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Changes in the marine-terminating glaciers of central east Greenland and potential connections to ocean circulation, 2000–2010

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Abstract

Outlet glaciers on the periphery of the Greenland Ice Sheet have undergone substantial changes in the past decade. Limited geophysical observations of the marine-terminating glaciers of eastern Greenland's Geikie Plateau and Blosseville Coast suggest rapid rates of mass loss and short-term variability in ice dynamics since 2002. Glaciers in this region terminate into the Denmark Strait, which is a thermodynamic transition zone between the Arctic and North Atlantic oceans spanning from 66° N to 69° N. We examine time series of thinning, retreat and flow speed of 38 marine-terminating glaciers along the central east Greenland coast from 2000 to 2010 and compare this record with coastal sea surface temperatures to investigate a potential relationship between warming of the sea surface and increased melt at the glacier termini. We find that glacial retreat, thinning and acceleration have been more pronounced throughout the Denmark Strait, supporting our hypothesis that ocean warming associated with shifts in the Irminger and East Greenland currents are causing increased melt at the ice-ocean interface.

1 Introduction

Rapid, unpredicted changes in the dynamics of fast-flowing outlet glaciers draining the periphery of ice sheets have lead to increased rates of mass loss (e.g. Rignot and Kanagaratnam, 2006; Tapley et al., 2004; Krabill et al., 1999, 2004; Luthcke et al., 2006; Thomas et al., 2006; Pritchard et al., 2009). Multiple studies using a range of methods show that mass loss in Greenland is due to both increased surface melting and discharge from marine-terminating outlets, especially in the southeast and northwest quadrants (Luthcke et al., 2006; Velicogna and Wahr, 2006; Velicogna, 2009; van den Broeke, 2009).

Previous studies have linked recent increases in mass loss to changes in ocean circulation (e.g. Holland et al., 2008; Hanna et al., 2009; Straneo et al., 2010). The observed speed-up of outlet glaciers in southeast Greenland in the early 2000's coincided with the onset of a warming trend in the subpolar North Atlantic Ocean (Straneo et al., 2010; Myers et al., 2007; Bersch et al., 2007; Thierry and Mercier, 2008). Additionally, abrupt warming of subsurface ocean temperatures in 1997 along Greenland's west coast correlates with thinning and retreat of Jakobshavn Isbræ, likely initiated by the influx of warmer water originating in the Irminger Sea off the southeast coast of Greenland (Hanna et al., 2009; Holland et al., 2008).

It is possible that warming of the ocean surrounding the Greenland Ice Sheet is increasing melt and retreat of the ice sheet's outlet glaciers, either independently of, or in addition to atmospheric warming (Box, 2009). Although the mechanisms driving the circulation of warmer North Atlantic waters are not well understood (e.g. Straneo et al., 2010), one hypothesis is that increased glacier runoff promotes convection of deep, warm fjord water through entrainment of relatively warm ocean water with more buoyant subglacial meltwater plumes, increasing melt rates at the calving front (Motyka et al., 2003; Rignot et al., 2010). Increased melt has been observed through limited in situ measurements at the ice-ocean interface throughout the last decade, with the temperature and renewal rates of ocean water suggesting that this water is causing increased submarine melting at the margin of the ice sheet (Seale et al., 2011; Straneo et al., 2010; Thomas, 2004; Nick et al., 2009). Recent oceanographic studies have demonstrated that although subtropical ocean waters reach glacier fjords in southeast Greenland, there is no proof that it comes into direct contact with glaciers. Alternatively, Straneo et al. (2010) indicated that warming of North Atlantic subsurface water itself could increase melt and calving rates. A recent study by Seale et al. (2011) suggests that warming of the North Atlantic via subtropical water transport by the Irminger Current may be causing increased inter-annual melt rates in east Greenland glaciers south of 69° N, with limited to no inter-annual glacier change occurring north of that latitude.

Numerous, large marine-terminating outlet glaciers drain the central-eastern part of the Greenland coast from Sermilik Fjord at roughly 66° N north to Scoresby Sound at 71° N latitude, including the Geikie Plateau and Blosseville Coast regions (Fig. 1).

This region includes the thermodynamic transition zone from the North Atlantic Ocean into the Arctic Ocean through the Denmark Strait, spanning from roughly 66° N to 69° N. Contrasting patterns of glacial change spanning the length of the Denmark Strait would provide further evidence that changes in the circulation of the North Atlantic Ocean are causing accelerated melt of the marine-terminating outlet glaciers in southeast Greenland.

This study uses satellite measurements to observe changes of these 38 marine-terminating glaciers wider than 2-km in central-eastern Greenland from ∼65°34′ N to ∼71°53′ N over the past decade. From these data, we identify differences in behavior between glaciers north and south of the Denmark Strait's northern limit (∼69° N) to test the hypothesis that such behavior is directly associated with changes in North Atlantic circulation. This study attempts to corroborate results by Seale et al. (2011) which suggested that a disparity in inter-annual glacier behavior north and south of 69° N may be caused by warm subsurface ocean conditions south of 69° N, by examining more glaciers near this oceanographic transition zone using imagery with a higher spatial resolution. Additionally, we assess the importance of the other mechanisms of glacier change in this region, such as surging and variability in dynamic thinning.

2 Data sources and methods

Data acquired from 2000 to 2010 over the Geikie Plateau and Blosseville Coast regions are sourced from the visible and near-infrared (VNIR) bands of the Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER) and the panchromatic band of the Landsat-7 Enhanced Thematic Mapper Plus (Landsat-7 ETM+) satellites. Imagery from these sources are used to create time series of front position, flow speed, and elevation change (from ASTER digital elevation models). Sea surface temperatures were derived from data collected by the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument.

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Imagery from the Landsat-7 ETM+ satellite was obtained from the United States Geological Survey (USGS) Global Visualization Viewer (GLOVIS, http://glovis.usgs.gov) public archive. Mostly cloud-free images were selected to create image mosaics of the area for each year of the study period. Orthorectified images and digital elevation models (DEMs) from ASTER were obtained from the USGS Land Processes Data Active Archive Center (LP DAAC, https://lpdaac.usgs.gov), including images that were cloud-free or partially clouded in order to quantify thinning rates with minimal error. ASTER's host satellite, Terra, has a 16-day repeat pass cycle but images are only acquired on-demand, so that few images are available for a given glacier each melt season (Joughin et al., 2008). DEMs are created using nadir and backward-looking VNIR image pairs acquired 57 s apart. Relative DEMs are produced without ground control and were later registered using offsets over off-ice terrain (i.e. stationary bedrock). Following this correction, DEM vertical accuracy is better than ±10 m over glacier ice.

MODIS sea surface temperatures (SSTs) were obtained from the Physical Oceanography Distributed Active Archive Center (PODAAC, http://podaac.jpl.nasa.gov). Identical MODIS instruments are onboard two NASA Earth Observing System (EOS) satellites, Terra and Aqua, making MODIS capable of covering the entire surface of the Earth twice daily. SSTs are determined using an algorithm described by Armstrong (2002), and have an accuracy of ±0.25 °C.

2.1 Front positions

Front positions for each glacier were manually digitized from Landsat-7 ETM+ and ASTER images using two methods of measurement: first, a polygon-vector method (e.g. Moon and Joughin, 2008; McFadden et al., 2011) was used to measure changes in the near-terminus area, and second, a centerline method was used to measure the intersection of the ice front with the central flow line of the glacier. The polygon-vector method accounts for asymmetric variations in front shape of each glacier because front position vector tracings give information on net area change of each glacier, but this method is time-consuming and inaccurate when the front is only partially visible. The

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centerline method, in contrast, is a less time-consuming process and measurements can be made even when the front is partially obscured by clouds, but this method only captures variability at a single arbitrary point along the front. In order to test the sensitivity of our results to either method, we mapped the fronts of 3 glaciers using both methods for comparison (Midgard, Kangerdlugssuaq, Sortebrae). These two methods yield very similar results (typically an offset of ±0.1 km between methods). We therefore used the more efficient centerline method to generate our dataset.

2.2 Surface elevations

Transects were drawn along the central flow line from sea level to the accumulation zone on the first Landsat-7 ETM+ image for each glacier (usually from 1999), and this transect information was transferred to the ASTER DEM subsets. Elevation profiles along these transects were generated for each glacier to quantify thinning. Individual elevation profiles were manually edited for errors resulting from clouds and failure of the DEM generation software (and subsequent generation of spurious elevation data). The data were then vertically registered by subtracting offsets in sea level (0 m a.s.l.) in sea ice-free regions. Multiple elevations for a given year were averaged together to give a single elevation profile for each year in the time series.

2.3 Surface speeds

We extracted glacier surface speeds from ASTER and Landsat image pairs using the IMMATCH/MIMC Repeat Image Feature Tracking (RIFT) software distributed by the Glacier Dynamics Group at The Ohio State University. A detailed description of the software, including a full error assessment and validation, is given in Ahn and Howat (2011) and a more brief description is found in Howat et al. (2010). Here we examine a time series of average surface speeds taken from a point along the centerline near the front of each glacier. Error in this method varies with pixel resolution and time between image pairs, and is less than 1 m d^{-1} for the data used in this study (Ahn and Howat, 2011).

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3 Results

We find a wide range in glacier behavior across our study area over the past decade. In general, our results support the findings of Seale et al. (2011) which suggested that a strong contrast in inter-annual glacier behavior north and south of 69° N may be caused by warm subsurface ocean conditions south of 69° N. A greater magnitude of change, especially in extent of front retreat, occurred on the glaciers terminating on the southern and eastern portions of the Geikie Plateau (Blosseville Coast) and along the Kong Christian IX Land coastline running from Sermilik Fjord to Kangerdlugssuaq Fjord (see Fig. 1), supporting the hypothesis that warming of Greenland's coastal waters is the primary trigger for change. In contrast, we find little change occurred on the glaciers found on the northern portion of the Geikie Plateau. Our results are presented in detail below.

3.1 Overview of front position changes

All 38 glaciers retreated between 2000 and 2010, but the magnitude of retreat was highly variable, ranging from $\leq$0.1 km to ~9 km. Only one glacier retreated less than 0.1 km (Gasegletscher), which is within the measurement error. The mean retreat for all 38 glaciers over the time period was 1.6 km, with the largest change observed to be 9.2 km from 2000 to 2010 (Midgard). Greater front retreat is found on the southern Geikie Plateau (Blosseville Coast) and the Kong Christian IX Land coastline, with 14 of the 25 glaciers in this area retreating >1.0 km over the time period. The mean total retreat of glaciers in this region of the study area was 2.1 km, while the mean total retreat of glaciers terminating into Scoresby Sound and further north was <0.5 km. The large retreats of a few glaciers, however, skew the mean front retreat; the median retreat for all 38 glaciers in the study area is only 0.9 km. Nearly half of the glaciers retreated $\geq$1.0 km during the study period. Figure 2 shows total front change for each glacier as the difference in front position from 2000 to 2010.

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3.2 Overview of surface elevation changes

Thinning rates were much more variable and not as spatially consistent as changes in front position. We generally observe no change on the glaciers terminating into Scoresby Sound and its channels north of the eastern-most point of the Geikie Plateau peninsula (70°9′ N, 22°3′ W). For glaciers south of 70°9′ N, rates of thinning 15-km inland of the front varied from ≥ 10 m of thinning to ∼155 m of thinning between 2000 and 2010. For glaciers north of 70°9′ N, thinning rates varied from ∼10 m of thickening to 35 m of thinning between 2000 and 2010. Only two glaciers thickened over the study period (by ∼5–7 m at 15 km inland from the termini), both of which were located north of 70°9′ N. Figure 3 shows surface elevation change from 2000 to 2010 at a location 15 km from the terminus for each glacier. Figure 4 shows annual elevation profiles for the six glaciers discussed in detail below.

3.3 Overview of surface speed changes

Surface speeds varied both spatially and temporally, with the highest speeds measured on Kangerdlugssuaq and Helheim glaciers during periods of acceleration between 2005 and 2006 (e.g. Howat et al., 2008a; Joughin et al., 2008; Luckman et al., 2006). Many of the glaciers in this study exhibit seasonal variability in surface speed, oscillating on the order of ±7 m d^{-1} each year, especially in the Scoresby Sound region north of the Geikie Plateau. For example, Daugaard Jensen had speeds varying annually by 25 % between 7.5 and 11 m d^{-1}, while Rolige Brae had surface speeds varying seasonally between 6 m d^{-1} in the summer to near stagnation in the winter. Kangerdlugssuaq displayed the largest range in its surface speed as a result of its sustained acceleration between 2004 and 2006, accelerating from 10 m d^{-1} to 27 m d^{-1}. Maximum surface speeds occurred in the summer for all glaciers, with a mean maximum summer surface speed of 7.5 m d^{-1} for all glaciers in the study. Figure 5 shows average surface speeds for all glaciers in the study area.

3.4 Spatial patterns of glacier change

Here we discuss differences in glacier change between the three major subregions of the study area, with several glaciers discussed in detail to highlight regionally representative behavior. The regions are presented from south to north.

3.4.1 Kong Christian IX Land (Sermilik Fjord to Kangerdlugssuaq Fjord)

This area underwent the greatest magnitude of change in dynamics (i.e. front retreat, thinning, surface speed), with particularly large change in the magnitude of front retreat. Peak rates of front change occurred between 2003 and 2005, suggesting a regional forcing that was at a maximum during this time. The mean front retreat of glaciers in this subset was 2.9 km, and the median front retreat was 1.6 km over the entire study period. The average thinning observed 15-km inland of the glacier terminus was 28 m, and the elevation profiles for roughly half of these glaciers show evidence of extensive thinning (i.e. mean thinning at 15 km from the glacier terminus >30 m). The mean maximum surface speed was 8.8 m d^{-1}, with a median maximum surface speed of 7.7 m d^{-1}. All maximum surface speeds occurred in the summer months.

Midgard Glacier, which terminates into the long northeast channel of Sermilik Fjord, underwent the largest magnitude of change in front position, thinning, and surface speed of the glaciers sampled (Fig. 6). Sustained, inter-annual retreat of Midgard increased in 2003, with a pronounced pattern of seasonal advance-and-retreat lasting through 2007. Between early 2008 and late 2009, the glacier retreated 4.0 km before a brief period of re-advance in late 2009/early 2010, and followed by an additional retreat of 1.5 km. The most significant thinning occurred below 1000 m a.s.l. elevation and within 40 km of the terminus; the glacier thinned ~100 m from 2000 to 2010 at 10 km from the terminus, decreasing up-glacier. This rate of thinning was consistent with the pattern of front retreat throughout the time series, with an overall acceleration in both front retreat and thinning occurring in late 2007 into 2008. Surface speeds increased from ~4 m d^{-1} in 2000 to 9 m d^{-1} in 2009 at a center point approximately 5 km up-glacier from the glacier's most retreated position.

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3.4.2 Southern Geikie Plateau, Kangerdlugssuaq Fjord to Scoresby Sound (Blosseville Coast)

The glaciers along the Blosseville Coast display the highest degree of variability in changes in front position, thinning, and surface speed. While most glaciers underwent substantial change, there was no clear temporal or spatial pattern. On average, glaciers in this region retreated by 1.6 km, with a median retreat of 0.9 km and a median thinning of 22 m at 15-km inland of the front. Thinning rates were highly variable, with dynamic thinning evident on 2 of the 14 glaciers in this area, suggested by rapid acceleration followed by extensive thinning and stretching originating at the front. Observations of dynamic thinning were most pronounced for Kangerdlugssuaq (160 m). The mean (median) maximum surface speed for the glaciers in this region was 7.4 m d^{-1} (5.9 m d^{-1}) during the study period. All maximum surface speeds occurred in June or July.

Kangerdlugssuaq and Frederiksborg are examples of two glaciers in close proximity to one another that display contrasting behavior. Kangerdlugssuaq is ~9 km wide and terminates into a 40-km long fjord (Fig. 7). Several studies have documented the large, inter-annual retreat, acceleration and thinning of Kangerdlugssuaq (e.g. Luckman et al., 2006; Howat et al., 2007, 2011). This glacier's front oscillated seasonally by almost 2 km between 2000 and 2004. Between late 2004 and early 2006, Kangerdlugssuaq retreated ~5 km. During retreat, the glacier accelerated from ~12 m d^{-1} in 2000 to 27 m d^{-1} in 2006 and thinned more than 150 m near the front. Thinning propagated up-glacier following the period of acceleration. Kangerdlugssuaq surface speeds slowed following the 2005–2006 acceleration, and the glacier re-advanced or thickened so that the front of the glacier maintained a stationary position at approximately 7 km from the front position in 2000.

Frederiksborg is a much narrower glacier, terminating at two calving fronts into the same fjord as Kangerdlugssuaq. Frederiksborg retreated ~1.5 km from 2000 to 2004, and has maintained a steady pattern of 0.7-km seasonal retreat and advance since

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2005. This glacier had negligible elevation change from 2000 to 2009. In 2010, however, the glacier thickened significantly at a location approximately 10-km from the front (no elevation data available closer to the front in 2010). Surface speeds for this glacier were relatively stable from 2000 to 2006, varying between 3 and 5 m d^{-1}, with no observed seasonality. Beginning in 2007, however, the glacier began to show a large seasonal cycle in surface speeds, from near stagnation in the winter to 13 m d^{-1} in mid-summer, coinciding with the large seasonal variation in front position.

Several glaciers in this region have been previously identified as surging glaciers, with two examples evident in this study (Sortebrae and Johan Petersen Bugt). Glacial surges likely occur due to increased subglacial water pressure resulting from a linked-cavity subglacial drainage system, leading to a large speed-up over a short time period (Kamb, 1987; Jiskoot et al., 2003). Sortebrae (68°44′ N, 26°59′ W) is a surge-type glacier (e.g. Jiskoot et al., 2001) that has a large central trunk with smaller subsidiary glaciers occupying several channels on the south facing side of the Geikie Plateau. Sortebrae retreated steadily at roughly 500 m per year from 2000 to 2010. Consistent with this steady retreat, the glacier thinned 60 m within 15 km of its front with no resolvable thinning above. Since this glacier is in a quiescent period of surge behavior (Murray et al., 2002; Jiskoot et al., 2001) surface speeds were relatively slow, ranging from near stagnation to 3 m d^{-1}, with slight seasonality.

3.4.3 Scoresby Sound and North of the Geikie Plateau

The glaciers terminating into and north of Scoresby Sound exhibited relatively little change in front position, thinning, and surface speed. The mean (median) front retreat of glaciers in this subset was 0.5 km (0.3 km) with strong seasonal variations in front position and speed. The mean (median) maximum surface speed was 6.6 m d^{-1} (5.3 m d^{-1}). The strong seasonal signal in front change observed in this region is typified by Daugaard Jensen, which undergoes a seasonal oscillation in front position of ~1 km annually. Its inter-annual mean front position, however, has not changed since 2000. The glacier thinned approximately 30 m below 400 m elevation, with negligible thinning at higher elevations. Daugaard Jensen was the fastest moving glacier observed in the Scoresby Sound region, with a maximum speed of 11 m d^{-1} in June 2006 and a strong seasonal pattern of acceleration and deceleration generally following the cyclic pattern of front advance and retreat.

4 Discussion

Changes in the front positions, surface elevations, and surface speeds of 38 marine-terminating glaciers in central east Greenland indicate that glaciers in Kong Christian IV Land and the Blosseville coast, which terminate into the Denmark Strait, thinned and retreated more extensively than glaciers north of the Denmark Strait, suggesting a relationship between the warming of the North Atlantic and enhanced melt of glaciers in southeast Greenland. The ten outlet glaciers on the coast from Sermilik Fjord to Kangerdlugssuaq fjords all underwent accelerated retreat following 2003, a year of anomalously high air and sea surface temperatures along the southeast Greenland coast (Howat et al., 2008a). While there is a clear latitudinal distinction between the magnitudes of change, the relative magnitudes of thinning and retreat varied substantially from glacier to glacier. The discussion presented below focuses on the contribution of surging to regional glacier change and the effects of dynamic thinning on glaciers in this region, particularly south of Kangerdlugssuaq Fjord. Additionally, the discussion outlines the relationship between sea surface temperatures and magnitude of glacier change, including the use of sea surface temperatures as a proxy for ocean circulation patterns.

4.1 Surging glaciers in East Greenland

Several tidewater glaciers in east Greenland have exhibited surge-like flow speed behavior and morphological attributes (Jiskoot et al., 2003; Murray et al., 2002). Glacial surges are short-term events (days to weeks) where a glacier advances at rates of hundreds of meters per day due to a sudden release of trapped subglacial water, which lubricates the bed and causes the flow speed to accelerate by an order of magnitude. A glacial surge follows a quiescent period of slow retreat, which can vary from years to decades. Several means exist to identify "surging" glaciers, including warped moraine shapes, sheared-off ice tributaries, varying crevasse patterns, and rougher-than-usual glacial surfaces (Jiskoot et al., 2003). Surging has been documented on Sortebrae, which surged for ∼19–35 months from 1992 to 1995 following a quiescent phase of between 39–49 yr. Ice flow during the surge event increased by up to 60–1500 times over the glacier's quiescent-phase speeds and was sustained at rates of up to 30 m d^{-1} for more than 12 months (Murray et al., 2002).

During the study period Sortebrae exhibited characteristics typical of a quiescent phase; steady retreat without a seasonal oscillation of front position, which contrasts with the other glaciers in this region. The thickness of the glacier changed little over the decade, and it is one of the slowest moving glaciers in this analysis, with a maximum surface speed measured to be less than 2 m d^{-1} (occurring in July 2010). While Sortebrae is the only glacier in central east Greenland where active surging has been observed by aerial imagery, other studies (e.g. Jiskoot et al., 2003; Weidick, 1988) have identified morphological signs of surging on other glaciers in this region, including Dendrit and Borggraven glaciers along the Blosseville Coast, which indicates that surging is a regional mechanism for glacier change. There is disagreement in the literature regarding the predominant factor dictating whether or not a glacier will exhibit surge-like qualities. It is suggested that underlying bedrock younger than Precambrian in age (roughly 542 Ma), relatively low glacier slopes, and high equilibrium line altitudes may lead to surge-like behavior (Weidick, 1988; Hamilton, 1992; Jiskoot et al., 2003). However, Jiskoot et al. (2003) found that the underlying geology of known surging glaciers in east Greenland is variable both in age and lithology, and that glacial valley shape, which has a significant impact on glacier geometry, could determine whether or not a glacier will surge.

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4.2 Mechanisms for glacier thinning

In addition to remotely sensed observations, ice flow models suggest that marine terminating glaciers are sensitive to changes at the ice front and hydraulic basal conditions, leading to dynamic instabilities and thinning (Nick et al., 2009). Dynamic thinning occurs when perturbations in glacier stresses at the calving front propagate upglacier, causing acceleration and thinning to migrate inland (Joughin et al., 2008; Nick et al., 2009). Dynamic thinning is the primary cause of observed thinning for marine-terminating outlet glaciers along the northwest and southeast margins of the Greenland Ice Sheet (Abdalati et al., 2001; Krabill et al., 2004; Howat et al., 2005; Pritchard et al., 2009).

Dynamic thinning has been observed on several glaciers in southeast Greenland, including Kangerdlugssuaq, where dynamic thinning is detectable from the glacier's terminus to ~100 km inland (Pritchard et al., 2009). Our observations suggest that roughly half of the glaciers between Sermilik and Kangerdlugssuaq fjords are experiencing rapid dynamic thinning as well, with the most dramatic example of the changes in Midgard Glacier. From the glacier's elevation profile, it is apparent that thinning began near the front of the glacier at the beginning of the time series and has since propagated at least 45-km inland. In our study region, dynamic thinning is mostly confined to the south of Kangerdlugssuaq, where mean and median surface speeds are the highest. Thus, it is likely that the smaller glaciers to the south of Kangerdlugssuaq are contributing a considerable amount of the mass loss measured from southeast Greenland as previously discussed in Howat et al. (2008b). This could explain the continued high rates of mass loss observed by GRACE in the southeast, despite decreased rates of loss at Kangerdlugssuaq, and mass gain at Helheim (Howat et al., 2011).

4.3 Oceanographic forcing of glacier melt

Limited studies of the subsurface ocean conditions of the North Atlantic surrounding southeast Greenland reveal a spike in temperatures of the subpolar North Atlantic Ocean from 2003 to 2004, which coincided with this regional acceleration of glaciers in southeast Greenland (Straneo et al., 2010; Myers et al., 2007; Bersch et al., 2007; Thierry et al., 2008). Examination of oceanographic data collected in the fjords and on the continental shelf near three of Greenland's largest glaciers, including Kangerdlugssuaq and Helheim on the east coast and Jakobshavn Isbræ on the west coast, suggests that changes in oceanographic conditions may be capable of triggering major changes at the termini of Greenland's marine terminating glaciers (e.g. Holland et al., 2008; Straneo et al., 2010). Holland et al. (2008) documented a sudden increase in ocean temperatures along the west coast of Greenland in 1997 that corresponded with rapid thinning at Jakobshavn Isbræ, a glacier that had been slowly thickening and decelerating throughout the 1990s. Warmer, more saline waters originating from the Irminger Sea off the southeast coast of Greenland likely migrated along the West Greenland Current and infiltrated glacial fjords along the west Greenland coast. Before 1997, Jakobshavn Isbræ terminated into a 15-km long floating ice tongue. A sudden increase in the temperature (+1.1 °C) of the fjord water could explain the roughly 80 m yr^{-1} of thinning that occurred between 1997 and 2001, and the disintegration of the glacier's floating tongue soon after (Motyka et al., 2011; Holland et al., 2008).

Although changes in oceanographic forcing have been correlated with the retreat of Jakobshavn Isbræ, widespread measurements of subsurface ocean conditions are not readily available and sea surface temperatures (SSTs) may not be a reasonable proxy for subsurface ocean temperatures for most Greenland outlet glaciers. However, the data derived from MODIS used in this study show a clear increase in SSTs in late 2003 at the southern-most study site (SST-A), which is ∼80 km south of the mouth of Sermilik Fjord and 140 km south of the terminus of Helheim Glacier. Maximum temperatures at this location increased from 6 °C in late 2002 to 9.5 °C in late 2003. Two other SST-observation sites, SST-B and SST-C, also show a slight increase in temperature from 2002 to 2003. Additionally, the temperature at SST-A appears to have increased in late 2010 although not as dramatically as in 2003, so continued monitoring of the glaciers in southeast Greenland is necessary to see if another regional glacier change event has been initiated. The two northern-most points chosen to observe SSTs do not contain the spike in temperature in 2003 or in 2010 as shown in Fig. 8. This spike in SSTs at the southern-most measuring point in 2003 in addition to the anomalously warm air temperatures observed in southeast Greenland at this time may have been the impetus for the glacier dynamics change on the Kong Christian IX Land coast from 2003 to 2005. Definitive conclusions cannot be drawn from this increase in sea surface temperatures and subsequent acceleration and thinning of southeast Greenland's marine-terminating glaciers, although the connection between ice and ocean dynamics is evident in this study and in previously published results (e.g. Holland et al., 2008; Howat et al., 2008a; Straneo et al., 2010; Murray et al., 2010).

5 Conclusions

Our analysis of changes in 38 marine-terminating glaciers in the Geikie Plateau and Blosseville Coast regions of Greenland's central east coast over the past decade reveal widespread retreat and acceleration through the Denmark Strait and little inter-annual change further north. This pattern suggests that accelerated melt and calving in southeast Greenland is linked to changes in the circulation of the North Atlantic Ocean, which supports the findings of Seale et al. (2011) by providing a closer look at a larger number of glaciers through the Denmark Strait. In addition, glaciers terminating into the Denmark Strait exhibited more synchronous behavior than glaciers north of the Denmark Strait, which also indicates that a regional forcing may be responsible for glacier acceleration and melt in this region.

Our initial hypothesis stated that, if ocean warming is driving glacier change, there would be a more pronounced changes in front position, elevation, and ice speed on glaciers south of Kangerdlugssuaq Fjord and south-facing glaciers of the Blosseville Coast compared to north-facing glaciers of the Geikie Plateau as a result of exposure to the warming of the North Atlantic and its associated coastal currents. While this analysis suggests that oceanographic forcing may be affecting glacier melt through the Denmark Strait, observations of glaciers in this region and of the surrounding ocean are still too limited to state definitively that changing ocean dynamics are the sole

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regional forcing affecting glacier dynamics in this region. Future studies must incorporate measurements from ocean monitoring stations near the outlet glaciers lining the Blosseville Coast and along the coast from Sermilik Fjord to Kangerdlugssuaq Fjord in order to obtain more information about the subsurface oceanographic conditions along the continental shelf and closer to outlet glacier termini.

The methods used in this study to quantify glacier change in central east Greenland can be applied to other areas where outlet glaciers are being assessed for ongoing changes in front position, surface elevation, and surface speed. However, the methods and imagery used in this analysis have limitations. The east Greenland coast is often obscured with clouds for much of the year, restricting the number of useable Landsat-7 ETM+ or ASTER images over a particular location. Future studies should incorporate all-weather and all-year synthetic aperture radar data and high-resolution commercial satellite imagery to provide a much more complete picture of change. Additionally, elevation data collected by airborne laser altimetry acquired as part of NASA's Operation IceBridge initiative will provide a more precise alternative to ASTER digital elevation models for measuring changes in glacier surface elevation.

Using a wide and growing array of airborne and satellite remote sensing platforms, observations and measurements of the continued mass loss and glacier change on the Greenland Ice Sheet are becoming more abundant and accessible for studying the effects of a warming climate on the ice sheet. Mass loss is occurring at accelerated rates on marine-terminating glaciers in the southeast drainage areas of the ice sheet, as shown by gravity anomalies, altimetry data, and imagery showing loss at glacier termini. The implications of melting glaciers in Greenland are global in scope; ongoing changes in ice cover are expected to continue contributing to changes in sea level, which is one of the greatest challenges facing coastal communities and heavily populated coastal urban centers. The areas of extreme glacier change discussed in this analysis indicate that continuous monitoring of ice sheet changes is necessary to develop a better understanding of the Greenland Ice Sheet's adjustment to atmospheric and oceanographic changes.

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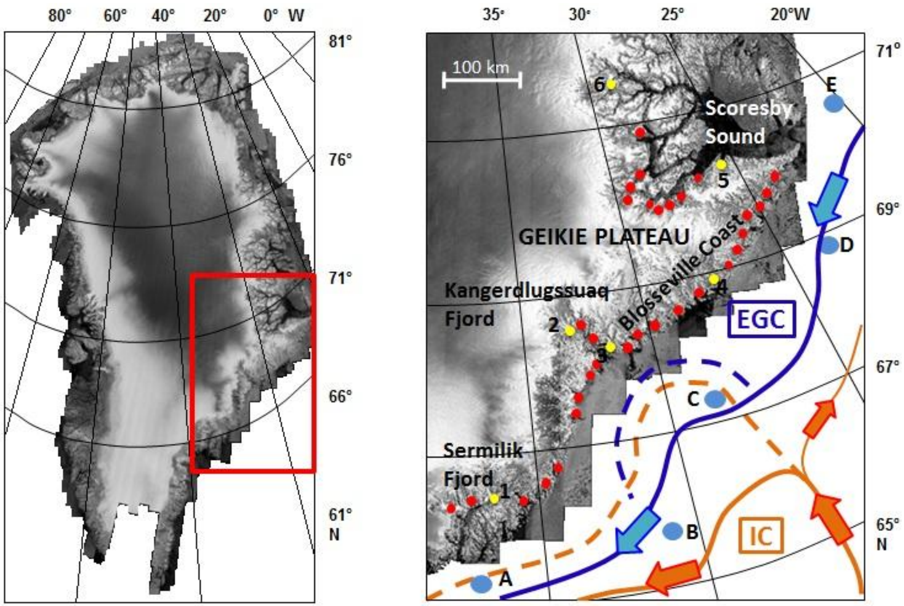

Fig. 1. RADARSAT mosaic showing area of study; including Sermilik Fjord, Kangerdlugssuaq Fjord, Geikie Plateau, Blosseville Coast, and Scoresby Sound; specific glaciers, sea surface temperature points, and relevant ocean currents in the region of study; red dots indicate each glacier; glaciers discussed in detail in the text are indicated by yellow dots and numerals (1 = Midgard; 2 = Kangerdlugssuaq; 3 = Frederiksborg; 4 = Sortebrae; 5 = Sydbrae; 6 = Daugaard Jensen); blue dots indicate sea surface temperature observation points (A through E); "IC" and the orange lines depict the Irminger Current; "EGC" and the blue lines depict the East Greenland Current; dotted lines represent variations in each ocean current.

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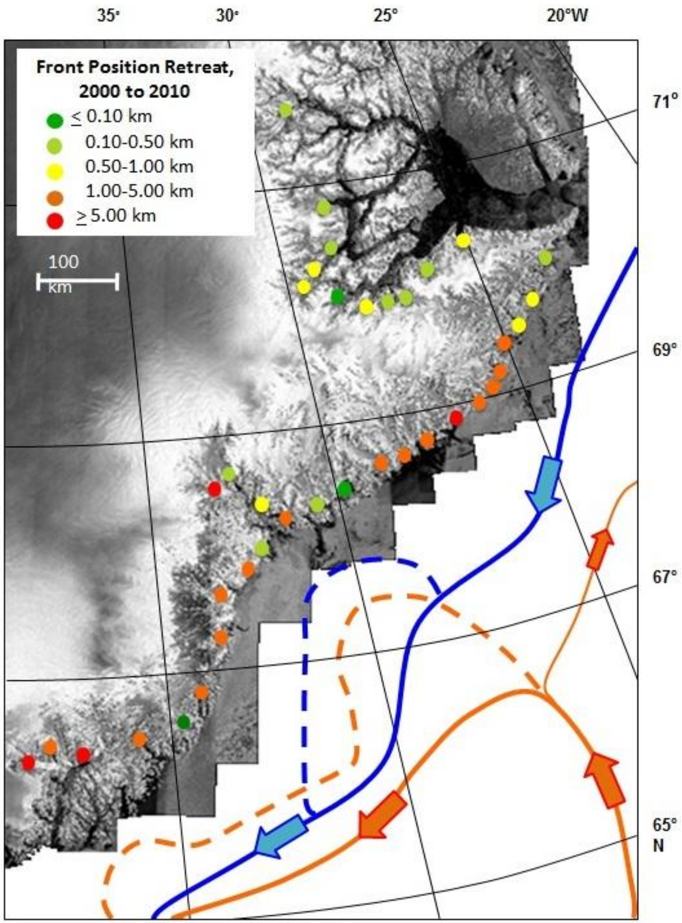

Fig. 2. Change in front position (2000–2010) for all marine-terminating outlet glaciers in this analysis. Circles indicate the location of each glacier and colors indicate magnitude of retreat.

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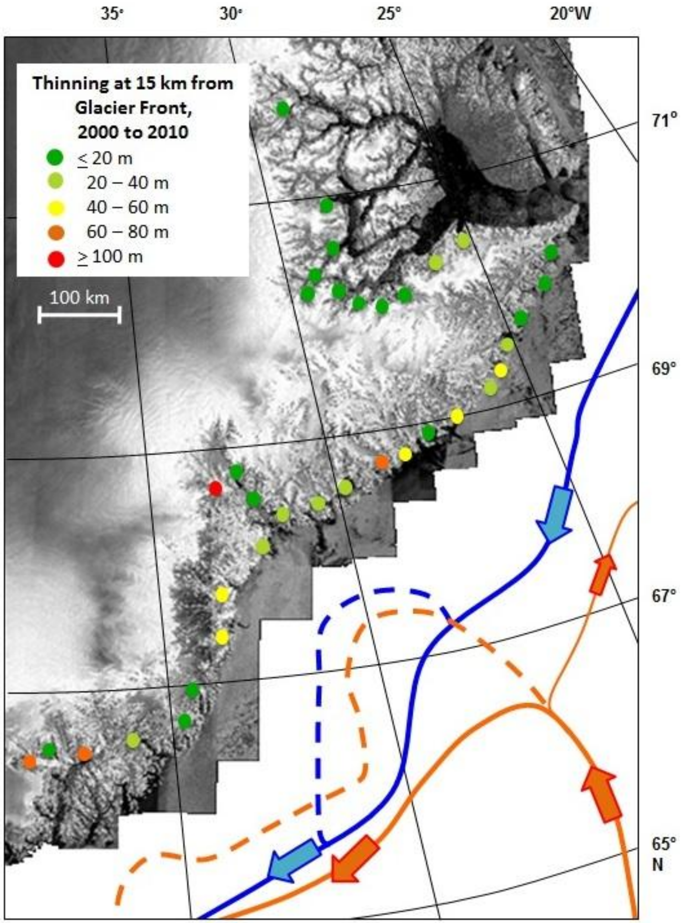

Fig. 3. Change in surface elevation (all values negative) (2000–2010) for all marine-terminating outlet glaciers in this analysis. Circles indicate the location of each glacier and colors indicate magnitude of thinning.

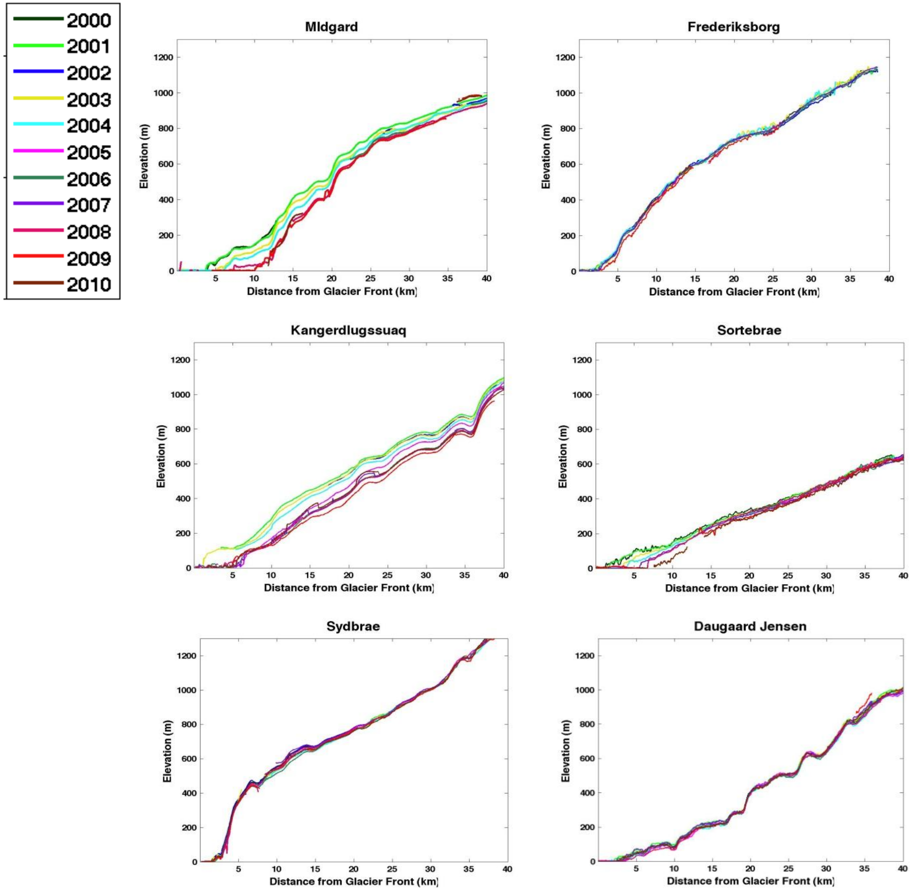

Fig. 4. Elevation profiles for six (6) marine-terminating outlet glaciers in the dataset. Latitude increases from top to bottom, starting with Midgard Glacier (66°26′ N, 36°45′ W) to Daugaard Jensen Glacier (71°54′ N, 28°36′ W). Elevation profiles show annual average elevation from the terminus upglacier to the accumulation zone for each glacier.

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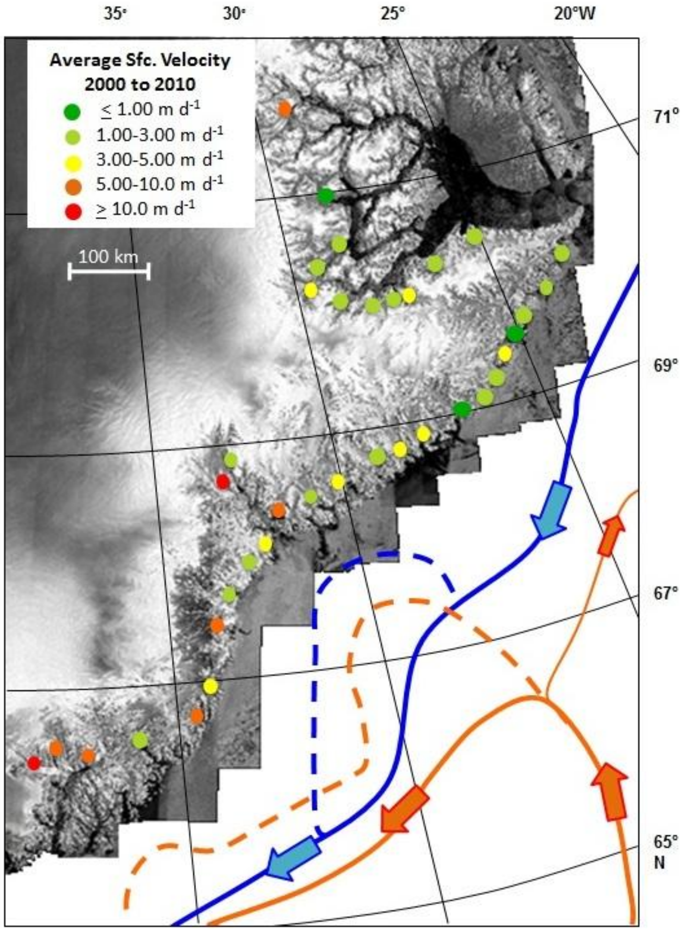

Fig. 5. Average surface speeds (in $\mathrm{m\,d^{-1}}$) for all marine-terminating glaciers in the data set. Circles indicate the location of each glacier and colors indicate magnitude of glacier speed.

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Fig. 6. Landsat-7 ETM+ image from 2000 showing progression of retreat in 2005 and 2010; Midgard has retreated roughly 9 km since 2000.

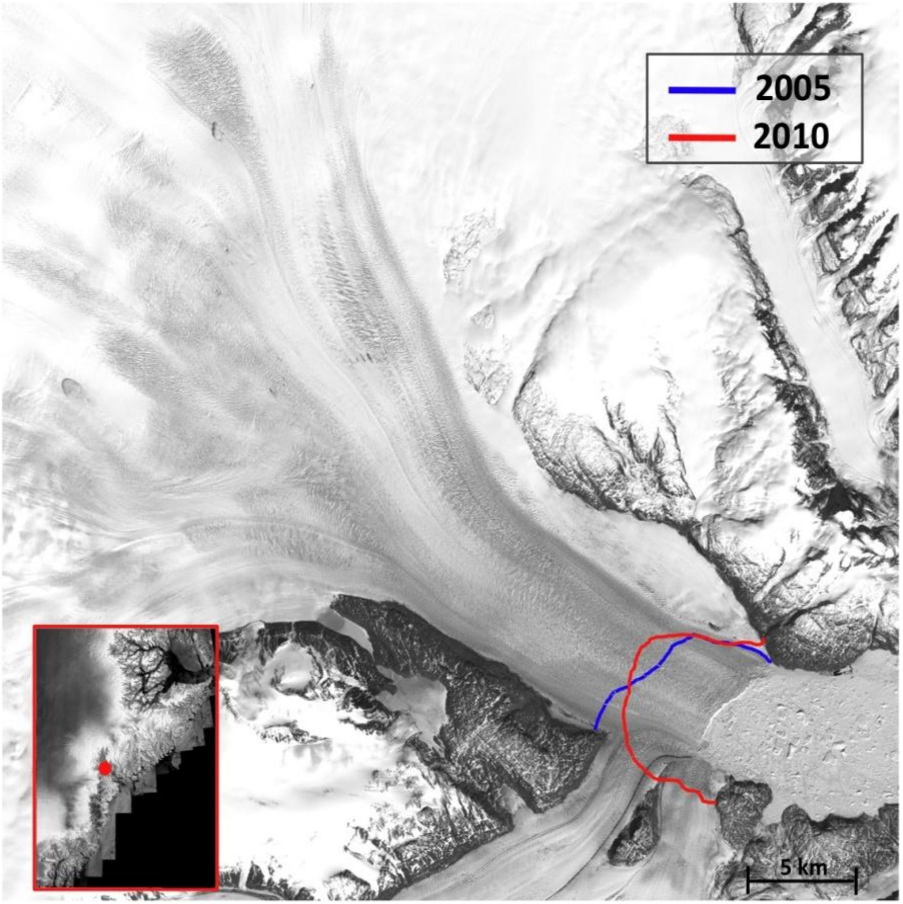

Fig. 7. Landsat-7 ETM+ image from 2000 showing progression of retreat in 2005 and 2010; Kangerdlugssuaq has retreated roughly 7 km since 2000.

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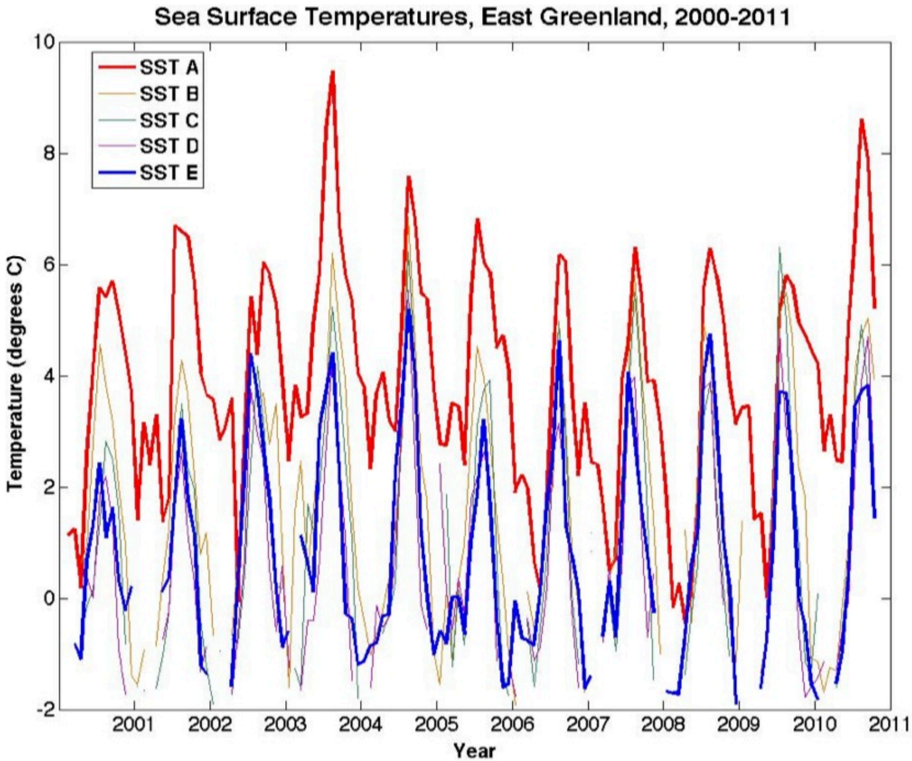

Fig. 8. Sea surface temperatures (SSTs) derived from MODIS data from 2000 to 2010 from five sites off of the central east Greenland coast; site SST-A is the furthest south and site SST-E is the furthest north. Of note is the clear spike in SSTs in 2003, which corresponds to a period of anomalously warm atmospheric temperatures as well (Howat et al., 2008a).

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