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Tracking changes in groundwater storage from GNSS geodesy in the Great Lakes region

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Introduction

In this study, we aim to infer changes in groundwater storage in the Great Lakes region of the central U.S. at sub-monthly time scales during WY 2020 (October 1st, 2019, to October 1st, 2020). We model and remove predicted vertical deformation due to soil moisture loading (NLDAS model), snow loading (SNODAS model), atmospheric-pressure loading (ECMWF model), non-tidal oceanic loading (MPIOM model), equivalent water thickness loading outside the Great Lakes region (GRACE model), and lake loading (NOAA model) from the GNSS position series. The vertical residual displacements at each GPS station is broke down with a root-mean-square-error (RMSE) reduction and principal component analysis (PCA) to further isolate the ground water signal.

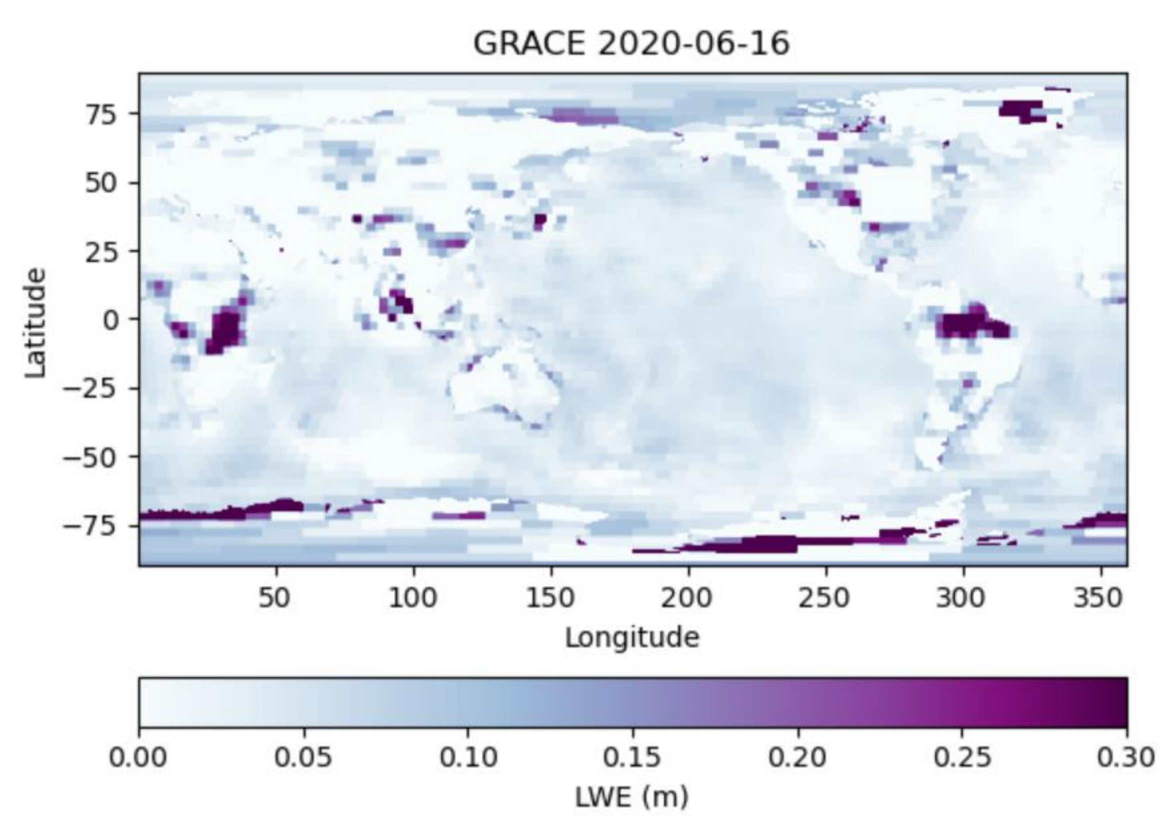

Figure 1. A grid file generated in *LoadDef* (Martens et al., 2019) of the Liquid Water Equivalent (LWE) from the GRACE mascon solutions on June 16th, 2020. The liquid water equivalent (LWE) is set to zero inside the Great Lakes region denoted as the white box in the grid.

Methods

To isolate the ground water storage in the Great Lakes region, predicted vertical deformation from known surface mass loads are modeled and removed from the GNSS position series.

- Soil moisture, snow water equivalent, GRACE mascon water equivalent thickness (Save, 2016) outside the Great Lakes region (see Figure 1), and lake loading are modeled and removed using a Python-based toolkit called *LoadDef* (Martens et al., 2019).
- NGL-IGS14 GNSS position series (Blewitt et al., 2019) are cleaned by removing outliers, offsets, and post seismic patterns, see Figure 2.
- NTOL and ATML from MPIOM and ECMWF are modeled and removed using GFZ solutions (Dill and Dobslaw, 2013; Martens, Argus, Norberg et al., 2020).

A principal component analysis adopted from Dong et al. (2006) is performed with north, east, and vertical residual displacements at 36 GPS stations in the Great Lakes region to further investigate the relationship of ground water storage and possible error in the displacement residuals, see Figures 3 and 4.

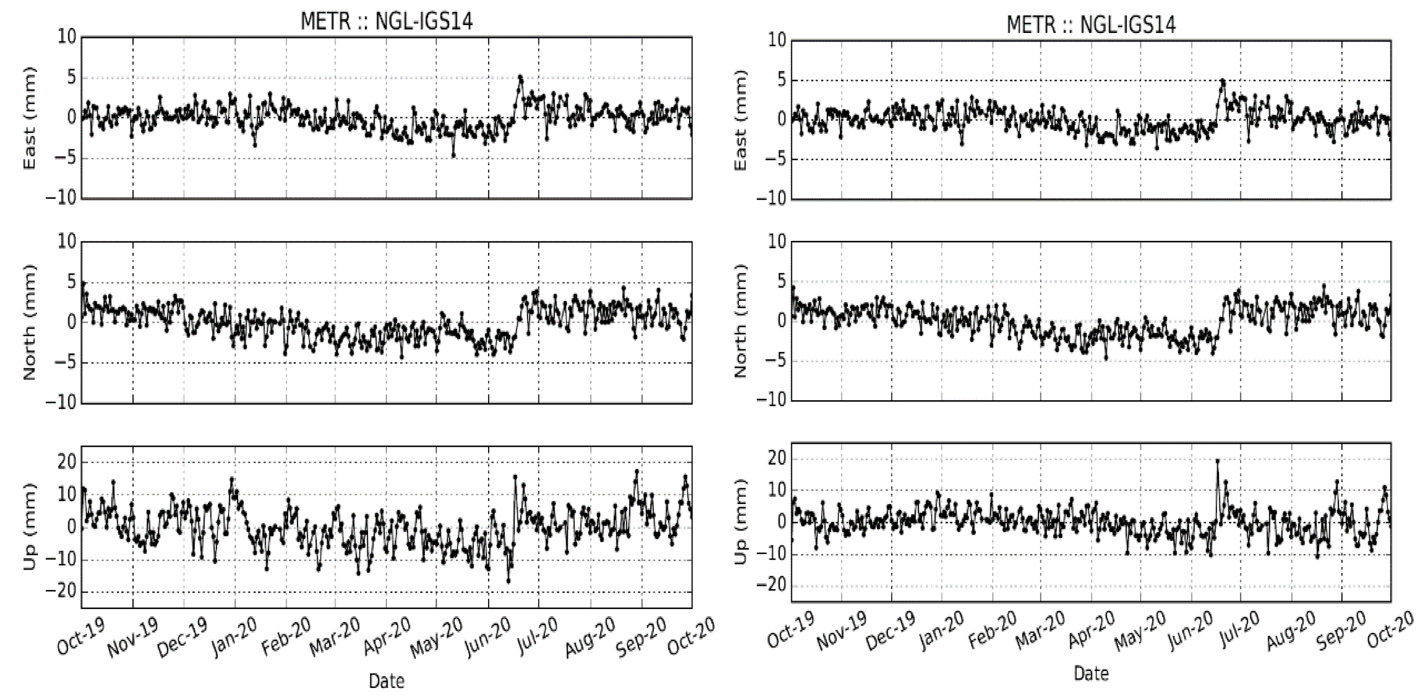

Figure 2. *(Left)* A cleaned time series of GPS station METR (42.685, -83.243) for WY2020 after removing outliers, offsets, and post seismic patterns. *(Right)* The residual time series for METR after the known surface load displacements are removed from the cleaned time series on the right. The top panels are the east displacements, the middle panels are the north displacements, and the bottom panels are the vertical displacements.

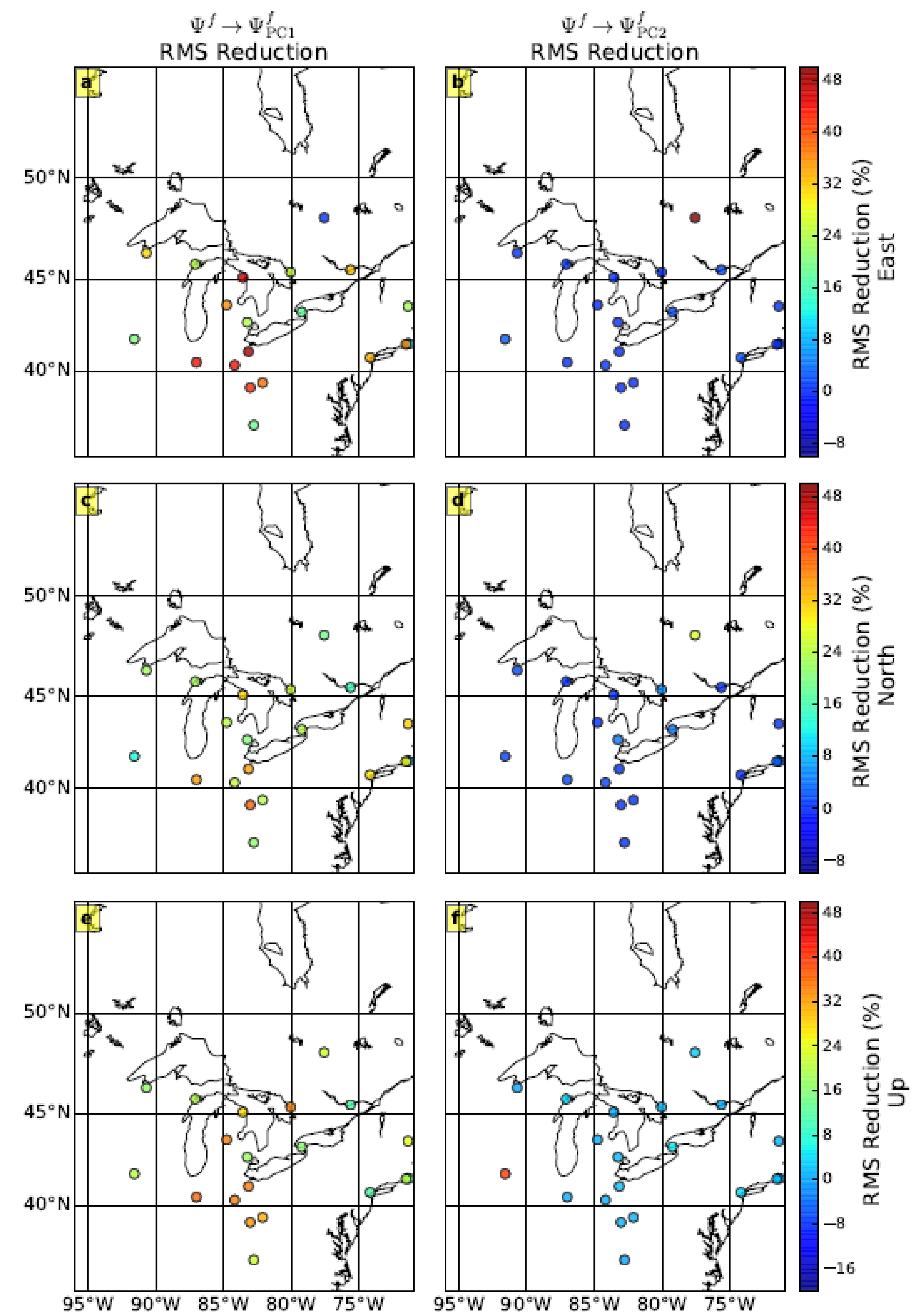

Figure 3. RMS Reduction after removing Principal Component 1 (Panels a, c, e) from the residual displacements and Principal Component 2 (Panels b, d, f) from the residual displacements. The top panels are the RMS Reduction in the east component, the middle panels are the RMS reduction in the north component, and the bottom panels are the RMS reduction in the vertical component.

Results

- The mean RMS reduction after removing PC1 in the vertical component is 24%, see Figures 3 and 4.
- The normalized eigenvectors after removing PC1 from the residual time series in the vertical component range from 0.3 to 1, see Figure 4.

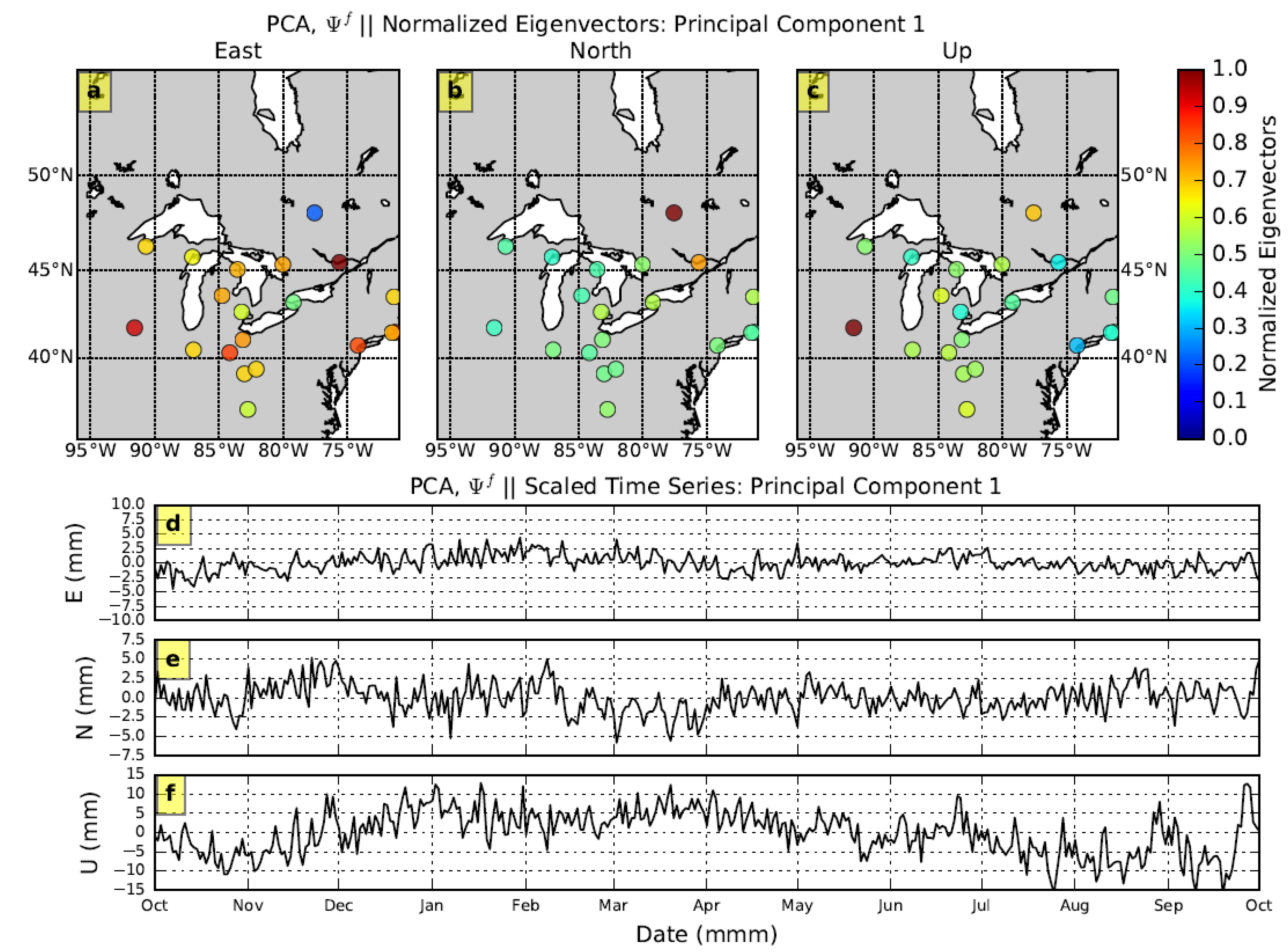

Figure 4. (Top panel, a,b,c) Normalized eigenvectors of Principal Component 1 for 36 GPS stations in the Great Lakes region. Panel a is the normalized eigenvectors for the east displacement, panel b is the normalized eigenvectors for the north displacement, and panel c is the normalized eigenvectors of the vertical displacement. (Bottom panel, d, e, f) Scaled time series of the residual (GPS – Models) from PC1. Panel d is the east displacement time series, panel e is the north displacement time series, and panel f is the vertical displacement time series.

Discussion

Since we removed all the known models from the GNSS time series, we hypothesize that the groundwater signal is preserved in the residual time series and is captured in the PC1 scaled vertical time series, see panel f in Figure 4. However, unknown/mismodeled loading sources and GNSS errors can mask the groundwater signal in the GNSS time series creating a challenge to infer if the PC1 scaled vertical time series captures the groundwater signal in the region. In future studies, we will compare the annual fluctuations in the PC1 scaled vertical time series and PC1 RMSE reduction from the GPS network in the Great Lakes region to other networks in North America. We suspect regions with more groundwater will have larger annual fluctuations in the PC1 scaled vertical time series and a higher PC1 vertical RMSE reduction compared to regions with less groundwater.

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