2 October 2014

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

Reference PWSRCAC Project #8551
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Report #5

1. Objective (from PSA Change Order 3, dated 14 August 2014): "Deliver Report on findings of terminus dynamics evaluation and whether any changes to the estimates established in Report 3 (11 December 2013) will be necessary"

2. Summary Findings: Field observations in October 2014 suggest that an episode of rapid calving and retreat further into the Main Branch is approaching, within 5 years but more likely within 1 year. This marks the incursion of the Main Branch terminus into the ice in the Main Branch Basin, analyzed in Report 1, Part II, but not necessarily the onset of complete evacuation of the Main Branch Basin. Most likely temporary pinning points and stable positions will punctuate this retreat. The analysis of ice in the East Basin is unchanged since Report 4 (October 2014). Iceberg sizes and rates of delivery to Heather Bay Moraine Shoal will vary episodically during the continued retreat, but over the long term, berg population and size will decrease as the glacier retreats.

No further information is available to assess the future behavior of the glacier's West Branch.

3. Summary of additional field operations Since Report 4

(Rob Campbell conducted oceanographic measurements in the Columbia Glacier forebay during October; the results of this work will be reported separately by him.)

During the first week of October 2014, a four-person field team flew to Columbia Glacier and established a camp on Great Nunatak near the present terminus. During the visit, the team operated a Gamma Remote Sensing Ground Portable Radar Interferometer (GPRI), on loan from the University of Alaska at Fairbanks, installed a GPS base station, and serviced the time lapse camera systems. The October timing of the field visit was made in hopes of capturing the response of the glacier and ocean to a heavy fall storm (meteorological records and time lapse sequences recorded during previous fall storms showed large shifts in patterns of flow and calving, which the teamed planned to capture in greater detail). As hoped, the field team was rewarded with five-plus days of heavy rain and snow starting the day after their arrival.

***Weather observations October 7-14*:** The remains of Typhoon Phanfone arrived on day 2 of the field team's visit (8 October) and deposited approximately 5 inches of snow, followed by heavy rain for two more days. Precipitation recorded by National Weather Service near Valdez, at Cannery Creek, totaled 2.1 inches over the period 7-14 October (See Table 1). Temperatures, wind and barometric pressure were recorded by our weather station at the Divider Mountain weather station, located in the glacier's catchment approximately 15 km ENE from the base camp. These data are shown in Figure 1.

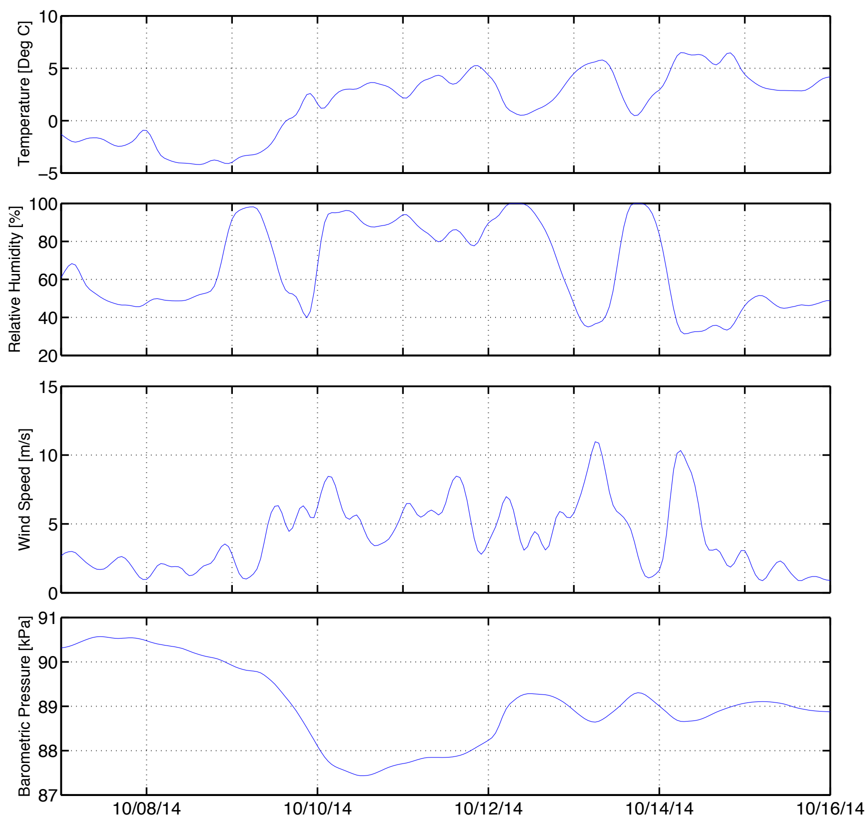

Figure 1*: Weather data from the trip including daily average temperature, pressure and wind speed, measured at Divider Mountain, 15 km ENE from the glacier terminus.*

Date	Precip (inches)	Description
7/10	0.01	Nice day
8/10	0.01	Overcast, late day snow
9/10	0.06	10-15 cm snow overnight. Rain evening.
10/10	0.51	Rain showers becoming heavy
11/10	0.76	Rain, heavy at times
12/10	0.55	Morning rain
13/10	0.18	Sunny by mid morning
14/10	0.02	Overcast
Total	**2.1 inches**	

Table 1: Daily precipitation at Cannery Creek (27 km distant, at sea level) are given together with a description of observed precipitation by the field party at Columbia Glacier

Camera Maintenance*:* The two time-lapse camera systems presently operating in Columbia Bay were prepared for winter. Each camera operated on schedule through the 2014 summer. We retrieved 5186 photos from the AK-01b camera and 2403 images from the AK-10b camera. While the field party was on-site, a temporary time-lapse camera was installed at the camp, acquiring images every 3 minutes on a similar schedule as the GPRI (3021 images).

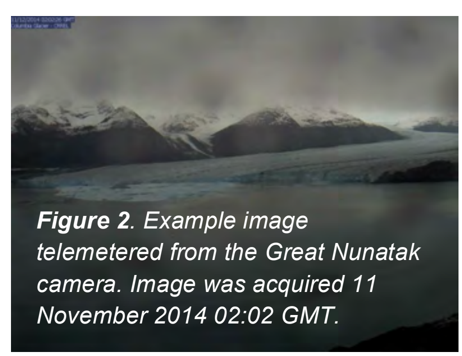

Figure 2*. Example image telemetered from the Great Nunatak camera. Image was acquired 11 November 2014 02:02 GMT.*

The StarDot/Iridium system above the camp was upgraded to a new camera and logger that allows some 2-way communication as well as on-site recording capacity, ensuring data capture beyond telemetered imagery. This system acquires images hourly, but only transmits 3-4 images a day. It is equipped with a light sensor to avoid capturing images during nighttime hours. The power system was upgraded to a lithium iron phosphate battery, which has improved operating capacity in cold temperatures and a longer shelf life. A sample image is shown in Figure 2.

GPS Base Station: A NetRS geodetic precision GPS base station was installed at the existing seismometer site. A choke ring antenna and radome were installed on a UNAVCO-style polar mount, and an air-alkaline power system was installed to power the instrument through winter. The receiver and antenna are on a long-term loan from Jeff Freymeuller (UAF Geophysical Institute). A tie survey was completed from the GPS station “Base” used in 2004-2010 surveys to determine the position of the new station. Data processing will be possible after the next service of the instrument and will compliment the existing time series of uplift at the site (Figure 3).

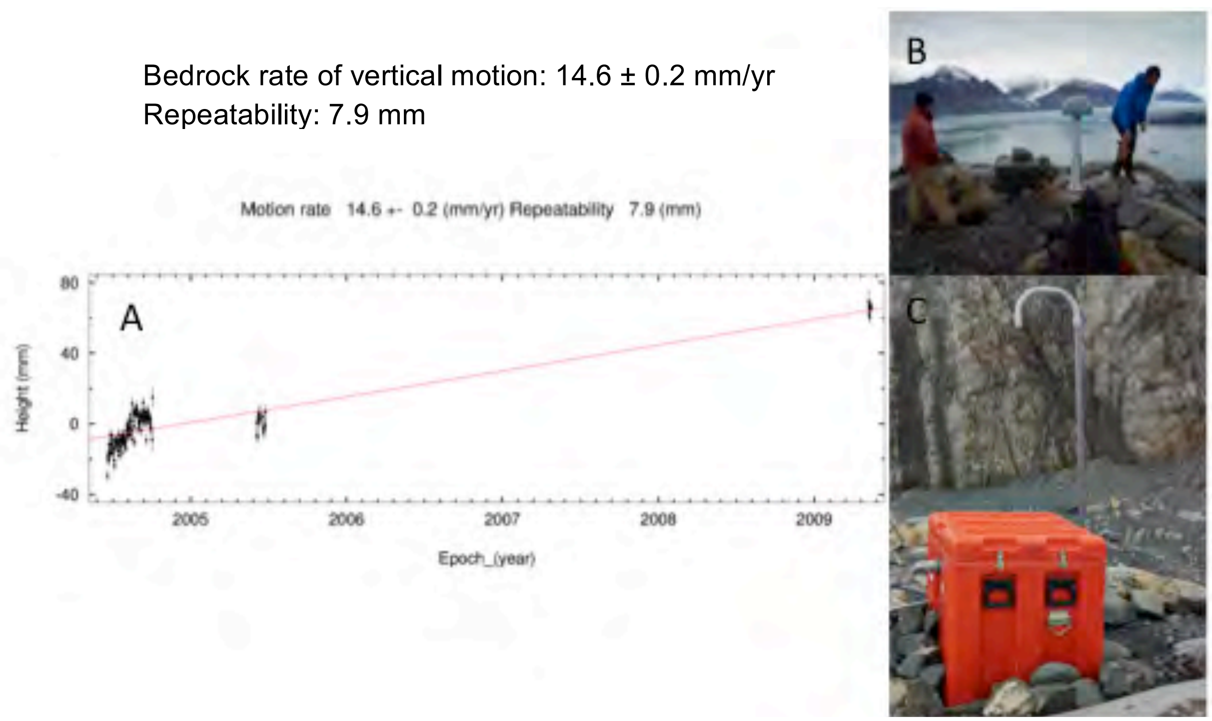

***Figure 3**. A) Time series of vertical displacement at the site CGNU located on the Great Nunatak near the 2004-2010 campsite. Processing of these data courtesy of Jeff Freymeuller, UAF. B) Polar mast antenna mount and Radome. C) Instrument and battery vault with ventilation snorkel.*

GPRI Installation: Three 2 m antennas of the instrument transmit and receive radar data on 3-minute intervals to be processed interferometrically. The sensor's range extends to 16 km, and can resolve mm-scale deformation across this range. At 1 km range this senor has an azimuthal precision of ~ 8 meters, and a range precision of 0.75 m. The instrument operated nearly continuously during the week, with 4 data gaps introduced due to high winds. Approximately 700 Gb of data were collected, and are stored in triplicate at the University of Alaska at Fairbanks, the USGS Alaska Science Center in Anchorage, and at the University of New Hampshire in Durham. Both topographic and differential interferograms are output from the sensor allowing construction of digital elevation models (DEMs) and point displacement maps, as discussed below.

Figure 4*. Gamma Remote Sensing Portable (GRSP) Radar Interferometer as installed at Columbia Glacier terminus.*

The GRSP radar backscatter images have been compiled as a movie, available at http://tintin.colorado.edu; a frame from this sequence is shown below in Figure 5. In this high-speed movie, calving events and their resulting wave trains and seiches are clearly visible. The measurements span a major fall storm that deposited substantial snow followed by rain. Calving events are clearly visible. Motion of the glacier is obvious if the movie is accelerated. Change in the west branch is evident, but the main branch geometry remained stable. Episodes of tidal mixing are evident, as are intervals of vigorous subglacial discharge. From time to time bergs become grounded in shallow locations of the fjord. Variable transport rates and directions evidence notable differences in iceberg draft. Whether berg motion is a result of current or wind forcing appears to be strongly related to the size of the berg. Newly exposed beaches clearly come and go with the tide. The local tide can be extracted using the slope of the beach and the timing of water level.

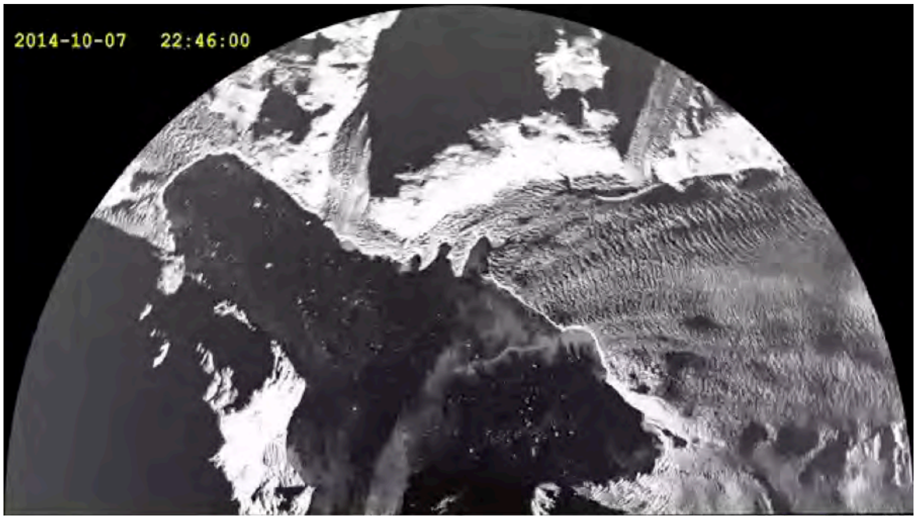

***Figure 5**. Radar backscatter still from the Great Nunatak camp in georeferenced coordinate system. The instrument located at the bottom, center of the frame. The main branch is visible on the right, and the west branch in the upper left of the image space. The sequence is rendered at 1080x or 18 minutes of real time per second of replay. See* http://tintin.colorado.edu *for the sequence.*

Further analysis and projected retreat: Determination of full, georeferenced flow fields will require georectification and referencing of the GRSP images. These will be performed by colleagues at UA Fairbanks; in the meantime we have line-of-sight velocities (i.e. at any given point on the glacier, the component of motion parallel to the vector joining the radar to that point), calculated both as contoured fields in map view (Figure 6) and as time series at various points extracted from the fields (Figure 7). Data are stacked over 1-hour intervals to reduce noise.

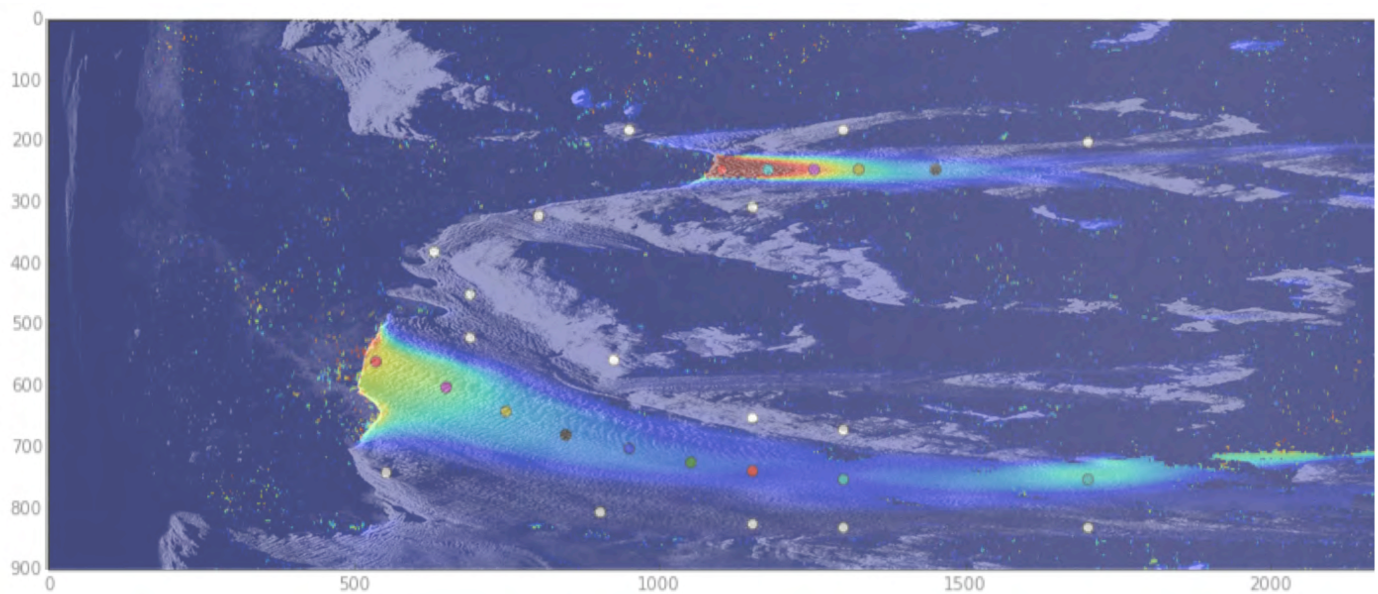

***Figure 6**. Line-of-sight velocity field, where red is the fastest flow (ca. 6 m/d). The image shown here is distorted by rendering the radial space shown in Fig. 5 as a rectangular region. The horizontal axis here corresponds approximately to distance from the radar (equivalent to radial distance in Figure 5); points along the left-hand margin of Figure 6 all map to one point, the location of the radar (at the center of the bottom margin of Figure 5). Faster speeds are shown red and diminish through yellow and green to blue at the lowest speeds. Colored circles indicate the position of time series shown in Figure 7, each plotted in like colors. Note that while the apparent velocity of the West Branch is greater in Figure 6, Figure 5 shows that the radar line-of-sight direction at the West Branch is very nearly parallel to the glacier flow direction, while on the Main Branch the line-of-sight is very oblique to the flow direction; this will cause the apparent flow speed on the Main Branch to be less than the true flow speed.*

Figure 6 shows that the line-of-sight flow speed decreases with increasing distance from the terminus in the Main Branch. From Figure 7, a strong tidal influence on speed is apparent, with maximum speeds at low tide. The amplitude of the tidal influence extends about 2.3 km upstream and decreases with distance from the terminus; the length scale of damping appears to be about 10 ice thicknesses. These are characteristic of grounded tidewater termini, but the amplitude and phase of the tidal signal is unusual: at 30% to 50% of the background velocity, the tidal signal is unusually strong, and there is not strong evidence of a phase lag moving upstream, away from the terminus. These conditions suggest that basal coupling is not strong in the Main Branch, probably caused by increasingly significant buoyancy forces as the glacier continues thinning at annual average rates of 10-20 m/yr.

Taken together with other current and historic observations, our preliminary analysis suggests that the lower glacier is poised for another episode of rapid change, not unlike the period of retreat between ca. 2008 and 2010. Following a period of very rapid flow and calving, but stable terminus position, between ca. 2001 and 2005, the glacier's speed dropped to (relatively) very low values and thinned rapidly near its terminus before beginning a rapid retreat from immediately upstream from the Kadin-Great Nunatak Gap to near its present position just above Juncture. The main branch terminus then stabilized in shallow water around several basal high spots, and has changed only small amounts since then. Following the pattern of the last decade, we expect an episode of retreat to occur, possibly within one year, but very likely within 5 years. Better knowledge of the basal topography of the Main Branch would help predict the glacier's near-term future, but precise knowledge of the onset and speed of this episode of retreat is probably unattainable in any case. Our group will closely monitor the daily image stream to assess glacier stability and will alert RCAC of any notable changes in terminus and iceberg conditions.

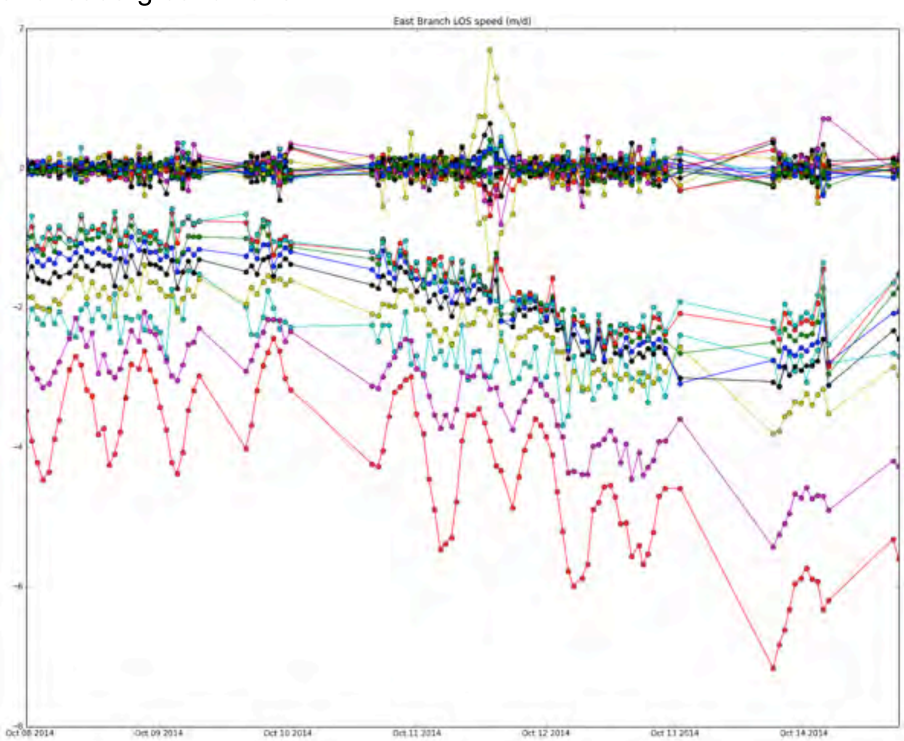

***Figure 7**. Time series of ice motion at colored dots shown in Figure 6. The top cluster of lines are on fixed bedrock points and gives a measure of the noise level in the radar time series following preliminary processing. Nine time series below show time-varying rates of motion toward the radar.*

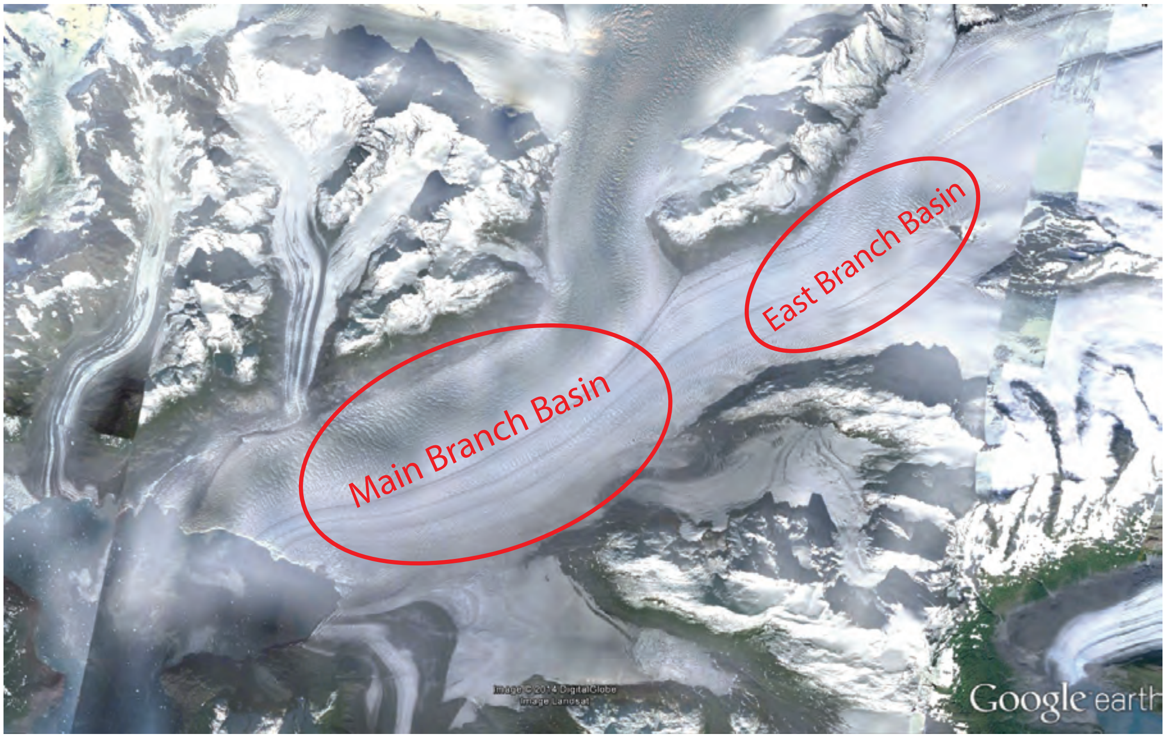

***Figure 8**: Main Branch Basin and East Branch Basin.*

4. Modifications to projections discussed in Reports 3 and 4

The findings of October, 2014, described above, led us to the important conclusion that an episode of rapid retreat and calving of ice from the Main Branch Basin (Figure 8) appears to be set to commence within 1 to 5 years, with the greatest likelihood occurring around one year. This is the first episode of removal of ice from the Main Branch Basin (see Figure 8), where ca. 5.7 – 7.2 x 10^{10} tons of ice are stored (see Report 1, Part II), but this does *not* necessarily represent the onset of the flushing of that entire basin. Without further measurements of the bed topography in the Main Branch Basin, we cannot determine if pinning points are present upstream where temporarily stable terminus positions might be reached. The approximate knowledge of the bed in the reach (e.g. through McNabb et al, 2012) indicates that the bed geometry is complex, with ridges and some local high spots, favoring temporary stabilization during a longer episode of retreat (Report 1, Part II)

The assessment of deeper ice in the East Branch Basin than given by earlier analyses, as detailed in Report 4, is unchanged here. The removal of ice from the East Branch Basin will clearly not commence until the Main Branch Basin is opened up, but nothing in the observations over the past two months alters our assessment given in Report 4.

No further analysis of the future behavior of the glacier's West Branch can be made at this time.

Current understanding of the transport and delivery of icebergs down Columbia Bay and to the Heather Bay Moraine Shoal (HBMS) was outlined in Report 3, and those findings are unchanged. Recapping the summary of Report 3 on iceberg transport:

While calving rates are declining over the long term, Columbia Glacier continues to produce icebergs at a rate faster than most Alaskan tidewater glaciers, and those icebergs are larger than icebergs produced at most other locations. Most of the calved ice is retained behind HBMS until the bergs deteriorate to smaller sizes or unless a high tide sweeps a cluster of bergs over the moraine (not uncommon). For these reasons alone, Columbia Glacier merits continued surveillance as it continues retreating, but other factors are at work to reduce iceberg sizes, including declining berg sizes at the time of calving (due to thinning ice), increasing distance from the glacier terminus to HBMS, and possible trapping of icebergs at shallow parts of either the Main or East Branch Basins. All of these conditions point toward prolonged but episodic future rates of iceberg calving and diminishing size of icebergs over time.