4 December 2012

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

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

Report #1
Part I: Data Report

1. Overview

Columbia Glacier has the world's longest and most detailed observational record of an ocean-terminating glacier in rapid retreat. The complexity and volume of data requires that its organization and archiving be managed with care. This report provides a compact overview of the available information, from raw data and imagery to maps, technical reports, and papers published in the scientific literature. The data is organized geographically, with observations of the sea floor and glacial bed followed by observations at the glacier surface and meteorological observations of the local atmosphere. Within each geographic section, observations are categorized by type or source (e.g. ship-borne sonar, aerial photography, ground-based time-lapse camera), and wherever possible, a citation or hyperlink to the data is provided. Finally, certain ancillary data, such as geodetic datum adjustments and photogrammetric control, are listed.

A full discussion of the scientific literature on the Columbia Glacier is beyond the scope of this summary. However, a compact bibliography is included, and references are cited whenever necessary to explain the origin of a listed data quantity.

History: Credit for the initiation of the Columbia Glacier data record goes to the U.S. Geological Survey (USGS), in particular the efforts of Mark Meier and Austin Post, who anticipated as early as the mid-1960s that Columbia Glacier was likely to begin a rapid retreat. The USGS research program produced a significant body of analysis, most notably the USGS Professional Paper Series 1258 A-H (1982-1989), and archived data, much of which was cataloged digitally and summarized by Robert Krimmer (2001).

Following the end of the first period of major USGS participation, in the mid-1980s, research continued, supported mainly by National Science Foundation (NSF) awards to the Institute of Arctic and Alpine Research (INSTAAR) at the University of Colorado. A field program in 1987, funded by NSF and led by Mark Meier (who by that time had moved to the University of Colorado) and Barclay Kamb of Cal Tech, marked the last on-site investigation at the glacier, until resumption of the field program in 2004, funded by NSF and led by W. Tad Pfeffer at the University of

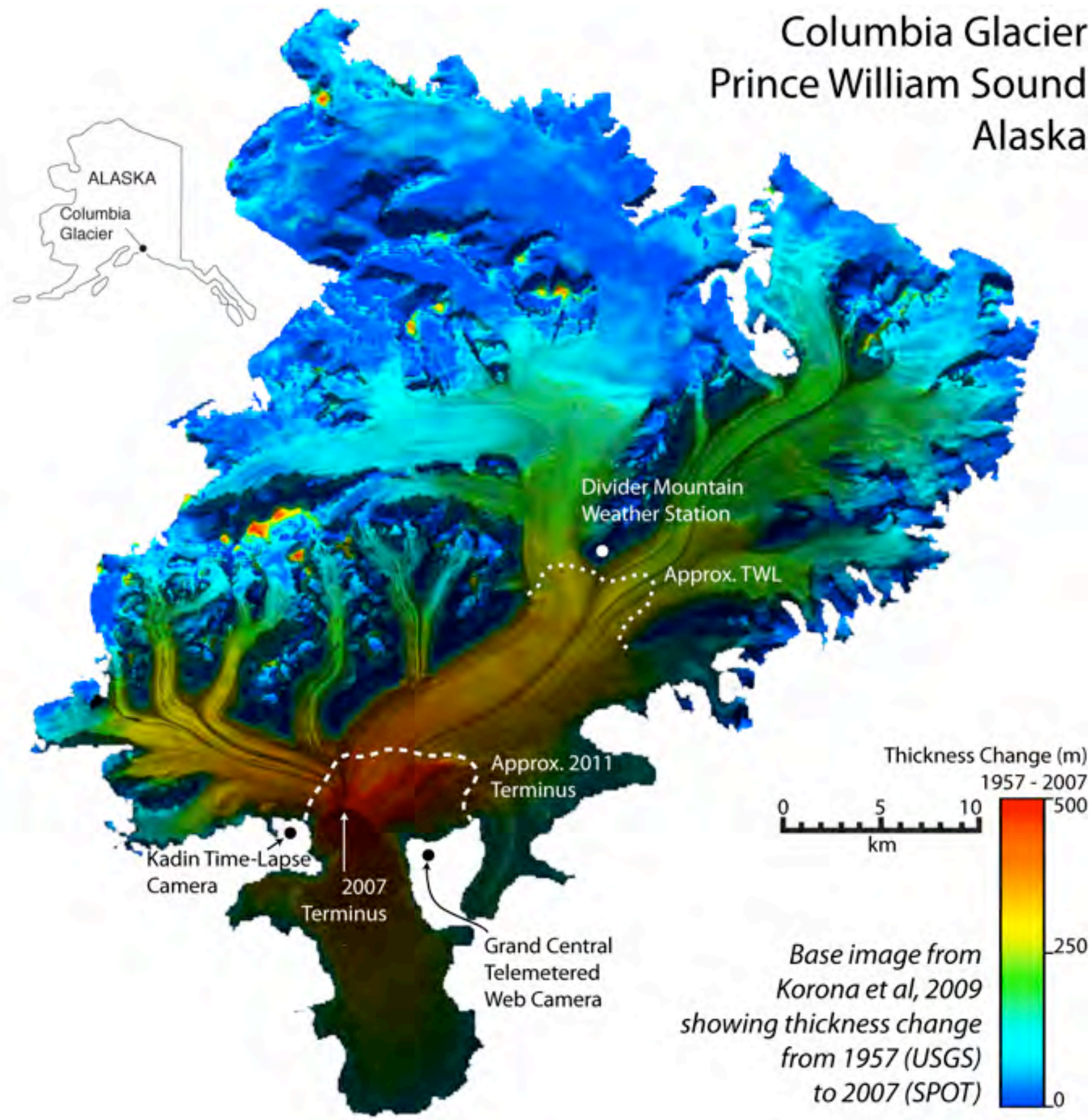


Figure 1a: Columbia Glacier Overview Map. Image shows surface elevation change from 1957 (
retreat geometry) to 2007. *Base image from Korona et al, 2009*

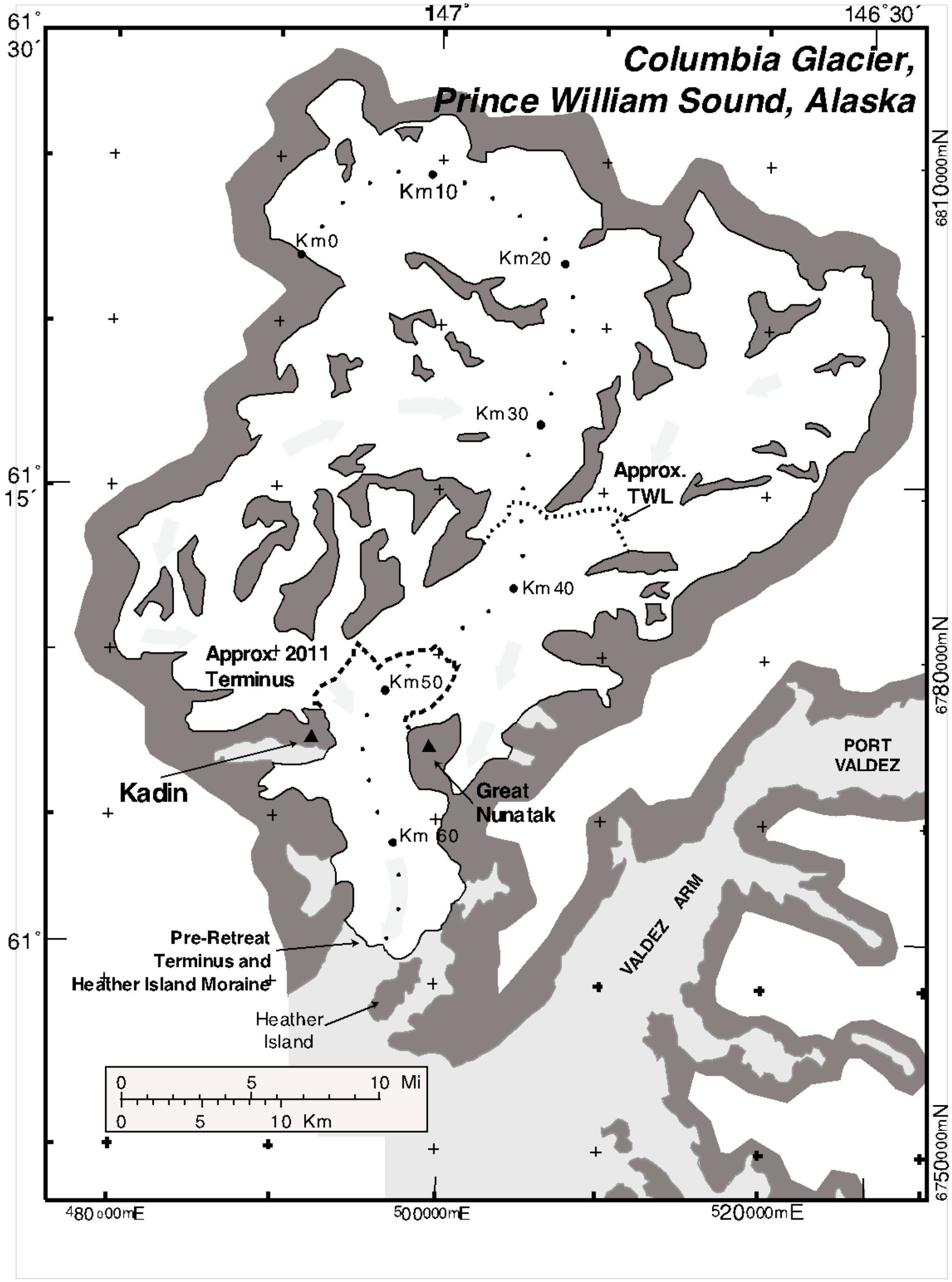


Figure 1b: Columbia Glacier, showing centerline coordinate system. Adapted from Krimmel, 2001.

Colorado. Regular acquisition of aerial stereo photography continued throughout the 1990s and 2000s, but was terminated in 2010. Data acquired and analyzed since the resumption of field operations in 2004 has been published in a variety of sources, and portions of that data (most notably the aerial and time-lapse photography) is archived at the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado.

In 2005, the National Oceanographic and Atmospheric Administration (NOAA) research ship *Rainier* conducted a marine bathymetric survey of the Columbia forebay (the waters between the Heather Island moraine shoal and the glacier terminus at that time); the data from that survey is archived by the National Geophysical Data Center (NGDC).

In 2004, Shad O'Neel (then a graduate student at the INSTAAR research group and now at the USGS in Anchorage, Alaska) started making digital time-lapse camera observations of the Columbia Glacier terminus. Austin Post, Robert Krimmel, and others at the USGS had made time-lapse observations at Columbia Glacier as early as 1978, and in 1996-2000, Post and Wendell Tangborn (Hydromet, Inc. of Seattle, Washington) captured several sequences of the glacier terminus and iceberg drift in the forebay as part of the Iceberg Monitoring Project (IMP). The INSTAAR time-lapse program was expanded in 2006 when Pfeffer and O'Neel built high-resolution digital single-lens-reflex (DSLR) time-lapse systems for the British Broadcasting Corporation (BCC) and acquired time-lapse sequences for BBC producers. The sequences shot at Columbia Glacier were used in the television series *Earth: The Power of the Planet*, broadcast in Britain in 2007, and in the US in 2008 (under the title *Earth: The Biography*). These developments led, by 2007, to collaborations with US photographer James Balog and the formation of the Extreme Ice Survey (EIS). One of the missions of EIS has been to acquire time-lapse photography of glacier changes that are both compelling imagery for public communication and detailed quantitative documentation of events at glacier termini, including iceberg calving. Our terrestrial photogrammetric analysis at Columbia Glacier, drawing on (as of this writing) more than 160,000 images taken from more than 30 different camera positions surrounding the lower glacier, gives us direct quantitative measures of such quantities as terminus position, terminus height, near-terminus ice velocity, iceberg flux, iceberg size distribution and drift rate, and the presence and concentration of ice in the forebay, at regular intervals ranging from seconds to hours. Most of the images and accompanying metadata are archived at NSIDC; analysis of the data is in progress, but is reported on in some of the INSTAAR and USGS publications.

In 2010, David Finnegan of the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, New Hampshire, built and deployed a telemetered web camera at "Grand Central" (see Figure 1a) and a telemetered weather station at "Divider." After some early equipment failures and vulnerabilities to weather and snow loads, these installations are now operating reliably and available to the public at www.glacierresearch.com. The images and meteorological data are archived and available to us for analysis. Both the camera and weather station are installed and maintained by CRREL at no cost to our project.

2. Data Types

2a. Ocean Bathymetry

Analyses of terminus retreat and iceberg discharge rely on knowledge of the bathymetry over the entire Columbia Glacier fjord, from the tidewater limit at approximately Km 35 (See Figure 1b) to the Heather Island moraine shoal at Km 69. The tidewater limit, marked as "TWL" in Figure 1b, marks the point at which the elevation of the glacier bed rises above sea level. (If the glacier were removed entirely, the coastline would reach the tidewater limit.) This tidewater reach, approximately half of the glacier's full length, is in direct contact with the ocean, and the evolving balance of stresses here are a primary control on the speed of ice flow, rate of vertical thinning, and rate of iceberg calving. The englacial and subglacial hydrology in the tidewater reach also influence the hydrology (and thus the flow dynamics) of the glacier lying above the tidewater limit. This linkage is hypothesized to be a primary control on the transfer of ice down over the tidewater limit from the upper glacier, a transfer that provided approximately 95% of the volume of ice lost from Columbia Glacier in 1995-2007. Understanding the dynamics and hydrological connection between the upper and lower glacier is thus a crucial part of making robust projections of future calving losses.

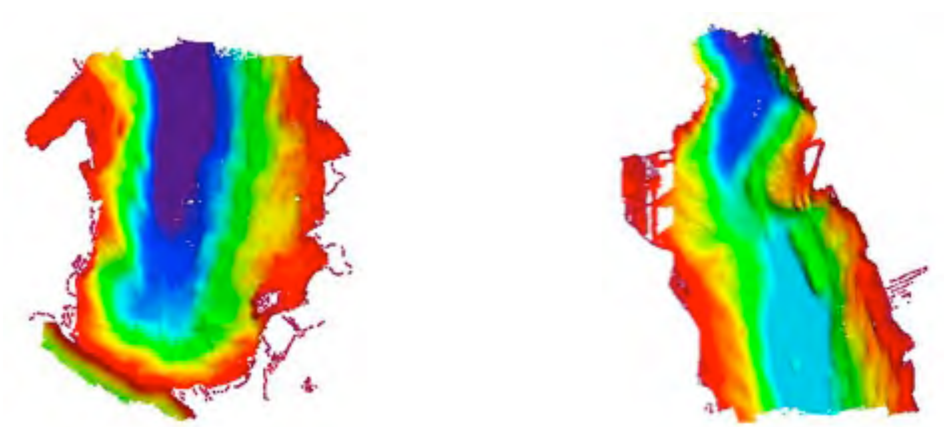


Figure 2a: Columbia Glacier forebay bathymetry, measured by NOAA (Noll, 2005) *Left*: Lower forebay; *Right*: Upper forebay. Note change in color coding of depths between panels; depth scale not available for these images. Maximum depths are ca. 400 m near join between images. *Source: Columbia Bay Hydrographic Survey RAP Sheets H11493/H11494. National Oceanographic and Atmospheric Administration. National Geophysical Data Center, National Ocean Service, Boulder, CO*

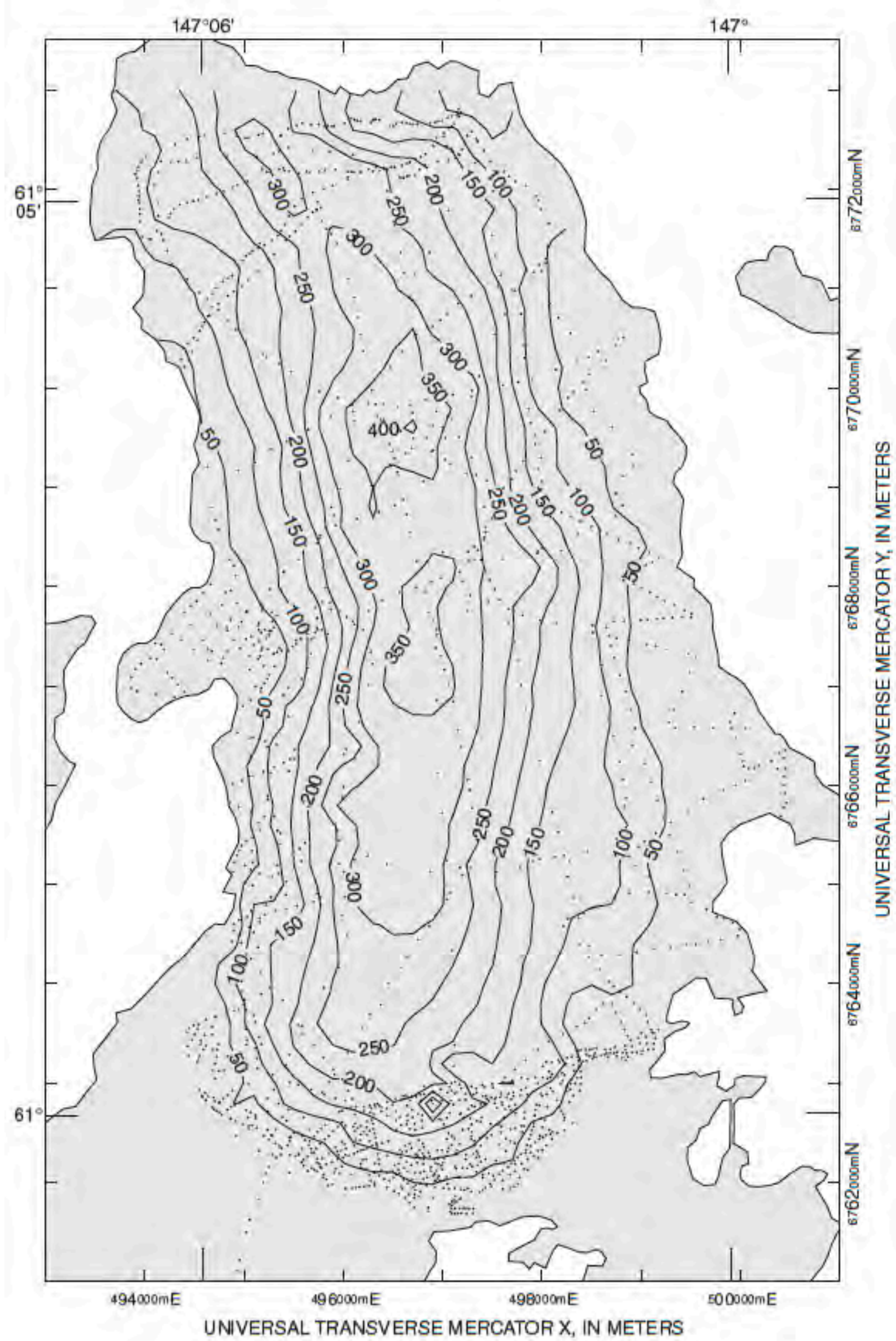


Figure 2b: Columbia Glacier forebay bathymetry from Krimmel (2001), based on USGS profiling.

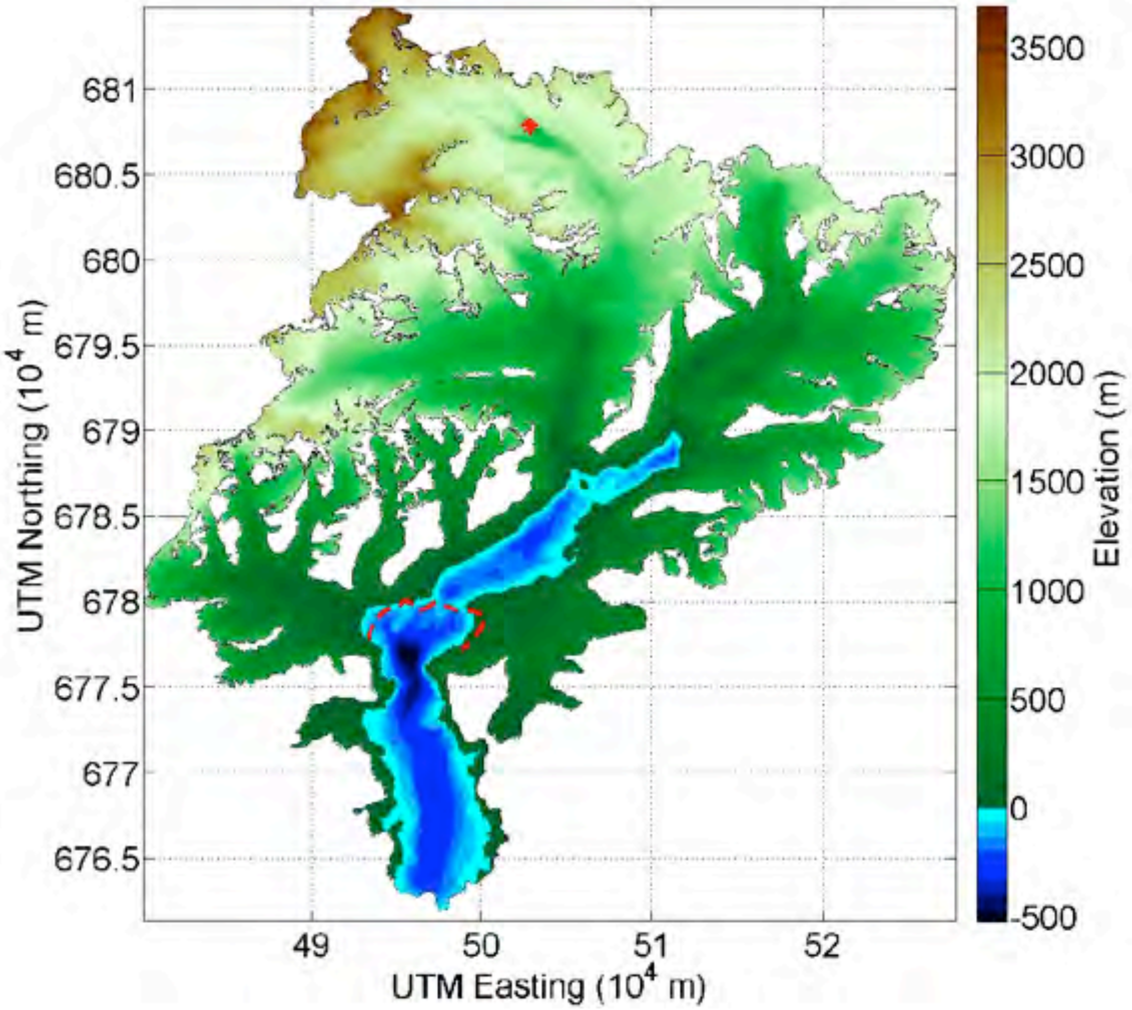


Figure 3: Fjord bed topography, combining NOAA survey data (Noll, 2005) and computed bathymetry (McNabb et al, 2012). The red dashed line shows the approximate position of the 2011-2012 terminus. *Source: Figure from McNabb et al, 2012.*

Subglacial bathymetry has been determined by three types of measurement: direct measurement of bathymetry in the open fjord below the terminus, computation of bathymetry above the terminus by ice flow modeling, and direct measurement of bathymetry above the terminus by ice-penetrating radar.

Sonar surveys: In the open fjord seaward of the glacier terminus, bathymetry can be measured directly by a variety of acoustic (sonar) techniques. Sonar surveys were conducted by the USGS research group periodically throughout the 1980s, but most of these were located in the immediate vicinity of the Heather Island moraine shoal because the forebay was almost continuously packed by calved ice. At certain times, however, the forebay was flushed clear of ice for days to years at a time. During the two-year period of ice-free conditions in 2004 and 2005, the NOAA ship Rainer entered the forebay and made a complete survey of fjord bathymetry up to ca. Km. 52 (Figure 1b). This survey is the most detailed and comprehensive map of bathymetry made to date.

Bathymetry by computation: The bathymetry below the ice can be deduced computationally by analysis of detailed maps of velocities at the ice surface. The spatial resolution of the computed bathymetry is limited to length scales of approximately one ice thickness (between ca. 500 and 1500 m in most parts of the fjord), but is our only spatially complete source of bathymetry to date. Computed bathymetry in the outer forebay, calculated from observed ice flow from the 1980s when that region was occupied by ice, has been validated by comparison to the sonar surveys described above, and gives us confidence in the quality of our computed bathymetry in the regions still occupied by ice. Bathymetric computations, based on Rasmussen (1989), have been made by O'Neel et al (2005), Engel (unpublished MS thesis), and McNabb et al (2012). Digital Elevation Models (DEMs) are available from all of these sources.

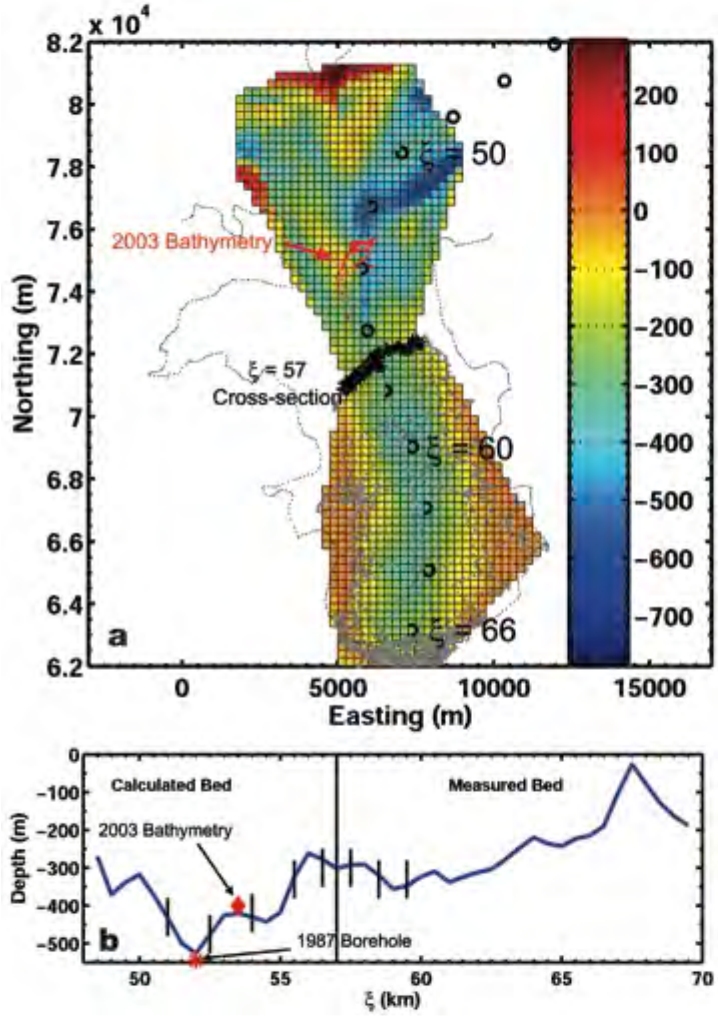


Figure 4a. Computed bathymetry from O'Neel et al, (2005).

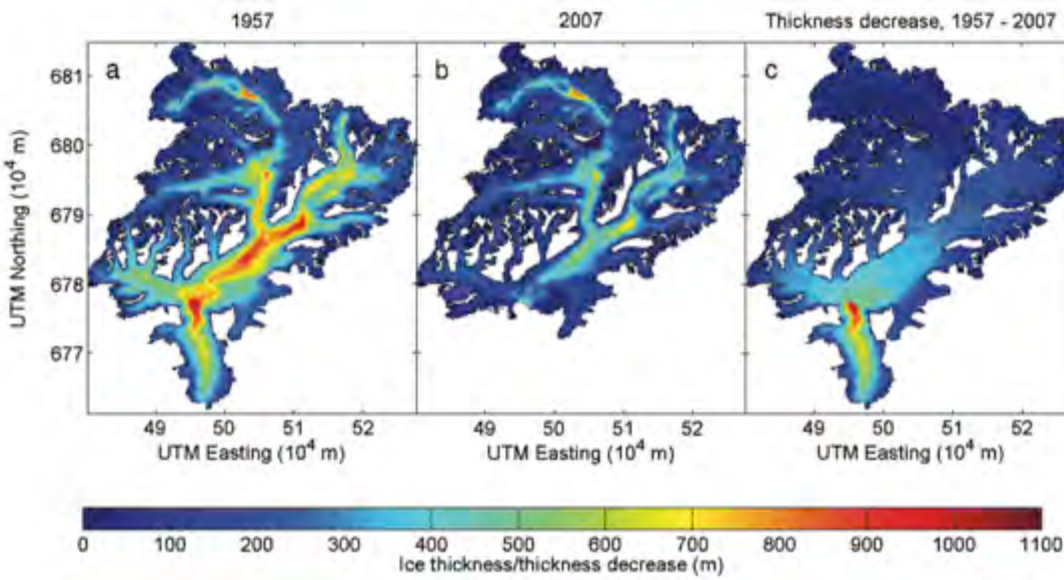


Figure 4b. Computed ice thickness (surface elevation – bed elevation) in 1957 (pre-retreat geometry) and 2007, from McNabb et al (2012). Their computed bed topography is shown in Figure 3b.

Ice penetrating radar: While widely used for depth sounding in polar ice, ice-penetrating radar has been difficult to adapt to temperate ice, where the presence of liquid water in the ice causes extensive scattering and attenuation of electromagnetic signals. Ground-based systems, where antennas laid on the surface are better coupled to the ice, are routinely used, but airborne systems have been much less successful, especially in thick, heavily crevassed ice typical of tidewater glaciers. Only in the past few years have airborne radar systems been developed that are capable of penetrating temperate glaciers as large and heavily crevassed as Columbia Glacier. Several airborne transects were flown successfully in 2010 (McNabb, et al, 2012) at Columbia Glacier. The soundings were profiles only (no grid surveys were flown), and their most immediate value for our purposes is as validation of the computed 2D bathymetry (Figure 5).

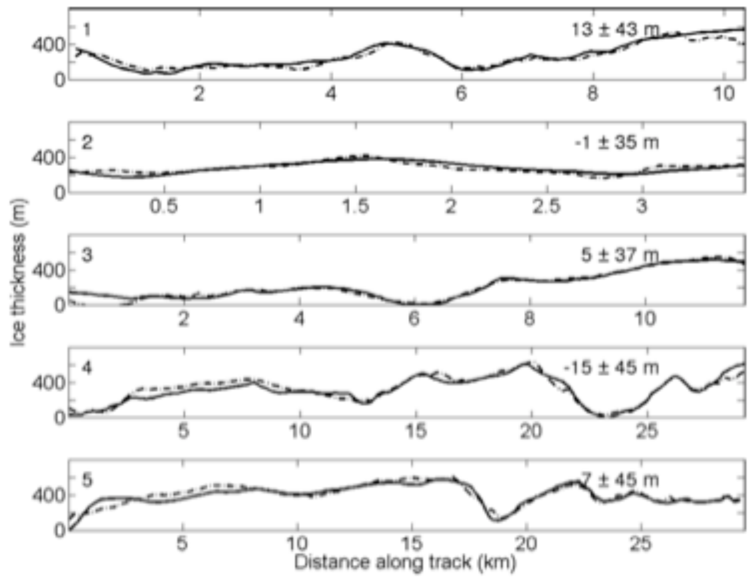


Figure 5: Computed (dash-dot line) compared to airborne radar soundings (solid line) for 5 different profiles at Columbia Glacier. The mean difference between computed and measured profiles is shown (in meters) on each panel. *From* McNabb et al, 2012; see the paper for location of profiles.

2b. Surface Topography

Over the three decades of retreat, the surface topography of the tidewater reach has been Columbia Glacier's most dramatically changing feature, and the documentation of that change is the most detailed record in the glacier archive. Sources of data include a pre-retreat (1957) USGS topographic map of the entire glacier (now digitized to a DEM), a full-glacier DEM derived from 2007 SPOT satellite imagery (Korona et al, 2009), periodic airborne laser profiles (Chris Larsen, UAF), a total of 135 vertical aerial photo missions covering 1974-2010, Worldview satellite and oblique aerial photo missions (and derived DEMs) starting in 2010, TerraSAR-X radar mapping at intervals starting in March 2011, and limited GPS and optical surveys of point locations throughout the project.

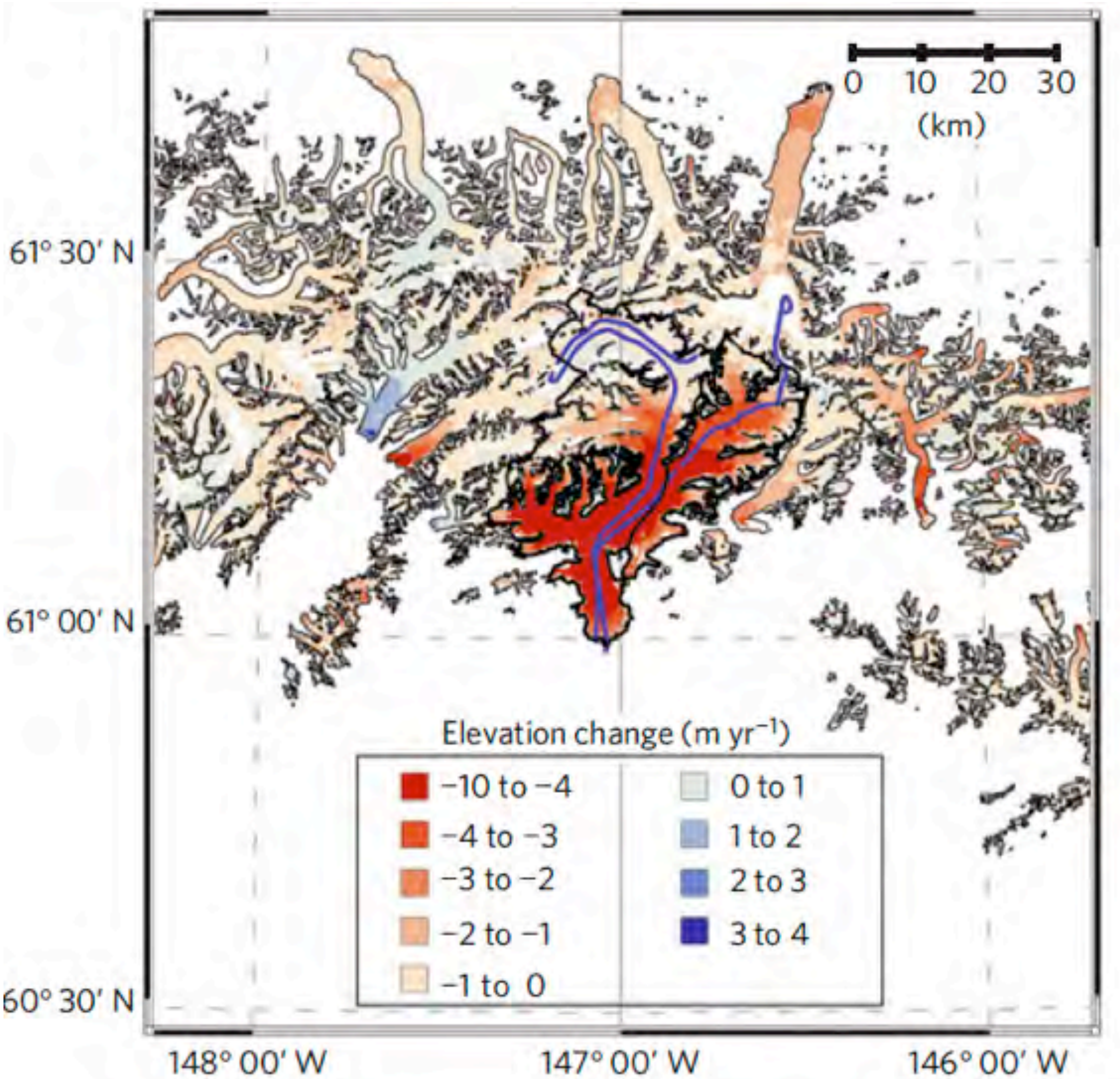


Figure 6a: Columbia Glacier elevation change, 1957-2007. Adapted from Berthier et al, 2010. Data sources are the 1957 USGS topographic map and 2007 SPOT5 Stereoscopic imagery (Korona, 2009).

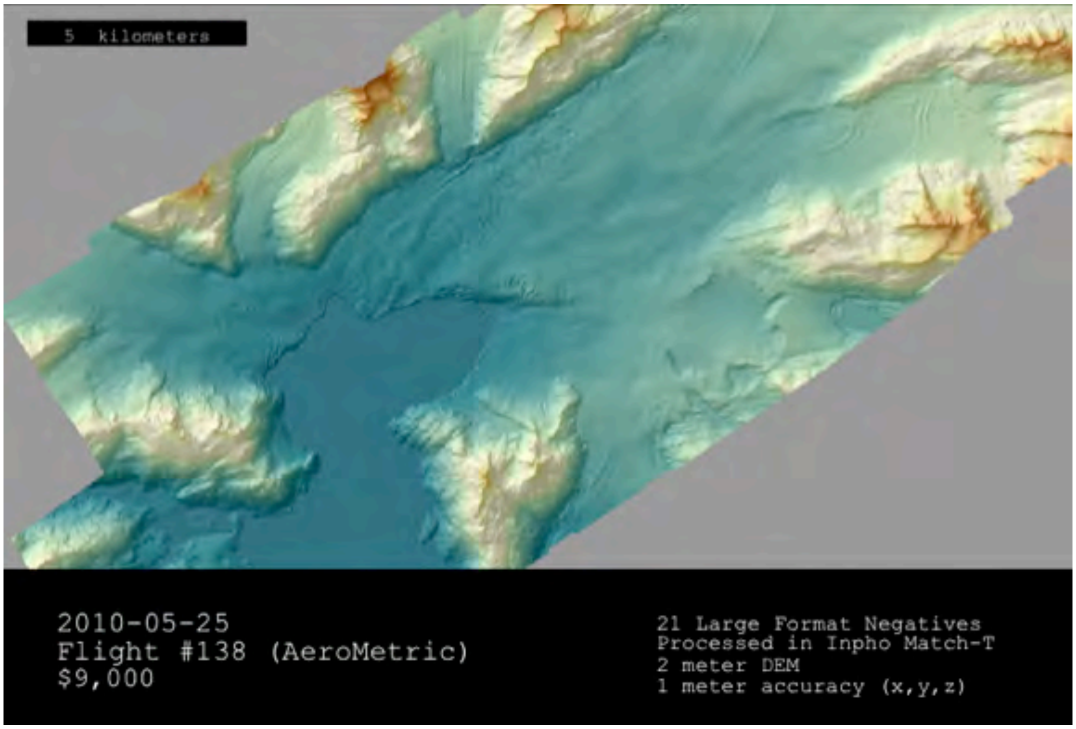


Figure 6b: DEM generated from vertical aerial photography and conventional photogrammetric analysis. Images acquired 25 May, 2010. Analysis: Aerometric Inc., and E. Z. Welty

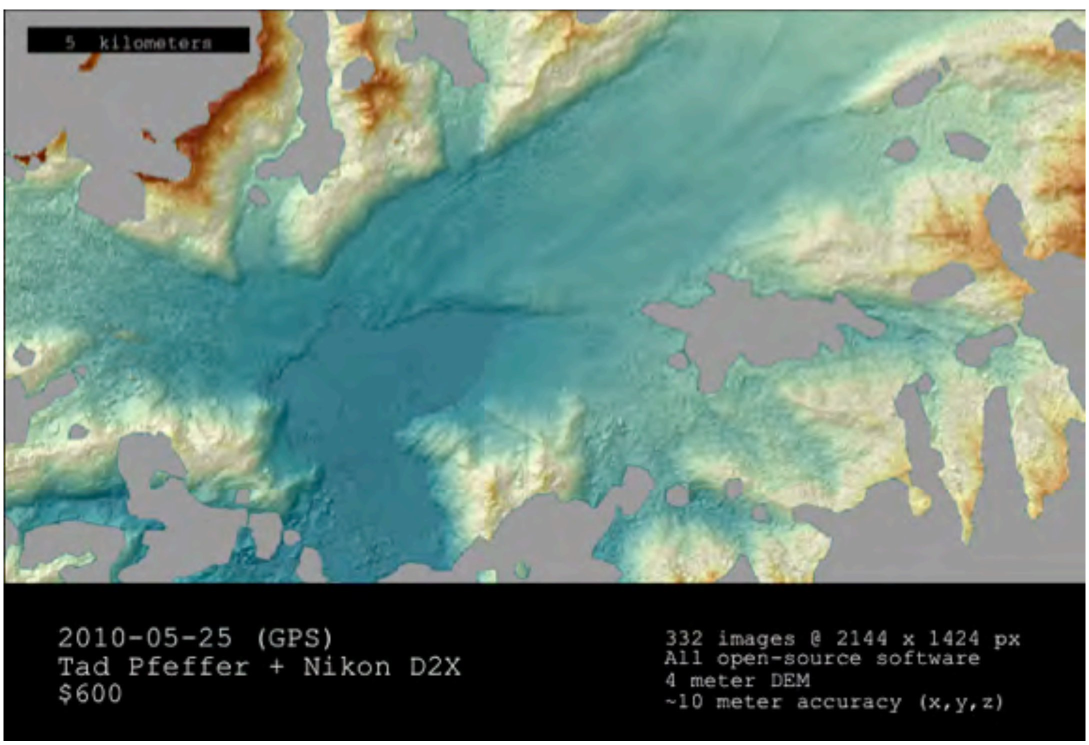


Figure 6c: DEM generated from oblique aerial photography and structure from motion (FM), images acquired 25 May, 2010. Analysis and plot: E. Z. Welty

Photogrammetric analyses by the USGS in the years up to 2001 were performed on analytical plotters, and feature tracking (for velocity determination) required manual point-by-point feature identification. As a result, topographic maps were made only on an as-needed basis (and most are unpublished) while velocity fields calculated during this time were generally very sparse, containing only a few hundred points. We have been working over the past several years to derive high resolution, digital maps of elevation and velocity using photogrammetric scans of the original film. This reanalysis has given us the opportunity to review and correct datum discrepancies (see section on ancillary data, below).

Most of the topographic analyses during the USGS Columbia Glacier project were focused on obtaining along-flow profiles of elevation change (Figure 6d), again because of the labor involved in making repeated topographic maps. Figure 6d shows an example of the evolution of glacier thinning and terminus retreat over the course of the retreat.

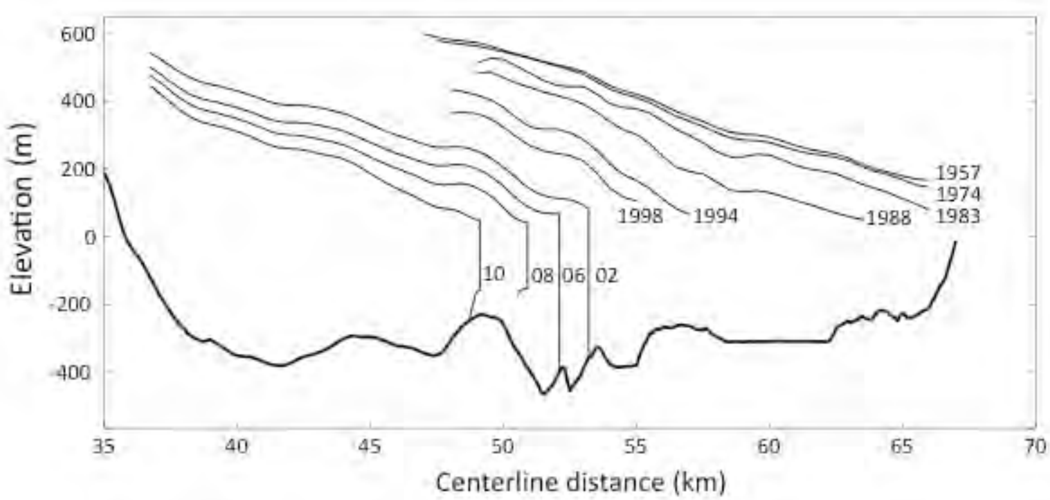


Figure 6d. Along-flow profile of surface elevation from pre-retreat (1957) to 2010. The profile follows the along-flow coordinate system shown in Figure 1b. The basal topographic profile is from McNabb et al, 2012. Plot: E. Z. Welty

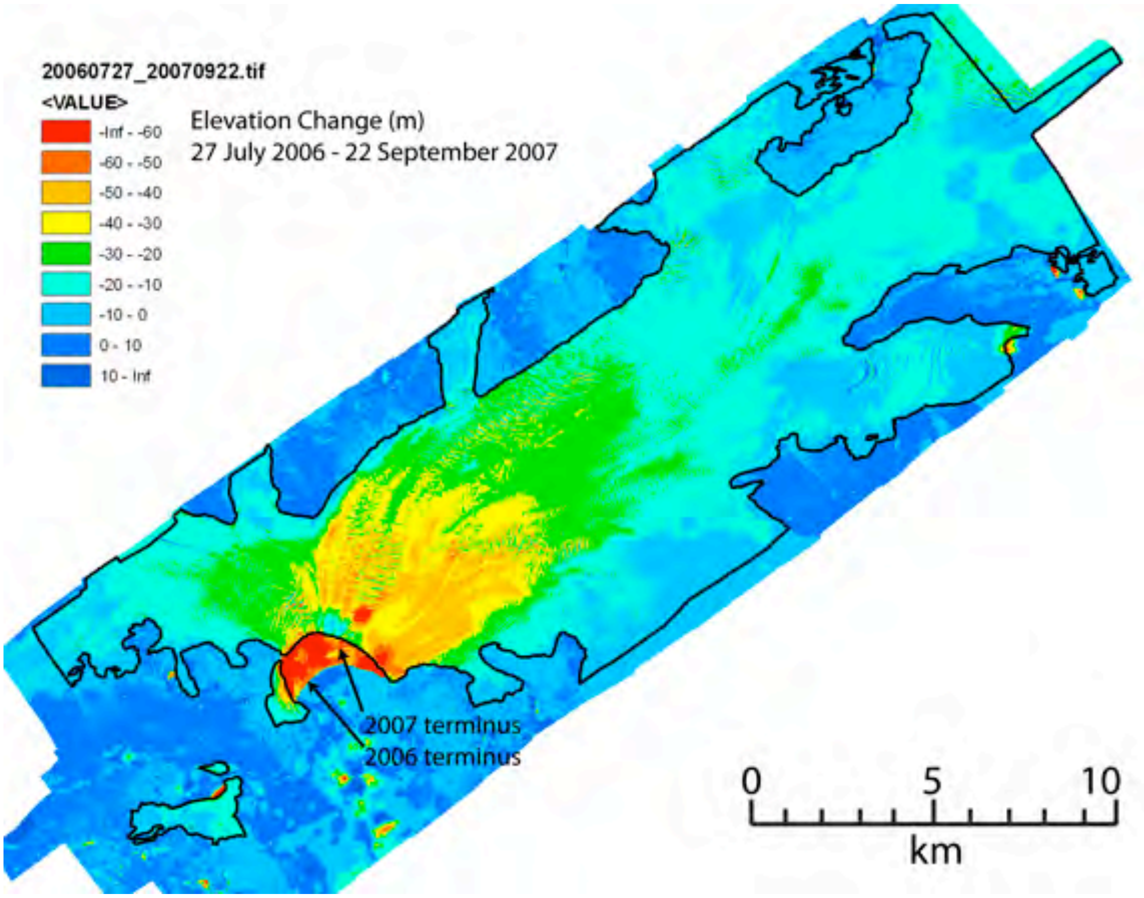


Figure 6e. DEM differencing from aerial photogrammetry obtained 27 July 2006 and 22 September 2007. Analysis: E. Z. Welty. The glacier is outlined in black; regions enclosed include the terminus, lowest part of the West Branch, and the Main Branch up to Divider Mountain. The thinning during this interval represents some of the maximum rates of observed change, when we observed a 5 x 5 km region that thinned in excess of 30 m in roughly 1 year.

2c. Terminus Retreat Rate

Terminus position has been measured over annual to seasonal time scales from vertical aerial and satellite photography, and on sub-seasonal to annual time scales using time-lapse photography. Assigning a single number to the terminus position (a glacier length) has been typically accomplished by averaging the position of the glacier terminus over a 1 km wide swath centered on the glacier flow centerline.

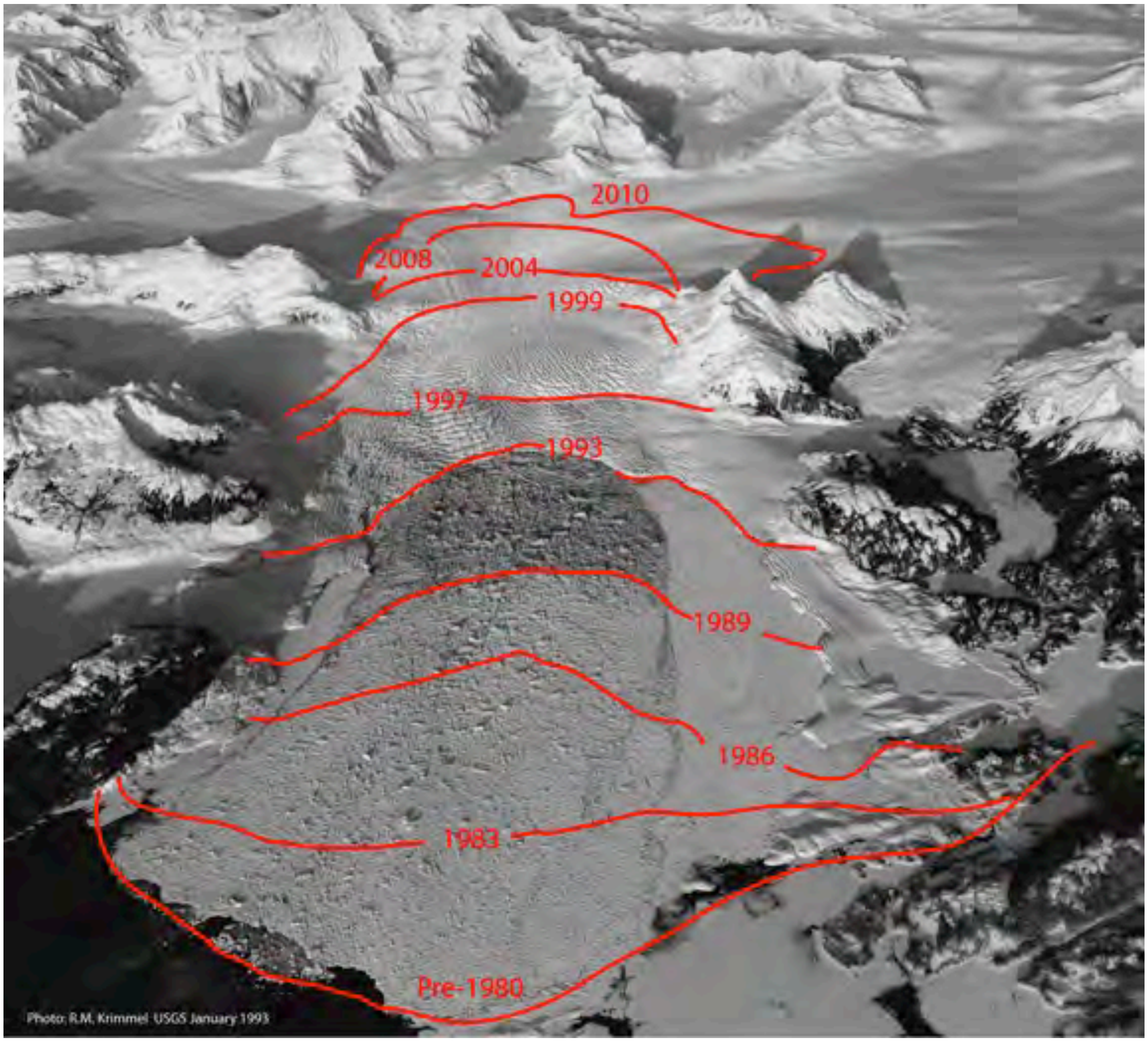


Figure 7a: Glacier terminus positions, pre-retreat to 2011. Photo: R.M. Krimmel, USGS

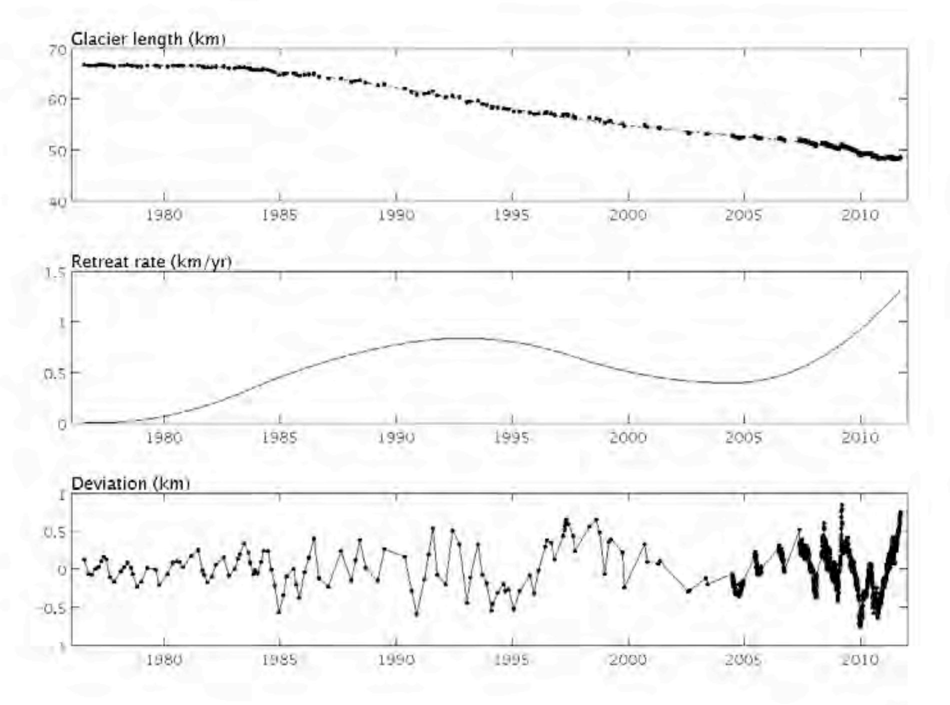


Figure 7b: Glacier length, terminus retreat rate, and deviation from local mean retreat rate. Analysis and Plot: E. Z. Welty

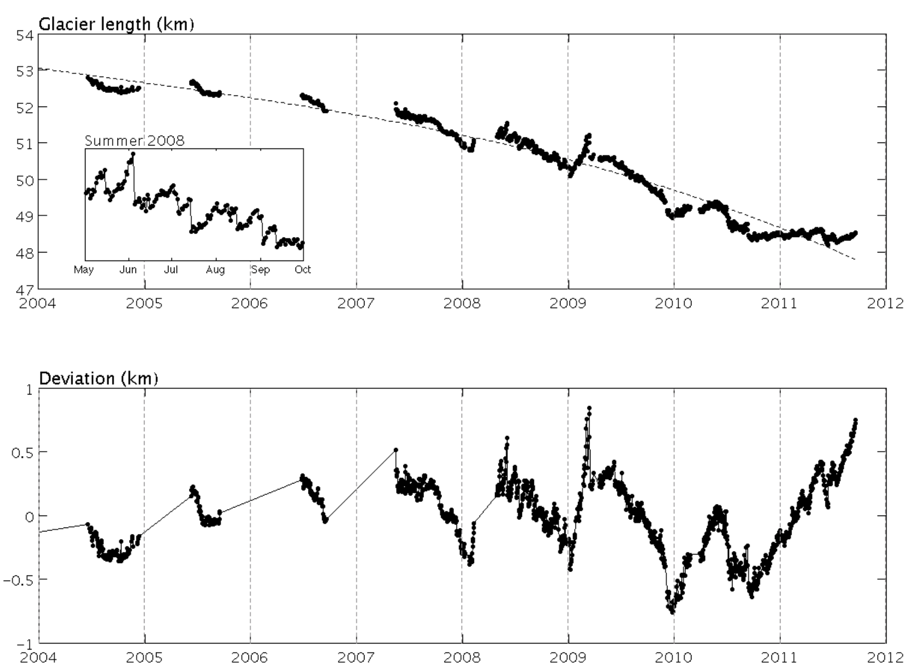


Figure 7c: Terminus position determined from time-lapse cameras, 2004-2012. Analysis and Plot: E. Z. Welty

2d. Ice Velocity

Measurements of ice surface velocity, together with thinning rate, provide the primary source of kinematic and dynamic information at Columbia Glacier. Velocity fields were calculated over the tidewater reach since the beginning of the USGS research program in the late 1970s, using manual point-by-point feature tracking. The coordinates of a distinctive feature visible in the first flight of a mission pair would be recorded and located again in the subsequent flight; the two 3D positions of the point divided by the time interval between the flights produces a 3D velocity vector for that period at that location. Manually identifying points was time consuming work, however, so velocities were measured for only a few hundred points in any given flight pair.

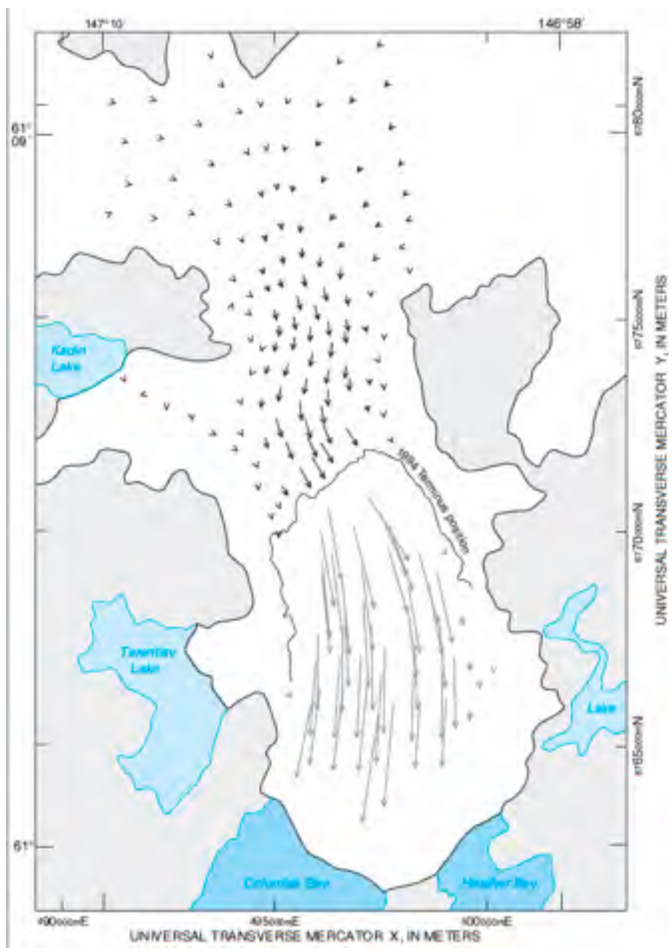


Figure 8a. Manually derived velocity field for the period August 13 – September 7, 1994. The velocity vectors are full scale: each connects the initial location of a feature to its final position 24 days later. Figure from Krimmel, 2001. Iceberg motion is shown in gray vectors.

After the conversion to digital photogrammetric analyses, it became feasible to use automated feature tracking, and the number of velocity vectors rose dramatically. Figure 8b shows a velocity map calculated using image processing and automated feature tracking.

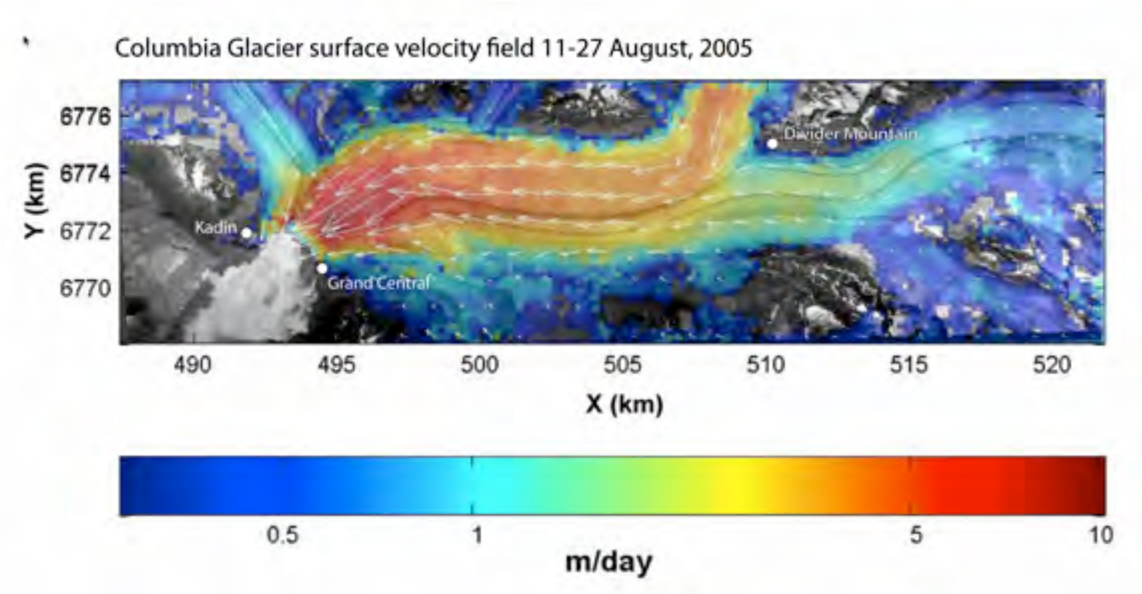


Figure 8b. Velocity field for 11-27 August, 2005, using automated feature tracking. Velocity points are determined on a 50x50 m grid. The entire field contains more than 120,000 velocity vectors. Analysis and image: Yushin Ahn.

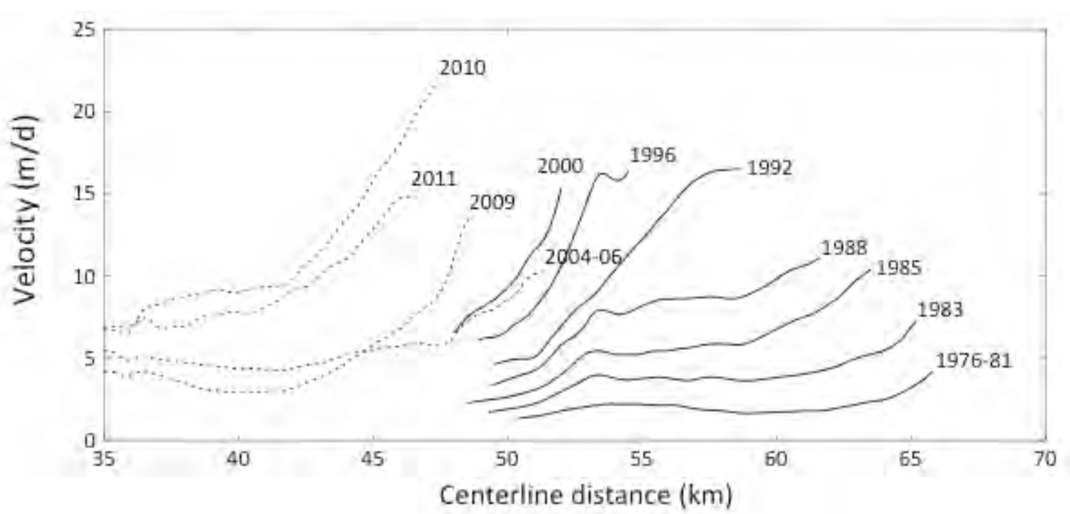


Figure 8c. Along-flow profile of surface velocity from pre-retreat (1957) to 2010. The profile follows the along-flow coordinate system shown in Figure 1b. Plot: E. Z. Welty.

Since the termination of aerial photogrammetric flights in 2010, we have obtained periodic high-resolution fields produced from TerraSAR-X radar imagery, courtesy of Ian Joughin (APL, University of Washington). The radar imagery covers the entire glacier, and is available at 11-day intervals, which greatly increases the quantity of information available to us, although presently we are focusing our attention on velocity information extracted along a flowline starting above the TWL of the Main Branch and extending to the terminus. Figure 8d shows velocity profiles for the period 16 February to 26 July, 2011.

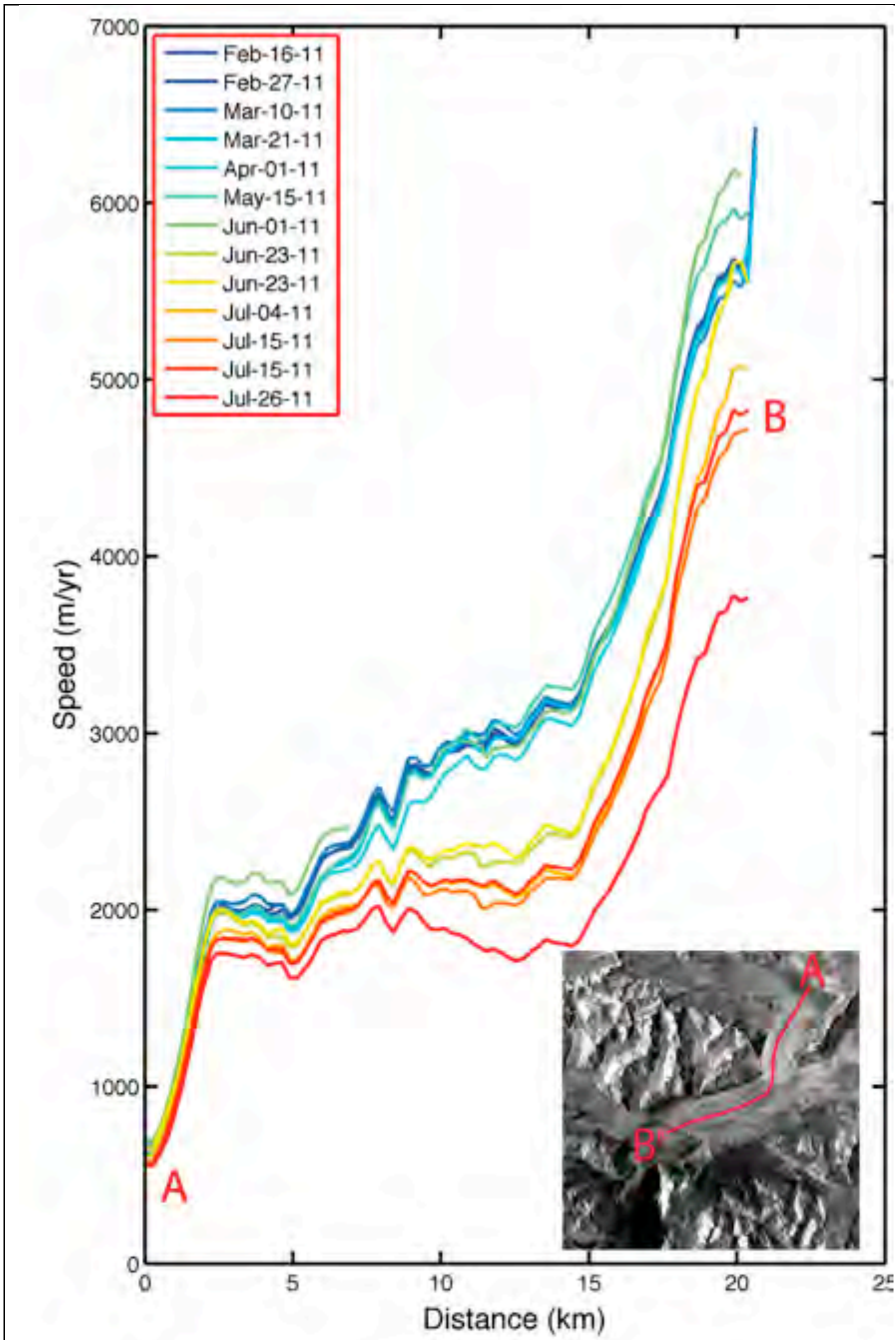


Figure 8d. Velocity profiles derived from TarraSAR-X radar data. Analysis and figure courtesy of Ian Joughin (APL, University of Washington)

2e. Calving

Calving flux – the volume (or mass) rate of ice leaving the glacier terminus as icebergs – is an easy quantity to define conceptually, but harder to quantify from measurements. If the glacier terminus is in steady state, neither retreating nor advancing, then the calving flux is simply the average terminus velocity times the full terminus cross sectional area. If the terminus is in motion, however, then the calving flux must be corrected for the amount of ice being consumed or lost in terminus advance or retreat, respectively. For this reason, calving flux requires measurements of both terminus (or near-terminus) velocity as well as the rate of terminus advance or retreat. Before continuous and reliable time-lapse cameras were in operation at Columbia Glacier, calving flux could only be determined for averaged rates over the intervals between flights. Since 2004, however, it has been possible to calculate calving flux on much shorter time scales. This is a useful source of information for analyzing short-term terminus dynamics; the analysis is ongoing.

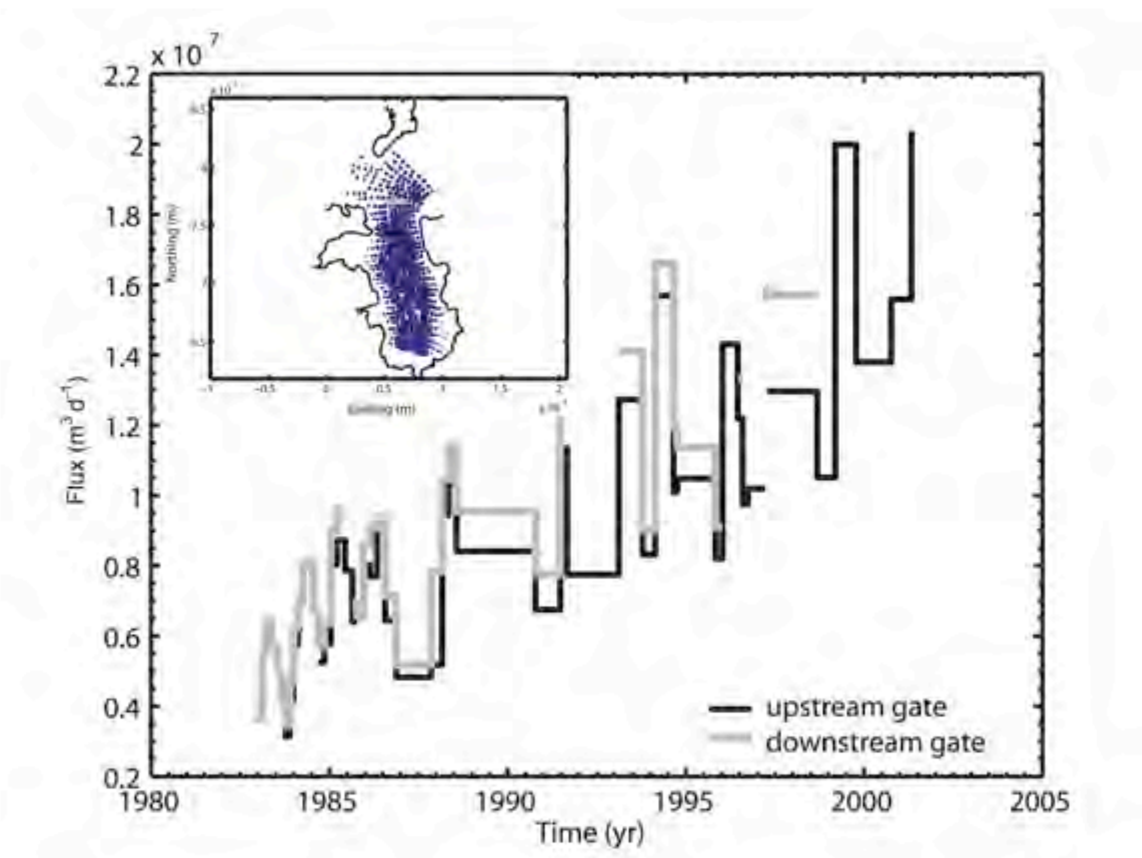


Figure 9a. Calving flux during Columbia Glacier's retreat up to 2003. From O'Neel et al, 2005.

2f. Mass Balance and meteorology

Measurements of glacier mass balance (the flux of mass into the glacier, primarily as snow, and flux out, primarily as iceberg calving and runoff of melt) require extensive and costly ground based measurements and regular surveys over long periods (years). The only mass balance data available for Columbia Glacier was obtaind during a comprehensive one-year survey in 1977-78, conducted by the USGS, and a much sparser survey, also conducted by the USGS (by Shad O'Neel) from 2010 to the present. This latter survey is ongoing. The results of these surveys are summarized in Figure 10.

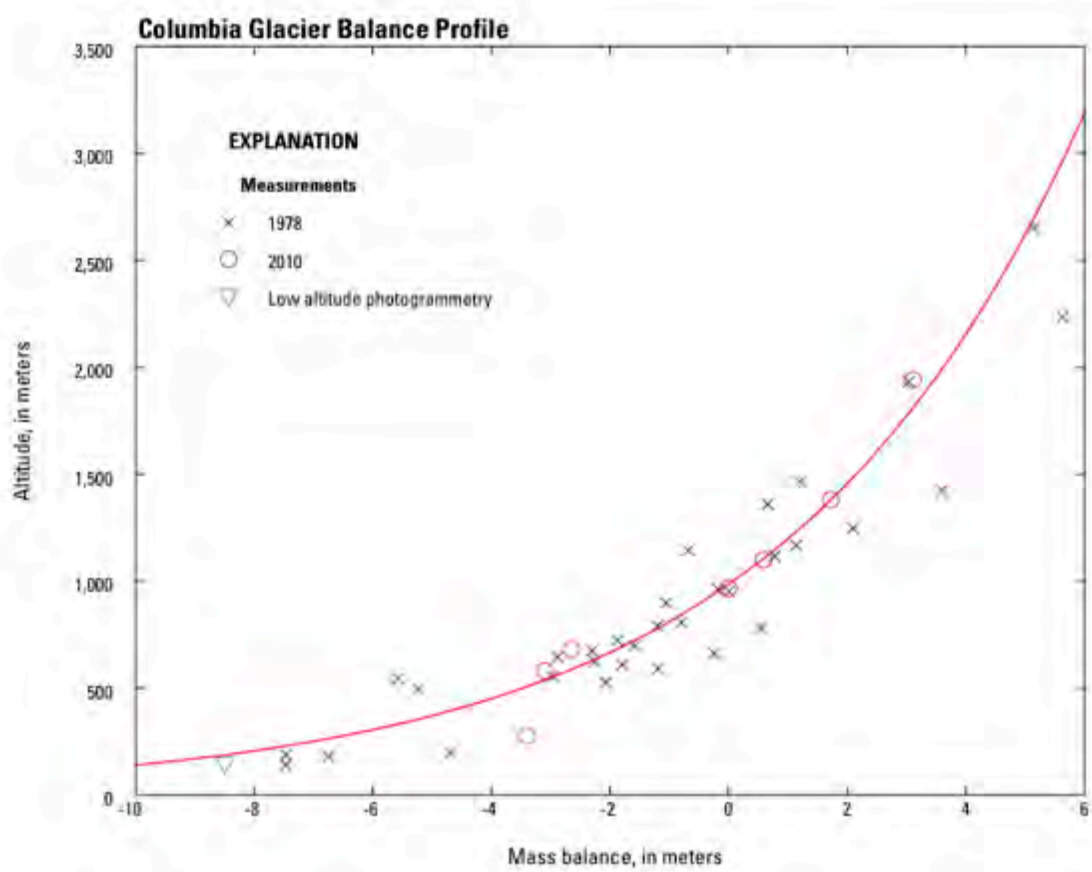


Figure 10. Mass balance, shown as the elevation distribution of net balance in meters^3 of water per m^2 per year (m yr^{-1}), for 1978 and 2010. *Source: O'Neel, 2012.*

Meteorological data is presently being recorded by an automated, telemetered weather station (operated by David Finnegan, USA CRREL) located at an elevation of 588 m (1929 ft.). Measured variables include air temperature, wind speed and direction, and barometric pressure. Seasonal mass balance measurements are conducted by Shad O'Neel. For the intervening period, calculated mass balance is provided by modeling, using regional meteorological observations, as described in

Rasmussen et al, 2011. Inferred mass balance for 1948-2007, in decadal periods, is shown in Figure 11.

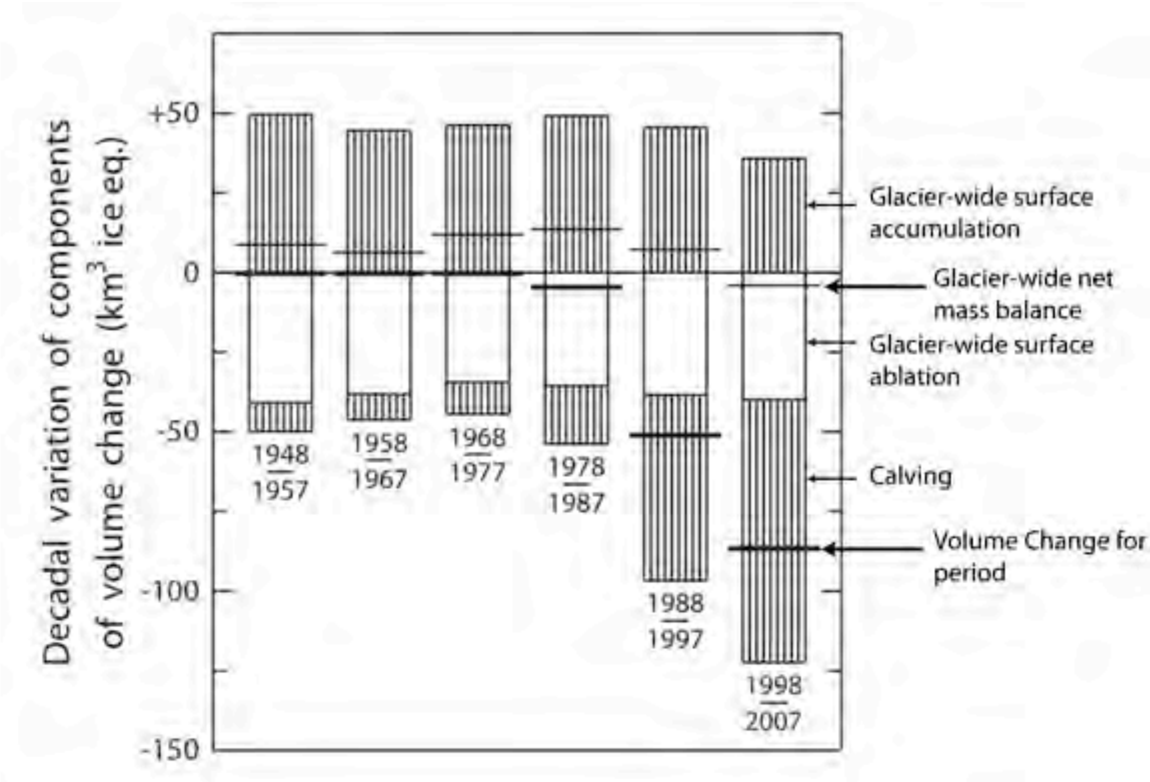
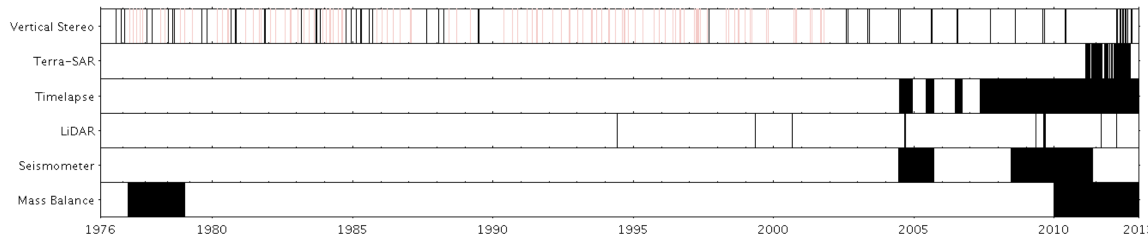
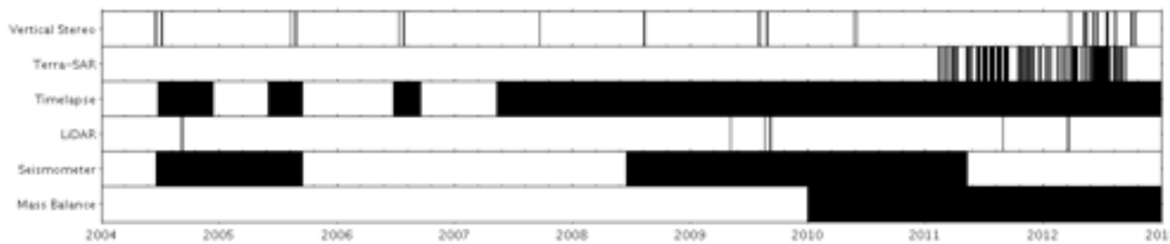


Figure 11. Decadal variation of mass balance components, from Rasmussen et al, 2011.

Time Line of Data Acquisition Figure 12a,b shows the distribution of the main observations conducted at Columbia Glacier between 1976 and the present, including the onset of retreat in the early 1980s .



12a



12b

Figure 12. Distribution of principal observational time series over the lifetime of Columbia Glacier observations. a) 1976-2012, b) expanded view of 2004-2012

2g. Ancillary Data

The following data is not directly a product of measurements on the glacier, but is required for processing and interpretation.

Camera time

All camera clocks have been calibrated to Coordinated Universal Time (UTC) using either environmental phenomena visible in the images (tides, solar angles, or large calving events identifiable in the seismic record) or, since August 2009, by comparison with reference UTC clock displays. The most contemporary sequences benefit from time adjustments that correct not only for a one-time offset, but also for linear clock drift as calculated from repeat comparisons to UTC.

Camera geometry

Photogrammetric analysis of the time-lapse imagery requires that both the position and orientation of the cameras be known. Position can be measured precisely with GPS, and once a camera is installed, its position is essentially constant. In contrast, orientation is both difficult to measure directly and can change substantially from image to image due to wind, snow drift, and settling of the ground or mounting hardware. So instead, orientation is calculated on an image-to-image basis using ground control, features of known 3D position that can be reliably identified in the oblique imagery.

Oblique ground control include points marked and surveyed in the field, natural features identified in the (2004-2010) orthoimagery and DEMs, and distant summits identified from USGS quadrangles. In the special cases that fixed control were insufficient, additional transient control were identified from same-day aerial-time-lapse pairs.

Columbia Glacier Time Lapse Camera External Orientations *data current 12/2011*

		UTM Coordinates			Camera Attitude				WGS84 Lat/Lon Pos	
Camera ID	Point Fixed(1)/ Variable(0) in solution	X_{wgs84}	Y_{WGS84}	Z_{HAE}	Azimuth deg from N + to E	Elevation deg from horizon Pos up	Roll deg about optic axis CW=+	Location Source	Lat	Lon
AK01	0	493221.97	6776736.40	463.26	60	-15	0	AK01b	61.1252	-147.1258
AK01b	1	493221.97	6776736.40	463.26	45	-15	0	GPS	61.1252	-147.1258
AK02	0	496804.14	6775877.21	88.62	-45	-5	0	GCP #3		
AK02b	0	496804.14	6775877.21	88.62	-10	-5	0	AK02		
AK03	1	497017.21	6776153.17	163.52	-45	-10	-2	AK03b	61.1200	-147.0554
AK03b	1	497017.21	6776153.17	163.52	-22.5	-5	3	GPS	61.1200	-147.0554
AK04	0	496703.89	6775902.28	86.57	-45	-5	0	GCP #1		
AK09	0	497331.58	6776358.62	235.44	-5	-15	0	AK09b		
AK09b	0	497331.58	6776358.62	235.44	30	-10	0	SfM		
AK10	1	499211.34	6783755.95	478.96	-165	-10	-4	GPS	61.1883	-147.0147
AK10b		499211.00	6783756.00	479.00				Handheld		
AK11	0				35	-15	0			
AK12										
AKJNC		494674.00	6780880.00	502.00						
AKH09	0				-10	-10	0			
AKHS1	0				-10	-20	0			
AKHS2	0				-10	-25	0			
AKHS3	0				-10	-20	0			
AKHS4	0				-15	-20	0			
AKST01A	1	496980.41	6776191.71	137.61	-10	-5	0	GPS	61.1203	-147.0560
AKST01B	1	496964.06	6776189.13	137.82	-5	-5	0	GPS	61.1203	-147.0563
AKST02A	0				10	-15	0			
AKST02B	0				5	-15	-3			
AKST03A	1	497415.25	6776328.42	270.83	0	-5	0	GPS	61.1216	-147.0480
AKST03B	1	497330.96	6776300.82	263.97	5	0	-4	GPS	61.1213	-147.0495
CG04	1	497294.99	6776046.32	266.15	-85	-5	-3	GPS	61.1190	-147.0502
CG05	1	496990.58	6776004.76	152.04	-65	0	0	CG06	61.1187	-147.0559
CG06	1	496990.58	6776004.76	152.04	-78	0	0	GPS	61.1187	-147.0559
CGBAY	0				-85	-10	0			
CGKDN	0	493222.00	6776736.40	463.30	120	-5	0	AK01b	61.1252	-147.1258
CGZM	0									
CG04	1	497294.53	6776046.63	268.47				BA		

Table 1: Columbia Glacier time lapse camera external orientation data

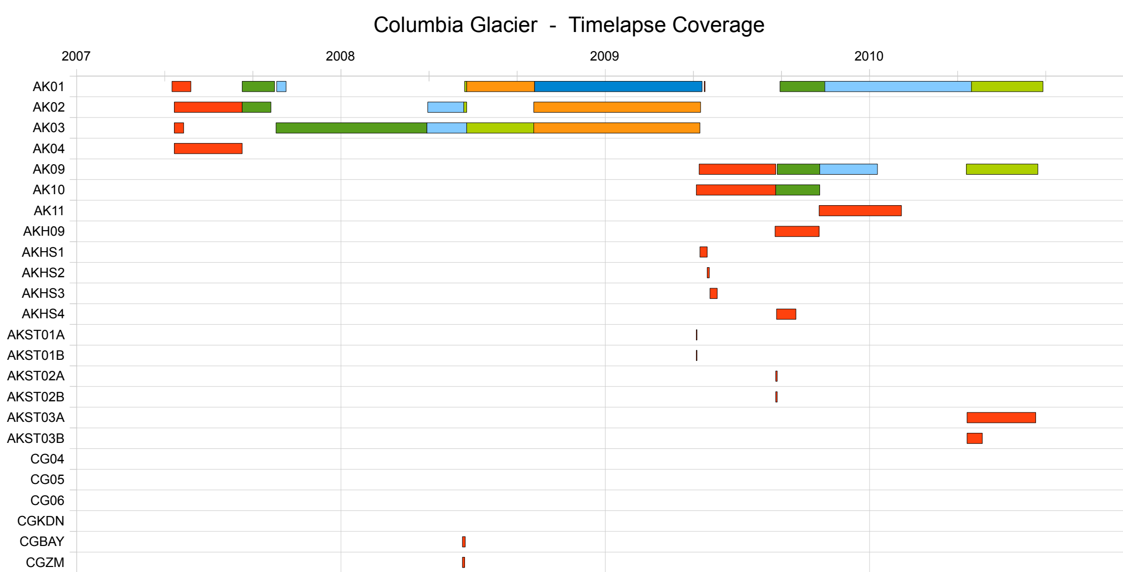


Table 2: Columbia Glacier time-lapse camera deployment intervals after start of the Extreme Ice Survey project. Time-lapse observations before 2007 are not shown.

Datum Convention

All data from 2002 to the present were produced directly in the reference datum WGS84. Horizontal coordinates (X and Y) are expressed as meters from the UTM Zone 6N origin, while elevations (Z) are expressed as height above the WGS84 ellipsoid (HAE).

In datasets reported through 2001, horizontal coordinates were referenced to the NAD27 datum, while elevations were referenced to the NGVD29 datum. These horizontal coordinates have been converted to our modern standard using the published transformation parameters for Alaska (excluding Aleutian Islands).

[Tx Ty Tz Rx Ry Rz s]= [-5 135 172 0 0 0 1]

The conversion from NGVD29 to WGS84 HAE is currently accomplished by an average +15 m adjustment, determined from GPS resurveying of historic USGS survey monuments at the Columbia Glacier.

Tides

Compiled hourly predicted and observed tides from the NOAA Station #9454240 in Valdez, Alaska (2000-2011), currently used for calculating the thickness of floating ice and determining terminus position with single-camera photogrammetry.

http://tidesandcurrents.noaa.gov/data_menu.shtml?stn=9454240%20Valdez,%20AK&type=Historic%20Tide%20Data

3. Data Sources

Forebay bathymetry

Mapping of the fjord bathymetry occurred in multiple campaigns over the past 30 years. At the very outset of the Columbia Glacier program, Post (1975) published preliminary soundings taken in the immediate vicinity of the glacier terminus in its pre-retreat position. Subsequent surveys were made during the 1980s, and although most of these results are unpublished, we have a number of plots in our library of materials that can be used if and when the need arises.

The 2001 Krimmel data report includes one generalized plot of bathymetry (shown here as Figure 2b).

The most recent and exhaustive effort occurred during 2005 by the NOAA ship *Rainier*. Their efforts (Noll, 2005) produced a 10 m gridded product that extends to within 2 km of the 2004-2006 terminus position. In addition to the Krimmel (2001) bathymetric data set, there were earlier efforts to map the geometry of the submarine terminal moraine during and pre-dating IMP.

Digitizing these early bathymetric measurements in the region of the terminal moraine are central to our IMP-2 efforts, and will allow us to determine if the moraine has been substantially eroded.

Aerial Photogrammetry
The US Geological Survey maintained a program of vertical aerial photogrammetry (Krimmel, 2001) that provides the basis of our knowledge at Columbia glacier. This record consists of 123 photo flight missions spanning 1957-2001. Each mission pair has an associated manually derived velocity field, consisting of 10's to hundreds of vectors. Also included in this data set is a terminus position for each flight, and several measured profiles from which surface elevation change is calculated. Fjord bathymetry, as measured in 1994, is included in this report.

Since the publication of the Krimmel report, our group has performed a geodetic datum transformation to all the 2001 data, so that these products are directly comparable to more recent data collected in the WGS84 datum. Krimmel's work was all completed using manual analytical stereo-plotting techniques, and no full glacier surface elevation models were produced. A reanalysis effort produced 10 DEMs over the interval 1976-2003, plus 5 additional, higher quality DEMs over the more recent interval 2004-2010. Each of these products also includes dense velocity fields produced using automated feature tracking algorithms.

Surface Mass Balance
An extensive surface mass balance campaign was conducted by the USGS in 1977 (Mayo and others, 1978; O'Neel, 2012), that provided very detailed mass balance information in both space and time, but lasted for only one year. The data were reanalyzed by O'Neel (2012) and more limited data collection occurred from 2010-2012.
Two models have also been constructed for surface mass balance. Tangborn (1987) used low altitude meteorological observations to model accumulation and ablation, while more recently Rasmussen et al. (2011) used upper atmosphere observations to constrain a similar model.

Remotely Sensed Imagery
Remote sensing image quality is now sufficient to provide meaningful analysis tools at Columbia Glacier. Through collaborations with Ohio State University and USGS, we have obtained multiple images of the terminus region from which digital elevation models (DEMs) can be constructed. Ten DEMs covering the terminus region have been produced from imagery acquired since March, 2012. These products tie in to the aerial photogrammetric data to broaden the surface elevation dataset.

A separate effort (Dept. of Interior Climate Science Centers) has resulted in collection of radar images from the TerraSAR-X satellite. Acquisition spans March 2011 to the present at nominal 11-day interval. Radar speckle tracking (Ian Joughin, U Washington) produces nearly full glacier velocity fields at 100 m spacing.

Airborne Lidar
Beginning in the mid-1990s, and ongoing at variable intervals since, the glaciology group at University of Alaska Fairbanks has measured surface elevation profiles of the glacier. Since approximately 2005 the profiling system has been upgraded to a 500 m swath LiDAR and measurements have occurred nearly seasonally.
Chris Larsen (UAF) now operates this program with support from NASA.

GPS/optical surveys
A semi-permanent GPS station was deployed approximately 7 km from the 2004 calving front and recorded data for 100 days. (Data archived with UNAVCO) During summers 2009 and 2010 experimental GPS rovers were deployed onto the glacier surface and recorded position information for days to weeks. (Ian Howat; Ohio State)

We conducted optical surveys of markers placed in close proximity to the calving front for intervals of days to weeks in 2004-06, and in 2008. This data is unpublished but in our possession.

David Finnegan (CRREL, Hanover, NH) conducted a ground-based LiDAR survey of the calving front in 2010. This data is available to us.

Passive Seismology
During 2004-2005 a 12-sensor passive seismology network was installed around the lower glacier to study the mechanics of iceberg calving. After 2005, a single station remained, and has operated intermittently to present. All 2004-09 data are archived at the IRIS Data Management Center in Washington DC, using the network codes YM (04-05) and XL (08-09).

Oceanography
We collected oceanographic measurements to characterize fjord conditions during 2005 and 2006. The cast data, which provide profiles of conductivity (salinity) and temperature as functions of depth, showed that thermal conditions in the deep water favor strong melting of the submarine terminus and icebergs. These records are unpublished but are in our possession.

Meteorology
In collaboration with Army Corps of Engineers, Cold Regions Research Laboratories (CRREL) we installed a high-elevation weather station (1000m) that measures temperature, wind, barometric pressure, and solar radiation. A near-real time camera was

installed near the glacier terminus, and transmits images every 4 hours during daylight hours. The initial installation was done in 2010, but hardware and transmission problems caused a variety of failures; the system was replaced in 2012 and is now performing reliably. Data can be viewed at glacierresearch.com and is archived on a CRREL server in Hanover NH.

Time-Lapse Imagery

To fill the need for direct observation of short-term glacier dynamics, time-lapse cameras have been deployed at the Columbia Glacier nearly continuously since 2004, photographing the near-terminus every 4 hours to 45 seconds. The result is a vast database of over 163,000 images documenting the retreat of a tidewater glacier in unprecedented detail. The imagery is archived by the National Snow and Ice Data Center at the following locations:

NSIDC Archive
Original Full Resolution Time-lapse Images for Columbia Glacier
Time-corrected High Resolution Time-lapse Images for Columbia Glacier
Time-corrected Low Resolution Time-lapse Images for Columbia Glacier
Time-corrected Low Resolution Time-lapse Movies for Columbia Glacier

Products Derived from Time-Lapse Imagery

Forebay Ice

The coverage of loose ice in the Columbia Glacier forebay was assessed visually from the time-lapse images (2004-2011) and rated on the following scale:

clear	0	forebay clear, or very lightly salt and peppered with ice
sparse	1	ice very loosely fills part of the forebay against the terminus
thin	2	ice mostly fills the forebay or upwelling visible at terminus
thick	3	ice fills the forebay and upwelling not visible
choked	4	ice fills the forebay and difficult to distinguish glacier terminus

The derived time series is shown in Figure 13.

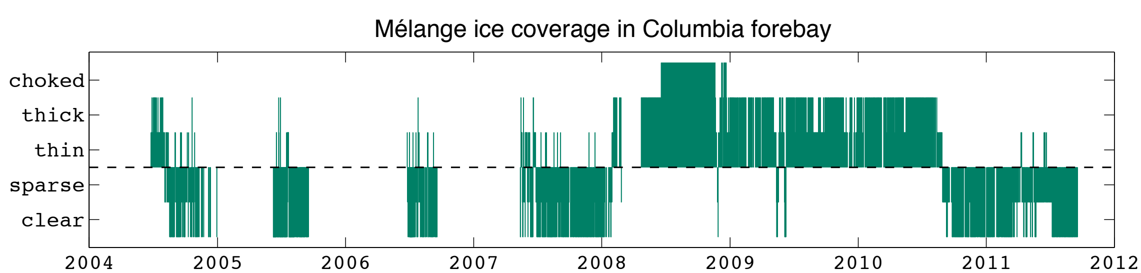


Figure 13: Ice coverage in Columbia Glacier forebay 2004-2012.

Terminus Position

The daily position of the glacier terminus was mapped for all 1,680 days from 2004 through 2011 during which a time-lapse camera was operating. These have been merged with the terminus positions reported in the Krimmel report (aerial photogrammetry, 1957-2001) and traced from modern orthoimagery (2002-2010).

Ice Cliff Height

Heights of the terminus ice cliff have so far only been compiled in the Krimmel report (aerial photogrammetry), and only for years 1978-1998.

Aerial Photographs from Columbia Glacier, 1976-2010
Digital Elevation Models for Aerial Stereographic Flights, 2002-2010
Hillshade Rasters for Digital Elevation Models, 2002-2010http://data.eol.ucar.edu/codiac/dss/id=106.376
Orthorectified Mosaics for Aerial Stereographic Flights, 2002-2009http://data.eol.ucar.edu/codiac/dss/id=106.382
Glacier Surface Velocity Fields from Columbia Glacier, 2004-2010
http://data.eol.ucar.edu/codiac/dss/id=106.379

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(http://data.eol.ucar.edu/codiac/dss/id=106.377)

Part II: First Order Estimates of Future Discharge

A complete iceberg delivery projection includes the following stages:
1) Project future retreat rate, velocity, upstream reservoir drainage, and time to stabilzation.
2) Analyze down-fjord iceberg transport.
3) Analyze transport across moraine.
4) Estimate iceberg size distribution and numbers leaving forebay.

Here we focus on the first of these objectives, and give three estimates of time to stabilization of the retreat of Columbia Glacier, iceberg discharge from the glacier during retreat, and net ice loss over the lifetime of the retreat.

Summary Results:
Time to stabilization: Approximately 17 to 24 years (2029-2036)
Typical iceberg flux during retreat: Approximately 3×10^9 tons year^{-1} (ca. 8.2×10^6 tons day^{-1})
Net loss over lifetime of retreat: 5.7 – 7.2 x 10^{10} tons

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1) First Order Model of remaining retreat and iceberg flux.

Note: Magnitudes of mass, length, speed, flux, etc are given in the discussion in mks units (e.g. km^3 of ice); summary quantities will be also given in English units (e.g. tons of ice) in Table 1.

While most aspects of iceberg calving and glacier dynamics relevant to the retreat of ocean-ending glaciers are understood in broad or conceptual terms, no validated, comprehensive numerical model exists to make reliable simulations of the retreat of glaciers like Columbia Glacier, and no precise, quantitative projection of the future retreat of Columbia Glacier (or any other glacier) is possible at this time. Despite this absence of a complete, model-based understanding of ocean-ending glacier dynamics, certain constraints can be placed on Columbia's future behavior. Some of these simplified approaches are demonstrated here, and the results provide us with a first-order estimate of the remaing years of Columbia Glacier's retreat. These estimates are based on the well-founded assumption that the rapid retreat of Columbia Glacier will cease when the terminus has receded to a point where the glacier bed rises above sea level (i.e. the tidewater limit, marked as "TWL" on Figure 1b), or to a point where both the calving flux and thinning rate can be matched by ice flow arriving from upstream. Here we present three analyses, based on different methods of projecting future retreat, including the monte carlo model recently published in the Cryosphere (Colgan et al, 2012), on which WTP is a coauthor. We compare the results of these analyses, and consider the spread of the results to be a first-order measure of our uncertainty. This uncertainty can be expressed quntitatively, but is nevertheless has a qualitative aspect since we cannot be sure at this stage that the methods bound the actual range of outcomes.

1a. Projection of extrapolation of observed retreat characteristics.

The simplest way to project Columbia Glacier's future retreat rate and calving flux is to project historically observed rates forward in time. This approach assumes that the processes governing retreat so far will continue to operate in the same way in the future. This approach can be refined later by modifying various controlling processes to reflect changing conditions as the retreat continues.

We consider the following observed characteristics:

1a.1 A further ~ 10 km separates the current terminus position from the TWL at the head of the fjord where the bed of the glacier rises above sea level.

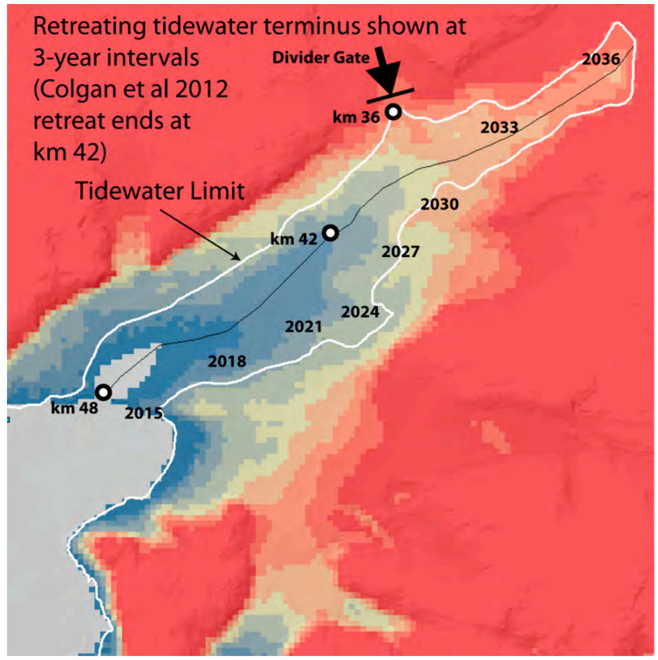
1a.2 The long-term retreat rate of the glacier over the 29-year lifetime of the retreat to date has been approximately 0.6 km year^{-1}.

1a.3 The flux of ice crossing the TWL, evaluated at the the Main Branch at Divider Mountain (referred to as the "Divider Gate") during this period from the upper glacier into the tidewater reach of the glacier is estimated to decline from its present-day value of ca. 2.6 km^3 yr^{-1} to approximately 2 km^3 yr^{-1}, its pretreat value.

The rapid, dynamically controlled retreat that has characterized Columbia Glacier since 1983 requires that the glacier be resting in water of sufficient depth for buoyancy forces to influence the balance of forces acting on the terminus (see Pfeffer, 2007). Thus, if the rapid dynamic behavior (including, notably, high rates of iceberg calving) of Columbia Glacier will end after another 10 km of retreat. We estimate calving flux and total ice calved by adding the volume of ice evacuated from the remaining tidewater reach of the glacier (i.e. the glacier volume from the TWL to the present terminus, see Figure 1) to the ice advected through the Divider Gate into the tidewater reach. For the present we neglect the added flux from the East Branch and calving from the West Branch. While probably not negligible, these additional sources are presently a small fraction of the total present-day mass loss, and we expect that relationship to continue.

We estimate the volume of ice to be evacuated from the Tidewater Reach during at 12.77 km^3, using data from McNabb et al (2012) and our own ice geometry data. The ice advected into the Tidewater Reach through the Divider Gate is estimated by multiplying the estimated gate cross sectional area times the declining ice velocity, and integrating the flux rate over the period of retreat.

Figure 1: Map of remaining ice in Tidewater Reach, from ca. km 36 upstream to ca. km 48 downstream. The color-coded contours show the position of the terminus at three-year intervals as determined by the $H_{ice} = 3/2H_{water}$ discussed in the text.



Linear Retreat Rate: If we assume that the observed rate of terminus retreat (0.6 km yr^{-1}) continues unaltered into the future, then the retreat will continue for 17 years, ending in 2029. Evacuating the 12.77 km^3 of ice in the tidewater reach over 17 years gives a constant flux of 0.75 km^3 yr^{-1}. Ramping the Divider Gate flux down from 2.6 to 2.0 km^3 yr^{-1} over 17 years provides another 29 km^3. Since some fraction of the mass loss occurs by melt and runoff, as opposed to iceberg calving, we reduce the calving flux by 4 m yr^{-1} times the declining area in the tidewater reach, equal in magnitude to 5% of the projected thinning rate of 20 m yr^{-1}. The declining calving flux vs time is shown in Figure 2 ("Linear Retreat"); the net mass loss over the 17 year retreat is 52.9 km^3.

Dynamically-Controlled Retreat Rate: The assumption that terminus retreat will continue at the long-term average rate of 0.6 km yr^{-1} is probably the weakest assumption in the linear retreat rate model. Here we replace this assumption by a calculation of the migration of a boundary of dynamic instability, driven by long-term thinning rate. In doing this we are trading the assumption of constant retreat rate by constant thinning rate, but the observed near-terminus thinning rate is observed to be less variable over the history of the retreat than retreat rate. An analysis of instability of a tidewater terminus is presented in Pfeffer (2007), where ice thickness relative to water depth determines a critical ice thickness, equal to 3/2 times the water depth (or, equivalently 4/3 times the ice floation thickness) below which further thinning leads to acceleration and an unrecoverable feedback. We simulated a instability-forced terminus retreat rate by thinning ice in the Tidewater Reach at a uniform 20 m yr^{-1} and following the progression of the boundary marking the position of $H_{ice} = 3/2*H_{water}$. This produces a non-uniform terminus retreat because the bathymetry of the tidewater (i.e. H_{water}) reach is non-uniform. The retreat to the TWL using this model is 24 years instead of 17. The declining calving

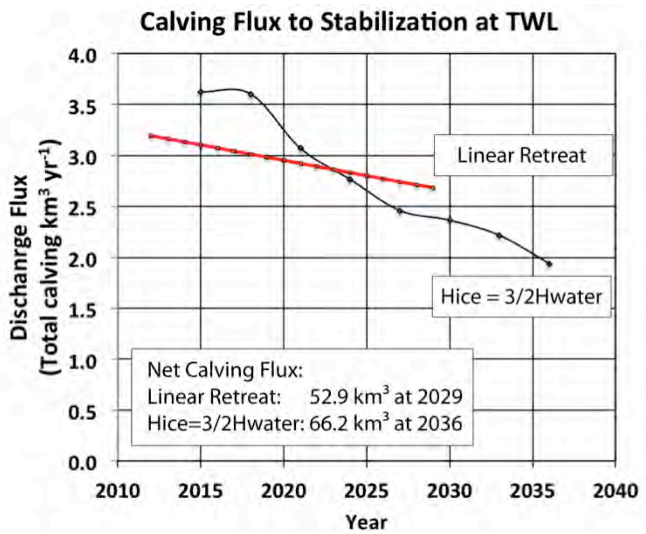


Figure 2: Calculated time series of calving flux from Columbia Glacier from 2012 to stabilization at the Tidewater Limit (TWL) for two models of terminus retreat. Both projections start in 2012; the non-linear "$H_{ice} = 3/2\ H_{water}$" model reports net flux in 3-year intervals, so the first point plotted represents 2012-2015.

flux vs time for this model is shown in Figure 2 ("$H_{ice} = 3/2H_{water}$"); the net mass loss over the 24 year retreat is 66.2 km^3. Note that the larger net loss in this case is due to the longer duration of the retreat; the volume of ice evacuated from the Tidewater Reach is unchanged.

Monte Carlo Model from Colgan et al (2012): Using fundamentally different procedures, including a 1D flow line model that takes account of the centerline bathymetric profile of the Tidewater Reach but not the full 2D bathymetry, Colgan et al (2012) project only 8 km further retreat, which will be complete by 2020 and will involve a loss of only 16 km^3 of ice. This retreat occurs at the same rate as the 0.6 km yr^{-1} used for the linear retreat case, and is complete after a shorter period only because Colgan et al's model find a more extended steady position for the terminus (at km 42) that used in either of the cases described above (km 36). The total calving loss is significantly less than the linear or non-linear models, however. This discrepancy appears to be due to two main factors; first, the volume of ice to be exavuated from the Tidewater Reach is determined in Colgan et al's case by intergrating a width function *w(x)* over the 8 km retreat distance, which produced a different (and probably less accurate) volume measure. Second, and more significant, is the fact that the Colgan et al model underestimates the flux entering the Tidewater Reach through the Divider Gate. This is discussed in their paper (in Section 3: Results) but not quantified.

The non-linear ($H_{ice} = 3/2\ H_{water}$) model can be adjusted to match the conditions of the Colgan et al model more closely, and the results can be compared more directly.

If the non-linear retreat model is run back only to km 42 and assumed to stabilize there, then the retreat ends eight years sooner, in 2021, essentially the same time that the Colgan model predicts. The volume of ice evacuated from the Tidewater Reach is also reduced, from 12.77 km^3, to 8.74 km^3. If the Divider Gate flux is then reduced to 30% of the value used in the non-linear model, the net non-linear model mass loss matches Colgan et al's result of 16 km^3. Thus, the differences between the models presented here and Colgan et al's model reduce to a different point of stabilization, and an anomalously low Divider Gate flux, already suggested by Colgan et al, to 30% of the value presently observed.

Year	Linear Model		Nonlinear Model*	
	$km^3\ yr^{-1}$	tons yr^{-1}	$km^3\ yr^{-1}$	tons yr^{-1}
2012	3.19	3.48E+09	* flux units are yr^{-1} but reported every third year	
2013	3.16	3.45E+09		
2014	3.13	3.41E+09		
2015	3.10	3.38E+09	3.63	3.96E+09
2016	3.07	3.35E+09		
2017	3.04	3.32E+09		
2018	3.01	3.28E+09	3.60	3.92E+09
2019	2.98	3.25E+09		
2020	2.95	3.22E+09		
2021	2.92	3.19E+09	3.07	3.35E+09
2022	2.89	3.15E+09		
2023	2.86	3.12E+09		
2024	2.83	3.09E+09	2.76	3.01E+09
2025	2.81	3.06E+09		
2026	2.78	3.03E+09		
2027	2.75	2.99E+09	2.46	2.68E+09
2028	2.72	2.96E+09		
2029	2.69	2.93E+09		
2030	End		2.36	2.57E+09
2031				
2032				
2033			2.22	2.42E+09
2034				
2035				
2036			1.94	2.11E+09
Total mass loss over retreat:	52.90 km^3	5.77E+10 tons	66.20 km^3	7.22E+10 tons

Table 1: Calving rates, over time and cumulatively, for two models of future Columbia Glacier retreat.

These three calculations are approximate estimates, and depend principally on assumptions about the speed of terminus retreat and the magnitude of ice flux devlivered to the Tidewater Reach through the Divider Gate. Both of these factors could be developed further, and these results could be refined. There is also another presently unquantified possibility that the future retreat and loss rate of the glacier may be significantly smaller and shorter lived than these estimates suggest. In a brief analysis in McNabb et all (2011), the instability theory developed by Pfeffer (2007) is applied to the Columbia Glacier's terminus geometry in its present configuration and the author's conclusion is that the glacier may be leaving the state of dynamic instability that has been driving its rapid retreat since the early 1980s. If so, the calving discharge from the glacier may soon drop dramatically.

All of the foregoing refers only to instability and projected loss rates from the glacier. Beyond these questions are the additional problems that must be addressed to make estimates of iceberg fluxes out of Columbia Bay into Prince William Sound. These include problems of iceberg transport down the lengthening fjord, melt and mechanical damage to bergs during their passage to the moraine shoal, and finally the problem of trapping by the moraine shoal. None of these have been studied as a regular part of past Columbia Glacier research projects, but they were a part of Austin Post's and Wendell Tangborn's IMP project, and an extensive literature exists on iceberg drift and melt. We will make full use of the existing literature, although we believe that some aspects of the problem may present some entirely new challenges.

2) Model Strategy for Improved Estimates

1. Calving discharge. Refinements can be made to iceberg discharge by process-based modeling of calving and flow dynamics. Calving mechanics models are not highly developed, however, and it is not clear that such refinements to our method of projection will actually reduce the uncertainty in range of projected outcomes. We will evaluate some model possibilites and consider whether sufficient gains in confidence in our projections can be achieved to justify this effort. We will also continue to refine the types of projections descrtibed here, and explore variations of these, to develop our confidence in the range of projections by comparing a variety of approximate methods.

2. Iceberg generation and transport. The evolution of size distributions as icebergs are carried away from the terminus and toward the moraine shoal is influence by both melt and fracture into smaller bergs. Our modern time-lapse records of the terminus provide us with observations of iceberg formation at the terminus over the past ca. 8 years. In addition to these images, Austin Post, Robert Krimmel, and other USGS personnel, operated time-lapse cameras at Columbia Glacier as early as 1978, so we also have records of calving from early in the retreat. Finally, the cameras now in operation will continue to operate for the forseeable future.

A substantial body of literature on iceberg drift and transport exists in the marine geology literature, and there are a number of experts in this area available at CU/INSTAAR for guidance and discussions. While extensive modeling of iceberg transport is beyond the scope of this project, we can investigate how to select the relevant processes to concentrate on and develop methods to constrain their probable influence.

3. Transport over the moraine shoal. The Heather Island moraine shoal is a major obstacle to free passage of Columbia Glacier icebergs into outer Columia Bay and Prince William Sound. Icebergs are generally trapped very effectively by the moraine shoal, but periodic “flushing” events occur when all of the grounded bergs at the shoal are swept over the moraine by some combination of currents and tides. We do not know the primary causes of these flushing events, but the time-lapse camera we will install at Heather Island will give us an opportunity to obeserve flushing events and match tidal and meteorological conditions to them.

The depth of the moraine crest is also a critically important factor in iceberg trapping. The shoal bathymetry has been carefully mapped on various occasions in the past, but there has been no organized survey done since 2005 when the NOAA survey ship *Rainier* made its complete bathymetric survey. We are very interested in whether erosion of the shoal has occurred since 2005 and plan to do some bathymetric profiling in Summer 2013, using on of the local charter vessels.

Finally, all of these pieces must be tied together into a single transport model that tracks ice flux from the glacier through the calving front, down the fjord, and over the moraine. This model will produce iceberg discharge scenarios that depend on a range of parameters and constraints that must wherever possible be tied to quantities that can be constrained, either by observation or calculation. This model will give us a tool to explore which input variables are the most significant controls on the end product of iceberg delivery into Prince William Sound, and allow us to focus our efforts on the most important of these.

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