



Drought Induced Groundwater Loss in and Around Great Salt Lake, Utah, Inferred from 3D GPS Displacements

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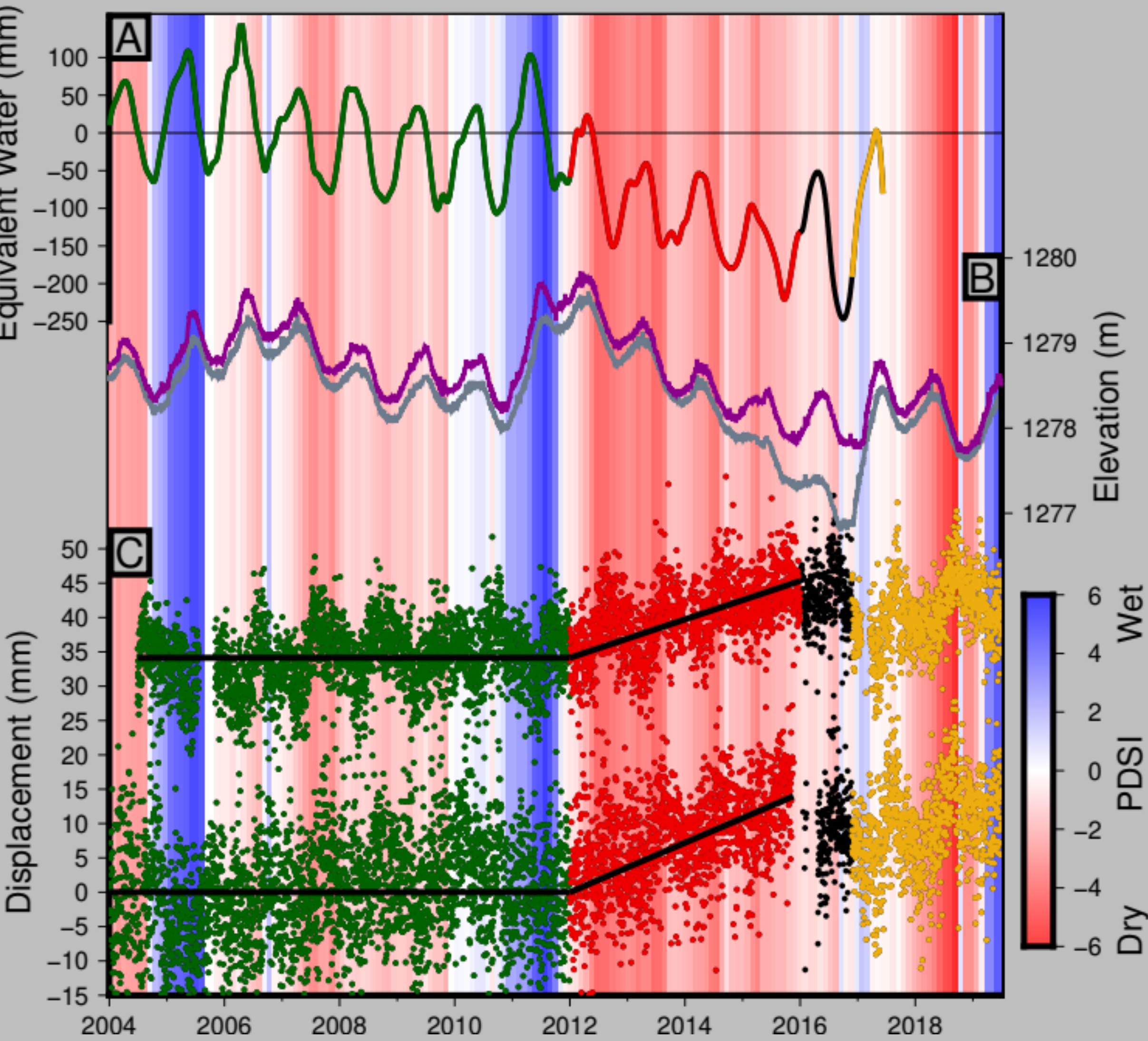


Abstract

The American Southwest experienced a massive drought between 2011 and 2016 with significant impacts to regional water storage. During this period, the Great Salt Lake (GSL), Utah, lost 1.84 meters of water and Global Positioning System (GPS) data show significant changes in nearby station positions during the same time. Although the GPS data show expected uplift and extension localized on the GSL, preliminary analysis suggests that the observed GSL unloading alone cannot fit the GPS displacements and contributions from groundwater loss surrounding the GSL are likely. This study applies a damped least squares inversion to determine the amount and distribution of groundwater removal consistent with the observed deformation. We test a large number of load distributions over a range of radial load rings and compare both the predicted vertical and horizontal displacements to the data. We estimate the loading coefficients of load belts using the code of D'Urso and Marmo (2013). Three dimensional inversion provides the most realistic distributions, compared to horizontal and vertical only solutions, and yield GSL unloading comparable with the observed water loss (i.e., a volume of 7.70 km³). The best model implies a radially decreasing mass loss up to 84 km from the edge of the lake at a volume of 54.54 km³, nearly three times the estimated volume of the entire GSL. The maximum localized unloading is on the lake itself; however, the contribution of exterior groundwater loss is substantial and greatly improves the fit to the data. In conclusion, we find that there is groundwater loss up to 84 km away from the lake and that the total amount of water loss surrounding the lake is ~7 times that for the lake itself.

Data

Figure 1: Comparison of GPS, GRACE, PDSI, and GSL surface elevation data. Background shading indicates the Palmer Drought Severity Index for Utah (NOAA, 2019). **A.)** Averaged GRACE data of four grid points centered nearest the GSL. Detrended relative to 2004-2012 (Landerer and Swenson, 2019). **B.)** GSL lake surface elevations for two monitoring sites separated by the railroad causeway. Station 10010100 is located on the northern side of the lake (gray), and Station 10010000 is located on the southern side (magenta). The mean difference between north and south is ~20 cm prior to 2012 (USGS, 2016). **C.)** Detrended GPS timeseries for stations P122 (top, north side of GSL) and COON (bottom, south side of GSL) (Blewitt et al., 2018). Trend lines are added to distinguish the change in velocity through the drought period.



PDSI and GRACE Data

- The Palmer Drought Severity Index provides a rating of the intensity of drought conditions in a region
- In Utah, between 2004 and 2012, mild dry conditions were observed with wet years in 2005 and 2011, followed by intense drought through 2016
- During the drought, the GRACE data closest to the GSL show a consistent loss of water mass of up to 74.5 mm relative to the pre-drought period

GSL Surface Elevation Data

- The water levels correlate very well with both the PDSI and GPS observations, with 1.84 meters of water lost between 2012 and 2016
- Opening of a new bridge on the railroad causeway allowed water to flow from the southern section of the GSL to the north in December 2016

GPS

- GPS data (NA12) reflect a sudden change in 3-D positioning coincident with the onset of the drought beginning in 2012
- Velocities are calculated using MIDAS, which employs median statistics and is robust against outliers (Blewitt et al., 2016)
- Relative velocities are calculated between drought and non drought periods
- Displacements are calculated as relative velocity over four years
- Only well behaved GPS stations which recorded for the duration of the drought and at least four years prior are included.

Damped Least Squares Results

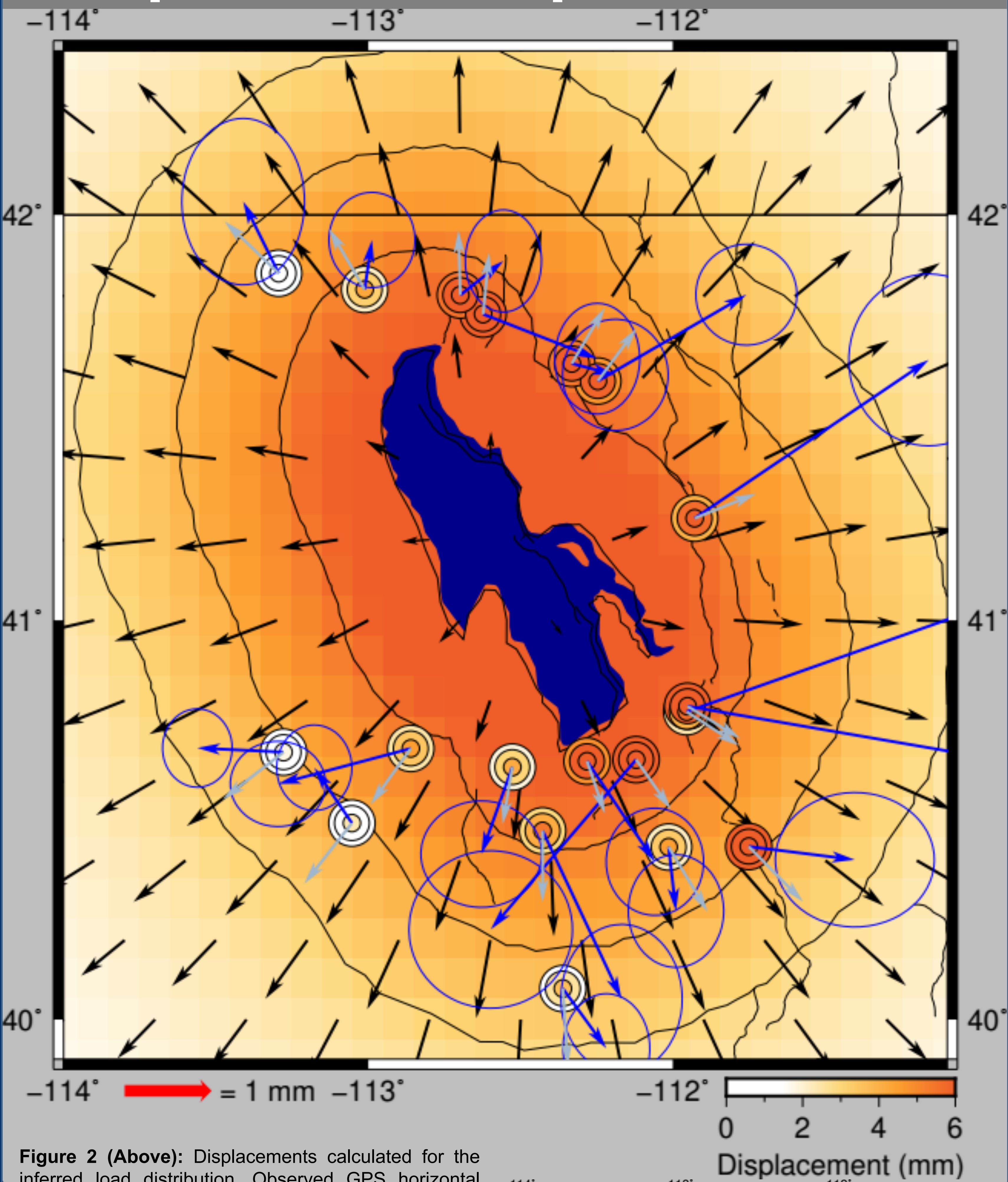


Figure 2 (Above): Displacements calculated for the inferred load distribution. Observed GPS horizontal displacements are shown by blue arrows with 95% confidence ellipses. Observed vertical displacements are the central circles with inner and outer circles representing one sigma deviation. Modeled horizontal displacements are shown at GPS sites as gray arrows and on a grid as black arrows.

Figure 3 (Right): Spatial distribution of calculated loads surrounding the GSL. Load belts are defined by buffer zones radial to the edges of the lake. This solution shows the most realistic solution and includes three rings exterior to the edge of the lake, an alpha of 3, and buffer widths of 28 km.

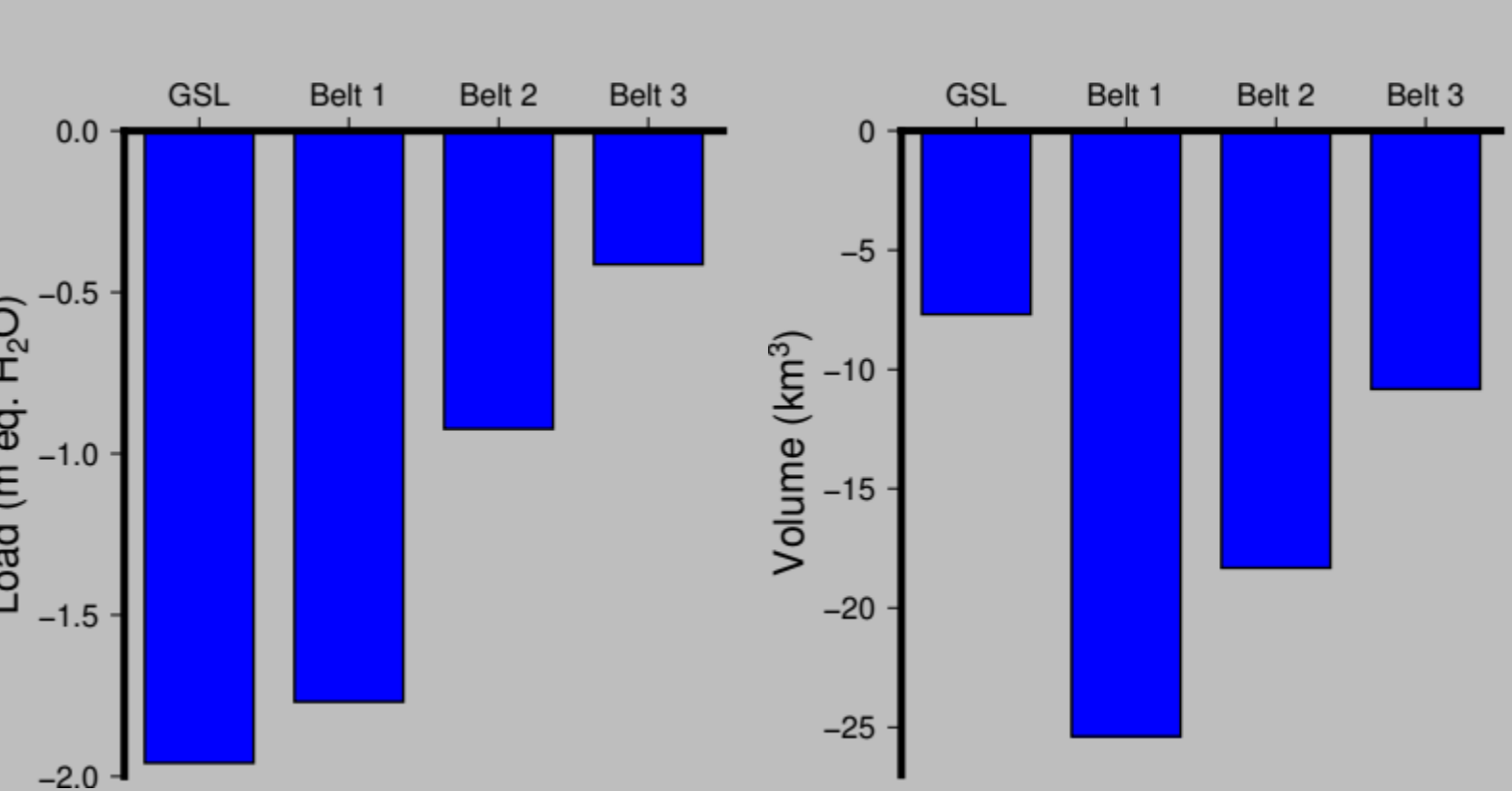
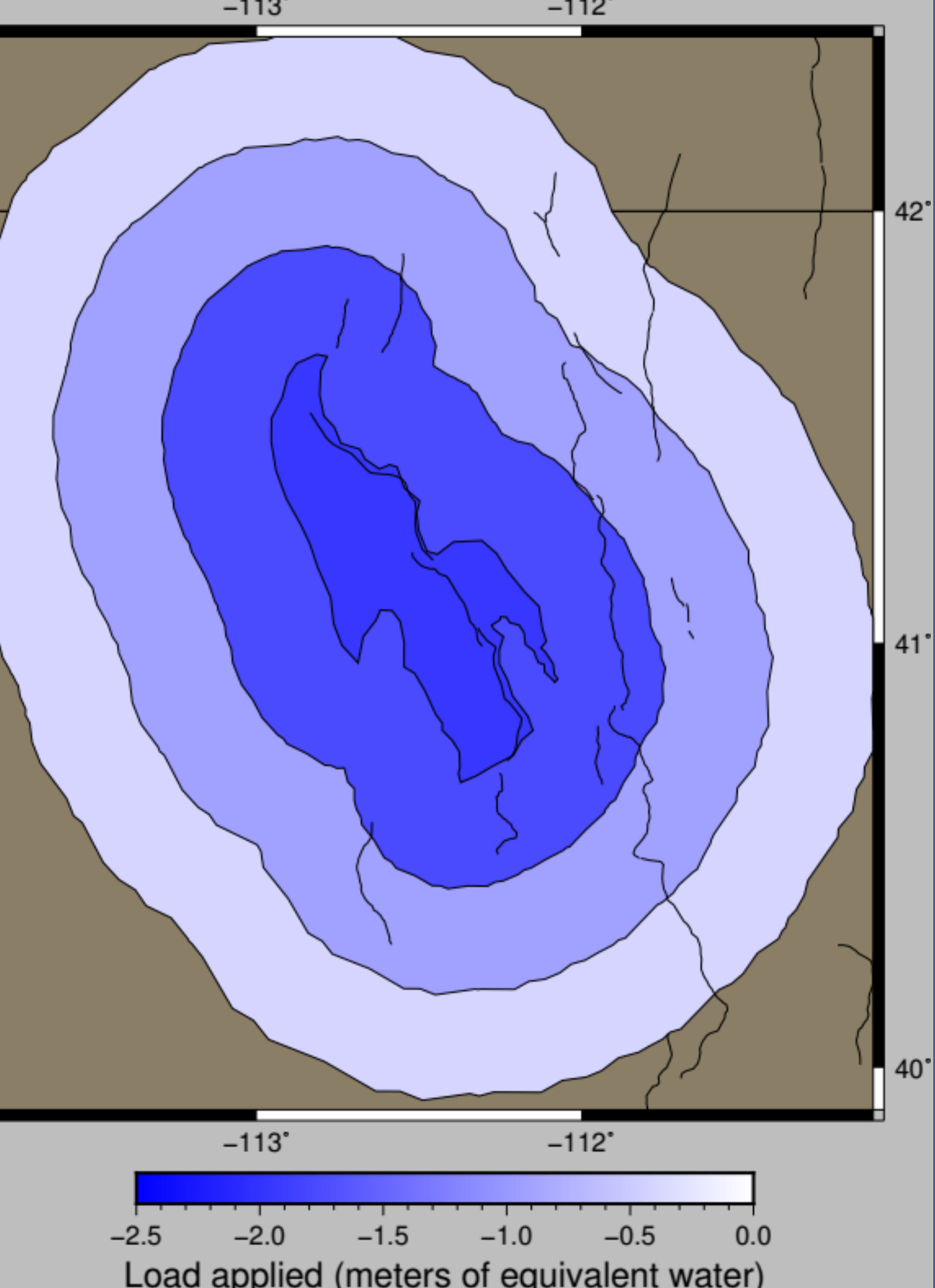


Figure 4: Calculated loads and volume by belt. The innermost belt is Belt 1. The volume lost on the lake itself and from the surrounding groundwater sources are 7.70 km³ and 54.54 km³ respectively.

Primary Findings

- Without contributions from groundwater sources, GSL water loss is estimated at unrealistically high levels.
- Results with groundwater loading belts surrounding GSL obtain loads comparable to GSL water loss of 1.84 m
- GRACE observes a deviation in water mass during the drought but spatial scales do not capture the magnitude
- 3-D GPS is essential to estimate localized loading
- Results indicate GPS is able to identify significant groundwater loss exterior to the GSL at 54.54 km³ at distances up to 84 km from the edge of the lake



	2012-2016	Volume
Observed North GSL Water Loss	-1.98 m	-7.78 km ³
Observed South GSL Water Loss	-1.70 m	-6.68 km ³
Preferred Model GSL Water Loss	-1.95 m	-7.70 km ³
Preferred Model Groundwater Belts Loss	-0.41 to -1.77 m	-54.5355 km ³
Preferred Model RMSE	2.23 mm	
GSL Water Loss w/o Groundwater Belts	-15.1 m	-59.33 km ³
GRACE Deviation	-74.5 mm	0.29 km ³
Estimated GSL Total Volume		18.92 km ³

Table 1: Results Summary

Velocity Deviations

Figure 5: (Left) Relative displacements for period 2012-2016 relative to 2004-2012 obtained by multiplying difference in MIDAS velocities with duration of 4 year drought period. (Right) Similarly, relative displacements for period 2016.9-2019.5 relative to 2012-2015. Arrows reflect horizontal motion with 95% confidence ellipses. Central circles indicate calculated vertical displacement with inner and outer circles showing one sigma deviation. Labels indicate stations from Figures 1, 6, and 7.

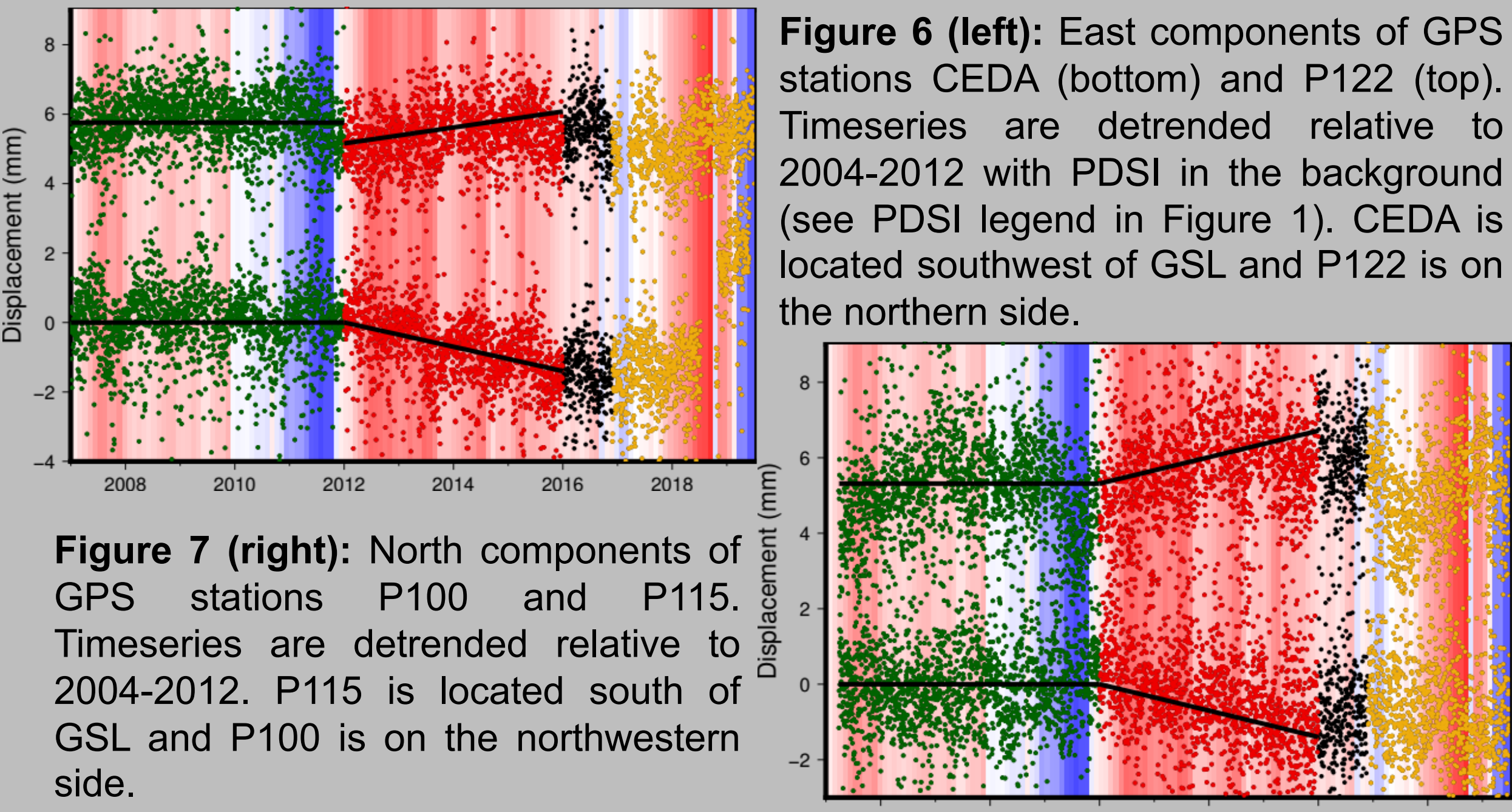
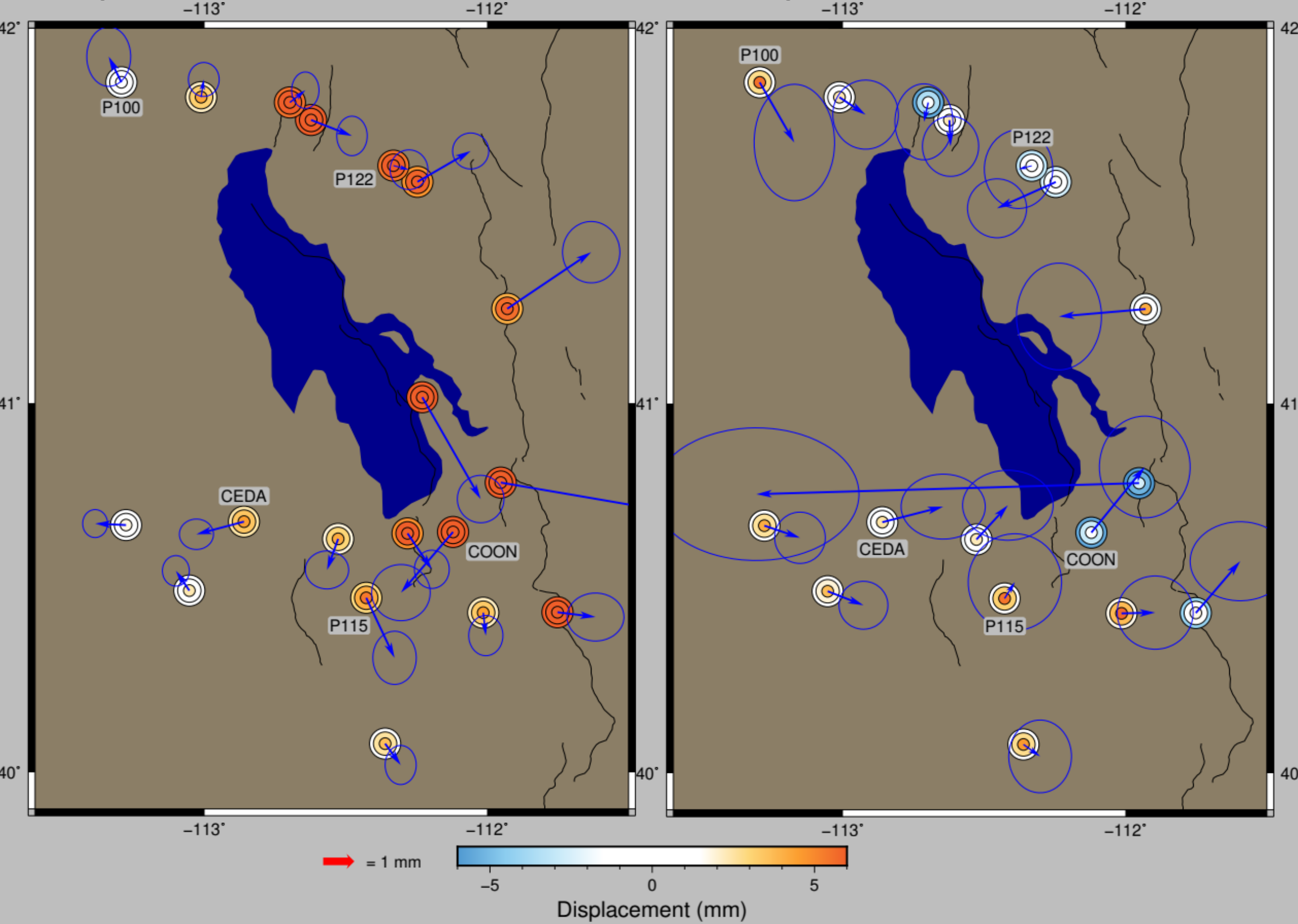
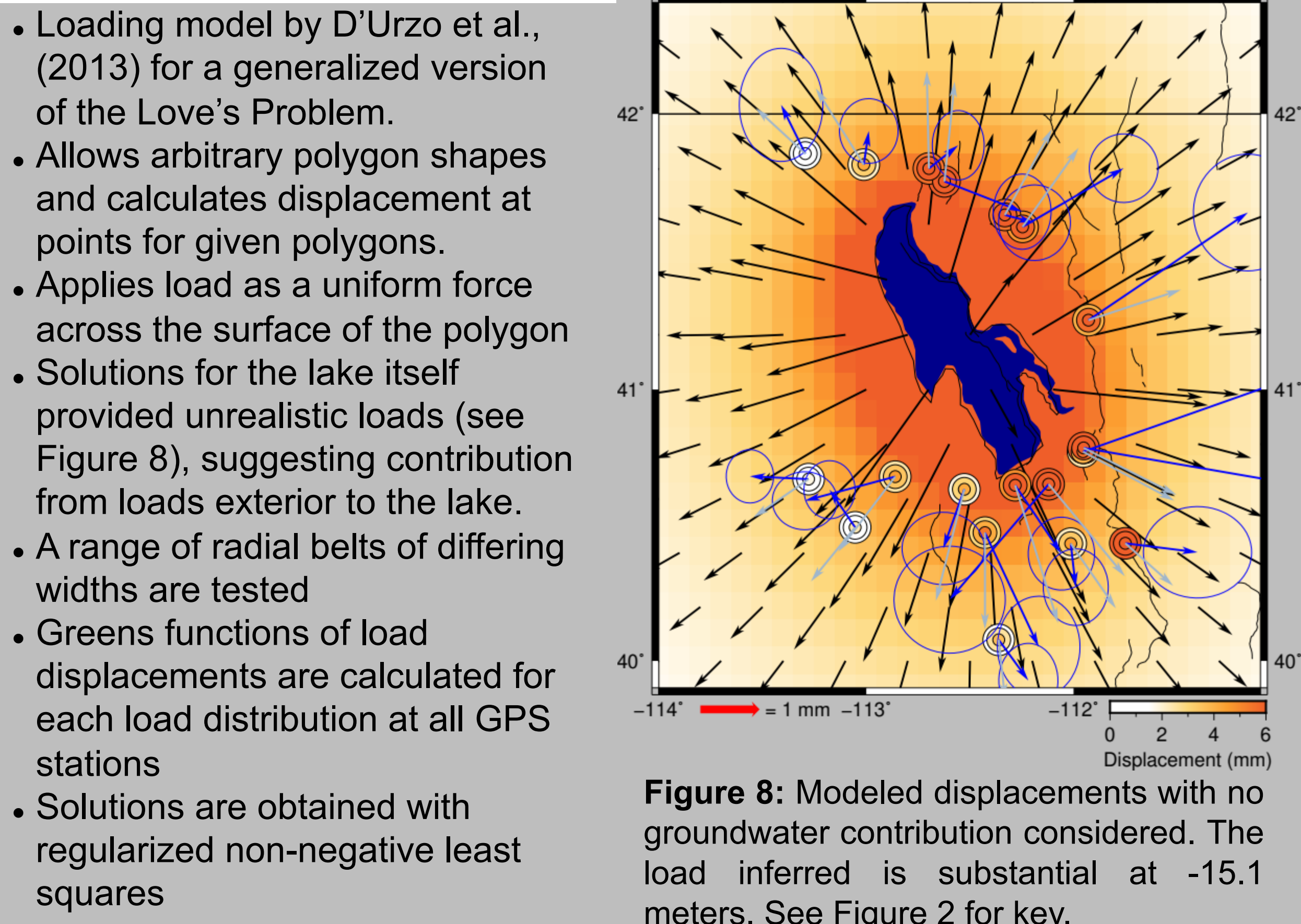


Figure 6 (left): East components of GPS stations CEDA (bottom) and P122 (top). Timeseries are detrended relative to 2004-2012 with PDSI in the background (see PDSI legend in Figure 1). CEDA is located southwest of GSL and P122 is on the northern side.

Figure 7 (right): North components of GPS stations P100 and P115. Timeseries are detrended relative to 2004-2012. P115 is located south of GSL and P100 is on the northwestern side.



- Loading model by D'Urso et al., (2013) for a generalized version of the Love's Problem.
- Allows arbitrary polygon shapes and calculates displacement at points for given polygons.
- Applies load as a uniform force across the surface of the polygon
- Solutions for the lake itself provided unrealistic loads (see Figure 8), suggesting contribution from loads exterior to the lake.
- A range of radial belts of differing widths are tested
- Greens functions of load displacements are calculated for each load distribution at all GPS stations
- Solutions are obtained with regularized non-negative least squares

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