Sea level rise at Honolulu and Hilo, Hawaii: GPS estimates of differential land motion

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[1] Since 1946, sea level at Hilo on the Big Island of Hawaii has risen an average of 1.8 ± 0.4 mm/yr faster than at Honolulu on the island of Oahu. This difference has been attributed to subsidence of the Big Island. However, GPS measurements indicate that Hilo is sinking relative to Honolulu at a rate of −0.4 ± 0.5 mm/yr, which is too small to account for the difference in sea level trends. In the past 30 years, there has been a statistically significant reduction in the relative sea level trend. While it is possible that the rates of land motion have changed over this time period, the available hydrographic data suggest that interdecadal variations in upper ocean temperature account for much of the differential sea level signal between the two stations, including the recent trend change. These results highlight the challenges involved in estimating secular sea level trends in the presence of significant low frequency variability. **Citation:** Caccamise, D. J., II, M. A. Merrifield, M. Bevis, J. Foster, Y. L. Firing, M. S. Schenewerk, F. W. Taylor, and D. A. Thomas (2005), Sea level rise at Honolulu and Hilo, Hawaii: GPS estimates of differential land motion, *Geophys. Res. Lett.*, *32*, L03607, doi:10.1029/2004GL021380.

1. Introduction

[2] Continuously operating GPS (CGPS) stations are being installed at tide gauges around the world in order to place these sea level records in a well-defined global reference system [*Carter*, 1994; *Bevis et al.*, 2002]. For the purpose of evaluating global sea level rise, or changes in absolute sea level over century-long time scales, estimates of the secular vertical velocity of the tide gauge sites are required. Determining these vertical velocities with an accuracy better than 1 mm/yr, even with a decade of CGPS observations, remains a very challenging problem. A major source of error is the lack of a true global reference frame for estimating vertical velocities [*Kendrick et al.*, 2001]. Reference frame errors, however, tend to be spatially coherent over small regions, such as the Hawaiian Archipelago, and therefore these errors largely cancel as one forms estimates of relative velocity (i.e., the difference in vertical velocities between CGPS sites). Until suitable global reference frames are determined, examination of relative land and sea level rates on regional scales is the best way to assess vertical motion of GPS-tide gauge sites.

[3] Over the past century, sea level at the Honolulu Harbor tide gauge, the longest Pacific island tide gauge record, has risen at 1.4 ± 0.3 mm/year (Figure 1a). Because this rate is similar to global sea level rise estimates (e.g., 1.8 mm/yr [*Church et al.*, 2004]), *Moore* [1970] and others have concluded that the island of Oahu is stable in the vertical. The rates from other Hawaiian tide gauges tend to increase with proximity to the Hawaiian Hot Spot. In particular, the sea level rise rate at Hilo Harbor on the island of Hawaii (referred to here as the "Big Island") is 3.1 ± 0.6 mm/yr since 1946 (Figure 1a). Over the common time period of the Hilo and Honolulu records, the rate difference between the two stations is 1.8 ± 0.4 mm/yr. *Moore* [1970] and others have attributed this difference to subsidence of the Big Island relative to Oahu. However, lithospheric loading models for the Big Island underpredict the rate implied by the tide gauge measurements [*Moore*, 1987]. In this paper, we compare GPS and tide gauge measurements at Hilo and Honolulu to determine whether land motions can reconcile the sea level rate differences.

2. Data and Methods

[4] A daily geodetic analysis is performed on CGPS measurements from all available Hawaii stations, including HNLC and HILO (Figure 2a), using GAMIT [*King and Bock*, 2000] and GLOBK [*Herring*, 2000] software and precise orbits computed by the Scripps Orbit and Permanent Array Center (the analysis follows that of *Kendrick et al.* [2001]). Vertical velocities at HNLC and HILO are calculated for the time period 1996–2002. Site surveys at Hilo have confirmed that relative motion between the CGPS and National Ocean Service (NOS) tide gauge (500 m separation) is negligible; at Honolulu the CGPS and NOS gauge are co-located. Therefore we assume that the CGPS station velocities indicate relative vertical motion of the tide gauges. We have not considered other Hawaii tide gauge stations because they have not yet been referenced to the CGPS array. The CGPS vertical velocity solutions are specified relative to a reference frame comprised of 30 stations in the Pacific and circum-Pacific region (Figure 2b) with 5 to 10 year record lengths [*Caccamise*, 2003]. Uncertainties represent 95% confidence intervals taking into account the serial correlation of the GPS time series [*Kendrick et al.*, 2001; *Zhang et al.*, 1997]. The velocity and error calculations were repeated using PAGES software, IGS orbital solutions and standard NGS processing methodologies. The different velocity solutions for HNLC

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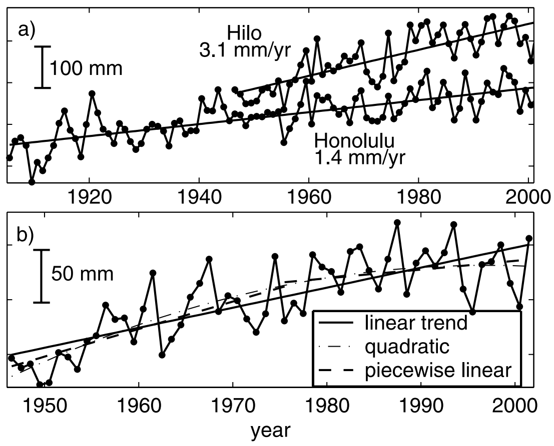

Figure 1. a) Annual mean sea level from the Honolulu and Hilo tide gauges, and b) the difference between the Hilo and Honolulu records. Least squares regression is used to determine linear (1.8 mm/yr), quadratic, and piece-wise linear (2.5 mm/yr, 1946–1975; 0.8 mm/yr, 1975–2001) trends.

and HILO were within 0.5 m/s, with similar error bounds. We conclude that our results are not dependent on the specific processing algorithm used.

[5] The sea level trends are computed using annual mean data, assumed to be statistically independent for the purpose of estimating 95% confidence intervals. The difference between the Honolulu and Hilo sea level rise rates is obtained by differencing the two time series (1946–2001) and computing linear, piecewise linear, and quadratic trends of the difference (Figure 1b) [*Caccamise*, 2003].

[6] World Ocean Atlas (WOA) temperature profile data (1945 to 1995) [*Levitus et al.*, 2000] are used to evaluate the contribution of thermal expansion to sea level. Steric sea level relative to 500 m is computed using climatological salinity from WOA and the gridded WOA temperature data. Although the gridded product is available to 3000 m, data around Hawaii are particularly sparse below 500 m.

3. Relative Trend Estimates

[7] The sea level difference between Hilo and Honolulu shows a change in linear trend over time, from 2.5 ± 1.0 m/s prior to 1975 to 0.8 ± 1.2 m/s after 1975. This is also evident in a statistically significant quadratic fit to the data. Earlier analyses of the trend difference [*Moore*, 1970, 1987] focused primarily on the pre-1975 time series, prior to the trend change.

[8] Vertical velocities for Hawaii CGPS stations (Figure 2a) generally are similar (i.e., within error bounds); however, the rates tend to increase closer to the Big Island. Our main finding is that HILO is sinking relative to HNLC at −0.5 ± 0.4 mm/yr. Accounting for pier motion at the two sites, evaluated using NOS historic leveling data, yields a rate difference of −0.4 ± 0.4 mm/yr. This is much weaker than the trend difference from the entire tide gauge record (1.8 mm/yr, note that a negative GPS velocity corresponds to a positive sea level rise), but consistent within error with the sea level trend difference since 1975 (0.8 mm/yr).

[9] One explanation for the change in the differential sea level trend around 1975 is that vertical land motion is not steady in time, and that higher subsidence occurred at Hilo relative to Honolulu prior to 1975. Lacking GPS measurements for this time period, we cannot assess this possibility directly. We note, however, that loading models do not account for a differential subsidence rate of this magnitude [*Moore*, 1987]. Although we cannot exclude the possibility of changing subsidence rates, we explore whether ocean effects alone can explain the change in differential sea level rise.

[10] Recent global sea level rise has been attributed in part to ocean warming [*Antonov et al.*, 2002; *Cazenave and Nerem*, 2004]. Historic ocean temperature data are poorly sampled in both space in time in this region, particularly below 500 m depth and before the 1980s. Nevertheless, steric sea level rates (1945–1995) show falling sea levels to the north of the Hawaiian Islands, and rising sea levels to the southeast (Figure 3a). The steric trends are characteristic of interdecadal patterns [*Mantua and Hare*, 1997; *Deser et al.*, 1996; *Firing et al.*, 2004]. *Church et al.* [2004] found a similar pattern in 1950–2000 trends reconstructed from tide gauge and satellite altimeter data. The strong steric trend gradient at Hawaii accounts for nearly one-half of the sea level rate difference, corrected for land motion, between Hilo and Honolulu. Small changes in the computation of the gradient would allow it to account for all of the difference.

[11] Furthermore, steric sea level exhibits the same trend change in the 1970s as the tide gauge data. At both Hilo and Honolulu, the sea level rise rate has decreased to near zero since 1975 (Figures 4a and 4b), as has the rate difference (Figure 4c). The steric sea level trends have decreased over the same period (Figure 4d), as has the spatial gradient in trend. Thus, sea level rise estimates from the tide gauges are strongly influenced by a multi-decadal fluctuation in the spatial structure and magnitude of upper ocean temperature (as has been noted by *Douglas* [1995]). The ungridded WOA data set shows a similar trend change, although neither gridded nor ungridded data provide statistically

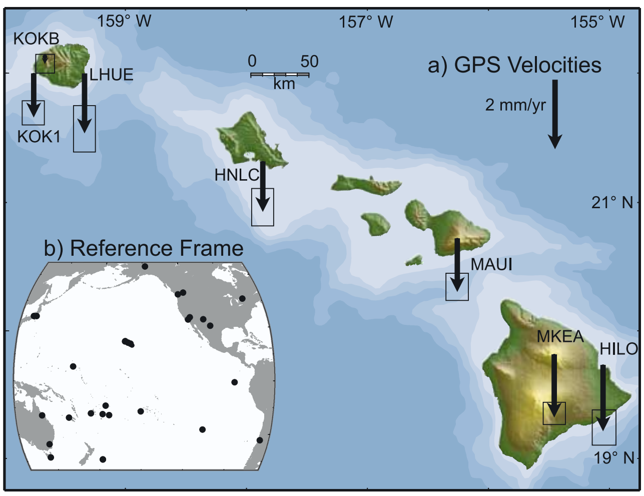

Figure 2. a) Vertical velocities at Hawaiian CGPS stations relative to b) the 30 CGPS stations used to establish a Pacific fixed reference frame. HNLC is located at the Honolulu Harbor tide gauge station; HILO is 500 m from the Hilo Harbor tide gauge station. 95% confidence intervals are given.

significant results. We believe the overall spatial pattern is meaningful, however, based on the aforementioned interdecadal studies in the Pacific and because recent sea surface height trends exhibit the same characteristic pattern (Figure 3b). The recent trends are an order of magnitude larger (note the scale difference in Figure 3) and the signs generally are reversed, presumably associated with a polarity change of the interdecadal fluctuation. The weak gradient in altimeter-based sea level trends around the Hawaiian Islands is consistent with recent tide gauge and temperature data (Figure 4).

[12] Our conclusion is that relative sea level rise rate differences at the Hawaiian Islands have been weak since the mid-1970s. Within error bounds, these findings are consistent with the CGPS estimates of weak relative land motion. Prior to 1975, the sea level trend difference between Hilo and Honolulu was greater, which prompted explanations in terms of variable subsidence of the Hawaiian Islands. A shift in island subsidence rates may account for the change in differential sea level trend, but given the correspondence to thermal data, we believe that upper ocean temperature changes are an important factor.

4. Discussion

[13] Additional CGPS and ocean temperature measurements in the region will help resolve the relative contributions of land and ocean effects to recent sea level changes at

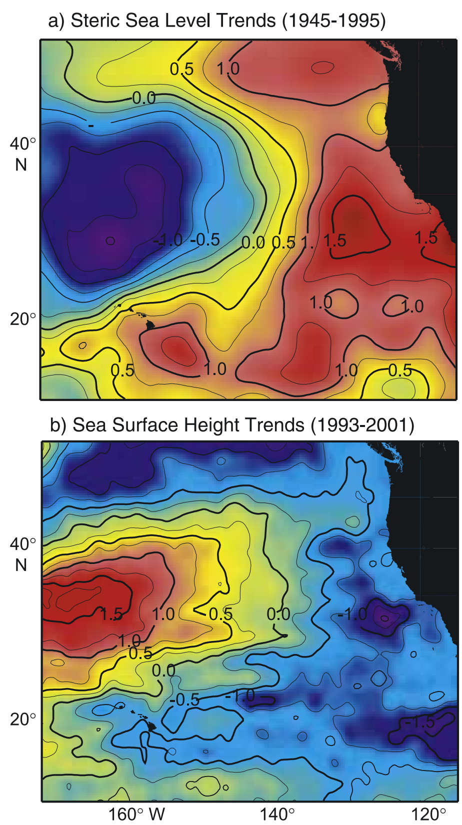

Figure 3. Linear trend in a) steric sea level relative to 500 m computed from the WOA gridded product (1945–1995), mm/yr, and b) sea surface height from TOPEX/Poseidon satellite altimeter data (1993–2002), cm/yr.

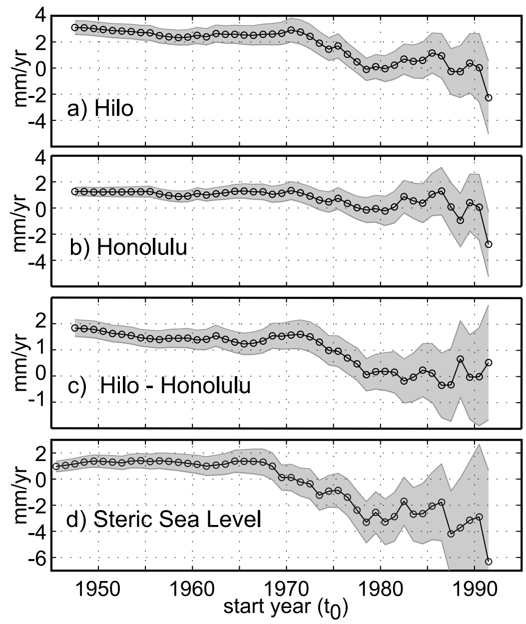

Figure 4. Linear trend over time for a) Hilo sea level, b) Honolulu sea level, c) the difference in Hilo and Honolulu sea levels, and d) steric sea level (relative to 500m) from the WOA gridded product at 19.5°N, 205.5°E near the Big Island. The trends are computed for progressively shorter record lengths by truncating the start of the original time series. The x axis represents the start date (t0) of the sub-record used to compute the trend (t0 through 2002). The shaded region represents the 95% confidence interval.

Hawaii. From an oceanographic perspective, our assessment contributes to the growing appreciation of the contribution of interdecadal timescale thermal variations to sea level. From a geological perspective, the findings appear to contradict previous estimates of island subsidence. Dating of drowned reefs offshore of the Big Island indicate a mean subsidence rate over the past few hundred thousand years of ~2.5 mm/yr [*Moore*, 1987], although the uncertainty of this estimate may be large [*Caccamise*, 2003]. Recent results indicate that a similar mean subsidence rate applies to the past 15 ky as well [*Webster et al.*, 2004], but no published evidence proves that the subsidence rate is constant until the present. Geological data from Oahu suggest an uplift rate of ~0.04 mm/yr since ~125 ka, which results in negligible vertical deformation with regard to this study [*Muhs and Szabo*, 1994]. On these longer time scales, the Big Island is sinking significantly faster relative to Oahu than the 0.4 mm/yr indicated by the CGPS measurements over the past 6 years. The assumption of a constant vertical velocity is questionable. Given the proximity of the Big Island to the Hawaiian Hot Spot, it seems probable that velocities vary significantly over geologic time scales, and perhaps even over recent times with changes in volcanic activity. Longer CGPS time series will help to determine the velocity variability on interannual and interdecadal time scales.

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