EOS
EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

VOLUME 92 NUMBER 37
13 SEPTEMBER 2011
PAGES 305–312

A Complex Relationship Between Calving Glaciers and Climate

PAGES 305–306

Many terrestrial glaciers are sensitive indicators of past and present climate change as atmospheric temperature and snowfall modulate glacier volume. However, climate interpretations based on glacier behavior require careful selection of representative glaciers, as was recently pointed out for surging and debris-covered glaciers, whose behavior often defies regional glacier response to climate [*Yde and Paasche,* 2010].

Tidewater calving glaciers (TWGs)—mountain glaciers whose termini reach the sea and are generally grounded on the seafloor—also fall into the category of nonrepresentative glaciers because the regional-scale asynchronous behavior of these glaciers clouds their complex relationship with climate. TWGs span the globe; they can be found both fringing ice sheets and in high-latitude regions of each hemisphere. TWGs are known to exhibit cyclic behavior, characterized by slow advance and rapid, unstable retreat, largely independent of short-term climate forcing. This so-called TWG cycle, first described by *Post* [1975], provides a solid foundation upon which modern investigations of TWG stability are built. Scientific understanding has developed rapidly as a result of the initial recognition of their asynchronous cyclicity, rendering greater insight into the hierarchy of processes controlling regional behavior. This has improved the descriptions of the strong dynamic feedbacks present during retreat, the role of the ocean in TWG dynamics, and the similarities and differences between TWG and ice sheet outlet glaciers that can often support floating tongues.

The Tidewater Glacier Cycle

The original identification of cyclic behavior in TWGs was made in Alaska, where present-day examples of each phase of the cycle (advance, retreat, transition) exist among the more than 50 TWGs draining Alaska's coastal mountains. A complete cycle includes a phase of prolonged, stable advance (10–50 meters per year) followed by a shorter period of drastic retreat (100–1000 or more meters per year) and dynamic instability [*Meier and Post,* 1987].

TWG advance is characterized by moderate ice flow and low iceberg calving rates. Stability of the terminus is provided by development of a submarine terminal moraine, which reduces buoyancy forces near the ice cliff, keeps the glacier grounded, and insulates the ice from warm, erosive seawater. Therefore, advance rate is limited by sediment supply and the rate at which the glacier can erode its terminal moraine and redeposit sediment on the downstream side [*Motyka et al.,* 2006].

Advances are abetted by the geometry of the glacierized basin, best parameterized by accumulation area ratio (AAR), the ratio of the area of the accumulation zone (region of mass gain) to the total glacier area. Advance is generally favored, regardless of atmospheric climate forcing, when the AAR exceeds about 0.8. Because retreats remove large portions of the ablation zone (the region of mass loss), a retreat will increase the AAR and may subsequently initiate advance in any climate. Sustained advance inherently enlarges the ablation zone, reducing the AAR and slowly increasing the glacier's sensitivity to climate cycles and regimes. Advances can persist for centuries, but eventually an extended geometry is attained, rendering the glacier susceptible to retreat, even with only small changes in climate.

TWG retreats are rapid and catastrophic, generally resulting in the loss of a substantial

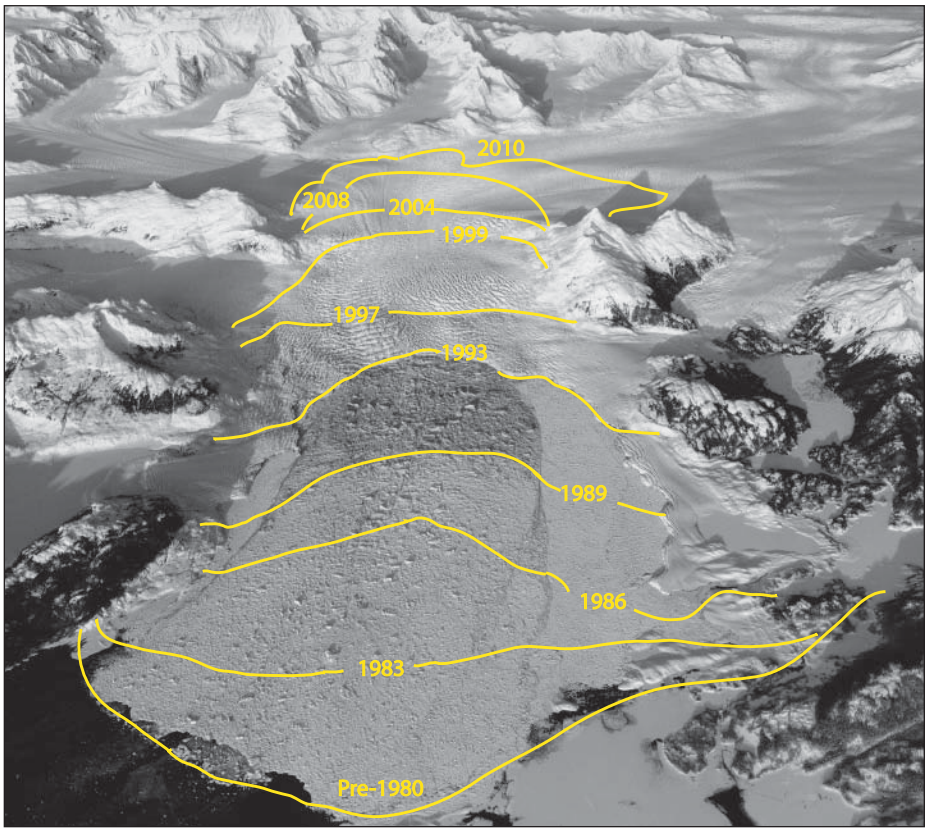

Fig. 1. This oblique photo, taken in 1993, shows the evolution of Columbia Glacier through its 20-kilometer retreat. Although length change slowed during transition through a 2-kilometer-wide channel constriction (1999–2006), mass loss rates were continuously high. Photo by R. M. Krimmel, U.S. Geological Survey.

By A. Post, S. O'Neel, R. J. Motyka, and G. Streveler

portion of the glacier over a matter of decades. The best studied example is Columbia Glacier, which entered retreat phase in the early 1980s [*Meier and Post,* 1987] and has since calved back 20 kilometers, thinned more than 500 meters, and delivered approximately 150 cubic kilometers (25%–40% of original volume) of ice to the Pacific Ocean [*Walter et al.,* 2010]. Glacial-geological observations chronicle similar past retreats including the 120-kilometer opening of Alaska's Glacier Bay [*Motyka et al.,* 2007] and the 40-kilometer opening of Icy Bay [*Calkin et al.,* 2001].

During retreat, rapid mass loss is facilitated by strong increases in the tightly coupled rates of ice flow (resupply) and calving. Overdeepened basins typically found behind terminal moraines support highly pressurized subglacial hydraulic systems, which increase the buoyancy near the terminus and foster accelerated retreat driven by high basal water pressures. This classic geometry of a slippery bed and poorly grounded calving front allows reinforcing feedbacks between dynamic processes to control the retreat [*Meier and Post,* 1987; *Amundson and Truffer,* 2010]. Little evidence links these retreats to atmospheric climate forcing—calving losses greatly exceed surface melt losses. Feedbacks between ice flow calving and drawdown of the parent ice field nonlinearly combine to accelerate ice delivery to the sea [*Pfeffer,* 2007]. Substantial drawdown of the upstream ice field reservoir is the end result of retreat, and stability of the TWG can be regained only by reduced buoyancy in the waters surrounding the terminus, e.g., at the shallow headwaters of the fjord.

Although quantitative understanding of the switch between the advance and retreat phases is of paramount importance for predictive modeling, it remains poorly understood. A dynamic transition occurs when the glacier terminus recedes from the stabilizing moraine into deeper water behind it. Destabilization can be triggered by climate-related glacier thinning (which alters flow and calving), oceanic forcing, or both.

TWG Climate Sensitivity

The climate system to which glaciers respond is traditionally thought to be composed of atmospheric processes (snow accumulation and ice melt). In this regard, Alaska's Chugach Mountains, where a single ice field houses glaciers in all phases of the TWG cycle, provides an excellent example of TWG insensitivity to climate forcing. The shores of Alaska's Prince William Sound are home to Columbia Glacier, which is in drastic retreat (Figure 1); Meares and Harvard glaciers, which are stably advancing; and Yale and Shoup glaciers, which are in stable, postretreat retracted positions. Similar observations exist worldwide. For example, Chilean Patagonia is home to rapidly retreating Marinelli Glacier [*Warren and Aniya,* 1999]. Meanwhile, the calving glaciers located at the head of adjoining Brookes Bay either terminate in their retracted positions or are slowly advancing into forested fjords.

Such regional-scale asynchronous behavior complicates the TWG-climate relationship, at least over decadal to centennial time scales. Records of TWG size and/or health are not robust indicators of climate and should not be used indiscriminately to interpret current or previous climate forcing. However, climate does appear to play a role over multicentury time scales, as evidenced by the preponderance of retreating TWGs in today's climate. In the complete absence of climatic control, the global distribution of TWGs would be dominated by advance phase, owing to the comparatively slow advance versus retreat rates.

The long-term influence of climate is supported by Alaskan TWGs; the last major climate shift, the Little Ice Age (LIA), which occurred roughly between the sixteenth and nineteenth centuries, resulted in widespread TWG advance as documented in the geologic record [*Calkin et al.,* 2001]. Expansion of large, low-elevation ablation areas during this advance phase rendered TWGs sensitive to climate change, and a northward progression of retreat ensued at the end of the LIA. With two important exceptions (Hubbard and Columbia glaciers), all of Alaska's TWGs retreated from their LIA moraines during the late eighteenth and nineteenth centuries. Some of these glaciers continue their retreat phase today, others have stabilized, and still others are now advancing. The two outliers to post-LIA retreat demonstrate how basin geometry can override climate in the TWG cycling process. The best example is Hubbard Glacier (AAR = 0.95), which continues to advance in a region where climate is not supportive of glacier growth [*Barclay et al.,* 2001]. It is unlikely that presently advancing glaciers will match historical advance positions, as recent warming trends will result in smaller extended geometries.

Improved Understanding

A critical step in developing a modern understanding of calving glaciers was the important realization that glacier length, although easily measured, is not a robust indication of retreat or stability. Restrictions or pinning points in the channel, such as narrows, abrupt turns, or bedrock shoals, may slow or even stop retreat; nonetheless, mass loss can still continue unabated due to glacier thinning and upstream drawdown [*Mercer,* 1961]. For example, Columbia Glacier retreated into a prominent constriction in its channel in the late 1990s (Figure 1), which stabilized the terminus for 6–8 years. Although length changes were minimal, surface lowering and rapid calving continued or accelerated, resulting in sustained mass loss rates [*Walter et al.,* 2010]. Strong similarities exist between Columbia Glacier's dynamics and the recent northward propagation of dynamic instability at Greenland's outlet glaciers. Feedbacks documented between thinning, calving, and fast flow [e.g., *Howat et al.,* 2007] are resulting in rapid mass loss from the ice sheet. The importance of calving is underscored, as discharge from these glaciers currently forms a primary constituent in global sea level rise [*Pfeffer et al.,* 2008], demonstrating a need to fully understand the calving glacier link with climate.

Feedbacks responsible for volume change and reservoir drawdown during retreat can ultimately manifest a second instability. When drawdown lowers the accumulation zone below the regional equilibrium elevation, the ice body will stagnate and disappear [*Bödvarsson,* 1955]. The ongoing collapse of Alaska's Yakutat ice field and the stranding of ice masses in Glacier Bay following the post-LIA calving retreat are good examples of this effect [*Motyka et al.,* 2007].

Although the ice-ocean boundary has traditionally evaded study, due in part to its inaccessible nature, recent emphasis has revealed surprisingly strong coupling between these two physical systems, providing richer understanding of the TWG system. Data from Alaska and Greenland demonstrate that ocean water temperature drives submarine melting, which is a substantial component of TWG and outlet glacier mass budgets [*Motyka et al.,* 2003]. Oceanic processes appear to exhibit strong control over the calving glacier stability [*Holland et al.,* 2008; *Motyka et al.,* 2011], in contrast to the terrestrial termini, where atmospheric processes steer the dynamics [*Bartholomew et al.,* 2010].

Sensitivity to ocean forcing increases dramatically when floating tongues exist at the terminus of a TWG, a situation common in Greenland but rare in Alaska. A strong response to the loss of floating ice appears ubiquitous: From Greenland to Alaska and the Antarctic Peninsula, flow accelerations occur when floating ice tongues or shelves disappear [*Scambos et al.,* 2004; *Joughin et al.,* 2008; *Walter et al.,* 2010], and even though flow speeds increase, the glaciers generally retreat. Additionally, the presence or absence of shallow sills that block fjord entrances and the depths of existing sills are likely critical controls on fjord circulation. Fjord circulation, through submarine melt, is intimately connected to glacier mass balance [*Rignot et al.,* 2010; *Straneo et al.,* 2011].

Better understanding of how TWGs respond to climate forcing, and the transitions between advance and retreat, may come from a shift in conceptualization of climate, where oceanic forcing is included as a strong control on glacier health. Recent work highlights the close coupling and strong feedbacks between glaciological atmospheric and oceanographic processes. As quantitative understanding improves, so will our ability to understand and forecast

the evolution of these systems in a warming climate and their role in related socioeconomic issues, especially sea level rise.

References

Amundson, J. M., and M. Truffer (2010), A unifying framework for iceberg-calving models, *J. Glaciol., 56*(199), 822–830, doi:10.3189/002214310794457173.

Barclay, D. J., P. E. Calkin, and G. C. Wiles (2001), Holocene history of Hubbard Glacier in Yakutat Bay and Russell Fiord, southern Alaska, *Geol. Soc. Am. Bull., 113*(3), 388–402, doi:10.1130/0016-7606(2001)113<0388:HHOHGI>2.0.CO;2.

Bartholomew, I., P. Nienow, D. Mair, A. Hubbard, M. A. King, and A. Sole (2010), Seasonal evolution of subglacial drainage and acceleration in a Greenland outlet glacier, *Nat. Geosci., 3,* 408–411, doi:10.1038/ngeo863.

Bödvarsson, G. (1955), On the flow of ice-sheets and glaciers, *Jökull, 5,* 1–8.

Calkin, P. E., G. C. Wiles, and D. J. Barclay (2001), Holocene coastal glaciation of Alaska, *Quat. Sci. Rev., 20*(1-3), 449–461, doi:10.1016/S0277-3791(00)00105-0.

Holland, D. M., R. H. Thomas, B. de Young, M. H. Ribergaard, and B. Lyberth (2008), Acceleration of Jakobshavn Isbræ triggered by warm subsurface ocean waters, *Nat. Geosci., 1,* 659–664, doi:10.1038/ngeo316.

Howat, I. M., I. Joughin, and T. A. Scambos (2007), Rapid changes in ice discharge from Greenland outlet glaciers, *Science, 315*(5818), 1559–1561, doi:10.1126/science.1138478.

Joughin, I., I. M. Howat, M. Fahnestock, B. Smith, W. Krabill, R. B. Alley, H. Stern, and M. Truffer (2008), Continued evolution of Jakobshavn Isbræ following its rapid speedup, *J. Geophys. Res., 113,* F04006, doi:10.1029/2008JF001023.

Meier, M. F., and A. Post (1987), Fast tidewater glaciers, *J. Geophys. Res., 92*(B9), 9051–9058, doi:10.1029/JB092iB09p09051.

Mercer, J. H. (1961), The response of fjord glaciers to changes in the firn limit, *J. Glaciol., 29,* 850–858.

Motyka, R. J., L. Hunter, K. A. Echelmeyer, and C. Connor (2003), Submarine melting at the terminus of a temperate tidewater glacier, LeConte Glacier, Alaska, U.S.A., *Ann. Glaciol., 36,* 57–65, doi:10.3189/172756403781816374.

Motyka, R. J., M. Truffer, E. M. Kuriger, and A. K. Bucki (2006), Rapid erosion of soft sediments by tidewater glacier advance: Taku Glacier, Alaska, USA, *Geophys. Res. Lett., 33,* L24504, doi:10.1029/2006GL028467.

Motyka, R. J., C. F. Larsen, J. T. Freymueller, and K. A. Echelmeyer (2007), Post Little Ice Age glacial rebound in Glacier Bay National Park and surrounding areas, *Alaska Park Sci. J., 6*(1), 36–41.

Motyka, R. J., M. Truffer, M. Fahnestock, J. Mortensen, S. Rysgaard, and I. Howat (2011), Submarine melting of the 1985 Jakobshavn Isbræ floating tongue and the triggering of the current retreat, *J. Geophys. Res., 116,* F01007, doi:10.1029/2009JF001632.

Pfeffer, W. T. (2007), A simple mechanism for irreversible tidewater glacier retreat, *J. Geophys. Res., 112,* F03S25, doi:10.1029/2006JF000590.

Pfeffer, W. T., J. T. Harper, and S. O'Neel (2008), Kinematic constraints on glacier contributions to 21st-century sea-level rise, *Science, 321*(5894), 1340–1343, doi:10.1126/science.1159099.

Post, A. (1975), Preliminary hydrography and historic terminal changes of Columbia Glacier, Alaska, *U.S. Geol. Surv. Hydrol. Invest. Atlases, 559,* 3 sheets, scale 1:20,000.

Rignot, E., M. Koppes, and I. Velicogna (2010), Rapid submarine melting of the calving faces of West Greenland glaciers, *Nat. Geosci., 3,* 187–181, doi:10.1038/ngeo765.

Scambos, T. A., J. A. Bohlander, C. A. Shuman, and P. Skvarca (2004), Glacier acceleration and thinning after ice shelf collapse in the Larsen B embayment, Antarctica, *Geophys. Res. Lett., 31,* L18402, doi:10.1029/2004GL020670.

Straneo, F., R. G. Curry, D. A. Sutherland, G. S. Hamilton, C. Cenedese, K. Våge, and L. A. Stearns (2011), Impact of fjord dynamics and glacial runoff on the circulation near Helheim Glacier, *Nat. Geosci., 4,* 322–327, doi:10.1038/ngeo1109.

Walter, F., S. O'Neel, D. McNamara, W. T. Pfeffer, J. N. Bassis, and H. A. Fricker (2010), Iceberg calving during transition from grounded to floating ice: Columbia Glacier, Alaska, *Geophys. Res. Lett., 37,* L15501, doi:10.1029/2010GL043201.

Warren, C., and M. Aniya (1999), The calving glaciers of southern South America, *Global Planet. Change, 22*(1-4), 59–77, doi:10.1016/S0921-8181(99)00026-0.

Yde, J. C., and Ø. Paasche (2010), Reconstructing climate change: Not all glaciers suitable, *Eos Trans. AGU, 91*(21), 189–190, doi:10.1029/2010EO210001.

Author Information

Austin Post, U.S. Geological Survey (Emeritus), Tacoma, Wash.; Shad O'Neel, Alaska Science Center, U.S. Geological Survey, Anchorage; E-mail: soneel@usgs.gov; Roman J. Motyka, Geophysical Institute, University of Alaska Fairbanks; and Gregory Streveler, Icy Strait Environmental Services, Gustavus, Alaska