

Context for the Recent Massive Petermann Glacier Calving Event

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On 4 August 2010, about one fifth of the floating ice tongue of Petermann Glacier (also known as “Petermann Gletscher”) in northwestern Greenland calved (Figure 1). The resulting “ice island” had an area approximately 4 times that of Manhattan Island (about 253 ± 17 square kilometers). The ice island garnered much attention from the media, politicians, and the public, who raised concerns about downstream implications for shipping, offshore oil and gas operations, and possible connections to Arctic and global warming.

Does this event signal a change in the glacier’s dynamics? Or can it be characterized as part of the glacier’s natural variability? Understanding the known historical context of this event allows scientists and the public to judge its significance.

An Overview of Petermann Glacier

Petermann Glacier is a major outlet that drains about 6% of the Greenland Ice Sheet area. It is one of four such major outlet glaciers surrounding Greenland that are grounded substantially (500 meters) below sea level and one of two that retain significant floating ice tongues. The Petermann ice tongue feeds into a high-walled fjord, 15–20 kilometers wide and about 80 kilometers in length. The main flow of ice that crosses the grounding line is augmented by smaller inflow glaciers descending along the sides of the fjord (Figure 1; see also Figure S1 in the online supplement to this *Eos* issue (http://www.agu.org/eos_elec/)). The ice tongue thins substantially from about 600 meters at the grounding line to 200 meters approximately 20 kilometers downstream of the line. It thins more gradually thereafter to 45–70 meters at the seaward edge,

corresponding to a height above sea level of only 4–7 meters [Rignot and Steffen, 2008].

Petermann’s ice tongue is supplied by flow from the Greenland Ice Sheet and a small amount of local precipitation. It loses ice via sublimation, runoff or evaporation after surface melting, calving, and melting from contact with seawater. Members of

the British Arctic Expedition first mapped the tongue’s ice front in 1876. It had a similar position in 1922 and was within 6 kilometers of this position in 1962, leading to speculation that the Petermann ice front was relatively stable despite regional warming during 1920–1950. Indeed, until the recent calving event, it had been presumed that the Petermann ice tongue was approximately in steady state even allowing for sporadic calving that occurs on a decadal time scale.

Rignot and Steffen [2008] have recently considered the Petermann ice tongue in mass balance terms. Combining measured

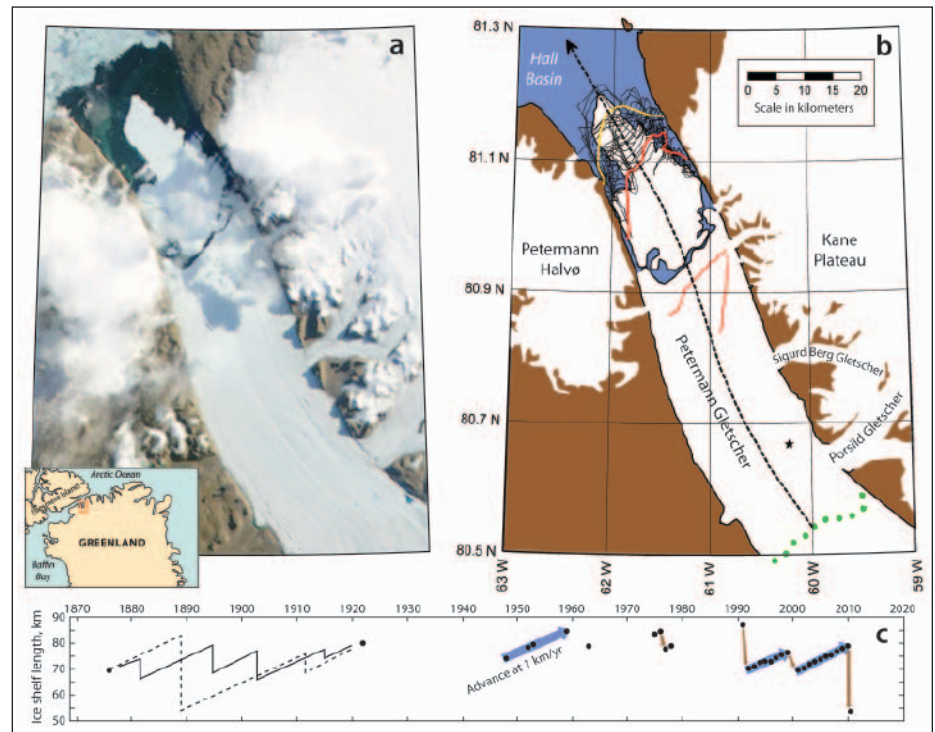


Fig. 1. (a) NASA Aqua satellite Moderate Resolution Imaging Spectroradiometer true-color image, taken 0840 UTC on 5 August 2010, showing calving of Petermann Glacier, northwestern Greenland. There was no sign of a break on 3 August (based on Envisat’s advanced synthetic aperture radar data from its wide-swath mode, observed at 1530 UTC), but Envisat imagery revealed the break on 4 August 2010. (b) A map of 31 known frontal positions of the ice tongue (sources are in Table S1). The seaward red curve is the ice front in 1876; behind it in red are the locations of large “fissures” also observed at that time. The yellow curve shows the frontal position in 1922; black curves represent frontal positions in 1948, 1952, 1953, 1959, 1963, 1975–1978, 1991–1999, 1999–2010, and July 2010. Green dots represent the grounding line, and the black star is the location of an automatic weather station [Rignot and Steffen, 2008]. The black arrow traces the total movement of the glacier from 1922 to 2010. White is glacial ice. (c) Times series of ice shelf length as measured along the central axis from the grounding line. Lines connecting 1876 and 1922 are hypothetical trajectories. Blue arrows indicate steady ice advance velocities between calving episodes (brown arrows).

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surface velocity and thickness at the grounding line during 2000–2006, they estimated that the ice sheet supplies about 12 cubic kilometers of ice per year to the tongue. Because Petermann is located in one of the driest regions of the Greenland Ice Sheet, surface losses from sublimation more than compensate for the 10–15 centimeters of snow accumulation per year, to result in 1.7 cubic kilometers of yearly surface ice loss. Time-averaged calving losses are of similar magnitude (about 1 cubic kilometer per year).

If one takes the system to be at steady state, these losses account for about 20% of the supply estimated by *Rignot and Steffen* [2008]. Thus, ocean melting presumably drives loss of the remaining 80%. Arctic seawater of Atlantic origin enters Petermann Fjord via Nares Strait and delivers ample heat to accomplish the basal melting [Johnson *et al.*, 2011]. Ocean observations are very limited, so specific mechanisms of ocean–ice shelf interaction remain uncertain; further research is required to reveal what limits basal melting and whether the rising temperature of Arctic intermediate water will affect melting and calving rates.

Calving Variability and Dynamics

Although loss due to calving has not been predominant to date, the question arises of whether the recent calving heralds a change in the system. Historical evidence suggests that a conclusion cannot yet be drawn. *Higgins* [1991] estimated ice tongue velocities of 0.8–1.0 kilometer per year, based on displacements of persistent surface features identified in aerial photographs covering 1947–1978. *Rignot and Steffen* [2008] reported similar values of 1.0–1.1 kilometers per year during 2000–2006, derived from interferometric synthetic aperture radar.

Near-constant glacial advance rates and ice shelf front position are consistent with calving at roughly decadal intervals (see Figure 1c). In fact, calving of a magnitude comparable to the recent event was documented for 1991 [Gudmundsen, 2001]. The 2010 calving is unusual in that the ice edge retreated much closer to the grounding line than previously observed (Figure 1). 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 highlighted in Figure 1c illustrate this point. While the solid line is in accord with the more detailed recent record, the scenario indicated by the dashed line cannot be ruled out for 1876–1922, 1922–1947, and the 1980s. At current ice tongue velocities, it should take approximately 2 decades for the ice front to return to its formerly “stable” ice front position.

The calving of an ice island is a dramatic event. Calving events at Petermann tend to involve the breakaway of a broad spine of the ice shelf that protrudes seaward once

ice near the sidewalls, calved into smaller pieces, has drifted away (see Figure 1, and Table S1 in the online supplement). This sequence may result from the severe deformation of ice along the margins as it moves (at 3 meters per day) down the progressively narrowing fjord. Landsat and aerial images of the smaller (≤ 2 -kilometer-wide) glaciers feeding the tongue along the sides of the fjord reveal highly fractured and likely thinner ice. Further, substantial transverse partial rifts tend to occur at intervals behind the ice front, as first noted in 1876 (Figure 1 and Figure S1). The currently most prominent rift extends halfway across the ice tongue, and 180 square kilometers of ice is encompassed between it and the glacier margin. Whether this rift persists unchanged over the next few decades or propagates across the fjord and leads to continuing retreat of the ice tongue will be important to monitor.

Several factors are thought to influence calving. The geometry of Petermann Fjord likely contributes—observed calving has been focused near its narrowest constriction. Tidal flexing has been proposed as a mechanism for breaking Antarctic ice shelves, but the separation of the Petermann ice island in 2010 occurred during the neap phase, when tidal amplitudes are minimal. Crevassing that occurs both above and below the waterline may determine break points. Surface water ponding has been reported on the Petermann ice tongue since the earliest observations and may promote surface cracking, as implicated in the breakup of other ice shelves. 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 the relatively short record preclude establishing a significant correlation with changing air temperature. Forces exerted by surface winds, too weak to initiate a calving event, probably drive calved glacial ice out of the fjord in the absence of a sea ice cover that is fixed in place. In fact, the “bright” sea surface observed by European Remote Sensing satellite (ERS-1) synthetic aperture radar indicates that a strong wind at the mouth of Petermann Fjord preceded the drift of an ice island out of the fjord in 1991. Simulations with a regional atmospheric model [Samelson and Barbour, 2008] for 3–6 August 2010 indicated wind speeds of 20 meters per second at the glacier’s surface aligned along the fjord toward Nares Strait, which could have been intensified by strong flows downslope of the local relief.

Certainly, sea ice that crowds the ice front is an inhibitor of calving along the coasts of Ellesmere Island and northern Greenland, 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. It is possible, though, that the Petermann 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. Indeed, stationary sea ice that typically forms in winter and prevents free movement of sea ice in Nares Strait for several months each year was virtually absent in 2006–2010 except for a 60-day period beginning in April 2008 [Kwok *et al.*, 2010]; such a sequence does appear to be unusual.

Tracking the Recently Calved Ice Island

Since breakup, the massive ice island that calved in 2010 has drifted out of the fjord into Nares Strait, where, after briefly hanging on Joe Island, it broke into two pieces. The larger fragment (about 155–160 square kilometers) remained wedged against Joe Island for a while before passing southward into Kane Basin, while the smaller fragment (roughly 83 square kilometers) immediately drifted south and passed into northern Baffin Bay. This is similar to the documented 1991 calving event that produced three ice islands with areas of 73.5, 47.1, and 15.1 square kilometers as well as many smaller icebergs [Gudmundsen, 2001].

Because of its relatively low profile above sea level, ice calved from Petermann Glacier can be difficult to detect. Fragments that may reach the Grand Banks off Newfoundland pose a serious threat to shipping and offshore oil and gas rigs and so are of much concern to national ice services and the International Ice Patrol. On 17 September 2010 the Canadian Ice Service succeeded in dropping a beacon on the smaller fragment to aid in tracking, and its progress can be followed at <http://sailwx.info/shiptrack/shipposition.phtml?call=47557>. As of this writing, the ice island had broken into more than a dozen identifiable fragments, some of which have already transited more than 1400 miles south in the Baffin Island Current and passed through or were within Davis Strait as of March 2011.

Implications of Further Calving

The glacial mass on the west side of northern Greenland is thinning [Joughin *et al.*, 2010] and contributing to a net ice mass flux to the ocean from Greenland, the absolute magnitude of which remains under refinement. Petermann Glacier has shown little net change up to now, but if it loses its ice tongue, buttressed reinforcement against the ice sheet flow would be diminished and there would be a direct oceanic conduit to the depressed interior bedrock of Greenland. As observed at Jakobshavn Isbrae in southwestern Greenland when it lost its floating shelf over the past decade [Joughin *et al.*, 2004], this would most likely result in accelerated land ice loss. Improved, more comprehensive observations of Petermann Glacier, its dynamics, and ocean

interactions are needed to determine its vulnerability to retreat in the coming decades.

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NEWS

Web Platform for Sharing Spatial Data and Manipulating Them Online

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To fill the need for readily accessible conservation-relevant spatial data sets, the Conservation Biology Institute (CBI) launched in 2010 a Web-based platform called Data Basin (<http://www.databasin.org>). It is the first custom application of ArcGIS technology, which provides Web access to free maps and imagery using the most current version of Environmental Systems Research Institute (ESRI; <http://www.esri.com/>) geographic information system (GIS) software, and its core functionality is being made freely available.

Data Basin includes spatial data sets (Arc format shapefiles and grids, or layer packages) that can be biological (e.g., prairie dog range), physical (e.g., average summer temperature, 1950–2000), or socioeconomic (e.g., locations of Alaska oil and gas wells); based on observations as well as on simulation results; and of local to global relevance. They can be uploaded, downloaded, or simply visualized. Maps (overlays of multiple data sets) can be created and customized (e.g., western

Massachusetts protected areas, time series of the Deep Water Horizon oil spill). Galleries are folders containing data sets and maps focusing on a theme (e.g., sea level rise projections for the Pacific Northwest region from the National Wildlife Federation, soil data sets for the conterminous United States).

People profiles can be searched to find data providers, potential collaborators, or simply interested colleagues. Teams of collaborators can create groups to share and manipulate specific data sets and maps. Basic tools are provided (e.g., to draw on maps, identify values of a spatial layer), and more will be developed with partners as funding permits. Groups have been used to organize hands-on workshops where participants have access to data presented during talks and are able to manipulate them, providing opportunities for new interpretations and discussions.

Data Basin users who create a free account are provided with a private area (My Workspace) to organize the content they contribute to or find in the system. Users can create and edit personal

profiles; track the creation of data sets, maps, and galleries; and manage their own group activity. All Data Basin content other than member profiles can be kept private, shared only within groups, or shared publicly.

Data Basin centers provide users with thematic entry points into Data Basin's vast library of spatial data. The Climate Center (<http://www.databasin.org/climate-center>), for example, provides direct access to peer-reviewed climate change projections such as simulations by J. Lenihan of the future impacts of wildfires in California under Inter-governmental Panel on Climate Change [Kattenberg *et al.*, 1995] emissions scenarios (e.g., IS92) and *Special Report on Emissions Scenarios*' Fourth Assessment Report future scenarios [Nakicenovic *et al.*, 2000]. The Climate Center also contains news briefs and short stories showcasing recent climate-related data sets, analyses, or noteworthy projects. For example, the center provides the opportunity to explore and use maps from Vörösmarty *et al.* [2010] on the global freshwater crisis (<http://databasin.org/climate-center/features/global-freshwater-crisis>).

CBI is actively developing specialized tools to enhance the understanding and interpretation of climate-related data. For example, a climate uncertainty index will soon result from a collaborative effort with the California Academy of Sciences (led by H. Hamilton) based on climate variability, topography, and other factors provided as data layers in Data Basin. CBI is looking for collaborators who would like to participate in Data Basin to advance effective conservation. A Power Point presentation introducing