JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 112, B04409, doi:10.1029/2006JB004606, 2007

Click Here for Full Article

Using global positioning system-derived crustal velocities to estimate rates of absolute sea level change from North American tide gauge records

Richard Snay,[1] Michael Cline,[1] William Dillinger,[1] Richard Foote,[1] Stephen Hilla,[1] William Kass,[1] Jim Ray,[1] Jim Rohde,[1] Giovanni Sella,[1] and Tomás Soler[1]

Received 30 June 2006; revised 19 November 2006; accepted 15 January 2007; published 25 April 2007.

[1] We identified 37 tide gauges; each located within 40 km of a geodetic station whose International Terrestrial Reference Frame of 2000 (ITRF2000) crustal velocity had been rigorously derived from continuous global positioning system (GPS) observations, spanning from 3 to 11 years. The tide gauges are located along the coasts of North America, Bermuda, Hawaii, and Kwajalein (in the Marshall Islands). We obtained the ITRF2000 crustal velocities by averaging values from six solutions; each produced by a team of investigators acting, essentially, independently of the other teams. We then applied crustal velocities to convert rates of relative sea level change to rates of absolute sea level change. In a sample containing 30 sites, we found that the mean rate of absolute sea level change equals 1.80 ± 0.18 mm/yr in the 1900–1999 period. The scatter about the mean for individual sites in this sample is characterized by a (weighted) RMS value of 0.85 mm/yr. This scatter primarily reflects the uncertainty associated with derived crustal velocities. The remaining seven sites, i.e., five sites on the Pacific coast of Alaska, one on Dauphin Island (Alabama), and one on Kwajalein (an atoll in the Pacific Ocean), experienced relatively low rates of absolute sea level change. We hypothesize the low rates in Alaska are caused by ongoing melting of mountain glaciers and ice masses near the stations, while the low rates found for Dauphin Island and Kwajalein remain unexplained.

Citation: Snay, R., M. Cline, W. Dillinger, R. Foote, S. Hilla, W. Kass, J. Ray, J. Rohde, G. Sella, and T. Soler (2007), Using global positioning system-derived crustal velocities to estimate rates of absolute sea level change from North American tide gauge records, *J. Geophys. Res.*, *112*, B04409, doi:10.1029/2006JB004606.

1. Introduction

[2] For explanation purposes, let $S(p)$ denote the rate of relative sea level change at a point p, as measured by a tide gauge (also called a water level station) that is sensitive to ocean levels. A positive value for $S(p)$ corresponds to the water level rising relative to the land at p. Furthermore, let $U(q)$ denote the vertical velocity at a point q, as expressed in the International Terrestrial Reference Frame of 2000 (ITRF2000) [*Altamimi et al.*, 2002]. This velocity is reckoned along a vector at q, which is normal to the Geodetic Reference System 1980 (GRS 80) geocentric ellipsoid [*Moritz*, 1980]. A positive velocity corresponds to motion away from the geocenter. Here each ITRF2000 vertical velocity has been determined, at a geodetic station, by using continuous global positioning system (GPS) observations. The quantity $S(p) + U(q)$ provides an estimate of the absolute sea level rate at p, denoted $A(p)$, when the distance between p and q is small. In this study, we shall consider sites where the distance between p and q is less than 40 km.

[3] Many authors have estimated the average value of $A(p)$ over the surface of the oceans, here denoted α. *Church et al.* [2004] provide a comprehensive summary of recent results. In particular, current estimates for α (based on tide gauge data) range from 1.5 to 2.0 mm/yr. For example, *Douglas* [1997] estimated α = 1.8 ± 0.1 mm/yr for the 1880–1980 period, based on $S(p)$ values from 24 globally distributed tide gauges and corresponding $U(p)$ values, predicted via a model for glacial isostatic adjustment (GIA) that incorporates the ICE-3G model for Late Pleistocene deglaciation [*Tushingham and Peltier*, 1991]. (Throughout this report, uncertainties represent one standard error, unless otherwise stated.) More recently, *Church and White* [2006] estimated α using $S(p)$ values from about 300 globally distributed tide gauges, with a model for sea level variation, derived from about 12 years (1993–2004) of satellite altimeter data. Similar to Douglas, Church and White applied GIA models to predict values for $U(p)$. In fact, they used three different GIA models, each yielding a slightly different value for α. Church and White concluded α = 1.7 ± 0.15 mm/yr for the 1900–2000 period, in close agreement with Douglas'.

[1]National Geodetic Survey, National Ocean Service, National Oceanic and Atmospheric Administration, Silver Spring, Maryland, USA.

This paper is not subject to U.S. copyright.
Published in 2007 by the American Geophysical Union.

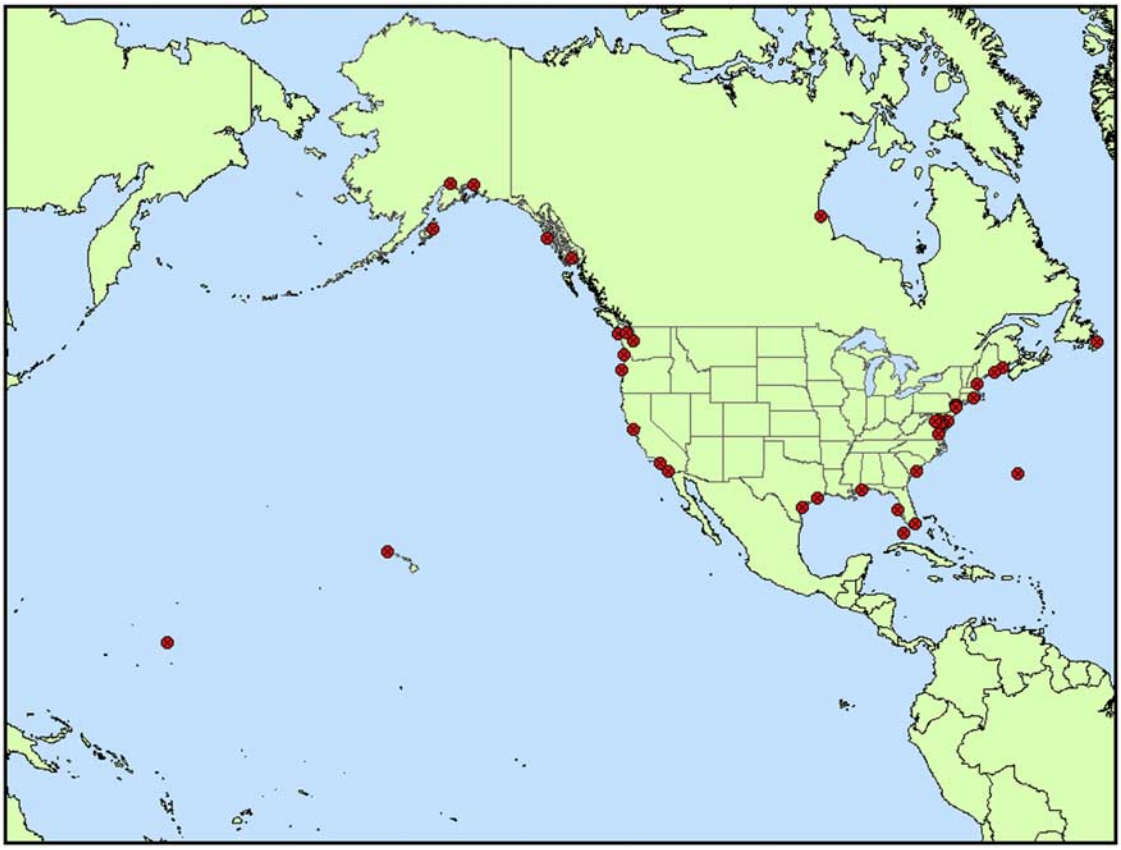

Figure 1. Tide gauges that are located within 40 km of a geodetic station whose ITRF2000 crustal velocity has been rigorously computed.

[4] In addition, *Church and White* [2006] found a significant acceleration of sea level rise of 0.013 ± 0.003 mm/yr^2 over the 1870–2004 time interval. This finding is supported by recent satellite altimeter data. In particular, *Leuliette et al.* [2004] applied satellite altimeter data (without any tide gauge data) to estimate that α = 2.8 ± 0.4 mm/yr for the 1993–2003 period. This latter estimate ignores the time dependence of the sea surface, due to GIA, but Leuliette et al. state that their estimate for α would increase by a few tenths of a millimeter per year if they were to correct it for GIA. A longer altimetry record is anxiously awaited to determine whether this relatively high rate for the 1993–2003 period will persist into the future or whether it reflects a temporary fluctuation in sea level rise.

[5] For our study, we bypass the need to use a GIA model by using relative sea level rates $S(p)$ from the 37 tide gauges, each located within 40 km of a geodetic station whose corresponding crustal velocity $U(q)$ has been derived from 3 to 11 years of GPS data. Hence we assume that these crustal velocities have remained constant over the multi-decadal time spans (30–144 years) of the sea level records (except for three sites in Alaska, as discussed later). Our study, moreover, is restricted to the coastline of North America and a few islands (see Figure 1 and Table 1). In addition, we shall discuss various error sources associated with our estimates of absolute sea level change.

[6] In this study, we will also search for spatial variations in absolute sea level rates. *Conrad and Hager* [1997], *Mitrovica et al.* [2001], and *Tamisiea et al.* [2001] have theorized that ongoing melting of glaciers and ice masses would cause absolute sea level rates to vary primarily as a function of the distance from these melting glaciers and ice masses. In addition, *Church et al.* [2004] have made the case for spatially varying absolute sea level rates based on results from satellite altimetry data. Indeed, for the tide gauges involved in this study, we find that absolute sea level rates at those located in southern Alaska differ significantly from such rates at those located elsewhere, with a couple of exceptions. Hence this study supports the case for spatial variability.

2. Tide Gauge Data

[7] The National Ocean Service (NOS), an agency of the United States' National Oceanic and Atmospheric Administration (NOAA), operates the U.S. National Water Level Observation Network (NWLON), which comprises a collection of tide gauges along the coasts of the United States, its territories, and a few foreign countries http://co-ops.nos.noaa.gov. In Canada, the Marine Environmental Data Service operates the Canadian tide gauge network http://www.meds-sdmm.dfo-mpo.gc.ca/meds/Home_e.htm. For this study, we selected 34 tide gauges from the U.S. network and 3 from the Canadian network, such that each is located within 40 km of a geodetic station whose ITRF2000 vertical velocity had been rigorously computed. These gauges do not include any located in the Great Lakes region because

Table 1. Tide Gauges and Associated Geodetic Stations

Tide Gauge	Latitude, deg N	Longitude, deg E	Relative Sea Level Rate (and Std. Error), mm/yr	Time Span for Tide Gauge Data	Geodetic Station ID	Distance From Gauge to Geodetic Station, km	ITRF2000 Vertical Velocity (and Std. Error), mm/yr	Time Span for GPS Data	Observed Absolute Sea Level Rate (and Std. Error), mm/yr	Discrepancy, $\varepsilon(p,q)$ from 1.80 mm/yr
St. John's, NF	47.567	307.283	2.18 (0.37)[a]	1959–1998	STJO	5.0	−0.27 (0.63)	1994–2005	1.91 (0.73)	0.11
Eastport, ME	44.903	293.015	2.12 (0.13)[b]	1929–1999	EPRT	0.8	−1.85 (1.00)	1998–2005	0.27 (1.01)	−1.53
Bar Harbor, ME	44.392	291.795	2.18 (0.16)[b]	1947–1999	BARH	1.4	0.28 (1.00)	1998–2005	2.46 (1.01)	0.66
Seavey Island, ME	43.080	289.258	1.75 (0.17)[b]	1926–1986	POR4	2.8	1.01 (1.16)	1999–2005	2.76 (1.17)	0.96
Newport, RI	41.505	288.673	2.57 (0.11)[b]	1930–1999	NPRI	0.5	−0.01 (1.16)	1999–2005	2.56 (1.17)	0.76
The Battery, NY	40.700	285.985	2.77 (0.05)[b]	1856–1999	NJI2	14.5	−1.35 (1.74)	2001–2005	1.42 (1.74)	−0.38
Sandy Hook, NJ	40.467	285.990	3.88 (0.15)[b]	1932–1999	SHK1	0.5	−2.20 (0.70)	1995–2005	1.68 (0.72)	−0.12
Lewes, DE	38.782	284.880	3.16 (0.16)[b]	1919–1999	CHL1	2.9	−1.12 (1.16)	1995–2001	2.04 (1.17)	0.24
Cambridge, MD	38.573	283.932	3.52 (0.24)[b]	1943–1999	HNPT	5.7	0.24 (1.16)	1999–2005	3.76 (1.18)	1.96
Annapolis, MD	38.983	283.520	3.53 (0.13)[b]	1928–1999	ANP1	11.6	−3.05 (1.74)	2001–2005	0.48 (1.74)	−1.32
Solomon Is., MD	38.371	283.547	3.29 (0.17)[b]	1937–1999	SOL1	0.2	−2.19 (1.16)	1999–2005	1.10 (1.17)	−0.70
Washington, DC	38.873	282.978	3.13 (0.21)[b]	1931–1999	USNO	6.4	−1.72 (1.39)	2000–2005	1.41 (1.41)	−0.39
Gloucester Pt., VA	37.247	283.500	3.95 (0.27)[b]	1950–1999	GLPT	0.2	−2.58 (1.16)	1999–2005	1.37 (1.19)	−0.43
Charleston, SC	32.782	280.075	3.28 (0.14)[b]	1921–1999	CHA1	8.2	−1.55 (0.87)	1995–2003	1.73 (0.88)	−0.07
Miami Beach, FL	25.768	279.868	2.39 (0.22)[b]	1931–1981	MIA3	4.8	0.21 (1.00)	1998–2005	2.60 (1.02)	0.80
Key West, FL	24.553	278.192	2.27 (0.09)[b]	1913–1999	KYW1	16.0	−0.05 (0.78)	1996–2005	2.22 (0.79)	0.42
St. Petersburg, FL	27.760	277.373	2.40 (0.18)[b]	1947–1999	MCD1	13.6	−1.16 (1.74)	2001–2005	1.24 (1.75)	−0.56
Dauphin Is., AL	30.250	271.925	2.93 (0.59)[b]	1966–1997	MOB1	5.5	−4.19 (0.78)	1996–2005	−1.26 (0.98)	−3.06
Galveston Pier 21, TX	29.313	265.207	6.50 (0.16)[b]	1908–1999	GAL1	5.8	−5.01 (0.87)	1995–2003	1.49 (0.88)	−0.31
Rockport, TX	28.022	262.953	4.60 (0.41)[b]	1948–1999	ARP3	20.4	−1.09 (0.70)	1995–2005	3.51 (0.81)	1.70
San Diego, CA	32.713	242.827	2.15 (0.12)[b]	1906–1999	PLO3	8.4	0.34 (0.78)	1996–2005	2.49 (0.79)	0.69
Los Angeles, CA	33.720	241.728	0.84 (0.16)[b]	1923–1999	TORP	10.2	0.73 (1.00)	1998–2005	1.57 (1.01)	−0.23
San Francisco, CA	37.807	237.535	2.13 (0.14)[b]	1906–1999	PBL1	6.5	−0.83 (0.70)	1995–2005	1.30 (0.71)	−0.50
South Beach, OR	44.625	235.957	3.51 (0.73)[b]	1967–1999	NEWP	4.7	−0.32 (1.00)	1998–2005	3.19 (1.24)	1.39
Astoria, OR	46.208	236.233	−0.16 (0.24)[b]	1925–1999	FTS1	14.6	1.97 (0.78)	1996–2005	1.81 (0.82)	0.01
Neah Bay, WA	48.368	235.383	−1.41 (0.22)[b]	1934–1999	NEAH	7.8	3.27 (1.00)	1998–2005	1.86 (1.02)	0.06
Seattle, WA	47.605	237.662	2.11 (0.10)[b]	1898–1999	SEAT	5.9	−0.68 (1.00)	1998–2005	1.43 (1.00)	−0.37
Victoria, BC	48.417	236.633	0.76 (0.15)[a]	1910–1999	ALBH	12.0	−0.15 (0.63)	1994–2005	0.61 (0.65)	−1.19
Ketchikan, AK	55.333	228.375	−0.11 (0.16)[b]	1919–2001	AIS1	29.5	−1.16 (0.78)	1996–2005	−1.27 (0.80)	−3.07
Sitka, AK	57.052	224.658	−2.17 (0.21)[b]	1938–2001	BIS1	25.1	0.23 (1.39)	2000–2005	−1.94 (1.41)	−3.74
Valdez, AK	61.125	213.638	−6.10 (1.4)[c]	1985–2004	POT3	19.6	4.82 (1.00)	1998–2005	−1.28 (1.72)	−3.08
Anchorage, AK	61.238	210.112	−1.70 (1.4)[c]	1985–2004	TSEA	5.7	2.56 (1.16)	1999–2005	0.86 (1.82)	−0.94
Kodiak Is., AK	57.732	207.488	−9.30 (1.2)[c]	1985–2004	KODK	0.7	7.83 (1.74)	2000–2004	−1.47 (2.11)	−3.27
Nawiliwili, HI	21.957	200.640	1.53 (0.38)[b]	1954–1999	KOKB	36.6	1.32 (0.63)	1994–2005	2.85 (0.76)	1.05
Kwajalein, Marshall Is.	8.730	167.732	1.05 (0.51)[b]	1946–1999	KWJ1	4.9	−2.06 (1.16)	1996–2002	−1.01 (1.27)	−2.81
Churchill, MB	58.767	265.817	−9.46 (0.75)[a]	1940–1994	CHUR	6.0	10.02 (0.70)	1995–2005	0.56 (1.03)	−1.24
Bermuda	32.373	295.297	1.83 (0.30)[b]	1932–1999	BRMU	0.7	−0.86 (0.63)	1994–2005	0.97 (0.70)	−0.83

[a]PSMSL
[b]*Zervas* [2001].
[c]C. Zervas (personal communication, 2005).

this study is restricted to only those gauges that are sensitive to ocean levels.

[8] We used rates of relative sea level change for the three Canadian gauges, provided by the Permanent Service for Mean Sea Level (PSMSL) http://www.pol.ac.uk/psmsl/datainfo/rlr.trends. We used rates of relative sea level change (computed earlier by NOS) for 31 of the U.S. sites, with their derived standard errors [*Zervas*, 2001]. The NOS computations are based on tide gauge data observed prior to the end of 1999. We used relative rates of sea level change, computed by Chris Zervas of NOS (personal communication, May 2005) for the remaining U.S. tide gauges. These three sites (Anchorage, Kodiak, and Valdez) are all located in Alaska, near the rupture zone of the magnitude 9.2 Prince William Sound earthquake of 1964. The relative sea level rate at these three sites has varied significantly during the initial decades following this earthquake, as documented by *Larsen et al.* [2003]. Because of this variation, Zervas used the tide gauge data for only the 1985–2004 period to compute a relative sea level rate for each of the three sites; the standard errors for their relative sea level rates are relatively high ($\geq$ 1.2 mm/yr) because of the short time span (20 years) of the tide gauge data. For the first 34 sites, our study used only the tide gauge data that have not been (to the best of our knowledge) significantly affected by earthquakes. In particular, our study used only that tide gauge data observed after the 1906 San Francisco earthquake along the northern California coast. For all 37 tide gauges, the sea level rates given in Table 1 were derived from monthly sea level means.

[9] *Douglas* [1991, 1995] has clearly demonstrated that only tidal records spanning more than 50 years are capable of delivering stable estimates of relative sea level rates, because of the strong interdecadal variability that tidal records contain. In this study, we have included several sites (for completeness), even though their tide gauge data span less than 50 years. In addition, to the three previously mentioned Alaskan sites, we included St. John's, Newfoundland (1959–1998), Dauphin Island, Alabama (1966–1999), South Beach, Oregon (1967–1999), and Nawiliwili, Hawaii (1954–1999). Relative sea level rates for these seven sites should be viewed with extra caution.

3. Geodetic Data

[10] The National Ocean Service manages the U.S. National Continuously Operating Reference Station (CORS) network http://www.ngs.noaa.gov/CORS/. Each CORS includes a ground-based sensor that continuously records signals from GPS satellites. The National CORS network spans the United States, its territories, and a few foreign countries. We analyzed GPS data for 550 CORS, with about 140 other globally distributed GPS base stations that are continuously operated. These global stations are managed under the auspices of the International Global Navigation Satellite System (GNSS) Service (IGS) http://igscb.jpl.nasa.gov. As part of this analysis, we estimated ITRF2000 vertical velocities for these 550 CORS and for the $\sim$ 140 IGS stations. Similarly, five other teams of investigators estimated ITRF2000 vertical velocities for collections of CORS and IGS stations. All six solutions are, essentially, independent of each other. Details about these six solutions are given in Appendix.

[11] Among all of the geodetic stations contained in the combination of the six solutions, we identified 37 located within 40 km of one of the previously mentioned tide gauges. Also, each of these 37 geodetic stations is contained in at least three of the six independent solutions. Table 1 presents the distance between each of these 37 geodetic stations and its corresponding tide gauge. Table 1 also contains an estimated ITRF2000 vertical velocity for each of the 37 geodetic stations. The tabulated velocity for each geodetic station represents the (unweighted) mean of corresponding velocities from three or more of the six solutions. The following paragraphs explain how we assigned a standard error σ_U to each vertical velocity appearing in Table 1.

[12] It has been recognized that the measurement noise associated with GPS observations is time-correlated. Possible sources of this correlation include monument motion (unrelated to the larger tectonic and/or GIA-induced motion that is of interest) [*Langbein and Johnson*, 1997], uncertainty in the satellite orbital parameters, and atmospheric and local environmental effects [*Mao et al.*, 1999]. As a result, the standard error of a GPS-derived velocity will be greatly underestimated unless these correlations are considered. Hence to assign a standard error σ_U to the computed ITRF2000 vertical velocity of a geodetic station, we applied the equation

$$\sigma_U = \left[\left(12\sigma_w^2/gT^3\right) + \left(\gamma\sigma_f^2/g^\beta T^2\right)\right]^{0.5} \quad (1)$$

as proposed by *Mao et al.* [1999]. Here g denotes the average number of days of GPS data used each year (g = 365 days per year in this study), T is the total time span of the GPS observations in years (3–11 years in this study), γ and β are empirical constants (γ = 1.78 and β = 0.22) determined by Mao et al., and σ_w and σ_f are the "white" and "flicker" noise magnitudes, respectively. White noise refers to that noise which is not time correlated. Flicker noise is but one type of time-correlated noise. Both Mao et al. and *Williams et al.* [2004] have shown that the time-correlated noise for GPS observations is adequately described by flicker noise.

[13] *Williams et al.* [2004] studied seven different regional solutions for time series, for daily positions derived from GPS data. Each solution involved numerous stations. For each solution, Williams et al. estimated the weighted mean of σ_w, as well as the weighted mean of σ_f for every station. For the seven solutions, these weighted means for σ_w range from 2.2 to 4.6 mm, and the weighted means for σ_f range from 4.9 to 11.0 mm/yr$^{1/4}$. On the basis of these results, we adopted a nominal value of 4.0 mm for σ_w and a nominal value of 10.0 mm/yr$^{1/4}$ for σ_f for each station in our GPS solution. Figure 2 displays how our resulting values of σ_U vary as a function of T.

4. Analysis

[14] We partitioned the 37 sites into four groups for our analysis of the data: (1) the "Atlantic" group which contains 15 sites located along the Atlantic coast of North

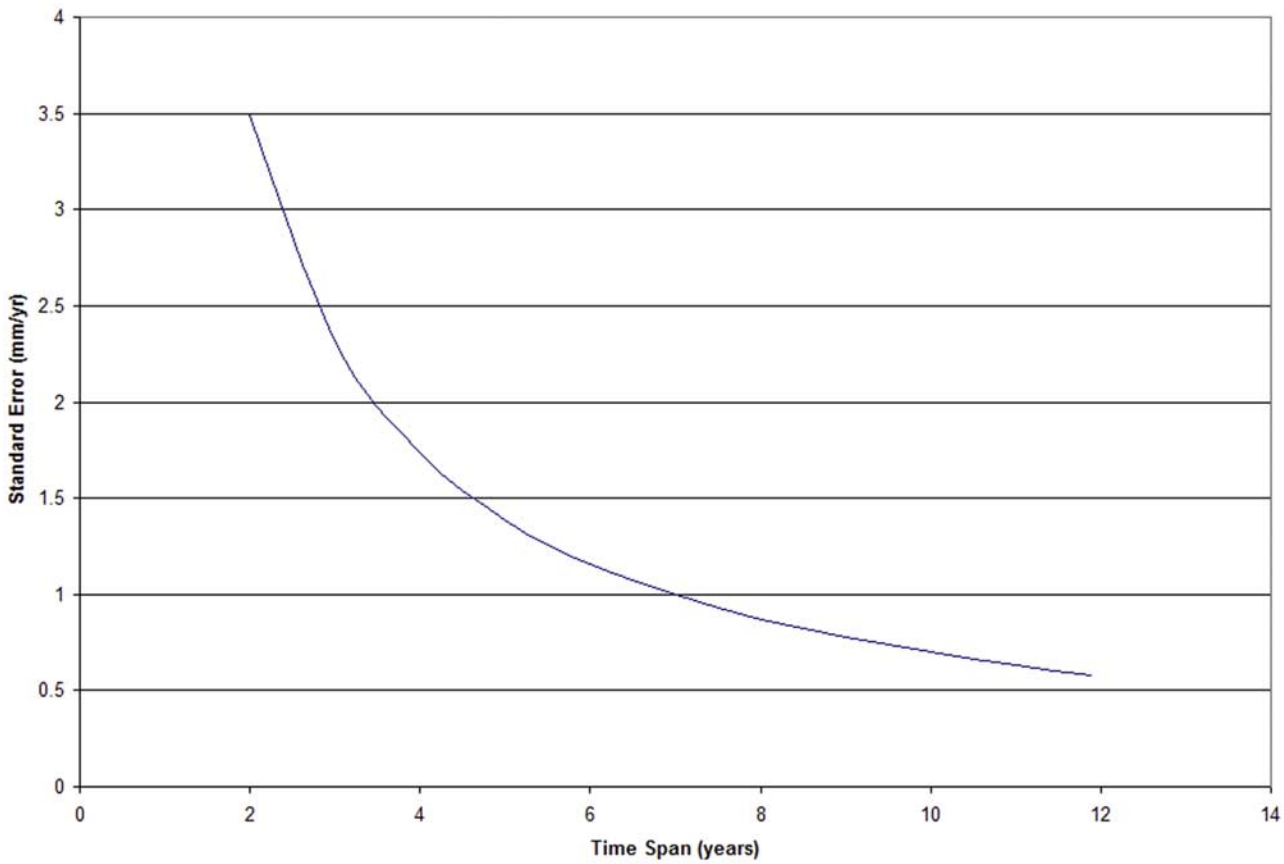

Figure 2. Predicted standard errors for GPS-derived vertical velocities σ_U as a function of the time span of the GPS data.

America, from St. John's, NF to Miami, FL; (2) the "Gulf" group which contains 5 sites located along the U.S. coast that borders the Gulf of Mexico, from Key West, FL to Rockport, TX; (3) the "Pacific" group which contains 13 sites located along the Pacific coast of North America, from San Diego, CA to Kodiak Island, AK; and (4) the "Other" group which contains 4 widely dispersed sites (Hawaii, Marshall Islands, Manitoba, and Bermuda). We then plotted $A(p)$ as a function of the latitude of p, as is shown in Figure 3.

[15] Figure 3 reveals that absolute sea level rates $A(p)$ are positive at all but 6 of the 37 sites: four in Alaska, one on Dauphin Island (in Alabama), and one on Kwajalein (in the Marshall Islands).

[16] At each of the six sites, $A(p)$ is between -2.0 and -1.0 mm/yr. *Conrad and Hager* [1997], *Mitrovica et al.* [2001], and *Tamisiea et al.* [2001] have provided a geophysical rationale for $A(p)$ being relatively low in southern Alaska. Namely, ongoing melting of mountain glaciers and ice masses in and around southern Alaska act to reduce the gravitational attraction near southern Alaska. Therefore sea and glacial waters tend to flow away from this region and accumulate at more distant locations. Consequently, $A(p)$ will be relatively lower in the vicinity of southern Alaska; and this near-field low will be compensated by a broad far-field region, where $A(p)$ will be larger than average.

[17] Using airborne laser altimetry, *Arendt et al.* [2002] measured volume changes for 28 Alaska glaciers from the mid-1990s to 2000–2001. Extrapolating their results, they estimate that the collection of all Alaska glaciers lost water at a rate of 96 ± 35 km^3/yr during this time period. We hypothesize that this wastage of the Alaska glaciers is causing absolute sea level to fall along the southern coast of Alaska, as is indicated by the Alaskan tide gauge data. Nevertheless, this wastage would cause absolute sea level to rise on average over the global ocean surface. According to Arendt et al., the average global rise due to the wastage of Alaska glaciers would equal 0.27 ± 0.10 mm/yr.

[18] Using a completely different data set, *Tamisiea et al.* [2005] obtained estimates similar to those of *Arendt et al.* [2002] for the wastage of Alaskan glaciers. In particular, Tamisiea et al. used space-based gravity data from the Gravity Recovery and Climate Experiment (GRACE) to estimate that Alaskan glaciers lost water at a rate of 110 ± 30 km^3/yr during the 2002–2004 period. This wastage rate would raise absolute sea level at a rate of 0.31 ± 0.09 mm/yr, on average, around the world.

[19] It should be noted that our study includes a total of five Alaskan sites, where $A(p)$ equals 0.86 ± 1.82 mm/yr for the Anchorage site and where $A(p)$ is less than -1.2 mm/yr for the other four Alaskan sites. Thus, $A(p)$ is relatively low at Anchorage, as compared to most of the 37 sites in our study, but it is not nearly as low as the values for $A(p)$ found for the other four Alaskan sites.

[20] While ongoing melting of mountain glaciers and ice masses provides a plausible explanation for the low $A(p)$ values found for the Alaskan sites, we know of no clear explanation for the extremely low $A(p)$ values found at

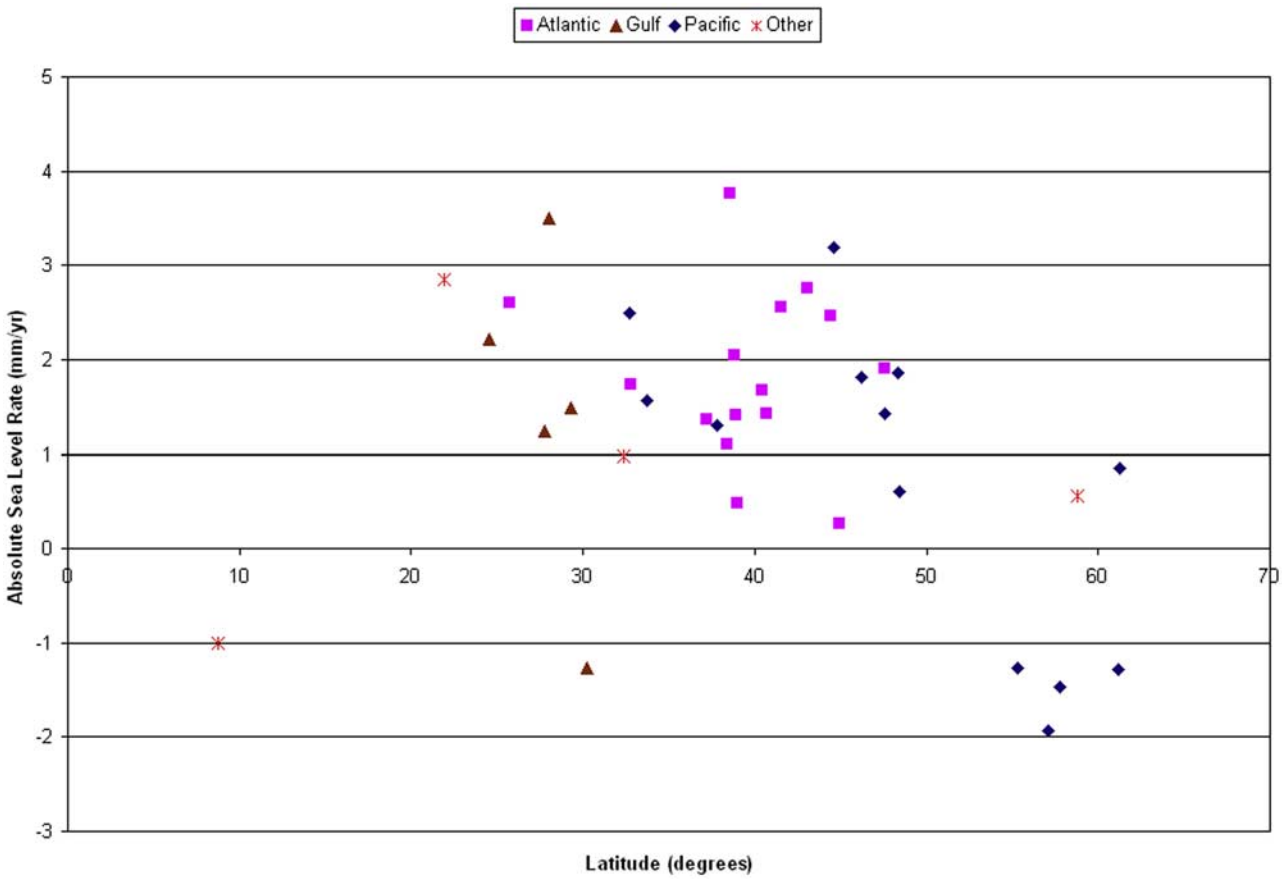

Figure 3. Absolute sea level rates $A(p)$ as a function of latitude for all 37 sites in this study.

Dauphin Island and Kwajalein. It is noted that the geodetic station (MOB1) is located relatively close (5.5 km) to the tide station at Dauphin Island, but it is located on a separate outer bank island across the ship channel. There may be differential rates of land movement on the "outer bank" islands. In addition, the relative sea level rate is computed using only 32 years of tide gauge data, resulting in a 0.59 mm/yr standard error. At Kwajalein, the geodetic station (KWJ1) is also located relatively close (4.9 km) to the tide station; however, the tidal time series is dominated by a strong periodic El-Niño-Southern-Oscillation signal that affects the calculation of the relative sea level rate, depending on the start and end times. Also, the tidal time series at Kwajalein yields a relatively high-standard error (0.51 mm/yr) for the associated relative sea level rate. As a result, we will exclude these two, and the five Alaskan sites, from consideration in estimating a mean rate of absolute sea level change. That is, we will estimate this mean rate using only the remaining 30 sites in this study.

5. Estimated Sea Level Rates

[21] Let β denote the mean absolute sea level rate for a sample of sites. To estimate β, consider the equation

$$S(p) + U(q) = \beta + \varepsilon(p, q) \tag{2}$$

where $\varepsilon(p,q)$ is the discrepancy between $S(p) + U(q)$ and the value of β. For each site, we considered the quantity $S(p) + U(q)$ as an observation with weight $w(p,q)$ defined by the equation

$$w(p, q) = 1/\left(\sigma_S^2 + \sigma_U^2\right) \tag{3}$$

where σ_S denotes the standard error of $S(p)$ (as given in Table 1) and σ_U denotes the standard error of $U(q)$ (as obtained from equation (1)). An estimate of β may be obtained by minimizing

$$Q = \sum w(p, q) \bullet \varepsilon(p, q)^2 \tag{4}$$

where the summation is taken over the sites in the sample being considered. This procedure yields $\beta = 1.80 \pm 0.18$ mm/yr for the 30-site sample obtained by excluding the five Alaskan sites, and the Dauphin Island and Kwajalein sites.

[22] Under the assumption that the discrepancies $\varepsilon(p,q)$ have a Gaussian distribution and the weights $w(p,q)$ are appropriate, the quantity Q/v with $v = 29 = (30 - 1)$ has a chi-square-over-degrees-of-freedom distribution with 29 degrees of freedom and an expected value of 1.00; our solution yielded a value of 0.81 for Q/v. This value does not differ statistically from 1.00 at the 95% confidence level. Nevertheless, the fact that it is less than 1.00 suggests that the assigned weights $w(p,q)$ may be too small, or equivalently, the values of σ_S and/or σ_U may be too large.

Table 2. Scatter Among Absolute Sea Level Rates for Various Samples

Range for Distance Between Tide Gauge and Associated Geodetic Station, km	Geodetic Stations in Sample	WRMS(ε) for Sample, mm/yr	95% Confidence Interval for WRMS(ε), mm/yr
0–5	BARH, BRMU, CHL1, EPRT, GLPT, MIA3, NEWP, NPRI, POR4, SHK1, SOL1, STJO	0.84	0.53–1.15
5–10	CHA1, CHUR, GAL1, HNPT, NEAH, PBL1, PLO3, SEAT, USNO	0.70	0.38–1.02
10–40	ALBH, ANP1, ARP3, FTS1, KOKB, KYW1, MCD1, NJI2, TORP	0.98	0.53–1.42
0–40	All 30 of the above sites	0.85	0.63–1.07

[23] When we applied this procedure to the 15 Atlantic sites, only, we obtained β = 1.89 ± 0.29 mm/yr. This estimate is slightly higher than that obtained by *Davis and Mitrovica* [1996]. These researchers used a GIA model to convert relative sea level rates into absolute sea level rates at several tide gauges located on the Atlantic Coast of North America. Their absolute rates vary with latitude: 1.45 ± 0.16 mm/yr for sites with latitudes between 23° and 35°, 1.71 ± 0.13 mm/yr for sites with latitudes between 35° and 40°, and 1.56 ± 0.15 mm/yr for sites with latitudes between 40° and 45°. The large uncertainty associated with our estimate of β for the Atlantic sites (0.29 mm/yr at the 1-sigma level) precludes us from distinguishing our estimated rate from those of Davis and Mitrovica at the 95% confidence level. Moreover, our uncertainty precludes us from evaluating the GIA model used in their study. However, both *Calais et al.* [2006] and *Sella et al.* [2006] have evaluated current GIA models by applying GPS data to compute ITRF2000 velocities for hundreds of geodetic stations in North America.

[24] Also, when we applied this procedure to the eight Pacific sites located outside of Alaska, we obtained β = 1.59 ± 0.30 mm/yr. Thus, we concluded that the mean sea level rate estimated for the Atlantic coast of North America is statistically the same, at the 95% confidence level, as that estimated for the (non-Alaskan) Pacific coast of North America, and these mean rates are statistically the same as that estimated for the set of all 30 sites considered in this analysis.

[25] When we applied this procedure to the five sites located in southern Alaska, we obtained β = −1.18 ± 0.59 mm/yr. Thus, we conclude that the mean absolute sea level rate estimated for southern Alaska differs statistically, at the 95% confidence level, from that for the set of 30 sites considered in our analysis.

6. Discussion

[26] Results from the past decade of satellite altimeter data indicate that absolute sea level rates vary as a function of time [*Leuliette et al.*, 2004]. Hence it is important to specify the time period for our estimated sea level rates. We have chosen to ascribe the 1900–1999 period to our estimate of β because this study includes pre-1900 data for only two tide gauges (The Battery, NY and Seattle, WA) and post-1999 data for only three tide gauges (Valdez, Anchorage, and Kodiak; all in AK). The 1900–1999 period includes more than 95% of the tide gauge data used in this study. Unfortunately, the data for most of our 37 tide gauges span only a fraction of the 1900–1999 period. As previously mentioned, we assume the crustal velocity at each geodetic station has remained constant over the period spanned by the data at its corresponding tide gauge, except in the vicinity of the 1964 Alaskan earthquake.

[27] The quantity $\varepsilon(p,q)$ appearing in equation (2) can be considered as a measure of error. Table 1 lists values for $\varepsilon(p,q)$ for the estimation process involving our selected 30 sites.

[28] Five error sources contribute to the values of $\varepsilon(p,q)$:

[29] (1) errors in the GPS-derived vertical velocities,

[30] (2) errors in the relative sea level rates derived from tide gauge data,

[31] (3) errors due to the tide gauges and the geodetic stations being situated at different locations,

[32] (4) errors associated with the approximation that all sites, in a particular sample, experience the same rate of absolute sea level change, and

[33] (5) errors associated with the approximation that ITRF2000 vertical velocities derived from a few years of continuous GPS observations have remained constant over the decades spanned by the tide gauge data.

[34] Consider the first four error sources:

[35] "Error in the GPS-derived vertical velocities" currently constitutes the dominant error source, based on our adopted GPS-error model. In most cases, σ_U is several times larger than σ_S (Table 1) because the time span of the GPS observations is relatively short as compared to the time span of the tide gauge observations. Fortunately, σ_U will decrease significantly over the next few decades as the GPS time span increases (Figure 2).

[36] "Errors associated with the relative sea level rates, derived from the tide gauge data" are generally much smaller than errors in the ITRF2000 vertical velocities. Error analyses of sea level rates from tide gauge data are discussed by *Zervas* [2001] and are highly dependent upon time series length.

[37] To quantify "errors associated with tide gauges and their associated geodetic stations being situated at different locations," we subdivided our sample of 30 sites into three bins, based on the distance between a tide gauge and its associated geodetic station. Then for each bin, we computed

$$\mathrm{WRMS}(\varepsilon) = \left\{ \left[\sum w(p,q) \bullet \varepsilon(p,q)^2 \right] / \left[\sum w(p,q) \right] \right\}^{0.5} \quad (5)$$

where each summation is taken over all sites where the distance between the tide gauge and its associated geodetic station is within the range of the specified bin. Our results (Table 2) indicate that these WRMS(ε) values do not differ significantly from one bin to another. For the

group composed of all 30 sites, we found WRMS(ε) = 0.85 mm/yr. This value is about the same as a typical value of σ_U for our geodetic stations. Hence until a longer GPS time span exists, we cannot effectively determine the magnitude of this type of error.

[38] Furthermore, this type of error may vary from one geographic region to another. In particular, where vertical crustal velocities vary significantly as a function of location, it would be critical to minimize the distance between a tide gauge and its associated geodetic station, as compared to a region where vertical crustal velocities vary little as a function of location. Hence near the glacier fields of southern Alaska, it is critical to minimize the distance between a tide gauge and its associated geodetic station because ongoing melting of the glaciers is causing large spatial variations in vertical crustal velocities [*Sauber et al.*, 2000 and *Larsen et al.*, 2003].

[39] It should be noted that, to the best of our knowledge, there has not been any attempt to directly measure the height changes of the 37 tide gauges relative to the height changes of the geodetic stations, for example, by repeated leveling observations. The National Ocean Service, however, has directly measured the height changes of its tide gauges relative to the height changes of several associated bench marks by using leveling observations. These leveling observations have been usually repeated on an annual basis. Unfortunately, the ITRF2000 vertical velocities of these bench marks are generally unknown.

[40] The fourth error source relates to the "approximation that all sites experience the same rate of absolute sea level change." Our Alaska results clearly reveal that this is not the case: the mean absolute sea level rate estimated for the five Alaskan sites (-1.18 ± 0.59 mm/yr) differs statistically, at the 95% confidence level, from the mean absolute sea level rate estimated for our 30 non-Alaskan sites (1.80 ± 0.18 mm/yr). We feel that other spatial variations in absolute sea level rates surely exist, although our data are insufficiently accurate to detect such variations. On the basis of the results from satellite altimetry data, *Church et al.* [2004] have made the case for spatial variation among absolute sea level rates. Detection of such spatial variations with tide gauge data will require the geodetic community to obtain more accurate crustal velocities than what currently exists.

7. Closing Comments

[41] We found that absolute sea level rates around North America have a mean value of 1.80 ± 0.18 mm/yr for the 1900–1999 period if we exclude the Alaskan, Dauphin Island and Kwajalein data. This rate is similar to the globally averaged rate derived by other investigators [*Douglas*, 1997; *Church and White*, 2006] for comparable periods. We also found that absolute sea level rates in Alaska are systematically lower than the globally averaged rate for the 1900–1999 period. We hypothesize that the low Alaskan rates are caused by ongoing melting of mountain glaciers and ice masses, in and around southern Alaska. Similarly, *Tamisiea et al.* [2001] have suggested that the anomalously low sea level rates observed in Europe may be due to ongoing melting of the Greenland ice sheet. We also note that the National CORS network is currently growing at a rate of more than 150 new stations per year. This network should soon include several more stations that are located close to existing tide gauges. In addition, NOS is making concerted efforts in field operations to make routine direct leveling connections between tidal bench marks and CORS reference bench marks (those located within a few kilometers of each other).

Appendix A

[42] We considered six separate solutions for estimating ITRF2000 velocities for geodetic stations. Each solution was conducted, essentially, independently of the others. The solutions included: (1) the NGS solution performed by the authors of this report as representatives of NOS' National Geodetic Survey (NGS); (2) the Miami solution performed at the University of Miami, FL; (3) the SOPAC solution performed at Scripps Orbit and Permanent Array Center (SOPAC) of the University of California, San Diego, CA; (4) the JPL solution performed at NASA's Jet Propulsion Laboratory (JPL), Pasadena, CA; (5) the CWU solution performed by researchers participating in the Pacific Northwest Geodetic Array (PANGA) program at Central Washington University (CWU) in Ellensburg, WA; and (6) the Purdue-Wisconsin solution performed collaboratively at Purdue University in Lafayette, IN and at the University of Wisconsin in Madison, WI. In the following paragraphs, we present pertinent information about each of these six solutions. We provide relatively more information about the NGS solution because, unlike the other solutions, the NGS solution has yet to be documented in the scientific literature.

A1. NGS Solution

[43] We analyzed GPS data for 550 CORS and about 140 IGS stations for a time period starting at the beginning of 1994 until the end of 2003. For efficiency, we employed only every third day of data. Each day, we processed the GPS data using the Program for the Adjustment of GPS Ephemerides (PAGES) software <http://www.ngs.noaa.gov/GRD/GPS/DOC/pages/pages.html> for each of several interlocking subnetworks, including (1) a subnetwork composed of the global IGS stations, (2) numerous other subnetworks each containing a cluster of about 20 CORS located within a relatively small geographic region, and (3) a "backbone" subnetwork containing about 30 GPS stations to interconnect the other subnetworks. For processing, we held fixed the "final precise" GPS orbits disseminated by the IGS <http://igscb.jpl.nasa.gov>, and we did not attempt to resolve integer ambiguities associated with the GPS data. Also, we did not attempt to remove spatial correlations among the daily positional coordinates associated with our geodetic stations. We rigorously combined the individual daily solutions at the normal equation level using the GPSCOM software <http://www.ngs.noaa.gov/GRD/GPS/DOC/gpscom/gpscom.html> that applies the Helmert blocking technique [*Helmert*, 1880]. As a result, each daily solution corresponds almost exactly to the solution that would have been obtained had we processed the daily data for all subnetworks simultaneously with PAGES. (Our Helmert blocking solution is not exactly the same as a simultaneous PAGES solution because we ignored mathematical correlations among certain estimated parameters for the purpose of efficiency.) We then integrated the daily

Table A1. ITRF2000 Vertical Velocities, mm/yr

Geodetic Station	Mean	NGS	Miami	SOPAC	JPL	CWU	Purdue-Wisconsin
STJO	−0.27	−1.70	−0.30	0.20	1.00		−0.55
EPRT	−1.85	−1.90	−2.80		−2.08	−1.20	−1.27
BARH	0.28	0.20	−0.60		0.82	0.20	0.78
POR4	1.01	0.10	−0.90		2.15	2.70	
NPRI	−0.01	0.30	−1.10			−0.30	1.07
NJI2	−1.35	−1.30	−1.70				−1.05
SHK1	−2.20	−1.80	−1.30		−2.68	−1.90	−3.31
CHL1	−1.12	−1.00	−1.40		0.64	−1.20	−2.66
HNPT	0.24	−0.50	0.50		−1.02		2.00
ANP1	−3.05	−2.90	−3.10				−3.16
SOL1	−2.19	−0.80	−2.40		−1.72	−4.30	−1.71
USNO	−1.72	−0.60	−2.40	−1.10	−1.26	−2.60	−2.36
GLPT	−2.58	−1.70	−3.50		−1.69	−3.10	−2.92
CHA1	−1.55	−1.00	−1.10		−2.37	−0.80	−2.46
MIA3	0.21	−0.30	−1.10	0.70	1.46	0.20	0.32
KYW1	−0.05	0.10	−1.00		0.89	−0.20	
MCD1	−1.16	−2.80	−0.10				−0.57
MOB1	−4.19	−4.30	−3.40		−3.96	−4.80	−4.49
GAL1	−5.01	−5.00	−4.30		−5.82	−6.00	−3.95
ARP3	−1.09	−1.80	−1.30		1.01	−2.10	−1.28
PLO3	0.34	−1.20	0.90	−1.90	2.59	1.30	
TORP	0.73	−0.50	1.50	−0.50	2.41		
PBL1	−0.83	−0.90	−1.10	−1.30	−0.03		
NEWP	−0.32	−1.20	0.50	0.70	−1.27		
FTS1	1.97	0.90	1.60	3.40			
NEAH	3.27	1.90	2.80	4.00	4.23	3.40	
SEAT	−0.68	−2.90	−1.10	−0.30	0.40	0.50	
ALBH	−0.15	−1.20	−0.80	0.40	0.45	1.40	−1.15
AIS1	−1.16	−2.40	0.20	−3.00	1.52	−2.10	
BIS1	0.23	−2.60	3.50			−0.20	
POT3	4.82	4.10	6.00		3.17	6.00	
TSEA	2.56	2.20	4.20	4.70	1.39	0.30	
KODK	7.83	6.80	7.80	9.10	7.62		
KOKB	1.32	1.00	0.80	2.30	1.81	0.70	
KWJ1	−2.06	−1.20	−0.70	−3.50	−2.82		
CHUR	10.02	8.30	10.70	9.10	9.86	11.40	10.79
BRMU	−0.86	0.10	−1.10	−1.20	−1.14	−1.10	−0.69

solutions into a multiyear solution to determine three-dimensional positional coordinates and constant velocities for all stations. Again, this integrated solution was performed with GPSCOM in such a way that our resulting multiyear solution was essentially equivalent to the solution that would have been obtained had we processed the data for all stations and all of the selected days simultaneously. Results were carefully edited to delete spans of bad data and introduce positional discontinuities, where necessary, usually due to equipment changes or nearby earthquakes. The solution was iterated until we effectively rectified any data-related problems we were able to detect.

[44] We aligned our multiyear solution to the IGb00 (also called the IGS00 v2) reference frame [*Ferland*, 2003] by minimizing the differences in positional coordinates and velocities for 69 of the 99 stations that define IGb00. That is, we estimated values for the seven Helmert parameters (three translations, three rotations, and a scale factor), together with values for the time-derivatives of the seven parameters; which served to transform our estimated positional coordinates and velocities into corresponding values that closely approximated adopted IGb00 positional coordinates and velocities for our selected 69 stations. By aligning our solutions to IGb00, we essentially aligned our solution to the ITRF2000 reference frame by virtue of the definition of IGb00. We feel that the IGb00 positional coordinates and velocities for our selected 69 stations provided a more accurate and consistent representation of the ITRF2000 reference frame than the actual ITRF2000 coordinates and velocities of the 69 stations.

A2. Miami Solution

[45] Researchers associated with the Geodesy Laboratory at the University of Miami are actively analyzing GPS data

for several hundred geodetic stations contained in the CORS and/or IGS networks. They process each day of data using the GIPSY/OASIS II software developed by JPL and non-fiducial satellite orbit and clock files provided by JPL [*Zumberge et al.*, 1997]. Their methodology for estimating crustal velocities is further described by *Sella et al.* [2002]. For this study, the University of Miami provided us with IGb00 vertical velocities derived using GPS data, spanning the period from the beginning of 1994 to July 2005.

A3. SOPAC Solution

[46] SOPAC researchers are actively analyzing GPS data for several hundred geodetic stations in the CORS, IGS, and other networks (the Plate Boundary Observatory network, the Southern California Integrated GPS Network, etc.). They process each day of data using the GAMIT-GLOBK software, developed at MIT, Scripps Institution of Oceanography, and Harvard University <http://www.gpsg.mit.edu/~simon/gtgk/>. SOPAC's methodology for estimating crustal velocities is described by *Nikolaidis* [2002]. For this study, we downloaded the SOPAC solution posted at <http://sopac.ucsd.edu> on 29 July 2005. The SOPAC solution is regularly updated.

A4. JPL Solution

[47] JPL researchers are actively analyzing GPS data for several hundred geodetic stations in the CORS, IGS, and other networks. They process each day of data using the GIPSY/OASIS II software they have developed. The JPL methodology for estimating crustal velocities is described at <ftp://igscb.jpl.nasa.gov/igscb/center/analysis/jpl.acn>. For this study, we downloaded the JPL solution posted at <http://sideshow.jpl.nasa.gov/mbh/all/table2.txt> on 29 July 2005. The JPL solution is regularly updated.

A5. CWU Solution

[48] CWU researchers are actively analyzing GPS data for several hundred geodetic stations in the PANGA, CORS, IGS, and other networks. They process each day of data using the GIPSY/OASIS II software. Their methodology for estimating crustal velocities is described by *Szeliga et al.* [2004]. For this study, we downloaded the CWU solution posted at <http://www.panga.cwu.edu> on 29 July 2005. The CWU solution is regularly updated.

A6. Purdue-Wisconsin Solution

[49] Researchers at Purdue University are analyzing GPS data for hundreds of geodetic stations using the GAMIT-GLOBK software. The Purdue methodology for estimating crustal velocities is described by *Calais et al.* [2006]. Independently, researchers at the University of Wisconsin-Madison are analyzing GPS data using the GIPSY/OASIS II software. The Wisconsin methodology for estimating crustal velocities is described by *Márquez-Azúa and DeMets* [2003] and by Calais et al. These two research teams combined their respective solutions into a composite solution they submitted to the IGS for updating ITRF2000 velocities throughout North America. Their composite solution included GPS data through mid-March 2005.

A7. Combined Solution

[50] Table A1 presents ITRF2000 vertical velocities obtained by each of the six independent solutions for the 37 geodetic stations considered in this study. The column labeled "Mean" in this table contains the simple arithmetic mean of the individual values for a particular station. The mean ITRF2000 vertical velocities are the values used for this study, as have been presented in Table 1. In each case, the mean velocity represents the results of at least three solutions. In some cases, the mean velocity represents the results of six solutions. The scatter among different velocities for the same station reveals the level of agreement among the six solutions.

[51] **Acknowledgments.** This paper benefited from helpful contributions by Cindy Craig (NOAA), James Davis (Harvard-Smithsonian Center for Astrophysics), Timothy Dixon (University of Miami), Bruce Douglas (Florida International University), Stephen Gill (NOAA), Ruth Osborne (NOAA), Chris Pearson (NOAA), Dan Roman (NOAA), Dru Smith (NOAA), and Chris Zervas (NOAA). The authors thank Eric Calais (Purdue University), Charles DeMets (University of Wisconsin), and their colleagues for providing a prepublished copy of their GPS solution.

References

Altamimi, Z., P. Sillard, and C. Boucher (2002), ITRF2000: A new release of the International Terrestrial Reference Frame for Earth science applications, *J. Geophys. Res.*, *107*(B10) 2214, doi:10.1029/2001JB000561.

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.

Calais, E., J. Y. Han, C. DeMets, and J. M. Nocquet (2004), Deformation of the North American Plate Interior from a decade of continuous GPS measurements, *J. Geophys. Res.*, *111*, B06402, doi:10.1029/2005JB004253.

Church, J. A., and N. J. White (2006), A 20th century acceleration in global sea-level rise, *Geophys. Res. Lett.*, *33*, L01602, doi:10.1029/2005GL024826.

Church, J. A., N. J. White, R. Coleman, K. Lambeck, and J. X. Mitrovica (2004), Estimates of the regional distribution of sea level rise over the 1950–2000 period, *J. Clim.*, *17*, 2609–2625.

Conrad, C. J., and B. H. Hager (1997), Spatial variation in the rate of sea level rise caused by the present-day melting of glaciers and ice sheets, *Geophys. Res. Lett.*, *24*, 1503–1506.

Davis, J. L., and J. X. Mitrovica (1996), Glacial isostatic adjustment and the anomalous tide gauge record of eastern North America, *Nature*, *379*, 331–333.

Douglas, B. C. (1991), Global sea level rise, *J. Geophys. Res.*, *96*, 6981–6992.

Douglas, B. C. (1995), Global sea level change: determination and interpretation, *Rev. Geophys.*, 1425–1432, Suppl.1997.

Douglas, B. C. (1997), Global sea level rise: A redetermination, *Surv. Geophys.*, *18*, 279–292.

Ferland, R. (2003), IGS00(v2) final, IGS Mail 4666, <http://igscb.jpl.nasa.gov/mail/igsmail/2003/msg00442.html>, 29 October 2003.

Helmert, F. R. (1880), *Die Mathematischen und Physikalischen Theorieen der Höheren Geodäsie*, G. B. Teubner, Leipzig, Germany.

Langbein, J., and H. Johnson (1997), Correlated errors in geodetic time series: Implications for time dependent deformation, *J. Geophys. Res.*, *102*, 591–603.

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, *J. Geophys. Res.*, *108*(B4), 2216, doi:10.1029/2001JB001685.

Leuliette, E. W., R. S. Nerem, and G. T. Mitchum (2004), Calibration of TOPEX/Poseidon and Jason altimeter data to construct a continuous record of mean sea level change, *Mar. Geod.*, *27*, 79–94.

Mao, A., C. G. A. Harrison, and T. H. Dixon (1999), Noise in GPS coordinate time series, *J. Geophys. Res.*, *104*, 2797–2816.

Márquez-Azúa, B., and C. DeMets (2003), Crustal velocity field of Mexico from continuous GPS measurements, 1993 to June 2001: Implications for the neotectonics of Mexico, *J. Geophys. Res.*, *108*(B9), 2450, doi:10.1029/2002JB002241.

Mitrovica, J. X., M. Tamisiea, J. L. Davis, and G. A. Milne (2001), Recent mass balance of polar ice sheets inferred from patterns of global sea-level change, *Nature*, *409*, 1026–1029.

Moritz, H. (1980), Geodetic Reference System 1980, *Bull. Géod.*, *54*(3).

Nikolaidis, R. (2002), Observation of geodetic and seismic deformation with the Global Positioning System, Ph.D. thesis, University of California, San Diego.

Sauber, J., G. Plafker, B. F. Molnia, and M. A. Bryant (2000), Crustal deformation associated with glacial fluctuations in the eastern Chugach Mountains, Alaska, *J. Geophys. Res.*, *105*, 8055–8077.

Sella, G., T. H. Dixon, and A. Mao (2002), REVEL: A model for recent plate velocities from space geodesy, *J. Geophys. Res.*, *107*(B4), 2081, doi:10.1029/2000JB000033.

Sella, G. F., S. Stein, T. H. Dixon, M. Craymer, T. S. James, S. Mazzotti, and R. K. Dokka (2006), Observation of glacial isostatic adjustment in "stable" North America with GPS, *Geophys. Res. Lett.*,*34*, LO2306, doi:10.1029/2006GL027081.

Szeliga, W., T. I. Melbourne, M. M. Miller, and V. M. Santillan (2004), Southern Cascadia episodic slow earthquakes, *Geophys. Res. Lett.*, *31*, L16602, doi:10.1029/2004GL020824.

Tamisiea, M. E., J. X. Mitrovica, G. A. Milne, and J. L. Davis (2001), Global geoid and sea level changes due to present-day ice mass fluctuations, *J. Geophys. Res.*, *106*, 30,849–30,863.

Tamisiea, M. E., E. W. Leuliette, J. L. Davis, and J. X. Mitrovica (2005), Constraining hydrological and cryospheric mass flux in southeastern Alaska using precise space-based gravity measurements, *Geophys. Res. Lett.*, *32*, L20501, doi:10.1029/2005GL023961.

Tushingham, A. M., and W. R. Peltier (1991), ICE-3G: A new global model of the Late Pleistocene deglaciation based upon geophysical predictions of postglacial relative sea level, *J. Geophys. Res.*, *96*, 4497–4523.

Williams, S. D. P., Y. Bock, P. Fang, P. Jamason, R. M. Nikolaidis, L. Prawirodirdjo, M. Miller, and D. J. Johnson (2004), Error analysis of continuous GPS position time series, *J. Geophys. Res.*, *109*, B03412, doi:10.1029/2003JB002741.

Zervas, C. (2001), Sea level variations of the United States 1854–1999, in *NOAA Technical Report NOS CO-OPS 36*, 186 pp., Silver Spring, MD. Available in pdf format at <http://co-ops.nos.noaa.gov/pub.html>.

Zumberge, J. F., M. Heflin, D. Jefferson, M. Watkins, and F. Webb (1997), Precise point positioning for efficient analysis of GPS data, *J. Geophys. Res.*, *102*, 5005–5017.

M. Cline, W. Dillinger, R. Foote, S. Hilla, W. Kass, J. Ray, J. Rohde, G. Sella, R. Snay, and T. Soler, National Geodetic Survey, National Ocean Service, National Ocean and Atmospheric Administration, Silver Spring, MD 20910, USA. (richard.snay@noaa.gov)