Crustal loading near Great Salt Lake, Utah

P. Elósegui,[1] J. L. Davis,[1] J. X. Mitrovica,[2] R. A. Bennett,[1] and B. P. Wernicke[3]

[1]   Two sites of the BARGEN GPS network are located ~30 km south of Great Salt Lake (GSL). Lake-level records since mid-1996 indicate seasonal water elevation variations of ~0.3 m amplitude superimposed on a roughly "decadal" feature of amplitude ~0.6 m. Using an elastic Green's function and a simplified load geometry for GSL, we calculate that these variations translate into radial crustal loading signals of ±0.5 mm (seasonal) and ±1 mm (decadal). The horizontal loading signals are a factor of ~2 smaller. Despite the small size of the expected loading signals, we conclude that we can observe them using GPS time series for the coordinates of these two sites. The observed amplitudes of the variations agree with the predicted decadal variations to <0.5 mm. The observed annual variations, however, disagree; this difference may be caused by some combination of local precipitation-induced site motion, unmodeled loading from other nearby sources, errors in the GSL model, and atmospheric errors.   INDEX TERMS: 1208 Geodesy and Gravity: Crustal movements—intraplate (8110); 1243 Geodesy and Gravity: Space geodetic surveys; 1299 Geodesy and Gravity: General or miscellaneous; 8164 Tectonophysics: Evolution of the Earth: Stresses—crust and lithosphere. Citation: Elósegui, P., J. L. Davis, J. X. Mitrovica, R. A. Bennett, and B. P. Wernicke, Crustal loading near Great Salt Lake, Utah, Geophys. Res. Lett., 30(3), 1111, doi:10.1029/2002GL016579, 2003.

1.   Introduction

[2]   Surface loading can be a significant source of crustal deformation. Recent investigations have demonstrated the ability of the Global Positioning System (GPS) to measure the Earth's elastic response to atmospheric pressure loading [van Dam et al., 1994], seasonal exchange of water and air between the northern and southern hemisphere [Blewitt et al., 2001], and the Earth's viscoelastic response to ancient glacial loads in Fennoscandia [Johansson et al., 2002].

[3]   The crust may also experience significant displacements due to localized loads, such as lakes. Two GPS sites of the Basin and Range Geodetic network (BARGEN) are located in the vicinity of GSL (Figure 1), which experiences significant variations in water elevation. In this paper, we use lake level records for GSL and a model for the elastic properties of the Earth to examine potential loading-induced three-dimensional deformation at these two GPS sites.

2.   Crustal Loading Near GSL: Theory

[4]   Lake level records (Figure 2) for GSL over the last 127 yr indicate seasonal water elevation variations of ~0.3 m amplitude superimposed on a "random" signal of ~6 m total water elevation variation. During the operation of BARGEN (mid-1996 to present) the seasonal signal is superimposed on a roughly "decadal" feature of amplitude ~0.6 m. (We loosely use the term "decadal" to describe this ~6 yr feature.) The long-term signal is presumably associated with climatic fluctuations. GSL can be hydrologically subdivided into northern and southern basins. A railroad causeway, constructed in 1957–59, cuts east-west across the middle of the lake, constraining the water flow between the basins. The water level of the southern basin is now consistently higher than that of the northern because its watershed is larger and receives more drainage [Arnow and Stephens, 1990]. Because GSL is located on a shallow playa, small changes in water elevation can result in significant changes in lake surface area, which has varied by about 8% since mid-1996 [Loving et al., 2000].

[5]   We computed the response to GSL loading by convolving the load with the Green's function [Farrell, 1972] for a spherically symmetric, self-gravitating, elastic planet with radial elastic properties derived from PREM [Dziewonski and Anderson, 1981]. We modeled the time-dependent load using two circular disks of constant density, fixed surface area, and varying height. We performed the calculations using a spectral formalism [Mitrovica et al., 1994] with a degree cut-off of 10,000 (4 km resolution). We assumed a water-load density of 1150 kg m^{-3}, the average value over the historic record, and a 2-disk surface area of 4563 km^2, the approximate area associated with the average water elevation since mid-1996. (The effect of density variations is negligible.)

[6]   A lake-level increase of 1 m yields a maximum radial displacement (Figure 3) of ~6 mm in the center of the each disk, decreasing with distance from the load. The calculated horizontal displacements are sub-mm, are directed towards the (positive) load, and decrease with distance from the load.

3.   Crustal Loading Near GSL: Observations

[7]   Two of the eastern sites of the BARGEN GPS network [e.g., Bennett et al., 1998], CEDA and COON, are located within ~30 km south of GSL and thus their measured position variations (Figure 4) can be examined for lake-loading effects. The root-mean-square (RMS) scatter for these time series (1–2 mm for the horizontal components, 4–7 mm for the radial) is larger than the predicted crustal loading signals for CEDA and COON. To examine the loading contribution to the observed site position variations, we estimated admittances for the lake level variations using

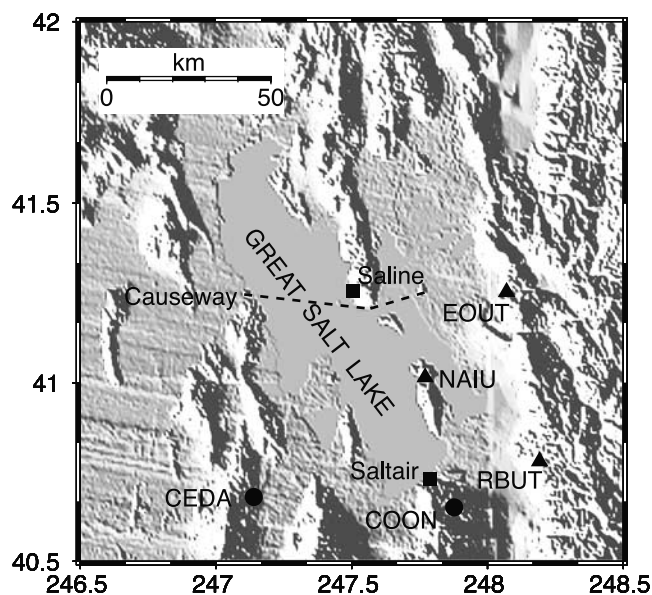$$R(t) = a_N L_N(t) + a_S L_S(t) + \epsilon(t), \qquad (1)$$

[1]Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts, USA.
[2]Department of Physics, University of Toronto, Toronto, Canada.
[3]Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California, USA.

Figure 1. Locations of GPS sites (circles and triangles) and lake-level stations (squares) used in this study. Sites CEDA and COON are part of BARGEN; other sites are part of the EBRY network [*Chang et al.*, 2001]. (The EBRY data are not used in this study due to the short time of operation.) The dashed line marks the location of the railroad causeway.

where the R are the GPS-based residuals of site displacement at time t, the a (north = N, south = S) are admittance parameters, the L are the lake-level variations (after removing a best-fit line), and ε is observational error.
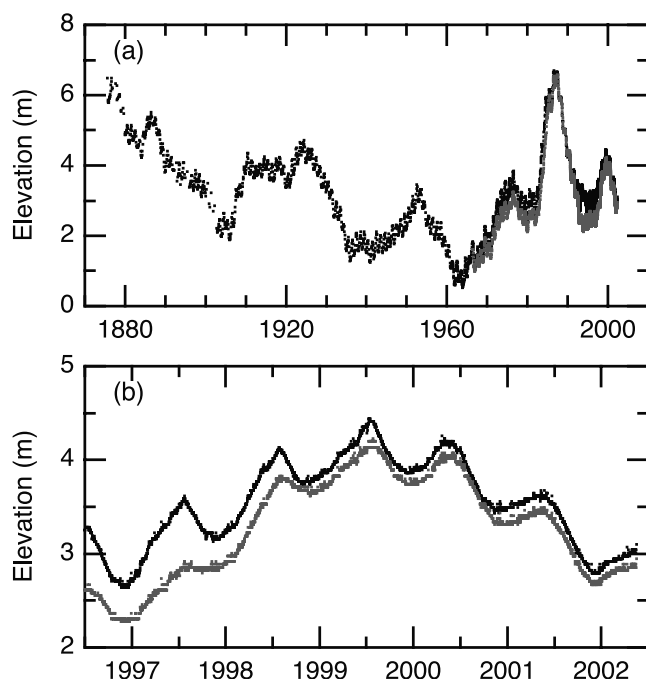

Figure 2. Lake water-height levels measured at Saltair (black) and Saline (gray) for (a) historical records and (b) the timespan of BARGEN. Each measurement represents an elevation difference relative to a nominal value of 1277 m. Note the difference in the scale between (a) and (b).
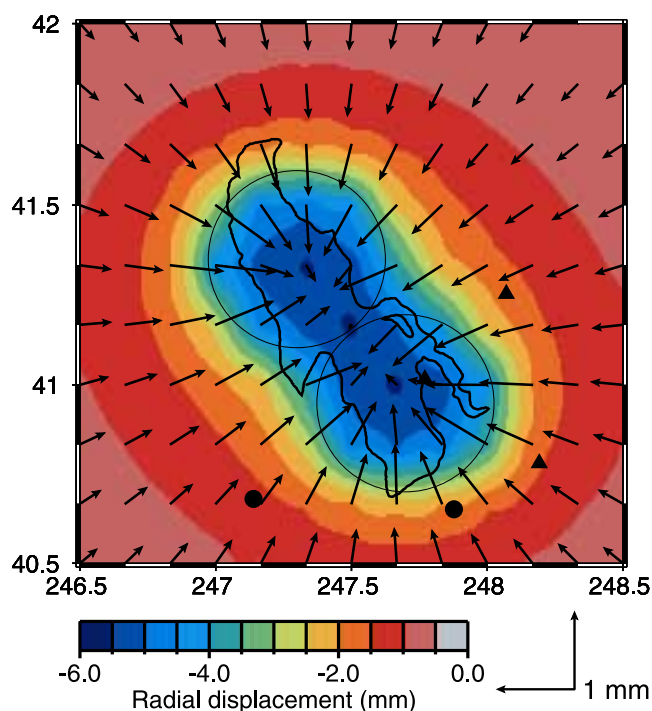

Figure 3. Predicted crustal displacements due to GSL loading. The load model uses two 27 km radius disks (thin black line) of 1 m height. The shoreline at average water elevation is shown by a thick black line. The radial displacement is color coded and the horizontal displacement is shown as a vector field. The locations of permanent GPS sites are indicated by circles (BARGEN) and triangles (EBRY). (The irregularities along the colored contours are due to surface interpolation to the grid values used for plotting.)

[8] We can use (1) to evaluate if the variations in the lake-level data are also present in the GPS residuals. If so, the time series based on admittances estimated from the GPS residuals (i.e., $\hat{a}_N L_N(t) + \hat{a}_S L_S(t)$, where the caret indicates best-fit value) should be equal to the response at the same site predicted by convolving the lake load model with the appropriate (radial, horizontal) elastic Green's function.

[9] We first consider the decadal variations, since these are larger than the seasonal signal. We removed a best-fit annual sinusoid from both the GPS time series and the lake levels prior to computing the admittances. Given the simplified disk-load model and the small size of the predicted variations compared to GPS uncertainties, the agreement between the predicted and GPS-derived load signals (i.e., calculated using $\hat{a}_N L_N(t) + \hat{a}_S L_S(t)$) is remarkable (Figure 5). The amplitudes of the decadal signals for all three components for both sites agree to better than 0.5 mm. COON east (Figure 5e), characterized by a very small signal, is the only component of the six for which the signs disagree.

[10] The better relative agreement for the radial components may indicate errors in the geometry for the disk-load model. Radial displacements are the simple sum of the absolute displacement due to each part of the water load. Loading at either the north or south part of GSL produces the same sign of radial displacement at a given site, and thus these signals interfere constructively. Therefore, the radial
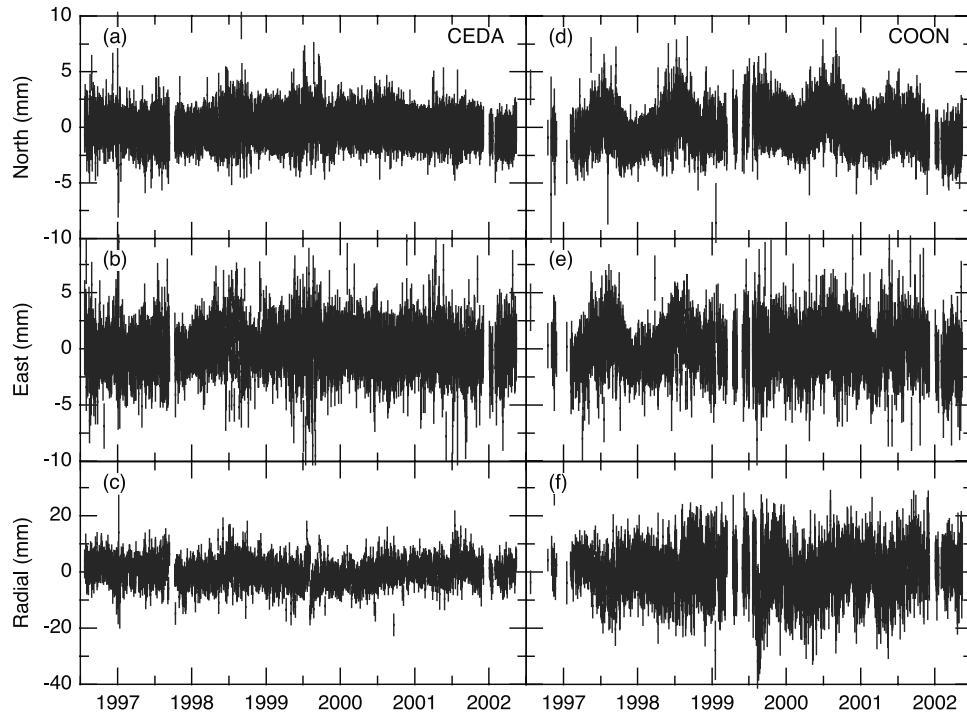
Figure 4. Estimates of the time-dependent components of site position for (a and d) north, (b and e) east, and (c and f) radial components at GPS sites CEDA and COON. Each estimate represents a residual difference relative to a best-fit linear (constant velocity) model. The error bars shown represent the 1-σ statistical uncertainties. Note the difference in the scales for the horizontal and radial components.
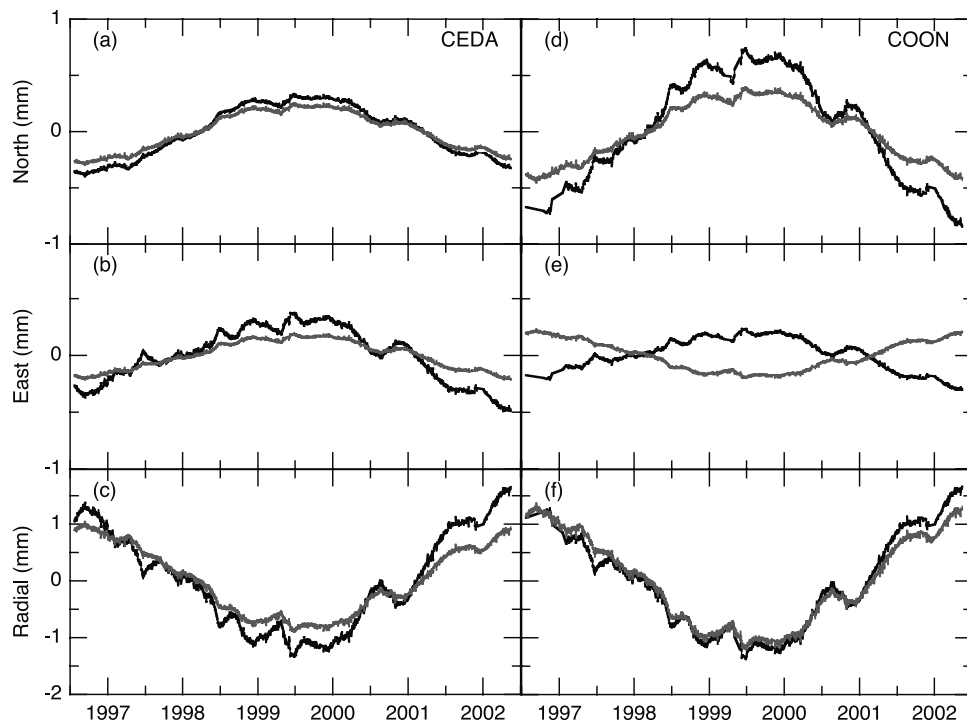

Figure 5. Comparison of (black) GPS-based estimates of the decadal crustal displacements from best fit to (1) and (gray) theoretical predictions of the loading signal based on the two-disk load model of Figure 3. (a and d) North, (b and e) east, and (c and f) radial components for CEDA and COON. Note the difference in the scales for the horizontal and radial components.

Table 1. Comparison of Amplitudes and Phases For the Annual Variation of the Radial Components

Site	Observed		Predicted	
	Amplitude (mm)	Phase (degrees)	Amplitude (mm)	Phase (degrees)
COON	1.6 ± 0.3	2 ± 9	0.4	316
CEDA	0.8 ± 0.1	239 ± 8	0.3	316

Uncertainties represent one scaled standard deviation.

displacements are sensitive to the magnitude and the general location of the load but are less sensitive to its detailed geometry. The same is true for north-south component of horizontal displacements. Since both sites are south of GSL, the north-south component predicted for both sites from any part of the GSL load will have the same sign and the different load contributions will again interfere constructively. Thus, the agreement in Figures 5a, 5c, 5d, and 5f is excellent. In contrast, the east-west components, particularly for COON, are smaller because the GSL loading signal has both positive (east) and negative (west) contributions; this destructive interference leads to a small signal. The east-west component of the predicted deformation is sensitive to small errors in the loading model. We therefore believe that the biggest contribution in the decadal error budget is the load geometry, which we intend to refine in follow-up work.

[11] Seasonal loading signals may also be significant. In performing the analysis above, annual signals were first removed since there may be several sources of such signals in GPS determinations of position, including: errors in the orbit model, the atmospheric delay model, and multipath; and site position variations due to atmospheric and hydrological loading and local monument motions. Removal of an annual signal does not, in fact, entirely remove the seasonal variations, indicating that these variations may not be purely annual.

[12] To investigate whether the annual GPS signals are related to GSL loading, we compared the estimated amplitudes and phases of the annual sinusoidal signals from the GPS and predicted loading time series (Table 1). Only the radial components have predicted amplitudes greater than 0.1 mm. In both cases, the amplitude observed in the GPS radial time series is a factor of 3–4 larger than that predicted based on GSL loading. The observed difference in phases is also large. These differences are an indication that effects other than GSL loading may be significant at seasonal periods.

4. Discussion

[13] The decadal loading signal is more distinctive than the seasonal signal and is therefore a better marker for the GSL loading signal. Seasonal signals in GPS time series may arise from several sources. Along with the sources listed in the previous section, we might also expect that there are hydrological signals associated with water use in the area or seasonal snow in the Wasatch Front only ~40 km east of site COON. (The radial response at site COON to 1 m of snow in the Wasatch Mountains may be as great as 0.8 mm.) For COON, local site motions may be significant. BARGEN sites have deep-anchored monuments; COON, however, is located on a slope and may therefore be sensitive to seasonal rains [*Langbein and Johnson*, 1997]. Potential loading sig-

nals resulting from mining activities at Bingham Canyon and Garfield tailing ponds near COON is secular, and an order of magnitude smaller than the decadal signal.

[14] It is unlikely that the decadal signals are mimicked by a GPS error source with their exact magnitude and sign, in all three topocentric components, for both sites. The comparison of these signals is therefore an unambiguous detection of crustal loading by GSL. The amplitude of these signals is much smaller than has been observed before, and illustrates the ability of continuous GPS to use spatial and temporal patterns to detect crustal deformation signals.

[15] Presently, the contributions of GSL loading to the estimated 3-D site velocities are <0.07 mm yr^{-1}. If data from 1996–99 only are used, however, the loading contributions to the estimated velocity are ~0.3 mm yr^{-1} horizontal and ~0.8 mm yr^{-1} radial. Thus GSL loading must be accounted for in the tectonic analysis of BARGEN results.

References

Arnow, T., and D. Stephens, *Hydrologic characteristics of the Great Salt Lake*, *Utah, 1847–1986*, U.S.G.S, Denver, 18–19, 1990.
Bennett, R. A., J. L. Davis, and B. P. Wernicke, Continuous GPS measurements of contemporary deformation across the northern Basin and Range province, *Geophys. Res. Lett.*, 25, 563–566, 1998.
Blewitt, G., D. Lavallée, P. Clarke, and K. Nurutdinov, A new global mode of Earth deformation: Seasonal cycle detected, *Science*, 294, 2342–2345, 2001.
Chang, W. L., R. B. Smith, C. M. Meertens, and R. Harris, Crustal deformation of the Wasatch Front, Utah, from GPS measurements, paleoseismicity and elastic-viscoelastic modeling, *Seismol. Res. Letters.*, 72, 281, 2001.
Dziewonski, A. M., and D. L. Anderson, Preliminary reference Earth model (PREM), *Phys. Earth Planet. Iner.*, 25, 297–356, 1981.
Farrell, W. E., Deformation of the Earth by surface loads, *Rev. Geophys. Space Phys.*, 10, 761–797, 1972.
Johansson, J. M., J. L. Davis, H.-G. Scherneck, G. A. Milne, M. Vermeer, J. X. Mitrovica, R. A. Bennett, B. Jonsson, G. Elgered, P. Elósegui, H. Koivula, M. Poutanen, B. O. Rönnäng, and I. I. Shapiro, Continuous GPS measurements of glacial adjustment in Fennoscandia, 1, Geodetic results, *J. Geophys. Res.*, 107(B8), 10.1029/2001JB000400, 2002.
Langbein, J., and H. Johnson, Correlated errors in geodetic time series: Implications for time-dependent deformation, *J. Geophys. Res.*, 102, 591–603, 1997.
Loving, B. L., K. M. Waddell, and C. W. Miller, *Water and salt balance of Great Salt Lake, Utah, and simulation of water and salt movement through the causeway, 1987–1998*, U.S.G.S. Water-Resources Investigations Rep. 00-4221, 2000.
Mitrovica, J. X., J. L. Davis, and I. I. Shapiro, A spectral formalism for computing three-dimensional deformations due to surface loads, *J. Geophys. Res.*, 99, 7057–7073, 1994.
van Dam, T., G. Blewitt, and M. Heflin, Atmospheric pressure loading effects on Global Positioning System coordinate determinations, *J. Geophys. Res.*, 99, 23939–23950, 1994.

R. A. Bennett, J. L. Davis, and P. Elósegui, Harvard-Smithsonian Center for Astrophysics, 60 Garden Street (MS-42), Cambridge, MA 02138, USA. (rbennett@cfa.harvard.edu; jdavis@cfa.harvard.edu; pelosegui@cfa.harvard.edu)
J. X. Mitrovica, Department of Physics, University of Toronto, 60 St. George Street, Toronto, M5S 1A7, Canada. (jxm@physics.utoronto.ca)
B. P. Wernicke, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125, USA. (brian@gps.caltech.edu)