Context for the Recent Ice Island Calving of Petermann Gletscher, northwest Greenland

Draft for submission to EOS as feature article: 1 September 2010

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About one fifth of the 1440 $km^2$ floating ice tongue or ice shelf of the Petermann Gletscher in northwest Greenland calved on 4-5 August, 2010 (Fig. 1). Much of the area lost has remained intact as an "ice island" of area (253$\pm$17 $km^2$) equivalent to four times that of Manhattan. With a 4-7 m freeboard and 45-70 m thickness, its initial volume (mass) was about 12 $km^3$ (11 Gt). The event garnered much attention from the media, politicians and the public who raised concerns about implications for shipping, offshore oil and gas operations, and possible connections to Arctic and global warming.

Observations extending back to 1876 suggest that the area of Petermann ice shelf has been approximately constant on a decadal timescale; observed fluctuations of up to 180 $km^2$ are linked to sporadic calving. It is supplied by flow from the Greenland Ice Sheet and a small amount of local precipitation. It loses ice via sublimation, run-off or evaporation after surface melting, melting from contact with seawater, and calving. Petermann is among the driest regions of the Greenland Ice Sheet [Steffen and Box, 2001] with 10-15 cm $yr^{-1}$ snow accumulation and 1.2 m $yr^{-1}$ net surface ablation [Rignot and Steffen, 2008]; hence surface processes amount to 1.7 $km^3$ $yr^{-1}$ ice loss. Using 60m thickness at the seaward end of the shelf and an ice advance of about 1 km $yr^{-1}$ across a 16 km front we find an average calving rate of 1 $km^3$ $yr^{-1}$. Measurements of ice surface velocity and thickness at the grounding line during 2000-2006 indicated a 12 $km^3$ $yr^{-1}$ ice flux to the shelf, thus more than 80% of the mass must be lost in basal melting [Rignot and Steffen, 2008].

Arctic seawater of Atlantic origin enters Petermann Fjord via Nares Strait and delivers ample heat to accomplish the basal melting [Johnson et al., 2010]. However, ocean observations are very limited and specific mechanisms of ocean-ice shelf interaction remain uncertain. Research is needed to reveal what limits basal melting and possible impacts of rising temperature of Arctic intermediate water [e.g. Dmitrenko et al., 2008] on melting and calving rates.

Members of the British Arctic Expedition first mapped the ice front in 1876 [Coppinger, 1877]. It had a similar position in 1922 [Koch, 1927; 1928] and was within 6 km in 1962, leading to speculation that the Petermann ice front was relatively stable despite regional warming during 1920-1950 [Fig. 1, Davies and Krinsley, 1962]. Higgins (1991) estimated ice velocities of 0.8-1.0 km $yr^{-1}$ based on displacements of persistent surface features identified in aerial photographs covering 1947-1978. Rignot & Steffen (2008) reported similar values of 1.0-1.1 km $yr^{-1}$ during 2000-2006 derived from interferometric synthetic-aperture radar. Changes in the ice front position between calving events over the last seven decades agree with velocities of about 1 km $yr^{-1}$ (Fig. 2).

Near constant glacial advance rates and ice shelf front position are consistent with calving at roughly decadal intervals [Higgins, 1991, Fig. 2]. The width near the calving front implies an areal accumulation rate of about 17.5 $km^2$ $yr^{-1}$ between calving events. Calving of 10-15 years of accumulated advance produces area loss comparable to the 2010 event. Indeed imagery from 1947-1951, 1959-1961 [Higgins, 1991], 1974-77, and 1991 [Gudmandsen, 2001, supplemental table] documents such events. Ice islands often break apart in transit to points further south. For example, the 1991 calving produced three ice islands with areas of 73.5, 47.1 and 15.1 $km^2$ as well as many smaller bergs [Gudmandsen, 2001].

The 2010 calving is unusual in that the ice edge (Fig. 2) retreated closer to the grounding line than previously observed. Gaps in the 134-year record of ice front position and the sporadic nature of the calving process, however, allow the possibility that the current position of the ice front is not unprecedented. Hypothetical trajectories are highlighted in the top panel of Figure 2 to illustrate this point. While the solid line is in accord with the more detailed recent record, the dashed scenario cannot be ruled out for 1876-1922, 1922-1947 and the 1980's.

Calving events at Petermann tend to involve the breakaway of a broad spine of the ice shelf that protrudes seaward when ice near the sidewalls, calved into smaller pieces, has drifted away [Dunbar, 1978, Fig. 1 and supplemental table]. This sequence may result from the severe deformation of ice along the margins as it moves (at 3 m $day^{-1}$) down the progressively narrowing fjord. Landsat and aerial images reveal inflow of smaller ($\leq 2$ km wide) side glaciers may contribute thinner ice along the margins that is more susceptible to fracturing. Substantial transverse partial rifts tend to occur at intervals behind the ice front as first noted in 1876 (Fig. 1 & supplemental image). Extension of the currently most prominent rift across the shelf would encompass 180 $km^2$ so is important to monitor.

The calving of an ice island is a dramatic event. Several factors are thought to influence calving. The geometry of the fjord likely contributes; calving has been focused near the narrowest constriction. Tidal flexing has been proposed as a mechanism for breaking Antarctic ice shelves but the recent separation of the Petermann Ice Island occurred during the neap phase. Crevassing that occurs both above and below the water line may determine break points. Surface water ponding has been reported on the Petermann since the earliest observations and may promote surface cracking as discussed in theory [Van der Veen, 2007] and implicated in the break up of other shelves [Scambos et al., 2009]. Surface temperatures in this region have risen during the past few decades [Box et al., 2009], with likely impact on surface melting. However, the sporadic nature of calving, and relatively short record, prevent us from establishing a significant correlation with changing air temperature. Forces exerted by surface winds, too weak to initiate a calving, probably drive subsequent down fjord drift in the absence of fast sea-ice. The 'bright' sea surface 'seen' by ERS-1 SAR is indicative of a strong wind at the mouth of Petermann prior to the drift-out of an ice island in 1991 [Gudmandsen, 2001]. Simulations with a regional atmospheric model [Samelson and Barbour, 2008] for 3-6 August 2010 indicated 20 m $s^{-1}$ synoptic-scale 10-m winds aligned approximately down-fjord, which could have been intensified by small-scale orography or supplemented by katabatic flows.

Certainly land-fast sea ice is an inhibitor of calving along the coasts of Ellesmere Island and northern Greenland [Higgins, 1988; Jeffries, 1987], resisting the free drift of ice islands and dissipating the energy of gravity waves from distant storms that might flex the ice shelf to breaking point [Bromirski et al., 2010; Macayeal et al., 2006]. It is possible that this ice shelf responds to oceanic change that has yet to be characterized at this location. Changing patterns of atmospheric pressure and temperature are affecting sea ice and ocean circulation in the Arctic. Stationary sea ice bridges that typically form and prevent free movement of sea ice in Nares Strait for several months each year, were absent in 2006-07 and 2009-2010. [Kwok et al., 2010; Muenchow et al., 2007].

Since breakup, the ice island has drifted out of the fjord and into Nares Strait and can be expected to continue southward from there into the Baffin Current. If it does not become grounded, its size is such that it should eventually reach the Grand Banks off Newfoundland within a few years, posing a serious threat to shipping and offshore oil and gas rigs along the way. With low freeboard, ice calved from Petermann can be difficult to detect and is of much interest to national ice services.

The glacial mass of western North Greenland is thinning [Joughin et al., 2010] and contributing to a net ice mass flux to the ocean from Greenland [Khan et al., 2010; van den Broeke et al., 2009], although Petermann has been relatively quiet prior to the 2010 calving event. Petermann Gletscher is a major outlet draining about 6% of the Greenland Ice Sheet area [Rignot and Kanagaratnam, 2006] and with a grounding line about 500 m below sea level. In the absence of its shelf, the oceanic conduit to the depressed interior bedrock of Greenland would likely accelerate Greenland ice loss. Improved more comprehensive observations of the Petermann Getscher, its dynamics and ocean interactions are needed to determine its vulnerability to retreat.

*Fig. 1: (a) NASA satellite Modis Aqua true color image, 08:40 UTC, 5 August 2010, showing calving of Petermann Gletscher, western Greenland. There was no sign of a rift on 3 August (cf. Envisat ASAR WSM, 3 Aug 10 15:30), and no useful coverage 4 August. (b) Depiction of 25 known frontal positions. In red: 1876 front and large "fissures"; yellow: 1922; black: 1948, 1952, 1953, 1959, 1963, 1975-78, 1991, 1993, 1999-2009, July 2010; green: grounding line* [Rignot and Steffen, 2008]*; black star: location Automatic Weather Station; black arrow: total movement 1922-2010; white: glacial ice.*

*Fig. 2: Time series of ice front position (for sources see supplemental table). Bottom panel shows ice shelf area. Dashed lines are the 95% confidence intervals on the trend, which is not statistically different from zero. Errors reflect quality of primary information. Middle panel is areal ice loss between observations, assuming an annual accumulation rate of 17.5 km2 $yr^{-1}$. Negative rates occur in years when the average advance rate exceeds calving. Top panel shows the change in ice shelf length from the grounding line (Fig. 1) to the protruding end of the shelf in the middle 50% of the fjord. Arrows indicate the steady advance rate of 1 km $yr^{-1}$ between calvings. Lines connecting 1876 and 1922 depict hypothetical trajectories (see text).*

*Past events summarized in Table: Given space limitations this will have to be supplemental material. In the table it will be noted that sightings of ice islands south of Nares Strait have been attributed to Petermann prior 1959-61. We do not consider these since there are a number of possible sources of similar ice shelves in northern Ellesmere* *and Greenland* [Helk and Dunbar, 1953; Higgins, 1991; Jeffries, 1987; Kollmeyer, 1978; Nutt, 1966].

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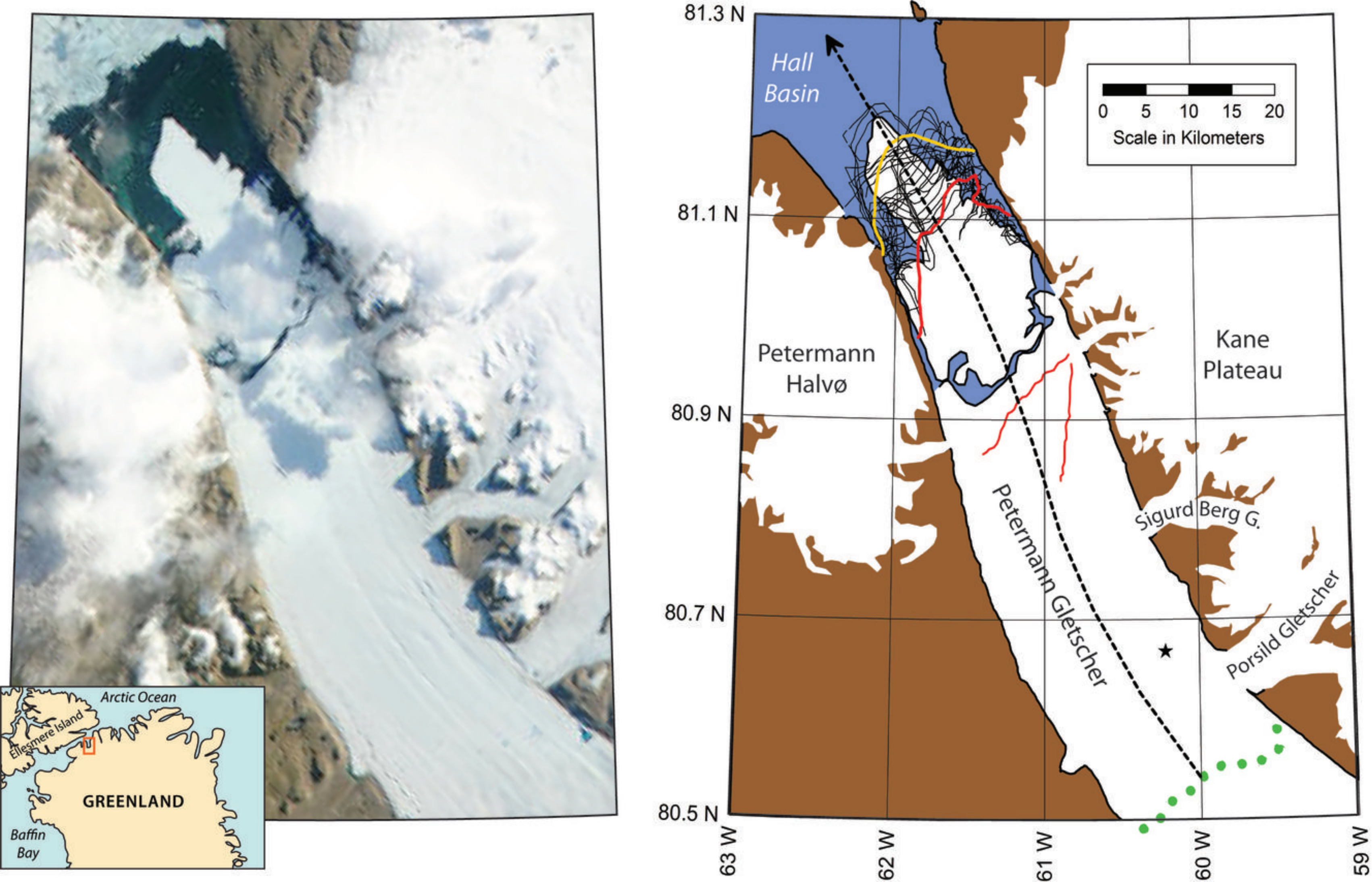
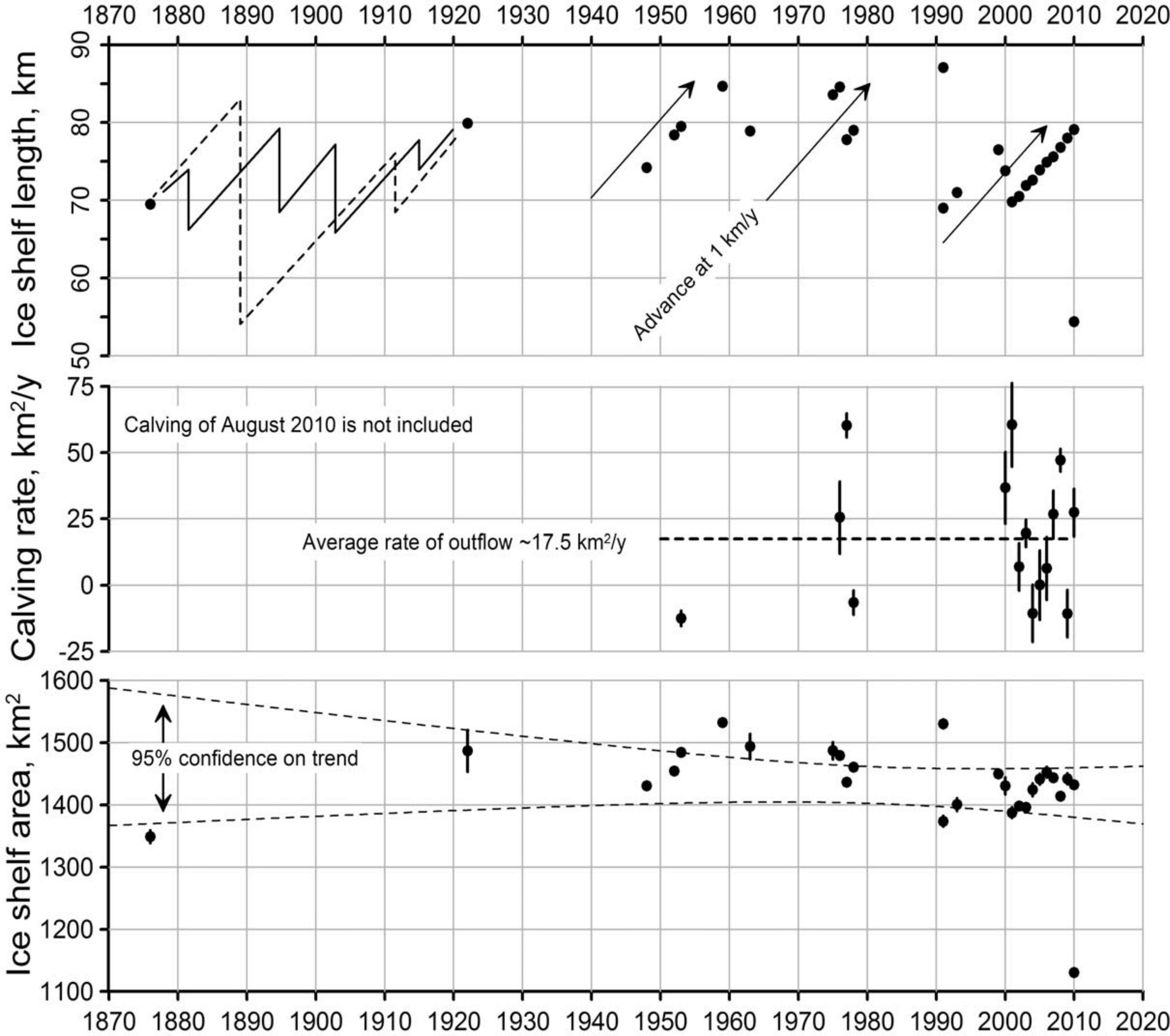

Arctic Ocean
Ellesmere Island
GREENLAND
Baffin Bay
81.3 N
81.1 N
80.9 N
80.7 N
80.5 N
63 W
62 W
61 W
60 W
59 W
Hall Basin
0 5 10 15 20
Scale in Kilometers
Petermann Halvø
Kane Plateau
Petermann Gletscher
Sigurd Berg G.
Porsild Gletscher



Ice shelf length, km
Advance at 1 km/y
Calving rate, km²/y
Calving of August 2010 is not included
Average rate of outflow ~17.5 km²/y
Ice shelf area, km²
95% confidence on trend