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Implications of changing winter fjord ice melanges for Greenland outlet glacier dynamics

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IMPLICATIONS OF CHANGING WINTER FJORD ICE MÉLANGES FOR GREENLAND OUTLET GLACIER DYNAMICS

BY

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DEDICATION

To my wife Megan, this would not have been possible without your sacrifice and support. You are an amazing woman and I am incredibly grateful and fortunate to have you in my life!

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ABSTRACT

IMPLICATIONS OF CHANGING WINTER FJORD ICE MÉLANGES FOR GREENLAND OUTLET GLACIER DYNAMICS

by

Ryan K. Cassotto

University of New Hampshire, December 2011

Recent studies have demonstrated rapid change along the margin of the Greenland Ice Sheet (GIS) over the last decade. In particular, increases in glacier velocities coincident with terminus retreat for many of Greenland's outlet glaciers have effectively increased the amount of ice discharged. Much of this calved ice passes through elaborate fjord systems en route to the ocean. This study utilizes remote sensing observations to investigate the changing conditions in several of Greenland's pro-glacial fjords and changes along glacier termini. The findings indicate that changes in the mix of calved ice and water in pro-glacial fjords have implications for the location of the calving front and for glacier speed and thickness in the near-terminus region on seasonal to interannual time scales. The ability of the fjord ice to influence terminus dynamics and glacier stability has implications for predicting ice loss over much longer time scales.

1 Introduction

The Greenland Ice Sheet (GIS) is the world's second largest ice sheet and is situated between the North Atlantic and Arctic Oceans. It extends more than 2400 km between 61° and 83°N and 1100 km East-West at its widest expanse (~78°N). The volume of the GIS has varied over geologic time; at present, it contains approximately 2.93 million km^3 of ice [*Dahl-Jensen et al.*, 2009].

Holocene variations of the GIS ice margin are modest in comparison to the major glacial cycles that dominated the Pleistocene, but they are nonetheless significant to the history of the GIS. As an example Jakobshavn Isbrae (JI, 69.1°N, 49.6°W), one of the world's faster outlet glaciers, exhibited considerable variability throughout the Holocene. Between 8 – 10 Ka the ice margin near JI was located ~50 km west (downstream) of its present location, near the mouth of Kangia Fjord; it retreated at least to and perhaps upstream of its current position between 8000 – 400 years ago, and then advanced to its late Holocene maximum (~35 km west of current position) during the Little Ice Age (LIA) [*Weidick et al.*, 1990; *Young et al.*, 2011]. In the 150 years following the end of the LIA (A.D. 1850 – 2000), the terminus of JI exhibited a gradual ~20 km retreat and even demonstrated a period of relative stability from the 1940s to the 1990s (Figure 1) before recent changes at the turn of the present century forced a rapid 15 km retreat of its calving front.

Overall, the GIS remained in a relatively stable configuration for most of the 20^{th} century; ice flux into the GIS through precipitation and accumulation generally kept pace with the ice flux out of the GIS through ablation, surface melt runoff, and iceberg calving; but a period of rapid change began in the mid-1990s that continues today. Tidewater outlet glaciers, which evacuate ice from the interior and deposit it into the ocean, in particular have exhibited drastic change; a number of them show increases in velocity [*Joughin et al.*, 2004], while their terminuses have retreated [*Moon and Joughin*, 2008]. Concurrent with these changes is a modest increase in snowfall in the interior which models have attributed to a warming climate [*Steffen et al.*, 2008]. The net result is a slow thickening in the interior of the ice sheet, and a thinning margin near the accelerated outlet glaciers [*Abdalati and Steffen*, 2001; *Krabill*, 2004; *Pritchard et al.*, 2009; *Steffen et al.*, 2008]. This new dynamic state is of particular concern to the glaciological community. If these observed changes continue to propagate upstream in the outlets and the margin continues to thin, mass loss may accelerate. The consequence of sustained fast "conveyor-like" outlet glaciers and subsequently a smaller ice sheet is an increase in sea level. These changes to the GIS increased its sea level contribution by a factor of ~2.5 between 1996 and 2005 [*Rignot*, 2006]. If this trend continues, it along with similar changes in Alaskan glaciers and Antarctica could eventually have a significant impact on major coastal cities. The objective of this study was to develop a satellite record of change around Greenland's margin to investigate the dynamic boundary between the ice sheet and the ocean, and in particular regions where tidewater outlet glaciers terminate into marine fjords.

2 Background

2.1 Recent Studies

Recent focus on climate change has resulted in many studies on the Greenland ice sheet (e.g. [*Box et al.*, 2009; *Holland et al.*, 2008; *Howat et al.*, 2008] *and several more).* Research is ongoing in areas such as ice thickness change [*Krabill*, 2004; *Pritchard et al.*, 2009; *Thomas et al.*, 2003], changing ice discharge [*Rignot et al.*, 2008], and changing surface melt (e.g. [*Abdalati and Steffen*, 2001]). Moon et al., (2008) used satellite remote sensing to examine the advance and retreat rates of glaciers around the Greenland margin over the last two decades; they found that many of the tidewater glaciers exhibited a retreat with the largest retreat rates occurring during the latter part of the record. Moon and colleagues also concluded that land-terminating glaciers exhibited no significant change in terminus position during the same period. Howat et al., (*2008*) suggested that anomalously high climate and ocean temperatures circa 2003 initiated glacier retreat in southeast Greenland. Most recently, publications [*Holland et al.*, 2008; *Straneo et al.*, 2010] have proposed advection of warm waters into Greenland fjords as a mechanism of increased retreat. Despite such active research, there remains little direct evidence of mechanisms behind ocean impacts on outlet glaciers, or even comprehensive studies of the relationship between outlet glacier dynamics and fjord surface conditions.

Future predictions of ice discharge remain difficult because: 1) the physics controlling outlet flow (e.g., sliding, calving, non-linear ice response to stress) are not well characterized, and are hard to model [*Solomon et al.*, 2007]; and 2) processes involved in ocean interactions with the ice are not well understood. The research presented here provides an initial investigation of changing fjord ice surface conditions and related glacier response around the Greenland margin.

2.2 Motivation

Despite ongoing research on the current changes affecting the GIS, little is known about the major mechanism(s) driving these changes. These deficiencies, coupled with the inability to adequately model outlet glacier flow, limit scientists' ability to predict future sea level impacts from changes in the GIS in a warming climate [*Dahl-Jensen et al.*, 2009; *Metz et al.*, 2008]. The primary motivation behind this study was to develop a proxy for changing fjord ice conditions using satellite data that could be used in conjunction with other records to constrain mechanisms behind changes in outlet glacier terminus stability. Secondary objectives addressed the following questions: 1) have the fjord ice-in seasons grown shorter? 2) has glacier calving, a predominately summer mass-wasting activity in Greenland, started to occur during the winter months? and 3) do glacier velocities show a flow response to observed changes in fjord ice conditions?

This study provides insight necessary for an improved understanding of the role warming ocean temperatures may have on outlet glacier dynamics. Specifically, the study focuses on ice mélange conditions in Greenland's pro-glacial fjords and uses remote sensing records to investigate mélange influence on terminus behavior. A mélange, in geologic terms, is defined as a mappable body of rock composed of broken rock fragments[1]. An ice mélange is simply a mélange whose main constituent is glacier

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[1] "Melange." Oxford Dictionary of Earth Sciences. 3rd edition. 2008. Print.

ice calved from the terminus. My hypothesis is that warming affects the sea ice mélange in many of Greenland's fjords, which has been proposed as a calving inhibitor at Jakobshavn Isbrae by preventing the heavily fractured ice at the terminus from overturning [*Amundson et al.*, 2010] and thus completing the calving cycle. This study begins with a focus on Jakobshavn Isbrae and then branches out to other outlet glaciers looking for possible trends in the remote sensing archive.

2.3 Jakobshavn Isbrae

Jakobshavn Isbrae (JI) is a tidewater outlet glacier in West Greenland that drains approximately 7% of the Greenland Ice sheet (GIS). Like many of Greenland's outlet glaciers, it has changed rapidly over the last 15 years. Since 2000, Jakobshavn's velocities have increased and its terminus has retreated, as a persistent floating ice tongue disintegrated and was replaced by an annual floating tongue, which is formed by ice advance in the winter that disintegrates each spring. Indeed, this rapidly changing glacier has become the poster child for climate change in Greenland and the World.

The Little Ice Age (LIA) was a cold period in the late Holocene, approximately AD 1400 – 1850 [*Grove*, 2004], in which global temperatures were cooler than modern day, and which is marked in many places around the globe by ice advances. At the end of the LIA, JI's terminus was located approximately half-way down the presently open part of Kangia Fjord, ~35 km west of the 2011 terminus. During the 100 years following the end of the LIA, the terminus retreated >25 km [*Weidick*, 1995]. Between 1940 and 1996, the terminus fluctuated around a relatively stable position (Figure 1, [*Sohn et al.*, 1998]); generally advancing ~2.5 km down-fjord during the winter months before retreating a similar distance during the summer. The terminus thus remained in a quasi-stable state; the dynamics driven largely by seasonal transitions from increased calving events during the summer to calving cessation and steady glacier flow in the winter [*Sohn et al.*, 1998]. This pattern was broken by the onset of changes in the terminus at the turn of the present century. Rapid increases in glacier flow [*Joughin et al.*, 2004; *Luckman and Murray*, 2005], terminus retreat [*Luckman and Murray*, 2005; *Moon and Joughin*, 2008], and the final disintegration of the floating tongue in 2003 all contributed to ice loss at the terminus through a process called '*dynamic thinning*' [*Thomas et al.*, 2003]. The glacier terminus continued to exhibit seasonal variations in position, but the dynamic range increased to ~6 km annually. Then during the 2010 winter (Oct 2009 – April 2010) the glacier failed to re-advance. A preliminary look at observations of early spring conditions revealed considerable differences in the ice mélange and unique winter fjord conditions; soon after evidence of increased winter calving emerged.

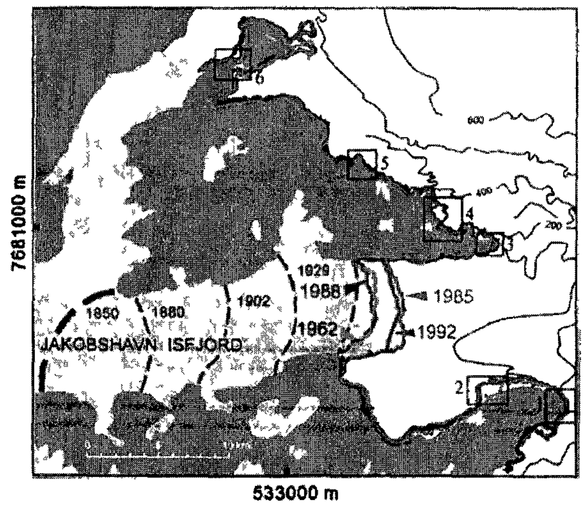

Figure 1: Illustration from [*Sohn et al.*, 1998] depicting history of Jakobshavn Isbrae's terminus location (dashed black lines) since the end of the LIA.

The unexpected change in terminus behavior during the 2010 winter became a focus for this study. Comparisons of winter fjord conditions and terminus behavior were made between 2009 and 2010. The study was extended back to 2000 using remote sensing records and a calving catalog generated by Amundson [*Amundson et al.*, 2008] to provide context for the recent change. The results of this work (see section 4.2.1) show a close connection between the winter conditions of the fjord ice cover, the winter calving behavior and re-advance of the glacier terminus, and the impact of winter terminus changes on the flow of the glacier farther upstream. The connections developed in this fjord led to investigations of other glacier/fjord systems around Greenland to see if similar connections between fjord ice cover and glacier terminus processes could be identified. Section 3 details the procedures used for the study of Jakobshavn Isbrae; Section 4 contains the results for this glacial/fjord system. Section 5 documents the work performed to detect similar glacier retreat patterns related to changes in fjord ice conditions for five other systems around Greenland.

2.4 Developing a fjord ice proxy

The last decade of change in terminus position and flow speed at Jakobshavn Isbrae must be correlated with changes in the near-terminus environment for that glacier, but records of what those changes might be are difficult to develop. This study utilizes the remote sensing record to develop a proxy for fjord ice conditions for this system over as long a time span as possible. The primary challenges to developing this type of record are finding a sensor that has sufficient spatial resolution to document conditions in the fjord, sufficient time resolution to make near-daily observations, and also the ability to image conditions in this system in the winter, in the absence of sunlight. These requirements led me to look at the 1-km resolution thermal imagery collected by NASA's (National Aeronautics and Space Administration) MOderate Resolution Imaging Spectroradiometer (MODIS). The MODIS sensor measures spectral radiance at a number of bands in the thermal infrared region that can be converted into surface temperatures after corrections for surface emissivities (which are equally high for ice and water at these wavelengths) and atmospheric losses, including scattering due to clouds.

Compiling a collection of thousands of full resolution MODIS granules (5 minutes worth of satellite data acquisition) is tedious. To expedite production of a time series of changes in Greenland's fjord systems a MODIS-derived thermal data product (the MODIS Sea Surface Temperature record - see section 3.2.2) was selected. This record, published by NASA Goddard Space Flight Center's (GSFC) OceanColor data center, has applied the necessary corrections and geolocation information and produced a 1-km thermal data set with near-daily temporal resolution spanning the decade-long record of recent change. Using this product to characterize ice conditions proved to be as effective as using the raw radiance data it was based on, and was much more time-efficient, as it was already aggregated and corrected for atmospheric effects. While the intent of the product is a record of sea surface temperatures (SST), and the algorithm used to come up with the SST values in the product assumes open water, the record over the ice-covered fjords in this study clearly reflects spatial and temporal variations in ice conditions and surface temperatures over the ice pack. The term SST is used for the data values from this product because of the product's initial intent, but it is acknowledged that true surface skin temperatures may be offset from these values. Nonetheless, the data set proved useful for this research as it clearly shows variations in fjord ice conditions in both space and time, and thus allows one to look at changes in this ice cover over a number of years.

2.5 Implications

2.5.1 Implications of Correlating Changes in Fjord Ice Cover with Retreating Outlet Glaciers

Calving at outlet glacier termini in West Greenland is most significant during the warm summer months [*Joughin et al.*, 2008; *Sohn et al.*, 1998]. At Jakobshavn Isbrae warm fjord surface temperatures appear to facilitate iceberg calving, significantly increasing the rate of retreat of the terminus. However, during cold winter months, the waters of at least some of Greenland's fjords freeze over and lead to the formation of a stiff ice mélange composed of icebergs and crumbled blocks of calved ice glued together by frozen surface waters. The ice-choked fjords appear to help stabilize the region by increasing backpressure on outlet glacier termini that help prevent calving [*Amundson et al.*, 2010]. The outlet glaciers remain in this more stable configuration until the fjord ice becomes mobile and terminus calving resumes. However, if temperatures increase to a point such that the ice mélange melts out and becomes mobile earlier in the year, or in the most extreme, the fjord fails to freeze during the winter months, the duration of the calving season would increase considerably; because terminus retreats that would ensue are related to accelerated glacier flow, this would increase the time of accelerated ice mass loss annually.

Our current climate is one of increased temperatures [*Metz et al.*, 2008]. If sea surface temperature changes and the timing of outlet glacier retreat were found to be correlative, and a mechanism were found to link this to more rapid ice discharge, this could suggest that warmer ocean surface waters would continue to reduce the GIS's mass in the future. Thus part of the objective in creating a comprehensive record of fjord surface conditions against changes along glacier termini was to test the idea that glaciers are responding to this forcing. This study also researches potential mechanisms behind observed changes in outlet glacier dynamics.

2.5.2 Global Implications

The major global implication of this study is that warmer surface waters around Greenland could increase ice discharge and melt rates, thereby contributing to sea level rise. While a number of changes have been noted in Greenland, progress on identifying direct ties to a changing environment has been slow. This study looks at the relationship between fjord conditions and outlet glacier flow; a relationship that must be understood to make predictions on sea level changes.

2.5.2.1 Outlet glacier dynamics

The rapid thinning and recession of Greenland's outlet glaciers has a profound impact on glacier dynamics. Outlet glaciers are generally thickest in the interior reaches, and progressively thin along the direction of flow. Where an outlet glacier flows into the narrow confinement of a fjord en route to the ocean, the stability of the glacier is controlled by a balance between the rate of along-flow stretching, which can thin the ice and lead to faster flow and eventual calving, and the increased discharge of ice from the interior that accompanies accelerated flow. Accelerated flow in the near-terminus region results in thinning, which promotes flotation, and further accelerates glacier flow. Basal shear is a minimal component of flow for tidewater glaciers grounded below sea level, thus sliding of the glacier along the basal layer dominates the flow regime. As discussed in Pfeffer (2007), a commonly used version of the sliding law is: $u = \frac{k\tau_d}{P_{eff}}$,

where u is the sliding speed, P_{eff} is the effective pressure (pressure difference between ice overburden and basal water), and τ_d is the driving stress further defined as $\rho g h sin(\alpha)$, where ρ is the density of ice, g is the acceleration due to gravity, h is the ice thickness, and α is the surface slope. The effective pressure is inversely related to sliding and thus exerts control over flow of a tidewater outlet glacier near flotation. As the effective pressure is reduced, the glacier approaches flotation, which in return influences ice flow speed, thinning, and calving. Up-glacier where effective pressure is larger, both sliding and flotation are inhibited by the increase in ice overburden (Figure 2). In the

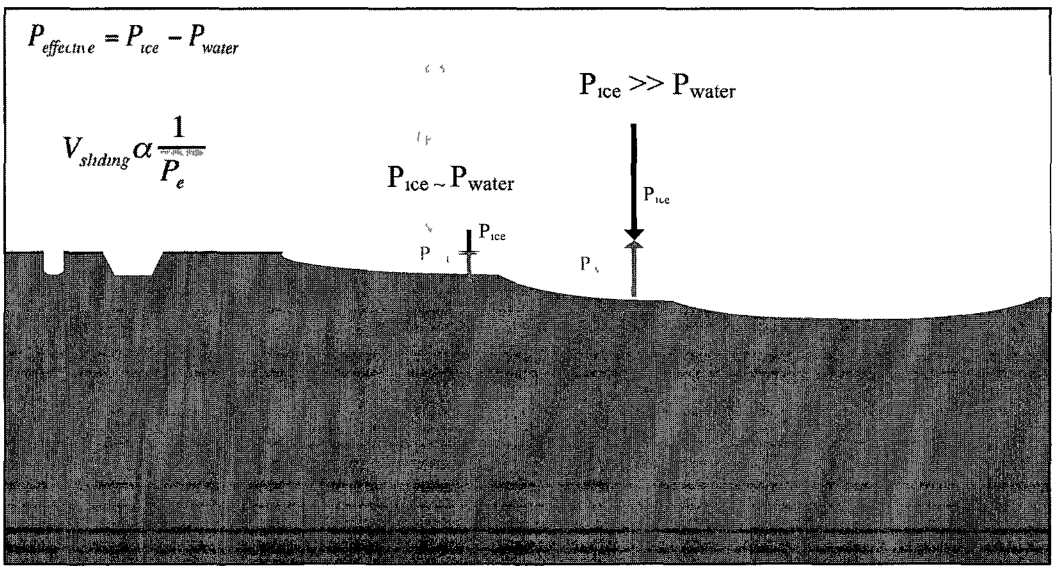

Figure 2: An illustration of a tidewater glacier afloat at the ocean/bedrock boundary. Effective pressure is proportional to glacier thickness. Far up-glacier, where the ice is thick, the exceedingly large magnitude of effective pressure forces the glacier down into the bedrock, opposing the down-gradient force of gravity. This prevents the glacier from freely sliding. Closer to the glacier terminus, the glacier thins and pressure due to ice overburden approaches the pressure due to basal water, and the terminus approaches floatation.

near-terminus region, a thinner glacier and basal water pressure that is tied to sea level translates to lower effective pressure and increased sliding as the glacier approaches flotation. If thinning along the GIS margins continues, lower effective pressures in tidewater glaciers will lead to faster flow that will likely propagate up-glacier, further reducing the effective pressure and increasing sliding, flotation, and calving in fjords where the bed is below sea level. Warmer surface temperatures in the fjord would enhance this process, and help destabilize the outlet glaciers in the region.

2.5.2.2 Sea Level Rise

The water mass equivalent ice volume of the GIS is equivalent to a sea level rise (SLR) of ~7 meters [*Dahl-Jensen et al.*, 2009]. The estimate of SLR contribution from the GIS was 0.23 mm/a ± 0.1 mm in 1996, but increased to 0.57 mm/a ± 0.1 mm by 2006 [*Rignot*, 2006]. If recent trends in increased Greenland outlet glacier velocities and subsequent ice evacuation from the interior continues without significant increases in replenishment of snow and ice accumulation, the GIS SLR contribution could reach 2.5 mm/a by the year 2100 [*Meier et al.*, 2007].

3 Methods

Fjord and glacier conditions were evaluated using satellite imagery, time-lapse photography, a seismically detected calving record, and weather data from stations operated and maintained by the Danish Meteorological Institute [*Cartensen et al.*, 2011].

3.1 Research Areas & Times of Observation

A total of six glaciers and their adjacent fjord systems were investigated in this study (Figure 3). The approximate locations (as of 2011) of the glacier termini are provided in Table 1. The observation period begins in July 2000 and extends through June 2011 for all glacier systems except for Helheim and Midgards Glaciers whose observations end in June 2010.

Table 1: Glaciers investigated in this study and the approximate geographic location of their respective termini in 2011. The last column contains a reference to the results section for each glacier.

Glacier Name	Latitude (°N)	Longitude (°W)	Section
Jakobshavn Isbrae (JI)	69.2	49.6	4
Narsap Sermia (NS)	64.6	50.0	5.1.1
Kangiata Nunaata Sermia (KNS)	64.3	49.6	5.1.2
Helheim	66.4	38.1	5.2.1
Midgards	66.5	36.7	5.2.2
Nunatakavsaup Sermia (NKS)	74.6	56.1	5.3

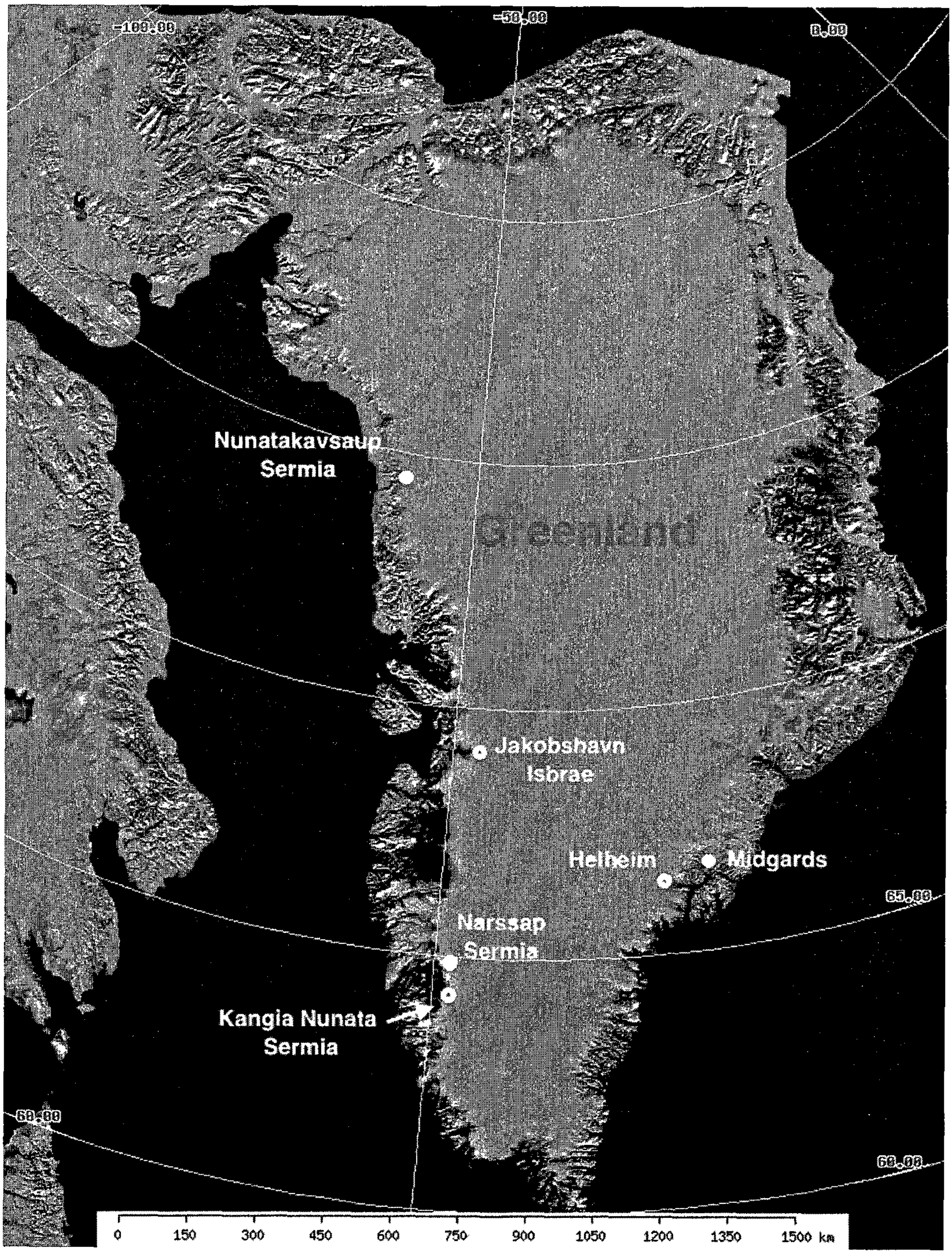

Figure 3: MODIS mosaic of Greenland with the names and locations of the glaciers addressed in this study.

3.2 Remote Sensing – Satellites

The bulk of the research used in this study derives from NASA and the United States Geological Survey's (USGS) Landsat satellites and NASA's MODIS sensor. The MODIS sensor was launched onboard the TERRA and AQUA satellites on December 18, 1999, and May 4, 2002, respectively, as part of the NASA's Earth Observing System (EOS) campaign. Both satellites have polar, sun-synchronous orbits, meaning they pass through the equator at the same local time of the day throughout the year. Both satellites orbit the earth at an altitude of ~705 km with a period of 100 minutes, resulting in a 16-day orbital repeat track. Both MODIS and Landsat sensors utilize passive remote sensing technology, that is, sensors onboard these platforms do not transmit a signal as part of the measurement process. Instead, they measure emitted or reflected energy from the earth's surface (e.g. land, ocean, and clouds) to make observations. In contrast, TerraSAR-X, which produced the ice velocity measurements used in this study, actively transmits a signal and measures the return phase to monitor changes along the Earth's surface.

3.2.1 Landsat (Tracking Ice Front Position Over Time)

The Landsat program consists of a series of satellites to monitor changes on the Earth's surface. The first three Landsat satellites, launched in 1970s, utilized the Multispectral Scanner (MSS) to observe light reflected from the surface in the visible (0.4 – 0.7 μm) and near-infrared (IR: 0.72 – 1.30 μm) regions using 4 channels, each with a pixel sampling and effective spatial resolution of >60 meters. Spatial resolution is defined as the minimum distance that can be resolved between two objects. Landsats 4 and 5, launched in the 1980s, improved on this resolution with the thematic mapper (TM), producing imagery with 30-meter pixel size. Landsat 7, launched in 1999, uses the

Enhanced Thematic Mapper Plus (ETM+) using 8 channels at various spatial resolutions, including the high-resolution (15-m) panchromatic band (0.52 – 0.90 nm). The sensor sweeps 183 km (cross-track) of the Earth in 170 km intervals (along-track) at nadir. This limits equatorial observations to 16 days, however, the convergence of polar orbits in high latitude areas, such as Greenland, can reduce this to as little as 2 days between observations. A very low number of scenes of Greenland from Landsats 1 – 5 limited the usefulness of these satellites for this study. Thus, the high spatial resolution of ETM+'s panchromatic band coupled with the high polar orbit and the large number of scenes acquired in Greenland made Landsat 7 the ideal satellite to monitor changes along glacier termini.

Cloud-free images were selected and downloaded from the USGS Earth Resources Observation and Science (EROS) Center's Global Visualization Viewer (GLOVIS). MATLAB ® was used to manually digitize the terminus in each scene, calculate the mean front position, and produce a time-series of the terminus history. For each scene, the dates and Universal Transverse Mercator (UTM) coordinates (red data points of Figure 4) of the entire terminus were recorded during the digitization process. The number of data points used to characterize each front varied by terminus shape and date. Only the data points within a specified distance (e.g. yellow data points in Figure 4) from the interpreted major flow line (blue line in Figure 4) were used to calculate the mean terminus position for a given date. Data points along the lateral fringes of the glacier were excluded to avoid skewing of the data due to slow or stagnated ice. For example, due to nearly 14 km of retreat, Jakobshavn Isbrae (Figure 4) now has two channels, the north branch and the south branch. The south branch flows at a faster rate (Figure 7) and calves more ice than the north branch and thus is considered to be the

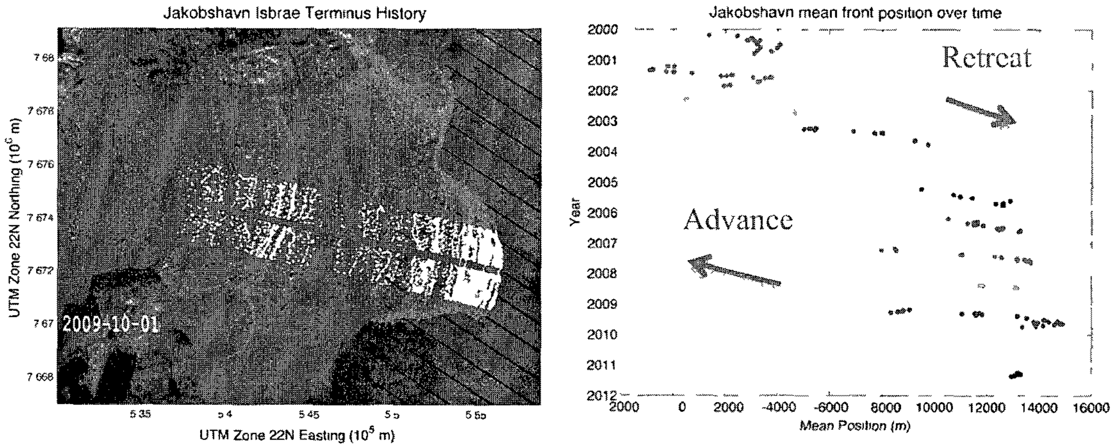

Figure 4: Terminus History of Jakobshavn Isbrae 2000 – 2011. (Left) Landsat derived digitized front positions. Red points outline the entire digitized front, blue line depicts the along-flow direction of the main channel, yellow highlights the points used (+/- 1.5 km of flow-line) in determining the mean position. (Right) Time-series of Jakobshavn Isbrae's mean front position. Each point represents the mean front position for 1 day. Y-axis is time. X-axis is the mean position (i.e. distance along the blue line in the left figure).

main channel. Additionally, bedrock rises (e.g. below convex neck between the north and south branches) and embayment areas adjacent to the main flow line (e.g. along south fjord wall) produce slow ice that is decoupled from the rapid changes. Once calculated, the mean position was then plotted over time to document 11 years of terminus variability (Figure 4, right) along the main flow line (blue line in Figure 4, left). More positive (or less negative) mean position values reflect a downfjord advance of the glacier. Lower (or more negative) values reflect an upfjord retreat.

The change in winter mean terminus position (e.g. Figure 20a) was also calculated to compare the amount of winter glacier re-advance against the change in winter fjord ice conditions (see 3.2.2). The difference between the minimum mean fall position (July to

December but typically ranging from August to October) and the maximum mean spring (January to June but typically ranging from March to May) position was used to calculate the winter terminus change. These intervals were large to accommodate the relatively sparse availability of Landsat images (due to clouds, seasonal solar illumination, orbital parameters) and seasonal variation in advance/retreat modes.

3.2.1.1 Limitations of the Landsat Data Set

There are two limitations to using the Landsat data set in this study: the failure of the scan line corrector (SLC), and the utilization of a passive optical reflectometer during an arctic winter. Cross-track scanning sensors, like those onboard Landsat, scan in a direction roughly perpendicular (cross-track) to the orbit (along-track), but due to satellite motion along orbit and the motion of the rotating Earth, the field of view of the sensor must be adjusted. If this motion is not accounted for a zigzag pattern appears in the raw data. The onboard SLC compensates for these motions, effectively removing the zigzag pattern to provide a continuous rectilinear image. On May 31, 2003, the SLC onboard the spacecraft failed, forever leaving data gaps that appear as black diagonal stripes in post-failure scenes. An estimate of maximum data loss for any given Landsat 7 image is ~22%[2] of the total scene, but gaps obscuring the terminus being digitized were no more than ~25% of the glacier front. The glacier terminus was manually interpolated across these data gaps where present.

Passive optical sensors utilize solar reflectance to record Earth observations. The high latitude of Greenland and resultant dark winters limits Landsat observations to

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[2] "SLC-off Products: Background," U.S. Department of Interior USGS. Last modified: 30 December 2010, Accessed: November 3, 2011
http://landsat.usgs.gov/products_slcoffbackground.php

periods when the sun illuminates the target region (Spring through Fall). Furthermore, clouds are opaque in the optical band, constraining summer observations to periods with low cloud cover.

3.2.2 MODIS (Fjord Ice Proxy)

The MODIS SST data product was used to generate a proxy for ice conditions in Greenland's fjords. MODIS is a 36-channel imaging spectroradiometer that measures energy in the thermal infrared (TIR) and visible regions of the electromagnetic spectrum. MODIS scans the Earth's surface in 2330-km wide (cross-track) swaths that span 10 km along track at nadir, 20 km at the extremities. The large swath width enables full global coverage every 1 – 2 days. The data are stored in 5-minute acquisition intervals called granules which cover ~2000 km of earth's surface along orbit. Two MODIS channels observe reflected light with 250-meter pixel sampling and effective spatial resolution, five with 500-meter sampling, and the remaining 29 channels record either reflected light or thermal emissions with 1-km pixel sampling and similar resolution.

NASA's GSFC processes and distributes MODIS-derived sea observations through its Ocean Data Processing System (ODPS). ODPS combines the measured values of MODIS channels 31 and 32 (11 and 12 microns, respectively) with reference values using the National Oceanic and Atmospheric Administration's (NOAA) Optimum Interpolation SST (OISST) product, which utilizes both in-situ and satellite observations, to generate the MODIS SST product. ODPS releases three different versions of processed data, all of which are derived from raw radiance values (level 0) received at the satellite. The level 1 data applies radiometric and geometric correction coefficients to the level 0 data and incorporates georeferencing information in the finished product. A geophysical parameter algorithm is then applied to the level 1 data to produce a SST data product (level 2). The data are further binned in time (daily, 8-day, or monthly) and are mapped in an equidistant cylindrical projection to produce a level 3 global data product. Modeled results of several combined measured values are released as a level 4 data product. The large spatial resolution (>4 km/pixel) of the level 3 and level 4 data products is best suited for open ocean observations and is too coarse for Greenland's narrow fjords, which vary between 4 – 10 km in width. The full resolution level 2 SST data product was used to generate the fjord ice condition proxy.

The level 2 SST data product this study utilized was available as granules based on the Terra MODIS 11-micron thermal emission channel. Granules were selected based on the proximity of the glacier terminus to the satellite's nadir position. In general, one image per day was acquired for the observation period. However, in some cases, particularly those in which the terminus was far from nadir, multiple overlapping granules were acquired for a single day. Temporal sampling inconsistencies were accounted for during the filtering process (see 3.2.2.1). The granule data were re-projected in MATLAB ® using the nearest neighbor criterion to produce surface temperature maps in a 1-km equally spaced projection for each of the study areas. These maps (e.g. Figure 5c) were then filtered (see 3.2.2.1) in the time dimension to reduce effects of temperature biasing due to clouds (Figure 5d), and a profile was extracted along the fjord center to create a time series of surface temperature conditions extending out from the glacier terminus. The resultant annual profiles (e.g. Figure 10) are centered on winters to highlight seasonal variations in fjord ice cover conditions.

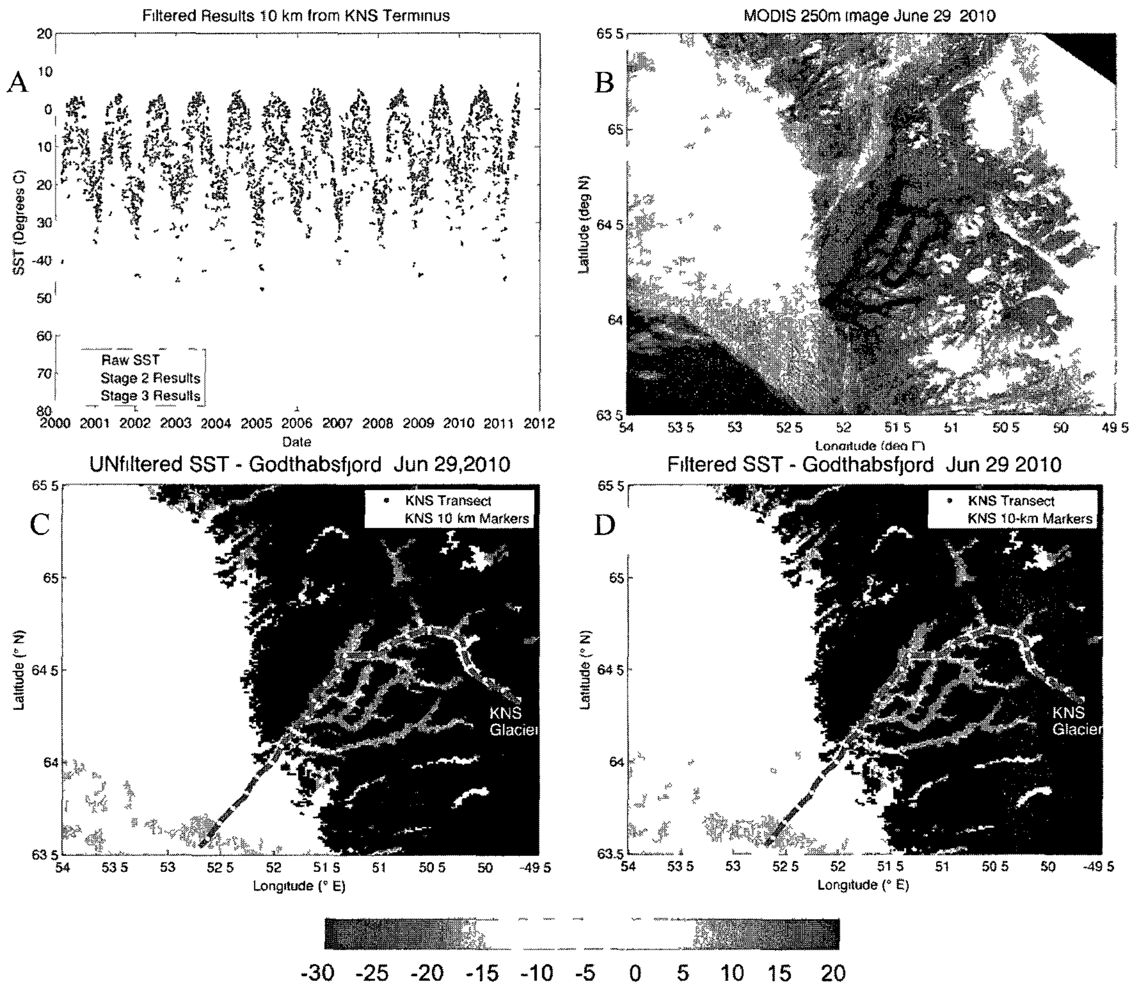

Figure 5: Results of the SST filter for persistent, thick cloud cover. (A) Filtered results for a single pixel located 10 km from the terminus of KNS glacier. Black data points are raw data, red are the 2nd stage output, and blue data points are the final filtered data points. (B) June 29, 2010 MODIS visible band image of Godthabsfjord. Note the thick layer of clouds in the northwest portion of the image. (C) Unfiltered and (D) Filtered MODIS thermal SST data products acquired at the same time as image in (B). Note, the cooling effect of the thick cloud layer in the northwest is not removed, but reduced, during the filtering process. The color bar represents the thermal SST values in figures (C) and (D). Units are in °C.

3.2.2.1 Limitations of the SST Data Product

The use of the MODIS SST level 2 data product to evaluate changes in fjord surface conditions is not without limitations. In addition to interpreting the data as a proxy for fjord ice conditions (section 2.4), there are two caveats in using this data product for this study: 1) the use by the ODPS of a land and glacier ice mask that predates the recent changes along some of the glacier fronts; and 2) cloud contamination. The land mask for the level 2 data is included in the finished SST product and cannot be backed out without reverting to the Level 1 radiance values. The obsolete land mask does not affect all of the fjord systems, and those that are affected contain enough surface temperature information to make adequate observations (e.g. pro-glacial fjords of Jakobshavn Isbrae and Midgards Glacier).

A limitation of using any satellite-based thermal infrared (TIR) measurement to monitor the earth's surface is cloud contamination. Clouds are somewhat opaque to TIR energy; meaning TIR satellite observations of the earth's surface include measurements of energy scattered and emitted by clouds that represents cloud temperatures. Thus they become a permanent part of the satellite TIR record and cannot be removed. However, although clouds can bias pixel values warm, observations made in this study demonstrated clouds had a dominantly cooling effect on the SST record (e.g. Figure 5). Raw SST data was passed through a 7-day moving average filter using MATLAB ®, to reduce few-day cooling events in the record resulting from clouds. The secondary objectives of the filter were to: 1) remove "no data" values for edge of scene (SST value = 999) and land and glacier ice mask (SST value = -163) pixels; and 2) provide a daily

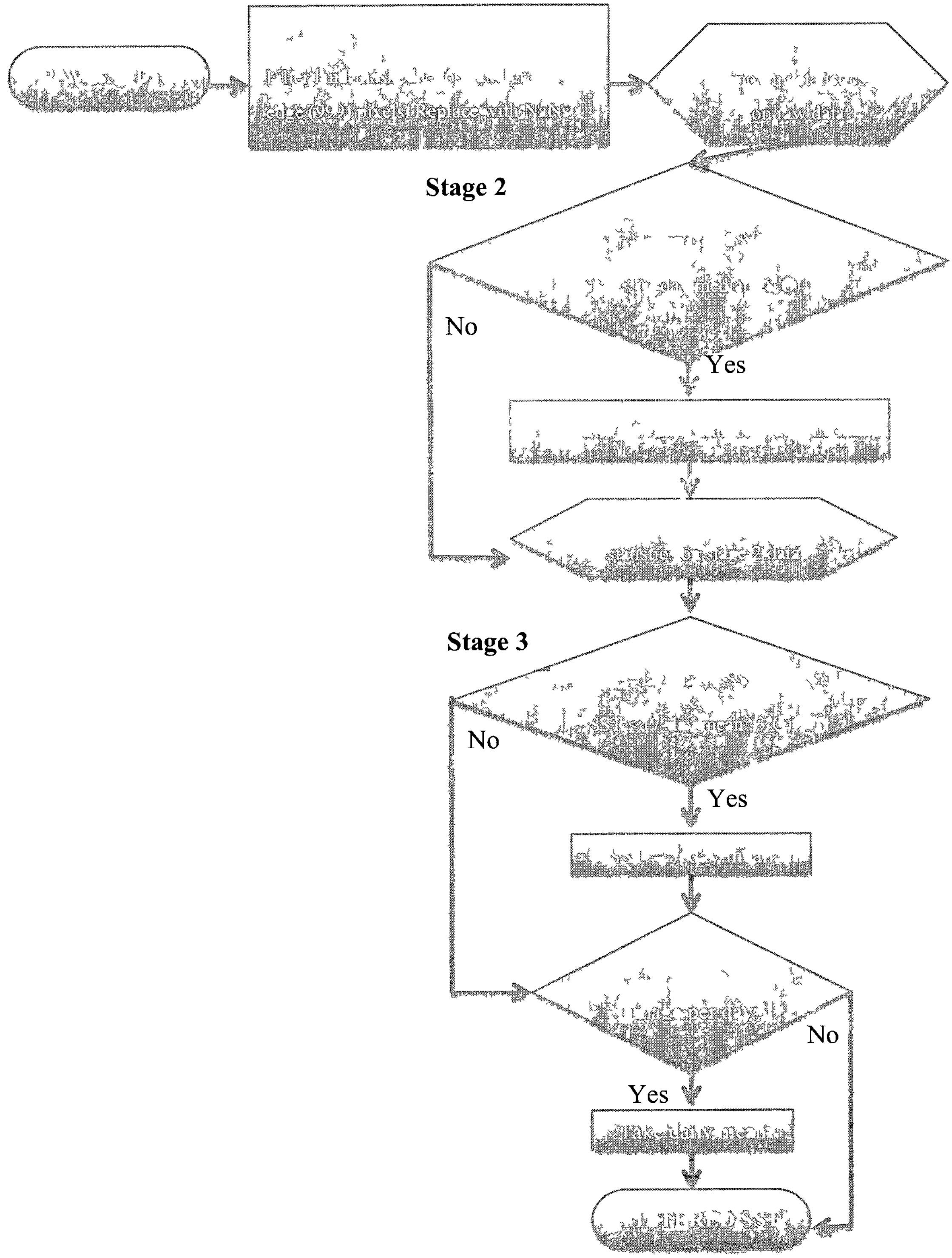

Figure 6: Flowchart algorithm for the SST filter. The primary objective of the filter was to reduce cold biasing from cloud contamination. Secondary objectives included removal of land-mask and scene edge pixel values, and computing a daily SST value for days with multiple MODIS acquisitions.

SST average or days with multiple satellite acquisitions. The algorithm for the filter used is shown schematically in Figure 6.

3.2.3 Glacier Flow Response from TerraSAR-X

TerraSAR-X is a German X-band (8 – 12 GHz) Synthetic Aperture RADAR (SAR) satellite that orbits the earth at an altitude of ~514 km. Glacier and mélange velocities used in this report were derived by Ian Joughin ([*Joughin*, 2002], Personal Communication) from data acquired onboard the TerraSAR-X satellite. Speckle (or feature) tracking was used on the very high-resolution (~100 meter) images to track changes over an 11-day orbital repeat interval from which maps of surface velocities near the terminus were derived (e.g. Figure 7- left). During winter months, when the

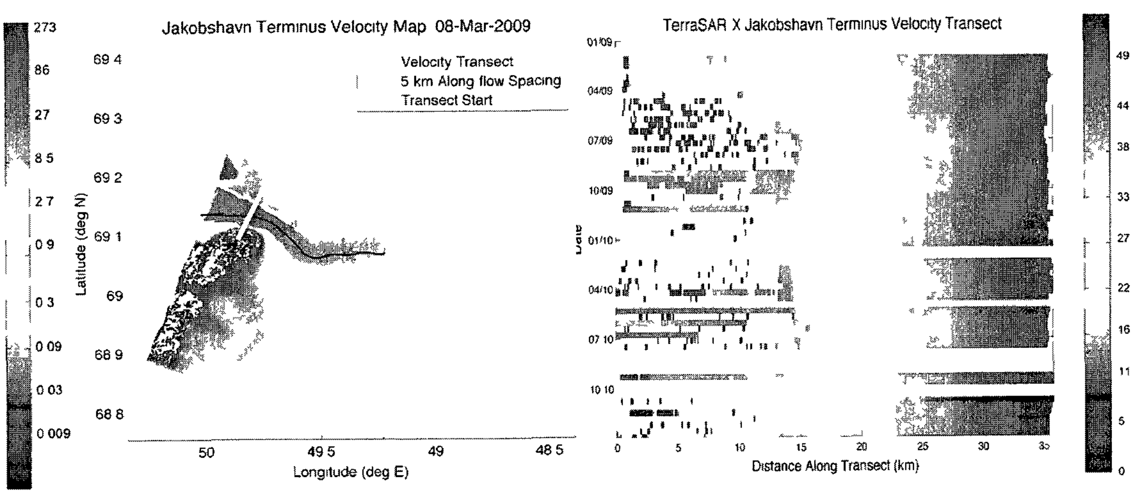

Figure 7: (Left) Jakobshavn Isbrae and ice mélange surface velocity map derived from TerraSAR-X. White line approximates location of terminus in velocity map. Black line depicts velocity transect used in image to the right. (Right) Time series of surface velocities along the transect for 2009 and 2010. The surface map (left image) is scaled logarithmically. The transect velocities (right image) are scaled linearly. The units of both scales are in meters per day.

consolidated fjord ice remains as a cohesive unit, TerraSAR-X also tracks the velocity of the mélange ice cover as it is pushed downfjord by the advancing glacier. Velocities were sampled along the major flow line of Jakobshavn Isbrae's southern branch and onto the mélange in the pro- glacial area (Figure 7- right). Each of these velocity transects were then differenced with the March 8, 2009 transect (a minimum velocity day) to remove the pattern of background velocities and highlight changes in time. A time-series of these velocity anomalies was then created to show changes in speed between the winters of 2009 and 2010 (Figure 14– far right) for Kangia Fjord only.

3.3 Remote Sensing – Other

For Kangia Fjord and Jakobshavn Isbrae the satellite records were supplemented with other data sets, including time-lapse photography, a calving induced seismic record, and meteorological data from the Danish Meteorological Institute (DMI,[*Cartensen et al.*, 2011]).

A series of digital cameras was deployed in Kangia Fjord beginning in 2007. Each camera is powered by a combination of solar power and high capacity (≥75 AH) deep cycle batteries. This power configuration allowed for year-round monitoring of fjord conditions with high temporal resolution (3 – 6 hour interval). The first camera, referred to as SUSE (69° 13.206', 49° 56.855' W), is located at the former (1940-1990s) terminus position, approximately 15 km downfjord from the 2009 fall terminus position. This camera faces west towards Disko Bay (e.g. Figure 9). Images from this camera were used as validation of interpreted ice conditions from the MODIS surface temperature transects (Figures 9, 10, 11) for the 2010 winter; it operated through the winter until experiencing a power failure on February 6, 2010. Additional cameras are located further upfjord near the terminus (FTC: 69° 7.765' N, 49° 43.296'W; FTC2 69° 7.480', 49° 41.746' W) and were used to monitor changes along the inner fjord and calving at the glacier front.

The majority of the calving record used in this study was derived by Jason Amundson from a longer record of seismic events detected 250 km away in Sondre Stromfjord at a station that is part of the Global Seismographic Network (GSN). Amundson supplemented the teleseismic record with observations from a local seismometer between May 2007 and August 2008; methods for both records are provided in *Amundson et al.,* (2008). In his approach, calving-induced events are characterized as having long periods (35 – 150 s) and large magnitudes (M_{SW} 4.6 - 5.1) [*Amundson et al.*, 2008]. This study uses only the timing component of the seismic record to identify when calving events occurred along the front of Jakobshavn Isbrae.

Meteorological data were obtained from the Danish Meteorological Institute's (DMI) weather station located at the Ilulissat Airport (69° 14'51''N, 51° 4'29'' W) ~ 50 km Northwest of the inner fjord. The data are used in the results section for interpreting some events.

3.4 Validation of MODIS SST data as a proxy for Fjord Ice Conditions

To validate the MODIS thermal SST record as a proxy for fjord ice conditions, the record was compared against fjord observations using Landsat and MODIS visible band images and time-lapse photography between August 2009 and February 2010. Figure 8 provides a MODIS visible band reference image of the Kangia Fjord study area on October, 1, 2009, the same day images in Figure 9 were acquired.

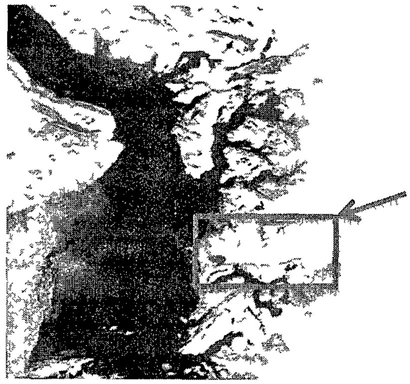

Figure 8: MODIS 250-meter visible band image from October 1, 2009. Note the clouds over the western portion of Disko Bay (bottom left quadrant) cool the SST map shown in Figure 9.

Figure 9 compares observations of Kangia Fjord conditions from October 1, 2009. The top image is a Landsat 7 panchromatic band scene of Kangia Fjord. Moving west to east (left to right) in the image: Disko Bay (furthest west) appears mostly ice free; several large icebergs are grounded at the fjord mouth; a small section of open water appears just inside the fjord east of these icebergs (~-50.9°E); then the remaining fjord is largely ice covered up to the north and south termini of Jakobshavn Isbrae (furthest east). Surface boundaries between fjord ice and open water are delineated by persistent temperature differences in the MODIS SST record (Figure 9 – middle images). Fjord ice (aqua-marine regions of Kangia Fjord) has SST values that range from -5°C to -10°C in this figure. In contrast, areas of open water, specifically the patch near the end of the fjord, adjacent tributaries of the fjord, and the visible region of Disko Bay, all appear yellow in the thermal maps and have SST values that range from 0 to +2°C. The red asterisk in the Landsat and MODIS images depicts the location of the time-lapse camera at SUSE, shown in the bottom images of Figure 9. The down-fjord photograph (bottom right) was taken 74 minutes after the MODIS SST data (middle images) was acquired and shows the

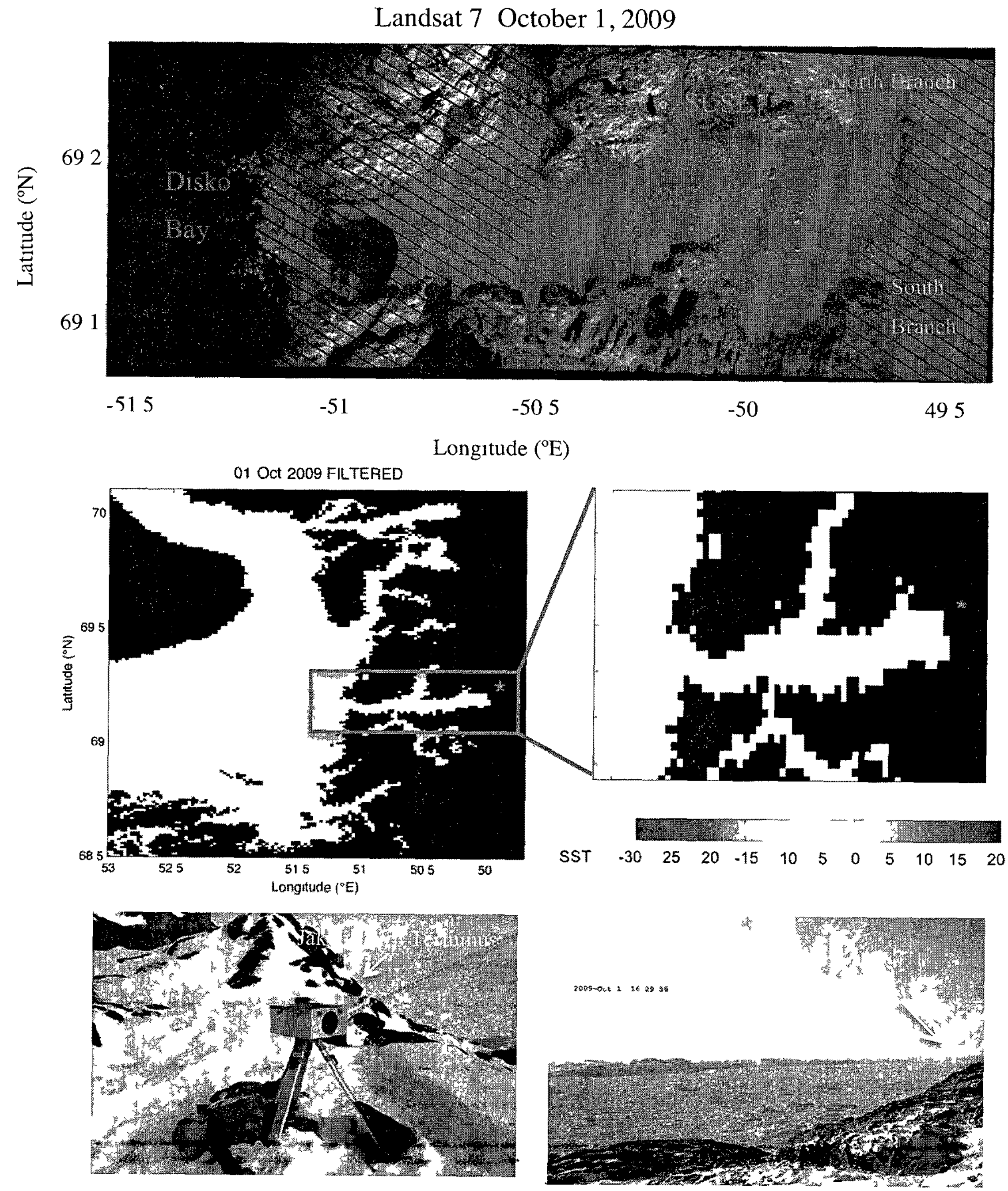

Figure 9: October 1, 2009 images of the Jakobshavn Isbrae study area. (Top) Landsat 7 image depicting the glacier's main channels, the 60-km long fjord, and Disko Bay to the west. (Middle) MODIS thermal IR map of Disko Bay and Kangia Fjord (red box). Units are degrees Centigrade (Bottom) Time-lapse camera setup and viewing angle of the middle fjord showing mostly consolidated ice mélange. Red asterisk depicts the location of SUSE time-lapse camera station.

ice mélange as a poorly sorted mix of icebergs calved from Jakbshavn's terminus. For reference, Disko Bay is in the background (to the West) in the bottom right image. The terminus of Jakobshavn Isbrae can be seen in the background (to the East in the bottom left photo) behind the camera setup.

Figure 10 and Figure 11 further validate the use of the MODIS thermal SST record to monitor the changing ice conditions. Both transects illustrate changing fjord conditions during the 2010 winter, a winter in which the ice mélange exhibited two episodes of mid-winter retreat. Figure 10 illustrates the winter 2010 transect (left) and SST maps (middle) of the region for December 5, December 24, and January 26. The corresponding time-lapse photographs from SUSE are provided along the right column. The ice mélange consolidated in early November (dark blue SST values < -20°C in the transect) and extended all the way to the outer fjord (-51°E). By early December (e.g. December 5 images) the cold, consolidated mélange front began a gradual retreat that resulted in 3 calving events on December 18, 22, and 27th (white lines along right margin of SST transect). By then the still ice-covered fjord appeared much warmer in SST images and started to disaggregate based on open water that appeared in both the thermal data and the time-lapse imagery from December 24 and the enhanced mobility of the ice mélange as seen in time-lapse images. The fjord ice surface cools again in January but the mélange did not get as cold, nor did it extend as far downfjord (e.g. January 26th) as it previously had in November. These three examples of observed coincident change between the thermal record and the time-lapse imagery help to validate the use of the MODIS SST record for monitoring changing ice conditions in the fjord.

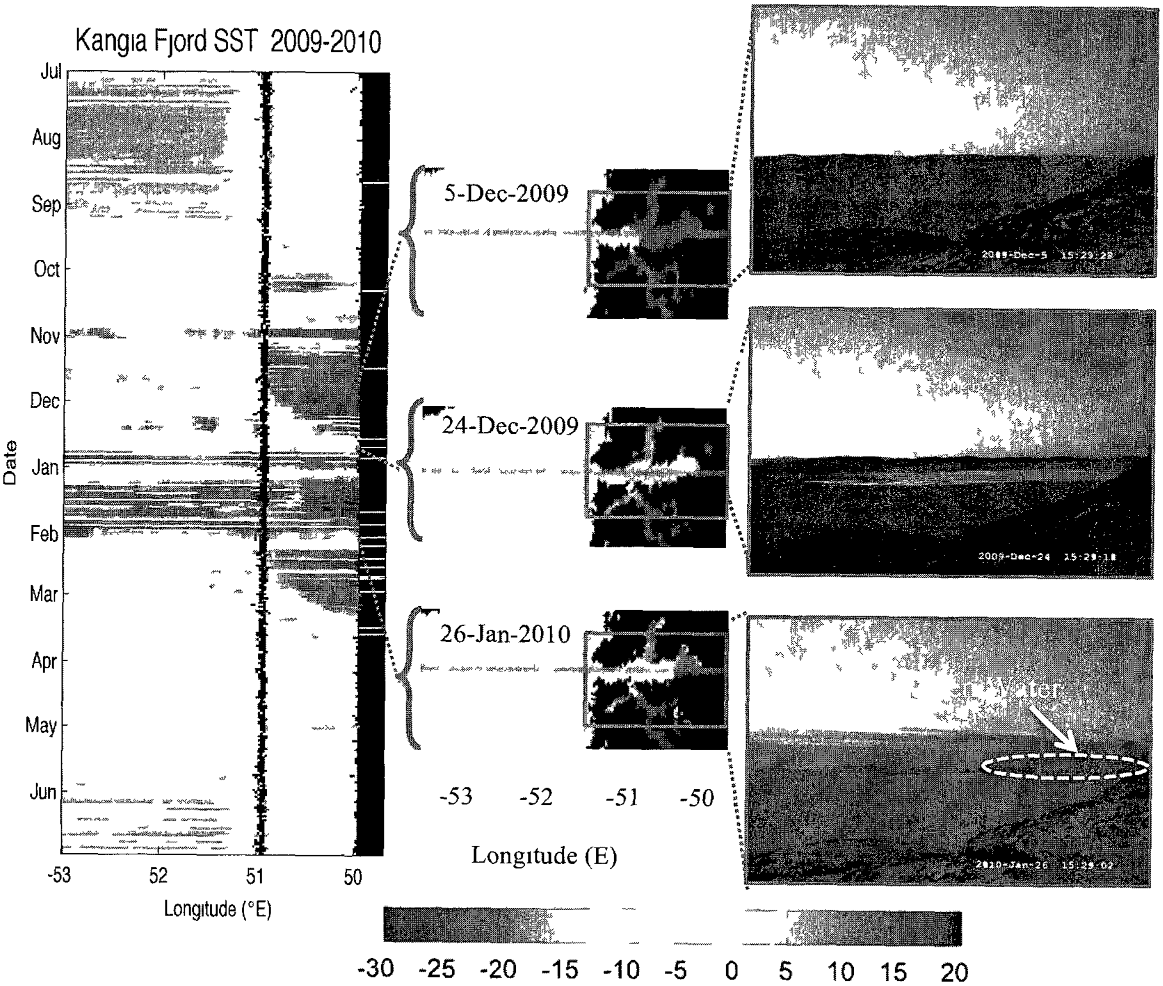

Figure 10: (Left) 2009 – 2010 SST profile along a longitudinal transect in Kangia Fjord. Fjord ice is present for most of the winter although the winter ice mélange is pushed back on at least two separate occasions mid-winter. (Middle) Subsets of the SST maps used with the longitudinal profile extracted to generate the transect. Mid-winter warming of the inner fjord is evident as cold surface temps (blue) give way to warmer open water (yellow) mid-winter. (Right) SUSE time-lapse images corresponding with the respective MODIS thermal images. Open water is evident in both the December 24, 2009 thermal and camera images.

Figure 11 compares observations from the full winter 2010 time-lapse record against the SST transect. Five regions within the viewing angle of each SUSE image were categorized manually by eye as having unconsolidated (mobile) ice (green triangles), consolidated ice (blue plus signs), or open water (red circles) These observations are superimposed on the winter 2010 SST transect (shown in Figure 11 with a copper color tone) and demonstrate that mélange mobility and temperature in the SST record are related The cold mélange appeared more consolidated and exhibited less mobility (displacement between images) in the time-lapse record as a result of increased structural rigidity Similarly, fjord ice cover varies between unconsolidated ice and open water when SST values are warmer The coincident change observed in both records

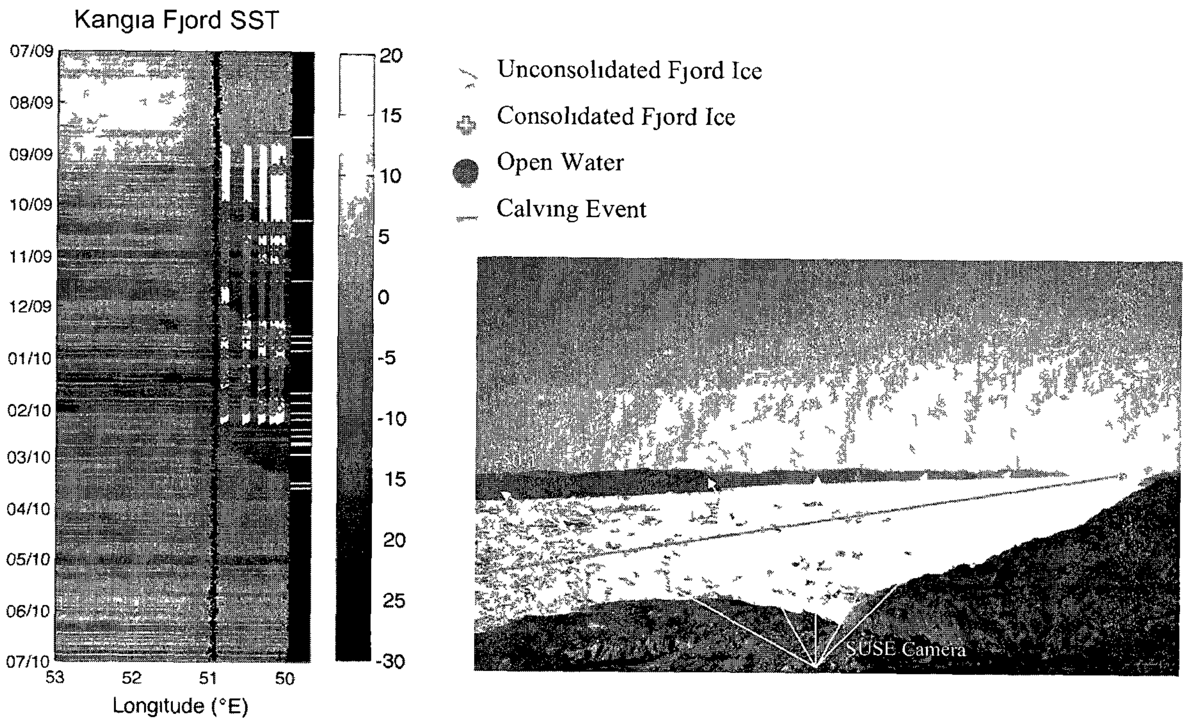

Figure 11: (Left) SUSE time-lapse observations of open water, unconsolidated, and consolidated fjord ice superimposed on a copper color mapped SST transect. Consolidated ice corresponds to the coldest part of the SST transect, while unconsolidated ice and open water appear during SST warming events. Units are degrees Centigrade. (Right) Photograph from SUSE depicting locations of time-lapse observations. Red line represents the location of the SST transect. Yellow numbers indicate the approximate geographic location (degrees of longitude) of the bedrock landmarks in the photograph.

suggests that MODIS thermal SST data can be used as a proxy for winter fjord ice conditions in Kangia Fjord. Furthermore, the onset of calving following mélange mobilization during the 2010 winter suggests that mélange conditions can affect winter calving activity.

3.5 Evaluating Coincident Change: '*The Degree Day Variable*'

A variable based on the SST record was created to quantify the 'rigidity' of the mélange or the amount by which the SST record showed cooling over the fjord, which as was demonstrated above, corresponds to times when the time-lapse imagery shows consolidated ice conditions. During periods when the fjord ice cover is consolidated, its surface will cool to reflect air temperatures in the fjord. Long cold periods in the SST record reflect extended periods of consolidated ice cover. It should be noted that the use of the term degree-day for this variable is starkly different than the traditional use in climatological estimates, though the variables are conceptually similar.

Herein, the '*cumulative degree day*' variable is defined as the sum of the difference between the temperature in each pixel and the minimum temperature in the record. The accumulation of ice-cover degree-days was summed over the region of the inner fjord between 50° and 50.5°W for each winter (October 1 – March 31) in the MODIS record. Mathematically it is defined as $dd = \sum_{Apr}^{Oct}[\sum_{50^{\circ}W}^{50.5^{\circ}W}(SSTpixel - Tmin)]$, where SST_{pixel} is the SST product value in each pixel and T_{min} is the minimum SST value in the record. A high number of cumulative degree-days indicate winters with sustained warm surface conditions and unconsolidated fjord ice, and thus represents winters with a weaker, less rigid mélange. The 'cumulative degree-day' formula serves to highlight the sustained occurrence of these warm conditions.

4 Results – Jakobshavn Isbrae and Kangia Fjord

4.1 Kangia Fjord Ice Conditions

As a result of recent change at Jakobshavn Isbrae, the glacier has two termini, both of which calve ice into Kangia Fjord ~60 km east of Disko Bay. Conditions in the fjord vary in space (Figure 12) and time (Figure 13). Spatially, conditions in the middle to outer fjord vary between unconsolidated fjord ice cover and open water, while conditions in the near-terminus region fluctuate seasonally between a consolidated and an unconsolidated ice mélange.

Fjord conditions are highly variable in time, with changes ranging from days to weeks. Generalizations about '*typical*' fjord conditions are made using the 11-year daily mean transect of SST values (Figure 13). The transect extends from the inner fjord (-50°E) west into Disko Bay (-51.2 to -53°E). During the summer, SST product values

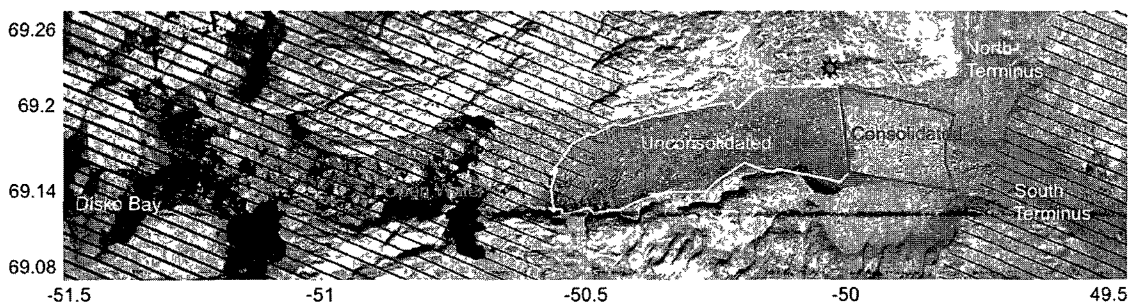

Figure 12: Landsat 7 panchromatic band image of Kangia Fjord from April 8, 2009 demonstrating the spatial variability of ice conditions in the pro-glacial fjord. This image shows a consolidated mélange nearest the terminus, an unconsolidated mélange in the middle part of the fjord, and a mix of open water, icebergs, and sea ice nearest the fjord mouth. Disko Bay, furthest west, had a mix of open water and fragmented sea ice.

approach +8°C in Disko Bay (51.5 → 53°W), while values in Kangia Fjord (50 → 51°W) are cooler and range from -5 → +1°C depending on ice cover. SST values decrease in Autumn and by winter, sea ice appears sporadically in Disko Bay SST (-15° → -10°C)

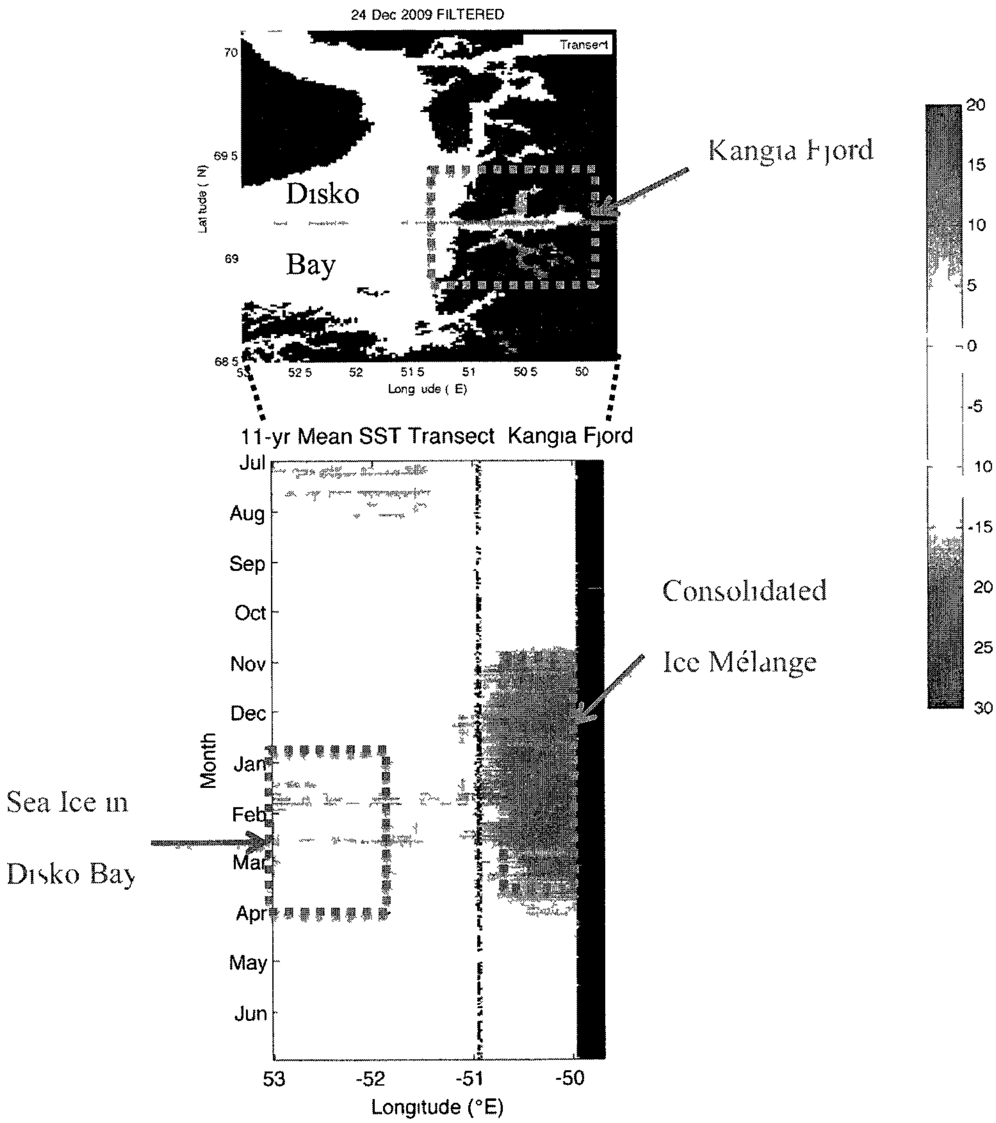

Figure 13: (Top) Thermal SST map of Kangia Fjord and Disko Bay from December 24, 2009. The magenta line through 69.2°N represents the location of the SST transect used to create the (Bottom) 11-year mean transect of fjord SST values over time. The transect begins in the inner fjord (to the right, at-50°E) and extends west (left) into Disko Bay (boundary ~ -51°E). Units for both figures are in degrees Centigrade.

To the east, a mix of icebergs, brash ice, and surface water in the mid to inner fjord freezes and consolidates and the cold SST values ($\leq$-20°C) reflect the cold surface of the fjord ice and the boundary layer with the atmosphere directly above the fjord surface. This now rigid mélange of consolidated ice persists through the winter until late March or early April when surface temperatures warm, and the mélange destabilizes.

4.2 Winter 2010: A Case Study

The winter with sudden, unexpected change

The pattern of rapid change at Jakobshavn Isbrae exceeded a new threshold during the 2010 winter (Nov. 2009 – March 2010) when the terminus failed to re-advance (e.g. Figure 14– left column). This sudden change followed multiple years of large (~ 5km) annual seasonal re-advance of the calving front; 2010 exhibited the smallest winter re-advance (~1.25 km) since the final disintegration of the floating tongue in 2003. The collapse of the floating tongue has been implicated as a mechanism for some of the changes in the terminus region including velocity increase [*Joughin et al.*, 2004] and thinning of the terminus region [*Krabill*, 2004]. The breakup was initiated in 1997 and coincides with the influx of warm subsurface waters into Disko Bay [*Holland et al.*, 2008]. The oceanographic link to changes at the terminus motivated efforts to create a proxy for fjord conditions based on the MODIS thermal SST record to analyze fjord conditions during the 2010 winter. Repeated patterns of seasonal ice mélange modulation, changes in mélange mobility, and calving events soon emerged from the records.

4.2.1 Winter 2009 versus Winter 2010

4.2.1.1 Characteristic Differences between Winter Mélanges

The winter mélanges of 2009 and 2010 exhibited two very different characteristics (Figure 14 – middle column). The ice mélange remained as a cohesive unit throughout the entire 2009 winter (top – middle); it held steadfast in the inner fjord for nearly 5 months. The mélange first consolidated in early November 2008 and did not break up until the spring thaw in late March 2009. Despite apparent mélange warm-up events in the SST record in January and February, the ice mélange boundary is clearly delineated throughout the thermal record (east to west gradient in fjord SST values), showing that the mélange remained intact for the entire the winter. Time-lapse observations (not included here) confirm an immobile ice mélange during the 2009 winter.

Contrasting with the quiescent winter activity of 2009 in the inner fjord was a warmer and more mobile ice mélange in the 2010 winter. Two mid-winter breakup events occurred: one in December 2009, and one in January 2010, before the final breakup in early March. Each breakup event depicts a unique characteristic retreat of the mélange front. Frequent days of warmer mélange SST values and thus surface temperatures suggests the mélange did not get as cold, and therefore was not as rigid, during the warmer mid-February reconsolidation as it was in November 2009, January 2010, and the entire 2009 winter. In total, the consolidated mélange occupied the inner fjord for ~3.5 months during the 2010 winter, and did not extend as far downfjord as the consolidated ice did in the 2009 season.

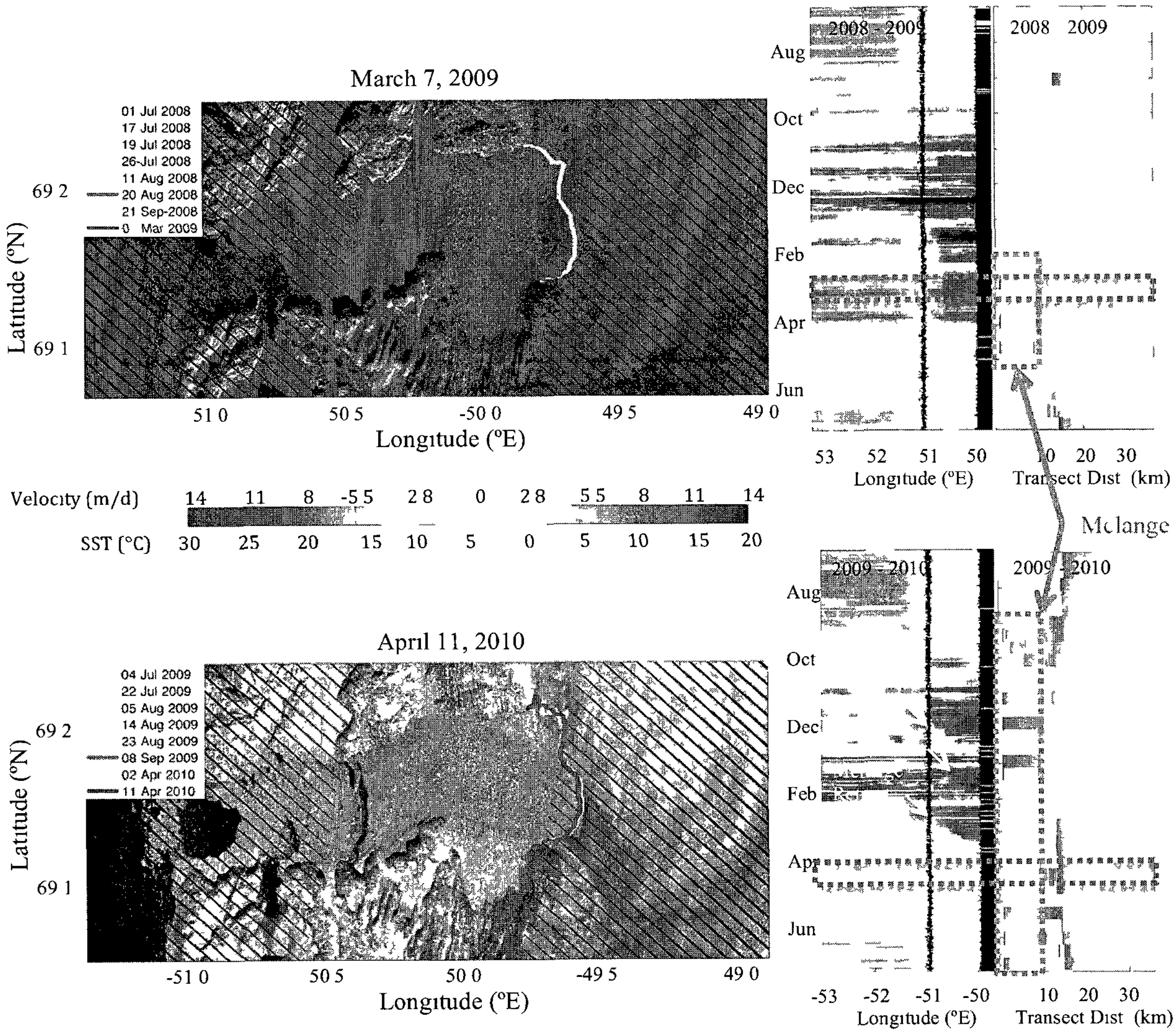

Figure 14: Glacier and fjord conditions for Winter 2009 (top) and 2010 (bottom). Datasets span from July of one year to June of the next. Top Row: (Left) Jakobshavn Isbrae terminus positions superimposed on March 7, 2009 Landsat 7 scene; (Middle) surface temperature transect for winter 2009, white lines along right margin indicate seismically detected calving events; (Right) Velocity anomalies from TerraSAR-X along flow-line for winter 2009 (Joughin, personal communication). Bottom Row: similar figures but for Winter 2010. Colorbar units are meters/day for velocity and degrees Celsius for SST values.

4.2.1.2 *Mélange influence on Winter Calving and Terminus Position*

Coincident with changes in winter ice mélange conditions within Kangia Fjord are changes along Jakobshavn Isbrae's calving front. Calving frequency during the 2009 winter was much lower than in 2010. No seismically detected calving events (white lines along right margin of SST transects – middle column of Figure 14) were reported during the 5 months the cold, stiff ice mélange occupied the inner fjord during the 2009 winter. The last reported calving event in 2008 occurred on September 13; calving ceased for 210 days, and began again on April 11, 2009 following a disaggregation of the consolidated ice mélange that had been present all winter. In stark contrast, a total of 16 seismically detected calving events occurred over the 2010 Winter (October 2009 through March 2010). This is a significant departure from the calving hiatus that is more typical of prior winter behavior in Kangia Fjord (e.g. [*Amundson et al.*, 2008; *Joughin et al.*, 2008], and this study Figure 19). This inverse relationship between winter calving frequency and the spatial extent and temporal duration of the consolidated mélange suggests the two phenomena are related. Glaciers that experience winters with a persistently cold and consolidated ice mélange in the pro-glacial fjord may well experience fewer calving events.

The timing of the winter 2010 calving events, coincident with a retreat of the mélange front, further suggests some sort of mélange control over winter calving. Three calving events occurred in late December 2009 (18^{th}, 22^{nd}, 27^{th}), each following the gradual retreat of the consolidated ice mélange. No calving events were reported in early January when the mélange reconsolidated, but calving resumes on January 21, concurrent with an increase in SST values, mélange mobility (Figure 11) and a retreat of the mélange front (Figure 14 – middle column, bottom row). The ice-covered fjord in mid-February was not as cold in the SST record as the consolidated ice in November and January, and likely lacked the structural rigidity to inhibit calving, thus permitting a series of calving events through March 19. This repeated pattern of changes in mélange stability that leads to mid-winter calving events implies that a cold, consolidated winter mélange has the structural rigidity to inhibit calving along the terminus.

In a Lagrangian reference frame, the location of the glacier terminus is governed by the interaction between glacier flow (ice flux in) and ice loss at the calving front due to calving processes (ice flux out). During most winters calving is minimized and glacier flow dominates the terminus regime, resulting in an advance of the calving front downfjord. For tidewater glaciers with terminus regions that are at or near floatation, such as Jakobshavn Isbrae, a floating tongue develops and advects downfjord. The glacier exhibited this type of behavior during the 2009 winter as it had in most prior years. The cold, rigid mélange inhibited calving, which kept the terminus region intact and allowed the calving front to re-advance more than 5 km from the minimum fall position (Figure 14 – top row, left column). Conversely, the instability of the 2010 winter mélange permitted several mid-winter calving events, which limited the winter re-advance to 1.25 km (mean position advance, Figure 14 and Figure 20a). These findings support the results of [*Amundson et al.*, 2010] who demonstrated that the mélange does not strongly influence the force balance at the calving front, but does prevent ice blocks from rolling over, allowing a seasonal floating tongue to develop and thus affecting the seasonality of the terminus position.

4.2.1.3 *Mélange Influence on Terminus Velocity*

Velocity anomaly transects for the winters of 2009 and 2010 (Figure 14– right column) reveal two very different stories for the glacier and ice mélange in adjacent winters. During winter 2009, InSAR measurements showed little to no observed change in the surface velocity between the mélange and the main glacier trunk. This suggests the glacier was pushing a consolidated and relatively strong mélange downfjord for the bulk of the winter. By early April temperatures started to warm and the mélange began to destabilize; becoming too mobile to remain coherent and trackable by InSAR. There was too much differential displacement in the pro-glacial fjord within the 11-day satellite pass interval to track the speckle or features; thus velocity was not measurable for the mélange in early April 2009. The mélange consolidated enough between calving events in mid-April to be briefly tracked by InSAR before it destabilized again and remained unconsolidated for the remainder of the spring; in this state the glacier shows an increase in near-terminus velocities. This velocity increase propagates up glacier throughout the summer until the ice mélange begins to gain structure in September.

Surface velocities begin to slow as Winter 2010 approaches. This slow-down coincides with the stiffening and consolidation of the mélange as shown by lower SST values and coherent velocity measurements from the TerraSAR-X data. However, the mélange retreat and subsequent calving events in late December 2009 result in increased near-terminus velocities. The mélange again consolidates in January, calving ceases, and velocities slow. A second mélange retreat in late January leads to more calving and consequently faster near-terminus velocities. The weakened February mélange does not keep the fragmented terminus from calving and icebergs from overturning. The net result of the 2010 winter is increased calving at the terminus leading to surface velocity increases up to 4.5 meters per day faster than in 2009; which further enhanced dynamic thinning.

4.2.2 Atmospheric Conditions and Weakening of the Ice Pack

Atmospheric conditions can affect the stability of the ice mélange; warm (> 0°C) air temperatures (AT) that persist for multiple days may warm and destabilize the ice pack. Evidence of such mélange warming events is seen in Figure 15. There were three multi-day warm-up events during the 2009 winter: air temperatures in Ilulissat reached a maximum +7.5°C between November 30 and December 2; +2.9°C between December 31 and January 2; and +3.9°C between February 3rd and the 9th. All other atmospheric warming episodes (AT > 0°C) that winter were less than 1 day in length and 3.3°C in temperature. Warmer (0°C< AT <+5°C) air temperatures were reported in late April 2009 but daily low AT did not regularly exceed 0°C until mid-May. By comparison, three strong multi-day warm-up events occurred during the 2010 winter following the November consolidation of the mélange ice: AT reached +10.9°C between December 11 and 16, +8.3°C between December 29 and January 2, and +8.3°C again for 10 days between January 27 and February 5, 2010. A smaller (~1.5 days in length) fourth event occurred on March 27 with AT that reached 3.3°C. Concurrent with extended periods of warm mid-winter air temperatures were mélange surface warming events shown in the SST data in both years (Figure 15) with mélange warming coinciding with or lagging the increase in air temperatures. There were no observations of mélange warming preceding the air temperature increase. Although episodes of atmospheric warming appeared to

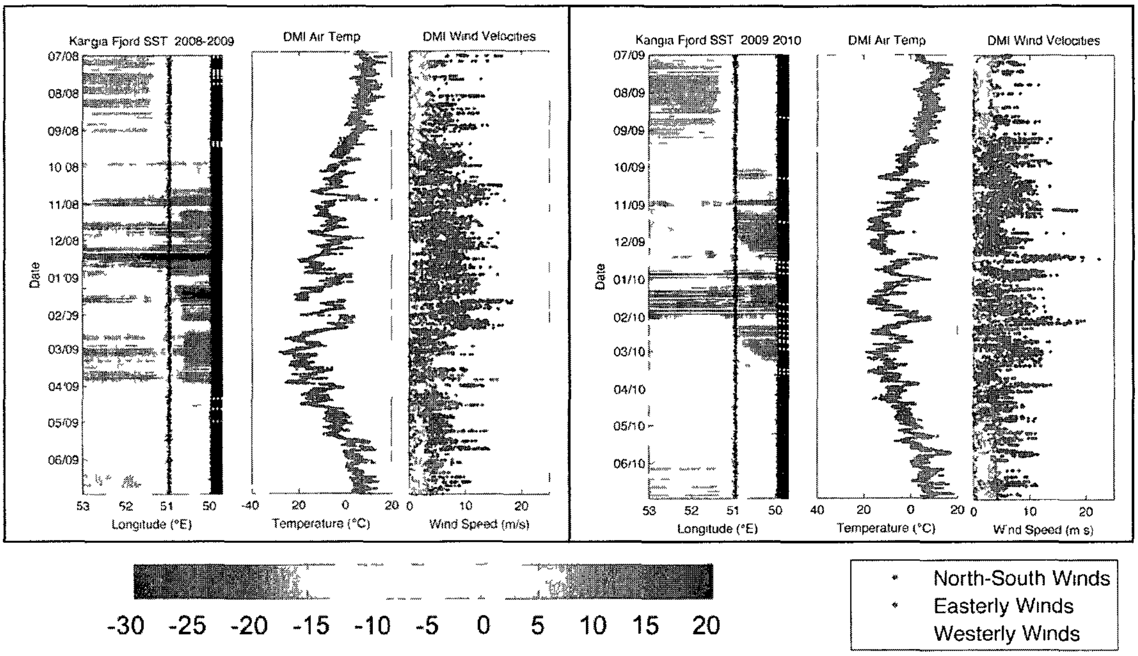

Figure 15: Differences in Atmospheric Conditions in Kangia Fjord for the Winters of 2009 and 2010. (Left) Cold air temperatures contributed to the cold, rigid mélange that occupied the inner fjord for much of the 2009 winter. Intervals of above freezing temperatures are generally less than 4°C and are brief in time. (Right) Extended periods of warm air temperatures coincide with high velocity easterly winds and mélange instability during the 2010 winter. The colorbar refers to SST in the transect and units are in °C. The colors in the wind profiles refer to the wind direction.

have affected the ice mélange SST values in both years (Figure 15), the 2010 winter ice mélange exhibited a stronger response.

Two of the warm-up events (mid-December 2009 and late-January 2010) that led to mélange destabilization and subsequent calving were looked at more closely (Figure 16); a third destabilization event in early November 2009 that did not result in calving was also investigated. Coincident with the episodic warming in December and January were anomalously high easterly winds (19.4 and 19.8 m/s, respectively) that likely pushed the newly unstable ice mélange west, away from the terminus, and thus reduced backpressure at the calving front. The sequence of events surrounding the December warm-up supports this assertion. In early December, the mélange front that had extended out to 51°W started a slow retreat and by December 9th the mélange begins to show surface warming. A large temperature increase (-12.0°C to +4.7°C) on December 11 further destabilizes the mélange as high velocity (up to 19.4 m/s) winds blow in from the east. The sustained pattern of warm air temperatures and high easterly (downfjord) winds persists for 5 days and pushes disaggregated pieces of the mélange west towards Disko Bay; this results in a variable SST record coincident with warm AT and high winds. This apparent noise reflects the surface temperature of a highly mobile fjord that is comprised of fragmented mélange ice and open water. The inherent lag in response time of the mélange to the changing atmospheric conditions allows the mélange to adjust and deform even while air temperatures decrease to slightly below freezing and winds return to normal ambient velocities. This lagged response and continued relaxation of the mélange lead to a series of calving events that begin on December 18. Time-lapse images from late December demonstrate the lagged response of the mélange as more ice displacement preceded the December 18th calving event than the calving events on December 22 and 27th.

Observations from late January 2010 exhibited a similar mélange response to atmospheric changes. Following the late December 2009 warm-up, air temperatures decreased below 0°C and the mélange re-consolidated; the mélange front now positioned at approximately 50.5°W. Despite low air temperatures in early January, a single calving event occurred on January 21, while the mélange front maintained its position at ~50.5°W. Over the next few days, the mélange front began another gradual retreat. On

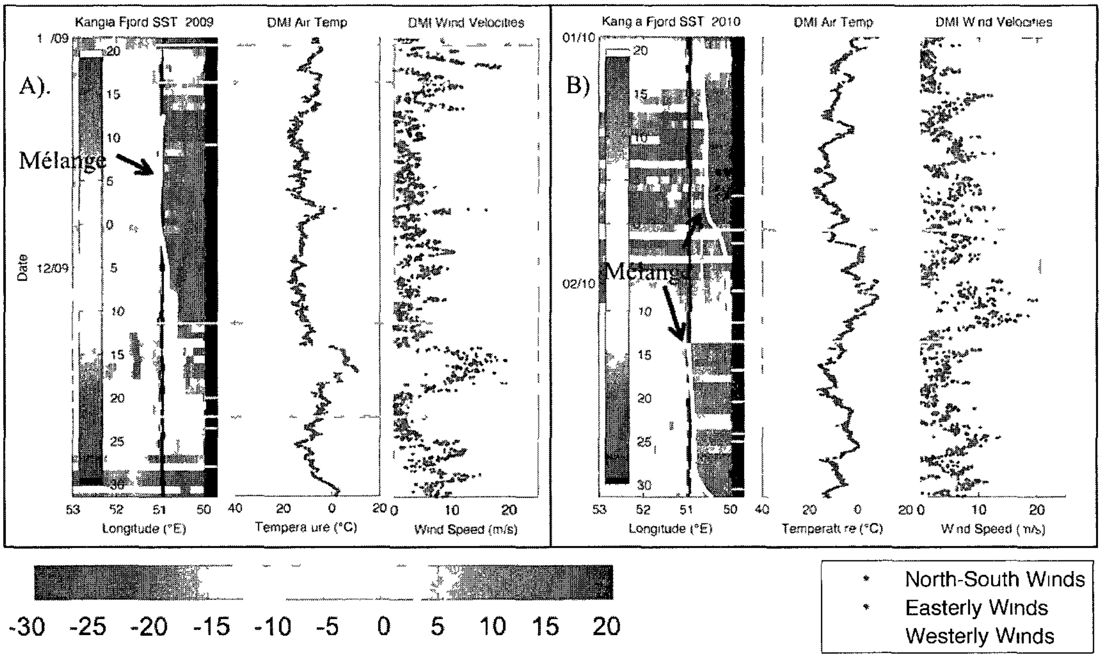

Figure 16: Kangia Fjord surface temperatures and meteorological data at Ilulissat Airport for (A) Nov/Dec 2009 and (B) Jan/Feb 2010. (A-Left) Surface temperature transect illustrates the consolidation of the ice mélange in mid-November followed by retreat of the mélange front and 3 subsequent calving events in late December 2009. Warm air temperatures (A-Middle) and high wind velocities (A-Right) in the region at this time likely weakened the mélange and forced it away from the terminus, easing the backpressure at the terminus, contributing to a series of calving events in December. (B-Left) After reconsolidating briefly in mid-January, the mélange retreats again as air temperatures approach +10°C (B-middle) and high easterly winds (B-Right) again blow the now unconsolidated ice out towards Disko Bay, leading to a second series of mid-winter calving events in February 2010.

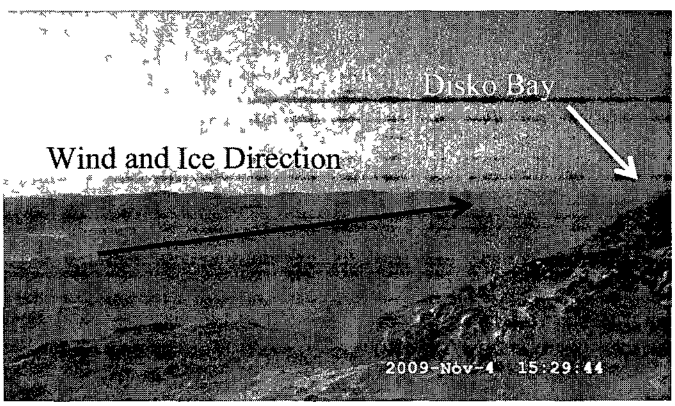

Figure 17: Mélange breakup event. High velocity (~18 m/s) easterly winds destabilized the ice mélange front and pushed it downfjord towards Disko Bay.

January 26, air temperatures increased sharply (-12.2°C to +2.8°C) as the wind shifted easterly and increased in velocity. A second calving event was detected on January 27th as the mélange front continued to deteriorate. Air temperatures cooled briefly before a 6-day warming streak prohibited the mélange from consolidating. Two more calving events occurred on February 2nd and 6th that likely resulted from warm air temperatures and decreased mélange rigidity. Air temperatures decreased below freezing but were still moderately warm (AT > -8°C) for several days, prohibiting the mélange from fully re-consolidating, and calving continued throughout the remainder of the winter.

One example of mélange mobility that did not result in calving occurred in early November 2009 (Figure 16a – top orange box). The thermal SST record indicates a warming event of the mélange surface in early November 2009. Air temperatures in the region were cold and varied between -4° and -14°C. The wind turned easterly on November 4 and peaked at 18.4 m/s. Despite cold air temperatures, the high velocity winds destabilized the mélange front and pushed the previously consolidated ice downfjord. Time-lapse images confirm the fjord was highly mobile and the strong winds as shown by snow visibly blowing from the tops of icebergs and along the bedrock (Figure 17). The mélange warming illustrated in the SST transect (Figure 16a) reflects the surface temperature of a mobile fjord mixed with unconsolidated ice, icebergs, and open water that was measured with 1-km spatial resolution. Despite the destabilization of the ice mélange, no calving-induced seismic events were reported. This may be due to the subzero temperatures in region at the time. The mélange is thickest directly in front of the glacier, 15 km behind (west) the camera, and thins downfjord. The lack of warm air temperatures (>0°C) may have helped keep the mélange in the immediate pro-glacial fjord intact such that high velocity winds did not have an impact on the mélange further upfjord. The TerraSAR-X data (Figure 14) show a stable mélange directly in front of the terminus that likely inhibited calving at that time.

The observations presented here provide evidence for atmospheric influence on ice mélange dynamics with consequences along the calving front. Large mid-winter air temperature increases that evolve into multi-day warming (AT > 0°C) periods can warm the surface of the mélange and subsequently reduce mélange rigidity. When warm air temperatures are persistent and coupled with highly directional winds that force the mélange away from the calving front, the loss of backpressure formerly imposed by the rigid mélange often result in calving at the terminus.

4.2.2.1 *Summary of Winter 2009 and 2010 Findings*

Changes in surface conditions observed in Kangia Fjord between the 2009 and 2010 winters suggest a strong correlation between the pro-glacial ice mélange and changes along the calving front. During the 2009 winter, the ice mélange remained cold in the SST data and held fast in the inner fjord for more than 5 months; calving ceased, and the terminus advected a floating tongue more than 5 km downfjord. In contrast, the 2010 winter ice mélange was plagued by repeated periods of instability, which resulted in at least 16 mid-winter calving events that ultimately limited the winter re-advance of the terminus. Sudden increases in air temperature coupled with high velocity winds destabilized the ice mélange in the pro-glacial fjord. This reduced mélange rigidity and the subsequent loss of backpressure at the terminus contributed to several mid-winter calving events that prohibited the development of a floating tongue. The loss of backpressure also failed to reduce longitudinal stress within the glacier, which then led to faster winter velocities at the terminus. These changes resulted in a significant departure from normal springtime conditions at Jakobshavn Isbrae; the calving terminus at the end of the Winter was located further back in the fjord than in other years and the glacier was thinner and faster in the terminus region. The implications of these findings are that mid-winter atmospheric changes, namely warm air temperatures and high wind events, can alter the behavior of a glacier terminus by initiating a sequence of events with multiple feedback loops (see Figure 22 in section 4.4).

This case study of winter observations in Kangia Fjord and at the terminus of Jakobshavn Isbrae demonstrates the types of influence a winter mélange can have on an outlet glacier system. Though the focus here was on the seasonal changes within the fjord and along the glacier, the consequences of failed winter re-advances can have long-lasting effects on glacier behavior. A thinning at the grounding line brings an outlet glacier closer to flotation, which accelerates flow there and thus drives a retreat of the groundling line, propagating the pattern of tidewater outlet glacier retreat.

4.3 Winters 2000 - 2011

The history of Jakobshavn Isbrae's calving terminus was expanded to include observations dating back to 2000 was and extended forward through June 2011 to document the continued evolution of this rapidly changing glacier. Over the last decade the front has showed regular seasonal variability, disrupted in some years by anomalously small winter re-advances. The terminus modulations were compared against winter mélange conditions for evidence of coincident change to see how generally applicable the results of the last section are.

4.3.1 Terminus Changes

Jakobshavn Isbrae's terminus position has exhibited seasonal variability while undergoing a ~15 km retreat since 2000 (Figure 18). During most winters the terminus advanced ~ 5km downfjord (Figure 18: more positive mean position) before calving initiated in late spring, was active throughout the summer, and ceased during the fall and winter. These results are consistent with previous studies which showed increased spring time calving rates leading to the loss of a winter-developed floating tongue [*Amundson et al.*, 2008; 2010; *Joughin et al.*, 2008]. The Landsat record (Figure 18) illustrates more limited re-advances during winters of 2003, 2005, 2006, 2010, and 2011. Figure 20a emphasizes these small winter advances by graphing the difference between the minimum fall position (annual maximum retreat) and the maximum spring position (annual maximum advance) available in the Landsat record. The terminus experienced a retreat of 190 meters over the 2003 winter, coincident with final break-up of the floating tongue. The winters of 2005 and 2006 showed 2.05 and 2.38 km of advance, while 2010

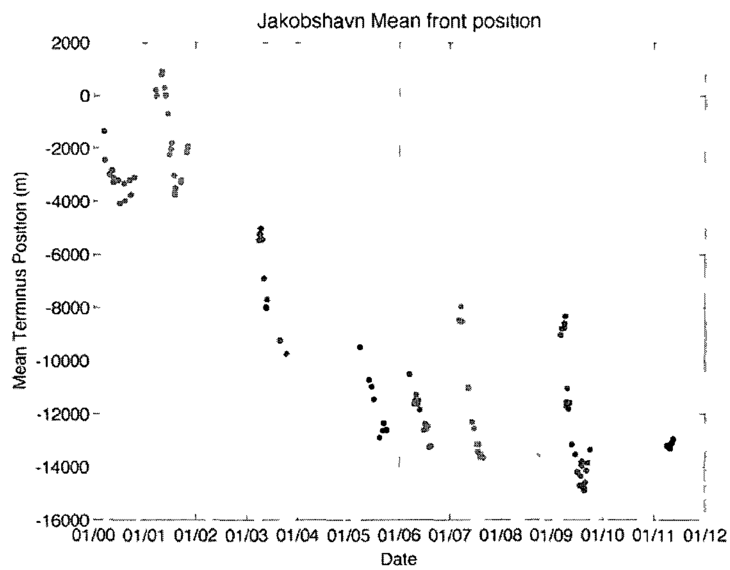

Figure 18: Landsat 7 derived terminus history of Jakobshavn Isbrae

and 2011 showed advances of 1.25 and 1.85 km, respectively, all less than half the advances observed in the remaining years.

To put these changes into historical context, Jakobshavn Isbrae retreated approximately 20 km in the 100 years following the end of the Little Ice Age [*Sohn et al.*, 1998; *Weidick*, 1995]. The front remained relatively stable for the remainder of the 20th century, annually modulating 2.5 km around a quasi-stable position [*Csatho et al.*, 2011; *Sohn et al.*, 1998], before the recent mode of retreat shown in Figure 18 was initiated.

4.3.2 Winter Variability in Mélange Fjord Ice

A time series of SST product values (Figure 19) illustrates the annual variability in ice mélange conditions. The delineation between the cold ice mélange in the inner fjord (50 - 51°W) and the warmer surface temperatures of the outer fjord and Disko Bay (west of 51°W) is apparent for most years. The winters of 2001, 2002, 2004, 2006, 2007, 2008, and 2009 all have a clearly defined front (boundary) between the cold consolidated mélange and the warmer unconsolidated ice and surface water in the outer fjord that persists though most of the winter; although the 2006 winter consolidation is short in duration, consolidating later in the winter and breaking up earlier in the spring. In contrast, the SST records of the mélange lack an enduring, pronounced front during the winters of 2003, 2010, and 2011, and show several mid-winter breakups. The winter mélange of 2005 was more typical for the record, although overall it showed warmer surface temperatures and did not extend as far downfjord as the other years in the record.

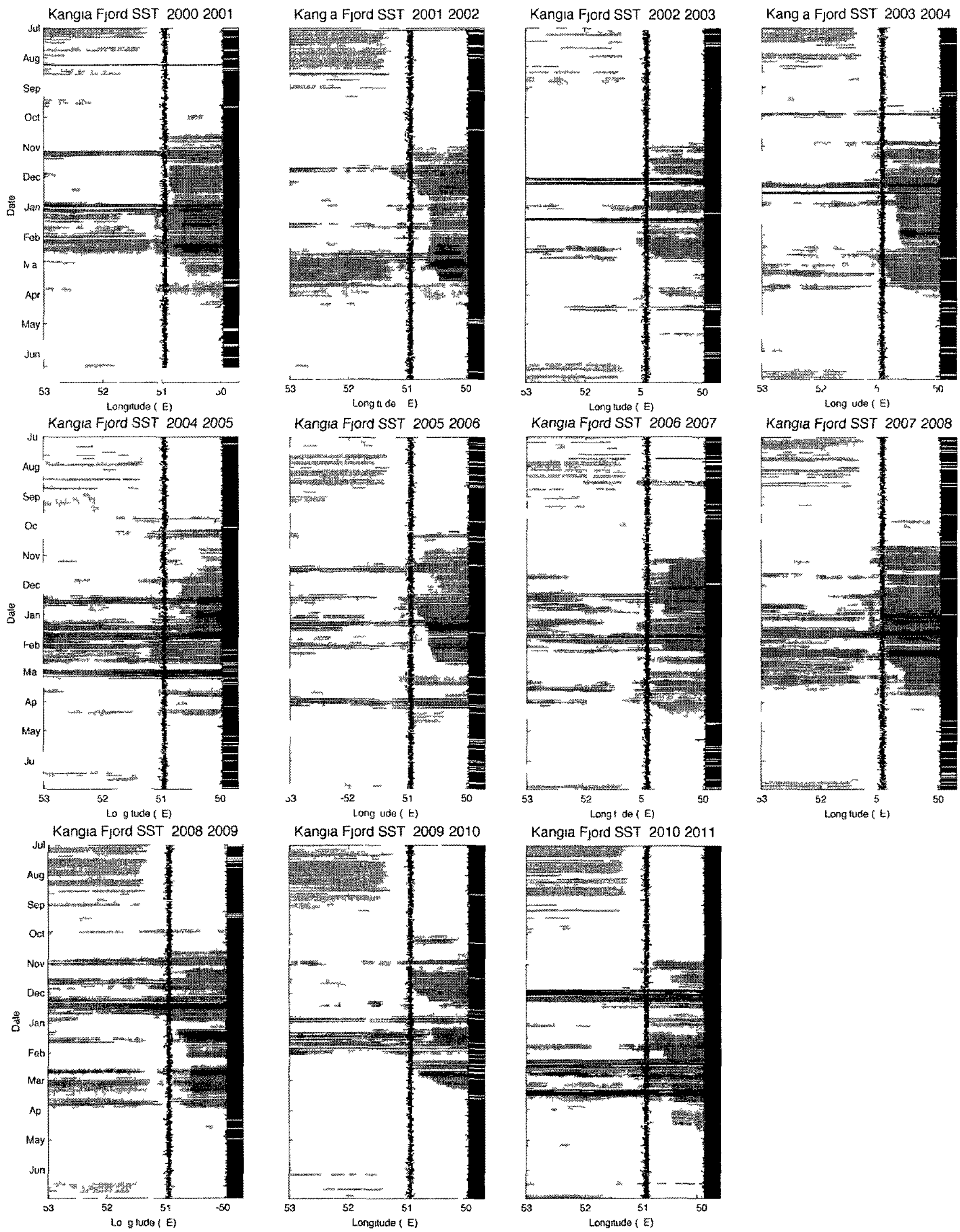

Figure 19: Time-series of Kangia Fjord surface temperatures centered on winter months. Y-axis is time. X-axis is longitudinal profile as depicted in Figure 10. White lines along right black margin denote seismically induced calving events.

4.3.3 Mélange Influence on Calving and Seasonal Terminus Position

Section 4.2.1 showed how a cold, rigid ice mélange during the 2009 winter corresponded with inhibited calving, and glacier advance. Observations made from Landsat, MODIS, and the calving-induced seismic records over the last decade further this phenomenon. There are far fewer calving events along Jakobshavn Isbrae's terminus during winters in which a cold, stable ice mélange occupies the inner portion of Kangia Fjord (Figure 19). The bulk of the calving occurs during the summer months when the ice mélange is warm, unconsolidated, and therefore less rigid. Likewise, during winters in which calving events were recorded, they coincided with warming and a destabilization of the mélange surface (Figure 19).

By inhibiting calving, a cold, stable, and rigid ice mélange should keep the terminus region intact and promote seasonal advance of the calving front. The bar graphs in Figure 20a demonstrate this inverse relationship between winter calving and terminus advance. Winters with small terminus advance had the highest number of winter calving events (2005, 2006, 2010), while the glacier terminus exhibited the largest re-advances during winters with few, if any, calving events. The 2003 winter was the sole exception; the glacier terminus experienced a net retreat and the seismic data suggests only one calving event occurred (Note: the calving-induced seismic record only includes data up through March 2010). This discrepancy can be explained by a difference in calving styles at the time. The final disintegration of Jakobshavn's floating tongue occurred in March 2003 [*Joughin et al.*, 2004]. Icebergs calved from a floating tongue are in general much larger and more tabular than icebergs calved from a grounded terminus [*Amundson et al.*, 2008; *Joughin et al.*, 2008]. As such, they drift away from the terminus largely intact and do not immediately roll as unbalanced icebergs do from a grounded front [*Amundson et al.*, 2010]. Thus more ice would be calved from the tongue but with minimal iceberg overturning and associated seismicity [*Amundson et al.*, 2008]. These observations demonstrate the control that mid-winter calving events have over the seasonal re-advance of the glacier terminus.

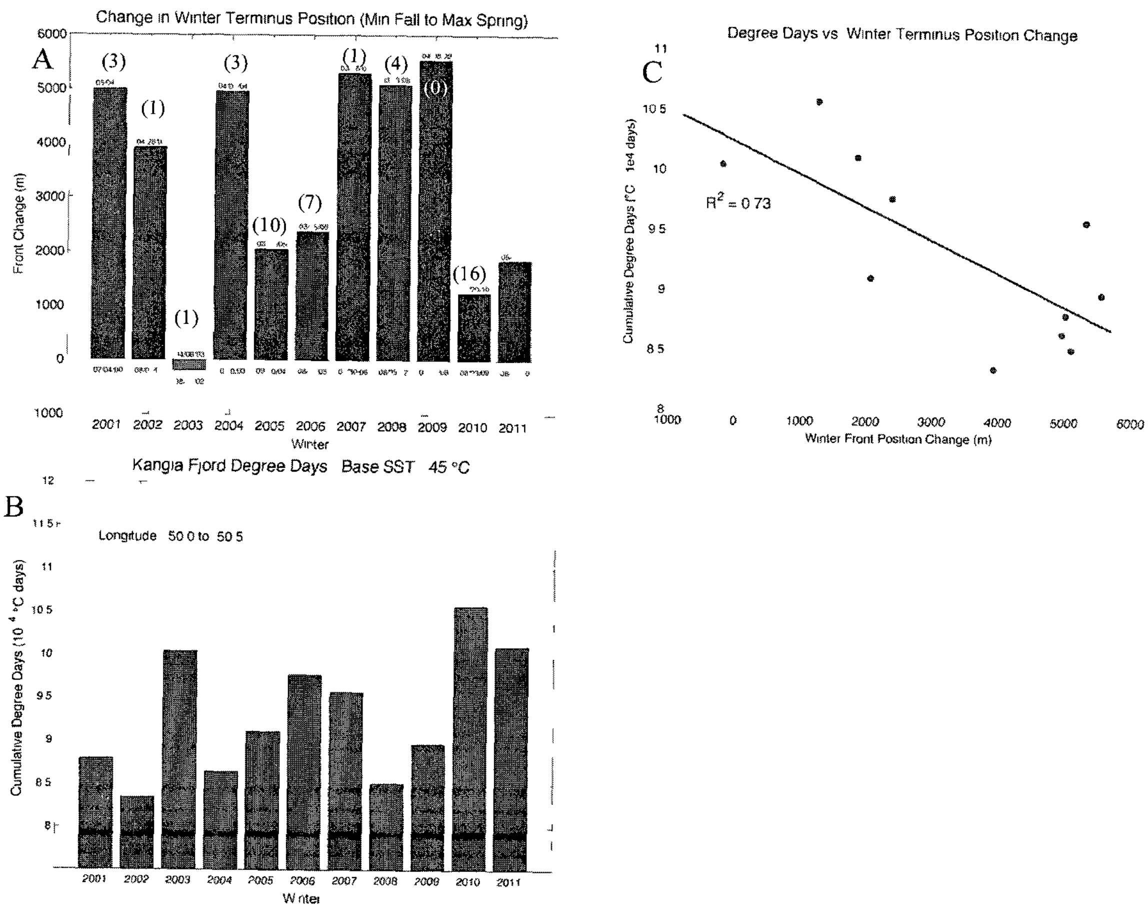

Figure 20: Counterclockwise from the top left: (A) Change in mean winter terminus position. The numbers in parentheses denote the number of winter calving events (October – March). (B) Cumulative SST "degree-days" each year between Oct 1 and March 31. (C) Linear Regression between cumulative "degree-days" and change in mean position at the glacier front.

To summarize briefly, a cold, stable winter ice mélange can inhibit calving, which keeps the terminus region intact and allows a floating tongue to develop and advect downfjord; producing the seasonal re-advance of the glacier terminus. At Kangia Fjord, where a seismic calving record is available, a direct connection was demonstrated between calving, SST-derived fjord ice conditions, and terminus advance. A comprehensive calving record is not available for the other glacier fjord systems in this study; thus a comparison was made between the MODIS SST record and the seasonal re-advance of the glacier terminus to demonstrate how this proxy for ice mélange variability can be related to the winter re-advance. Changes in fjord ice conditions in Kangia Fjord coincided with variability in the seasonal readvance of the glacier terminus (Figure 20). Years with small winter terminus advance (2003, 2005, 2006, 2010, 2011) coincided with years where the cumulative number of winter SST "degree-days" in the inner fjord was quite high (Figure 20b,c). For example, the winters of 2010 and 2011 showed the highest cumulative degree-days (9.8×10^4 and 9.3×10^4 °C-days) while the terminus showed the smallest winter advances (1.25 and 1.85 km, respectively). Likewise, the winters of 2005 and 2006 exhibited high cumulative degree-days (8.4×10^4 and 9×10^4 °C-days) in the fjord while the glacier experienced the next smallest seasonal advances (2 and 2.4 km, respectively). In general, as shown in Figure 20c, this relationship holds for the 11-year record.

The most anomalous year, the winter of 2007, shows a considerable advance (~5 km) of the terminus despite a high SST product cumulative degree-day value. The high product value is likely driven by the late February warm-up evident in the higher than normal values shown in the transect (Figure 16). Warm air temperatures and moderate easterly winds reported at Ilulissat Airport (Figure 21) preceded mélange warm-up events, but were likely insufficient to weaken the fjord ice at the calving front at that time.

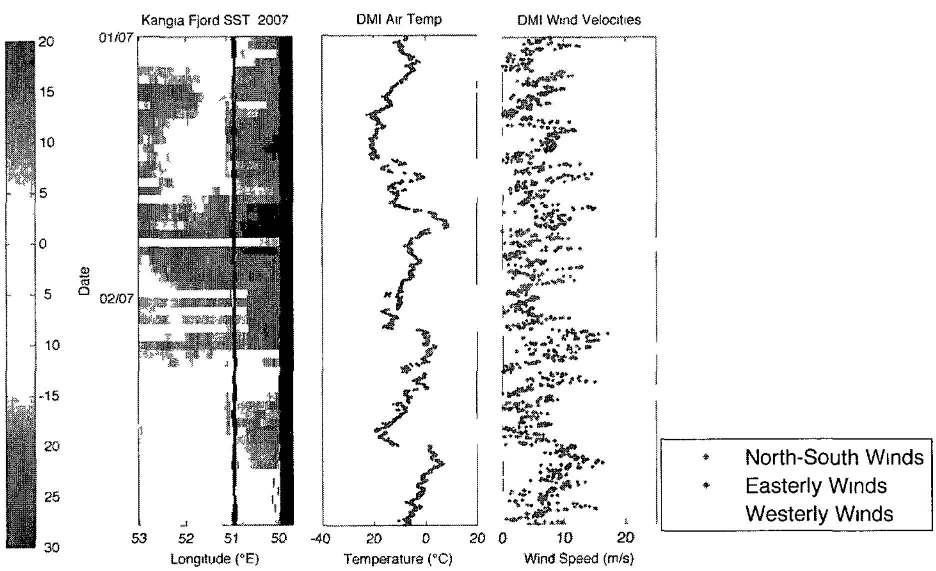

Figure 21: January – February 2007 conditions in Kangia Fjord. (Left) SST transect in the fjord; (Middle) air temperatures and (Right) wind conditions at Ilulissat Airport. Warm air temperatures (AT >0°C) and high easterly winds precede mélange warming events.

The data presented here suggest that winter fjord ice conditions influence seasonal modulation of terminus position of Jakobshavn Isbrae. Overall, winters that are "warm" and have an unconsolidated ice pack in the inner fjord coincide with years of minimal terminus advance. Conversely, winters that are "cold" in the mélange region generally experience a seasonal advance of ~5km. A linear regression of these variables (Figure 20c) further supports the hypothesis that winters with a warmer, weakened mélange experience minimal advance.

4.4 Summary of Results at Jakobshavn Isbrae

The results shown here for Kangia Fjord and Jakobshavn Isbrae demonstrate that winter fjord ice conditions can be monitored with high temporal resolution using thermal satellite imagery. Winter conditions of the pro-glacial ice mélange in Kangia Fjord influence seasonal readvance of Jakobshavn Isbrae's calving front and have implications for terminus dynamics (Figure 22). During a typical arctic winter, air temperatures fall below freezing (AT <0°C) and remain cold for several months. In response, the unconsolidated matrix of water and brash ice between icebergs freezes and the mélange becomes a rigid body; this in turn increases backpressure at the glacier's calving front which then alters glacier dynamics in multiple ways. First, the rigid mélange inhibits winter calving by preventing ice along the heavily fractured terminus from overturning [*Amundson et al.*, 2010]. The glacier continues to flow as calving ceases; thus a floating tongue develops and advects downfjord. The floating tongue interacts with the fjord walls and ice, which reinforces the backpressure imposed by the rigid mélange (a positively feedback loop), and both processes reduce the longitudinal stress within the grounded portion of the glacier in the near-terminus region. This reduction in longitudinal stress results in slower velocities and less extension in the near-terminus region, resulting in a thickening of the glacier at the grounding line. The additional ice thickness increases the normal force on the bed in the near- terminus region which moves the glacier further away from flotation [*Pfeffer*, 2007]. Since glacier velocities are inversely related to the effective pressure, the glacier slows. The initial glacier slowdown imposed by backpressure from the rigid winter mélange can positively feed back to temporarily thicken the glacier and further reduce winter velocities.

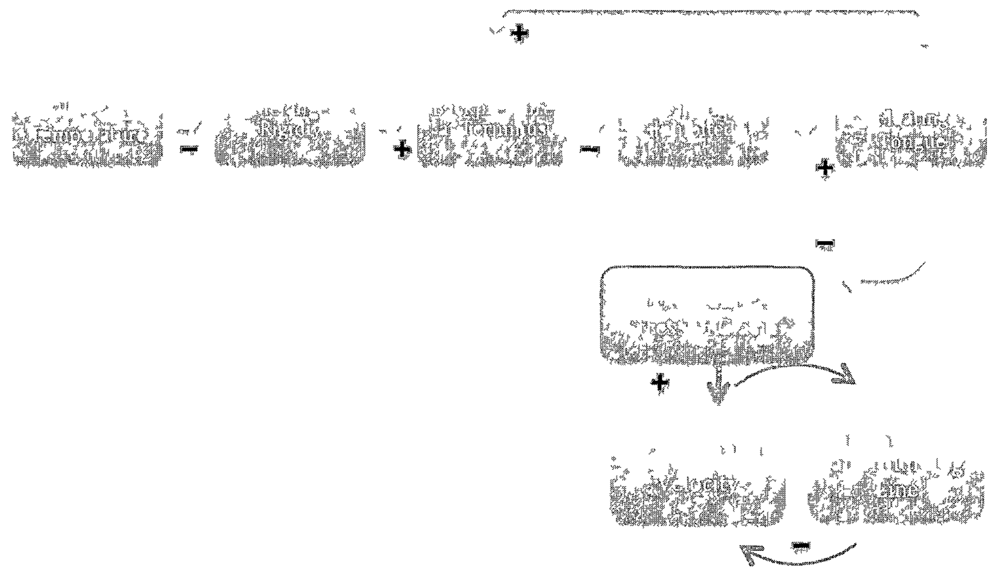

Figure 22: Block diagram model depicting the feedback loops set in motion by a change in the air and sea temperatures in Kangia Fjord during the winter months. Positive (+) signs indicate positive relationship with reinforced effects. Negative (-) signs indicate inverse relationships.

For winters with a cold consolidated ice mélange, the glacier terminus experiences a 4 – 5 km advance, while years with a warmer unconsolidated mélange have much smaller seasonal modulations. The data suggest that warm temperatures weaken the mélange, and when coupled with high winds that are sustained, the mélange becomes mobile. The increased mobility destabilizes the near terminus region by reducing backpressure at the glacier terminus and leading to winter calving events. A change in winter calving has serious implications for glacier dynamics including the seasonal re-advance of the glacier terminus, changes in thickness of the glacier at the grounding line, and velocity changes in the near-terminus region. If sustained, these changes will affect the ice flux out of the ice sheet and reduce the ice volume of the Greenland Ice Sheet.

5 Results – Other Greenland Fjord Systems

5.1 Godthabsfjord, Narsap Sermia and Kangiata Nunaata Sermia

Godthabsfjord (Figure 23) is a long anastomosing fjord in southwest Greenland. Meltwater from more than a half dozen outlet glaciers drains into this 180 km long fjord before emptying into Davis Strait at the northern extent of the Labrador Sea (64°N, -51.8°E). Narsap Sermia (NS) and Kangiata Nunaata Sermia (KNS) are two tidewater outlet glaciers in this fjord network; each of which has demonstrated a different pattern of retreat since the LIA. NS has maintained a stable position since the end of the LIA (until the 2011 winter), while KNS has retreated more than 6 km from its 1930s position [*Timm*, 2010]. Trim lines and submerged sills in the pro-glacial fjord support these

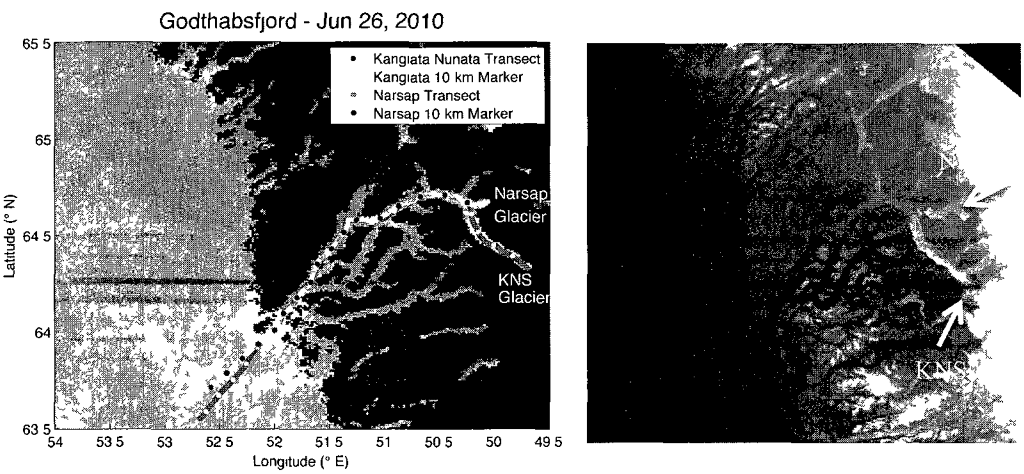

Figure 23: MODIS derived images of Godthabsfjord, West Greenland June 26, 2010. (Left) Thermal-band SST map with the locations of two SST transects. (Right) Visible band image of the region. Both images depict the location of the two glaciers studied in this fjord system: Narsap Sermia (NS) and Kangiata Nunaata Sermia (KNS).

findings and also suggest KNS may have retreated more than 20 km since the end of the LIA. Over the last decade, NS's terminus has exhibited little (~10's of meters) annual variability in position, while KNS's calving front has fluctuated ~0.5 km seasonally. Both glaciers showed considerable change over the 2011 winter.

5.1.1 Narsap Sermia

5.1.1.1 Terminus Position

Narsap Sermia's 11-year history of mean terminus position (Figure 24a) demonstrates an outlet glacier system possibly just starting a period of rapid change. The calving front showed slight seasonal variability, but was stable annually over the early part of the record (2000 – 2003). The terminus then exhibited two years of little to no seasonal re-advance, followed by four more years of annual variability with increased seasonal range around a mean terminus position. The last two years of the record show a strong retreat of the terminus and a lack of winter re-advance.

The most notable change throughout the entire record occurred during the 2011 winter. The mean terminus position retreated 220 meters (Figure 26b) behind the previous summer minimum, which continued into the 2011 summer with the terminus retreating more than 400 meters since the 2010 Spring. Figure 24c exhibits this unexpected change to the winter terminus. The October 15, 2010 terminus (red trace) is superimposed on the April 25, 2011 Landsat image with the terminus traced in blue. A large section of the terminus calved during the winter, accounting for much of that winter's retreat, which was nearly 10 times the second largest retreat that occurred during the 2005 winter (29 meters). The winters of 2004 and 2010 exhibited negligible re-advance with 2004 showing a mean position gain of 4 meters and 2010 showing a mean position loss of 1.4 meters. These failed winter re-advances, followed by spring and summer retreats, contributed largely towards the more than 0.6 km retreat NS has experienced since 2000 (Figure 24b). Additionally, based on the well-developed vegetation just outside the ice margin held between 2000 – 2004, the 2010 – 2011 retreat appears to be the first and most significant retreat since the glacier's LIA maximum position.

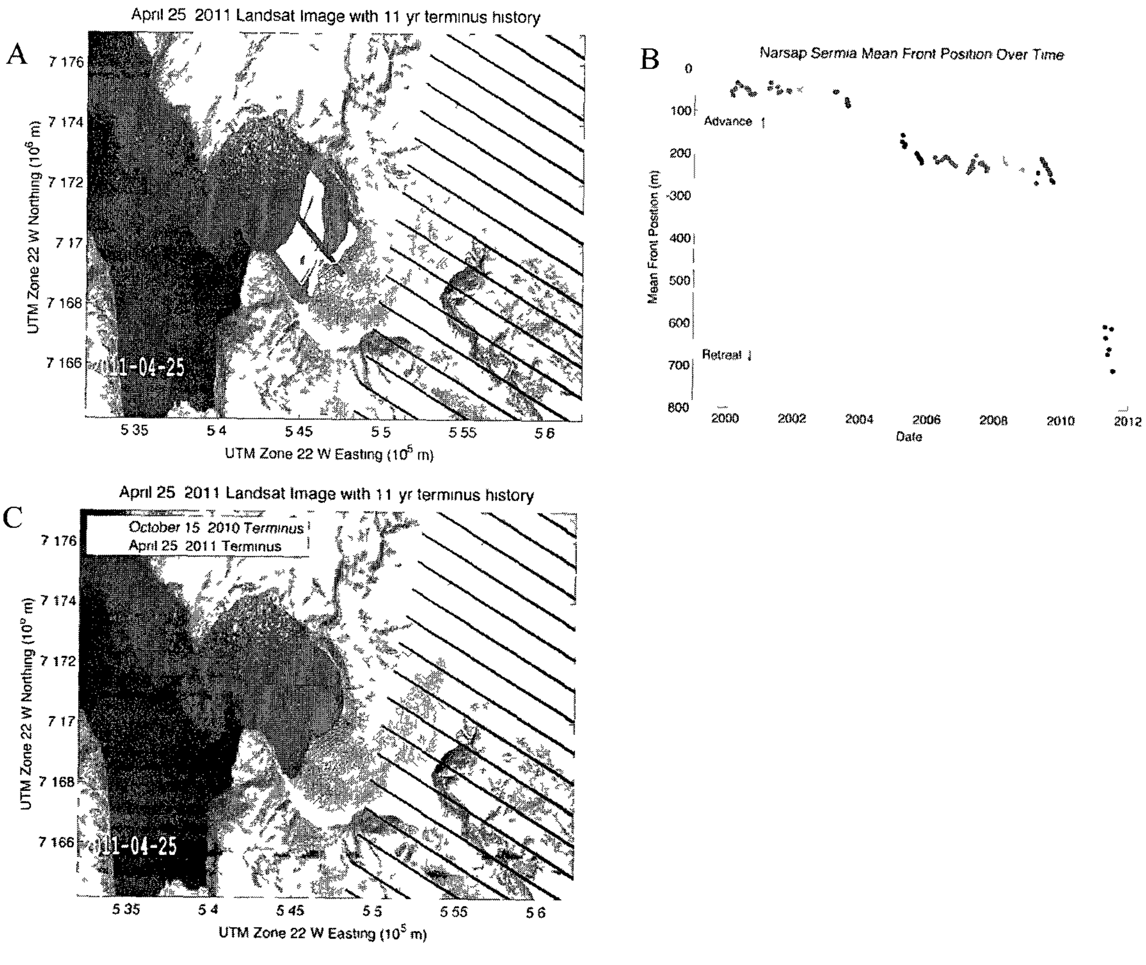

Figure 24: (A) Landsat derived front positions of Narsap Sermia in Godthabsfjord. (B) Time series of the mean front position. (C) Change in winter 2011 terminus.

5.1.1.2 Fjord Ice Conditions

Coinciding with the pattern of wintertime changes at NS's terminus is a progressive shift in ice mélange behavior in the pro-glacial fjord. Figure 25 provides the SST transects of the pro-glacial fjord. Superimposed on these transects are the annual winter mélange boundaries inferred from the transition between the cold, consolidated fjord ice nearest the terminus and the warmer unconsolidated mix of brash ice and open water further away from the terminus. Fjord ice conditions show regular seasonal variations spatially and temporally; however, fjord ice conditions during the winters of 2005, 2010, and 2011 are markedly different. The duration of the cold, consolidated ice mélange in the early part of the record (2000 – 2004) characteristically ranges between 3 and 5 months and often extends more than 20 km out from the terminus of NS. This changes in 2005, when the winter consolidation period shortens to 2.5 months and the mélange extent is less than 10 km. The mélange appears cold and consolidated for the 2006 - 2009 winters, before warm conditions return for 2010 and 2011. The winter of 2010 begins with a cold consolidated mélange in November 2009. Surface temperatures warm in mid-December; drop again for a short time in January before warming again in February 2010. There appears to be a brief return to consolidated conditions in March 2010, but temperatures are generally warmer indicating a mix of brash and sea ice and unconsolidated mélange. Conditions for mélange consolidation during the winter 2011 are only favorable for a brief period in March 2011.

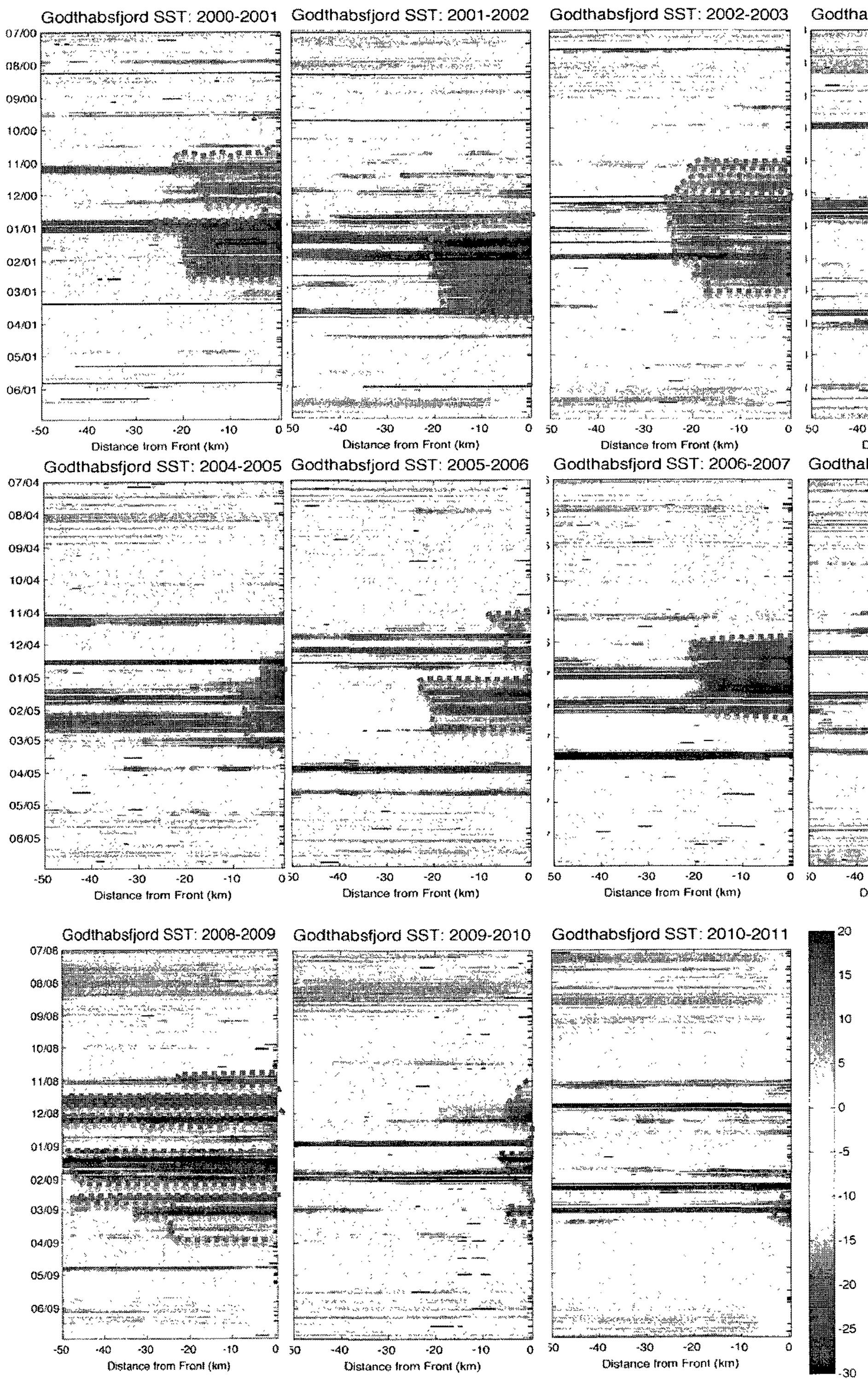

Figure 25: Godthabsfjord ice conditions derived from the MODIS SST data product. Red dotted lines are the inferred boundary between cold, consolidated fjord ice and the warmer temperatures of open water and brash ice further away from terminus. The location of the transect is illustrated in Figure 23 (blue trace).

5.1.1.3 Mélange influence on glacier dynamics

To allow relative comparisons between years in this record, the cumulative degree-day values (Figure 26a) were compared against the change in mean terminus position (Figure 26b) for each winter. A regression analysis between the SST product temperatures in the fjord (as a proxy for ice conditions) and the change in terminus position (Figure 26c) indicates that terminus re-advance is related to winter fjord ice cover, though the relationship is not as compelling as that seen in Kangia Fjord discussed in section 4.3. This is due to the disproportionate response of the glacier to the three

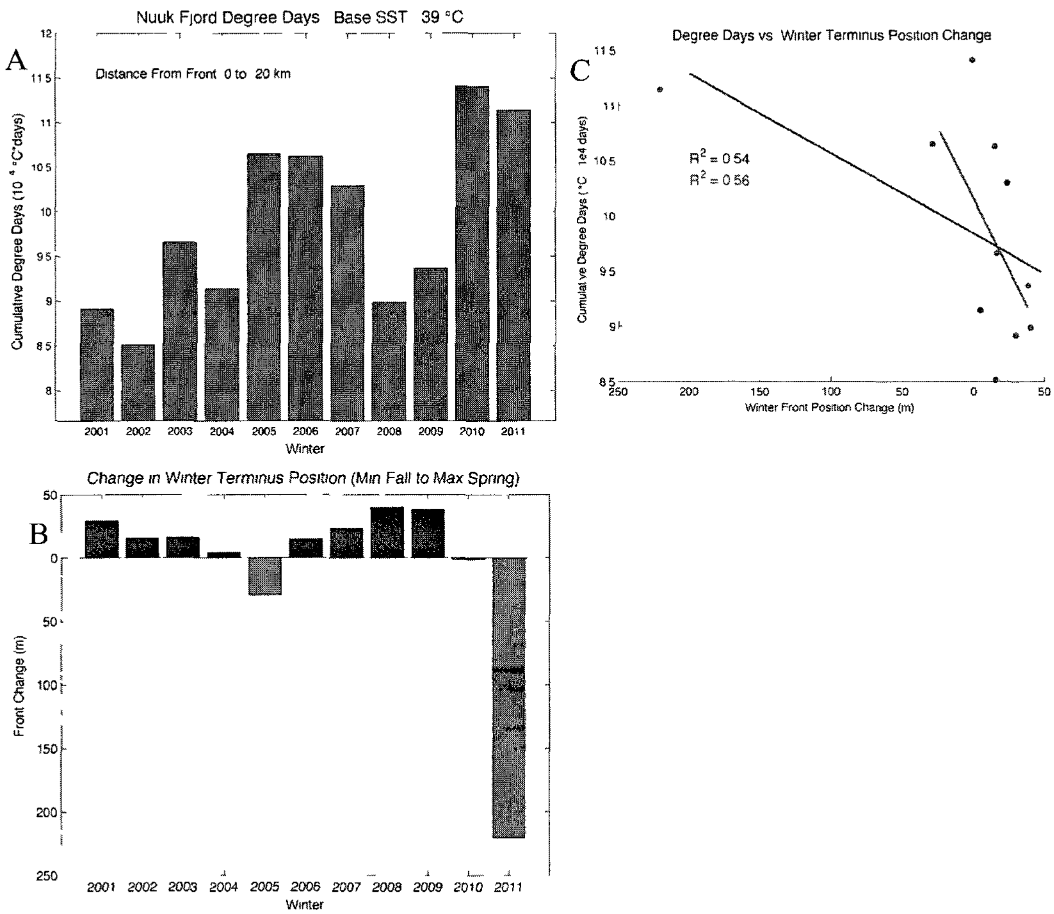

Figure 26: (A) Cumulative SST degree-days each year between Oct 1 and March 31. (B) Change in mean winter terminus position. (C) Regression analysis between cumulative degree-days and change in mean position at the glacier front.

warmest winters in pro-glacial fjord: 11.5 x 10^4 °C*days when the glacier showed no retreat or advance in 2010; 11.2 x 10^4 °C*days when the glacier retreated 221 meters in 2011; and 10.7 x 10^4 °C*days when the glacier retreated 30 meters in 2005. These complications likely result from time-evolution in response of the glacier to the stress changes within the terminal reach and the mélange, but may also represent a limitation of using an SST data product as a proxy for mélange strength and rigidity. The assumption is that cold ice in the record is rigid while warm SST values represent more mobile warm ice and open water, but no data are available to quantify the stress or mobility changes involved with temperatures observed in the SST record. Nonetheless, the conclusion can be made that Narsap Sermia's terminus experienced retreat in winters in which the cold, consolidated ice mélange was disturbed or largely non-existent.

The recent changes observed at Narsap Sermia exhibit a behavior that may typify the evolution of a tidewater outlet glacier in retreat. The glacier begins in a quasi-stable equilibrium state (2000 – 2003) in likely the same position it held for some time, moderately fluctuating seasonally around a mean position; a shift in outlet glacier dynamics occurs, possibly driven by a warmer, weakened ice mélange (2005), resulting in winter calving and enhanced ice discharge into the fjord. The additional winter calving and faster flow would thin the terminus region of a glacier that is already near flotation, producing an even greater increase in surface velocities (*see 4.2.1*). The additional ice discharge could temporarily bolster the winter mélange to stall the retreat mode and allow the terminus to re-advance seasonally. Coupling the effects of a now-faster moving glacier and a temporarily renewed winter ice mélange would increase the dynamic range of the terminus position annually (e.g. 2007 – 2009). Warming of the area and mélange continues, further destabilizing the winter terminus and the retreat pattern escalates (e.g. 2010 and 2011). This continued pattern of retreat could lead to a new equilibrium state of large-scale seasonal fluctuations such as those exhibited at Jakobshavn Isbrae (section 4.3.1), KNS (section 5.1.2), Helheim (section 5.2.1.1), or Midgards (section 5.2.2.1), or may lead to a series of positive feedbacks that could further enhance terminus retreat (e.g. the 'Jakobshavns Effect' [*Hughes*, 1986]).

5.1.2 Kangiata Nunaata Sermia

5.1.2.1 Terminus Changes

Kangiata Nunaata Sermia's (KNS) terminus is, at present, located only ~50 km upfjord (southeast) of Narsap Sermia, yet the observed changes at these glaciers are quite different. NS's retreat appears to have been until recently largely relatively evolutionary with stepped changes of equilibrium along the terminus driven predominately by changes during the winter months. In contrast, the retreat at KNS has been more continuous with summer calving, particularly in 2004 and 2005, having a slightly stronger influence on

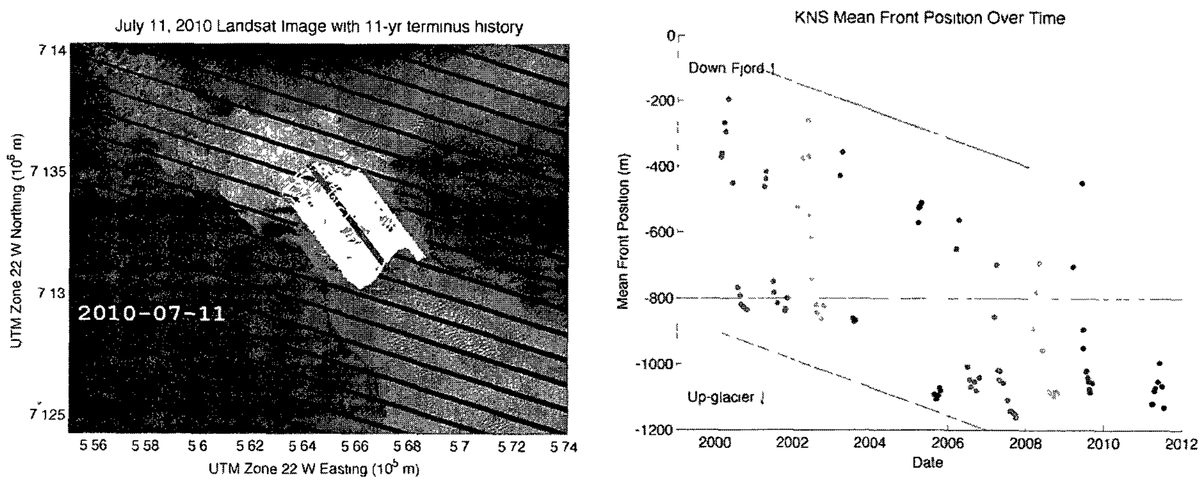

Figure 27: (Left) Landsat-derived front positions of Kangiata Nunaata Sermia in Godthabsfjord. (Right) Time series of the mean front position.

overall terminus retreat than winter calving (Figure 27, Figure 29b). However, this glacier also calved several times over the 2011 winter and as a result the glacier only re-advanced 120 meters, ~ 340 meters less than the mean advance of 460 meters. KNS's terminus also has a much larger seasonal dynamic range than NS, fluctuating ~ 250 meters around a mean annual position.

5.1.2.2 Variability in the Ice Mélange and Relation to Terminus Position

The SST values show the ice mélange as a prominently cold (consolidated) block in the inner fjord for the first 8 winters of the MODIS record. Spatially, this block extended more than 40 km from the KNS terminus and remained cold and consolidated for no less than 3 months, and in some winters as long as 5 months. The spatial and temporal characteristics of the ice mélange began to change, however, during the 2009 winter when the mélange exhibited several warm-up events; one in December and one in February. The SST transect indicates the inner fjord remained ice covered during these events (SST < -5°C) and the distinct boundary between the inner and outer fjord returned after each warm up with the consolidated ice extending more than 60 km from the glacier terminus.

The winters of 2010 and 2011 are noticeably different; each lacked the spatially cohesive cold SST signature that defined the ice mélange in previous winters. Though less coherent, the SST directly in front of KNS remained cold (SST < -15°C) for most of the 2010 winter, indicating the immediate area in front of the glacier remained ice choked. The fjord narrows from 5 km down to 3 km approximately 7 km out from the terminus. One possibility is that the fjord ice within this region remained cold and coherent enough to inhibit calving and allow a floating tongue to develop, thus promoting

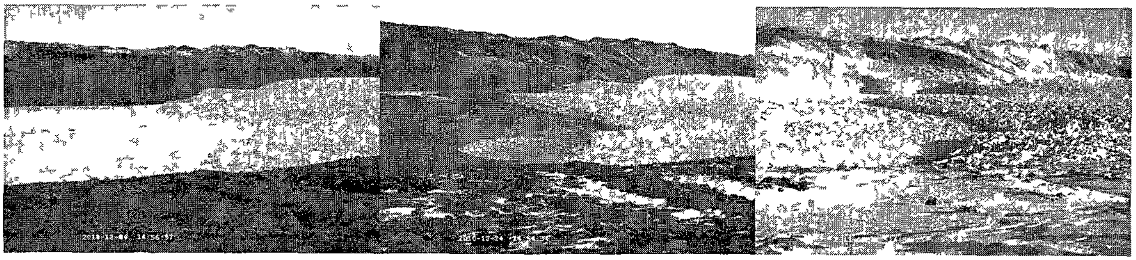

Figure 28: KNS pro-glacial mélange conditions during the 2011 winter. (Left) Unconsolidated ice on December 6; (Middle) Open water on December 24; (Right) Consolidated ice on February 21.

the more 'typical' 405 meters of winter advance that occurred that winter. In contrast, the 2011 winter ice mélange was unconsolidated through mid-January with SST in the near terminus region showing surface temperatures as warm as -5°C. These warm values showing seemingly unconsolidated ice were confirmed with time-lapse images that show a weakly consolidated and mobile ice mélange throughout this period (Figure 28 - left) mixed with intervals of open water (Figure 28 – middle) at the glacier terminus. Time-lapse photography also confirms the consolidation of the fjord ice directly in front of KNS (Figure 28 – right) for approximately 2 months between mid-January and mid-March. It was during this cold, consolidated period that the glacier developed a floating tongue and advanced 120 meters downfjord.

Overall, the glacier and the pro-glacial mélange exhibited a regular pattern of seasonality. During most years, a cold, consolidated ice mélange occupied the inner fjord and extended more than 40 km from the terminus; in those same years, the glacier advanced 400 – 600 meters. The winter mélange exhibited an unstable configuration over the last two winters, though the glacier only experienced a minimal advance during the 2011 winter. The regression of SST values and terminus advance (Figure 29c), though not an ideal fit, loosely supports the interpretation that a colder, more rigid mélange allows for a floating tongue to develop and advance downfjord. The small seasonal terminus modulations (meters as opposed to kilometers in JI, Helheim, or Midgards) and regular annual behavior (except for 2011) do not produce a strong signal that rises above background variability for this glacier.

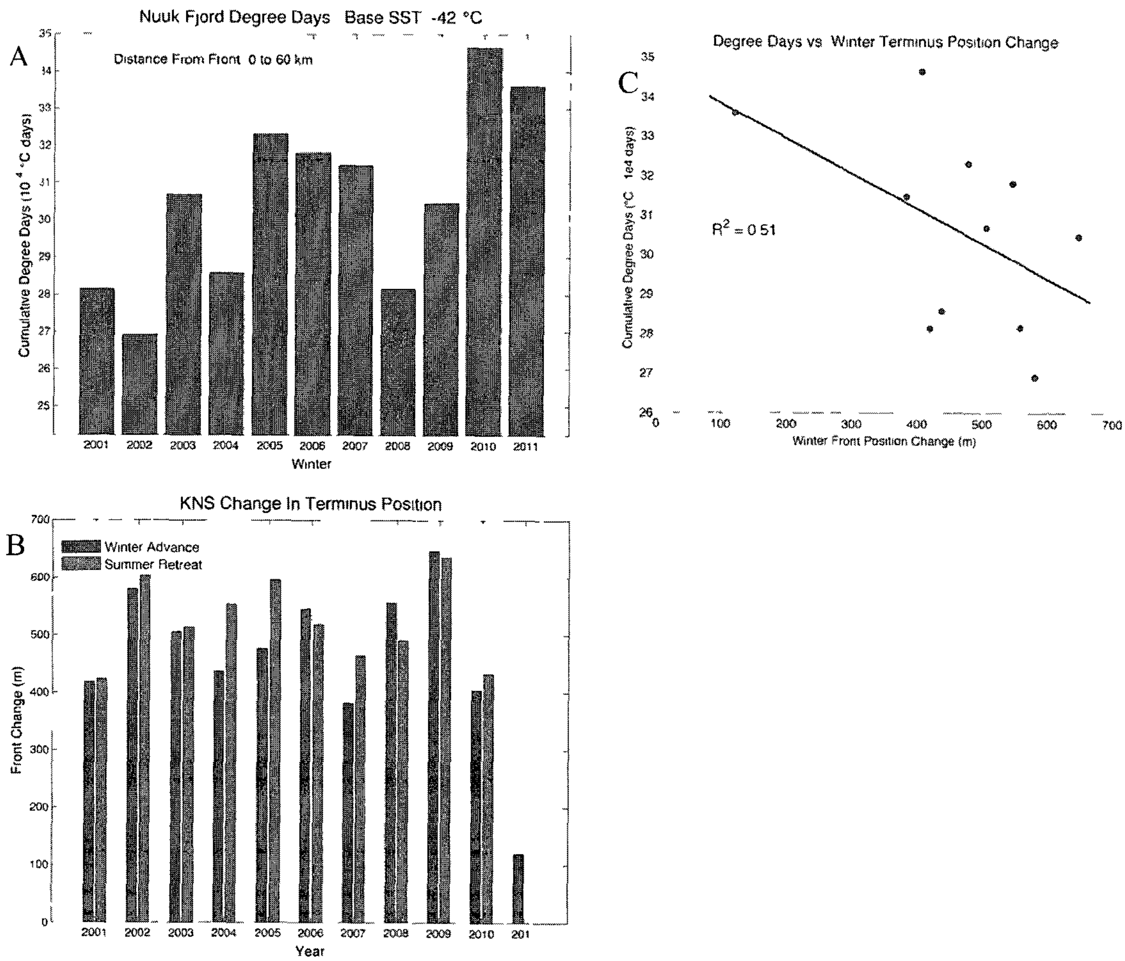

Figure 29: KNS Fjord Conditions. (A) Cumulative SST degree-days each year between Oct 1 and March 31. (B) Change in mean terminus position; red values indicate summer retreat; blue values indicate winter re-advance. (C) Regression analysis between cumulative degree-days and change in mean position at the glacier front.

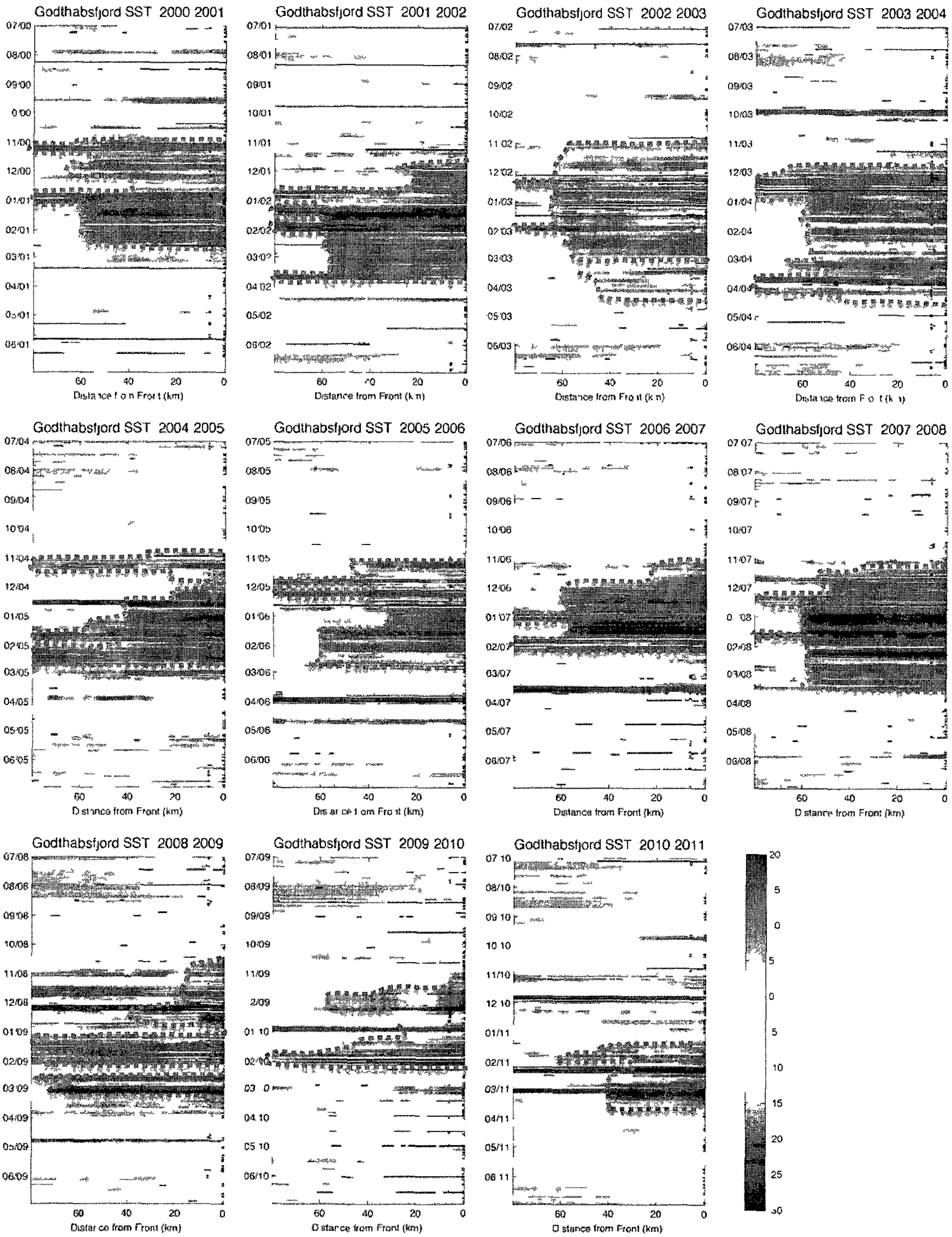

Figure 30: SST product values for first 70 km of ice mélange and pro-glacial fjord of KNS in Godthabsfjord. The transect begins at the terminus of KNS (0 km) and moves downfjord, past Narsap Sermia (~50 km) and continues out towards Davis Strait as shown as the green profile in Figure 23.

5.2 Sermilik Fjord and Midgards and Helheim Glaciers

Sermilık Fjord (Figure 31) is a ~124 km long fjord in Southeast Greenland. Two large tidewater outlet glaciers, Helheim and Midgards, terminate within thıs fjord. Both glacıers have experienced rapid retreat since 2000, each with a unique pattern.

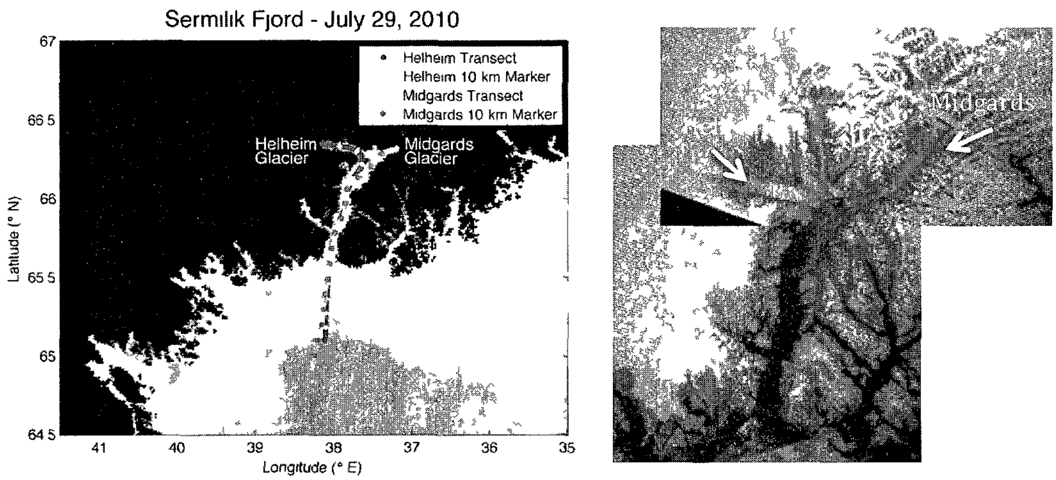

Figure 31: (Left) MODIS thermal SST map of Sermilik Fjord for July 29, 2010. The location of the two SST transects used for this fjord are shown. (Right) Compilation of Landsat 7 visible band images acquired on June 27, 2011. Both images depict the location of the two glaciers studied in this fjord system: Helheim and Midgards Glaciers.

5.2.1 Helheim Glacier and the Pro-Glacial Fjord

5.2.1.1 Terminus Changes

Helheim Glacıer terminates into a branch of Sermilık Fjord ~110 km from the confluence with Denmark Strait. Overall, the glacıer has retreated 4 km back from ıts mean 2000 position (Figure 32), though the retreat has been sporadic. Following two relatively quıescent years of modest seasonal fluctuations around a quasi-stable front, the glacier began a kilometer scale retreat during the winter of 2002 (Figure 32), retreating 0.6 km beyond its mean fall position. The glacier continued to retreat that summer before re-advancing several hundred meters during the winter of 2003. The terminus then showed considerable seasonality (> 1km) for the next two winters before again failing to readvance during the winter of 2005. The terminus reached a new minimum by the end of the summer 2005, before experiencing the largest winter re-advance (4 km) of the record in 2006. The terminus continued to fluctuate seasonally, but has not reached the minimum position attained in late 2005.

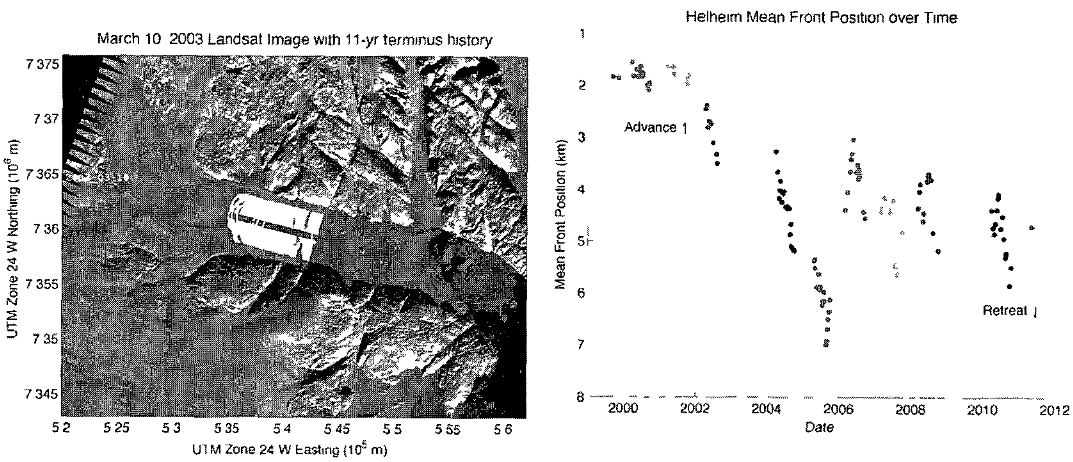

Figure 32: (Left) Landsat derived front positions for Helheim Glacier. (Right) Time series of the mean front position. The glacier did not re-advance during the winters of 2002 and 2005, but had a large winter re-advance during the winter of 2006.

5.2.1.2 Winter Fjord Ice Conditions

The winter fjord ice conditions in the pro-glacial area of Helheim Glacier (Figure 33) are noticeably different than JI, NS and KNS. Based on the SST values, Helheim's mélange appears much more variable and episodic, with frequent periods of warming. Whereas the boundary between winter fjord ice and open water are clearly expressed in

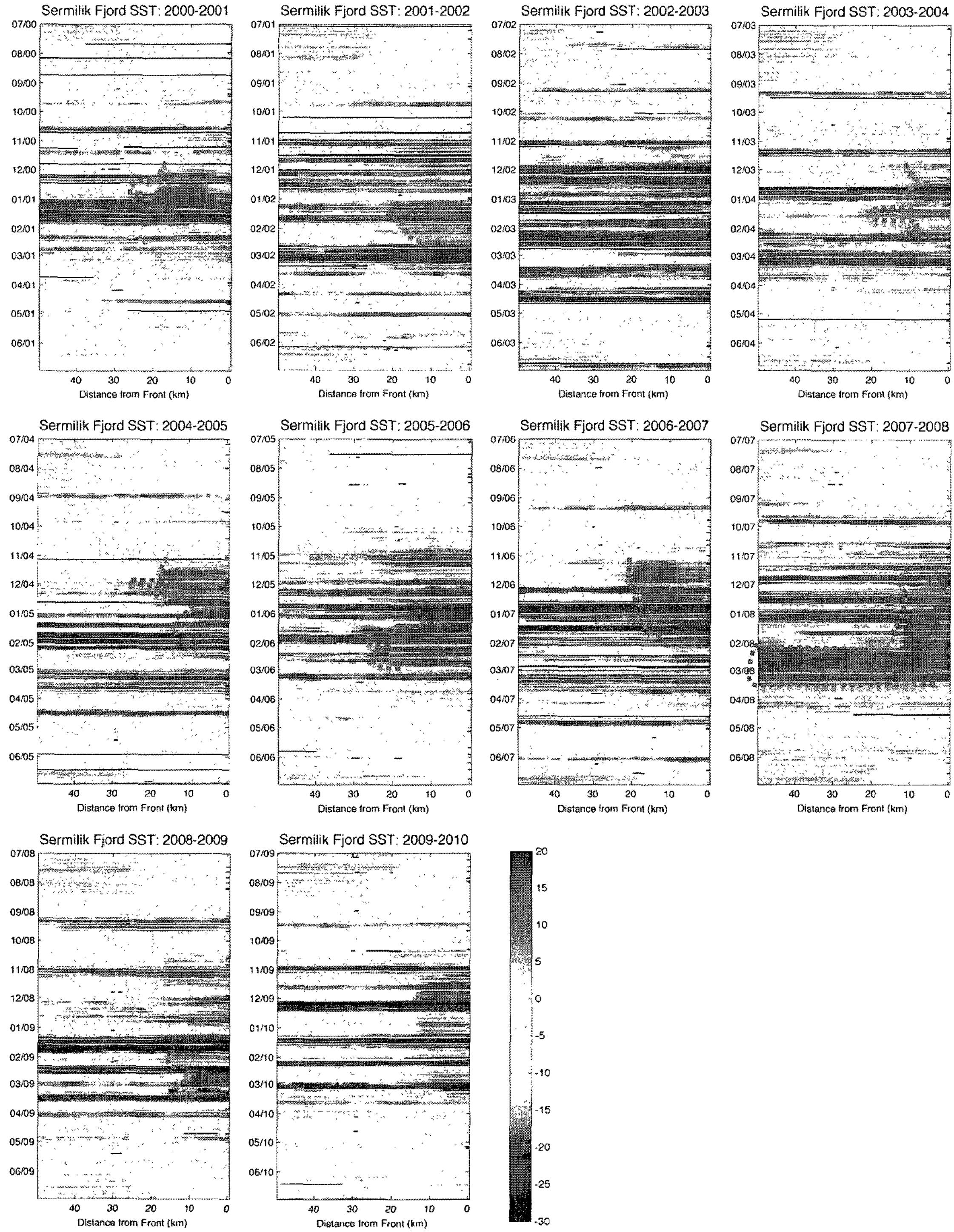

Figure 33: SST product value transects for Sermilik Fjord beginning at the terminus of Helheim Glacier (0 km) and moving downfjord into Denmark Strait (~90 km) along the blue line in Figure 31. The red dashed lines indicated interpreted boundaries between consolidated ice mélange and more mobile ice cover in the fjord.

the MODIS record of JI, NS, and KNS glacier systems (Figure 17, Figure 25, Figure 30), the boundary in Sermilik Fjord is not well defined. Nonetheless, interpretations of this boundary were made (red dotted lines in Figure 33) and examples of winter fjord ice influence on terminus position were observed (Figure 34).

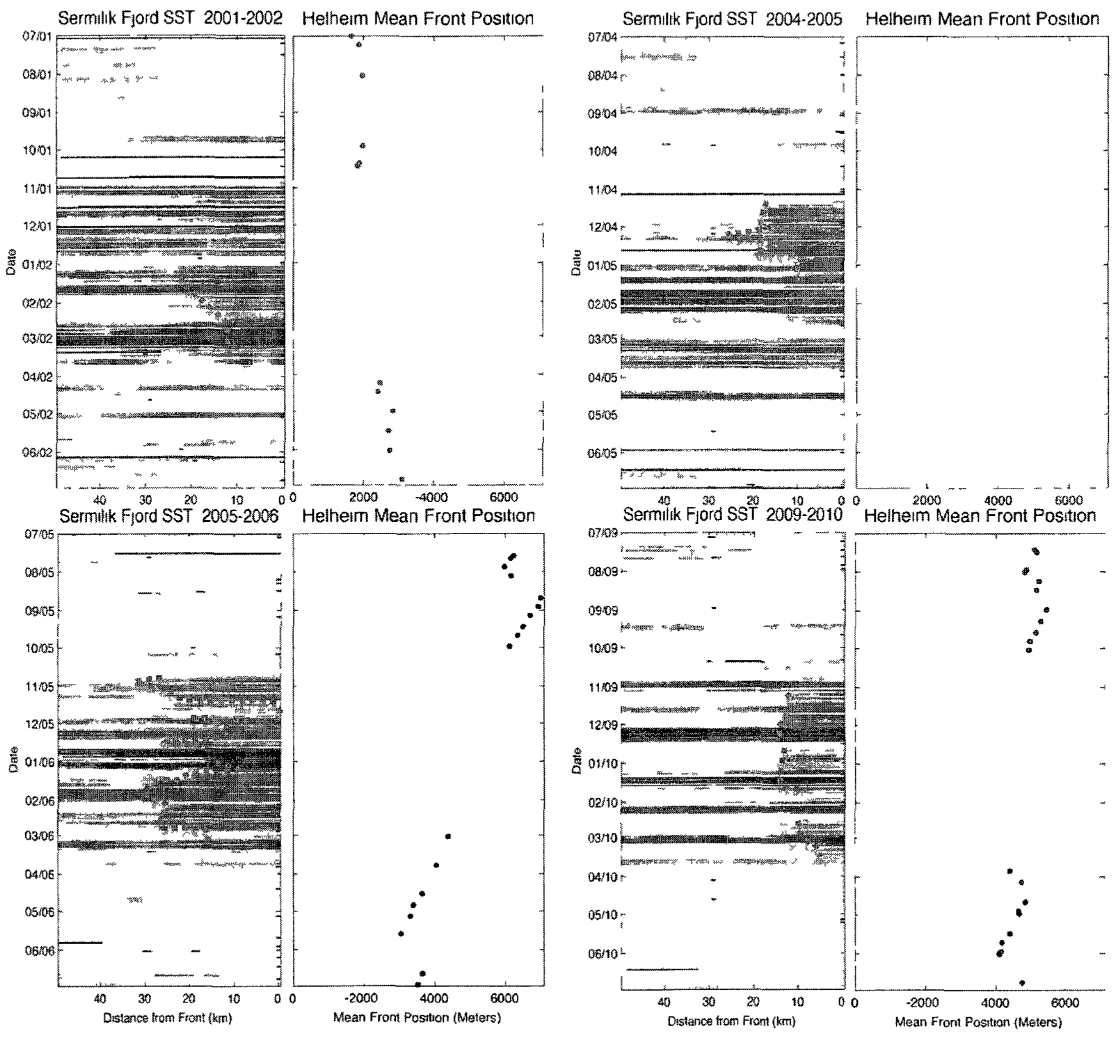

Figure 34: Time-series of SST product value transects (left in each series) in the pro-glacial fjord and the mean front position (right in each series) for Helheim Glacier. Years are centered on the winters to illustrate relationship between fjord ice and terminus position. Clockwise from top left: winter 2002; winter 2005; winter 2010; and winter 2006. The diffuse nature of the boundaries makes interpretations (red dashed lines) difficult.

The fjord ice cover during the winters of 2002 and 2005 exhibited the shortest duration in the record, only lasting for approximately 2 months. These are the only two winters in the record in which the glacier did not re-advance. In contrast, the calving front experienced the largest winter re-advance (4 km) during the 2006 winter when the mélange occupied the inner fjord for approximately four months and extended nearly 30 km away from the terminus. Depicting more 'typical' Sermilik Fjord ice behavior, the winter of 2010 had multiple warm up events and an ice pack that extended ~ 15 km out from the terminus and lasted for approximately 5 months.

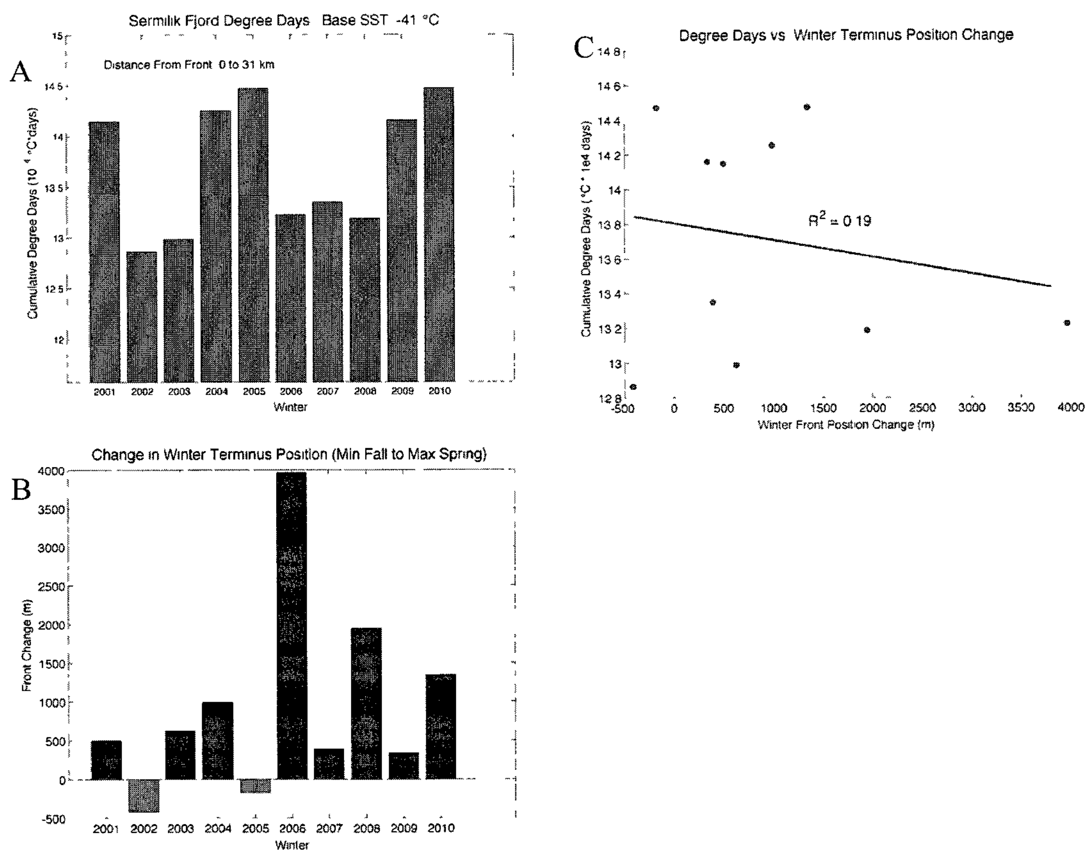

Figure 35: Sermilik Fjord Conditions. Counterclockwise from the Top Left: (A) Cumulative SST degree-days each year between Oct 1 and March 31. (B) Change in mean winter terminus position. (C) Regression analysis between cumulative degree-days and change in mean position at the glacier front.

Despite examples of glacier response to ice mélange conditions, the low correlation between cumulative degree-days and the change in winter terminus position (Figure 35) suggests the ice mélange had little influence on changes in the seasonal re-advance of the glacier over the last decade. There are a number of reasons that might explain this: The fjord is often choked with ice (e.g. Figure 32), however, the frequency of winter warming events in the thermal record suggests the ice in front of Helheim Glacier generally does not consolidate and become a rigid body as the mélanges in Kangia Fjord and Godthabsfjord do. Rather, surface conditions in the immediate pro-glacial area keep the ice mélange at some intermediate state. Although unlikely, a second possibility for the poor linear fit might be excessive cloud cover obscuring the surface in the SST record for this fjord. The 7-day moving median filter used to reduce cloud effects (section 3.2.2.1) may be inadequate if the pro-glacial fjord was plagued by cloud cover that frequently exceeded 7-days. Still, a third alternative might be that the mélange relationship to terminus retreat is not simple; perhaps a stable mélange contributed to the seasonal re-advance in cold winters (e.g. 2006), but other glacial processes exerted dominant control on Helheim's retreat over the last decade.

The results of winter mélange influence on Helheim's terminus are somewhat inconclusive. Observations of winter fjord ice variability and terminus behavior suggest there is a relationship. However, the high level of interannual variability and lack of a pronounced consolidated mélange front implies the process is not the dominant control on the behavior of the calving terminus for this glacier.

5.2.2 Midgards Glacier and the Pro-Glacial Fjord

5.2.2.1 Terminus Retreat

Midgards Glacier terminates in Sermilik Fjord on a different branch, further upfjord (northeast) of Helheim Glacier. Like Helheim, Midgards has retreated several kilometers (Figure 36) over the last decade. Between 2000 and 2003, the front exhibited small (< 0.5 km) seasonal fluctuations around this quasi-stable position. Changes began during the winter of 2003 when the terminus failed to re-advance. The glacier retreated ~ 1 km that summer before again failing to re-advance during the 2004 winter. Large scale (> 2 km) seasonal fluctuations of the terminus continued until the winter of 2008, when the glacier re-advanced ≤ 1 km, maintained a stable position that summer, then failed again to re-advance during the 2009 winter. The glacier continued to change during the 2009 summer when the calving front retreated more than 5 km. The glacier re-advanced ~1 km during the 2010 winter before exhibiting another 3 km loss by the end of the summer 2010 calving season. In all, Midgards has retreated 13 km behind its mean 2000 position.

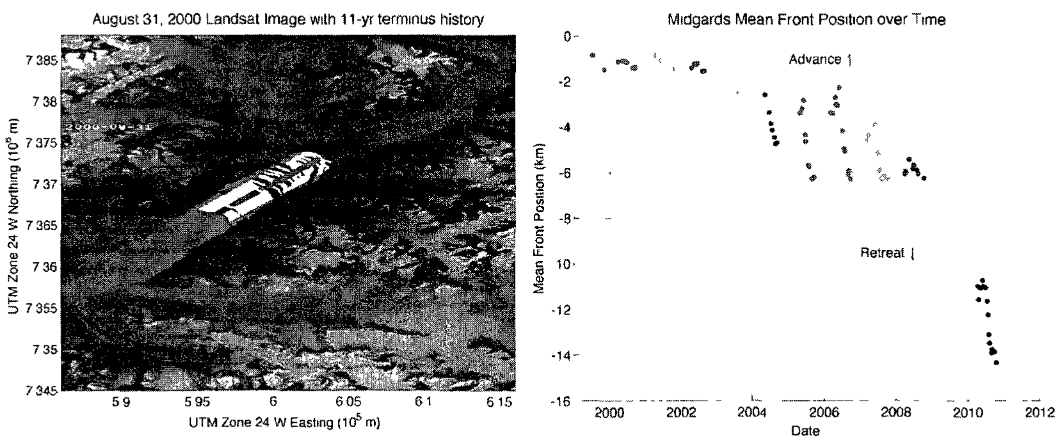

Figure 36: (Left) Landsat derived front positions for Midgards Glacier. (Right) Time series of the mean front position.

5.2.2.1 *Winter Fjord Ice Conditions*

The SST product value transects for Sermilik Fjord originating in the pro-glacial fjord of Midgards Glacier are provided in Figure 37. Note: the land (and glacier ice) mask used by OceanColor for Sermilik Fjord in these transects excludes the first ~18 km (from the mean 2006 position) of fjord SST data *(refer to section 3.2.2).* As a result, the full extent of fjord ice conditions in the immediate pro-glacial fjord area is not contained in this data set.

As with Helheim, winter mélange boundaries for Midgards are difficult to identify in the MODIS thermal record. While this is likely due in part to the masked area of the pro-glacial fjord (see above), there is another explanation. There are at least three winters (2005, 2006, and 2007) in which a mélange boundary can be delineated (red dashed lines in Figure 38). Coincidentally, these are the only winters in the record that demonstrate large-scale seasonality of the glacier front (Figure 36), that is, those years showed big (> 2 km) frontal retreats followed by equally big winter re-advances, thus the glacier was in a temporary (3 year) state of dynamic equilibrium. This occurred during a transitional part of the 10-year record, following a quiescent period (prior to 2003), and preceding the large retreat of 2008 – 2010. A glacier with a large seasonal range would be exporting copious amounts of ice into the fjord, contributing to the development of an ice mélange. Depending on regional atmospheric and fjord surface conditions, a well established ice mélange could freeze and consolidate in the winter, reducing overturning of calved ice, thus allowing a seasonal floating tongue to develop [*Amundson et al.*, 2010]. If conditions changed, for example the warm surface temperatures of winters 2009 and 2010 (Figure 37), a less consolidated ice mélange would provide little to no back stress to the calving terminus, thus promoting winter calving and retreat.

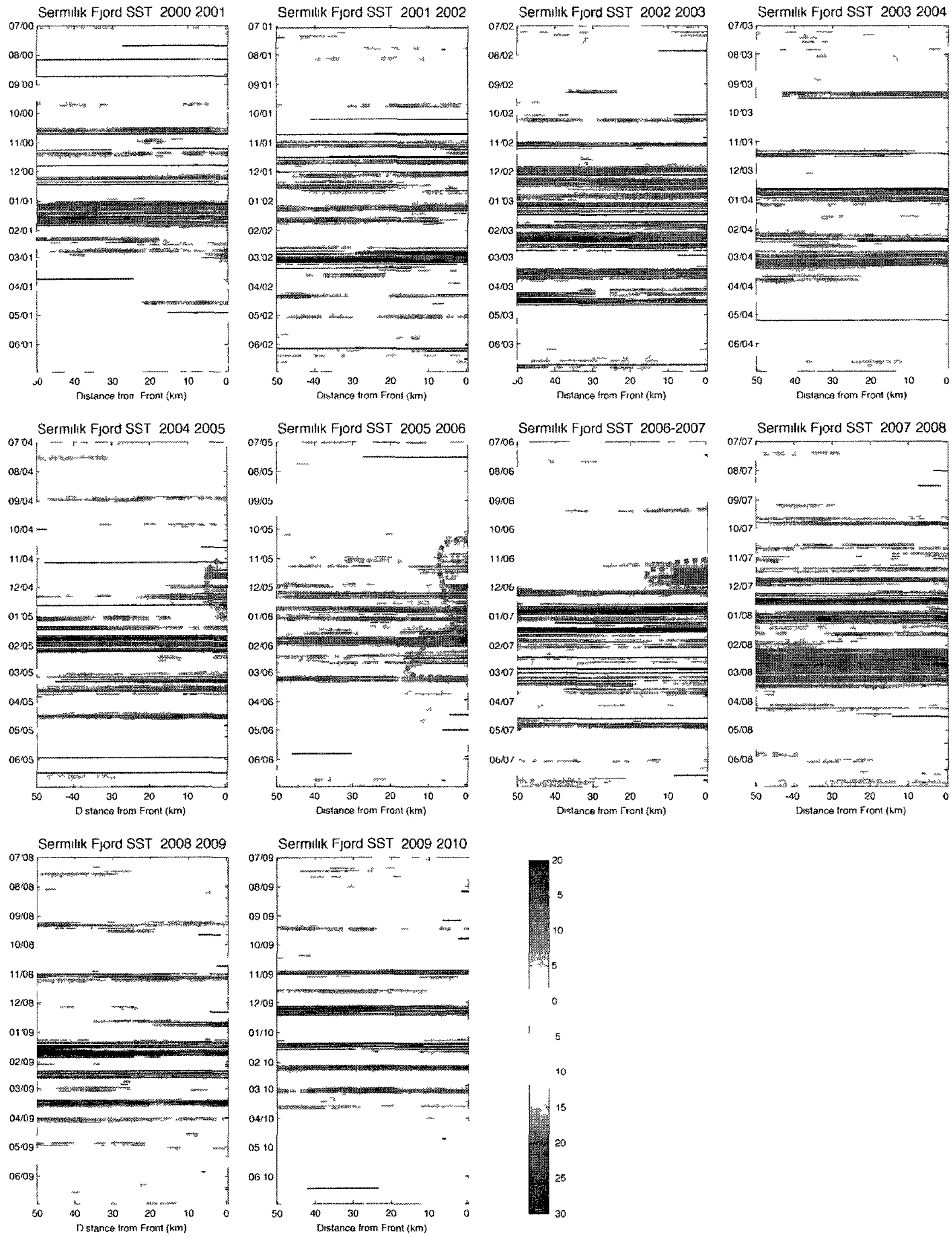

Figure 37: Sermilik Fjord SST product values beginning ~18 km downfjord from the 2006 terminus of Midgards Glacier (0 km), and moving south towards Denmark Strait (~90 km from the Midgards terminus) along the green line in Figure 31. Red dashed lines are the inferred mélange boundary.

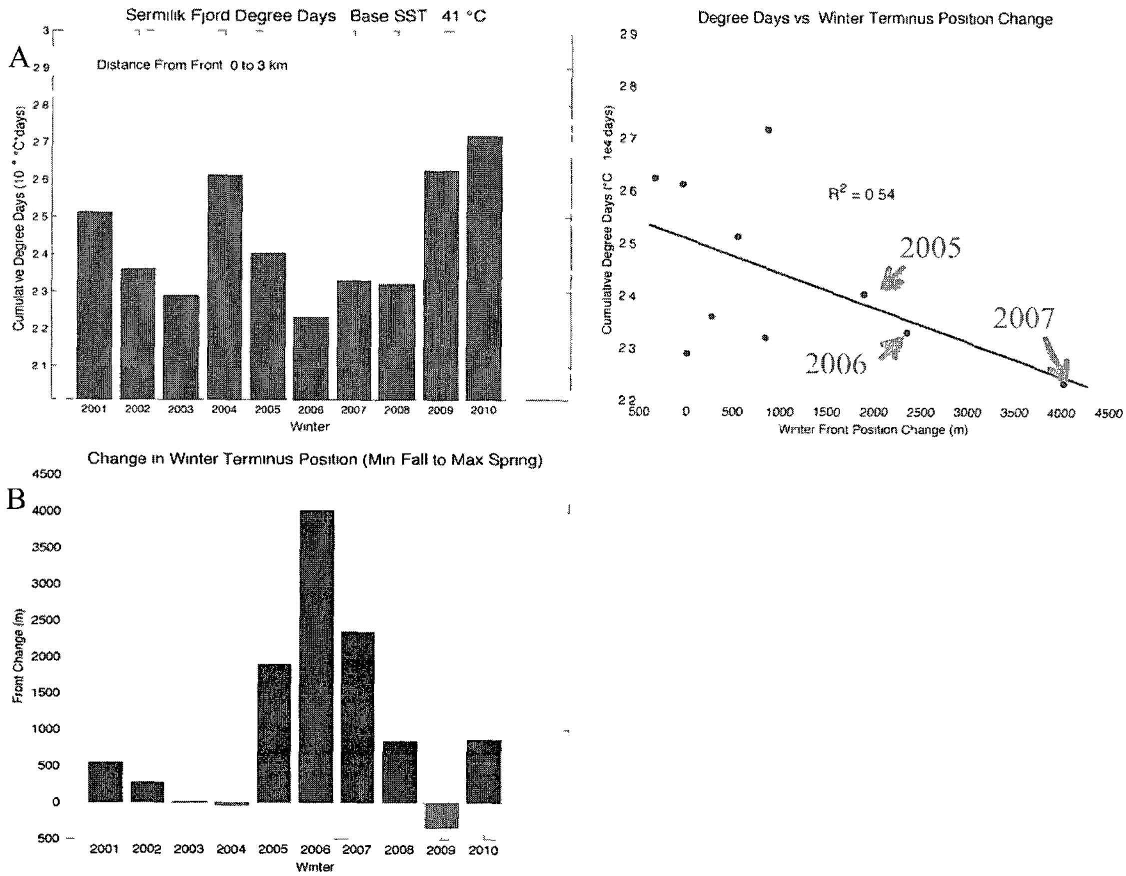

Figure 38: Sermilik Fjord and Midgards pro-glacial fjord conditions. Clockwise from the Top Left: (A) Cumulative SST degree-days each year between Oct 1 and March 31. (B) Change in mean winter terminus position. (C) Regression analysis between cumulative degree-days and change in mean position.

The land and ice mask in the MODIS SST record for this fjord (~18 km from the 2006 mean position) limited observations of the ice mélange in most years. Evidence of ice mélange consolidation is apparent only during the 2005, 2006, and 2007 winters. The SST record for the remaining years likely reflects the surface temperature of mobile ice and water (e.g. fjord water that freezes as sea ice but contains less calved ice) in the fjord. Observations of cumulative degree-days were limited to the first 3 km of the fjord transect to minimize "noise" from non-mélange ice, but the effects could not be eliminated.

5.2.2.2 *Atmospheric Conditions at Tasiilaq*

Air temperatures recorded in Tasiilaq, a town located at the mouth of Sermilik Fjord, are provided in Figure 39. Temperature anomalies (deviation from the 20 year monthly mean) over the last two decades (Figure 39a) indicate air temperatures overall were warmer during the latter part of the record, and that temperature increase began in 2002, coincident with the onset of changes at Midgards Glacier (Figure 36). Since then, there have been at least four periods of sustained winter warmth (Figure 39b), three of which may have influenced mélange conditions. Air temperatures during the 2003 winter were the warmest of the record (Figure 39), with temperatures 2 – 4°C warmer (November 2002 and March 2003) than the 20-year monthly means (Figure 39b). This corresponds to the start of change at Midgards when the glacier exhibited virtually no (~ 6 meters) winter re-advance (Figure 38). The glacier again failed to re-advance during the 2004 winter when air temperatures were nearly 4°C warmer than the 20-year monthly mean in March. Air temperatures were warmer (+2.5 – 4.5°C) in February and March 2005, coincident with a retreat of the ice mélange front towards the inner fjord (out of view of the SST record in Figure 37). While the glacier did exhibit a 1.9 km advance during this winter (Figure 38), it was the smallest of the terminus advances when an ice mélange was detected in the SST record; implying warmer than normal air temperatures may have weakened the ice mélange which led to winter calving and reduced the winter advance of glacier.

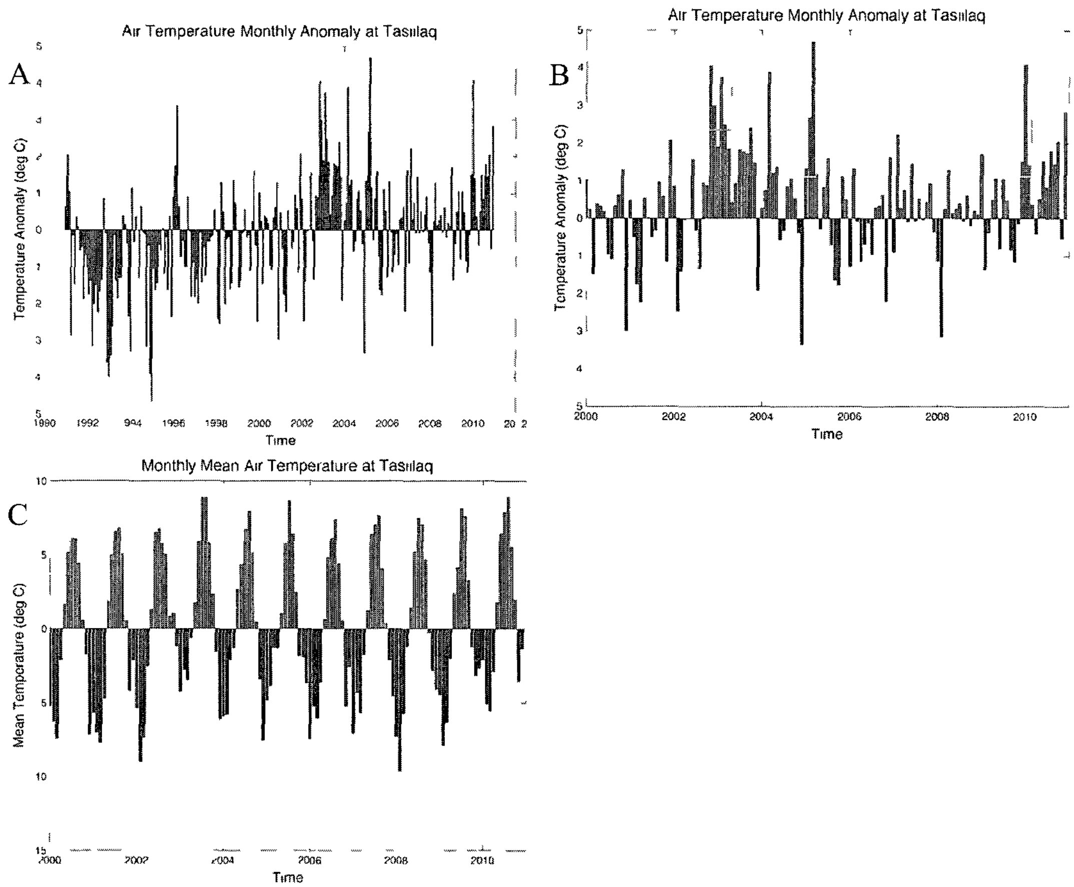

Figure 39: Monthly mean air temperature anomalies (deviation from the 20-yr monthly mean) at Tasiilaq (A) 1991 – 2010 and (B) 2000 – 2010. (C) Monthly mean air temperatures 2000 – 2010.

5.3 Nunatakavsaup Sermia and Northeast Baffin Bay

5.3.1 Terminus History

Nunatakavsaup Sermia (NKS) is an outlet glacier in Northwest Greenland (74.61°N, 56.13°W) that has exhibited rapid retreat since 2002 (Figure 40b). The pattern of retreat, however, is different than others in this study. While other outlet systems showed considerable seasonal variability of the calving front over the last decade (e.g. JI, Helheim, Midgards), Nunatakavsaup Sermia shows reduced seasonal modulation of the terminus. Instead, the primary mode of the glacier over the last decade has been a continuous retreat. Where the terminus did experience winter re-advance (Figure 40c), the advance was generally far less than the adjacent summer retreat, which ultimately drove the overall retreat of this tidewater glacier.

NKS's calving front retreated more than 10 km over the last decade. The retreat began in 2002 when the winter terminus failed to re-advance and quickly escalated as the terminus retreated more than 7 km over the next 3 years. The rate of terminus retreat slowed between 2006 and 2010 as the terminus retreated a total of 2.25 km, and the calving front reached a region of converging ice flow at the head of the fjord.

The glacier terminus failed to re-advance a total of five winters (2002, 2003, 2005, 2008, and 2011) over the last decade. The largest retreat of the record, summer or winter, occurred during the 2005 winter when the terminus retreated ~2.24 km behind the fall minimum position. The terminus retreated 0.6 km during the 2011 winter after re-advancing during the 2009 and 2010 winters. The calving front moved very little (10's of meters) during 2002, 2003, and 2008 winters; coupled with km-scale summer retreats in those years, the lack of winter re-advance contributed to the overall retreat of the glacier terminus. The continuous retreat and overall lack of seasonality along the calving front differentiate NKS from the other glaciers researched in this study.

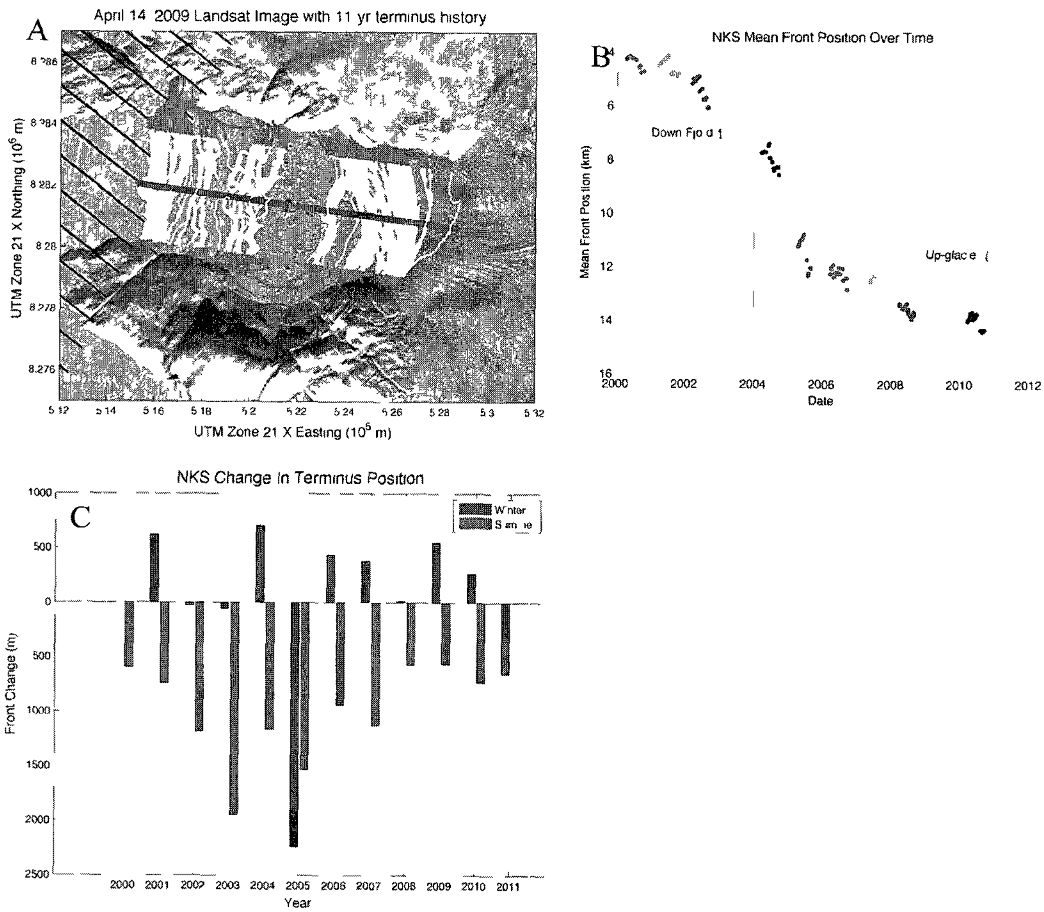

Figure 40: Landsat derived terminus history of Nunatakavsaup Sermia. (A) 10 years of digitized fronts. (B) Time series of the mean front position. (C) Seasonal change in mean terminus position. Positive values indicate a mean advance of the calving front, negative values denote a mean retreat. Red bars indicate summer changes; blue bars represent winter changes. Despite seasonal advances in some winters up to 500 meters, NKS generally exhibited between a pattern of winter retreat.

5.3.2 Sea Ice Conditions in Baffin Bay and Implications for NKS Terminus

The MODIS SST record for NKS begins at the former location of the glacier terminus in 2000, ~4 km east of the mouth of the fjord, and extends west into Baffin Bay (Figure 41). It is important to note the record for NKS only includes ~4 km of fjord surface temperatures; the majority of the record reflects the SST record of Baffin Bay. This is a departure from the transects of the other glacier systems in this study which included substantial coverage in the inner and middle sections of the fjord surface.

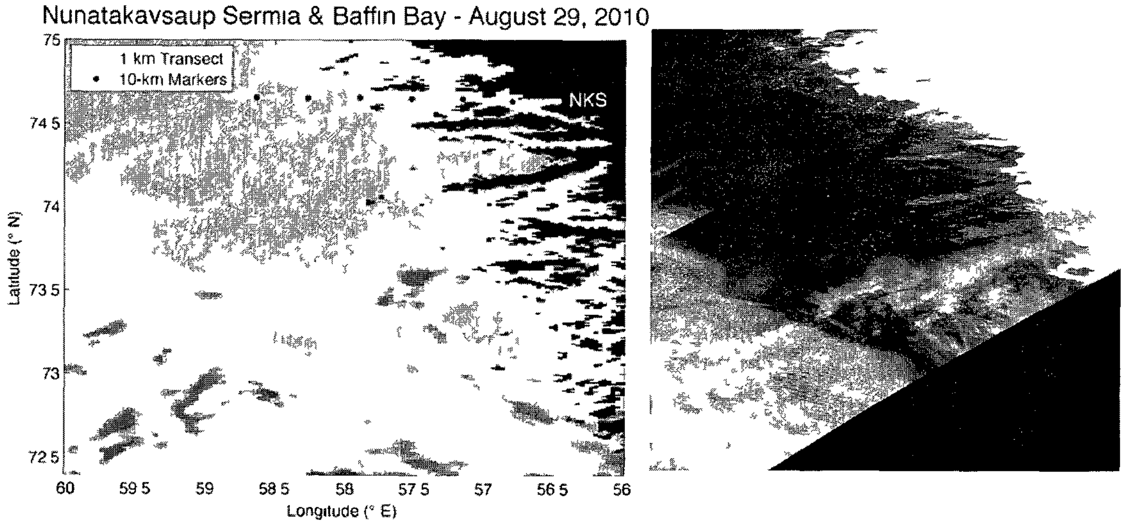

Figure 41: MODIS derived images of Northwest Greenland and Baffin Bay acquired on August 29, 2010. (Left) Thermal SST map with the location of the SST transect; (Right) Visible band image.

The sea ice temperatures at this high latitude were well below -20°C for several months of the year, freezing up in December and remaining cold and coherent until mid-late April for each year in the record (Figure 42). Note that the January –April timeframe is also when this slowly moving glacier showed periods of re-advance. Overall, the MODIS SST record indicates the sea ice was extensive and largely homogenous throughout Baffin Bay. Despite little spatial and temporal variability in the sea ice cover, the glacier exhibited continuous retreat throughout the record, suggesting the sea ice in Baffin Bay has little effect on calving at the NKS's terminus.

There are several reasons NKS shows different behavior than the other systems covered here. The long cold periods (e.g. Figure 42) and slow glacier flow of NKS limit the total amount of calved ice in the system. In addition, the difference in fjord geometry of NKS might also influence terminus behavior. As stated earlier, the fjord system of NKS is notably shorter than the other fjord systems researched in this study. For example, at present, JI terminates into the head of a fjord 60 km east of Disko Bay; NS and KNS terminate in the long and winding Godthabsfjord, ~110 and ~160 km, respectively, from Davis Strait; and Helheim and Midgards Glaciers terminate in Sermilik Fjord, ~110 and ~124 km respectively, away from Denmark Strait. These long fjords provide some protection for the ice mélanges and glacier terminuses from ocean processes. In contrast, NKS presently terminates into a 14-km long fjord east of Baffin Bay, which prior to the recent change in 2000 was only 4 km long. The relatively short length of the fjord means that the limited amount of ice calved from NKS, predominately during the summers, has a much shorter distance to travel to escape the confining walls of the fjord and thus could be dispersed faster to the open waters. The shorter residence time of icebergs in the fjord meant that less ice was available to develop as an ice mélange in the pro-glacial fjord. Without a well-developed matrix of ice calved from a glacier terminus bound together by sea ice [*Amundson et al.*, 2010], the structural rigidity of the sea ice in the fjord is likely decreased significantly.

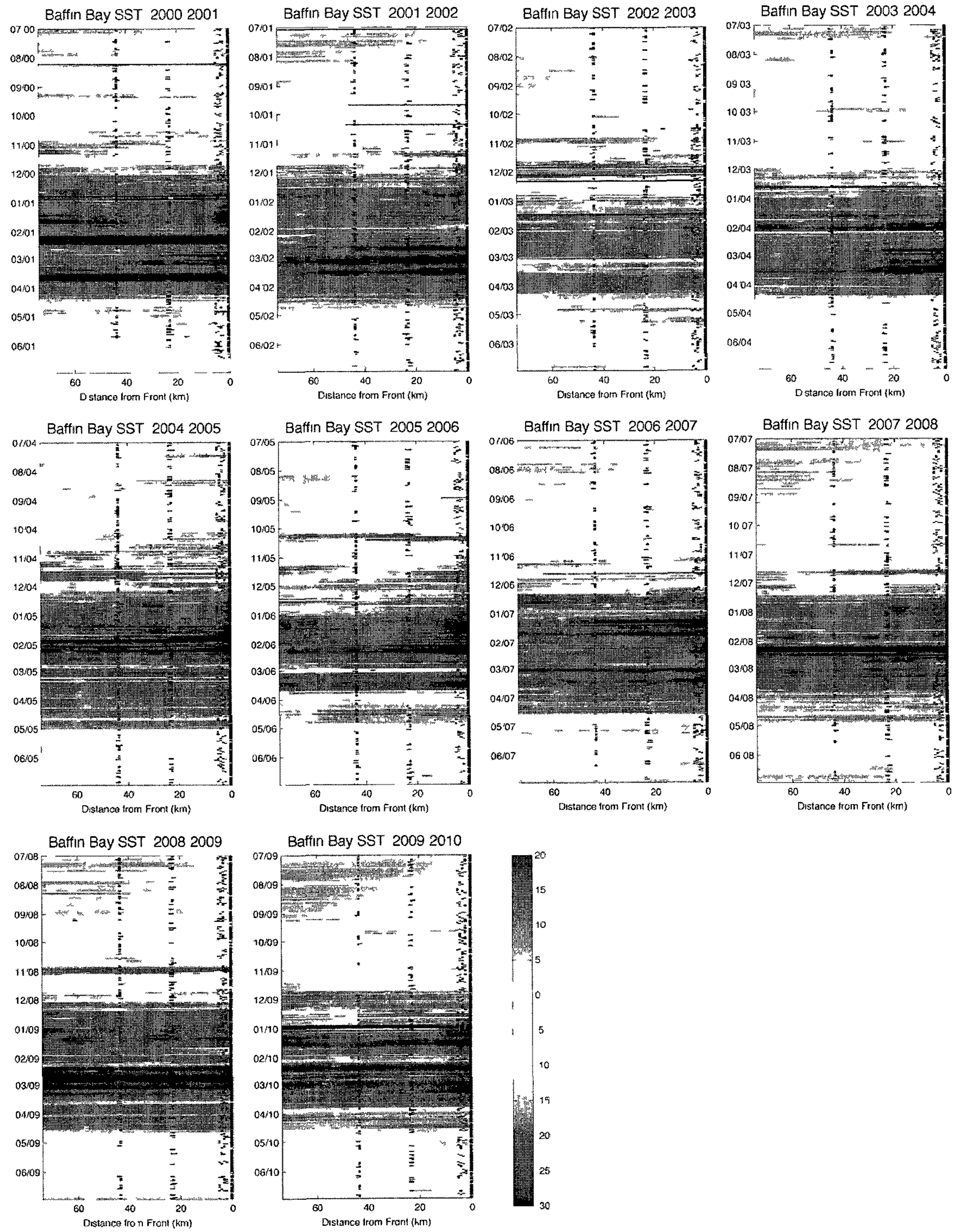

Figure 42: SST data values for a transect beginning nearest the terminus of Nuntakavsaup Sermia (0 km) moving west into Baffin Bay.

6 Discussion and Conclusions

6.1 Discussion

Recent changes in outlet glacier behavior (e.g. glacier velocity increase and terminus retreat) have increased the flux of ice discharged into Greenland's fjords, which has bolstered ice mélange development. Ice mélange characteristics can vary by fjord; while some (e.g. KNS and NS in Godthabsfjord) have ice mélanges composed of smaller bergs and brash ice that experience repeated breakups with open water frequently appearing at or near the glacier terminus, others, such as Jakobshavn Isbrae have mélanges that are densely packed and made from icebergs with dimensions up to 1 – 2 km, and remain cohesive enough to prevent open water within 5 km or more of the terminus (at least since the collapse of the floating tongue). Overall, the mélange ice is largely unconsolidated and mobile during the warm summer months; but during cold arctic winters, the water at the surface within the mélange freezes and it consolidates to form a rigid body that can have a profound effect on outlet glacier dynamics. Winter fjord ice cover conditions can be highly variable, however, and several factors can influence the structural integrity of the winter ice mélange, including the size and quantity of icebergs in the pro-glacial fjord, fjord water temperatures, and atmospheric conditions. Consequently, such winter mélange variability can have a significant impact on the dynamics of Greenland's outlet glaciers.

6.1.1 Ice Mélange Development

Amundson et al. (2010) define the ice mélange as a matrix of calved ice and disintegrated icebergs in the pro-glacial fjord that are bound together by sea ice. By definition, sea ice alone does not constitute an ice mélange; it lacks the structural rigidity to inhibit winter calving and evidence from NKS (section 5.3.2) and Midgards Glacier (section 5.2.2.1, 2000 – 2004 and 2008 – 2010) support this assertion. Glacial ice calved from a terminus, specifically copious amounts of calved ice, is a necessary component of an ice mélange.

A retreating outlet glacier will generally calve more ice into the fjord than an advancing glacier [*MF Meier and A Post*, 1987]; the increase in calved ice into the pro-glacial fjord can lead to a thicker, more densely packed ice mélange if iceberg residence times are sufficiently long and surface temperature conditions are favorable. The ice mélange in Kangia Fjord is perhaps the classic example of this phenomenon. Following the collapse of the floating tongue in 2003, glacier velocities increased along JI while the calving front retreated several kilometers; this newly added ice was introduced into an already ice-filled fjord and likely bolstered the mélange strength which ultimately contributed to an increase in the dynamic range of the seasonal variations in terminus position. During cold winters (e.g. 2001, 2002, 2004, 2007 - 2009) the ice mélange promoted a 5-6 kilometer re-advance of the terminus, an increase from the 2.5 km seasonal modulation of the calving front JI exhibited during the late 20th century, prior to the recent changes [*Sohn et al.*, 1998].

6.1.1.1 *Significance of Fjord Geometry on Ice Mélange Terminus Control*

The characteristics of fjord geometry affect mélange control of the calving front in two ways: 1) by aiding in iceberg retention, and 2) by applying pressure along the sides of the rigid winter mélange. Intricate fjord systems that aid in the retention of icebergs increase the residence time of calved ice in the inner fjord, which can bolster the mélange fabric. Complex, elongated fjords such as Kangia Fjord and Godthabsfjord have well-developed ice mélanges in part because of the protective and confining nature of their narrow fjord walls. In contrast, the relatively short length and non-confining walls of the recently exposed Nunatakavsaup Sermia fjord failed to retain enough calved ice in the pro-glacial fjord to build a well-structured mélange that could inhibit winter calving. As a result the terminus showed limited seasonal variability; instead it exhibited a near decade-long pattern of continuous retreat to its current position at the convergence of multiple glaciers at the ice sheet margin.

The long, exposed bedrock walls and local constrictions in Greenland's fjords create a rigid boundary for a consolidated ice mélange. Narrowing of the walls present a bottleneck to a rigid mélange as it is pushed downfjord by the advancing glacier. Thus the shear supported along the lateral edges of an ice mélange by the fjord walls contributes to the overall backpressure imposed by the mélange at the glacier terminus; a less compacted and more mobile mélange would otherwise be pushed easily downfjord, unimpeded by the stress imposed by the fjord walls.

6.1.2 Temperature Control on Mélange Rigidity

Fjord water temperatures and atmospheric conditions also factor into mélange stability. Warm temperatures at the boundary layer between the fjord surface and the atmosphere or at the base of the fjord ice cover in contact with warm fjord water can inhibit freezing of the sea ice that binds the matrix of calved ice together; this results in a less consolidated mélange that is much less rigid and thus unlikely to provide enough backpressure to the terminus to inhibit calving. Episodes of sustained mid-winter warming were observed in Kangia Fjord during the 2010 winter; warm air temperatures persisted for multiple days and may have ultimately softened the winter ice mélange. When coupled with high velocity downfjord winds, the ice mélange became mobile which reduced the backpressure imposed by the mélange at the calving front and ultimately led to winter calving (section 4.2.2).

6.1.3 Mélange Influence on Outlet Glacier Dynamics

A well-developed ice mélange has several implications for outlet glacier dynamics. A temperature-modulated mélange can impact winter calving and affect the seasonal location of the calving front, which influences glacier speed and thickness, and has implications for the stability of the glacier and the location of the grounding line. Conversely, the development of a cold, rigid ice mélange can slow the retreat of an unstable tidewater glacier.

6.1.3.1 Seasonal Influence of a Rigid Mélange on Glacier Dynamics

As was demonstrated, the cold air temperatures of the arctic winter (section 4.2.2.1) can cause a well-developed ice mélange to freeze, become rigid, and impose enough backpressure to a glacier terminus to inhibit calving. The glacier continues to flow as calving ceases and thus the terminus advances. For many tidewater outlet glaciers, certainly for Jakobshavn Isbrae, the ice in the terminus region has thinned to near flotation and the basal water pressure at the terminus is close to the pressure from the ice overburden. As calving ceases, the glacier terminus advances and a floating tongue develops. The development and advection of the floating tongue initiates two feedbacks that can contribute to a slower, thicker glacier terminus region. First, the addition of the floating tongue, which is essentially a thicker, more robust version of the ice mélange, reinforces backpressure in the terminus region. The additional backpressure reduces the longitudinal stress and lowers rates of internal deformation within the glacier as glacier velocities slow in the terminus region (e.g. Figure 14). Velocities further up glacier, however, remain unchanged and the near-terminus slow-down results in ice thickening at the grounding line. As the near-terminus region thickens, the effective pressure increases and the terminus region slows even more. The process continues as long as the mélange in the pro-glacial fjord remains cold, consolidated, and rigid enough to inhibit winter calving. When sustained for an entire winter, the process results in a slower, thicker, and thus more stable springtime glacier configuration with the calving front located several kilometers downfjord. This is consistent with *Amundson et al., (2010)* who first proposed the mélange could indirectly affect glacier flow in the near-terminus region. If, however, the winter ice mélange is destabilized such that winter calving is no longer inhibited, the advection of the floating tongue is minimized, longitudinal stresses within the glacier remain high and the glacier enters the spring season flowing faster and in a thinner configuration

The change in the effective pressure in the terminal reach of an outlet glacier has implications beyond glacier velocity. As an outlet glacier thins, the glacier moves closer to flotation, less of the glacier is grounded and thus moves towards an unstable configuration [*Pfeffer*, 2007]. The consequent retreat of the grounding line propagates thinning inward, accelerating flow further upglacier as flotation there is approached. This unstable situation can be reached in an outlet glacier that is dynamically thinning for a longer duration of the year; if sustained in many systems, it will effectively reduce the mass of the GIS.

6.1.3.2 Mélange Control on Calving Front Position

The process of a cold, stable winter ice mélange promoting advection of a floating tongue occurred repeatedly over the last 8 years in Kangia Fjord and along Jakobshavn Isbrae and typically resulted in the development of an annual ~5 km long floating tongue. During winters in which the mélange exhibited unstable behavior, the winter advance was much smaller. This demonstrates that a winter ice mélange can act as a control on winter advance of the terminus and subsequently the location of the springtime calving terminus. For Kangia Fjord and Jakobshavn Isbrae, this relationship was well correlated over the last decade (Table 2); this correlation helps demonstrate that this winter re-advance is enhanced during winters in which the fjord surface remained cold and consolidated. Though the relationship was not as strong at KNS, NS, and Midgards, the correlation still suggests the pro-glacial ice mélanges in the fjords of these glaciers exerts some control on the winter re-advance of the calving fronts. The relationship was

Table 2: Summary of regression results for mélange influence on winter advance

Glacier	Linear Fit	Slope
Jakobshavn Isbrae	$r^2 = 0.73$	Negative
Kangiata Nunaata Sermia	$r^2 = 0.51$	Negative
Narsap Sermia	$r^2 = 0.55$	Negative
Helheim	$r^2 = 0.17$	Negative
Midgards	$r^2 = 0.54$	Negative
Nunatakavsaup Sermia	n/a	n/a

poor for Helheim Glacier and was not calculated for NKS, which exhibited limited seasonal modulation of the calving front. These results are not all that surprising. JI drains approximately 7% of the GIS; its fast flow and large drainage area is why many scientists (e.g. [*Holland et al.*, 2008]) consider JI to be Greenland's largest exporter of ice. A glacier with such large ice export would have the necessary components to develop a sustainable ice mélange that could influence glacier dynamics as strongly as the regression suggests. Mélange ice in Kangia Fjord is observed to be much thicker and thus more robust than the mélange in Godthabsfjord, which often experiences open water at the termini of NS and KNS. This might explain the particularly strong relationship between JI and the mélange ice in Kangia Fjord compared to the rest of the glacier systems looked at in this study.

6.1.3.3 Mélange Influence on Stepped Retreat of Outlet Glaciers

Narsap Sermia and Midgards Glacier exhibited similar patterns of retreat that were remarkably different than the other glaciers in this study. Although both glaciers demonstrated mélange driven seasonal variability of the calving front, the unique pattern of step-like retreat that resembles a sort of punctuated evolution of outlet glacier retreat behavior suggests some hysteresis in the mélange ice – glacier terminus relationship that ultimately slowed the retreat of the calving fronts. Both glaciers were relatively stable during the early part of the decade; an initial perturbation forced a retreat of both glaciers, which put more ice into the pro-glacial fjord. The newly added ice may have then fortified the ice mélange, which stabilized the terminus region and temporarily stalled terminus retreat for a few years, while also increasing the dynamic range of the seasonally modulating terminus. Another perturbation occurred during the last two warm winters of the record that disrupted mélange stability and both glacier fronts continued to retreat but at a much higher rate. The mélange character and terminus response of NS and Midgards demonstrate the temporarily stabilizing effect that a cold, rigid winter mélange can have on glacier retreat.

6.2 Conclusions

Cold, rigid winter mélange ice can have a significant impact on glacier dynamics in Greenland fjords. It can exert influence on the seasonal position of the calving front, which may then have implications for glacier thickness, speed, and overall stability of the front at the onset of springtime conditions. Interannual variation in conditions in the winter mélange ice helps explain the seemingly erratic behavior of outlet glaciers in Greenland over the last decade. The process appears to work in both directions; a cold, rigid, winter mélange can slow a tidewater glacier in retreat and allow a floating tongue to develop which has implications for thickening at the grounding line and glacier stability.

This study created a record of fjord ice conditions for six of Greenland's pro-glacial fjords with near-daily temporal resolution. The record showed that for many of Greenland's fjord systems the duration of the winter in which consolidated fjord ice persists in the pro-glacial area has decreased over the last decade, with the biggest changes occurring during the latter part of the record. These changes in consolidated fjord ice are correlated with changes in the glacier terminus; winters with shorter periods of cold rigid mélange ice correlate with winters in which the calving fronts exhibited minimal seasonal re-advance. For Jakobshavn Isbrae and Kangia Fjord, mid-winter calving generally occurred when the mélange ice experienced episodes of warming and increased mélange mobility. A comprehensive calving record was not available for the other glacier systems looked at in this study, but correlation between the duration of a cold rigid mélange in the inner fjord and the magnitude of the winter re-advance suggests that winter calving has indeed occurred at other Greenland fjord systems, and may ultimately control the overall retreat of the glacier termini. Lastly, velocities in the terminal reach of Jakobshavn Isbrae exhibited a response to the destabilizing mélange ice; seasonal velocities of the terminus region were faster when the mélange ice destabilized and a floating tongue failed to develop.

Limited understanding of glacier dynamics at the ocean-glacier interface has confounded attempts to make accurate predictions of the future behavior of the major ice sheets and estimates of global sea level rise. This study of observed coincident change between changing fjord conditions in Greenland and outlet glacier behavior provides some insight into the relationship at the ocean-glacier boundary. Winter ice mélanges in Greenland's pro-glacial fjords can play an important role in the evolution of tidewater glacier retreat. When fjord and temperature conditions allow, an ice mélange can inhibit winter calving; the cessation of calving triggers a series of mechanisms that ultimately influence outlet glacier behavior. The observed ice mélange control on outlet glacier dynamics in Greenland's fjords begins to answer some of the questions about how glaciers respond to a warmer climate. Ultimately arctic winters that experience periods of sustained warmth can inhibit winter ice mélange consolidation in Greenland's fjords which have implications for the pace at which outlet glaciers deliver ice to the oceans; the effect of which will impact ice volume of the world's major ice sheets and consequently global sea level.

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