Post Little Ice Age Rebound in the Glacier Bay Region

Roman J. Motyka[1,2], Christopher F. Larsen[1], Jeffrey T. Freymueller[1], and Keith A. Echelmeyer[1]

Abstract. Extreme uplift and sea level changes in southeast Alaska have been documented by (1) a regional GPS deformation array consisting of 74 sites; (2) 18 tide gage measurements of sea-level changes; and (3) 27 raised shoreline measurements of total uplift. The GPS data show peak uplift rates of 30 mm/yr in Glacier Bay, and also delineated a second center of rapid uplift east of Yakutat with peak rates of 32 mm/yr. These studies documented rapid and continuous total sea level changes of up to 5.7 m, and constrained the age of the ongoing uplift to less than 250 yrs. The raised shorelines show a pattern of higher uplift surrounding the region of peak GPS uplift rates in Glacier Bay, while the dating of these shorelines shows that they began uplifting at the same time the massive Glacier Bay Icefield began its retreat. This is a direct observation of glacial isostatic rebound processes acting on timescales of only a few hundred years in southern Alaska.

Introduction

Icefields and glaciers in the coastal mountains of southern Alaska and Canada have undergone rapid thinning over the last 250 years (Arendt and others, 2002) and the associated unloading of the Earth's surface has led to isostatic rebound of southern Alaska. In this study, we compared changes in sea level derived from tide gage observations and raised shoreline studies, and uplift rates derived from Global Positioning System (GPS) measurements to uplift predictions from viscoelastic rebound models. Here we present the results of our data acquisition. The raised shoreline data constrain both the timing and total magnitude of the ongoing uplift. The ultimate goal is to test various Earth models against all of the uplift observations (Larsen and others, 2004). The results provide robust constraints of lithospheric and asthenospheric structure, as well as the statistically significant conclusion that the regional uplift is primarily a consequence of isostatic rebound associated with post-Little Ice Age deglaciation of southern Alaska.

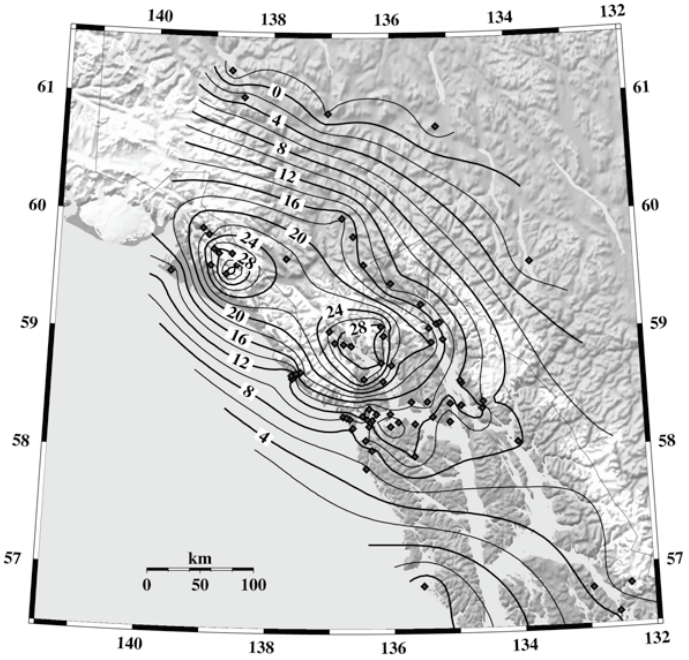

Figure 1. GPS uplift rates (mm/yr). GPS stations are shown as diamonds. Contour interval is 2 mm/yr. Peak uplift rates are in Glacier Bay (southern peak) and the Yakutat Icefield (northern peak).

Methods

Three methods were used in determining vertical crustal changes: GPS, tide gage data, and raised shoreline surveys.

With the exception of the two continuous stations at Whitehorse and Gustavus, all of the GPS data are from 72 campaign-style surveys (fig. 1), with each site typically having 2–4 occupations over 3–5 years. GPS measurements also provided data for horizontal vectors. Collection and analysis of these data is similar to methods described in Freymueller and others (2000). The GPS data were analyzed using the GIPSY software with simultaneous data from global International GPS Services (IGS) stations (e.g., Freymueller, and others, 2000). The daily free network solutions were transformed into the International Terrestrial Reference Frame, epoch 1997 (ITRF97). These daily solutions were used to estimate station velocities that were transformed into a North America fixed reference frame based on the REVEL model (Sella and others, 2004). The overall average 1σ uncertainties for velocities are: horizontal= ±0.8 mm/yr, vertical= ±2.1 mm/yr.

The tide gage data come from permanent NOS gages, NOS temporary gages and our own temporary gages (Larsen and others, 2004). We have augmented sea level rates measured at 4 permanent tide gages (Larsen and others, 2003) with temporary tide gage measurements at 18 sites throughout the northern part of southeast Alaska (fig. 2). Temporary tide

[1] Geophysical Institute, University of Alaska Fairbanks, 903 Koyukuk Dr, Fairbanks, Alaska 99775.

[2] Corresponding author: jfrjm@uas.alaska.edu 907-586-1994.

gages typically record sea-level over the course of one or more monthly tidal cycles, and the elevation of the gage is then surveyed relative to a local network of benchmarks. Mean sea level at the site is calculated and referenced to the benchmarks. When this procedure is repeated some years later, sea level change can then be determined relative to the benchmarks. The average overall uncertainty in this method is 1σ= ±5 mm/yr.

Raised shorelines were demarcated at 27 sites by: (1) a paleo-seacliff, (2) change in thickness of organic-rich soil, (3) termination of beach deposits, and (or) (4) an abrupt change in age of trees (fig. 3). The difference in elevation of the raised shoreline relative to current sea level provides the total amount of sea-level change while tree ages below the raised shoreline provide a minimum estimate of the onset of land emergence. Details of the methodology used in identifying and surveying the vertical positions of the paleo and modern shorelines are discussed in Motyka (2003) and Larsen and others (2004) as are the methods used for tree ring dating and estimating onset of land emergence. The average overall uncertainty in estimating change in shoreline position is 1σ= ±0.3 m.

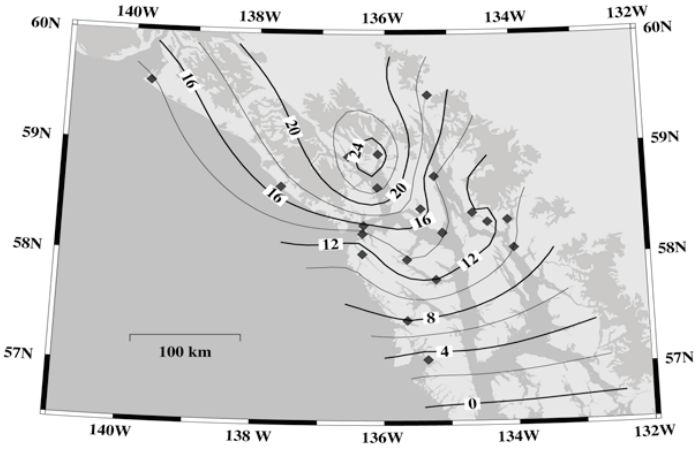

Figure 2. Average rate of sea level change (mm/yr) as determined from tide gage measurements.

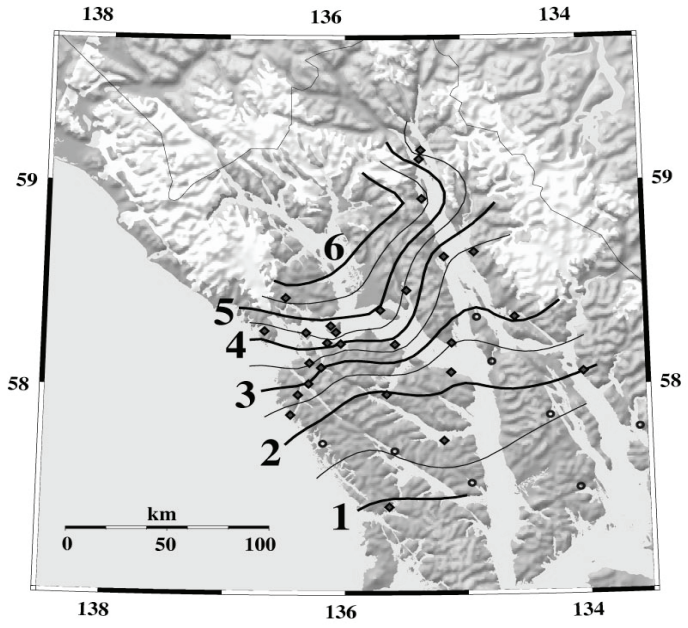

Figure 3. Total land emergence since 1770±20 AD from raised shoreline data. Contour interval is 0.5 m.

Results

The results of our data analyses are illustrated in figures 1, 2, and 3. The pattern of sea level changes at the tide gage sites indicates that the fastest sea level changes in southeast Alaska are in Glacier Bay (fig. 2). This finding is in general agreement with Hicks and Shofnos (1965), although we find peak sea level rates in upper Glacier Bay rather than at Bartlett Cove near the mouth of the bay. Overall, the newer sea level rates presented here are consistent with those determined earlier (Hicks and Shofnos, 1965) when the associated errors are considered (Larsen and others, 2004). We therefore conclude that both 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. This finding is in agreement with the linear sea level rates over the entire permanent gage records at Sitka, Juneau, and Skagway (Larsen and others, 2003). The pattern of sea level rates also agrees well with the pattern of uplift rates from GPS measurements in the Glacier Bay region (fig. 1).

GPS data, not being limited to the coastline, provide a much broader spatial description of the uplift pattern (fig. 1). The GPS data delineate two centers of uplift in southeast Alaska: the first over Glacier Bay (30 mm/yr), the second over the Yakutat Icefield (32 mm/yr) (fig. 1).

The total sea level change at the raised shoreline sites also describes a regional pattern surrounding Glacier Bay (fig. 3). Quite notably, the greatest sea level change occurs at the sites closest to the peak uplift and sea level rates. Total uplift is greatest in regions proximal to Glacier Bay (5.7 m) and declines away from Glacier Bay (fig. 3). Dates for 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 (LIA) maximums (Larsen and others, 2005).

Discussion and 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 gages. The uplift pattern documented here spans an area of over 10^5 km^2, centered on the coastal mountains along the Gulf of Alaska (figs. 1, 2, and 3). GPS studies of glacier rebound have importance for deciphering crustal and mantle properties (Larsen and others, 2004). Glacier rebound affects sea level measurements, and can lead to increased erosion and therefore additional isostatic effects. Furthermore, rebound can affect

fault stability, and release of overburden stress caused by melting mountain glaciers has increased rates of seismicity in tectonically active southern Alaska (Sauber and Molnia, 2004).

The data set depicts a regional pattern of sea level rates from 3 to 32 mm/yr, with peaks centered over upper Glacier Bay and Yakutat Icefield. Raised shorelines that date back to 1770±20 AD indicate total uplift change in the range of 1.0 to 5.7 m. The onset of uplift measured at the raised shoreline sites occurred at the same time the Glacier Bay Icefield began its dramatic collapse. These results provide robust constraints on lithospheric elastic thickness, asthenosphere thickness and asthenosphere viscosity (Larsen and others, 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.

The remarkably large amplitude and short timescale of this uplift is evidence that rapid changes of glacier systems and ice caps, triggered by climate, can excite a very large solid earth response, much larger than has been previously appreciated. Such flexure can impact regional faulting and seismic activity, and thus has implications for attempts to derive long-term kinematic models and orogenic histories from observations of current crustal movement.

Management Implications

The fastest rates of glacier rebound in the world currently are occurring in the Glacier Bay region. These adjustments to LIA loading and unloading are producing significant stresses on the earth's crust which can affect seismicity and regional tectonics. The rising land also is continually changing the 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 National Science Foundation Grant EAR-9870144. We wish to express our gratitude for logistical support provided by Glacier Bay National Park and to the many field assistants who have participated in this study.

References Cited

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

Freymueller , J.T., Cohen, S.C., and Fletcher, H.J., 2000, Spatial variations in present-day deformation, Kenai Peninsula, Alaska, and their implications: Journal of Geophysical Research, v. 105, p. 8079-8101.

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

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

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

Larsen, C.F., Motyka, R.J., Freymueller, J.T., Echelmeyer, K.A., and Ivins, E.R., 2005, Rapid viscoelastic uplift in southeast Alaska caused by post-Little Ice Age glacial retreat: Earth and Planetary Science Letters 23, p. 548-560.

Motyka, R.J., 2003, Little Ice Age subsidence and post Little Ice Age uplift at Juneau, Alaska—Inferred from dendrochronology and geomorphology: Quaternary Research, v. 59, p. 300-309.

Sauber, J.S., and Molnia, B.F., 2004, Glacial ice mass fluctuations and fault instability in tectonically active southern Alaska: Global and Planetary Change, v. 42, p. 279-293.

Sella, G.F., Stein, S., Wdowinski, S., Dixon, T.H., Craymer, M., and James, T., 2004, Direct constraints on GIA motion in North America using GPS [abs]: Eos Transactions of the American Geophysical Union, v. 85, no. 17, Joint Assembly Supplement, Abs. G33A-03.

Suggested Citation

Motyka, R.J., Larsen, C.F., Freymueller, J.T., and Echelmeyer, K.A., 2007, Post little ice age rebound in the Glacier Bay Region, *in* Piatt, J.F., and Gende, S.M., eds., Proceedings of the Fourth Glacier Bay Science Symposium, October 26–28, 2004: U.S. Geological Survey Scientific Investigations Report 2007-5047, p. 57-59.