15 June 2015

Report to Prince William Sound Regional Citizens' Advisory Council:
Future Iceberg Discharge from Columbia Glacier, Alaska

Reference PWSRCAC Project #8551
Contractor: W. T. Pfeffer Geophysical Consultants, Nederland, Colorado

Report #6 FINAL REPORT

Abstract

Columbia Glacier, in the northeastern corner of Prince William Sound and ca. 12 miles distant from the path of tankers leaving the southern terminus of the Alaska Pipeline, has been in a state of rapid tidewater retreat since the early 1980s. Icebergs discharged by the glacier during the retreat have largely been contained within the moraine shoal at the position of the terminus prior to the glacier's retreat, but the fraction of icebergs crossing the moraine and entering Prince William Sound proper still pose a potential hazard to ship traffic in the Sound.

This study assesses the current and future status of iceberg discharge from Columbia Glacier. There is a long history of glaciological research at Columbia Glacier that we can draw on, much of it conducted by the US Geological Survey in the 1970s and 1980s. In addition to these resources, starting in 2012 and continuing at present, we have worked on the glacier and in the fjord collecting and compiling new datasets, including time-lapse photography, weather data, tectonic uplift, ice motion (diurnal to annual time scales), bathymetry, ocean water properties, and ice surface topography. The details of these investigations are described in our five earlier reports to PWSRCAC, but the overall conclusions of the project are stated here, and we make our final assessment of Columbia Glacier's future retreat, the characteristics of iceberg discharge, and our judgment of the primary hazards posed by the glacier in the future. We estimate that the tidewater retreat phase of Columbia Glacier may continue for as long as another 20 years, but that icebergs discharged from the retreating terminus in future will be reduced both in size and number. The increasing distance that icebergs must traverse between the retreating terminus and the moraine shoal at Heather Island (where the vast majority of icebergs are trapped and prevented from escaping into the Sound proper), as well as increasing water temperature, will also contribute to further degradation of icebergs before they reach the shoal. Risk to tanker traffic from icebergs will thus likely be reduced, but not absent, in the next two decades. In addition to risk to tankers, however, a new class of risk may be developing to other boat traffic in the inner Columbia Fjord, as this area becomes more accessible with declining iceberg density.

Introduction

This project is focused on assessing the current and future status of iceberg discharge from Columbia Glacier, a large tidewater glacier that terminates in Prince William Sound, Alaska. The Prince William Sound Regional Citizen's Advisory Council (PWSRCAC) initiated Project #8551 with W.T. Pfeffer Geophysical Consultants, LLC in 2012 as a follow-up to the 1996-1998 Iceberg Monitoring Project (IMP) conducted by Austin Post and Wendell Tangborn. The principal objectives of the present study are to summarize the glacier's retreat since 1996-1998, reevaluate methods for assessing and projecting glacier retreat and iceberg calving, estimate the duration of remaining glacier retreat, and project iceberg production and drift for the next decade (to 2022). To these ends, we have worked on the glacier and in the fjord collecting and compiling new datasets, including time-lapse photography, weather data, tectonic uplift, ice motion (diurnal to annual time scales), bathymetry, ocean water properties, and ice surface topography. Our report also discusses colleagues' findings, including fjord sedimentation, ice thickness, and mass balance measurements. All are aimed at understanding the present stability of the Columbia Glacier and improving forecasts of the continued retreat over the coming decade.

Background

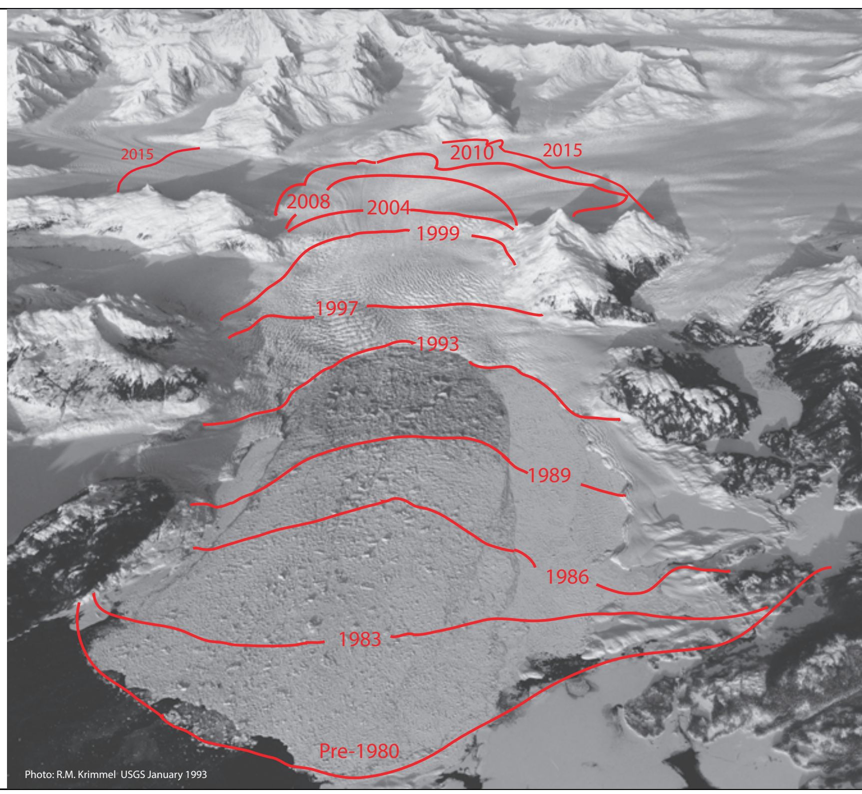

Figure 1. Columbia Glacier in 1993 with terminus positions throughout the retreat overlaid.

Columbia Glacier began rapidly retreating in the early 1980s. Since 1982, the glacier terminus has retreated over 20 km. Rapid thinning and discharge has reduced the total volume of the glacier by about 50% (**Figure 1**). The data compiled during this period represents the most detailed observational record of tidewater glacier retreat ever assembled (**Figure 2**).

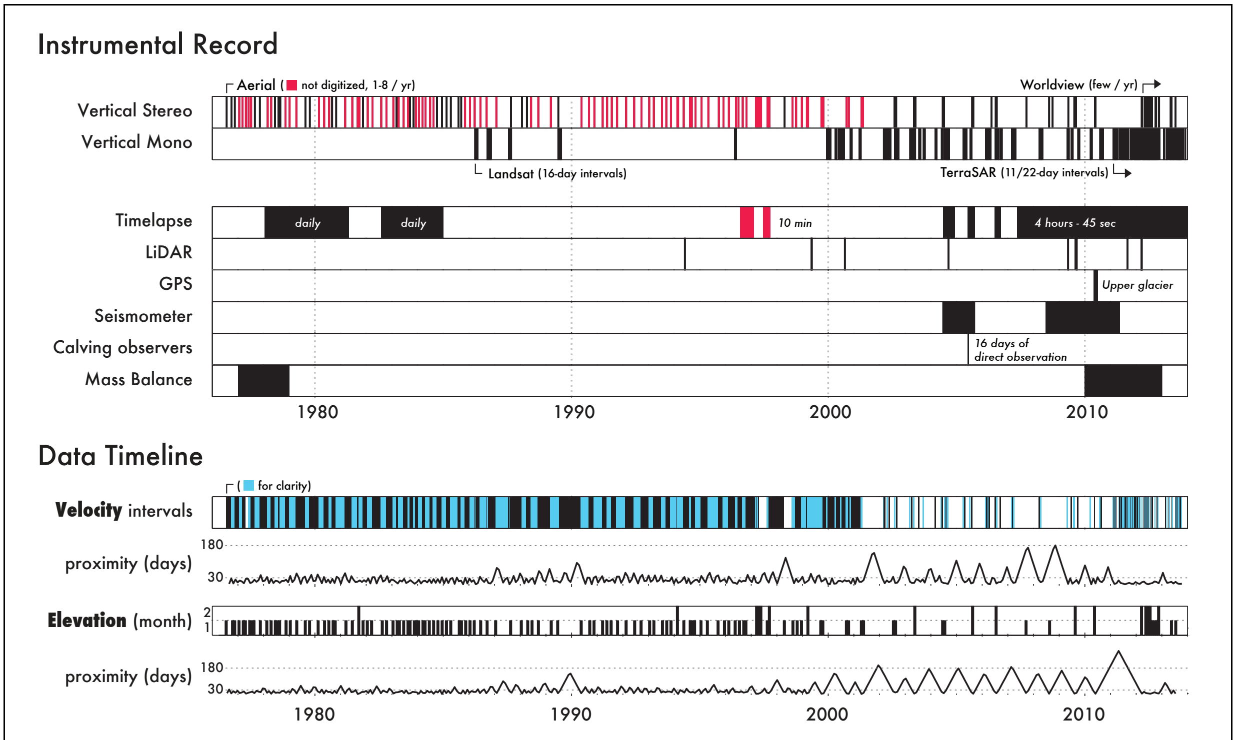

Figure 2. Distribution of principal observational time series over the lifetime of Columbia Glacier research, from 1976-2012

Columbia Glacier is one of the fastest changing landforms on Earth. The rate of ice loss is spectacular relative to the glacier's total size, and for nearly a decade (between 1998 and 2007) accounted for roughly 1% of global sea level rise (Rasmussen et al., 2011). The processes characterizing the retreat provide insight into other tidewater and outlet glacier retreats around the globe. Locally, icebergs calved from Columbia Glacier have been a hazard to ship traffic in eastern Prince William Sound, while the combined flux of ice and meltwater almost certainly have a significant influence on salinity and acidity in the Sound (Evans et al., 2014).

Iceberg hazards have been an issue of great concern to stakeholders in Prince William Sound. Accordingly, our wide-ranging investigations at Columbia Glacier, although serving a number of valuable scientific goals, also bear on the question of present and future iceberg discharge into the Sound. We describe our investigations in general terms below, and address the specific iceberg hazard issues that motivated this work in the Summary Evaluation and Recommendations.

Data Collection and Interpretation (since RCAC Report 5)

Time-lapse photography

Four time-lapse cameras have been in operation since Report 5 was delivered to RCAC in December 2014. These cameras were last serviced in March 2015. Although power supply issues plagued the telemetered camera through winter, the power system was replaced and improved and the camera is operating once again. The DSLR camera at Kadin(AK-01) operated through winter. A solar panel failure at the upglacier DSLR camera (AK-10) caused a gap in photographic coverage, but this was repaired in March. The Heather Island camera also had a short gap in coverage during the winter (potentially from limited sunlight), but was operating when we arrived. This camera was removed in March 2015, after having recorded over 20,000 images since its deployment in May 2013.

Geodetics

A geodetic GPS base station was installed during the October 2014 field visit (see Report 5) and operated from October 2014 to February 2015; the collected data has been sent to Jeffrey Freymueller (University of Alaska) for processing, including a survey tying the new antennae location to an older reference point (established 2004). Despite efforts to ventilate the air-alkaline batteries, insufficient airflow is likely to have caused the premature failure of the station. The receiver was brought back to Anchorage in March 2015, and a new power system is being designed using funds leveraged from other projects. The station is scheduled to deploy in June 2015 with a rechargeable lithium iron phosphate (LiFePo) battery and solar power system.

Ice motion

Since Report 5 (December, 2014), we have performed ice motion observations on a range of time scales. Ground-based portable radar interferometry (GPRI) data was collected over a weeklong, 3-minute repeat interval survey in fall 2014, and analysis is ongoing (**Figure 3**).

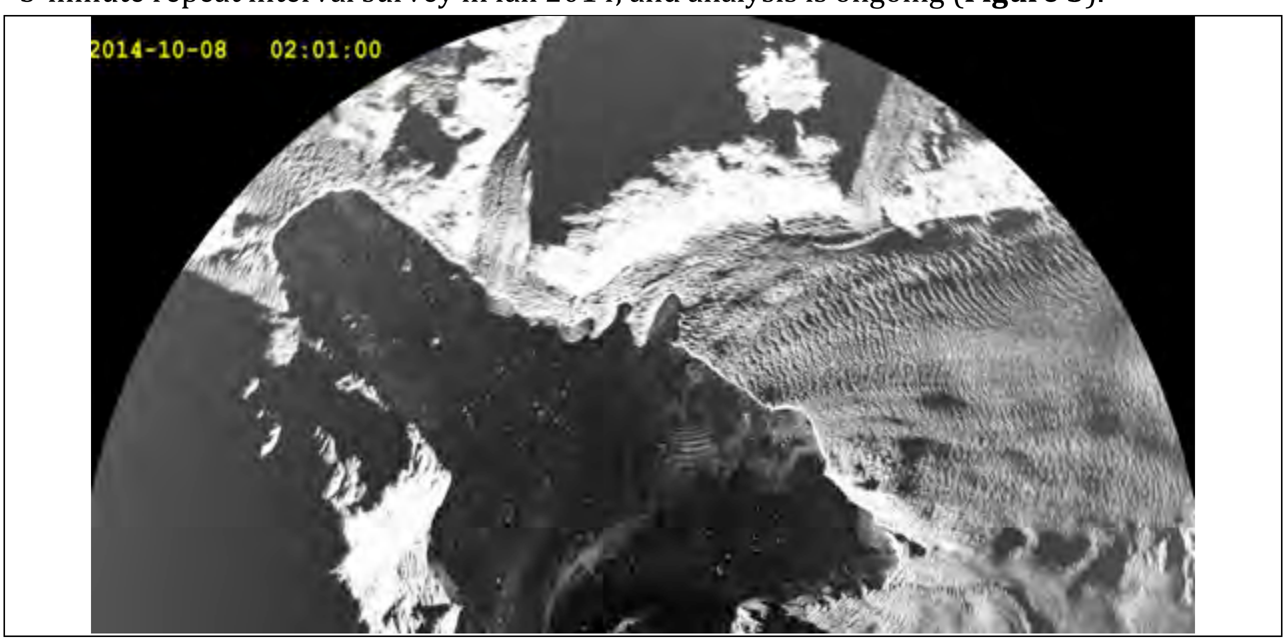

Figure 3. Radar backscatter still image from the Great Nunatak camp. The ground-based radar interferometer is located at the center of the bottom edge of the image, and collects data in a radially symmetric pattern. In this reference frame the main branch is located on the right hand side of the image, and the west branch on the left side of the image.

PhD student Ryan Cassotto (University of New Hampshire) is leading this work, and the algorithms needed to process such data are being developed with NSF funding (once ready, they could be used to process the data collected last fall). The data are presently in a line-of-sight (LOS) reference frame, complicating the location of features in the imagery, but we expect only small changes to our interpretations of ice motion when the data is transformed to a standard, gridded coordinate system.

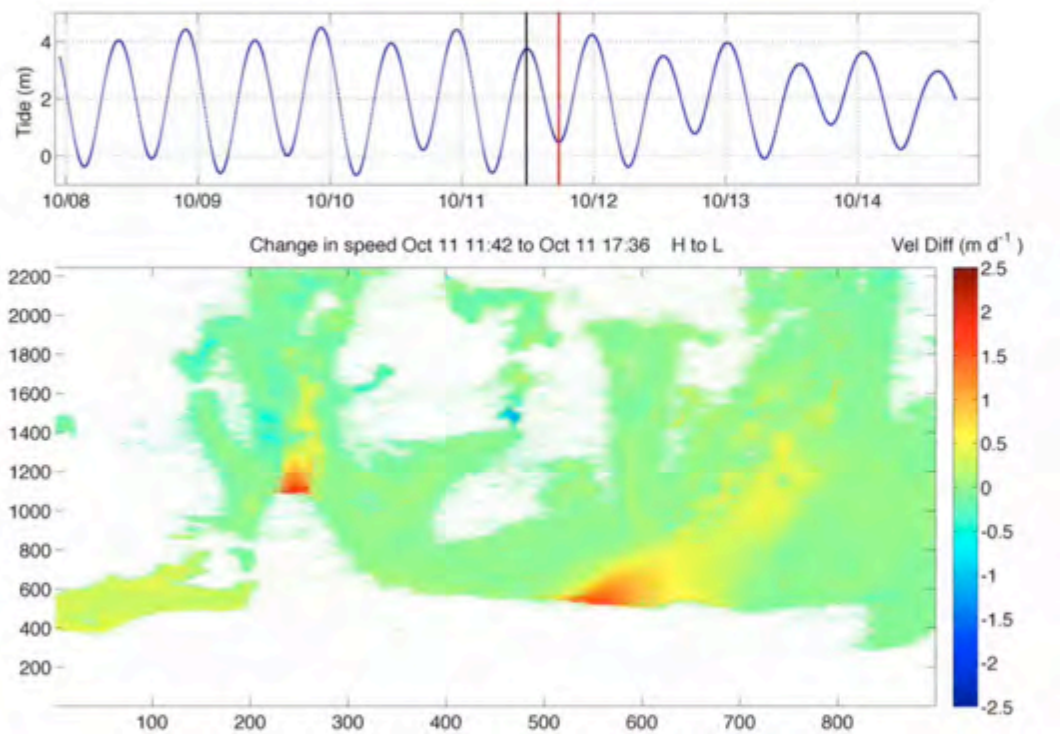

Figure 4. Tidal variations in motion. The top panel shows the regional tide with vertical bars indicating the timing of the two scans that are differenced in the color plot below. This example shows the difference between high and low tide on October 11 and the associated speed up at the West and Main calving fronts. Red colors indicate faster motion for the second interval, blue colors slower motion.

So far, our analysis has confirmed that tides force velocity variations in the glacier (**Figure 4**), with slower speeds occurring at high tide and faster speeds occurring at low tide. This is expected of grounded tidewater glaciers (e.g., Walters and Dunlap, 1987; O'Neel et al., 2001);

however, the velocity perturbation reaches further upstream than we expected (**Figure 5**). Precipitation may also have a very large influence on glacier speed: the lower glacier accelerated up to 300% beginning 1-1.5 days after the onset of sustained rainfall (**Figure 6**). Walters and Dunlap (1987) analyzed along-flow speed variations at Columbia Glacier very early in the glacier's retreat and reported an "e-folding" (1/e ≈ 0.37) damping length scale of ~2 km. The damping lengths we observe today are ~5 km (**Figures 4,5**), meaning that velocity fluctuations are propagating more than twice as far up the glacier now as they did in the 1980s.

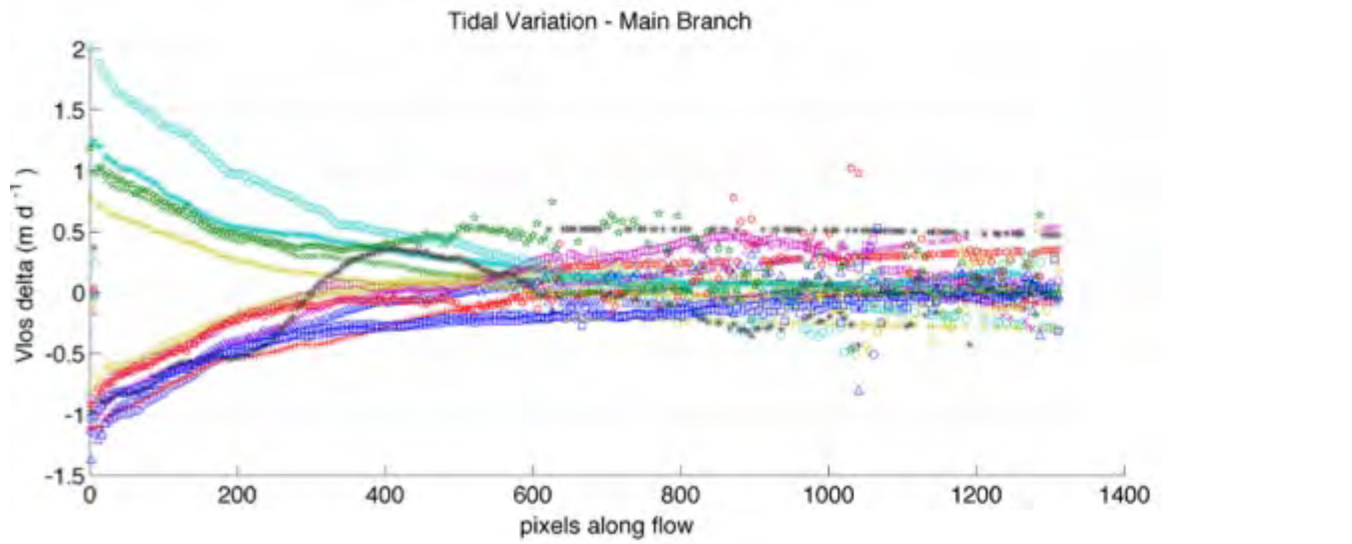

Figure 5. Ice flow velocity plotted vs. along-flow distance, approximated by pixel positions in the images. The 1300-pixel length of the profile corresponds to roughly 10 km in the upstream direction.

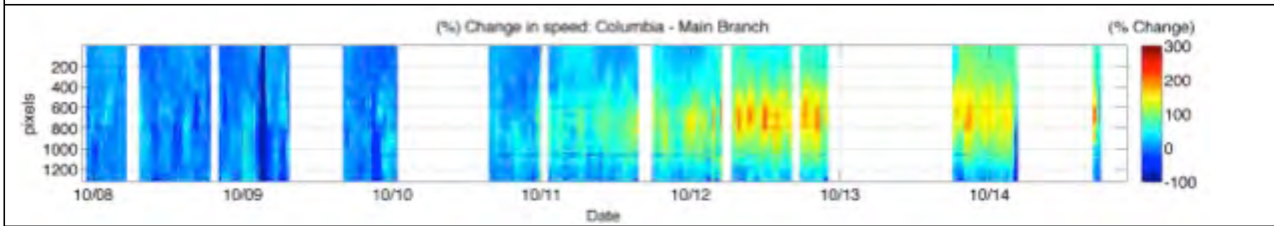

Figure 6. Influence of precipitation on ice motion is shown as a percent deviation from initial speed. The terminus is across the top (pixel 0) and speeds are shown along the centerline profile extending up the main branch. Accelerations up to 300% the initial speed are seen after water inputs, which began on the evening of 10/9 and persisted through the morning of 10/12.

We have also obtained TerraSAR-X velocity fields (through 25 July 2014) from UW collaborator Ian Joughin (**Figure 7**). These data show that overall glacier velocities are continuing to decline over time. The glacier continues to exhibit strong seasonal fluctuations in flow speed, with a rapid spring acceleration, culminating in the fastest observed speeds, followed by a slow decline through summer and into fall, followed by a slow acceleration through the winter (**Figure 8**).

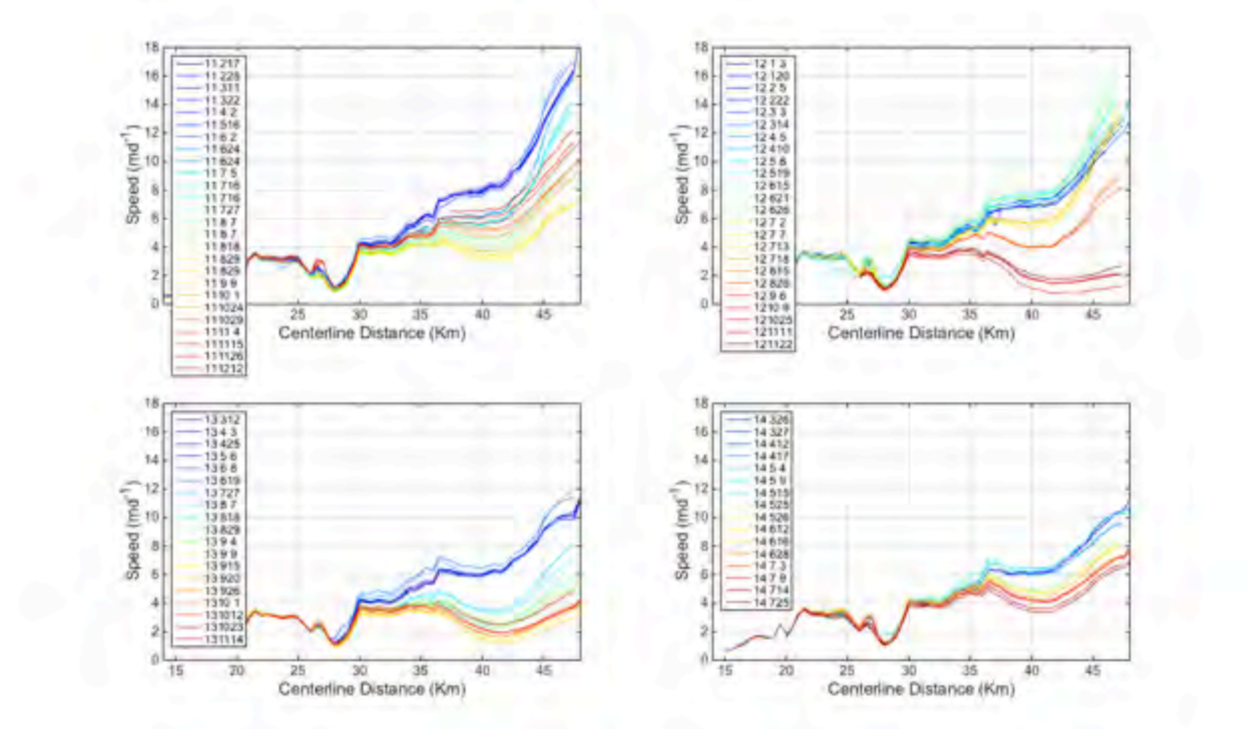

Figure 7. Centerline speed profiles extracted from TSX velocity fields. For 2011 – 2014. Note the general decline in terminus speed since 2011.

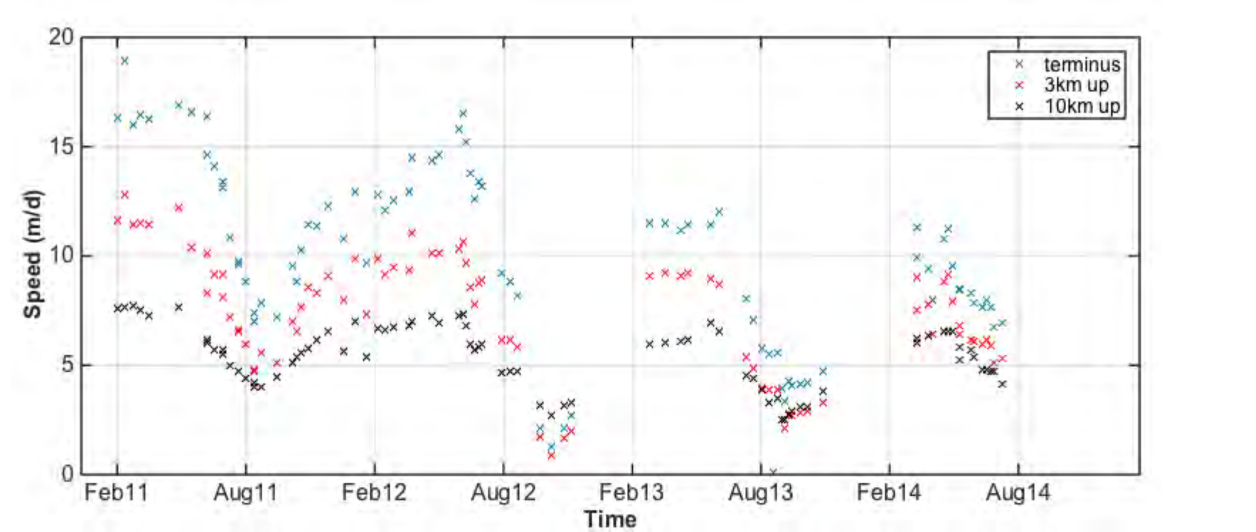

Figure 8. Time series of centerline speed (m/yr) over the 2011-2014 interval. Speed has been increasing slowly through spring and summer but has tended to decelerate rapidly in late summer. Over the three years of TSX acquisition, there is an overall trend of reduced speed and lower amplitude seasonal variability.

Overall Project Summary

Over the lifetime of this project (2012-present), we analyzed existing data, collected new data, and incorporated data from other investigators to make predictions about the discharge of icebergs from Columbia Glacier in the future. We recovered a significant volume of early photogrammetric data, conducted an extensive time-lapse survey of the glacier, and installed an iridium-telemetered timelapse camera to monitor the terminus for signs of destabilization in real-time. The images are viewable on the site glacierresearch.org, which has been moved to a more stable server and redesigned with a greatly improved interface.

Stability of the moraine shoal

Early in our work, we investigated whether or not the moraine shoal west of Heather Island has been substantially eroded (Report 2 and Figure 9). Within the precision of the data, which was limited by the poorly resolved tide stages of the 1977 and 1994 surveys, we found no large-scale changes to the topography of the shoal, which continues to be the main obstacle to large icebergs escaping from the Columbia fjord into Prince William Sound. Although the size distribution and rate of iceberg production at the terminus remain important variables in determining the size distribution of icebergs reaching the Sound (see Report 2), melt and fragmentation of the icebergs during their journey to the shoal are becoming critically important processes as the distance from the terminus to the shoal increases as the glacier retreats.

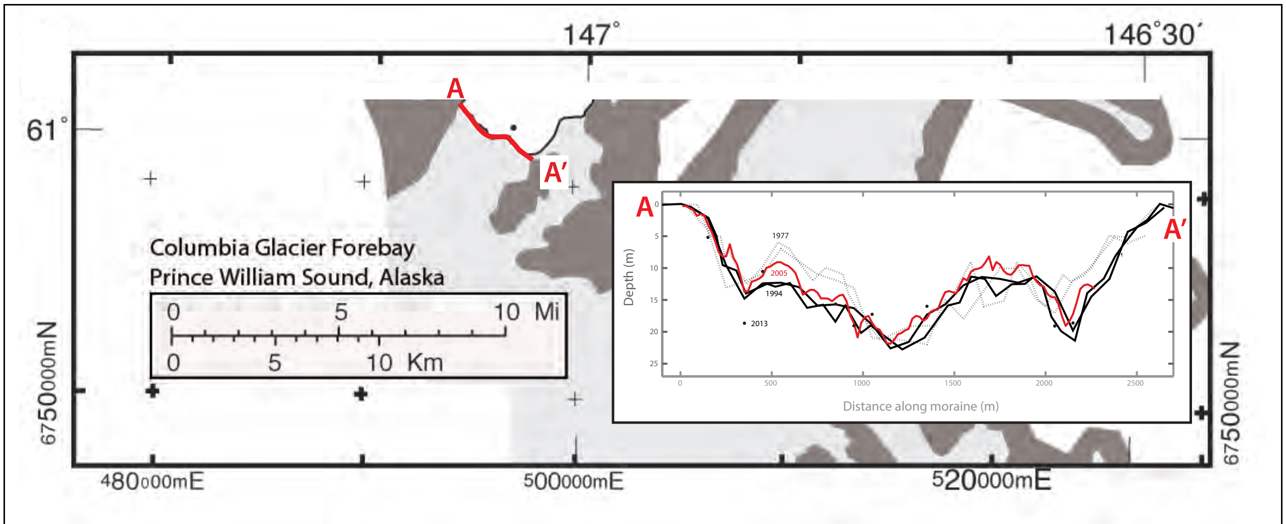

Figure 9. Bathymetric profiles across the Columbia Bay Entrance Sill the west shore of the fjord (0 m) to Heather Island (3000 m).

Iceberg calving and transport

The calving flux discharged by Columbia Glacier over the nearly 30-year lifetime of the retreat to date has been marked by variations closely tied to changes in the fjord geometry in the immediate vicinity of the retreating terminus (Figure 10). The future long-term thinning of the glacier and retreat of the glacier terminus into narrower and shallower waters constrains the future rate and size of icebergs discharged into the fjord. The glacier has thinned over 500 m at the current terminus position since the onset of retreat. The deep-water channel to which the terminus is exposed has narrowed significantly (from ~5 km in 1982 to ~2 km at the Kadin-Great Nunatak gap, for example) and water depths in the vicinity of the present terminus are variable and generally shallow (less than 200 m). All of these changes suggest that the terminus will produce smaller and smaller icebergs over the long term and that the larger icebergs will be more likely to become grounded in their journey down-fjord to the moraine shoal.

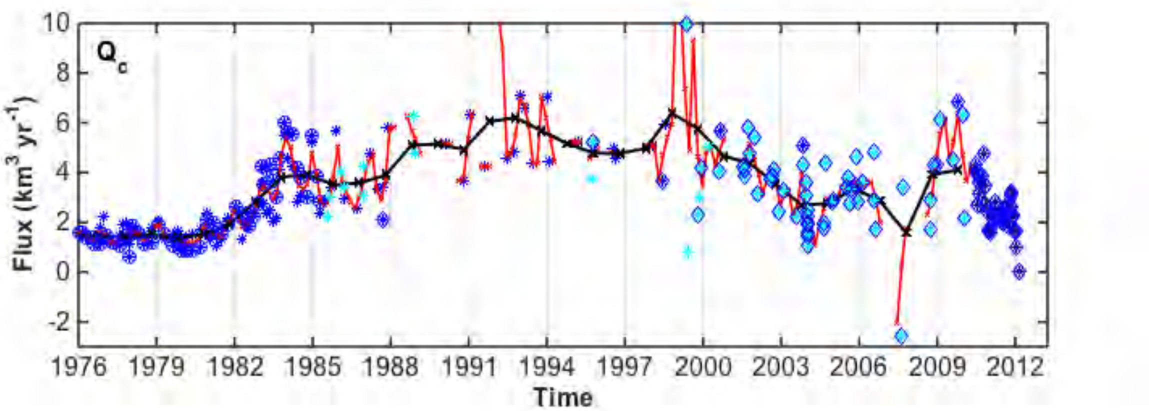

Figure 10. Columbia Glacier calving flux estimates over the history of the retreat produced using a flux gate analysis (described below). The red curve is smoothed over 3 month intervals, and the black curve depicts annual smoothing.

However, periods of increased – and possibly dramatically increased – rates of calving are still possible. Since the rapid opening of the inner fjord in 2007-2010, the terminus position of the Main Branch has remained relatively stable (with minor adjustments and embayments but no significant change in position). The glacier is also flowing and thinning at comparatively slow rates. However, relative to the past ca. 2 years, variations in speed have become well correlated over large horizontal distances (i.e., a perturbation in speed near the terminus is reflected several km upstream with little delay). This coherence suggests that basal drag is presently very low and that the glacier is near flotation over a large region upstream from the present terminus. Judging from past behavior and our latest observations, the glacier may soon enter a period of rapid terminus retreat, increased iceberg production, and larger iceberg sizes.

In 2006, when the glacier terminus was thicker but located at a similar pinning point in the fjord, iceberg size increased dramatically as the glacier thinned, transitioned to flotation (2007), and retreated out of the pinning point and the deeper water immediately up-fjord (2008-2009). During the 18-month period the terminus was floating, many of the icebergs produced were "tabular," a classification describing icebergs that are much wider than they are thick. The tabular icebergs were heavily fractured, and rapidly disintegrated into smaller icebergs, but some potential remains for large, thin icebergs to be carried over the moraine shoal and into the Sound.

However, other changes in the fjord will reduce the likelihood of large icebergs escaping. The inner fjord (the recently opened reach up-fjord of the Kadin-Great Nunatak Gap), and in particular the Main Branch side of the inner fjord, contains a number of shallow reefs, features not present in the main, or outer, fjord, downstream from the constriction between Kadin Peak and the Great Nunatak (referred to here as the "Kadin-Great Nunatak Gap"). Grounding on these reefs not only slows the passage of icebergs down-fjord, but also subjects them to strong tidally-forced rotations which tend to break the icebergs into smaller pieces. In turn, the increased surface-to-volume ratio of the smaller bergs accelerates melt, further reducing the total volume of ice reaching the moraine shoal.

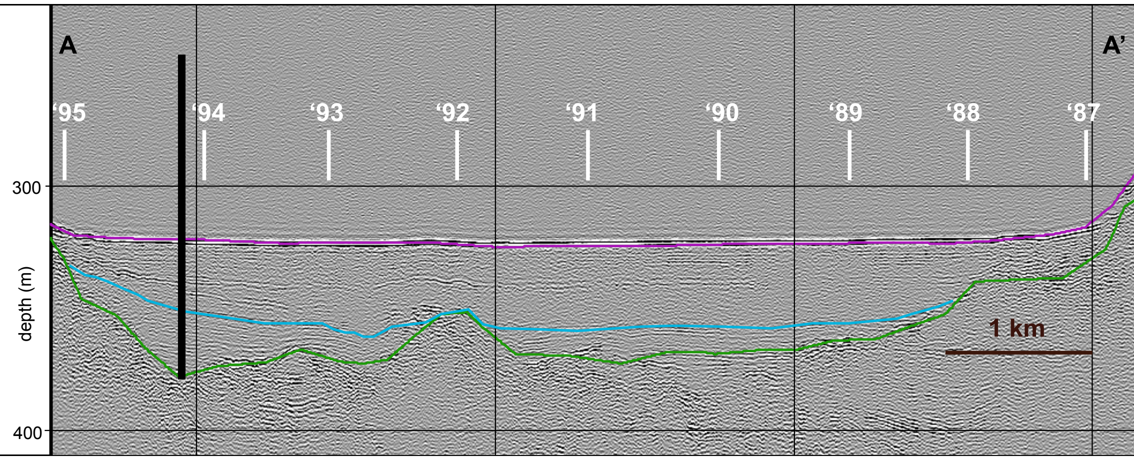

Figure 11. Active-source seismic mapping of bedrock and sediment geometry along the centerline of the outer bay of Columbia Glacier's fjord. White bars show the location of the terminus in year indicated. The black line represents the position and depth of a 1987 borehole (Meier et al., 1994). The base of the sediment deposit is shown with a green line. The blue line indicates seabed depth in 1997, and the pink line shows the seafloor in 2011.

Sedimentation in the fjord

A study of sedimentation rates and processes by colleagues at the University of Washington (UW) is nearing submission to the Journal of Glaciology (Boldt et al., in prep). Their work shows that sedimentation is very rapid, with sediment fluxes upwards of 19 million cubic meters per year, or an average sedimentation rate of 20 cm/yr throughout the fjord. The sedimentation rate is episodic, with variations linked more closely to changes in the fjord geometry near the current terminus position than to variations in ice flux or calving speed. A new model developed by the UW team is able to reproduce the spatial and temporal patterns observed in the fjord stratigraphy (**Figure 11**), and their results should give us valuable insights into subglacial erosion, spatial variations in basal sliding, and – possibly of greatest interest to RCAC – insights into processes governing the delivery of sediments, associated nutrients, and changes in water chemistry not only to the Columbia fjord but to Prince William Sound.

Measurements of bed topography

Recently discovered errors in the subglacial topography produced by McNabb et al. (2012) are proving to have a significant effect on many important results and predictions. In 2014, the West Branch retreated suddenly and unexpectedly to a position where the bed was earlier predicted to be 100 m above sea level, whereas bathymetric data collected in fall 2014 showed that the water depth in fact approaches 300 m in this location (**Figure 12**). We suspect that the large modeling errors in McNabb et al. (2012) are largely the result of not considering the magnitude of changes in bathymetry caused by deposition and evacuation of basal sediments – conditions that we had no knowledge of prior to the work by Boldt et al. (see above). There is also a trend toward larger errors as the terminus retreats further upstream, away from the bathymetric measurements made in open water earlier in the glacier's retreat and used as initial conditions in the model. The recent bathymetric measurements by Rob Campbell in the inner fjord will provide new constraints if and when the McNabb bed model is improved and re-run.

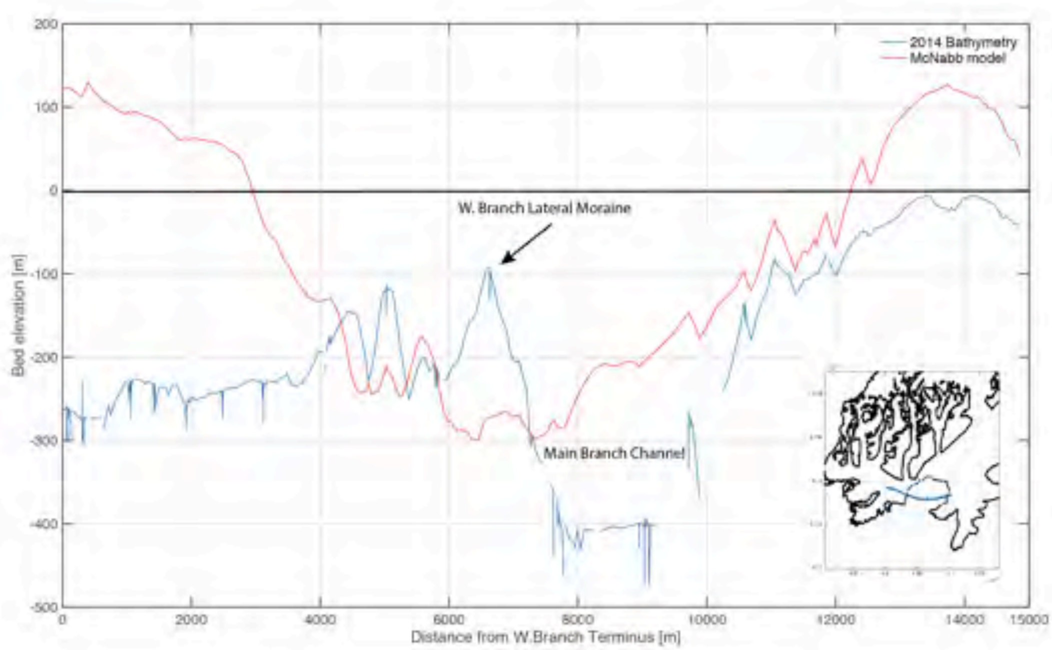

Figure 12. The 2012 bed model (McNabb et al., 2012) is plotted along a bathymetric profile taken perpendicular to the fjord and extending up into the west branch as shown in the inset figure. At the location of the October 2014 survey, the model estimate was ~350 m shallower than measured. The reverse slope bed in this location is an indication of continued susceptibility to unstable flow and calving.

Tectonics

The GPS record of uplift at the Great Nunatak site extends back to 2004 (Figure 13). The time series of elevation at that site reveals that local uplift from ice unloading is rapid, 14.6 mm/yr, or roughly half as fast as the fastest rates ever recorded near Glacier Bay (Motyka et al., 2007).

The observations and analyses summarized above and in our 5 previous reports form the core knowledge that we draw from to answer those questions about future iceberg calving and transport most relevant to the RCAC. In the sections that follow we address those questions more explicitly, first with a synthesis of the various observations in context, then with a list of recommendations and a final statement about the projected future retreat.

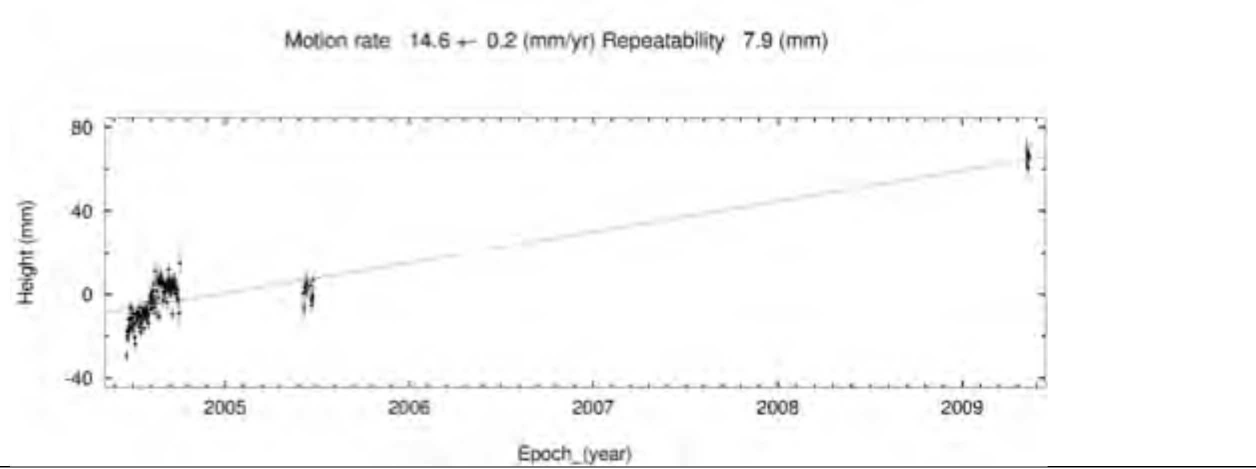

Figure 13. GPS-derived elevation of benchmark BBB at Great Nunatak, Columbia Glacier, Alaska, showing tectonic uplift of ca. 14.6 mm per year.

Discussion: Integrated Insight

We assembled a long-term record of calving discharge through the retreat using the Krimmel (2001) aerial photogrammetry data set (1977-1999), LANDSAT visible imagery (1986-2010), WorldView visible imagery (2008-2014), and TerraSAR-X radar imagery (2011-2014). The flux record is shown in **Figure 10**, where calving flux (Q_c) is plotted vs. time from 1976 to 2013.

The calving flux is calculated as the sum of the incoming ice flux (Q_{in}) passing through a "gate" located some distance upstream from the terminus and the volume change (dV/dt) in the region between the gate and the terminus:

$$Q_c = Q_{in} - dV/dt \quad (1)$$

The incoming flux at the upstream gate Q_{in} was calculated by multiplying the observed cross-glacier-average surface ice speed u at the gate (assumed equal to the depth-averaged speed) by the glacier's cross-sectional area at the gate (A):

$$Q_{in} = A \cdot \vec{u} \tag{2}$$

The cross-sectional area A was determined from the difference between the measured surface topography and the calculated subglacial topography (from McNabb et al., 2012) at the gate. Several gates were used to calculate Q_{in} to accommodate the long distance traversed by the retreat over the 37-year record. We defined a set of 4 gates, and for each time interval estimated Q_{in} at all gates upstream of the terminus position. Volume change (dV/dt) in the region between any gate and the terminus was calculated from the corresponding map-plane area change measured in the imagery. The measured area changes were multiplied by ice thickness (H) then scaled by the time interval (Δt) over which they were made:

$$dV/dt = \Delta A * H / \Delta t \tag{3}$$

Ice motion varies strongly over seasonal time scales, and the temporally inconsistent sampling challenges interpretation without introducing aliasing biases related to the sampling time. For example, a change in speed over a year may be misrepresented if one image in a pair was captured at maximum speed and the second captured at mean speed rather than at the time of minimum speed. Our annual estimates of speed are resolved with confidence but seasonal changes are often poorly constrained.

Our results indicate that the highest calving flux of the entire retreat to date, 8-10 $km^3\ yr^{-1}$, occurred during the early stages of entrapment of the terminus in the Kadin-Great Nunatak Gap (1998-2000). Comparable fluxes occurred in the early 1990s and during the opening of the inner fjord in 2008-2010. Since then calving flux has declined to essentially pre-retreat levels (2 $km^3\ yr^{-1}$). Since the onset of retreat, more than 150 km^3 of ice has been lost to a combination of melt and calving, with calving dominating melt by a factor of 3 to 2 (Rasmussen et al., 2011). However, despite the high rate of retreat, the incoming flux Q_{in} still dominated the volume change at the terminus (dV/dt) over most of the retreat. This means that the high iceberg discharge was mostly drawing from large reservoirs of ice far upstream and the rate of terminus retreat was slower than it otherwise would have been.

The spatial and temporal patterns in the discharge data illustrate of how fjord geometry is a primary control on discharge. Early in the retreat, when the glacier terminus was located in the shallow regions around the moraine shoal, ice flow was generally stable, with seasonal retreats and recovering advances. Meanwhile, long-term climatically-forced thinning of the lower glacier (not visible in the glacier-wide mass balance) was leading the near-terminus glacier geometry toward a dynamically unstable configuration (defined by Pfeffer (2007) as approximately 3/2 of the flotation thickness), and in 1982-1984 the pattern of seasonal retreat and advance was replaced by accelerating retreat, thinning, flow speed, and calving rate. Sustained retreat, modulated by modest seasonal re-advances, persisted through the 1990s as the terminus retreated upstream through the broad and deep lower fjord. Not until the terminus started to engage with the Kadin-Great Nunatak gap, around 1998-1999, did the retreat rate slow down, although ice flux through the terminus (i.e. calving) remained initially high.

Peak discharge rates exceeding 10 km^3 per year occurred in 1999-2000, coincident with the retreat of the terminus onto a steeply reverse-sloped bed in the deepest portion of the outer fjord, at the Kadin-Great Nunatak Gap. While the terminus position was temporarily pinned by lateral convergence in the Gap (2001-2006), ice flux declined and the West-Main Branch confluence immediately upstream of the constriction thinned until the ice reached flotation again, leading to the opening of the inner fjord (2007-2010). This episode of thinning, flotation, retreat, and restabilization in the shallow water of the Main Branch was analyzed in detail in Report 2. The pattern seems to be somewhat cyclic, and the glacier terminus, which has continued to thin since 2010, now may be approaching another episode of instability. We discuss this further below.

Hydrographic and bathymetric measurements performed in October 2014 by Rob Campbell in Columbia Glacier's inner fjord reveal several further links between the ocean and the glacier. As discussed above, the sudden 1.5 km retreat of the West Branch was a surprise. Not only is the ice in the West Branch ~400 m thicker (and the fjord 400 m deeper) than previously thought, but the new bathymetry reveals that the fall 2014 terminus was located on a reverse-slope bed (where bed depth increases with distance upstream), a geometry known to be unstable (e.g. Meier and Post, 1987; Cuffey and Paterson, 2010).

The reverse bed slope explains the continued West Branch retreat through winter 2014-2015. However, it is unlikely that the bed extends below sea level for much further upstream, and unlikely that the West Branch will continue to retreat for much longer, as the bed rises steeply immediately upstream of the present terminus and rock is showing through the ice in one location. Campbell's measurements also show large differences in water circulation and heat transport between the eastern and western parts of the inner fjord. A counterclockwise circulation, possibly linked to the predominant winds and resulting Eckman transport in the inner fjord, limits the circulation of warm water into the West Branch, while allowing warm upwelling in the Main Branch. Iceberg trains and plumes of brash ice visible in the GPRI image sequences (Figure 3) suggests that three initially independent water masses are mixing in the open area between the Kadin-Great Nunatak Gap and Juncture. These are the two freshwater inputs from the West and Main Branches, and the ocean water carried up the fiord by tidal currents.

The 2014 bathymetry also provides strong constraints on the geometry of the Main Branch. Like the West Branch, a narrow segment of the Main Branch channel is deeper than previously thought by at least 50 -100m, although deep water in this region has been hypothesized as early as Engel (2008) but never confirmed.

Vertical profiles of temperature obtained from Campbell's measurements show that warm water was present in Columbia Bay in October 2014. Although the atmosphere generally cools by this time of year, ocean temperatures remain warm substantially later in the year, which results in elevated rates of iceberg melt. Warm water is also an important driver for melting along the submarine ice cliff. This kind of submarine melting can account for 50% of the total mass flux discharged at the terminus (e.g. Motyka et al., 2013) when the warm water is convectively mixed by freshwater subglacial discharge. Turbidity measurements from the same observations suggest that freshwater is being discharged by the glacier, but the vigorous estuarine circulation seen in other glacierized fjords is not obviously present here. Similar data collection at a coarser scale in 2006 was interpreted as indicating estuarine circulation, comparable to data from LeConte and Yahtse glaciers. These new data suggest that the submarine melt process may have a strong seasonal component.

Iceberg processes

Our observations of the moraine shoal indicate that erosion at the crest has been inconsequential since the onset of the glacier's retreat. Within the limited precision of the earlier bathymetric surveys, the moraine geometry has remained constant and the limit imposed by the moraine on the size of escaping bergs thus has not changed. The largest icebergs that do escape pass through a low trough (Report 2, Figure 2-3, 18 m below Mean Lower Low Water) in the moraine. Our qualitative assessment of iceberg passage over the moraine (from time-lapse photography) indicates that icebergs are flushed quasi-periodically through this gap and over the moraine, with both tides and wind governing their escape.

Characteristics of future iceberg discharge

Given the stability of the moraine shoal, the factors that will control the number and size of icebergs reaching Columbia Bay and Prince William Sound in the future are (a) the number and size of icebergs produced at the terminus of Columbia Glacier, including the possibility of transient episodes of accelerated calving and ice flux, and (b) the rate of fragmentation and melt of icebergs as they travel down-fjord to the moraine shoal.

Our original research plan included the development of a transport model for icebergs moving down-fjord from the calving terminus to the moraine shoal; the number density and size distribution of icebergs was to be calculated based on fluid mechanics and heat transfer principles, providing the sizes and numbers of icebergs arriving at the moraine shoal. Subsequent observations of currents in the fjord, and especially those observations made by

GPRI in the inner fjord, revealed a far more complex and unpredictable pattern of currents than we originally estimated, and this model ultimately proved to be intractable. However, our observations also gave us important insights to the processes driving iceberg transport and degradation on a qualitative level, and from these we are confident in drawing conclusions that constrain the characteristics of icebergs arriving at the moraine shoal in the future. We discuss those conclusions here.

The largest icebergs calved at the terminus of Columbia Glacier in the future will almost certainly be smaller than the largest icebergs recorded in the past. The part of the glacier resting below sea level is significantly thinner than the ice passing through the terminus in the past, both because of the shallower bed upstream of the present terminus and the thinning of the glacier throughout the tidewater reach over the course of the retreat. Smaller icebergs have a smaller mass to be melted and have a larger surface-area to volume ratio, making them more susceptible to melt by contact with a warm environment. Furthermore, the journey from the glacier terminus to the moraine shoal is much longer now than it was in the early years of the retreat. Not only is the distance is greater, but the path is more circuitous and icebergs may be caught in gyres that carry them up- and down-fjord repeatedly as tides and winds change. This effect was amplified following the opening of the inner fjord (2007-2010), and the mixing of currents producing high vorticity relative to the outer fjord. The inner fjord also contains shallow reefs where icebergs are regularly seen to ground at high falling tide and fracture under their own weight with continued tidal fall.

Finally, the rate of iceberg production, while generally reduced in magnitude, is likely to remain episodic for the remaining future of the retreat. Ice flux and ice speed vary strongly with the seasons, with the peak calving rate typically occurring in spring, and multi-year intervals of accelerated retreat (like those seen at Columbia Glacier in the past) will continue to occur. In fact, the geometric conditions indicative of an episode of retreat are once again taking shape. The near-terminus ice is approaching flotation thickness (as indicated by the long propagation up-glacier of velocity variations at the terminus, as discussed above), and the bed is believed to be deeper immediately upstream of the present terminus (although the bed in the Main Branch above the present terminus position is imperfectly known).

The "tidewater limit" – the upstream point at which the glacier bed rises above sea level – marks the upstream extent of the glacier's susceptibility to the ocean. In the upper Main Branch, which climbs rapidly to the west of Divider Mountain into the upper reaches of Columbia Glacier (See Report 1, Figures 1a, 1b), the tidewater limit lies another 8-10 km upstream of the present terminus. We anticipate that the glacier terminus will reach this tidewater limit by 2029 – 2036 (Report 2), with modeled maximum calving rates as high as 6.2 $km^3\ yr^{-1}$ during brief (less than one year) episodes of accelerated retreat. Predicting calving rates and retreat for a separate terminus moving up the glacier's East Branch (passing to the east of Divider Mountain) will be difficult given the very large uncertainty for the ice thickness in the East Branch (see Reports 4 and 5). When the glacier's terminus reaches this basin, likely sometime after 2035, another episode of rapid calving and retreat may occur, possibly in thick ice. That event is distant enough in time that no quantitative prediction of ice flux can be made, but three significant points can be noted. First, the terminus by that time will be more than 35 km from the moraine shoal, exposing icebergs to yet more melt and degradation over the extended path to the shoal. Second, the inner-fjord shoals in the vicinity of the present terminus will trap a significant fraction of any large icebergs coming from the deep water of the East Branch. Third, thinning may have progressed to the point that, by the time the terminus enters the East Branch basin, the remaining ice below the tidewater limit may be in a state of so-called "disarticulation" (Molnia, 2007) distinguished by the absence of a clearly defined calving terminus and disintegration of all floating ice more or less simultaneously. If this occurs with a shallow barrier, or sill, on the downstream side of the basin (and radar data suggests that such a sill exists, as discussed in Report 4), the disarticulated icebergs may be trapped in the basin and subject to much higher melt rates (by their increased surface-to-volume ratio) relative to intact ice.

All of these factors work towards reducing the likely future iceberg flux and iceberg size coming from the East Branch basin at some point in the future. This is the last known reservoir of thick ice grounded below sea level and subject to rapid tidewater retreat. However, our evaluation is that the probability of large or numerous icebergs issuing from this reservoir at some future time is very low.

Summary Evaluation and Recommendations

The series of 6 reports we have submitted to the Prince William Sound Regional Citizen's Advisory Council form the scientific basis of the following evaluation and recommendations regarding future hazards arising from icebergs originating from Columbia Glacier.

- The retreat of the Columbia Glacier is predicted to cease by 2029 – 2036 (Report 2).
- The maximum calving rate (ice flux at the terminus) during the remainder of the retreat is estimated to range from 5.8 to 6.2 $km^3 yr^{-1}$ (Report 2).
- More episodes of elevated calving flux are expected, with one episode imminent (Report 5).
- Efforts to construct an explicit iceberg transport model failed, due to the increasing complexity of ocean circulation in the fjord (Report 6).
- Despite the absence of a transport model, a number of factors all act to reduce the initial size of calved icebergs, increase the residence time of ice in the fjord, and increase water temperatures, leading us to these further qualitative conclusions:
    - Individual initial iceberg size is estimated to be smaller in the future than at present (2012-2015) (Reports 3-6).
    - The degradation of icebergs between the time they are calved from the terminus to the time the arrive at the moraine shoal is very likely to increase significantly in the future, meaning that the total ice flux arriving at the shoal, as well as the size distribution of icebergs, will be yet smaller than the predicted ice flux and size distribution predicted for the calving terminus itself.
- Bathymetry at the moraine shoal (Report 2) indicate that the shoal has not suffered erosion over the course of the retreat.
- The likelihood that the shoal will be eroded in the future is extremely low. Erosion would occur from the dragging of iceberg keels across the top of the shoal, but the size and number of icebergs present at the moraine shoal was vastly larger in the past than it is today (and is predicted to be in the future) and no erosion has yet occurred. These observations suggest (with a high degree of confidence) that the capability of the shoal to block the passage of large icebergs out of the fjord and into Columbia Bay will continue undiminished in the future.
- Note that the factors detailed above all act toward reducing the size of icebergs arriving at the Heather Island moraine shoal. This also means that a larger fraction of icebergs may have sufficiently shallow drafts to be able to escape over the moraine. The combined effect of smaller but more numerous icebergs in Columbia Bay proper on overall risk to ship traffic depends in part on what size classes of icebergs are viewed as posing the greatest hazard to ship traffic moving in and out of Port Valdez. We do not address this question.

Risks Icebergs crossing the moraine shoal in Columbia Bay and Prince William Sound proper will continue in the future, but at lower and declining rates, both in terms of iceberg size and frequency of occurrence. Episodes of significantly elevated ice flux in the Sound are possible but infrequent, but will be composed of icebergs generally smaller in size than what is observed today. Our model projections suggest that the retreat will persist for another ca. 20 years at most, at which time the ocean-ending termini of the glacier will have retreated to the tidewater limit. At this point continued calving will occur, but at rates comparable to other retreated glaciers in the Sound.

The primary increase in risk associated with Columbia Glacier's continued retreat may not be to ship traffic in Prince William Sound proper, but rather to boat operations (e.g., private operators, tour boats) entering upper Columbia Glacier fjord and being exposed to icebergs and waves produced in calving events at the glacier terminus, and to already-calved icebergs that roll or split. This has been a hazard ever since the ice mélange in the fjord upstream from the moraine shoal was clear enough to allow boats access to the terminus, but the risk of encounters will most likely increase in the future as the fjord grows in size, becomes more accessible, and becomes a more popular and desirable destination.

References

Cuffey, K. M., & Paterson, W. S. B. (2010). *The Physics of Glaciers, Fourth Edition* (4th ed.). Academic Press.

Engel, C. S. (2008). *Defining basal geometry and force balance at Columbia Glacier, Alaska* (M.S.). University of Colorado at Boulder.

Evans, W., J. T. Mathis, J. N. Cross (2014). Calcium Carbonate Corrosivity in an Alaskan Inland Sea. Biogeosciences 11(2): 365–379.

Krimmel, R. M. (2001). *Photogrammetric data set, 1957-2000, and bathymetric measurements for Columbia Glacier, Alaska* (No. 2001-4089) (p. 50). U.S. Geological Survey. Retrieved from http://pubs.usgs.gov/wri/wri014089/

McNabb, R. W., Hock, R., O'Neel, S., Rasmussen, L. A., Ahn, Y., Braun, M.,Truffer, M. (2012). Using surface velocities to calculate ice thickness and bed topography: a case study at Columbia Glacier, Alaska, USA. *Journal of Glaciology*, *58*(212), 1151–1164. http://doi.org/10.3189/2012JoG11J249

Meier, M. F., and Austin Post. (1987). Fast Tidewater Glaciers. Journal of Geophysical Research: Solid Earth 92(B9): 9051–9058.

Meier, M., Lundstrom, S., Stone, D., Kamb, B., Engelhardt, H., Humphrey, N., ... & Walters, R. (1994). Mechanical and hydrologic basis for the rapid motion of a large tidewater glacier: 1. Observations. Journal of Geophysical Research: Solid Earth (1978–2012), 99(B8), 15219-15229.

Molnia, B. (2007). Disarticulation of Temperate Glaciers-The Dynamics of Passive Calving. In *Geophysical Research Abstracts* (Vol. 9, p. 09788). Retrieved from http://meetings.copernicus.org/www.cosis.net/abstracts/EGU2007/09788/EGU2007-J-09788.pdf

Motyka, R. J., Larsen, C. F., Freymueller, J. T., & Echelmeyer, K. A. (2007). Post Little Ice Age Glacial Rebound in Glacier Bay National Park and Surrounding Areas. *Alaska Park Science*, *6*(1), 36–41.

Motyka, R. J., Dryer, W. P., Amundson, J., Truffer, M., & Fahnestock, M. (2013). Rapid submarine melting driven by subglacial discharge, LeConte Glacier, Alaska. *Geophysical Research Letters*, *40*(19), 5153–5158. http://doi.org/10.1002/grl.51011

O'Neel, S., K.A. Echelmeyer, and R.J. Motyka (2001). Short-Term Flow Dynamics of a Retreating Tidewater Glacier: LeConte Glacier, Alaska, U.S.A. Journal of Glaciology 47(159): 567–578.

Pfeffer, W. T. (2007). A simple mechanism for irreversible tidewater glacier retreat. *J. Geophys. Res*, *112*.

Rasmussen, L. A., Conway, H., Krimmel, R. M., & Hock, R. (2011). Surface mass balance, thinning and iceberg production, Columbia Glacier, Alaska, 1948–2007. *Journal of Glaciology*, *57*(203), 431–440. http://doi.org/10.3189/002214311796905532

Walters, R. A., & Dunlap, W. W. (1987). Analysis of time series of glacier speed: Columbia Glacier, Alaska. *Journal of Geophysical Research: Solid Earth*, *92*(B9), 8969–8975. http://doi.org/10.1029/JB092iB09p08969