (520-900 nm) band 8
DEM and orthophotographs of Greenland based on aerial photographs (1985)	X: 513095-556861 Y: 7631994-7781221	2 m	data.nodc.noaa.gov	

Table 1: Compilation of basic information for each dataset used in the study.

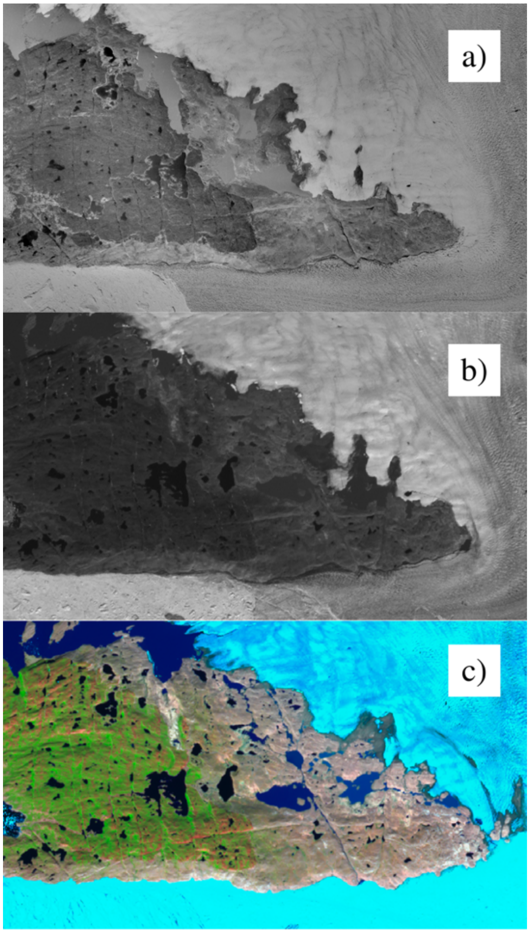

Figure 2: From top to bottom: images of the region just North of the Jakobshavn Glacier in a) 1985, b) 2001, and c) 2020. Obtained from the datasets described in Table 1.

2.2 Retreat Area Data Collection

We decided to use manual delineation of the retreat areas for each of the regions. We started on the south and north shore of the Ilulissat fjord and worked up to the respective marginal areas proximal to the southern and northern drainage divides of the glacier. We did not track the changes in the position of the calving front of the Jakobshavn Glacier, as this has been done many times.

2.2.1 Polygons and Area

To quantify the retreat by area, the datasets were loaded into QGIS, and sections of the retreat were mapped by creating polygons. Four sets of polygons were made by hand: two sets of polygons for each of the sets of years of retreat. Both the 1985 to 2001 and the 2001 to 2020 retreats had one set for the peninsula to the north of the fjord and one set for the land to the south—as seen in Fig. 3. These polygons covered both the land and water-terminating margins of the ice.

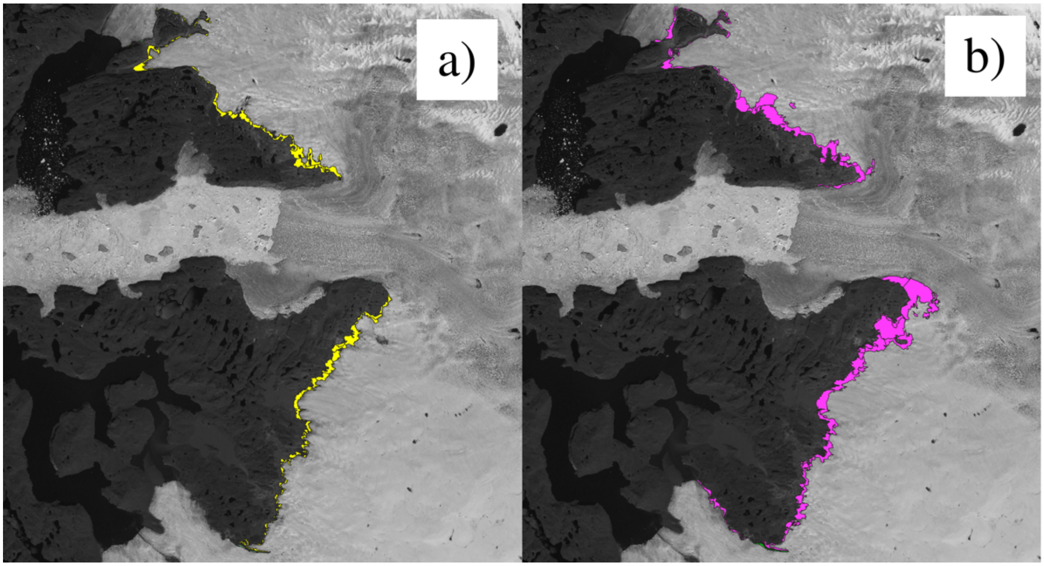

Figure 3: Polygons marking the margin retreat for a) 1985-2001 North and South in yellow (left), margin retreat for b) 2001-2020 North and South in pink (right).

2.2.2 Centers, Latitude, Retreat Rate

To calculate the retreat rate of each polygon, the UTM Zone 22W x and y coordinates of the centroid were noted for each polygon. Then, the length of the polygon was approximated to be the distance to the surrounding polygons' centroids halved and combined. For polygons where this was not applicable, such as those on nunataks (isolated areas of rock surrounded by ice), this method was not used. Rather, a line was drawn along the long axis of the polygon, and its length recorded. The retreat rate was then quantified as the area of retreat for each polygon divided by the length of the polygon.

3 Results

3.1 Main Results

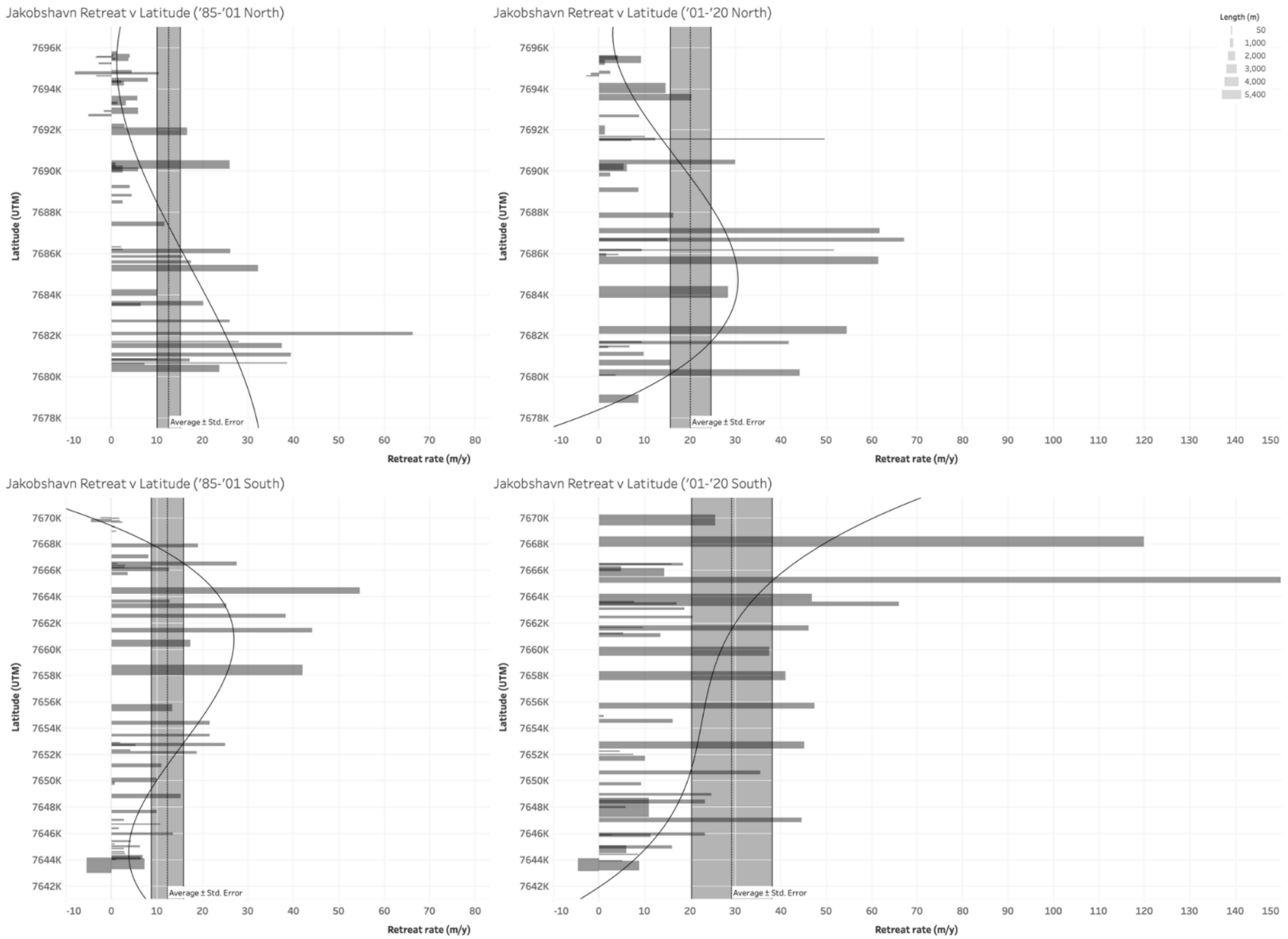

Figure 4: Starting from the top-left and going clockwise, graphs showing approximate retreat rate v latitude: 1985-2001 North, 2001-2020 North, 2001-2020 South, and 1985-2001 South. Each is plotted with a 3rd degree polynomial trend line and an average retreat rate across the region ± std. error of the mean.

3.1.1 Retreat Acceleration

Fig 4. summarizes our main results; showing the varying retreat rates both across the years as well as across latitudes. The ice sheet retreat has accelerated in both the northern and southern adjacent regions. The spatially averaged retreat rate as seen in the figures for each region, was:

1985-2001 North: 12.5 ± 2.6 m/y

1985-2001 South: 12.3 ± 3.5 m/y

2001-2020 North: 20.1 ± 4.5 m/y

2001-2020 South: 29.2 ± 8.9 m/y

The average retreat rates for the first period (1985-2001) are within the standard error of the mean for both the southern and northern study regions. However, the average retreat rates for the later period (2001-2020) are significantly higher for both regions. Thus, there has been an average acceleration of the retreat of about 0.7 meters per year squared from around 1993 to 2010. Resulting in retreat rates increasing by approximately a factor of two between the two periods.

3.1.2 Spatial Retreat

The retreat rates as related to the UTM y-coordinate for '85-'01 North and South were respectively described by the trend lines following Eq. (1) and Eq. (2):

$$r = 8.32451 * 10^{-12} * \mathrm{y}^3 - 19.1932 * 10^{-4} * \mathrm{y}^2 + 1475.07 * \mathrm{y} - 3.77882 * 10^9 \;\; [R^2 = 0.50], \tag{1}$$

$$r = -1.09149 * 10^{-11} * \mathrm{y}^3 + 2.50584 * 10^{-4} * \mathrm{y}^2 - 1917.62 * \mathrm{y} + 4.89162 * 10^9 \;\; [R^2 = 0.48], \tag{2}$$

And for '01-'20 North and South following Eq. (3), and Eq. (4):

$$r = 3.19678 * 10^{-11} * \mathrm{y}^3 - 7.37563 * 10^{-4} * \mathrm{y}^2 + 5672.36 * \mathrm{y} - 1.45414 * 10^{10} \;\; [R^2 = 0.21], \tag{3}$$

$$r = 7.93457 * 10^{-12} * \mathrm{y}^3 - 1.82206 * 10^{-4} * \mathrm{y}^2 + 1394.7 * \mathrm{y} - 3.55857 * 10^9 \;\; [R^2 = 0.17], \tag{4}$$

where r is the retreat rate estimated by the trend line in meters per year and y is the value of the y-coordinate in UTM Zone 22W at the point for which this estimation is being made.

In broad terms, these equations and trend lines show that (generally speaking) as the y-coordinate moves closer to the fjord, the retreat rate increases significantly. We notice that the main exceptions to this rule appear at large bodies of water.

4 Discussion

In the earlier period studied (1985-2001), retreat rates were modest and slow, consistent with relatively stable position of the calving front of Jakobshavn Glacier between 1964 and 2001. The margin retreat rate was not zero, likely due to a combination of atmospheric warming, increasing surface melt, and the 40 km retreat of the Jakobshavn Glacier which took place in the 100 years before 1964 [Csatho et al., 2008]. Over the entire study period, retreat rate accelerated, probably in response to the well documented 15 km retreat of the Jakobshavn Glacier since 2001 [Joughin et al., 2008].

The paramount importance of Jakobshavn Glacier retreat in driving the retreat of the land-based ice sheet margin is illustrated by the fact that the highest retreat rates between 2001 and 2020 occur in the vicinity of the fjord. The retreat rates at the margins of our study area, which are the furthest from Jakobshavn Glacier, are near zero within uncertainties. In these areas, we even observe small margin advances. These observations emphasize that the position of the ice sheet margin in the study area is more sensitive to the behaviour of the major fjord glacier than to surface melting which is known to have increased in this part of Greenland over this period [Mote et al., 2007].

Generally, we interpret that rapid ice sheet drawdown caused by retreat and acceleration of a major fjord glacier is a more effective agent driving the retreat of neighboring ice sheet margin than widespread ice thinning associated with increasing surface melting. It is somewhat surprising that the parts of the margin removed from Jakobshavn Glacier are experiencing no or small retreat, in spite of the fact that surface melting rates have been increasing over the observation period. We conjecture that these sections of the ice sheet margin might turn into dead ice terrain, rather than retreat like the areas closer to the major fjord. Hence, the topology of ice sheet marginal retreat may differ depending on the predominant process which is driving ice sheet thinning. This may have implications for ice sheet simulations and predictions of ice-climate feedbacks. One of the strongest such feedbacks is the ice-albedo feedback which tends to reinforce warming climate trends by exposing low-albedo bedrock and sediments in areas that used to be covered by higher albedo ice. In addition, geologic materials newly exposed by ice sheet retreat provide substrata for soil formation which represents a sink for carbon. However, these feedbacks are muted if ice sheet thinning translates into slow or no ice margin retreat. We urge that future work on the subject takes these nuances into account.

5 Conclusion

Satellite and aerial images of the region to both the north and the south of the Ilulissat Fjord from 1985, 2001, and 2020 were analyzed in QGIS, with the areas of retreat being mapped out manually. This analysis indicated that the closer to the fast-moving marine outlet glacier the faster the retreat rates are. More generally, the retreat of the ice margin has accelerated significantly between the two periods. The vicinity to a glacier likely impacts the retreat rate of the ice sheet around it, specifically muting feedback such as ice-albedo feedback in areas far from the fjord, a factor which warrants further study due to its impact on the future modeling of glacial systems and predictions.

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