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Key Points:
- Study highlights agreement between vertical displacements derived from ground-based GPS, GRACE, and Catchment in a snow-dominated basin
- Ground-based GPS captures the prolonged drought after the 2010–2011 winter better than the Catchment land surface model
- Study shows potential of using a data assimilation framework incorporating GRACE and ground-based GPS to improve estimated TWS

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Comparison of Vertical Surface Deformation Estimates Derived From Space-Based Gravimetry, Ground-Based GPS, and Model-Based Hydrologic Loading Over Snow-Dominated Watersheds in the United States

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Abstract Spatiotemporal variability in Earth's terrestrial water storage (TWS) causes changes in surface deformation. The potential for using ground-based Global Positioning System (GPS) vertical displacement observations for estimating TWS is explored through a comparison of vertical displacements derived from space-based gravimetric retrievals, ground-based GPS, and model-based hydrologic estimates. The study presented here focuses on two snow-dominated basins in the Western United States for the years 2003–2016. Seasonal variations are observed in the vertical displacements derived from all three data sets, and the variation is coherent with the changes in hydrologic loading. Good consistency is observed between any two of the three data sets with gravimetric retrievals and hydrologic model estimates providing the highest level of agreement (i.e., all examined stations with correlation coefficient $R > 0.70$). Vertical displacements derived from gravimetric retrievals and ground-based GPS yielded $R > 0.70$ for more than 89% of the stations. In addition, it is found that both GPS-derived and space-based, gravimetry-derived vertical displacements clearly reflected the impact of climate variation (i.e., heavy precipitation during 2010–2011 winter followed by prolonged drought). Vertical displacements derived from the hydrologic model highlighted the relatively large precipitation convergence phase during late 2010 to early 2011 at some stations but not the prolonged drought that followed. The results indicate that ground-based GPS observations of vertical displacement have the capability to capture variations in TWS changes, which can be systematically merged in conjunction with Gravity Recovery and Climate Experiment (GRACE) into a land surface model to improve TWS estimates in a follow-up study.

Plain Language Summary Terrestrial water storage (TWS) is the sum of all forms of water over land, and it is critically important for the global hydrologic cycle and climate system. The spatial and temporal distribution of TWS is important for studies in droughts, floods, and water management. Satellite-based (GRACE) TWS retrievals and land surface models are often used to estimate TWS changes, but they both have limitations such as the coarse resolution of GRACE retrievals and lack of physical representations in models. This study uses ground-based Global Positioning System (GPS) observations of vertical displacement to estimate TWS changes, which allows the study of TWS changes at a finer spatial scale. The mechanism that connects TWS changes with the ground-based GPS observations is the elastic response of the Earth's surface to the redistribution of TWS. In snow-dominated regions, processed ground-based GPS observations show coincident seasonal variations with water changes that cause downward motion in vertical displacement during the winter season and uplift during the summer season due to snow accumulation and ablation. Additionally, ground-based GPS successfully detected heavy precipitation during the 2010–2011 winter and the following drought in the Great Basin and Upper Colorado basins, which was not well captured by the land surface model.

1. Introduction

Terrestrial water storage (TWS) plays an important role in the global hydrological cycle and Earth's climate system (Ferreira et al., 2019; Houborg et al., 2012; Rodell & Famiglietti, 2001; Syed et al., 2008). Variations in TWS can cause deformation of the Earth's crust. Observations of surface deformation (a.k.a., displacement), in turn, can be used to study terrestrial hydrology after properly accounting for other loads and sources of deformation such as atmospheric mass redistribution, ocean tides, tectonic motions, and earthquakes (Han, 2017). Due to the relationship between mass redistribution and crustal deformation, the changes as measured by Global Positioning System (GPS) observations of surface displacement can be used to infer water mass redistribution. With increasing spatial coverage and positioning accuracy in ground-based GPS stations, GPS displacement observations are increasingly being used in hydrology studies related to drought (Borsa et al., 2014; Chew & Small, 2014), large-scale storm event (Milliner et al., 2018), snow water equivalent estimation (Ouellette et al., 2013), ice mass loss (Khan et al., 2010), and regional TWS estimation (Argus et al., 2014, 2017; Fu & Freymueller, 2012; Wang et al., 2017).

The Gravity Recovery and Climate Experiment (GRACE) mission was launched in 2002 to measure anomalies in the Earth's gravity and thus retrieve TWS estimates through the impact of water mass distribution on Earth's gravity field (Tapley et al., 2004). GRACE-based TWS retrieval provides an estimate of TWS anomaly (i.e., perturbation relative to the long-term mean) that causes long wavelength effects at monthly sampling with a spatial scale around 400 km. GRACE TWS retrievals provide important information for studies in drought monitoring (Houborg et al., 2012; Thomas et al., 2014), flood potential (Reager & Famiglietti, 2009; Reager et al., 2014), and groundwater depletion (Famiglietti et al., 2011; Rodell & Famiglietti, 2001). Using a model, GRACE-derived TWS variation can be converted into crustal deformation in both vertical and horizontal directions and then be used to compare against GPS-based displacement observations (Fu & Freymueller, 2012; van Dam et al., 2007). A number of studies comparing surface displacements derived from GRACE and GPS have been conducted over different spatial scales ranging from global (Tregoning et al., 2009) to regional (Chanard et al., 2014; Fu & Freymueller, 2012; Han, 2017; Liu et al., 2014; Nahmani et al., 2012; Tan et al., 2016; van Dam et al., 2007).

van Dam et al. (2007) compared the vertical displacements from GPS and GRACE over Europe and found a poor consistency between the annual height signal from GPS and GRACE with obvious differences in both amplitude and phase. The discrepancies were inferred to be caused by an insufficient GPS data processing technique; Tregoning et al. (2009) showed a good agreement between GRACE-derived and GPS-estimated deformation, especially in areas with large hydrologic signals across a broad spatial region. Differing from the results shown in the study of van Dam et al. (2007), a good coherence was observed in Europe due to the improved accuracy of the GPS solutions with reduced spurious signals at quasi-annual and semiannual periods (related to, e.g., the atmospheric pressure tidal loading) in Tregoning et al. (2009). Nahmani et al. (2012) compared the three-dimensional deformation derived from GPS, GRACE, and loading models (i.e., hydrological, atmospheric, and nontidal ocean loading models) in response to the West African monsoon, and a good consistency between GPS, GRACE, and the loading model simulations was observed. Fu and Freymueller (2012) analyzed GPS observations in the Nepalese Himalayas, and a consistent result between GPS height and GRACE-derived vertical displacement was reported. Additional studies comparing surface displacements derived from ground-based GPS and space-based GRACE over southern Alaska (Fu et al., 2012), Southeast Asia (Fu et al., 2013), North China Plain (Liu et al., 2014), California (Tan et al., 2016), and Australia (Han, 2017) further demonstrated that GPS-based surface displacements in both vertical and horizontal directions yield good agreement with GRACE-derived displacements.

All data sets (i.e., GRACE, GPS, and models) have their own strengths and weaknesses in detecting TWS changes due to their unique uncertainties, error characteristics, and spatial and temporal resolutions. Therefore, this study is partly motivated by the potential merger (in a Bayesian sense) of ground-based GPS observations and GRACE-based TWS retrievals into a land surface model (LSM) in order to enhance the accuracy and mitigate the uncertainty of estimated TWS beyond what is achievable with single data source estimation. Before the merger, however, a careful analysis of each data set's behavior and error characteristics is needed to conduct a multivariate TWS merger in a follow-on study. Therefore, a comparison of displacements derived from GPS, GRACE, and an advanced LSM was performed over two large, snow-dominated watersheds (i.e., Great Basin and Upper Colorado) in the western United States. Further, the discrepancies between the information contained in GPS, GRACE, and the LSM data were explored. Considering the relatively large amplitude of the vertical displacement observations relative to the horizontal displacements (Fu et al., 2013; Nahmani et al., 2012), vertical displacement was made the focus of comparison and discussion in this study.

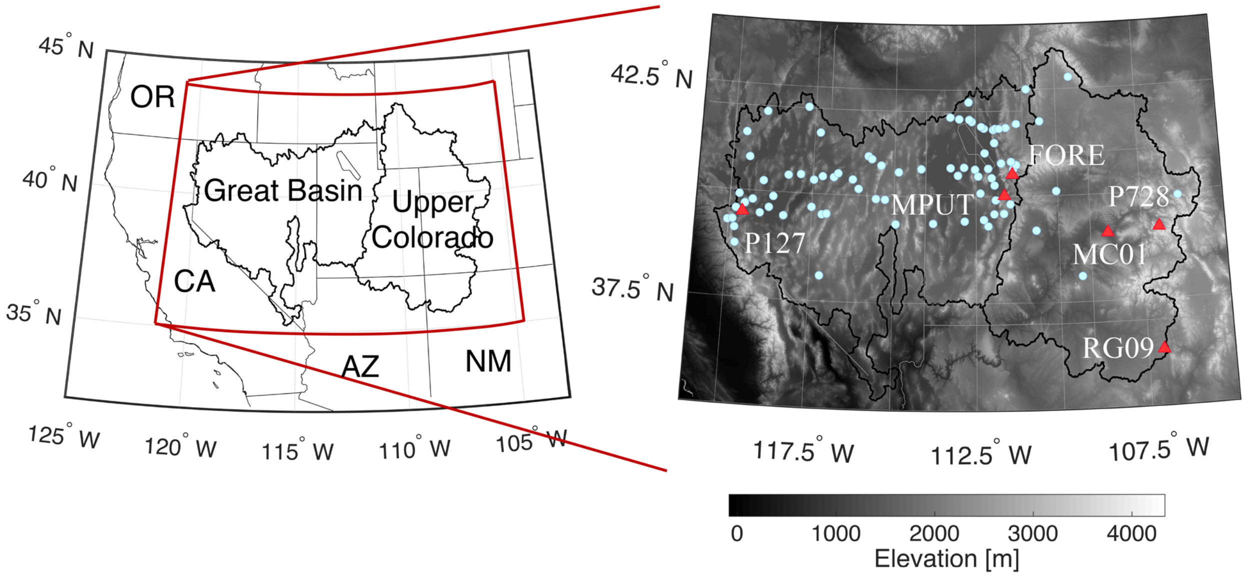

Figure 1. Study area including the Great Basin and Upper Colorado watersheds along with the GPS permanent stations shown as light blue dots. Three representative stations in each of the two watersheds used for discussion in section 3 are shown as red upper triangles along with their four letter codes.

Data sources as well as the processing procedure of each data set are introduced in section 2. The comparison of seasonal and seasonally adjusted changes in vertical displacements derived from the different data sources is conducted in sections 3.1 and 3.2. The connection between hydrology processes and vertical displacement is discussed in section 3.3. The influence of atmospheric circulation, particularly the La Niña event in 2010–2011, on vertical displacement of the land surface is discussed in section 3.4. Section 3.5 summarizes the possible explanations for discrepancies between vertical displacements derived from GPS, GRACE, and the LSM as well as the error sources in each data set.

2. Study Area and Methodology

2.1. Study Area

The study was conducted in the western United States and includes the Great Basin and Upper Colorado watersheds as shown in Figure 1. The watershed shapefiles used in Figure 1 were acquired from the Watershed Boundary Dataset provided by United States Geological Survey (USGS; https://water.usgs.gov/GIS/huc.html). The Great Basin watershed covers almost all of Nevada, a large portion of Utah, and a small region of California, Oregon, Idaho, and Wyoming with a total area of about 367,000 km^2. The Upper Colorado watershed is to the east of the Great Basin watershed and covers a large area of Utah and Colorado and portions of Wyoming, New Mexico, and Arizona with a basin area of approximately 293,000 km^2. The two watersheds generally have warm summers and cold winters with snow being a critical reservoir of fresh water (Peel et al., 2007).

2.2. GPS Data

The ground-based GPS data used in the study is the Level 2 daily position data from the Plate Boundary Observatory (PBO; https://www.unavco.org/data/data.html) project aimed at quantifying Earth's three-dimensional deformation across the boundary between the Pacific and North American plates (Herring et al., 2016). Data were archived by the Geodesy Advancing Geosciences and EarthScope (GAGE) Facility at UNAVCO. Data processed by the New Mexico Tech analysis center were used instead of the combined data solution from two data analysis centers because a network-wide vertical shift in December 2011 was observed in the GPS data processed by the Central Washington University analysis center (Borsa et al., 2014) but not in data processed by the New Mexico Tech analysis. In order to ensure that the vertical displacements observed in the GPS record reflects only hydrologic loading variation and thus can be compatible with GRACE-derived vertical displacements, all nonhydrologic loading effects must first be removed.

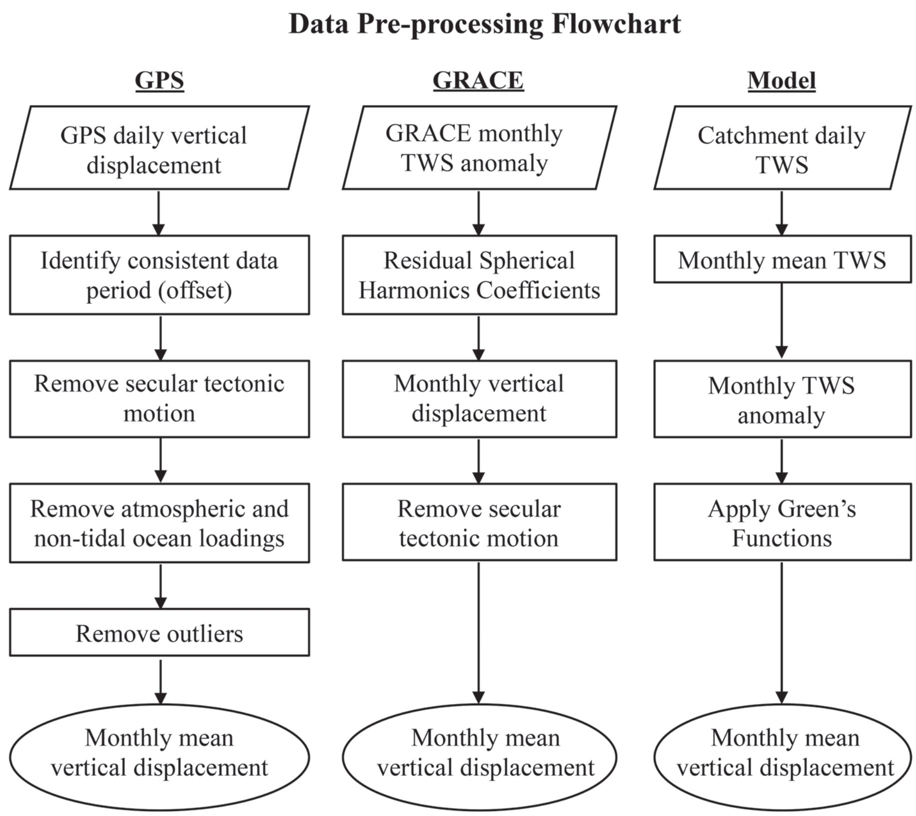

Figure 2. Flowchart of GPS, GRACE, and hydrologic model (i.e., NASA's Catchment model) data preprocessing.

There are 123 GPS stations providing records during the study period from January 2003 to March 2016 in the study area, but only stations with continuous displacement records (i.e., without an offset event) that cover at least 50% of the study period were selected for use. The offset in displacement is a sudden step-like shift of displacement associated with an earthquake, changing of antenna, or other miscellaneous reasons. The occurrence of offsets was obtained from UNAVCO (Herring et al., 2016). Earth vertical displacement caused by nonhydrologic variations such as glacial isostatic adjustment (GIA) and tectonic effects can, at times, appear in the GPS record of vertical displacement. Based on previous studies (Borsa et al., 2014; Chew & Small, 2014; Han, 2017), a long-term linear trend can be used to remove the secular trend effect without evident impact on the analysis of seasonal and interannual change. In addition, the GRACE retrieval used in this study accounted for the effects of atmosphere and nontidal ocean using the atmosphere and ocean de-aliasing (AOD) model. Therefore, the AOD model was similarly used to remove atmosphere and nontidal ocean effects from the ground-based GPS observations using the monthly averaged AOD Level 1B Release 05 (GAC solution with degree and order 100) from the German Research Centre for Geosciences (GFZ; https://www.gfz-potsdam.de/en/aod1b/) (Flechtner et al., 2014). Due to the strong sensitivity of GPS observations to crustal movement, GPS observations larger than three times the standard deviation of the time series (relative to the mean) were considered as outliers and removed from the record. Afterwards, the processed daily GPS vertical displacements were converted into monthly averages in accordance with the dates used in the corresponding GRACE solutions. The processed, monthly GPS vertical displacements were then used to compare against GRACE and the hydrologic model (more details in section 3.1). Figure 2 illustrates the general processing stream of the ground-based GPS observations. One factor that has considerable influence on the observed vertical displacement is groundwater pumping with more details discussed in section 3.5. However, according to Konikow (2013), most of Great Basin and Upper Colorado watersheds do not have significant groundwater pumping issues, and therefore, the groundwater pumping effect is not explicitly considered in this study.

In the Great Basin, there are 109 GPS stations with vertical displacement records between January 2003 and March 2016. After removing stations with relatively short time spans (i.e., records less than half of the period from January 2003 to March 2016), a total of 77 GPS stations remained that were then used in the study as shown in Figure 1. For the Upper Colorado region, 14 GPS stations are available, and after completing quality control, a total of 10 GPS stations remained as shown in Figure 1.

2.3. GRACE Data

GRACE Level 2 monthly TWS mass concentration (mascon) solutions from NASA's Goddard Space Flight Center (GSFC; https://neptune.gsfc.nasa.gov/grace/) (Loomis et al., 2019) were used in this study. The mascon technique applies a priori information during the least squares adjustment procedure that prominently reduces signal leakage across region boundaries (Luthcke et al., 2013). Therefore, the mascon technique provides a more optimal solution to balance the trade-offs between noise reduction and signal attenuation compared to the spherical harmonic (SH) solutions. The GSFC mascon product provides monthly estimates of time variable gravity in the form of equivalent water height (EWH) for a global set of 1×1 arcdeg equal-area mascons. The monthly mascon solution for the period from January 2003 to March 2016 (without GIA removed) was used, and it was converted into normalized SHs up to 60° to prepare for the computation of vertical displacement. The geocenter correction has been applied in the GSFC mascon product (Swenson et al., 2008), which allows for the comparison of vertical displacement derived from GPS and GRACE in the center of figure (CF) frame. GRACE C20 terms have also been replaced using results from the Satellite Laser Ranging measurements in the mascon product in order to obtain a higher accuracy in the C20 terms (Cheng & Ries, 2012). Assuming a homogeneous reaction of the Earth's crust to mass loading changes, the induced vertical displacement was represented (Kusche & Schrama, 2005; van Dam et al., 2007) using SH coefficients for the gravity field and load Love numbers via

$$dr(\theta,\phi) = R\sum_{l=1}^{\infty}\sum_{m=0}^{l}\tilde{P}_{lm}(\cos\theta)(\Delta\tilde{C}_{lm}\cos m\phi + \Delta\tilde{S}_{lm}\cos m\phi)\frac{h_l'}{1+k_l'} \tag{1}$$

where $dr(\theta, \phi)$ is the vertical displacement in the radial direction, θ and ϕ are colatitude and east longitude, respectively, R is the average Earth radius, $\tilde{P}_{lm}$ is the fully normalized Legendre functions of degree l and order m, $\Delta\tilde{C}_{lm}$ and $\Delta\tilde{S}_{lm}$ are the SH coefficients of the time variable Earth's gravity field relative to a long-term average, and h_l' and k_l' are the elastic load Love numbers. After converting the GRACE TWS retrieval into vertical displacements at each GPS station location, a linear trend was also removed from each displacement time series in the same way as for GPS data in order to remove any remaining secular trend artifacts.

2.4. Land Surface Model

The NASA Catchment LSM (a.k.a. Catchment; Ducharne et al., 2000; Koster et al., 2000), a physically based numerical model, was used to calculate the redistribution of hydrological mass loadings that was then used to compute vertical displacement. Traditional LSMs discretize soils into vertical layers, but the horizontal structure of soil is assumed to be uniform spanning over tens of kilometers (Ducharne et al., 2000). This assumption neglects the impact of horizontal variability of soil moisture and its effects on evapotranspiration and runoff. Catchment improves upon traditional LSMs by importing an explicit treatment of subgrid soil moisture variability and thus explicit modeling of evapotranspiration and runoff mechanisms (Ducharne et al., 2000; Koster et al., 2000). Hydrological Catchments were used as the fundamental land surface unit instead of a traditional grid in order to account for subgrid heterogeneity. Modeled daily TWS was projected to the Equal-Area Scalable Earth (EASE) grid with a spatial resolution of 25 km × 25 km. The Catchment model was run on the University of Maryland supercomputing cluster (Deepthought2) using meteorological fields provided by the Modern Era Retrospective Analysis for Research Application version 2 product (MERRA-2; Gelaro et al., 2017) as boundary conditions. Catchment-derived TWS was converted into vertical displacement using Green's function (Farrell, 1972; Wahr et al., 2013) based on the Preliminary Reference Earth Model (PREM; Dziewonski & Anderson, 1981). Assuming a disc loading with angular radius α, the vertical displacement with respect to the distance to the center of the disc can be calculated as

$$\begin{aligned} dr &= \sum_{l=0}^{\infty} h_l'\Gamma_l\frac{4\pi GR}{g(2l+1)}P_l(\cos\lambda) \\ \Gamma_l &= \frac{1}{2}\left[P_{l-1}(\cos\alpha) - P_{l+1}(\cos\alpha)\right] \qquad l>0 \\ \Gamma_0 &= \frac{1}{2}(1-\cos\alpha) \end{aligned} \tag{2}$$

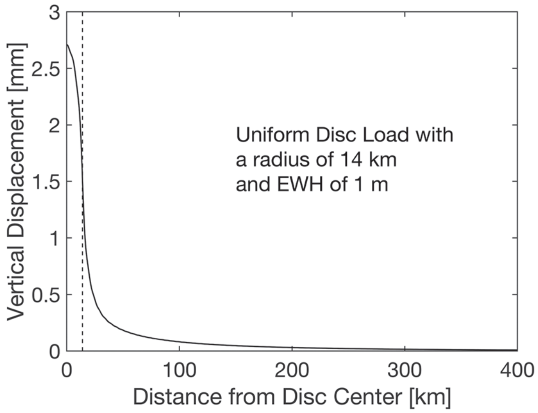

Figure 3. Vertical displacements caused by a removal of a uniform disc load with radius of 14 km and equivalent water height (EWH) of 1 m. The vertical dashed line represents the edge of the disc.

where P_l is the Legendre polynomials for degree $l \in [0, \infty]$, G is Newton's gravitational constant, g is the gravitational acceleration at the Earth's surface, and λ is the angular distance of the observation location to the center of the disc loading. In this study, $h'_1 = -0.269$ was used corresponding to the CF frame (Kusche & Schrama, 2005).

The spatial resolution of 25 km × 25 km at which Catchment was run is roughly the same area as a disc with a radius of 14 km. The vertical displacement in elastic response to a removal of a uniform disc load with radius 14 km and EWH of 1 m is shown in Figure 3. Crustal deformation caused by the disc load is most significant at the center with vertical displacement around 2.7 mm and then decreases rapidly away from the center. At the edge of the disc, the resulting vertical displacement is about 1.5 mm, and when the distance from the disc center becomes 400 km, the value becomes less than 0.01 mm. The Catchment-based vertical displacement at each GPS station was computed by convolving the impact of TWS change of each 25 km × 25 km pixel on land on to the GPS stations at a global scale. The Catchment-derived daily vertical displacements were then converted to monthly vertical displacements using the same time span as used in the GRACE solutions.

2.5. Evaluation Metrics

In order to analyze the agreements between different vertical displacement time series derived from ground-based GPS, space-based GRACE, and model-based Catchment, the correlation coefficients (R) of vertical displacement of (1) GPS versus GRACE, (2) GPS versus Catchment, and (3) GRACE versus Catchment were computed. The same computation was repeated after removing the mean seasonal cycle from each data set, respectively, in order to evaluate the interannual variation agreements of the three data sets. Note that correlation coefficient can only reflect the agreement of two time series in terms of variation phases, whereas the differences in amplitudes are not assessed. Therefore, the weighted root mean square (RMS) reduction as defined in Equation 3 (van Dam et al., 2007), which takes both amplitude and phase differences into consideration, was also used. RMS reduction computes the variance reduction of subtracting one time series from another and thus can be used to analyze the seasonal agreement between the vertical displacements derived from two data sets (e.g., GPS and GRACE). A large positive RMS reduction value represents a good agreement between two time series in amplitude and phase.

$$\mathrm{RMS}_{\mathrm{reduction}} = \frac{\mathrm{RMS}_A - \mathrm{RMS}_{A-B}}{\mathrm{RMS}_A} \times 100\% \quad (3)$$

where RMS_A is the variance of data set A (i.e., GPS), RMS_{A-B} is the variance of the time series after subtracting data set B from A where data set B is either GRACE- or Catchment-based monthly time series in this study.

3. Results and Discussion

3.1. Monthly Vertical Displacement Analysis

Monthly vertical displacements derived from GRACE, GPS, and Catchment in the Great Basin and Upper Colorado watersheds were acquired through the procedure outlined in section 2. For each watershed, three different GPS stations corresponding to the maximum, median, and minimum correlation coefficient between GRACE- and GPS-based vertical displacements were selected as representative examples as shown in Figure 4. Selected station information and statistical values are summarized in Table 1. The six representative stations shown in Figure 4 all display the expected seasonality in vertical displacement time series, with negative values found during the winter due to snow accumulation and positive values in the summer due to snow ablation. For the Great Basin, the lowest R between GRACE- and GPS-derived vertical displacement is found at station MPUT with a value of 0.59, whereas the highest R is found at station FORE with a value of 0.89. For the Upper Colorado watershed, the corresponding lowest and highest R values are 0.48 at station RG09 and 0.86 at station P728, respectively. The exceptionally small R values related to GPS-based vertical displacement at station RG09 are notable. From the time series of GPS vertical displacement at station RG09 in Figure 4, an obvious decrease of annual peak displacement from 2003 to early 2011 followed

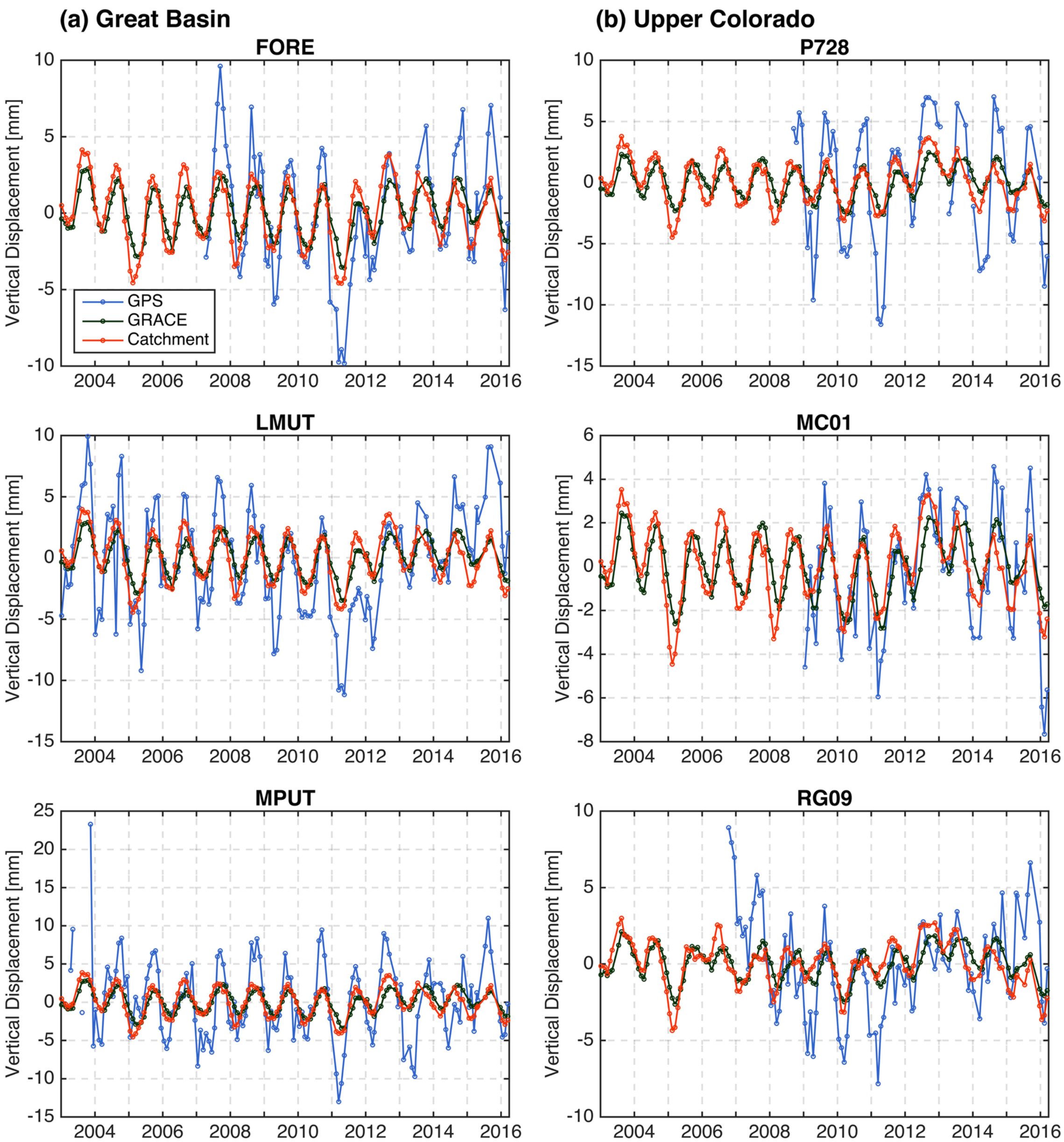

Figure 4. Comparison of monthly vertical displacements derived from ground-based GPS (blue), GRACE TWS retrievals (dark green), and Catchment model output (red) for stations in column (a) the Great Basin watershed and column (b) the Upper Colorado watershed.

by an increase of upward deformation until 2016 can be observed. However, this change is not captured by GRACE or Catchment.

Time series amplitudes estimated from GPS are consistently larger than for GRACE or Catchment. For all 77 GPS stations located in the Great Basin watershed, an average annual response amplitude of 4.7 ± 2.6 mm (shown as mean ± standard deviation) was derived from the GPS-based vertical displacement records, which is on average 2.4 times larger than the amplitude from GRACE (1.9 ± 0.8 mm). The amplitude of vertical displacements estimated from Catchment is between the scale of GPS and GRACE, which is 2.6 ± 0.9 mm. Similar amplitude characteristics are found for the stations in the Upper Colorado watershed of which the corresponding amplitudes are 4.3 ± 2.3 mm, 1.7 ± 0.6 mm, and 2.1 ± 1.0 mm for GPS, GRACE, and Catchment, respectively. The phase differences between the vertical displacement time series derived from three data sets were also investigated. The timing of the maximum vertical displacement (i.e., less water loading) and minimum vertical displacement (i.e., more water loading) varies by year and station location. For each station, if over 50% of the yearly peak or yearly trough values are found in the same month, the station is

Table 1
Correlation Coefficient, R, of Vertical Displacement Time Series Derived from (1) GPS Versus GRACE, (2) GPS Versus Catchment, and (3) GRACE Versus Catchment and RMS Reduction After Removing GRACE and Catchment From the GPS Signal, Respectively

			R (unitless)			RMS reduction (%)	
	Station	Location	GPS vs. GRACE	GPS vs. Catchment	GRACE vs. Catchment	GPS vs. GRACE	GPS vs. Catchment
Great Basin	FORE	40.51°N, 111.38°W	0.89	0.80	0.86	31	33
	LMUT	40.26°N, 111.93°W	0.77	0.70	0.86	23	27
	MPUT	40.02°N, 111.63°W	0.59	0.61	0.86	13	17
Upper Colorado	P728	39.18°N, 106.97°W	0.86	0.84	0.81	22	27
	MC01	39.09°N, 108.53°W	0.75	0.83	0.79	29	38
	RG09	36.30°N, 107.06°W	0.48	0.35	0.77	11	6

Note. The selected stations correspond to the minimum, median, and maximum correlation coefficient between GPS- and GRACE-derived vertical displacement in the Great Basin and Upper Colorado watersheds.

defined to experience a maxima or minima, respectively, in that month. For GRACE-based vertical displacement, all examined station locations experienced maximum displacement during September or October and minimum displacement during March or April. For Catchment, the peaks are found in August or September, and the troughs are in February or March for all station locations, which are both one month earlier than for the GRACE-based time series. The 1-month earlier peak found in the Catchment-based vertical displacement could be attributed to a lack of a dynamic surface water routing module, differences in snow melt processes (e.g., Catchment snow often melts earlier than snow-covered area retrievals suggest; Toure et al., 2018), precipitation errors in the boundary conditions, or model structure errors related to other physical processes in Catchment (Xia et al., 2012). A combination of these errors likely results in surface water exiting the basin earlier than in reality. As for GPS, the maxima and minima timings show slightly greater variability than GRACE or Catchment, with peaks ranging from August to October, and troughs ranging from February to April. It is difficult to say with certainty, but the larger spread in the GPS maxima and minima is likely due to the enhanced spatiotemporal resolution of the GPS observations.

The correlation coefficient maps of (1) GPS versus GRACE, (2) GPS versus Catchment, and (3) GRACE versus Catchment including all examined GPS stations in the two watersheds are shown in Figure 5. The average correlation coefficient between GPS and GRACE pairs is 0.77 for the Great Basin and 0.73 for the Upper Colorado watershed. Over 89% of all the examined GPS stations in the study area (i.e., in both Great Basin and Upper Colorado watersheds) provide an R value greater than 0.70. The correlation coefficient between GPS and Catchment is comparable but slightly low as compared to GPS versus GRACE, with the averaged values of 0.76 and 0.72 in the Great Basin and Upper Colorado watersheds, respectively. The percentage of stations that provide a R value larger than 0.70 is 80%. The consistency between GRACE and Catchment is generally the highest among the three comparison cases for both the Great Basin ($R = 0.87$) and Upper Colorado ($R = 0.81$) watersheds. All stations located in the study area yield R values larger than 0.75. In all three comparison cases, a consistently lower agreement was found in the Upper Colorado watershed, which is due to the limitation of Catchment in modeling dynamic surface water routing of the Colorado River (Girotto et al., 2016). Most stations with large R values are found in the north of the Great Basin watershed located in the Bear and Great Salt Lake subbasins that experience longer snow seasons than in areas at lower elevations and closer to the basin outlet.

The RMS reduction as introduced in section 2.5 is another metric used to indicate the agreement between two data sets through the subtraction of one data set time series from the other. Removing the GRACE and Catchment time series, respectively, from the GPS signal for each station leads to the computation of the RMS reduction (Figure 6). A positive RMS reduction suggests a decrease in variance, and the larger the RMS reduction value, the better the agreement. For all of the examined stations in the two watersheds, there are no negative RMS reduction values found for either the GRACE or Catchment cases, which indicates a general agreement between the GPS, GRACE, and Catchment data sets. Removing Catchment from the GPS signal (Figure 6b) shows relatively larger RMS reduction values in comparison with the case of removing GRACE (Figure 6a) from the GPS signal. This behavior is slightly different from the results of the correlation analysis that suggested better consistency between GPS versus GRACE as compared to GPS versus Catchment. This difference is attributable to the fact that the correlation coefficient R considers only the seasonal phase

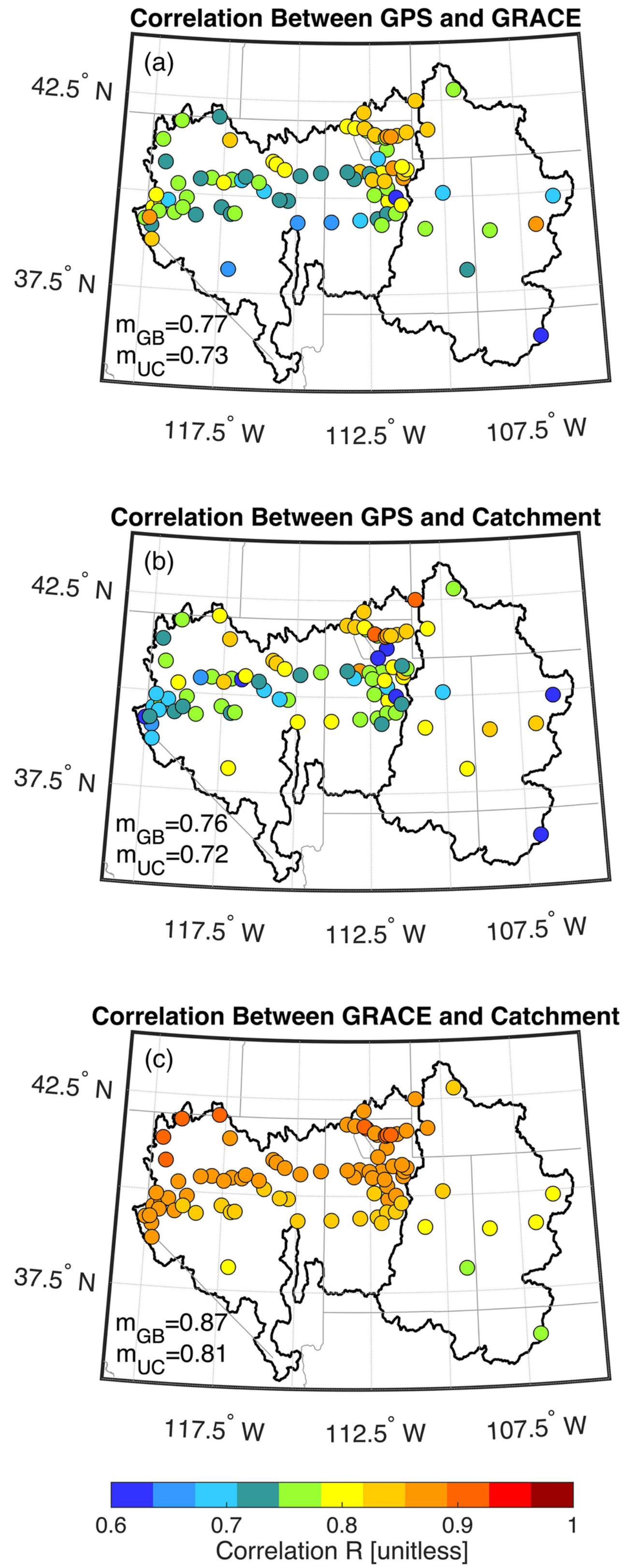

Figure 5. Correlation coefficient maps of vertical displacements derived from (a) GPS versus GRACE, (b) GPS versus Catchment, and (c) GRACE versus Catchment for all examined GPS stations in the Great Basin and Upper Colorado watersheds. m = watershed-averaged *R*; GB = Great Basin; and UC = Upper Colorado.

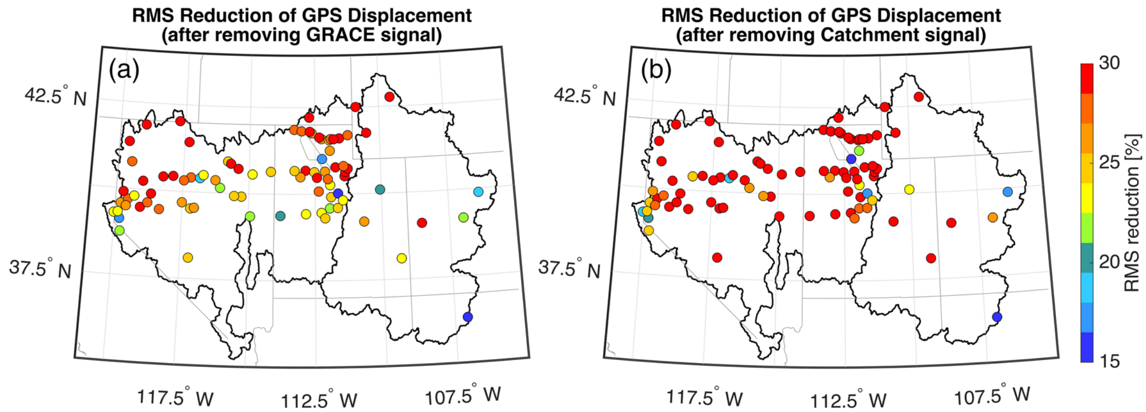

Figure 6. Maps of RMS reduction of vertical displacements derived from (a) removing GRACE time series from GPS time series and (b) removing Catchment time series from GPS time series.

consistency between two data sets, while RMS reduction takes both seasonal phase and amplitude into consideration. When the amplitude difference between two different data sets is significant, RMS reduction will be small even when the seasonal phase is identical. The relatively larger R values and smaller RMS reduction between GPS and GRACE (as compared to GPS versus Catchment) indicate that GPS and GRACE are in good agreement in terms of seasonal variation, whereas the amplitude differences cannot be neglected.

Following Knappe et al. (2019), the network-wide mean vertical displacement time series derived from ground-based GPS, GRACE, and Catchment using all stations were calculated as to represent the regional signal as illustrated in Figure 7. In the Great Basin watershed, the network mean time series derived from ground-based GPS shows a relatively consistent variation before 2011 and then an abrupt step that can be

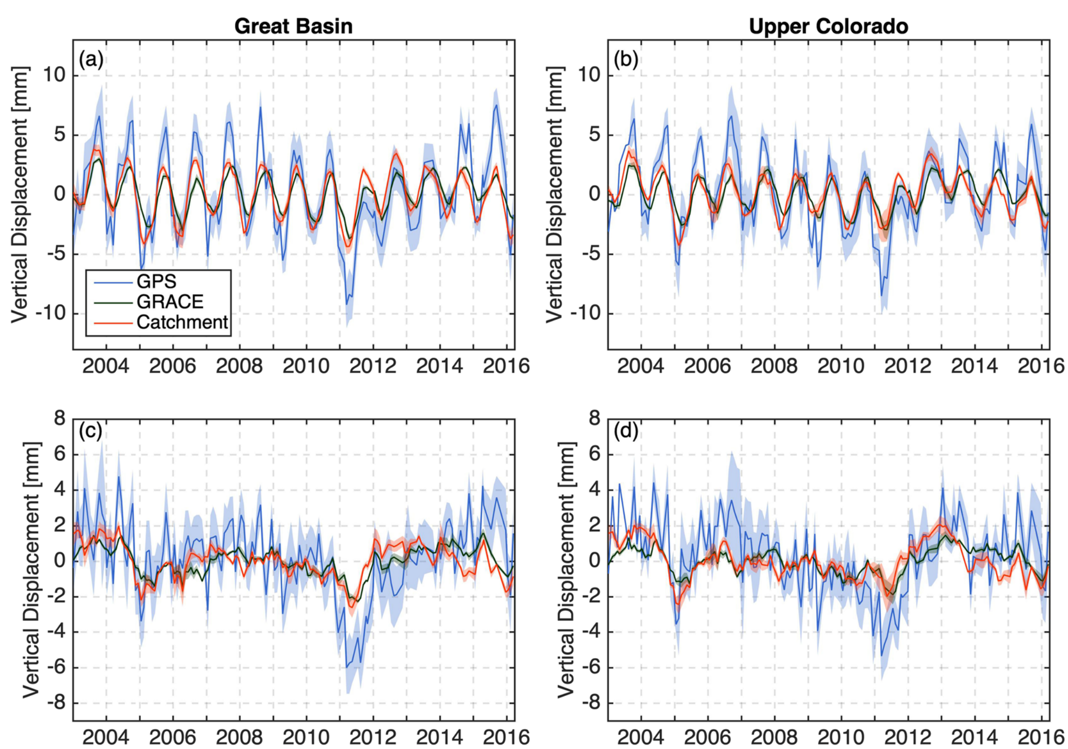

Figure 7. Network-wide mean vertical displacement time series derived from ground-based GPS (blue), GRACE (dark green), and Catchment model (red) in the (a) Great Basin watershed and (b) Upper Colorado watershed, and the corresponding network-wide mean seasonally adjusted vertical displacement time series in the (c) Great Basin watershed and (d) Upper Colorado watershed. The mean ± 1 std (standard deviation) are shaded with corresponding transparent colors.

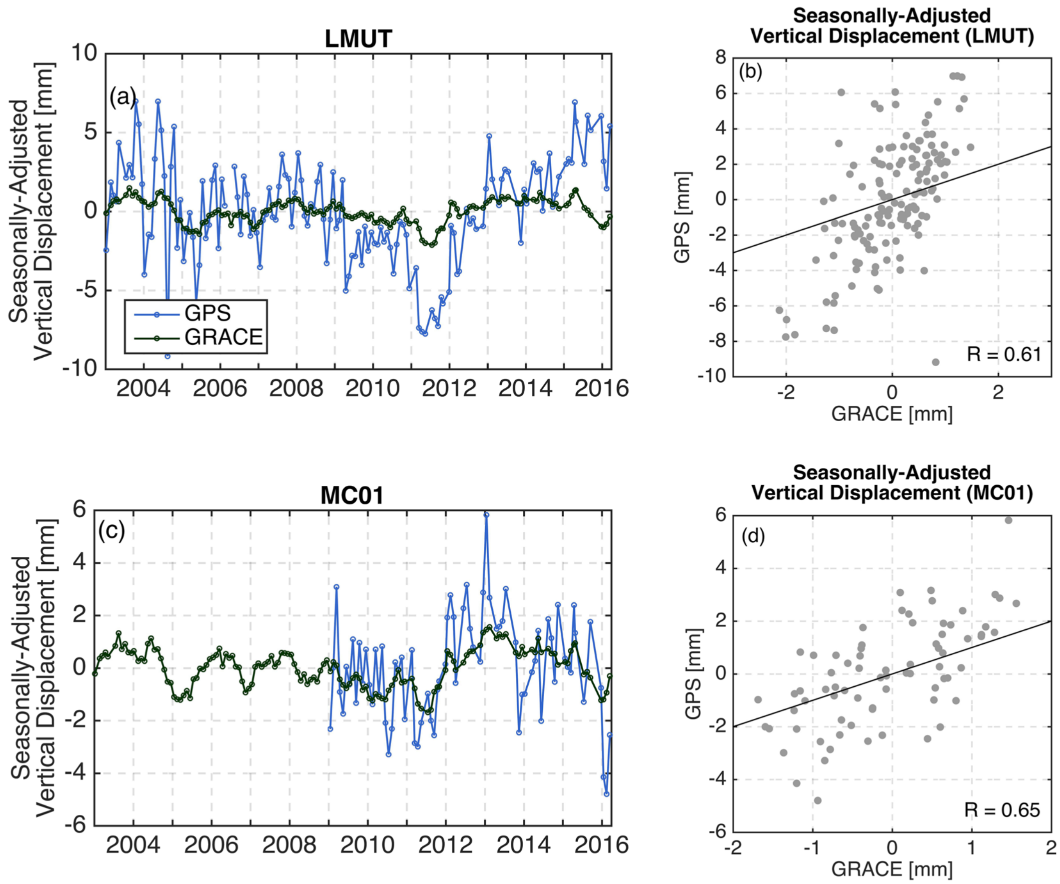

Figure 8. Comparison of seasonally adjusted vertical displacements derived from ground-based GPS (blue) and GRACE TWS retrievals (dark green) for stations (a) LMUT in the Great Basin watershed and (b) MC01 in the Upper Colorado watershed. The corresponding scatter plots between GPS and GRACE are shown in (b) and (d) along with correlation coefficient *R* values listed in the lower right-hand corner. The black lines in (b) and (d) represent the 1:1 line.

observed in early 2011 that is then followed by an increase of upward deformation after 2011. In the Upper Colorado watershed, a similarly abrupt step in the 2010–2011 winter can be detected from the GPS time series, but the following rebound is not as apparent. The correlation coefficients of (1) GPS versus GRACE, (2) GPS versus Catchment, and (3) GRACE versus Catchment were computed using the network mean time series. The computed *R* values are 0.83, 0.83, and 0.88 in the Great Basin and 0.81, 0.81 and 0.82 in the Upper Colorado Basin, respectively. A slightly higher consistency is found in the Great Basin than in the Upper Colorado watershed, which is coincident with the previous individual station analysis. As discussed earlier, an approximately 1-month phase lag was found between the GRACE and Catchment time series. Adjusting for the 1-month phase lag and recomputing the correlation coefficients between mean vertical displacement time series derived from GRACE and Catchment, the *R* values increased from 0.88 to 0.91 in the Great Basin and from 0.82 to 0.89 in the Upper Colorado.

3.2. Seasonally Adjusted Variation Analysis

The potential of using ground-based GPS vertical displacements to represent TWS interannual variations was investigated via the removal of the mean seasonal cycle (i.e., the multiyear average of each month) of vertical displacement embedded within the time series derived from GPS, GRACE, and Catchment. Again, the network-wide mean of seasonally adjusted vertical displacement time series following Knappe et al. (2019) was calculated for GPS, GRACE, and Catchment as shown in Figure 7. A positive, residual vertical displacement (i.e., after removing the mean seasonal cycle) represents a larger than multiyear averaged displacement for that particular month, which indicates less hydrologic loading than during expected climatology. On the contrary, a negative residual vertical displacement corresponds to more hydrologic loading for that particular month. For both the Great Basin and Upper Colorado watersheds, two distinguishable negative troughs were

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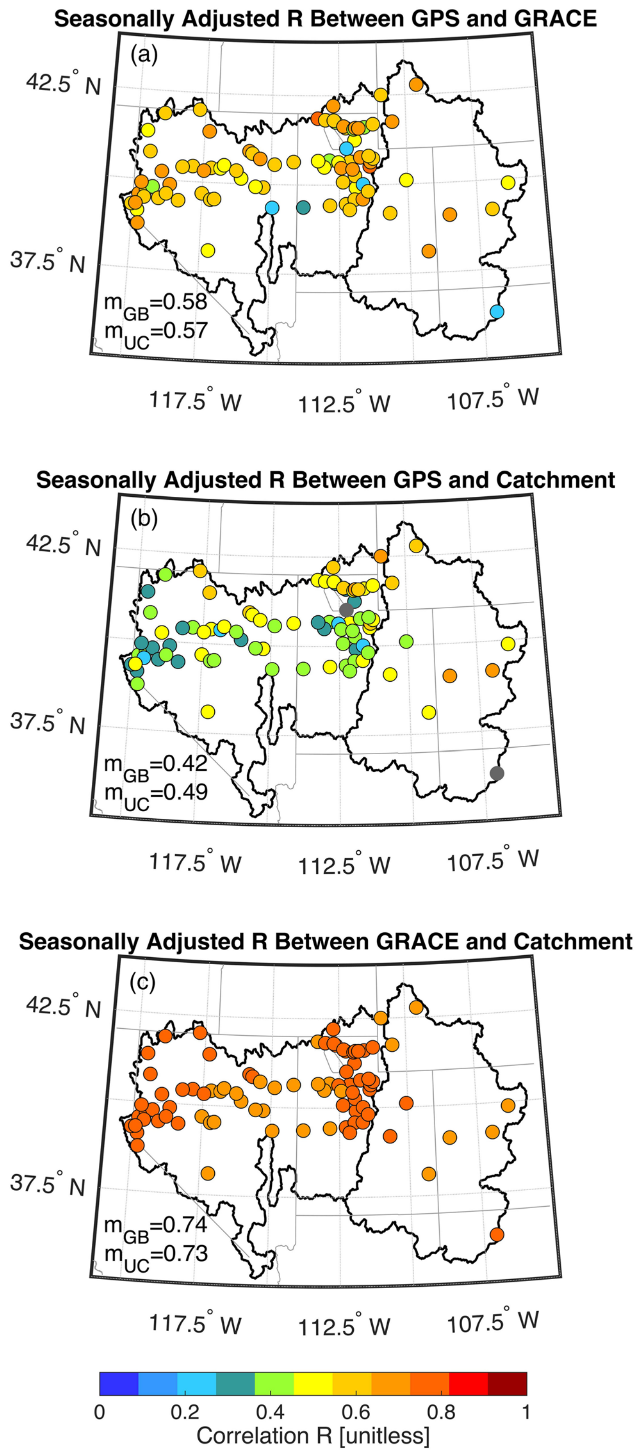

Figure 9. Seasonally adjusted correlation coefficients of vertical displacement after removing the mean seasonal cycle for (a) GPS versus GRACE, (b) GPS versus Catchment, and (c) GRACE versus Catchment for all examined GPS station locations in the Great Basin and Upper Colorado watersheds. The gray dots in (b) represent stations that provides a seasonally adjusted correlation coefficient not statistically different from zero. m = watershed-averaged seasonally adjusted *R*; GB = Great Basin; and UC = Upper Colorado.

captured during the 2004–2005 winter and 2010–2011 winter from estimates derived from GPS, GRACE, and Catchment. The residual displacement before and after the two evident troughs is continuous, positive values indicating potential drought periods, which are coincident with the percent area of drought time series provided by the U.S. Drought Monitor (Svoboda et al., 2002) (data accessible from https://www.drought.gov/drought/states).

For each watershed, one example representing a typical, seasonally adjusted vertical displacement variation along with the scatter plots between GPS and GRACE is shown in Figure 8. Considering the consistency of residual vertical displacements derived from GPS, GRACE, and Catchment, the seasonally adjusted correlation coefficient was calculated and subsequently mapped (Figure 9). For the Great Basin watershed, the average seasonally adjusted R between GPS and GRACE is 0.58, and the value for GPS versus Catchment is 0.42. The agreement between GRACE and Catchment is the highest ($R = 0.74$). The comparison results are similar in the Upper Colorado watershed with average seasonally adjusted R values of 0.57, 0.49, and 0.73, respectively for the cases of (1) GPS versus GRACE, (2) GPS versus Catchment, and (3) GRACE versus Catchment.

3.3. Surface Deformation and Hydrologic Loadings

Processed GPS observations of vertical displacement (i.e., after removing nonhydrological loadings) can help reflect TWS changes across local and regional scales. Knappe et al. (2019) found that seasonal synoptic precipitation patterns dominate the displacement observed by individual GPS stations. Therefore, in order to better to investigate the hydrologic cause of seasonal changes in the GPS time series, the most important hydrologic boundary condition precipitation is further explored here. Note that during the winter season in this region, most of the mass (precipitation) falls as snow. Hence, precipitation runoff is minimal during the winter season. Further, most vegetation is dormant during this period; hence, evaportranspiration is minimal during the winter season. Therefore, careful consideration of precipitation (snowfall) is most important in the context of hydrologic loading (mass accumulation) because there are relatively few outflows of water during the winter season.

Ground-based observations of SWE from the SNOwpack TELemetry (SNOTEL) network were used to examine the impacts of snowfall on the vertical displacement time series at both watershed and subwatershed scales. SNOTEL stations located inside the watershed boundary with a measurement record of SWE consisting of more than half of the study period were selected; the daily observations of SWE were averaged to monthly SWE according to the GRACE retrieval dates. There are 105 and 106 SNOTEL stations available for the Great Basin and Upper Colorado watersheds, respectively, as shown in Figure 10c with an annually averaged maximum magnitude of SWE presented in order to illustrate which areas receive the most snow relative to other measured areas. For each watershed, the SNOTEL-based SWE time series for each station was stacked from which the computed mean time series was used to represent the network-wide mean SWE as shown in Figure 10. Both watersheds exhibit clear seasonality in snow accumulation during the winter and snow ablation in the spring. The network-wide mean SWE using SNOTEL and network-wide mean vertical displacement time series derived from GPS, GRACE, and Catchment yield a large, negative correlation, indicating that snow is an important hydrologic loading in the study area. More specifically, R values against SNOTEL-based SWE in the Great Basin watershed are −0.74, −0.80, and −0.88 for GPS, GRACE, and Catchment, respectively. R values in the Upper Colorado watershed are −0.73, −0.77, and −0.81 for GPS, GRACE, and Catchment, respectively.

Considering the point-scale nature of ground-based GPS measurements, vertical displacement derived from GPS is expected to better represent local (~10 km) hydrologic loading variation as compared to GRACE and Catchment, which have coarser spatial resolution. The Great Basin watershed is used as a representative example to investigate the capability of GPS-based vertical displacement in inferring local hydrologic loading changes due to snow. Following the methods described in Knappe et al. (2019), the local variability in vertical displacement was extracted by subtracting the network-wide mean, vertical displacement time series from individual GPS-based monthly vertical displacement time series. The correlation coefficient between the residual vertical displacement (i.e., residual after removing the network-wide mean vertical displacement) and SWE time series was then calculated for all GPS-SNOTEL pairs whose separation distance is less than 10 km in the watershed. Note that network-wide mean SWE was not removed from individual SNOTEL SWE time series because at each SNOTEL station, the observations of SWE represent the truly local snow mass changes rather than the spatially integrated effects as measured by ground-based GPS. The same

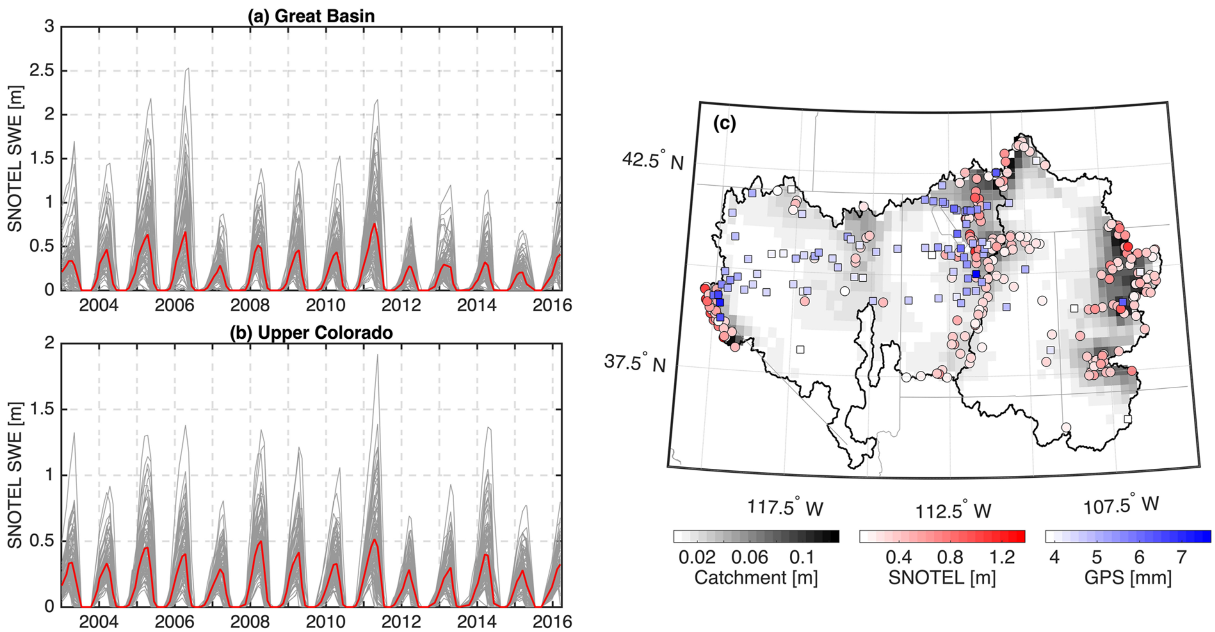

Figure 10. SWE time series derived from ground-based SNOTEL stations in the (a) Great Basin and (b) Upper Colorado watershed, with individual station time series in gray and station ensemble mean time series in red. (c) shows the annually averaged, maximum SWE derived from Catchment (gray scale), SNOTEL (red circles), and the annually average amplitude of ground-based GPS vertical displacement (blue squares). The annual amplitude of GPS vertical displacement is calculated by dividing the difference between the maximum and minimum of each year by two.

procedure was also conducted for vertical displacement derived from GRACE and Catchment. The correlation coefficients that are statistically significant to a level of significance $\alpha = 0.05$ are used for analysis. It is found that the residual vertical displacement is generally negatively correlated with SNOTEL SWE, with network-wide averaged R values of −0.46, 0.04, and −0.28 using the residual vertical displacement derived from GPS, GRACE, and Catchment, respectively. The anticorrelated behavior is not detected when using GRACE-derived residual vertical displacement due to the relatively coarse spatial resolution of GRACE TWS retrievals (∼400 km) that cannot resolve local hydrological loading variations at ∼10-km spatial scale. On the contrary, the more negative correlation between GPS-derived residual vertical displacement and SNOTEL SWE demonstrates the capability of ground-based GPS observations in providing information related to local-scale changes in TWS.

However, the negative correlations between residual vertical displacement and SWE are not especially strong for a variety of reasons including the following: (1) vertical displacement is influenced by changes in TWS, of which SWE is only a small component; hence, changes in TWS not related to SWE could weaken the correlation between vertical displacement and SWE; (2) the method of extracting local variability in displacement by removing the network-wide mean time series from all of the stations is not always ideal; (3) SNOTEL SWE measures mass loading resting on a snow pillow, and any mass moving off the sensor (e.g., via snow melt or wind redistribution) generally remains in the surrounding region and, by construct, is measured in the integrated TWS signal but not measured in the local SNOTEL SWE signal (Knappe et al., 2019); and (4) the separation distance between GPS and SNOTEL stations is not the only factor that influences the correlation; e.g., other factors such as elevation difference between the stations should also be considered. Errors in the collection and processing of GPS and SNOTEL measurements can also introduce additional discrepancies.

3.4. Interannual Change Since Late 2010

As discussed in section 3.1, a significant, negative vertical displacement followed by an increase in upward deformation can be clearly observed in the GPS vertical displacement time series starting in late 2010. A similar negative vertical displacement (and a corresponding rebound) can also be detected in most of the GRACE signals even though they are not as pronounced as for GPS. In Catchment-derived vertical displacement, the abnormally large, negative displacements seen in late 2010 as well as the prolonged vertical rebound is not captured at most stations. According to the National Climate Report (NOAA National Centers for

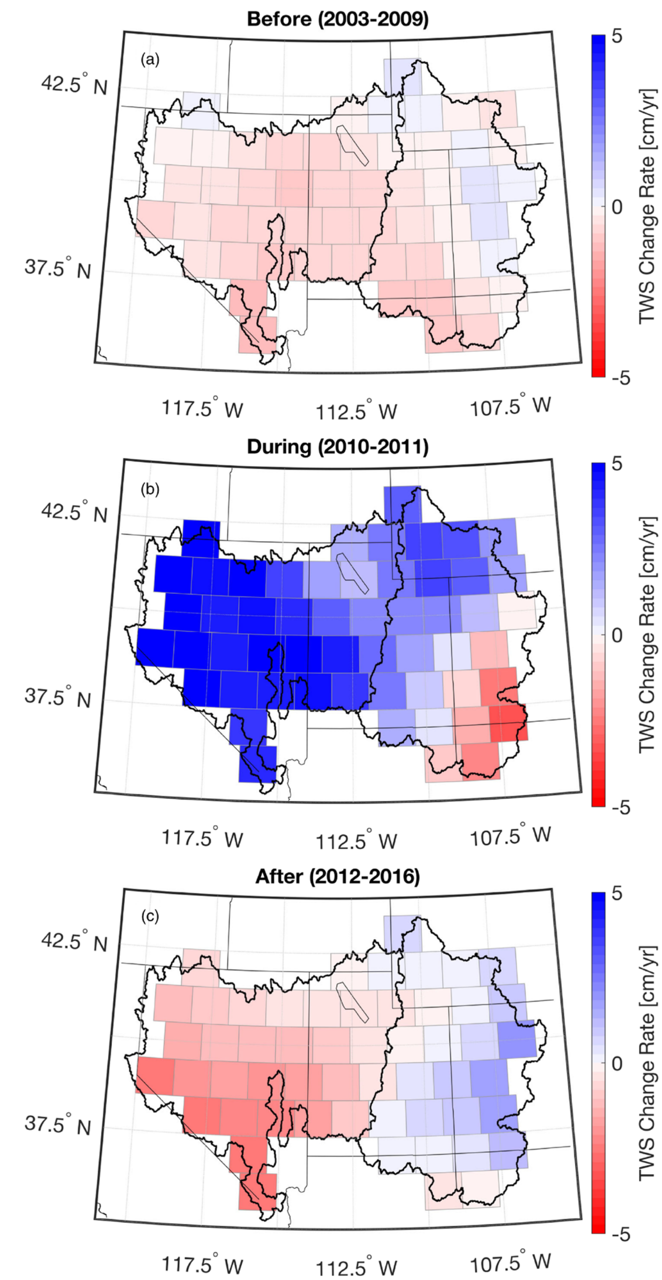

Figure 11. Slope of linear regression fitted to GRACE-derived TWS change in units of cm/yr (a) before (2003–2009), (b) during (2010–2011), and (c) after (2012–2016) the 2010–2011 La Niña event following the method described in Han (2017).

Environmental Information, 2011) for December 2010, Nevada and Utah had the wettest December in the 116-year record due to winter storms resulting from deep low-pressure systems that developed in a strong west-to-east flow in the jet stream circulation. The movement of cold fronts and low-pressure systems was influenced by two large-scale atmospheric circulation patterns, which are the La Niña and the Arctic Oscillation.

In order to quantitatively compare the increase of upward deformation since late 2010 as shown in the vertical displacement time series derived from GPS, GRACE, and Catchment, an uplift rate was fitted to the vertical displacement time series from October 2010 to March 2016 using the seasonally adjusted vertical displacements derived from GPS, GRACE, and Catchment. A statistical test was then conducted on the fitted uplift rate to examine if the rate is statistically different from zero or not. Based on the t test (level of significance $\alpha = 0.05$), 90% of GPS station locations yielded a positive uplift rate that is statistically different from zero using GPS-derived time series. The percentage when using GRACE-derived time series was 97%. For Catchment-derived time series, none of the station locations provided an uplift rate that is significantly different from zero. Hammond et al. (2016) studied vertical motions in Nevada using GPS observations, and a similar increased uplift velocity was observed; the reason for the step before and after 2011 was explained by heavy precipitation in the winter of 2010–2011 with a 5-year drought that followed. According to Adusumilli et al. (2019), there was a strong La Niña event during 2010–2011. A negative correlation coefficient between the Oceanic Niño Index (ONI) and TWS anomaly was reported in most regions of our study area, which suggests an increased TWS anomaly during the La Niña event.

In order to have a more straightforward view of the effect of La Niña on TWS changes, the TWS change rates before (2003–2009) and after (2012–2016) the La Niña event were estimated individually following a method from Han (2017) using TWS retrievals from GRACE. The estimated characteristics of TWS changes before, during, and after La Niña are shown in Figure 11. Before La Niña (2003–2009), there is no significant water mass loss or gain in either of the two watersheds. Most regions experience a negative water balance approximately −0.5 cm/yr (i.e., less precipitation than evapotranspiration) except for the eastern portion of the Upper Colorado watershed. During the La Niña event (2010–2011), a significant increase of TWS was observed in all areas of the Great Basin and over half of the Upper Colorado relative to the water storage during 2008–2009. The magnitude of increase in water storage decays when moving from west to east, which is consistent with previous studies showing a weaker anticorrelation between ONI and TWS anomaly toward the east (Adusumilli et al., 2019), and is relatively uncorrelated in the Colorado Basin (Ni et al., 2018). The TWS changes in the western portion of the Great Basin was around 8 cm/yr, whereas the southeast corner of the Upper Colorado had a negative water balance of around −3 cm/yr. After La Niña (2012–2016), the region effectively begins to dry out with a decrease of TWS of approximately −2.5 cm/yr in the western Great Basin. The areas less influenced by La Niña undergo a relatively smaller decrease in TWS. In areas showing a negative TWS change in the Upper Colorado during La Niña, a positive water balance around 1.5 cm/yr is observed after the La Niña event (2012–2016).

The TWS changes before, during, and after the La Niña event that occurred in 2010–2011 using GRACE-derived TWS retrievals show good consistency with the changes in vertical displacement derived from GPS. During the La Niña event (2010–2011), a significant water increase resulted in an extreme, negative vertical displacement detected in most of GPS observations. The extended water loss after the

La Niña event (2012–2016) resulted in the increase of upward deformation in GPS observations of vertical displacement. The good agreements between TWS change and GPS-derived vertical displacement demonstrate that GPS observations can be a good indicator of TWS change at relatively fine spatial scales. Catchment-derived vertical displacements show better consistency with GRACE-derived vertical displacements with larger R values; however, the prolonged drought after the La Niña event cannot be accurately reflected by the Catchment-based estimates even though some stations show an extremely large negative water balance in early 2011. Therefore, ground-based GPS deformation observations are a valuable data source for investigating TWS variations, especially at a relatively fine spatial resolution.

3.5. Analysis of Discrepancies and Error Sources

The comparison of vertical displacements derived from GPS, GRACE, and Catchment shows that a good agreement often exists with GPS time series showing a larger amplitude, which is approximately 2.4 times larger than the GRACE-derived vertical displacement time series amplitude. The amplitude difference between vertical displacement derived from ground-based GPS and space-based GRACE is also found in other studies. Khan et al. (2010) estimated a scale factor of ~2.5 between the vertical displacement derived from GPS and GRACE in Greenland. Fu et al. (2013) provides a scale factor of ~1.1 in the Amazon and ~1.2 in Southeast Asia between the GPS- and GRACE-based vertical displacement. The relatively larger amplitude in the GPS signal (relative to GRACE and Catchment) is anticipated as GPS is more sensitive to short wavelength local mass load variations as compared to long wavelength variations (Fu et al., 2013; Tesmer et al., 2011). On the contrary, GRACE can only sense long wavelength loading variations at monthly time scales, which results in a broader spatial scale (but smaller amplitude) of vertical displacement. Tesmer et al. (2011) compared vertical deformations from GRACE and GPS across the globe using 131 GPS stations whose vertical displacement time series are not dominated by local effects, and an improved consistency between GPS and GRACE was witnessed. Therefore, the spatial smoothing of many of the fine-scale features in smaller areas of the basin caused by the large, effective field of view of GRACE, in conjunction with leakage errors associated with large amounts of water concentrated in small regions (Figure 10c), likely manifests itself in the form of a reduction in annual amplitude in GRACE-based vertical displacement. As for Catchment, the model only includes shallow groundwater storage and hence, when converted, does not consider vertical deformation associated with changes in deep groundwater storage. Therefore, a smaller amplitude of vertical displacements via Catchment (relative to GPS) is anticipated.

The errors in GPS observations, GRACE retrievals, and Catchment estimates as well as the errors introduced during the processing procedure were investigated. GPS provides a direct measurement of surface deformation, which includes not only TWS variation but also nonhydrologic changes that may not be removed precisely or completely (Borsa et al., 2014; Herring et al., 2016). A number of studies explored the possible causes of errors in the ground-based GPS observations such as orbit mismodeling (Horwath et al., 2010), errors in ocean loading model (Tesmer et al., 2011; van Dam et al., 2007), and height changes caused by a negative relationship between the tropospheric zenith delay and the station heights in the original GPS system of equations (Tesmer et al., 2011). In many studies comparing GRACE and GPS vertical displacements, the atmospheric and nontidal ocean loadings were added back to GRACE to maintain consistency between the comparisons (Han, 2017; Tesmer et al., 2011; Zou et al., 2015). However, in this study, the focus is on the hydrologic loadings in the GPS signals, and thus, the AOD Level 1B product (GAC) used to remove atmospheric and nontidal ocean loading effects from GRACE was removed from the GPS signal instead. Considering the scale difference in the AOD model relative to the GPS observations, the removed atmospheric and nontidal ocean loading may not properly capture the local effects and thus may result in a discrepancy between the GPS and GRACE estimates. Another factor that may cause errors in the estimates of vertical displacement, but one that is not explicitly accounted for in this study, is groundwater pumping. GPS stations located on top of aquifers often respond nonelastically to large groundwater changes (due to land subsidence and subsurface consolidation), which is opposite to Earth's elastic response to snow (Argus et al., 2017). Earth's surface subsides when groundwater withdrawal occurs and rebounds when the aquifer is recharged. Although the study area used here is not significantly influenced by groundwater pumping activities, there will still be some scattered regions with groundwater pumping activities that merit further investigation. Therefore, a closer investigation into each single GPS station will help remove those stations influenced by local groundwater storage changes.

During the conversion of GRACE-derived TWS to vertical displacement, a homogeneous reaction of the Earth's crust to mass loading is assumed, which is not always appropriate and may result in some systematic regional effects (Tesmer et al., 2011). Further, as discussed before, GRACE-based TWS only detects mass load variations that cause long wavelength effects. Therefore, local mass variations may not be detected by GRACE and thus may not be represented in the GRACE-based vertical displacement time series.

As for the Catchment-derived vertical displacement, two main sources of error that should be highlighted are (1) error in Catchment-modeled TWS and (2) error in vertical displacement estimates via Green's function. Catchment only simulates shallow groundwater, which may result in significant errors especially during severe drought years (Houborg et al., 2012; Li et al., 2012). As for the second error source, the conversion of Catchment TWS to vertical displacement is conducted using Green's function assuming a PREM Earth model. The reaction of crustal deformation to changes in mass loading is assumed homogeneous, which may be unrealistic in some areas. Due to the large amplitude difference in the vertical displacements derived from GPS and GRACE (or Catchment), and given that many different factors likely contribute to these discrepancies, more exploration should be conducted in the future on the explicit justification of the impact of each factor in order to aid future investigations of TWS.

4. Conclusion

This study compared vertical displacements derived from ground-based GPS, space-based GRACE TWS retrievals, and model-based Catchment TWS estimates for the Great Basin and Upper Colorado watersheds in the United States. A good agreement between vertical displacements derived from the three distinct data sources was found; i.e., the $R_{\mathrm{GPS-GRACE}}$, $R_{\mathrm{GPS-Catchment}}$, and $R_{\mathrm{GRACE-Catchment}}$ values are greater than 0.8 using the network-wide mean vertical displacements derived from GPS, GRACE, and Catchment. When considering just GPS and GRACE, over 89% of all stations show a correlation coefficient of $R > 0.70$. The RMS reduction after removing GRACE from the GPS signals is consistently positive, indicating a good agreement between GRACE- and GPS-based vertical displacement time series. The highest consistency is found between GRACE and Catchment with all examined stations providing $R > 0.70$. As the information embedded in the GRACE TWS retrieval is related to TWS changes associated with hydrologic loading only, the positive correlation between GPS and GRACE indicates potential in merging the two distinct, yet complementary, information sources to better characterize TWS.

A noticeable change in vertical displacements in early 2011 was observed in most GPS time series, followed by an extended period of upward deformation. A similar pattern was observed in a number of GRACE-derived vertical displacement time series, but not in the Catchment-derived time series. Through an analysis of water balance interannual variation using TWS retrievals from GRACE, it was found that heavy precipitation induced by a strong west-to-east flow in the jet stream circulation from 2010 to 2011 influenced a large portion of the study area, especially the Great Basin, causing large, negative vertical displacements from late 2010 to early 2011 associated with a La Niña event. A prolonged drought after the La Niña event resulted in a rebound of vertical displacements. When accounting for the capability of GPS vertical displacement observations in reflecting TWS variability, it is considered a valuable source of information for water storage change at a finer spatial and temporal resolution relative to GRACE or global-scale LSMs. The ground-based GPS sensors can also help bridge the spatial scales between point-scale (e.g., SNOTEL) and satellite-scale (e.g., GRACE-FO) estimates of terrestrial mass change.

Additional research on the improvement of GPS processing procedures is needed to reduce the potential errors discussed in section 3.5 (e.g., atmospheric loading modeling and groundwater changes) in order to provide a more accurate time series of vertical displacement in response to changes in hydrologic loading. An investigation of incorporating horizontal displacement measured by ground-based GPS into the hydrologic loading analysis should also be explored in order to better resolve hydrologic loading changes in smaller regions such as lakes or other surface water impoundments (Wahr et al., 2013). Despite their limitations, given the related information content found in the GPS observations and the GRACE TWS retrievals, this work suggests that there is great potential to combine the two distinct information sources as part of a Bayesian merging procedure to be completed in a follow-on study with the ultimate goal of improving TWS estimation at finer spatial and temporal scales.

Data Availability Statement

UNAVCO provided GPS data products (https://www.unavco.org/data/data.html); NASA's Goddard Space Flight Center (GSFC) provided GRACE mascon solutions (https://neptune.gsfc.nasa.gov/grace/); GFZ German Research Centre for Geosciences (GFZ) provided AOD1B product (https://www.gfz‐potsdam.de/en/aod1b/); and NRCS National Water and Climate Center provided SNOTEL data. NASA's Global Modeling and Assimilation Office (GMAO) provided the Catchment Land Surface Model code and the Catchment output which are available at https://drum.lib.umd.edu/handle/1903/26166.

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