
Holland America Line
Zaandam

Post Little Ice Age Glacial Rebound in Glacier Bay National Park and Surrounding Areas

By Roman J. Motyka, Christopher F. Larsen, Jeffrey T. Freymueller and Keith A. Echelmeyer

(Left and Above) Researchers Chris Larsen and Ellie Boyce set up GPS units over benchmarks set into bedrock at various locations in Glacier Bay.

Photographs by R.J. Motyka

Introduction

The fastest measured rates of uplift in the world today are in Southeast Alaska: in Glacier Bay National Park and east of Yakutat *(Figure 1)*. The first measurements of this rapid uplift were done the mid-twentieth century through tide gauge studies, which suggested that land in the Glacier Bay region was emerging at 1.18 in/yr (30 mm/yr) and faster in Glacier Bay *(Hicks and Shofnos 1965)*. However, the cause of the uplift was still being debated when we initiated our investigations in 1998. To determine whether this uplift was driven by tectonics or glacial rebound we embarked on a field program that included:

1) repeating and reviewing the original tide gauge measurements,
2) measuring the current rates of uplift with modern GPS geodetic techniques,
3) defining the regional pattern of uplift,
4) determining when this episode of uplift began, and
5) assessing the total amount of uplift that has occurred.

Uplift Measurements

We used three complimentary methods to measure uplift:

1) precision GPS geodesy,
2) relative sea-level change from tide gauge measurements, and
3) raised shoreline studies.

Precision GPS geodesy has many distinct advantages—it can be done anywhere there is stable bedrock, thus allowing much broader spatial coverage than the other two methods; researchers can measure benchmark positions relative to a global reference frame with high accuracy (± 0.08 in, ± 2 mm); and it measures both vertical changes and horizontal motion, latter of which is very important in this tectonically active region. We established over 70 measurement stations distributed across the region *(Figure 2)*, with each site typically having two to four occupations over three to six years. By assessing the change in position over these intervals, we determined bedrock motion on an annual basis. The results of our GPS investigations for vertical motion are shown in *Figure 2*. A double bulls-eye of contours delineates two centers of rapid uplift in Southeast Alaska: over Glacier Bay (1.18 in/yr, 30 mm/yr) and over the Yakutat Icefield (1.26 in/yr, 32 mm/yr) *(Larsen et al. 2005)*. Uplift rates decrease smoothly away from these peaks. The uplift pattern documented here spans an area of over 40,000 mi^2 (100,000 km^2). As we shall see later, the centers of peak uplift coincide with places that have experienced some of the greatest losses of ice.

The tide gauge data used in our second method come from permanent National Ocean Service (NOS) gauges, NOS temporary gauges and our own temporary gauges *(Larsen et al. 2003, 2004)* for a total of 22 sites *(Figure 3)*. Temporary tide gauges typically record sea-level over the course of one or more monthly tidal cycles, and the

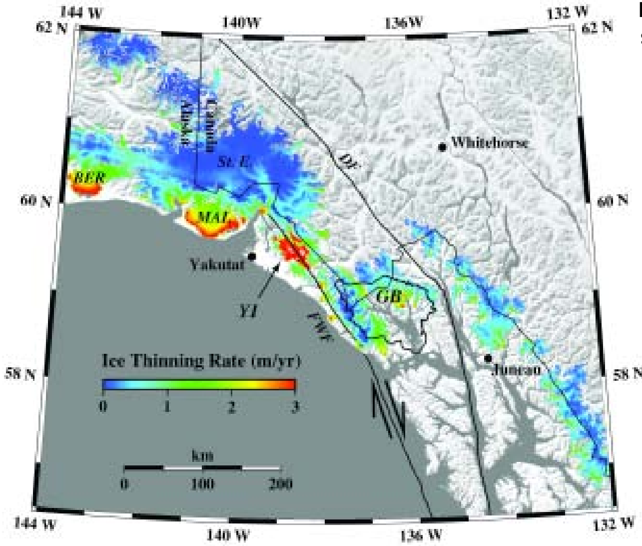


Figure 1. Location map, showing tectonic setting and present day glacier wastage *(from Larsen et al. 2005).* Ice thinning rates follows Arendt et al. (2002). The fastest changes are occurring at lower elevations, such as the termini of the Bering (BER) and Malaspina (MAL) glaciers. The Yakutat Icefield (YI) is an exception, where thinning rates are about three times greater than the regional average and are driving the greatest ongoing unloading in Southeast Alaska. The Glacier Bay Little Ice Age Icefield is outlined (GB). Most of this icefield disappeared over the last ~250 years. Tectonic deformation along the North America Pacific Plate boundary occurs as strike-slip motion on the Fairweather Fault (FWF), and to a lesser degree, the Denali Fault (DF).

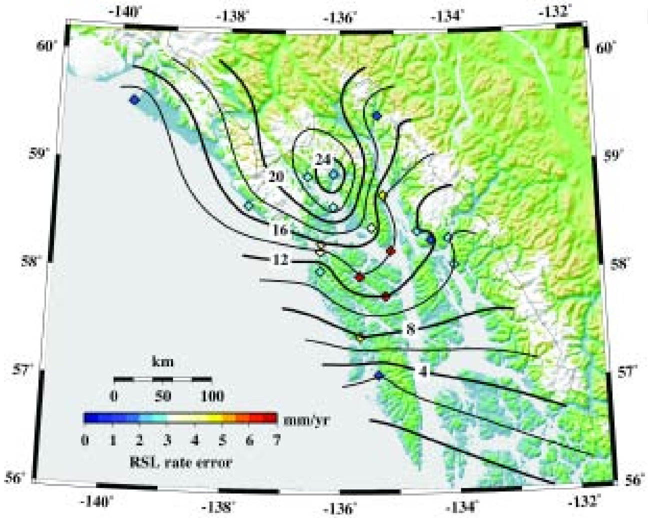


Figure 3. Negative sea level rates from tide gauge data (from *Larsen et al. 2004*). Contour interval is 0.08 in/yr (2 mm/yr). Red diamonds indicate tide gauge sites.

elevation of the gauge is then surveyed relative to a local network of benchmarks. When this procedure is repeated several decades later, sea level change can then be found relative to the benchmarks. The average overall uncertainty in this method is 1σ = ±0.2 in/yr (5 mm/yr). The pattern of sea level changes found at the tide gauge sites indicates that the fastest sea level changes in Southeast Alaska are found in Glacier Bay *(Figure 3)*. This finding is in general agreement with Hicks and Shofnos *(1965)*, although we determined that the peak uplift rate found by Hicks and Shofnos at Bartlett Cove is almost certainly biased by unstable reference benchmarks there. After we rejected the data from this point, we found that overall the pattern and magnitude of regional sea level rates have remained essentially constant at the level of measurement accuracy since the time of the earliest rate measurements *(Larsen et al. 2005)*. The pattern of sea level rates also agrees well with the pattern of uplift rates from GPS measurements within the Glacier Bay region *(Figure 2)*.

In the third method, we measured raised shorelines at 27 different coastal sites. Coastal regions in and around Glacier Bay National Park clearly show the effects of rapid uplift through recent land emergence, young shoreline forests, new shoals, raised shorelines, and wave-cut benches *(Motyka 2003)*. Raised shorelines were identified by:

1) a wave cut step or riser in the slope,
2) a change in thickness of organic-rich soil,
3) termination of beach deposits, and/or
4) an abrupt change in age of trees *(Figure 4)*.

The difference in elevation between the raised shoreline and the current maximum high tide level provided us with the total amount of sea-level change. Dating tree ages just below the raised shoreline provide a minimum estimate of the onset of land emergence *(Motyka 2003, Larsen et al. 2005)*. The average overall uncertainty in estimating change in shoreline elevation is 1σ = ± 1 ft (0.3 m). The results shown in *Figure 5* show that the total sea level change found at the raised shoreline sites also describes a regional pattern surrounding Glacier Bay. Quite notably, the greatest amount of sea level change occurs at the sites closest to where the peak rates of uplift and sea level fall are found. Dates for

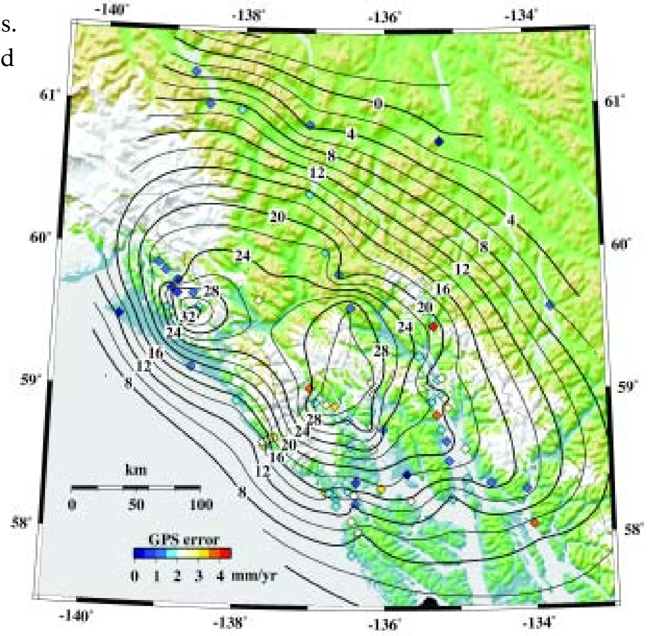


Figure 2. GPS uplift observations in Southeast Alaska *(from Larsen et al. 2005).* GPS uplift rates are in mm/yr; contour interval is 0.08 in/yr (2 mm/yr). GPS stations are shown with diamonds, colored according to the uplift rate error at each site as indicated by the color scale bar. Peak uplift rates are found in Glacier Bay (southern peak) and the Yakutat Icefield (northern peak).

the initiation of emergence is estimated to have begun 1770 ± 20 AD, the same period that Glacier Bay and other regional glaciers began retreating from their Little Ice Age maximums *(Motyka and Beget 1996, Larsen et al. 2005)*.

Glacial Rebound

The correlation of the onset of uplift with the retreat of glaciers in and around Glacier Bay makes unloading of the earth's crust through loss of glacier ice a prime suspect for driving the regional uplift. This is because one of the consequences of changes in glacier ice mass is a readjustment of the earth's crust and underlying layers in response to the changing weight, a process known as "glacial isostatic adjustment" (GIA). The effect is akin to the well-known Archimedes Principle, e.g., when you add or remove weight in a floating boat, it will sink or rise in the water. The earth's crust responds in a similar way but with a substantial time lag: unlike water, the material beneath the earth's crust (know as mantle) is extremely viscous and it takes considerable time (centuries to millennia) for it to respond to a change in load. Examples of long lasting viscoelastic response are well documented in regions that were covered by continental ice sheets during the Last Glacial Maximum 16,000 years ago, e.g., Hudson's Bay and Scandinavia. In a similar way the rapid uplift rates observed in Glacier Bay are related to recent ice loss. To test this hypothesis, our next step was to determine how much glacier ice has been lost in the region and whether GIA response to this changing load could account for the entire strong uplift signal. If so, then the results would also tell us much about the properties of the earth's crust and mantle in this region.

Glacier Ice Loss

Just over 250 years ago a vast ice field blanketed much of what is now Glacier Bay National Park. The main exit for much of this ice was into Icy Straits *(Figure 6)*. The period over which this ice accumulated and expanded to fill the entire bay is known as the Little Ice Age (LIA), which began during the thirteenth century in southeastern Alaska. During the mid-eighteenth century a period of climatic warming appears to have affected the entire region as evidenced by a number of glacial retreats starting about this time *(Motyka and Beget 1996)*. Glacier Bay was no exception and this warm period triggered a dramatic calving retreat of glacier ice that lasted into the twentieth century.

Glaciers leave behind tell-tale signs of their maximum expansion, and we utilized these markers to reconstruct what Glacier Bay looked like at its LIA maximum. These signs include forest trimlines, lateral moraines, terminal moraines, and glacier outwash. We used light aircraft overflights to identify these geomorphic markers as

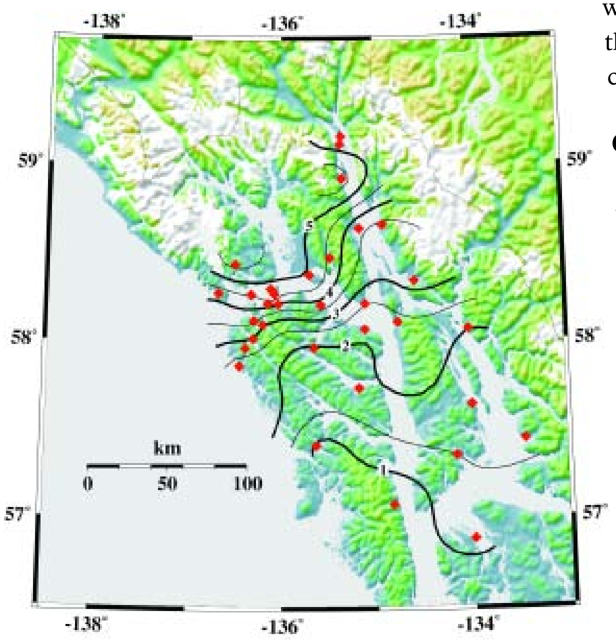
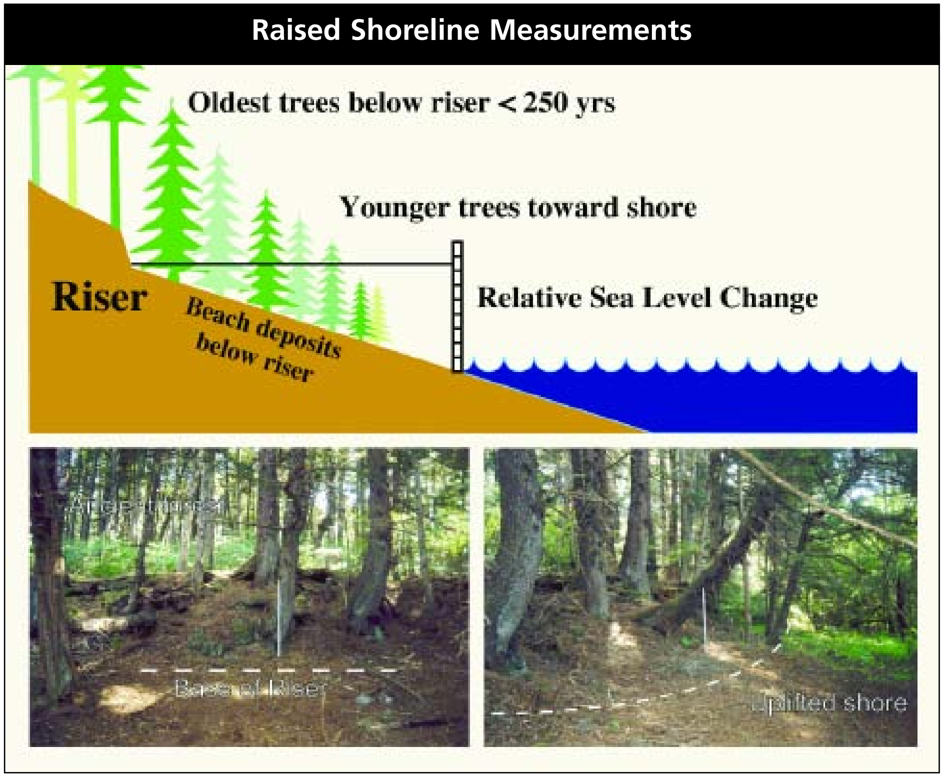


Figure 5. Relative sea level change (from *Larsen et al. 2005*). Raised shoreline sites are shown with red diamonds. Contour interval is 1.64 ft (0.5 m).



Photographs by C.F. Larsen

Figure 4. Schematic of a typical raised shoreline measurement in Southeast Alaska (above), and photographs of a site at Swanson Harbor (below). Dendrochronology of Sitka spruce *(Picea sitchensis (Bong.) Carr)* rooted at the base of the raised shorelines brackets an onset date of 1770 AD (± 20 yrs) for the current uplift. Raised shoreline heights, determined from level-line surveys, are greatest at those sites closest to Glacier Bay (19 ft/5.7 m measured maximum) and diminish to less than 3.3 ft (1 m) 93 mi (150 km) southeast of the bay, a pattern similar to present day uplift rates.

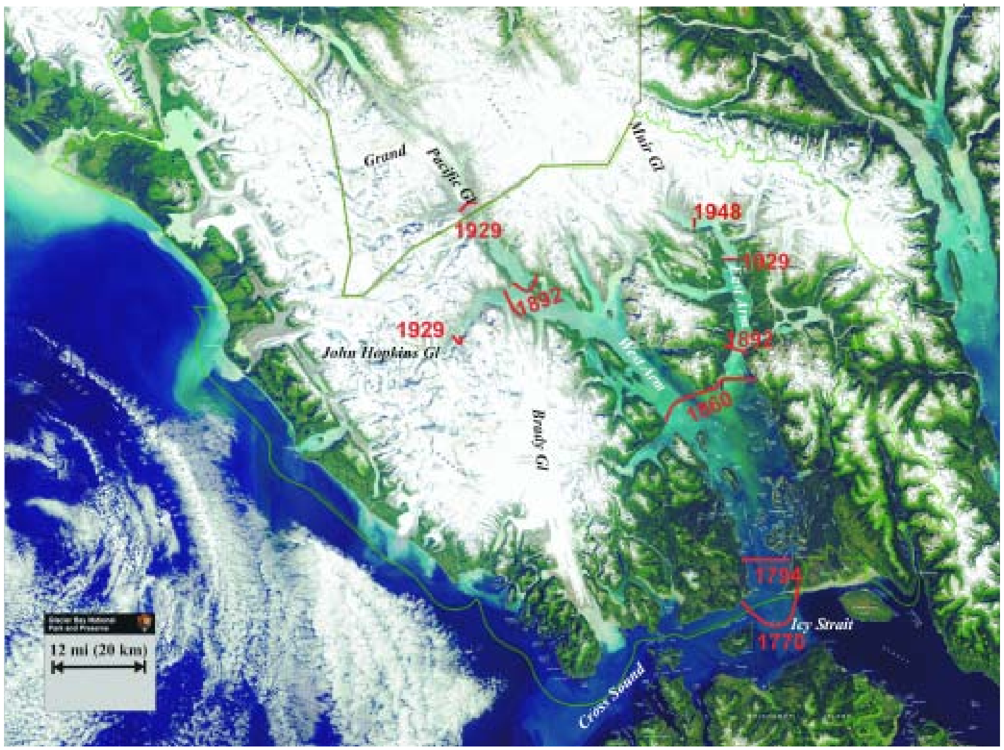


Figure 6. This image was created using satellite imagery, collected on August 1, 1999, and August 10, 2000. The red lines mark glacial extent over the last 200 years. We know from moraines and submarine topography that the terminus extended into Icy Strait, which tree ring dating puts at about 1770 AD. The icefield underwent a rapid calving retreat soon after, retreating 75 mi (120 km) in 160 years in the West Arm. Some tidewater glaciers are now re-advancing, most notably John Hopkins and Grand Pacific glaciers, while others continue to retreat, e.g., Muir Glacier. (Image by NPS Landcover Mapping Program)

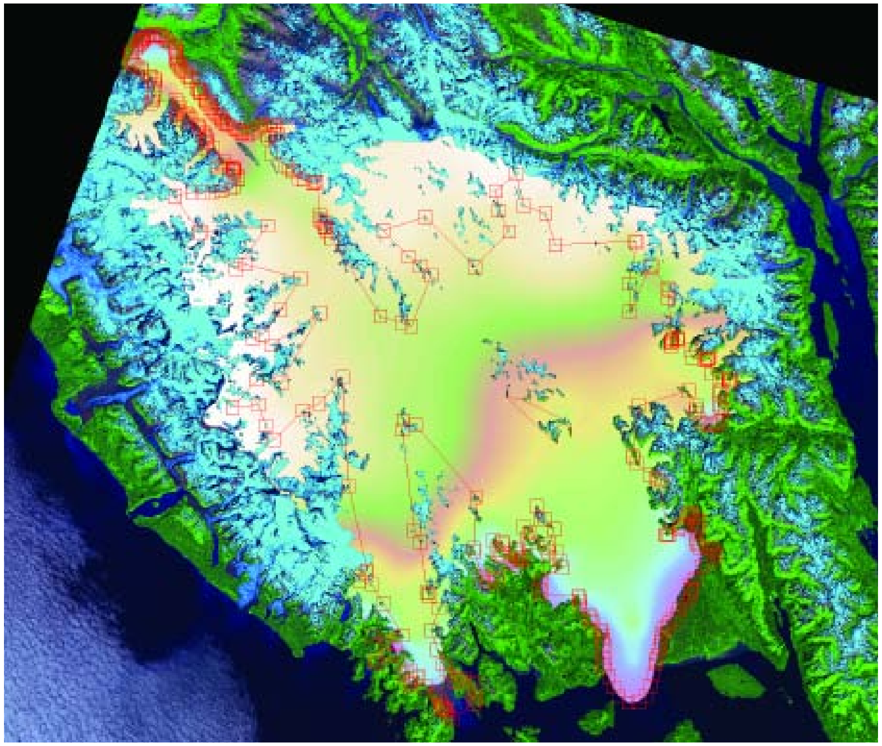


Figure 7. Reconstruction of LIA maximum glacier surface in Glacier Bay (~1750 AD) *(modified from Larsen et al. 2005).* The LIA maximum ice surface was determined by mapping geomorphic markers shown as squares (trimlines, lateral moraines and terminal moraines). These markers were identified through aerial inspection, vertical airphoto analysis, high resolution digital elevation model (DEM) analysis, and field observations. Modern-day glacier analogues were used to construct the Glacier Bay LIA icefield surface from the geomorphic markers. This surface was then differenced with a DEM of present-day topography to determine ice thickness change since LIA.

well as analysis of vertical airphotos, satellite imagery and digital elevation models to determine heights and locations of these indicators of maximum ice extent. Our results in *Figure 7* show that Glacier Bay contained a huge continuous icefield up to 0.9 mi (1.5 km) thick that covered more than 2350 mi^2 (6000 km^2) at the peak of the LIA (1770 AD). Rapid calving and associated upstream drawdown lead to its collapse in less than 160 years, with the main trunk of the icefield retreating 75 mi (120 km) in fjords as deep as 1640 ft (500 m). Using our reconstruction we calculated that an ice volume of about 820 mi^3 (3450 km^3) was lost above sea level during the post-LIA collapse, comparable in volume to Lake Huron, and equivalent to a global rise in sea level of nearly 0.4 in (1 cm). An additional 60 mi^3 (250 km^3) of below sea level glacier ice was lost in the fjords. To our knowledge this retreat in Glacier Bay is the largest post-LIA deglaciation in the world.

Ice continues to melt in Glacier Bay and other ice fields in the region *(Larsen et al. 2006)*, in some cases at an accelerating rate as documented in separate programs *(Arendt et al. 2002)*. This ongoing ice melt continues to contribute to rebound effects already underway.

Glacial Rebound Model

Armed with knowledge of the region's ice load history, our next task was to construct an earth model that would satisfy the uplift observations. If we could produce a statistically valid model that satisfied our data constraints, then we could show that the regional uplift is primarily a consequence of GIA associated with post-LIA deglaciation of southern Alaska. We tested various earth models against the uplift observations *(Larsen et al. 2004, 2005)*, and found that GIA could completely account for the observed uplift. The results also provided robust constraints of lithospheric and asthenospheric structure *(Figure 8)*. Futhermore, the models indicate that GIA from the collapse of Glacier Bay is about at the halfway point and that this glacial rebound driven uplift should continue for several more hundred years. Of course, additional ice loss from regional glaciers continuing their trend of wastage and thinning will only add to this effect.

Conclusions

In Southeast Alaska we have measured the world's fastest present-day isostatic uplift using GPS geodesy combined with studies of raised shorelines and tide gauges. The uplift pattern documented here spans an area of over 40,000 mi^2 (100,000 km^2) centered on the coastal mountains along the Gulf of Alaska *(Figures 2, 3, and 5)*. The data set depicts a regional pattern of uplift, with peaks of 1.18-1.26 in/yr (30-32 mm/yr) centered over upper Glacier Bay and Yakutat Icefield. The peak uplift rates are found in regions that have experienced the highest rates of ice loss. Raised shorelines that date back to 1770 ± 20 AD indicate total sea level fall in the range of 3.3 to 18.7 ft (1.0 to 5.7 m). The onset of uplift measured at the raised shoreline sites correlates with when the Glacier Bay Icefield began its dramatic collapse. GIA modeling results provide robust constraints on lithospheric elastic thickness, asthenosphere thickness and asthenosphere viscosity *(Larsen et al. 2005)*. The simultaneous onset of unloading and sea level change is a direct observation of the causal relationship between glacial unloading and the region's uplift. Climate changes rather than tectonic forces have primarily forced these regional sea-level changes.

These adjustments to LIA glacier loading and unloading are producing significant stresses on the earth's crust in Glacier Bay, which can affect seismicity and regional tectonics. The rising land is also continually changing the shorelines and geomorphic texture of shoreline throughout the park and causing changes in hydrologic patterns, erosion and sedimentation. All these changes have a direct impact on the ecosystems of the park.

Acknowledgments

This work was supported by grants from National Science Foundation, Earth Sciences. We wish to express our gratitude for logistical support provided by Glacier Bay National Park and to the numerous field assistants who have participated in this study.

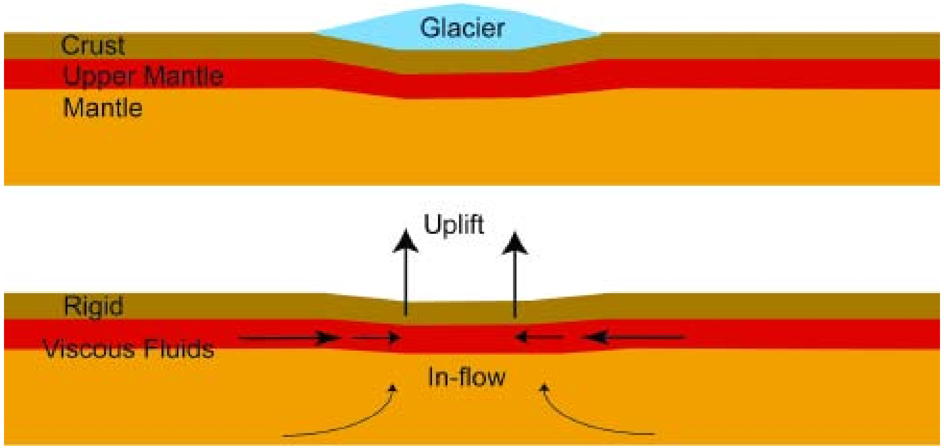


Figure 8. A diagram of the earth models used in our study. In the upper panel, a depression has formed on the surface of the earth, where the weight of the glacier has pressed down the rigid crust, displacing some of the viscous mantle beneath. When the glacier melts, the crust rebounds causing uplift, which is prolonged somewhat by the slow response of the viscous mantle flowing back into equilibrium.

REFERENCES

Arendt, A.A., K.A. Echelmeyer, W.D. Harrison, C.S. Lingle, and V.B. Valentine. 2002. *Rapid wastage of Alaska glaciers and their contribution to rising sea level.* Science 297:382-386.

Hicks, S.D., and W. Shofnos. 1965. *The determination of land emergence from sea-level observations in southeast Alaska.* Journal of Geophysical Resources 70:3315-3320.

Larsen, C.F., K.A. Echelmeyer, J.T. Freymueller, and R.J. Motyka. 2003. *Tide gauge records of uplift along the northern Pacific-North American plate boundary, 1937 to 2001.* Journal of Geophysical Resources 108: 2216. DOI:10.1029/201JB001685.

Larsen, C.F., R.J. Motyka, J.T. Freymueller, K.A. Echelmeyer, and E.R. Ivins. 2004. *Rapid uplift of southern Alaska caused by recent ice loss.* Geophysical Journal International 158:1118-1133.

Larsen, C.F., R.J. Motyka, J.T. Freymueller, K.A. Echelmeyer, and E.R. Ivins. 2005. *Rapid viscoelastic uplift in southeast Alaska caused by post-Little Ice Age glacial retreat.* Earth and Planetary Science Letters 237:548-560.

Larsen, C.F., R.J. Motyka, A.A. Arendt, K.A. Echelmeyer, and P.E. Geissler. 2007. *Glacier changes in southeast Alaska and northwest British Columbia and contribution to sea level rise.* Journal of Geophysical Research 112, doi:10.1029/2006JF000586.

Motyka, R.J. 2003. *Little Ice Age subsidence and post Little Ice Age uplift at Juneau, Alaska inferred from dendrochronology and geomorphology.* Quaternary Research 59(3):300-309.

Motyka, R.J., and J.E. Beget. 1996. *Taku Glacier, southeast Alaska, U.S.A.: Late Holocene history of a tidewater glacier.* Arctic and Alpine Research 28 (1):42-51.